EM 1110-2-3800
30 Oct 2018

US Army Corps
of Engineers®
ENGINEERING AND DESIGN

BLASTING FOR ROCK EXCAVATIONS

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DEPARTMENT OF THE ARMY U.S.
Army Corps of Engineers
Washington, DC 20314-1000

CECW-CE
Manual
No. EM 1110-2-3800

30 October 2018

Engineering and Design
BLASTING FOR ROCK EXCAVATIONS

1. Purpose. This manual describes theory, concepts, and procedures surrounding rock excavation through the use of blasting agents and methods for use on Civil Works and Military Construction projects. It is intended to provide guidance to U.S. Army Corps of Engineers personnel (USACE) involved in the planning, design, monitoring, or implementation of blasting programs for rock excavation.

2. Applicability. This manual applies to Headquarters, U.S. Army Corps of Engineers (HQUSACE) elements, major subordinate commands (MSCs), Districts, laboratories, and field operating activities involved with the planning, design, monitoring, or execution of blasting programs for USACE.

3. Distribution Statement. Approved for release, distribution is unlimited.

4. References. Required and related references are located in Appendix A to this document.

5. Scope. The scope of this manual is limited to the use of blasting agents and methods for the purposes of rock excavation. While this may involve the removal of overburden, blasting near structures, and other specialty methods, this manual does not cover demolition of structures, or the use of explosives for ordinance. It is intended to acquaint the practitioner with the materials, tools, and methods for executing blasting programs for rock excavation. It is also intended as a guide for engineers and geologists designing excavation programs and for construction monitoring of those programs.

6. Discussion. There are many tools and techniques available for rock excavation, but few are as economical as the use of explosives. Rock blasting is effective for work as small as boulder removal (which use only very small amounts of explosives), to large scale excavations for mining, dam foundations, building foundations, lock construction, tunneling, and roadway building. The U.S. Geological Survey reports that, in 2012, total annual explosives consumption in the United States was 3.38 million metric tons and that explosives are used in "…virtually every segment of the manufacturing and major construction industry" (Apodaca 2012). Even though blasting materials are potentially dangerous and must always be handled with respect, caution, and great care, these blasting agents are vital part of the engineering toolbox.

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*This manual supersedes Engineer Manual 1110-2-3800, dated 1 March 1972.

7. Roadmap to this Manual.

a. Chapter 1 of this manual introduces the subject of blasting, briefly reviews blasting terminology, and introduces the types of rock blasting. The discussion of basic blasting terminology and introduction to the types of blasting are intended for novice readers and also for those returning to the subject who need terminology "refresher." More in-depth definitions are contained in the Glossary located at the end of this manual.

b. Chapter 2 discusses the many different types of explosives, the basic theory behind rock breakage, characteristics of explosives, and how explosives and blasting agents are chosen for a project. This includes the use of boosters, primers, and initiation systems. This chapter is intended to cover the topic of the materials and tools used to execute blasting programs.

c. Chapter 3 provides an in-depth discussion of the geologic considerations that may affect blasting operations, including rock type, rock mass structure, groundwater, and site exploration and characterization. All these geologic aspects must be considered to execute a successful program. Site characterization is a vital part of any blasting program. A better understanding of the site geology will lead to better blasting results.

d. Chapter 4 reviews drilling technologies and considerations, as very few rock excavation programs can be executed without drilling holes. This chapter covers drilling techniques commonly in use in blasting programs.

e. Chapter 5 covers the details of surface and underground blast design for the removal of rock. It introduces the principals of blast pattern design and outlines design considerations for the better control of rock fragmentation, fly rock, air blast, and vibration. This chapter discusses special situations such as rip-rap production, sinking cuts etc., and chapter ends with a discussion of the appropriate blast design documentation.

f. Chapter 6 delves into specialty blasting techniques including trim blasting, boulder blasting, cast blasting, and alternatives to blasting.

g. Chapter 7 addresses the topic of underwater blasting. As this topic could be a topic of a standalone manual, it is separated into its own chapter to give the reader a solid introduction to the topic.

h. Chapter 8 covers damage prediction, prevention, and control. While it is seldom possible to prevent all potential issues with blasting, a well-designed blast program can mitigate potentially problematic effects such as airblasts, excessive vibration, and fly rock.

i. Chapter 9 discusses preparation of contract specifications for USACE projects. While it does not include a guide specification, this chapter discusses types of contracting, needed language, and elements of successful specifications.

j. Chapter 10 includes an in-depth discussion of the documentation and monitoring needs during construction and execution of a blasting program.

k. Appendix A to this manual includes references and recommended reading list.

l. Appendix B contains blank examples of common blasting forms that can be used as a guide for developing specific forms for documenting blasting.

m. The Glossary to this manual defines technical terms, acronyms, and abbreviations used throughout this document.

FOR THE COMMANDER:

KIRK E. GIBBS
Colonel, EN
Chief of Staff

3 Appendices
(See Table of Contents)

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CHAPTER 1

Introduction

1-1. Purpose. This manual describes theory, concepts, and procedures surrounding rock excavation through the use of blasting agents and methods for use on Civil Works and Military Construction projects. It is intended to provide guidance to U.S. Army Corps of Engineers personnel (USACE) involved in the planning, design, monitoring, or implementation of blasting programs for rock excavation.

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1-6. History of Blasting.

a. Explosives have been used in mining and construction applications since 1627, the date of the first recorded use of black powder for rock blasting in a gold mine in Hungary. Before this, black powder was used primarily for military applications, signals and fireworks. The first recorded civil structure using black powder was the construction of the Malpas Tunnel of the Canal du Midi in France in 1679. Black powder remained in common use for construction and mining from the 1600s until the invention and application of nitroglycerine dynamite by Alfred Nobel in 1866. For much of that time, the composition of black powder remained unchanged with constituents of 75% saltpeter (potassium nitrate), 15% charcoal and 10% sulfur. Then in 1858, an American industrialist, Lammot du Pont began making sodium nitrate powder, a less expensive alternative to potassium nitrate based powder, but its use was curtailed after the invention of dynamite. Both were less effective in rock blasting than dynamite, which quickly superseded the older blasting technology.

b. Nitroglycerine, invented by the Italian chemist Ascanio Sobrero in 1847, was notoriously unstable, could explode when jolted, and was extremely sensitive to heat, sparks, or other ignition sources. Its power and ability to remain viable when wet were distinct advantages over black powder, thus it was used for excavation of some of the hardest rock along the U.S. transcontinental railroad under construction in the 1860s. State laws on transport necessitated manufacturing on site, and it remained considerably more dangerous than black powder.

c. The invention of the blasting cap, by Alfred Nobel in 1864 and the stabilization of nitroglycerine through the use of diatomaceous earth changed this situation. Nobel's dynamite allowed the easier transportation and more controlled initiation of blasting than could be achieved with nitroglycerine alone and was intended for use in mining and construction. In the United States, dynamite came into common usage after 1867 when Nobel licensed his process to a U.S. manufacturer. It became the first "high explosive" used in commercial blasting and saw its first large scale use in the construction of Hoosac Tunnel in 1876. Nobel went on to patent gelatin dynamites in 1875. Trinitrotoluene (TNT) was also developed in 1863 by Joseph Wilbrand as a yellow dye, but it was not used as an explosive for many years after its invention due to its high activation energy. It is less powerful than dynamite and has primarily been used as explosive ordinance. Dynamite remained the explosive of choice in construction and mining until 1956 when Robert Akre patented a lower cost alternative called Akremite that was made from ammonium nitrate and coal dust.

d. Later diesel oil was substituted for the coal dust, ammonium nitrate and fuel oil (ANFO) has stayed in common use since that time for rock blasting due to its stability and low cost. As of 2012 ANFO is by far the most commonly used explosive in North America. Other developments have expanded the blasters' toolbox since the development of ANFO with newer explosive products such as slurries, water gels, and emulsions.

e. Slurries and water gel explosives were invented by Dr. Melvin Cook in 1956 and was an alternative to ANFO in wet blastholes. Later emulsion explosives (1969) were developed by the blasting industry.

f. Developments in detonation cords, electric delay detonators, and shock tube detonators have further widened the available tools and techniques that can be used to fragment rock and better control the effects of blasting.

1-7. Basic Blasting Terminology.

a. A complete glossary is included in the appendix of this manual. However, since the next several chapters will use many of the terms listed here in their technical senses, this section is provided as a quick review for those readers who are beginning the study of blasting, or for those who need a refresher.

b. Explosives are chemical mixtures or compounds that, when subjected to shock, impact, or heat, produce a rapid chemical reaction, accompanied by a shock wave in the product, that results in the sudden release of energy through the process of detonation. This sudden release of energy, mostly in the form of hot gas, when properly confined and initiated, can be used to perform mechanical work on the surrounding material. There are four basic components in commercial explosives: carbon, hydrogen, nitrogen, and oxygen. These components are combined so that the explosive mixtures are part oxidizer and part fuel or sensitizer (Figure 1-1).

Oxidizers	+	Fuel	=	Explosives
Ammonium Nitrate (AN)		Fuel Oil (FO)		ANFO
Potassium Nitrate (saltpeter)		Sulfur and Charcoal		Black Powder

Figure 1-1. Example Formulations of Two Common Explosives.

c. Combustion is the exothermic chemical decomposition of a compound. It is a reaction between a fuel and an oxidizer.

d. Detonation occurs when the combustion of the explosive compound occurs more rapidly than the speed of sound. It propagates through the explosive material by a detonation, or shock wave. The speed of this wave through the surrounding rock will vary by explosive used, properties of the rock, and appropriate design of a blast.

e. Detonation Velocity is the speed that the detonation travels through the explosive once it has reached a steady state velocity.

f. Deflagration, or burning, occurs when the combustion of the explosive compound occurs at less than the speed of sound. It propagates through the explosive material through a flame front (heat transfer) with no shock wave.

1-8. Basic Blasting Terminology – Blast Design and Physical Layout of Explosives.

a. Rock Blasting is usually achieved by the drilling of holes into the rock. These holes are spaced to achieve the appropriate rock fragmentation, shearing, and heave needed for the project. Several common terms are used to refer to the blast design and physical layout of the explosives and holes. Rock blasting is the science and art of the use of controlled explosive energy to fragment, displace, and shear — thus facilitating the removal of rock. It can be used both for surface and subsurface rock excavation and for rock removal underwater. When this explosive energy is released inside rock, it produces both fragmentation of the rock and heave (displacing the rock from its in-situ condition). Blasts can be designed to fragment rock only for ease of removal, but can also be designed to fragment rock into smaller sizes useful for the production of rock products such as rip-rap.

b. Backbreak and Overbreak are fairly self-explanatory terms that denote rock breakage beyond the intended limits of excavation. In some usage, these terms are distinguished in that “backbreak” refers to fracturing beyond the limits of excavation, “endbreak” refers to fracturing beyond the edge or side limits of the blasting pattern, and “overbreak” refers to the actual removal of rock beyond the intended limits of the excavation.

c. Boreholes are holes drilled in rock into which explosives are placed (Figure 1-2). These are generally drilled using “destructive” drilling techniques that do not leave a rock sample such as core behind.

d. Burden is the volume of rock to be fragmented and displaced by blasting. There are two kinds, the drilled burden and the shot burden. (Figure 1-3) Illustrates this and next four terms.)

e. Drilled Burden is defined as the distance between a row of boreholes and the nearest free face. It is always measured perpendicular to a row. It is also the distance between any two rows of boreholes. When laying out a blasting pattern for a shot, this is the term usually meant when using the word "burden."

Figure 1-2. Empty Boreholes on a Regularly Spaced Pattern.

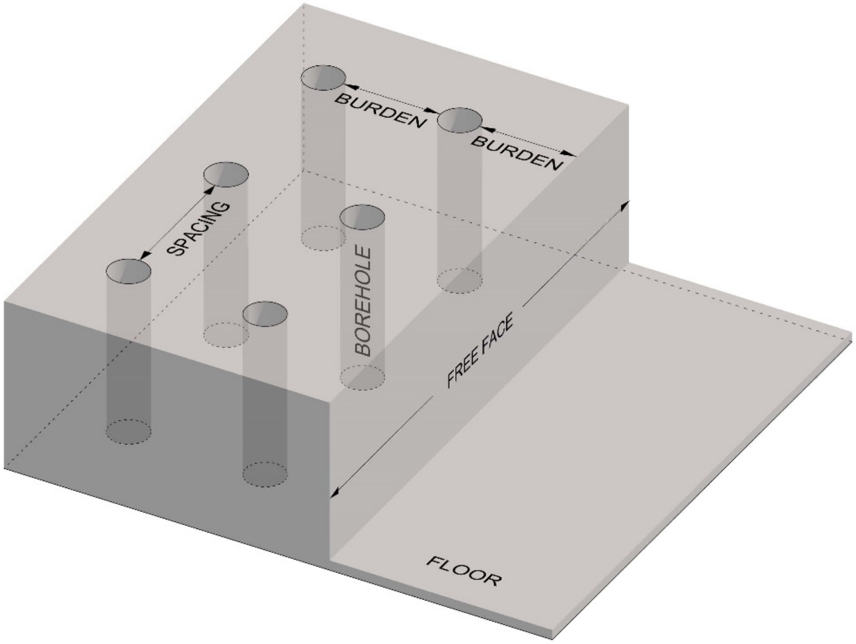

Figure 1-3. Blasting Layout Terminology.

f. True Burden is defined as the perpendicular distance between a single borehole containing explosives and the nearest free face.

g. Spacing is defined as the distance between holes that are located in a row. Drilling patterns are always defined as this spacing and the burden and spacing (e.g., for a 5 x 6 pattern, the blast design has a burden of 5 ft and a spacing between boreholes of 6 ft).

h. Relief is the presence of a free face in the rock mass such that the blasted rock can displace into that space as it heaves and expands due to the detonation. It can be a ledge or bench face or an internal face created by previous holes firing.

i. Free Face is defined as the nearest open face or relief. In rock blasting, this is at the edge of the rock face or relief created by previously fired blastholes. It is also the top surface of the rock that will be blasted. Features such as joints, faults, bedding planes, voids, and other discontinuities are not considered free faces because they do not allow for relief.

j. Decking is a method to create unloaded zones in an explosive column in a blasthole. “Decks” are often created by using stemming to separate several layers of explosives in a loaded hole. Decks may be used to increase the efficiency of the blast, to limit the amount of explosives at any given delay, or to accommodate a weak layer or void that has been encountered in the rock. Air decks are unloaded portions of the explosive column that contain no explosive or stemming materials.

k. Depth of Advance (underground blasting) is the total length of the borehole that broke from the formation or the distance a blaster wants to break down to the intended grade of the blast.

l. Stemming is the inert material put in a borehole to provide confinement along the axis of the borehole. Material used for stemming is commonly small sized crushed aggregate (Figure 1-4). Note that Corps’ practice generally forbids the use of drill cuttings as stemming.

m. Subdrill is the length of borehole drilled below finished grade or the bottom grade of the intended blast.

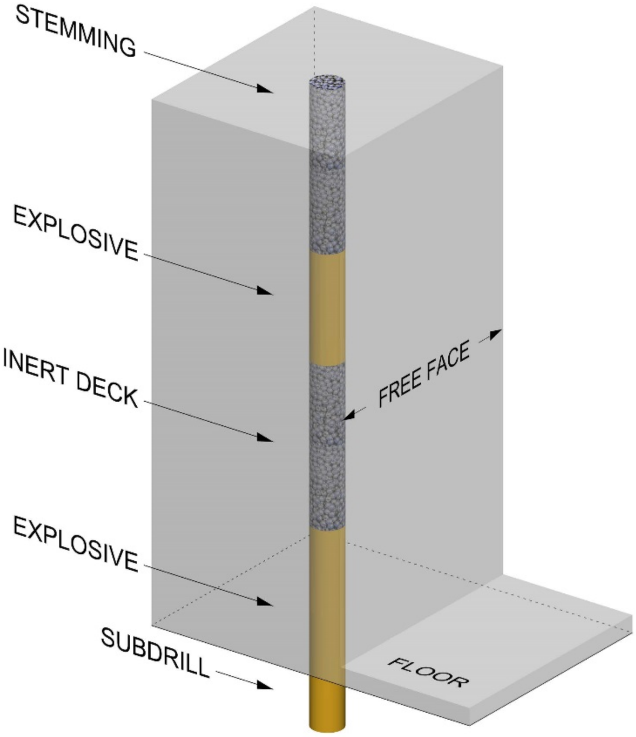

Figure 1-4. Borehole Explosive Layout Terminology.

n. Swell is the term used to account for the increase in volume of rock that has been blasted or otherwise excavated. The volume increases from the in-situ or in-bank condition because the piled rock fragments take up more space after the blast because when there is considerably more void space between the rock boulders and fragments than in the intact (pre-blast) condition.

o. Swell Factor is the percentage of increase in volume expected due to blasting or excavation.

1-9. Basic Blasting Terminology – Classification of Explosives.

There are a number of classifications schemes for explosives, but the U.S. Department of Justice Bureau of Alcohol, Tobacco, Firearms, and Explosives (ATF) divides explosives into three categories based on the behavior of the material when unconfined:

(a) Blasting Agents are high explosives that are less sensitive to initiation and cannot be detonated using a No. 8 strength blasting cap. These are also called “booster sensitive” or “non-cap sensitive” explosives. They require a booster to detonate. The most common blasting agent is ANFO.

(b) Low Explosives are an explosive material that deflagrates (or burns) at a high rate of speed when unconfined. The most common example is black powder.

(c) High Explosives are highly sensitive explosives that when unconfined can be can be detonated using a No. 8 strength blasting cap. A high explosive detonation is accompanied by a shock wave moving through the explosive. Dynamite is a type of high explosive.

1-10. Basic Blasting Terminology – Parts of Blasting Systems.

a. Blasting Caps are small, sensitive explosive devices that are generally used to transmit the detonation signal into a blasthole and detonate cap sensitive explosives. Blasting Caps can initiate instantaneously or can contain delay element so that the cap fires at a predetermined delay time in milliseconds.

b. No. 8 Blasting Cap is an industry standard blasting cap used as a detonator (Figure 1-5). It contains two grams of a mixture of 80% mercury fulminate (a secondary explosive) and 20% potassium chlorate (a primary explosive), or a blasting cap of equivalent strength. An equivalent strength cap comprises 0.014-.016 oz of pentaerythritol tetranitrate (PETN) base charge pressed in an aluminum shell with bottom thickness not to exceed 0.03 in., to a specific gravity of not less than 0.81 oz/in^3, and primed with standard weights of primer depending on the manufacturer. It is the most common type of blasting cap in use as of 2016.

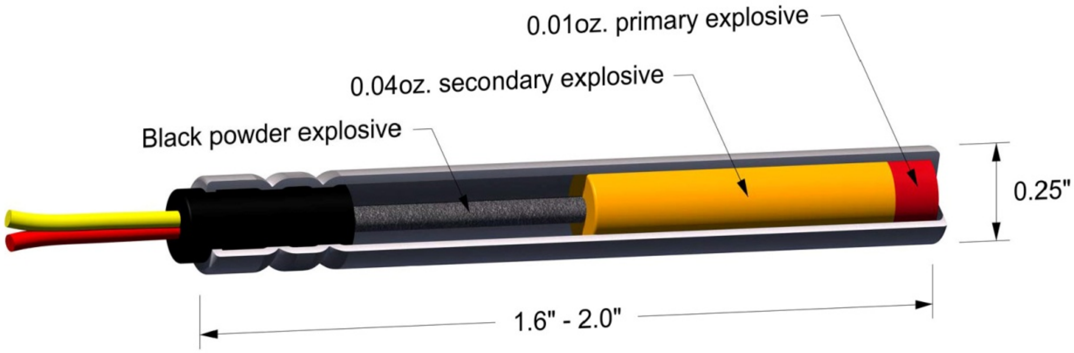

Figure 1-5. Example of No. 8 Blasting Cap.

c. A Booster is a sensitive, high energy, charge that can be used to set off a less sensitive explosive. Blasting agents such as ANFO require a booster to achieve detonation. A booster can be a more energetic charge placed in a specific location in a blasthole to have more energy in a harder rock layer.

d. A Delay is the time interval between successive detonations. These are used by the blaster to provide a progressive relief for rock to displace into as the shot evolves.

e. Detonating Cord is a round, high detonation velocity, flexible cord containing a center core of high explosive, usually PETN, within a reinforced waterproofing covering.

f. A Detonator is a device, either electric or non-electric, that is inserted into an explosive and used to cause the detonation.

g. The Initiation System is the entire system used to initiate the blast. This includes the detonator (electric or non-electric), delay devices, and all their connecting parts.

1-11. Basic Blasting Terminology – Introduction to Types of Rock Blasting. Conventional blasting techniques include several different types of blasting that are commonly used:

a. Production Blasting is a blast that is intended to fragment and displace a designed volume of rock. The focus of this blast is the maximum volume of rock fragmented per amount of explosive used. This blasting technique by itself will produce a ragged rock face and does not provide protection against back break or overbreak at the new rock face.

b. Secondary Blasting is a secondary blast used to fragment rock that was not adequately fragmented by the initial production blast.

c. Presplit Blasting is a controlled blasting procedure that is used to produce a shear plane within the rock mass. Most often used to produce a clean, relatively solid rock cut face, presplit blasting involves the use of boreholes that are more closely spaced and lightly loaded than production blastholes. A crack propagates along this line of more lightly loaded holes that are detonated ahead of the main production blast. The crack is intended to protect the new rock cut face, or some other perimeter, by allowing the blasting gases to escape and for blasting cracks to terminate at the presplit creak. This has the effect of reducing backbreak, or overbreak in the new rock wall, thus preserving its structural integrity. This method is used extensively for roadway rock cuts, lock walls, and any other cuts to produce a solid wall with little or no backbreak is needed. It is used to reduce the amount of rockfall that can occur from the exposed face than could be expected using production blasting alone. When well executed, the exposed rock face may contain “half casts” of the boreholes used for blasting. Presplit blastholes are fired before the production blast, which is between the presplit blast and the free face. The production blast may follow the presplit blast with a connected delay or fire completely separate from each other. During the initial evaluation period of pre-splitting results it is recommended that the presplit blast be its own blast that way the results can be evaluated.

d. Precision Presplit Blasting is a controlled blasting procedure that is used to produce a shear plane within a weak rock or one that is geologically complicated with the minimum amount of explosive and minimum overbreak. Used to produce a clean, relatively solid rock cut face where rock is weak or rock has extensive geologic discontinuities such as closely spaced jointing. Precision presplit blasting involves the use of boreholes that are more closely spaced and loaded lighter than standard Presplit blastholes. A crack propagates along this line of more lightly loaded holes that are detonated ahead of the main production blast. The crack is intended to protect the new rock cut face, or some other perimeter. When well executed, the exposed rock face may contain “half casts” of the boreholes used for blasting. Precision Presplit blastholes are fired before the production blast, which is between the presplit blast and the free face.

e. Smooth Blasting, commonly called “Trim Blasting” is similar to presplit blasting, but the holes are detonated after the production blastholes are detonated. The purpose is to blast loose remaining burden with lighter charges while not causing any additional damage to the new rock wall face. Smooth blasting is commonly used underground.

f. Precision Trim Blasting is a controlled blasting procedure that is used to produce a shear plane within a weak rock or one that is geologically complicated with the minimum amount of explosive and minimum overbreak. It is used to produce a clean, relatively solid rock cut face where rock is weak or rock has extensive geologic discontinuities such as closely spaced jointing. Precision trim blasting involves the use of boreholes that are more closely spaced and loaded lighter than standard Trim blastholes. Precision Trim blastholes are fired after the production blast, which is between the perimeter and the free face.

g. Buffer Blasting refers to a designated section of rock between a slope or wall to be formed by line drilling or presplitting during excavation and the production blast. The explosives in the buffer blasthole and the burden in the buffer zone are reduced to prevent damage to the final rock slopes or face. Buffer blasting can be fired after the adjacent production blast or as a separate shot.

h. Sinking Cut Blast is where a blast has only the top or horizontal face and has no vertical or sloped free face (Figure 1-6). Rock cannot be displaced sideways in this type of blasting and thus it must be expelled upwards. Flyrock is a particular problem with this type of blast as it is not possible to direct the blasting energy in any direction but up. This must be accounted for during design and monitoring.

Figure 1-6 Sinking Shot Loaded and Hooked up for Excavating a Lock Monolith Foundation.

1-12. Basic Blasting Terminology – Features of Rock Blasting and Control.

a. Flyrock is the rock that is launched into the air and travels further than was intended by the blast design. Flyrock can cause considerable damage.

b. Blasting Mats are used to help control flyrock (Figures 1-7 and 1-8). These are very heavy mats usually made from rubber tires, conveyor belts, steel cables, or other similar materials. Blasting mats are of particular use where flyrock may damage buildings or other structures.

Figure 1-7. Rubber Blasting Mats Being Lowered Onto Shot at Kentucky Lock.

Figure 1-8. Wire Blasting Mats Protects Structures (Courtesy of Mazzella Mats).

c. Heave (also called Throw) is the distance the rock displaces from the in-situ condition due to blasting.

d. Powder Factor is the ratio between the weight of explosives that have been detonated and the total volume of rock that was blasted. For construction practice, this volume is measures in cubic yards or cubic meters. The powder factor of the blast includes the total weight of explosives and the total volume of rock above grade level. The powder factor should always be reported on construction monitoring documents. The units of powder factor are pounds per cubic yard or kilograms per cubic meter.

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CHAPTER 2

Explosives

2-1. Introduction. In excavation, explosives are used as a tool to provide the energy needed to fragment and displace the rock. This energy is provided by a rapid chemical reaction in the explosive induced by shock, impact, or heat. Modern explosives used for construction purposes require an initiation system of some kind, a shock, impact, or heat to start the chemical reaction needed to produce the work required. This chapter discusses the types and characteristics of explosives as well as initiation systems used in rock excavation. It begins with some theory on the mechanics of rock breakage to give the reader an introduction to how explosives work, and ends with a discussion of some safety and transportation issues surrounding the use of explosives.

2-2. Mechanics of Rock Breakage.

a. There are four basic effects of the detonation of explosives used for rock excavation: (1) rock fragmentation, (2) rock displacement, (3) ground vibration and (4) air overpressure. These effects are controlled by the confinement of the explosive and also the two basic forms of energy that are released when high explosives detonate: (1) shock energy and (2) gas energy. Explosives can be detonated in an unconfined or confined manner. An example of a confined application is when explosives are used in a borehole with stemming material and surrounded by rock.

b. Although both types of energy are released during the detonation process, the blaster can select explosives with different proportions of shock or gas energy to suit a particular application. If explosives are used in an unconfined manner, such as mud capping boulders (see Chapter 6) or for shearing structural members in demolition, the selection of an explosive with high shock energy is advantageous. On the other hand, if explosives are used in boreholes and confined by the use of stemming materials, an explosive with a high gas energy output is beneficial.

c. To help form a mental picture of the difference between the two types of energy, compare the difference in reaction of a low and high explosives. Low explosives, such as black powder, are those that deflagrate, or burn, very rapidly. These explosives may have reaction velocities of 2000 to 5000 ft. per second and produce no shock energy. They produce work only from gas expansion. High explosives, such as dynamite, detonate and produce not only gas pressure, but also shock pressure.

d. Figure 2-1 shows these differences with a diagram of reacting cartridges of low explosive and a high explosive. For a low explosive, if the reaction is stopped when the cartridge has been partially consumed and the pressure profile is examined, one can see a steady rise in pressure due to the reaction until the maximum pressure is reached. Low explosives produce only gas pressure during the combustion process. A high explosive detonates and exhibits a different pressure profile producing shock energy at the reaction front followed by the gas pressure.

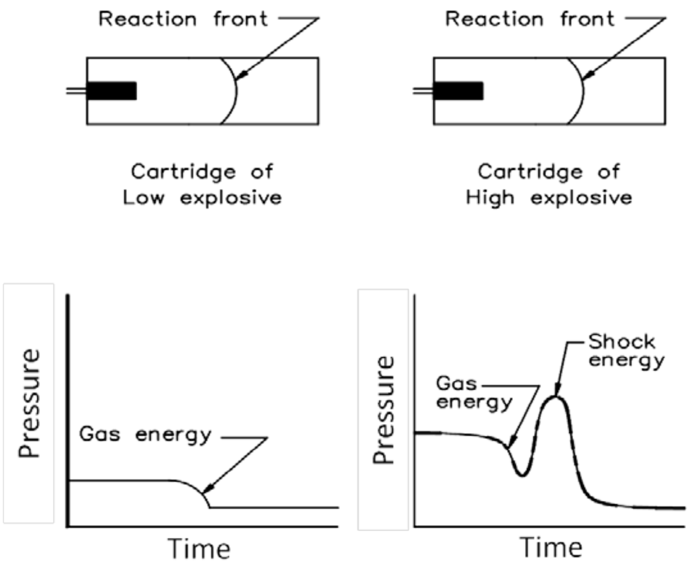

Figure 2-1. Pressure Profiles for Low (Left) and High (Right) Explosives.

e. This shock energy produced by the high explosive normally results in a higher pressure than gas expansion produces. After the shock energy passes, gas energy is released. The gas energy in high explosives is much greater than the gas energy released in low explosives. The shock pressure is a transient pressure that travels at the explosives rate of detonation. This pressure is estimated to account for only 10% to 15% of the total available useful work energy in the explosion. The gas pressure accounts for 85% to 90% of the useful work energy and follows the shock energy. However, unlike the transient shock energy, the gas energy produces a force that is constantly maintained until the confining vessel, usually the borehole, ruptures. This causes fracturing in the rock that is continued until this pressure is relieved. In an ideal model, a homogeneous rock mass, the shock energy will propagate outward, out running the growing fracture tips at the edges of the rupture, much like the ripples on a pond. This energy will attenuate proportional to the square of the distance from the blast and in relation to the elastic properties of the rock. While this picture is more complicated when taken from the ideal of homogeneous rock and applied in a rock mass where the reaction will be modified by the presence of inhomogeneities and discontinuities it is useful to understand how this energy will move through and idealized rock before adding the complicating factors of more site specific rock mass.

f. The shock energy is commonly believed to result from the detonation pressure of the explosion. The detonation pressure, a form of kinetic energy, is a function of the explosive density times the explosion detonation velocity squared. Determination of the detonation pressure is very complex but an estimate of the detonation pressure can be calculated with:

$$P = \frac{4.18 \times 10^{-7} \times Ve^2 SG_e}{1+0.8SG_e} \tag{2-1}$$

where:

P = Detonation pressure (Kilobar, 1 Kilobar = 14,504 psi).

SG_e = Specific Gravity of the explosive.

Ve = detonation velocity (ft/s).

g. The detonation pressure or shock energy can be considered similar to kinetic energy; it is at its maximum in the direction of travel. This means the detonation pressure will be highest in the end of the explosive cartridge opposite where the initiation occurs. This property explains why when mudcapping boulders, it is more effective to place the cartridge with the bottom directed toward the boulder, rather than placed sideways on the boulder (Figure 2-2). Therefore, to maximize the use of the detonation pressure, the explosive should be in good contact with the rock to be blasted. An explosive with high density and high detonation velocity will result in a high detonation pressure.

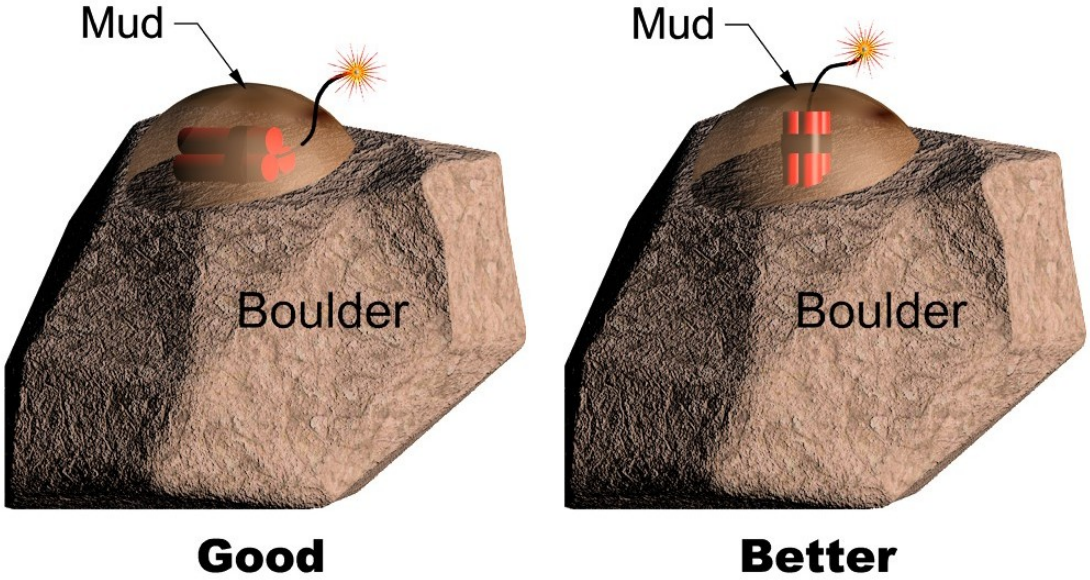

Figure 2-2. Mudcapping Explosive Placement.

h. The gas energy released during the detonation process causes the majority of rock breakage in rock blasting where charges are confined in boreholes. The gas pressure, often called explosion pressure, is the pressure that is exerted on the borehole walls by the expanding gases after the chemical reaction has been completed.

i. Explosion pressure results from the amount of gases liberated per unit weight of explosive and the amount of heat liberated during the reaction. The higher the temperature produced, the higher the gas pressure. If more gas volume is liberated at the same temperature, the pressure will also increase. For a quick approximation, it is often assumed that explosion pressure is approximately one-half of the detonation pressure. The nomograph pictured in Figure 2-3 shows explosive density, explosion pressure, detonation pressure, and detonation velocity.

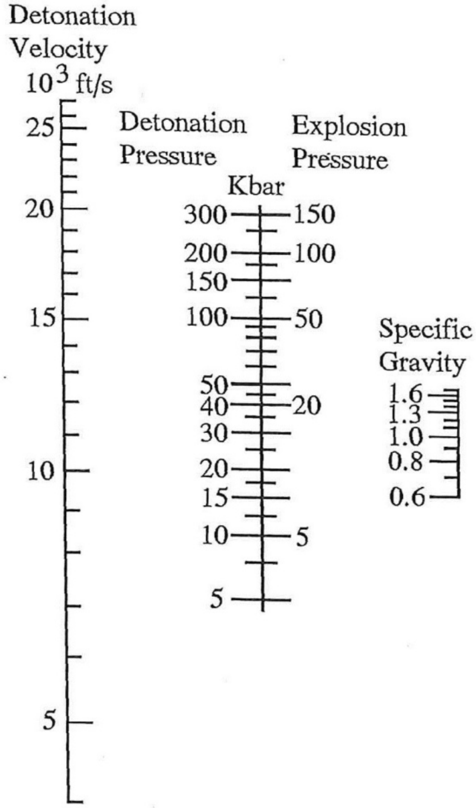

Figure 2-3. Nomograph of Detonation and Explosion Pressures.

j. Confinement of the charge also has a significant effect on the amount of energy that is directed toward the rock fragmentation as opposed to air overpressure or air blast. Figure 2-2 demonstrates, with the older mechanism of mudcapping, that the mud placed on top of an unconfined explosive charge in either configuration provides almost no confinement for an explosive. Unconfined charges placed on boulders and subsequently detonated produce shock energy that will be transmitted into the boulder at the point of contact between the charge and the boulder. Since most of the charge is not in contact with the boulder, the majority of the useful explosive energy travels out into space and is wasted. This wasted energy manifests itself in excessive air blast overpressure. Gas pressure can never build since the charge is essentially unconfined; therefore, gas energy does little work. The mud does couple the explosive to the rock and acts as a wave trap that reflects some of the escaping shock energy downward toward the boulder (Figure 2-4). Ultimately, if a borehole charge was used instead of placing the charge on top of the boulder considerably less explosive can be used as it will harness both the shock and the gas energy.

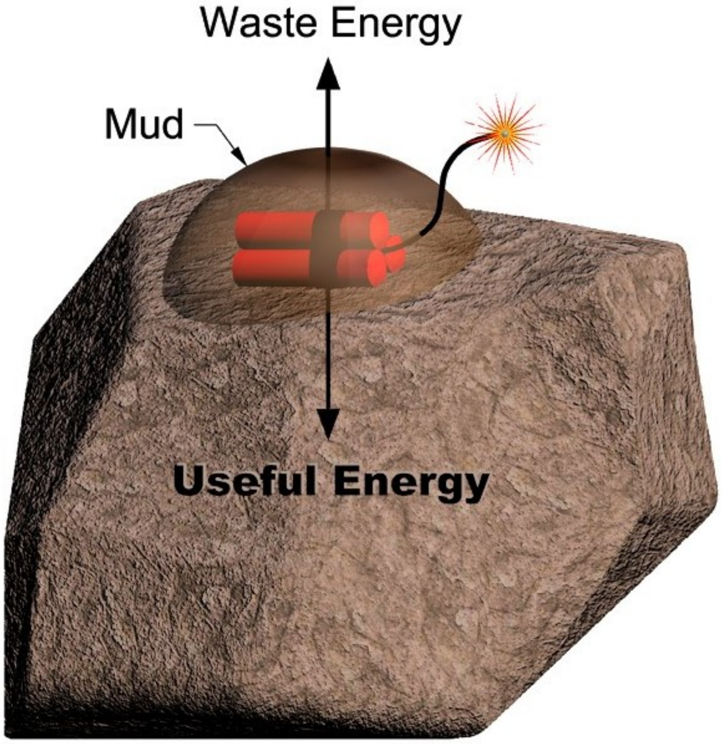

Figure 2-4. Reflection of Energy into the Boulder from the Older Method for Mudcapping Cartridge Placement.

k. Confined charges have four basic mechanisms that contribute to rock breakage: (1) shock wave, which can initiate microfractures on the borehole wall and moves through the rock uniformly in all directions around the charge causing initial radial microfractures, (2) sustained gas pressure, which penetrates and extends the radial microfractures toward the face, (3) the face begins to bend outward due to the expanding gases, and (4) fractures are created in the third dimension as a result of this flexural failure or bending.

l. The first occurrence in time, but the least significant mechanism of breakage, is caused by the shock wave or stress wave. At most, the shock wave causes radial microfractures to form on the borehole walls and may initiate microfractures at major discontinuities in the burden. This transient pressure pulse quickly diminishes with distance from the borehole. Since the propagation velocity of the pulse is approximately 2.5 to 5 times the maximum crack propagation velocity, the pulse quickly outruns the crack propagation or fracture propagation.

m. The more important mechanism is the sustained gas pressure. When the solid explosive is transformed into a gas during the detonation process, the borehole acts similar to a cylindrical pressure vessel. Failures in pressure vessels, such as water pipes or hydraulic lines, offer an analogy to this mechanism of rock breakage. When the vessel is over pressurized, the pressure exerted perpendicular to the confining vessel's walls will cause a fracture to occur at the weakest point. In the case of frozen water pipes, a longitudinal split occurs parallel to the axis of the pipe (Figure 2-5).The major difference between pressurizing a borehole and pressurizing a water pipe is rate of loading. A borehole is over pressurized almost instantaneously and therefore does not fail at one weakest point along the borehole wall. Instead, it will simultaneously fail in many locations in a geometric pattern. Each resulting fracture will be oriented parallel to the axis of the borehole. Failure by this mechanism has been recognized for many years and is commonly called radial cracking. Figure 2-6 shows this same radial fracturing in rock at the bottom of a borehole after rock has been removed.

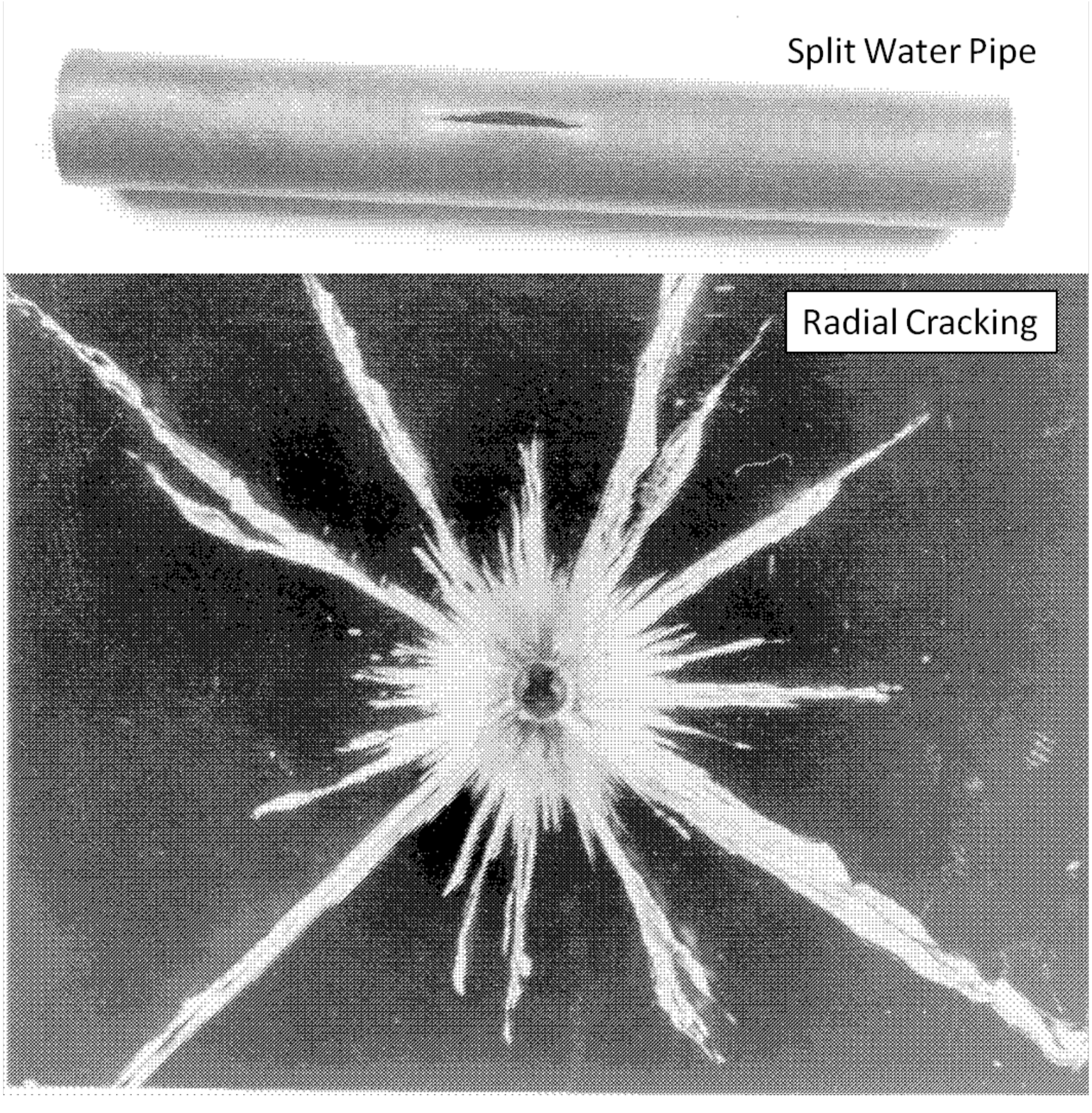

Figure 2-5. Split Water Pipe Due to Overpressure and Radial Cracking Around a Hole in Plexiglas.

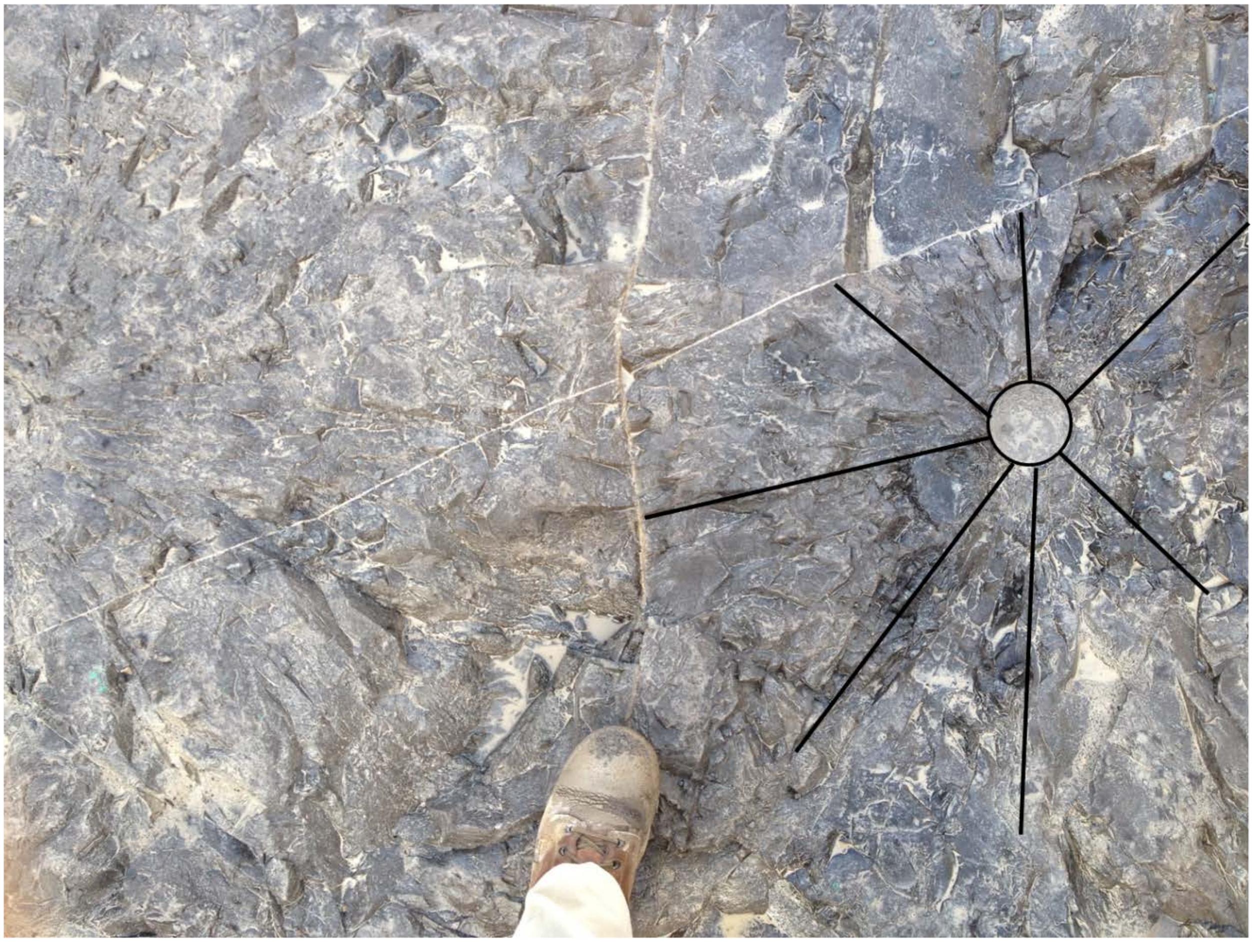

Figure 2-6. Radial Fracturing in the Subdrill Due to Blasting.

n. The third mechanism is relief of the sustained gas pressure by the free face and movement of the cracked rock mass. There is a time lag in the rock mass from the formation of the initial radial cracking and the extension of that radial cracking toward the relief face. The distance of that face influences the formation of the radial crack system. Here the burden in the rock is transformed from a solid rock mass into one that is broken by the radial cracks in many wedge-shaped or pie-shaped pieces. These wedges function as columns, supporting the burden weight. Columns become weaker if their length-to-diameter ratio or slenderness ratio increases. Therefore, once the massive burden is transformed into pie-shaped pieces with a fixed bench height, it has been severely weakened due to the fact that its slenderness ratio has increased.

o. The high pressure gases subject the wedges to forces acting perpendicular to the axis of the hole that push toward relief or toward the line of least resistance. This concept of relief perpendicular to the axis of the hole has been known for well over a hundred years. Relief must be available perpendicular to the axis of the hole for borehole charges to function properly. If relief is not available, only radial cracks will form. As a result, boreholes will crater or the stemming will be blown out. In either case, the fragmentation suffers and environmental problems result. The direction and extent of the radial cracking system is controlled by the selection of proper burden from the borehole to the face (Figure 2-7).

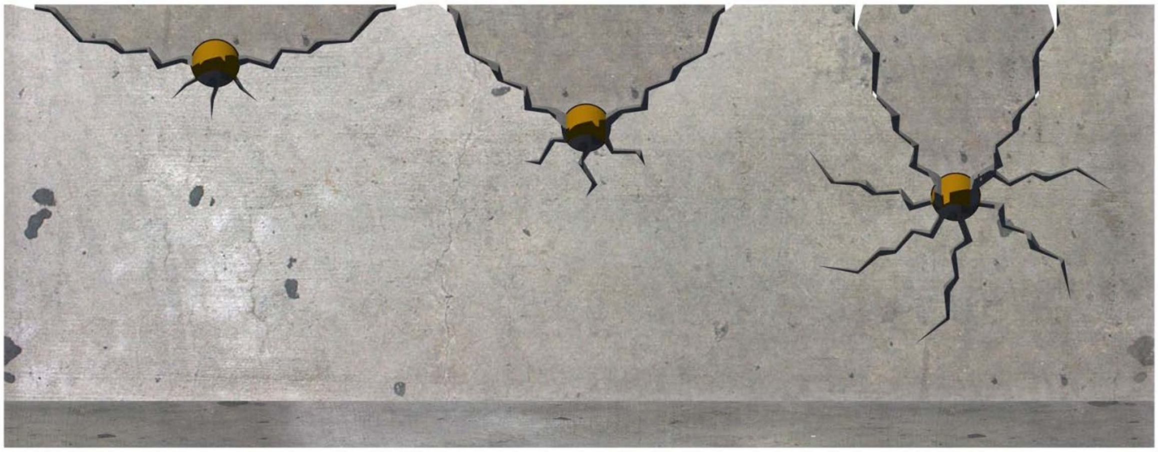

Figure 2-7. Influence of Distance to the Relief Face on Development of Radial Cracks.

p. Finally, the flexure of the entire mass ensures cracking in the third dimension so that the rock is displaced outward from the face. This is the second major breakage mechanism called "flexural failure." In most blasting operations, the first visible movement occurs when the face bows outward near the center (Figure 2-8a). In other words, the center portion of the face is moving faster than the top or bottom of the burden. This type of bowing or bending action does not always occur. One can find cases where instead of the center bowing outward, the top or bottom portion of the burden is cantilevering outward. These other two cases cause problems in blasting. The blast design controls the mechanism of "flexural failure." Figure 2-8 shows the three mechanisms often seen in rock blasting.

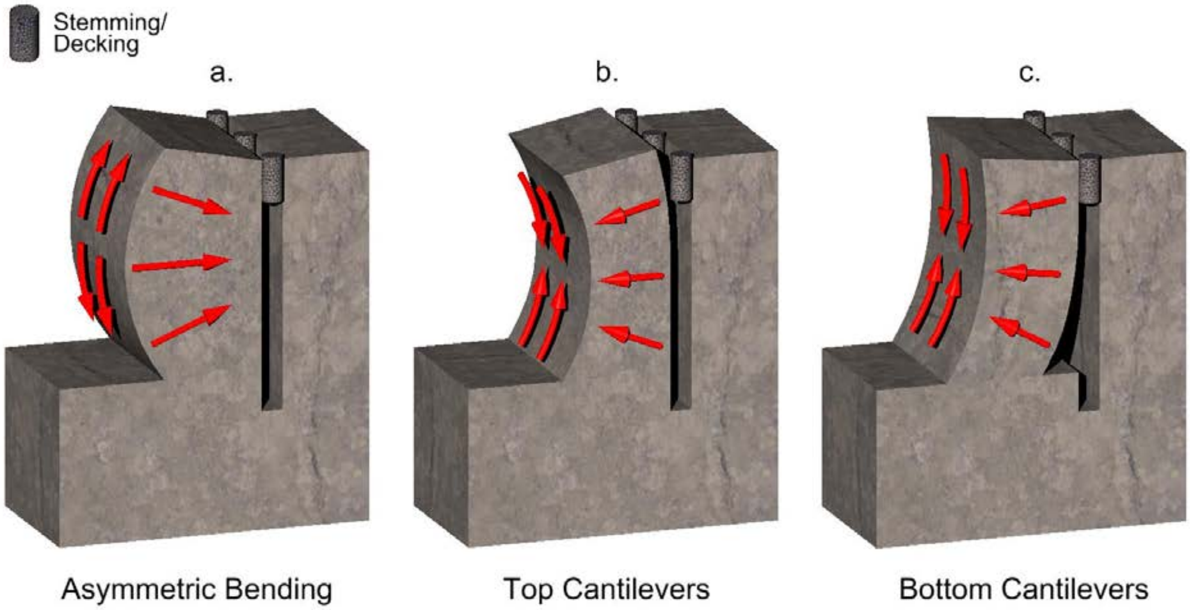

Figure 2-8. Flexure and Direction of Displacement of the Rock Mass.

q. Two general modes of flexural failure of the burden exist. In one case, the burden bends outward or bulges in the center more quickly than it does on the top or bottom (Figure 2-8a). When the burden rock bulges at its center, tensile stresses result at the face and compression results near the charge. Under this type of bending condition, the rock will break from the face back toward the hole. This mode of failure generally leads to desirable breakage.

r. In the second case, the top or the bottom of the burden moves at a higher rate than the center (Figure 2-8. b,c) so the rock is cantilevered outward. The face is put into compression and the borehole walls are in tension. This mechanism occurs when cracks between blastholes link before the burden is broken; it is normally caused by insufficient blasthole spacing. When the cracks between holes reach the surface, gases can be prematurely vented before they have accomplished all potential work. Air blast and flyrock can result along with potential bottom problems.

s. For all three cases, this breakage mechanism is called flexural rupture or flexural failure. The individual pie-shaped columns of rock caused by the radial cracking will also be influenced by a force perpendicular to the length of the column. This would be similar to beam loading conditions. When discussing beam loading, the stiffness ratio is significant. The stiffness ratio relates the thickness of the beam to its length. The effect of the stiffness can be explained by using, for example, a full length pencil. It is quite easy to break a full length pencil by grasping the pencil on either end. However, if the same force is exerted on a much shorter, for example 2 in long pencil, it becomes more difficult to break. The pencil's diameter has not changed; the only thing that has changed is its length. A similar stiffness phenomenon also occurs in blasting. The burden rock is more difficult to break by flexural failure when bench heights approach the burden dimension in length. When bench heights are many times the burden in length, the burden rock is more easily broken.

t. The bending mechanism or flexural failure is controlled by selecting the proper blasthole spacing and initiation time of adjacent holes. When blasthole timing results in charges being delayed from one another along a row of holes, the spacing must be less than that required if all the holes in a row were fired simultaneously. The selection of the proper spacing is further complicated by the stiffness ratio. As bench heights are reduced compared to the burden, one must also reduce the spacing between holes to overcome the problems of stiffness.

2-3. Types of Explosives.

a. General.

(1) The products used as the main borehole charge can be broken into three generic categories, dynamite, slurries, and blasting agents such as ANFO (Figure 2-9). A fourth, very minor, category will be added to the discussion, which is the binary (or two-component) explosives. Although the volume of binary explosives sold annually is insignificant when compared to the other major generic categories, its unique properties warrant its mention.

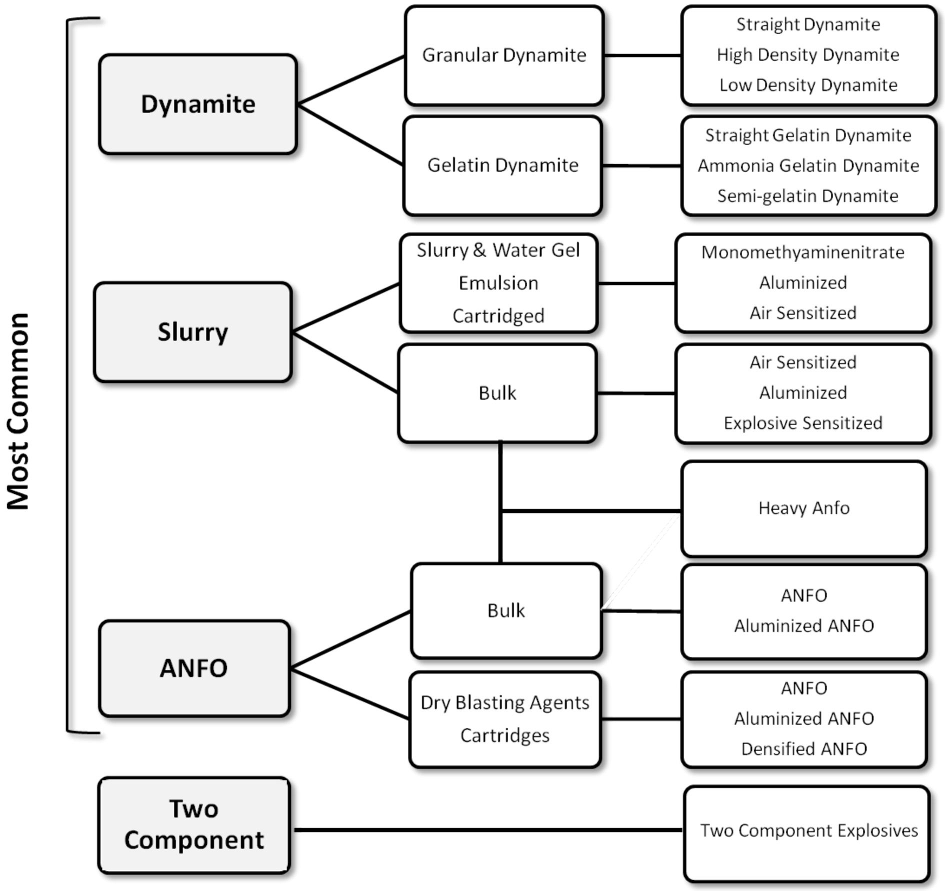

Figure 2-9. Types of Explosives Commonly Used for Rock Excavation.

(2) The term "high explosive" most often refers to any product used in blasting that is cap sensitive and that reacts at a speed faster than the speed of sound in the explosive media. The reaction must be accompanied by a shock wave for it to be considered a high explosive. All the generic categories discussed in this section are high explosives from the standpoint that they will all detonate.

(3) A blasting agent is a classification based on storage and transportation and is a sub-class of high explosive. Explosives that are blasting agents are less sensitive to initiation and therefore can be stored and transported under different regulations than what would normally be used for more sensitive high explosives. ANFO is most often called a blasting agent, but does not detract from an explosive's ability to detonate or function as a high explosive.

b. Dynamite.

(1) Most dynamites are nitroglycerin-based products. A few manufacturers of dynamite have products in which they substituted non-headache producing high explosives such as nitrostarch for the nitroglycerin. Dynamites are the most sensitive of all the generic classes of explosives. Because of their sensitivity, they offer an extra margin of dependability in the blasthole since gaps in loading within the explosive column and many other environmental factors that cause other explosives to misfire do not occur as often with dynamite.

(2) There are two major sub-classifications within the dynamite family: granular dynamite and gelatin dynamite (Figure 2-10). Granular dynamite is a compound that uses a single high explosive base such as nitroglycerin. Gelatin dynamite is a mixture of nitroglycerin and nitrocellulose that produces a rubbery waterproof compound.

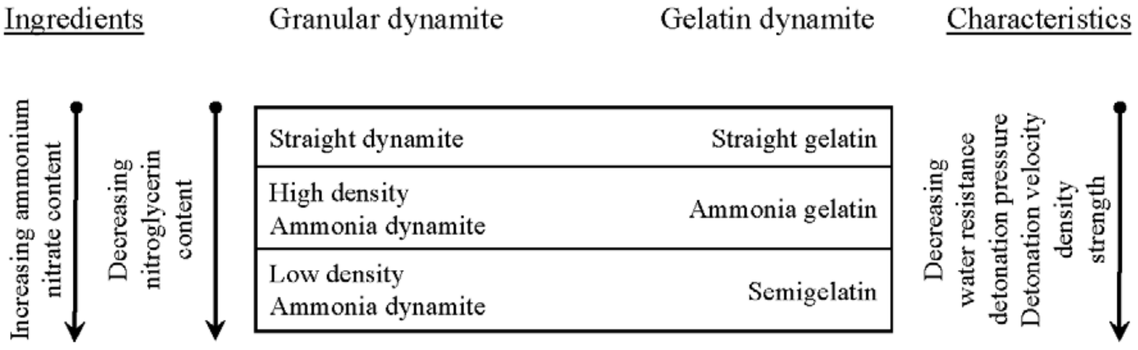

Figure 2-10. Classification of Dynamite.

(3) Straight dynamite consists of nitroglycerin, sodium nitrate, carbonaceous fuels, sulfur, and antacids. The term “straight” means that the dynamite contains no AN. Straight dynamite is the most sensitive commercial high explosive in use today. It should not be used for most construction applications since its sensitivity to shock can result in sympathetic detonation from adjacent holes, firing on an earlier than planned delay. On the other hand, straight dynamite is an extremely valuable product for dirt ditching (excavation of a ditch in dirt using an explosive compound). The sympathetic detonation previously discussed is an attribute in dirt ditching because it eliminates the need for a detonator in each and every hole.

(4) High density extra dynamite is the most widely used product. It is similar to straight dynamite except that some of the nitroglycerin and sodium nitrate is replaced with AN. The ammonia or extra dynamite is less sensitive to shock and friction than the straight dynamite. It has found broad use in all applications, quarries, underground mines, and construction.

(5) Low density extra dynamites are similar in composition to the high density products, except that more nitroglycerin and sodium nitrate is replaced with AN. Since the cartridge contains a large proportion of AN, its’ bulk or volume strength is relatively low. This product is useful in soft rock or where a deliberate attempt is made to limit the energy placed into the blasthole.

(6) Straight gelatins are blasting gels with additional sodium nitrate, carbonaceous fuel, and sometimes sulfur. In strength, it is the gelatinous equivalent of straight dynamite. A straight blasting gelatin is the most powerful nitroglycerin-based explosive. A straight gel, because of its composition, is also the most waterproof dynamite.

(7) Ammonia gelatin is sometimes called special or extra gelatin. It is a mixture of straight gelatin with additional AN added to replace some of the nitroglycerin and sodium nitrate. Ammonia gels are suitable for wet conditions and are primarily used as bottom loads in small diameter

blastholes. Ammonia gelatins do not have the water resistance of a straight gel. Ammonia gels are often used as primers for blasting agents.

(8) Semi gelatin dynamite is similar to ammonia dynamite except it normally contains additional AN. This product has moderate water resistance and is a low cost water resistant product commonly used by the construction industry.

c. Slurry Explosives.

(1) A slurry explosive is a mixture of AN or other nitrates and a fuel sensitizer, which can either be a hydrocarbon, or hydrocarbons and aluminum. In some cases explosive sensitizers, such as TNT or nitrocellulose are used, along with varying amounts of water (Figure 2-11). There are two general classes of water based slurries; watergels and emulsions. An emulsion is somewhat different from a water gel slurry in characteristics, but the composition contains similar ingredients and functions similarly in the blasthole. In general, emulsions have a somewhat higher detonation velocity and in some cases, may tend to be wet or adhere to the blasthole causing difficulties in bulk loading. For discussion purposes, emulsions, and water gels will be treated under the generic family of slurries.

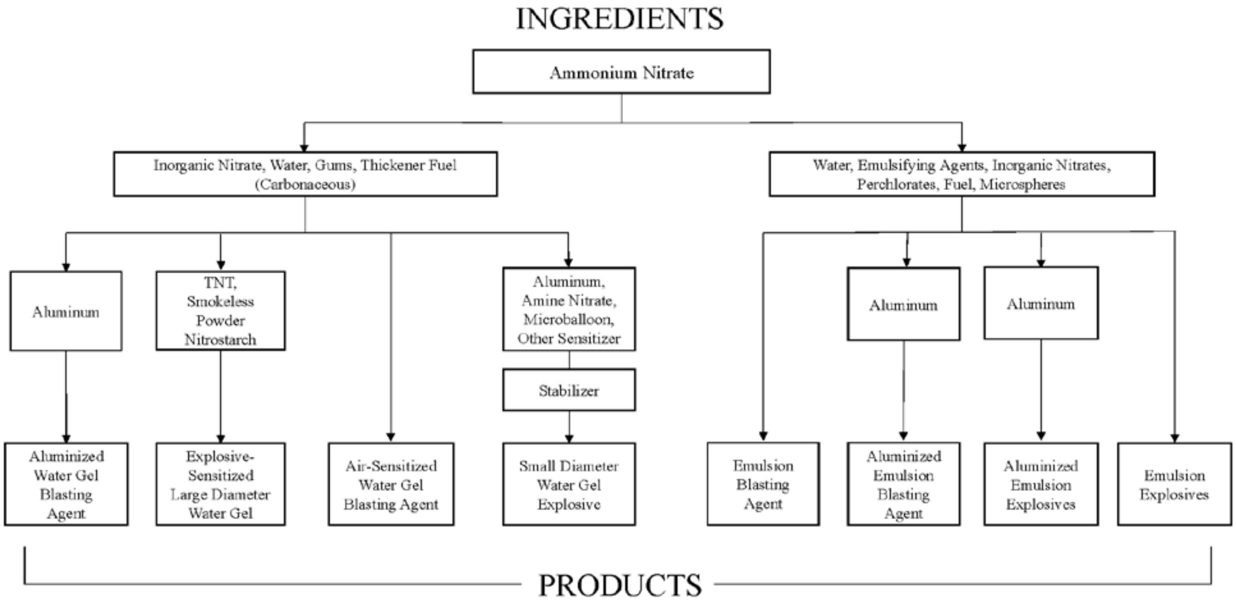

Figure 2-11. Classification and Types of Slurries.

(2) Cartridge slurries come in both large and small diameters. In general, cartridges less than 2 in. in diameter are made cap sensitive so that they can be substituted for dynamite. The temperature sensitivity of watergel slurries and their lower sensitivity can cause problems when substituted for some dynamite applications. The blaster(s) must be aware of some of the limitations before trying a one-for-one substitution. The larger diameter cartridge slurries may not be cap sensitive and must be primed with cap sensitive explosives. In general, large diameter slurries are the least sensitive. Cartridge slurries are normally sensitized with monometholamine nitrate or aluminum, and are also air

sensitized. Air sensitizing is accomplished by the addition of microspheres, chemical gassing, entrapping air, or gas during the mixing process itself.

(3) Bulk slurries are sensitized by one of three methods: air sensitizing, addition of aluminum and addition of nitrocellulose or TNT. Air sensitizing can be accomplished by the addition of gassing agents, which after being pumped into the blasthole, produce small gas bubbles throughout the mixture. Slurries containing neither aluminum nor explosive sensitizers are the cheapest, however, they are often the least dense and the least powerful. In wet conditions where dewatering is not used or where it is not practical, low cost slurries offer competition to ANFO. Table 2-1, below, is a comparison of the properties of water gels and emulsions.

Table 2-1. Properties of Water Gels and Emulsions.

Property	Watergel	Emulsion
Highest Detonation Velocity		X
High Electrical Conductivity	X	
Contains High Explosive	X	
Problems in Cold Environments	X	
Hazardous to Manufacture	X	
Highest Cost	X	

(4) It should be noted out that these slurries have less energy than ANFO on a by weight basis. Higher cost aluminized slurries and those containing significant amounts of other high explosive sensitizers produce significantly more energy because of their density and are used for blasting wet blastholes. An alternative to using high energy slurries is dewatering blastholes, where possible, with submersible blasthole pumps and using polyethylene blasthole liners within the hole with AN as the explosive. Another option is to use the cartridge ANFO products. In most applications, the use of pumping for water removal with sleeves and AN, or the use of cartridge ANFO products, will produce blasting costs that are significantly less than would result from using higher priced slurries. These supplies are available from many explosive distributors (Figure 2-12).

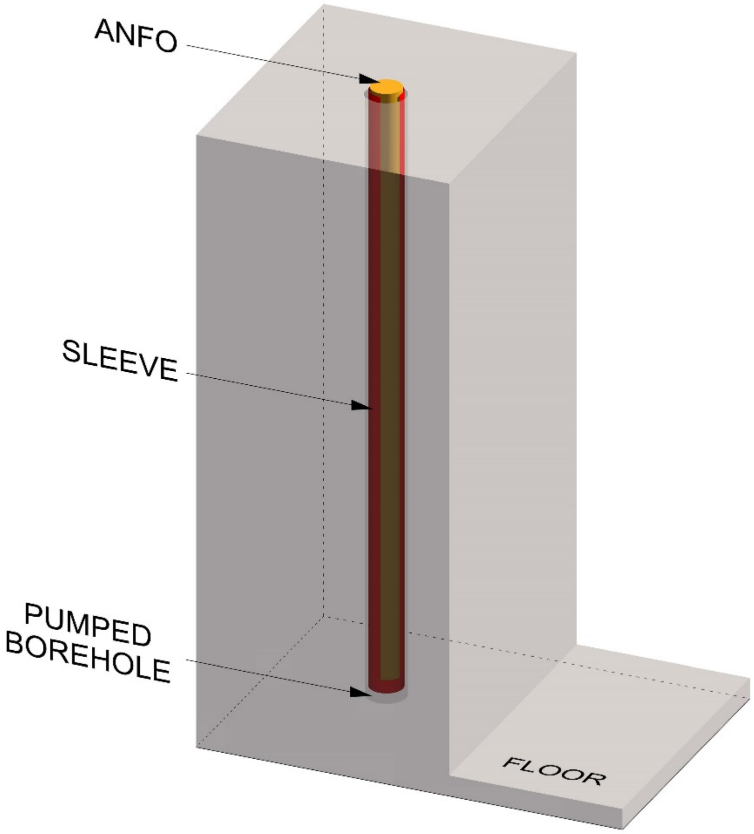

Figure 2-12. Pumped ANFO with Sleeve in Borehole.

d. ANFO and Dry Blasting Agents.

(1) Dry blasting agents are the most common of all explosives used today. Approximately 80% of the explosives used in the United States are dry blasting agents. The term dry blasting agent describes any material in which no water is used in the formulation. Figure 2-13 shows the commonly used AN-based blasting agent formulations.

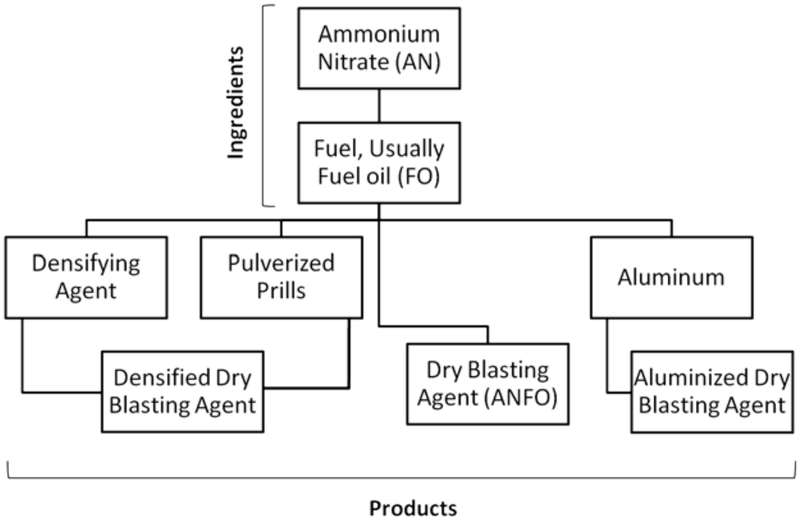

Figure 2-13. AN-Based Formulations.

(2) Early dry blasting agents employed fuels of solid carbon or coal dust combined with AN in various forms. Through experimentation, it was found that solid fuels tend to segregate in transportation and provide less than optimum blasting results. It was found that diesel oil mixed with porous AN prills gave the best overall blasting results. The term ANFO has become synonymous with dry blasting agents. An oxygen balanced mixture of ANFO is the cheapest source of explosive energy available today. Adding finely divided aluminum to dry blasting agents increases the energy output, but also increases cost.

(3) Bulk ANFO is prilled ammonium nitrate and fuel oil. The prills are spherical particles of AN manufactured in a prilling tower with a similar process to that used in making bird shot for shotgun shells. AN prills are also used in the fertilizer industry although there are differences between the fertilizer grade and the blasting grade prills. The blasting prill is considered a porous prill, which better distributes the fuel oil and results in better blasting performance. Table 2-2 lists the difference in properties of fertilizer and blasting prill. Figure 2-14 shows ANFO prills alongside a typical set of car keys (for scale).

Table 2-2. Properties of Fertilizer and Blasting Prills (Atlas).

Property	Fertilizer Prill	Blasting Prill
Inert Coating	3-5%	0.5-1%
Hardness	Very Hard	Soft
Physical Form	Solid Crystal	Porous
Fuel Oil Distribution	Surface Only	Throughout Prill
Minimum diameter for unconfined detonation	9 in	2.5 in
4 in Confined Velocity	6,000 ft/s	11,000 ft/s

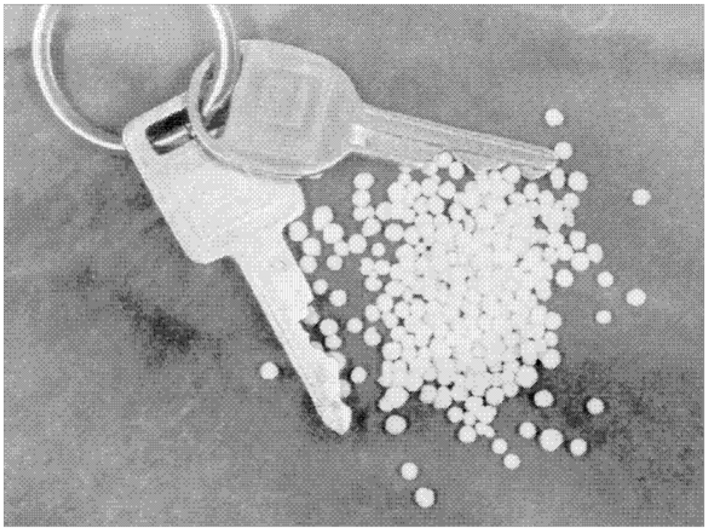

Figure 2-14. ANFO Prills.

(4) The prills are often either blown or augured into the blasthole from a bulk truck. The premixed ANFO can be placed in the truck for borehole loading, or the dry ammonium nitrate and diesel oil can be mixed in the field as the material is being placed in the borehole. The blasting industry has a great dependence on dry blasting agents because of the large volume used. Dry blasting agents will not function properly if placed in wet holes for extended periods of time. For this reason, the blaster should know the limitations the product.

(5) AN, when bulk loaded into a blasthole, has no water resistance. If the product is placed in water and shot within a very short period of time, marginal detonation can occur with the production of rust colored fumes of nitrous oxide. The ammonium nitrate will dissolve in water and the ammonium nitrate will slump and often break initiator leads. The liberation of nitrous oxide is commonly seen on blasts involving bulk AN when operators have not taken the care to load the product in a proper manner, which ensures that it will stay dry.

(6) When such a marginal detonation occurs, the product produces significantly less energy than it would be capable of producing under normal conditions. For this reason, blastholes geyser, flyrock is thrown, and other problems arise from using AN fuel oil mixtures in wet blastholes. If AN is placed in wet blastholes, it will absorb water. When the water content reaches approximately 9%, the AN may not detonate regardless of the size primer used. Figure 2-15 indicates the effect of water content on the performance of AN. As water content increases, minimum booster values also increase and detonation velocity decreases significantly.

(7) For wet hole use, where blastholes are not pumped, an aluminized or densified ANFO cartridge can be used. Densified ANFO is made by: (1) crushing approximately 20% of the prills and adding them back into the normal prill mixture or, (2) adding iron compounds to increase the density of the cartridge. In both cases, the object is to produce an explosive with a density greater 1 so that it will sink in water.

(8) Another type of ANFO cartridge is made from the normal bulk ANFO with a density of 0.8. This cartridge will not sink in water. However, it is advantageous to use this type of cartridged ANFO when placing in wet holes that were recently pumped and that contain only small amounts of water.

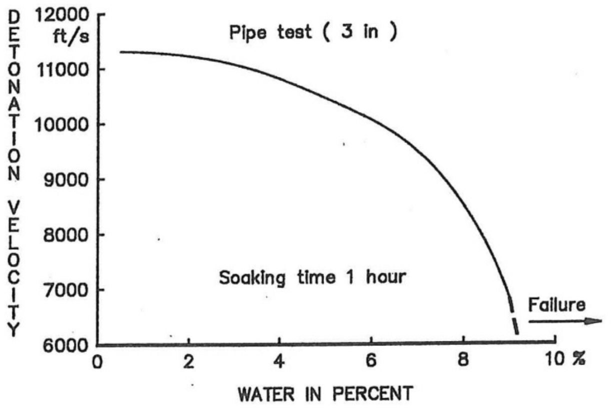

Figure 2-15. Effects of Water in ANFO on Detonation Velocity

(9) Cartridge loading of explosives is more tedious and requires more personnel since the cartridges have to be physically taken to the blast site and stacked by each hole. The cartridges are then dropped into the borehole during the loading process. Heavy ANFO requires fewer personnel since the explosive is pumped directly into the blasthole from the bulk truck.

(10) Heavy ANFO or ammonium nitrate blends are mixtures of ammonium nitrate prills, fuel oil, and slurries. The advantage to using heavy ANFO blends is that they can be mixed at the blasthole and quickly loaded into the hole (Figure 2-16). The ratio of the amount of slurry mixed with the ANFO can be changed to offer either a higher energy load or a load that is water resistant. The cost of heavy ANFO rises with increasing amounts of slurry. The advantage over cartridged products is that the entire blasthole is filled with energy and there is no wasted volume, such as would result from cartridge loading. A disadvantage with using the blends is that, since the explosive occupies the entire volume of the blasthole, any water in the hole is forced upward. This means that one may have to use the blend in the entire hole. Conversely with cartridge products, because of the annular space around the cartridge, one can build up to get out of water and then use the lower priced bulk ANFO.

Figure 2-16. Heavy ANFO Bulk Loading Truck

(11) Some operators try to use heavy ANFO in wet holes. However, they do not use mixtures that contain sufficient slurry. To provide the necessary water resistance, it is recommended that at least 50% slurry be used in heavy ANFO, which is to be used under wet borehole conditions.

e. Two-Component Explosives. Two-component explosives are often called “binary explosives” since they are made of two separate ingredients. Neither ingredient is explosive until mixed. Binary explosives are normally not classified as explosives. They can be shipped and stored as non-explosive materials. Commercially available, two-component explosives are a mixture of pulverized AN and nitromethane that have been dyed either red. These components are brought to the job site and only the amount needed are mixed. On mixing the material, it becomes cap sensitive and is ready to use. These binary explosives can be used in applications where dynamite or cap sensitive slurries would otherwise be used. Binary explosives can also be used as primers for blasting agents and bulk slurries. In most states, binary explosives are not considered explosive until mixed. They, therefore, offer the small operator a greater degree of flexibility on the job. Their unit price is considerably higher than that of dynamite. However, the money saved in transportation and magazine costs outweighs the difference in unit price. If large quantities of explosives are needed on a particular job, the higher cost per weight and the inconvenience of onsite mixing negates any savings that would be realized from less stringent storage and transportation requirements.

2-4. Environmental Characteristics of Explosives. The selection of the type of explosive to be used for a particular task is based on two primary criteria. The explosive must be able to function safely and reliably under the environmental conditions of the proposed use, and the explosive must be the most economical to use. Before any blaster selects an explosive to be used for a particular task, one must determine which explosives would best suit the particular environment and the performance characteristics that will suit the economy of the job. Five environmental characteristics are considered in the selection of explosives: (1) sensitiveness, (2) water resistance, (3) fumes, (4) flammability and (5) temperature resistance.

a. Sensitiveness (Critical Diameter)

(1) Sensitiveness is the characteristic of an explosive that defines its ability to propagate through the entire length of the column charge and controls the minimum diameter for practical use. It can be expressed as the maximum separation distance (in centimeters) between a primed donor cartridge and an unprimed receptor cartridge, where detonation transfer will occur. It is measured by determining the explosive's critical diameter. The term "critical diameter" is commonly used in the industry to define the minimum diameter in which a particular explosive compound will detonate reliably.

(2) All explosive compounds have a critical diameter. For some explosive compounds, the critical diameter may be as little as a millimeter. On the other hand, another compound may have a critical diameter of 4 in. The diameter of the proposed borehole on a particular job will determine the maximum diameter of explosive column. This explosive diameter must be greater than the critical diameter of the explosive to be used in that borehole or it may not detonate. Good planning for a site is to allow for a somewhat larger borehole, often around an inch larger, than the critical diameter for the particular compound(s) to be used. Table 2-3 lists the critical diameter of some commonly used explosives.

Table 2-3. Sensitiveness (Critical Diameter) of Explosive Products.

	Critical Diameter		
Type	< 1 in	1 – 2 in	> 2 in
Granular Dynamite	X		
Gelatin Dynamite	X		
Cartridged Slurry*	X	X	X
Bulk Slurry*		X	X
Air Emplaced ANFO	X		
Poured ANFO		X	
Packaged ANFO*		X	X
Heavy ANFO			X

* Range due to different potential materials (see technical data sheets for particular material)

(3) Water Resistance.

(a) Water resistance is the ability of an explosive to withstand exposure to water without suffering detrimental effects in performance. Explosive products have two types of water resistance, internal and external. Internal water resistance is defined as water resistance provided by the explosive composition itself. For example, some emulsions and water gels can be pumped directly into boreholes filled with water. These explosives displace the water upward, but are not penetrated by the water and show no detrimental effects if fired within a reasonable period of time. External water resistance is provided not by the explosive materials itself, but by the packaging or cartridging into which the material is placed. For example, ANFO has no internal water resistance yet, if it is placed in a sleeve or in a cartridge within a borehole, it can be kept dry and will perform satisfactorily. The sleeve on a cartridge provides the external water resistance for this particular product.

(b) The effect that water has on explosives is that it can dissolve or leach some of the ingredients, or cool the reaction to such a degree that the ideal products of detonation will not form even though the product is oxygen balanced. The emission of reddish-brown or yellow fumes from a blast often indicates inefficient detonation reactions frequently caused by water deterioration of the explosive. This condition can be remedied if a more water resistant explosive or better external packaging is used.

(c) Manufacturers can describe the water resistance of a product in two different ways. One way would be using terms such as excellent, good, fair, or poor (Table 2-4). When water is encountered in blasting operations, the explosive with at least a fair water resistance rating should be selected and this explosive should be detonated as soon as possible after loading. If the explosive is to be in water for an appreciable amount of time, it is advisable to select an explosive with at least a good water resistance rating. If water conditions are severe and the exposure time is significant, the prudent blaster may select an explosive with an excellent water resistance rating. Explosives with a poor water resistance rating should not be used in wet blastholes. Because of this, General USACE practice for blasting requires the use of packaged ANFO rather than bulk ANFO due to the likelihood on many USACE projects for encountering water in a borehole.

Table 2-4. Water Resistance of Commonly Used Explosives.

Type	Resistance
Granular Dynamite	Poor to good
Gelatin Dynamite	Good to excellent
Cartridged Slurry	Very good
Bulk Slurry	Very good
Air Emplaced ANFO	Poor
Poured ANFO	Poor
Packaged ANFO	Very good *
Heavy ANFO	Poor to very good
* Becomes poor if package is broken.	

(d) Water resistance ratings have also been given numbers, such as a Class 1 water resistance would indicate 72 hours of exposure to water with no detrimental effects; Class 2 – 48 hours, Class 3 – 24 hours, and Class 4 – 12 hours. The descriptive method of rating water resistance is the one commonly seen on explosive data sheets. In general, product price is related to water resistance: the more water resistant the product, the higher the cost.

(e) Water pressure tolerance is the ability to remain unaffected by high static. Some explosive compounds are densified and desensitized by hydrostatic pressures, a condition, which results in deep boreholes. Combinations of factors such as cold weather and small primers will contribute to failure. Under these conditions, energy release may be minimal. Problems with water pressure tolerance most often occur with slurry and heavy ANFO.

(4) Fumes

(a) The fume class of an explosive is the measure of the amount of toxic gases produced in the detonation process. Carbon monoxide (CO) and oxides of nitrogen are the primary gases that are considered in the fume class ratings. Carbon monoxide is a colorless and odorless gas that in sufficient concentrations can displace oxygen in the blood, depriving organs and brain of required oxygen. Although most commercial blasting agents are near oxygen balanced to minimize fumes and optimize energy release, fumes will occur and the blaster should be aware of their production. In underground mining or construction applications, the problems that can result from producing fumes with inadequate ventilation is obvious and can be deadly. It should be pointed out that in surface operations, especially in deep cuts or trenches, fume production and retention can also be hazardous to the personnel on the job as ventilation may not be sufficient to displace CO generated by the blasting. Certain blasting conditions may also produce toxic fumes even when the explosive is oxygen balanced. Some conditions that can cause toxic fume production are insufficient charge diameter, inadequate water resistance, inadequate priming, and premature loss of confinement.

(b) The Institute of Makers of Explosives (IME) have adopted a method of rating fumes. The test is conducted by the Bichel Gauge method. The volume of poisonous gases released per 0.44 pounds of explosives is measured. If less than 276 in^3 of toxic fumes are produced per 0.44 pounds of explosives, the fume class rating would be 1. If 276 in^3 to 570 in^3 of poisonous gases are produced, the fume class rating is 2, and if 570 in^3 to 1,158 in^3 of poisonous gases are produced, the fume class rating is 3. Table 2-5 lists fume ratings of commonly used explosives.

Table 2-5. Fume Ratings of Commonly Used Explosives.

Type	Resistance
Granular Dynamite	Poor to good
Gelatin Dynamite	Fair to very good
Cartridged Slurry	Good to very good
Bulk Slurry	Fair to very good
Air Emplaced ANFO	Good *
Poured ANFO	Good *
Packaged ANFO	Good to very good
Heavy ANFO	Good*
*Can be poor under adverse conditions.	

(c) Strictly speaking, carbon dioxide is not a fume since it is not a toxic gas by itself. However, many deaths have occurred over the years due to the generation of large amounts of carbon dioxide during blasting in confined areas. Although carbon dioxide is not poisonous, it is produced in large quantities in most blasts. In sufficient concentrations it has the effect of causing the involuntary muscles of the body to stop working. In other words, the heart and lungs would stop working if one was placed in high concentrations of carbon dioxide. If concentrations are 18% or higher in volume, death can occur by suffocation. An additional problem with carbon dioxide is that it has a density of 1.53 as compared to air and it would tend to pocket in low places in the excavation or where there is little movement of air. A simple solution to the problem is to use compressed air or ventilation fans to dilute any possible high concentrations in depressions of trenches.

(d) A special note should be made here regarding ANFO and the fuel oil content on production of fumes at the site. Due to production methodology there can be some variability in the oil content in the ANFO prills. Particular attention should be paid to “red/orange fumes” where there is no water as this may indicate production of nitrous oxides. If carbon black appears on rocks after a blast or there are very dark grey gases, production of carbon monoxide may be suspected. CO content of the air can also be tested. Rowland and Mainiero in 2000 (Rowland and Mainiero, 2000) performed testing on types of fume productions depending on the oil content. Generally where ANFO prills are too dry there will be increasing Nitrous Oxide fumes, where the prills are too wet, there is increasing Carbon Monoxide fumes. This can be an important safety consideration on a project. Testing can be performed to check the ANFO prill oil content. If other factors are well controlled, and there are still indications of a problem such as blasting gas color, or tests indicate excessive CO, ANFO product should be tested.

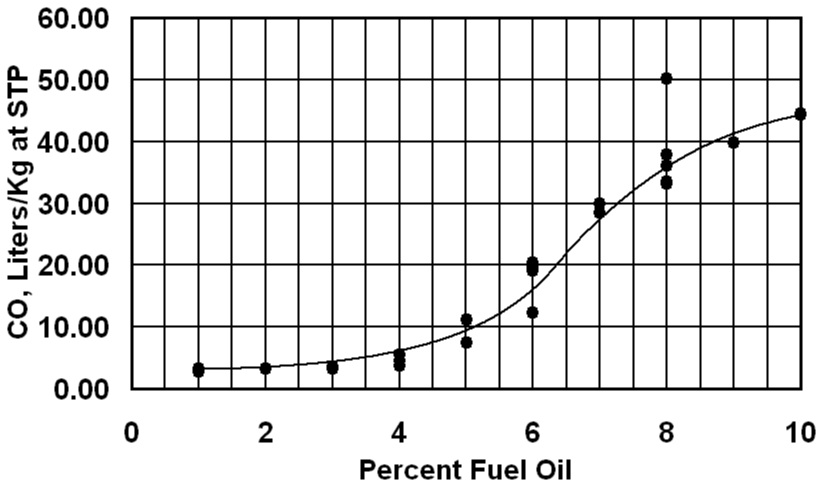

Figure 2-17. Effect of ANFO fuel oil content on carbon monoxide production (Rowland and Mainiero, 2000).

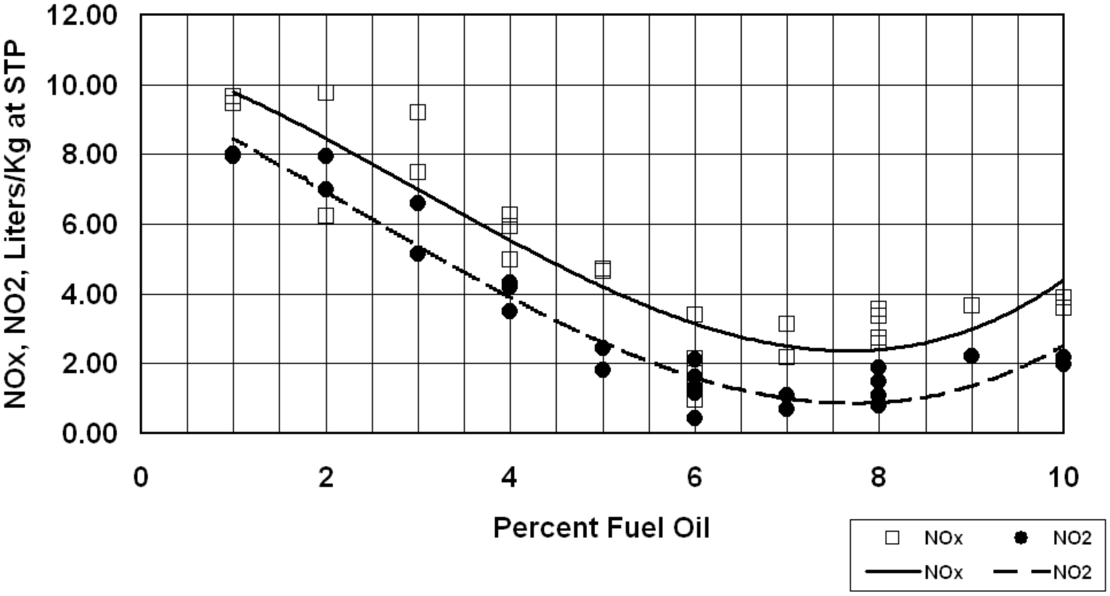

Figure 2-18. Effect of ANFO fuel oil content on nitrogen oxides and nitrogen dioxide production (Rowland and Mainiero, 2000).

(5) Flammability

(a) The flammability of an explosive is defined as the characteristic that deals with the ease of initiation from spark, fire, or flame. Some explosive compounds will explode from just a spark while others can be burned and will not detonate. Flammability is important from the standpoint of storage, transportation, and use. Some explosives, although very economical, have lost their marketability due to flammability. A good example is liquid oxygen and carbon, which was used in the 1950's as a blasting agent. Its flammability and inherent safety problems caused its demise. Most explosive compounds used today are not anywhere near as flammable as liquid oxygen. However, accidents still occur due to flammability.

(b) Over the past 2 decades, explosive products, in general, have become less flammable. Some manufacturers indicate that certain products can be burned without detonation in quantities as large as 44,093 pounds. This can lead to a false sense of security and the assumptions that all modern products today are relatively inflammable. This false sense of security has led to the death of people who have been careless with explosives. All explosive compounds should be treated as highly flammable and no smoking or open flames should be allowed.

(6) Temperature Resistance.

(a) Explosive compounds can suffer in performance if stored under extremely hot or cold conditions. Table 2-6 lists the temperature resistance of commonly used explosives. Under hot storage conditions, above 90°F, many compounds will slowly decompose or change properties; shelf life will be decreased. Storage of AN blasting agents in temperatures above 90°F can result in cycling, which will affect the performance and safety of the product.

Table 2-6. Temperature Resistance of Commonly Used Explosives.

Type	Resistance between 0 and 100°F
Granular Dynamite	Good
Gelatin Dynamite	Good
Cartridged Slurry	Poor below 40 F
Bulk Slurry	Poor below 40 F
Air Emplaced ANFO	Poor above 90 F
Poured ANFO	Poor above 90 F
Packaged ANFO	Poor above 90 F
Heavy ANFO	Poor below 40 F

(b) The chemical formula for AN is NH_4NO_3. For its weight, it supplies more gas volume on detonation than any other explosive. In pure form, AN is almost inert and is composed of 60% oxygen by weight, 33% nitrogen, and 7% hydrogen. With the addition of fuel oil, the ideal oxygen balanced reactions for NH_4NO_3 is:

$$3N_2H_2O_3 + CH_2 \rightarrow 3N_2 + 7H_2 + CO_2 \tag{2-2}$$

(c) Two characteristics make this compound both unpredictable and dangerous. AN is water soluble and, if uncoated, can attract water from the atmosphere and slowly dissolve itself. For this reason, the spherical particles, called prills, have a thin protective coating of silica flour (SiO_2), which offers some amount of water resistance. The second and most important characteristic is a phenomenon called cycling. Cycling is the ability of a material to change its crystal form with temperature. AN will have one of the five crystal forms depending on temperature:

- Above 257°F, cubic crystals exist.
- Above 184°F and below 257°F, tetragonal crystals exist.
- Above 90°F and below 184°F, orthorhombic crystals exist.
- Above 0°F and below 90°F, pseudotetragonal crystals exist.
- Below 0°F, tetragonal crystals exist.

(d) The cycling phenomena can seriously affect both the storage and performance of any explosive that contains AN. Most dynamites, both regular nitroglycerine (NG) or permissibles, contain some percentages of AN while blasting agents are composed almost totally of this compound. The two temperatures at which cycling will occur under normal conditions are 0 and 90°F. Therefore, any products that are stored over the winter or for a period of time during the summer most likely will undergo some amount of cycling. During the summer in a poorly ventilated powder magazine or storage bin located in the sun, the cycling temperature may be reached daily. The effect of cycling on AN when isolated from the humidity in the air is that the prills break down into finer and finer particles.

(e) The prills are made up of pseudotetragonal crystals. When the temperature exceeds 90°F, each crystal breaks into smaller crystals of orthorhombic structure. When the temperature again falls below 90 F, the small crystals break into even finer crystals of the pseudotetragonal form. This process can continue until the density is no longer near 50 lb/ft^3, but can reach a density near 75 lb/ft^3. The density increase can make the product more sensitive and contain more energy per unit volume.

(f) To further complicate the situation, some cartridged blasting agents or those stored in bins may not efficiently exclude humidity. After the AN has undergone cycling, the thin water resistant coating (silica flour) is broken and the water vapor in the air condenses on the particles. As cycling continues water collects on the particles and the mass starts to dissolve. Recrystallizing into large crystals can occur with a reduction of temperature. Therefore, it is evident that a volume of AN after cycling may have very dense areas with decomposed prills and areas of large crystals. The performance of this product may range from that of a very powerful explosive to one that deflagrates or even one that will not shoot at all. Figure 2-19 shows the effect of this temperature cycling. Compare this to Figure 2-14, which shows intact prills.

Figure 2-19. AN Prills after Temperature Cycling

(g) Extreme cold conditions can also affect the performance of products. Most dynamites and blasting agents will not freeze under ordinary exposure under the lowest temperature encountered in the United States. This is because the manufacturers have added ingredients to these products that allow them to perform properly in spite of the cold weather. Some products may tend to stiffen and become firm after prolonged exposure to low temperatures and may become more difficult to use in the field.

(h) Slurry explosives, which include water gel and emulsions, can have serious detonation problems if stored in cold temperatures and not allowed to warm up before they are detonated. Slurries are quite different from the other products previously mentioned, such as dynamite and blasting agents. The problem comes about because in the past the blaster has been accustomed to using blasting agents from any manufacturer without having any problems due to cold weather. The blaster also has become accustomed to using dynamites from any manufacturer with good results. Today the slurry explosives do not all perform identically. Some can be used immediately if stored at temperatures of 0 °F where others will not detonate if stored at temperatures below 40°F.

The sensitivity of the product can become affected. The priming procedure, which was employed when the produce was stored at 68°F, may cause a misfire if the product is stored at 43°F. It is a good practice to consult the manufacturer's data sheet whenever any new product is introduced on the job, but it is absolutely essential to consult that data sheet if any new slurry explosives are introduced, since their properties and performance with temperatures can vary greatly.

2-5. Performance Characteristics of Explosives. In the explosive selection process, the environmental conditions at the site can eliminate certain types of explosives from consideration. After the environmental conditions have been considered, one must consider the performance characteristics of explosives. Characteristics of main concern are: (1) sensitivity, (2) velocity, (3) density, (4) strength, and (5) cohesiveness.

a. Sensitivity. The sensitivity of an explosive product is defined by the amount of input energy necessary to cause the product to detonate reliably. This is sometimes called the minimum booster rating or minimum priming requirements. Some explosives require little energy to detonate reliably. The standard No. 8 blasting cap will detonate in dynamite and some of the cap sensitive slurry explosives. On the other hand, a blasting cap alone will not initiate bulk loaded ANFO and slurry that has not been altered by water. Cycled ANFO can be more sensitive than unaltered ANFO. For reliable detonation, one would have to use a booster or primer in conjunction with the blasting cap. Hazard sensitivity defines an explosive's response to the accidental addition of energy, such as bullet impact. Table 2-7 lists the sensitivity of commonly used explosives.

b. Velocity.

(1) The detonation velocity is the speed at which the reaction moves through the column of explosive. It ranges from 5,000 ft/s to 25,000 ft/s for commercially used products. Detonation velocity is an important consideration for applications outside a borehole, such as plaster shooting, mud capping or shearing structural members. Detonation velocity has significantly less importance if the explosives are used in the borehole. Table 2-8 lists the detonation velocities of commonly used explosives.

Table 2-7. Sensitivity of Commonly Used Explosives.

Type	Hazard Sensitivity	Performance Sensitivity
Granular Dynamite	Moderate to high	Excellent
Gelatin Dynamite	Moderate	Excellent
Cartridged Slurry	Low	Good to very good
Bulk Slurry	Low	Good to very good
Air Emplaced ANFO	Low	Poor to good *
Poured ANFO	Low	Poor to good *
Packaged ANFO	Low	Good to very good
Heavy ANFO	Low	Poor to good*
* Heavily dependent on field conditions.		

Table 2-8. Detonation Velocities of Commonly used Explosives.

Type	Diameter		
	1.25 in	3 in	9 in
Granular Dynamite	7,000 – 19,000 ft/s		
Gelatin Dynamite	12,000 – 25,000 ft/s		
Cartridged Slurry	13,000 – 15,000 ft/s	14,000 – 16,000 ft/s	
Bulk Slurry		14,000 – 16,000 ft/s	12,000 – 19,000 ft/s
Air Emplaced ANFO	7,000 – 9,800 ft/s	12,000 – 13,000 ft/s	14,000 – 15,000 ft/s
Poured ANFO	6,000 – 7,000 ft/s	10,000 – 11,000 ft/s	14,000 – 15,000 ft/s
Packaged ANFO		10,000 – 12,000 ft/s	14,000 – 15,000 ft/s
Heavy ANFO			11,000 – 19,000 ft/s

(2) The detonation pressure is the near instantaneous pressure derived from the shock wave moving through the explosive compound. Table 2-9 lists detonation pressures of commonly used explosives. When initiating one explosive with another, the shock pressure from the primary explosive is used to cause initiation in the secondary explosive. Detonation pressure can be related to borehole pressure, but it is not necessarily a linear relationship. Two explosives with similar detonation pressures will not necessarily have equal borehole pressure or gas pressure. Detonation pressure is calculated mathematically and reported as kilobars.

Table 2-9. Detonation Pressures of Commonly Used Explosives.

Type	Detonation Pressure (kbar)
Granular Dynamite	20 - 70
Gelatin Dynamite	70 -140
Cartridged Slurry	20 - 100
Bulk Slurry	20 - 100
Air Emplaced ANFO	7 - 45
Poured ANFO	7 - 45
Packaged ANFO	20 - 60
Heavy ANFO	20 - 90

(3) The detonation pressure is related to the density of the explosive and the reaction velocity. When selecting explosives for primers, detonation pressure is an important consideration.

c. Density.

(1) The density of an explosive is important because explosives are purchased, stored, and used on a weight basis. Density is normally expressed in terms of specific gravity, which is the ratio of explosive density to water density. The density of an explosive determines the weight of explosive that can be loaded into a specific borehole diameter. On a weight basis, there is not a great deal of difference in energy between various explosives. The difference in energy on a unit weight basis is nowhere near as great as the difference in energy on a volume basis. When hard rock is encountered and drilling is expensive, a denser product of higher cost is often justified. Table 2-10 lists the density of commonly used explosives.

Table 2-10. Density of Commonly Used Explosives.

Type	Density (Specific gravity)
Granular Dynamite	0.8 – 1.4
Gelatin Dynamite	1.0 – 1.7
Cartridged Slurry	1.1 – 1.3
Bulk Slurry	1.1 – 1.6
Air Emplaced ANFO	0.8 – 1.0
Poured ANFO	0.3 – 0.9
Packaged ANFO	1.1 – 1.2
Heavy ANFO	1.1 – 1.4

(2) The density of the explosive is commonly used as a tool to approximate strength and design parameters between explosives of different manufacturers and different generic families. In general terms, products with higher explosive density are more energetic. A useful expression of density is what is commonly called “loading density” or the weight of explosive per length of charge at specified diameter. Loading density is used to determine the total kilograms of explosive that will be used per borehole and per blast. The density of commercial products range from about 0.3 to 1.6 g/cm^3.

(3) An easy method to calculate loading density is:

$$d_e = 0.34 \text{ x } \mathrm{SG_e} \text{ x } \mathrm{D_e}^2 \tag{2-3}$$

where:

d_e = Loading density (lbs/ft).

SG_e = Specific gravity of the explosive (g/cm^3).

D_e = Diameter of the explosive (in).

d. Strength.

(1) Strength refers to the energy content of an explosive, which in turn is the measure of the force it can develop and its ability to do work. Strength has been rated by various manufacturers, both on an equal weight and an equal volume basis, and is commonly called weight strength and cartridge or bulk strength. There is no standard method to measure strength universally used by the explosives manufacturers. Instead many different strength measurement methods exist such as the ballistic mortar test, seismic execution values, strain pulse measurement, cratering, calculation of detonation pressures, calculation of borehole pressures, and determination of heat release. However, none of these methods can be used satisfactorily for blast design purposes. Strength ratings are misleading and do not accurately compare rock fragmentation effectiveness with explosive type. In general, one can say that strength ratings are only a tool used to identify the end results and associate them with a specific product.

(2) One type of strength rating, the underwater shock and bubble energy test used to determine the shock energy and the expanding gas energy, is used by some for design purposes. The bubble energy tests produce reliable results that can be used for approximating blast design dimensions.

(3) In the United States, explosives are commonly rated by methods called relative weight strength and relative bulk strength. Relative weight strength refers to an arbitrary index that compares the strength of equal weights of the explosive being rated and the standard explosive, which is ANFO. Relative bulk strengths compare to relative strengths of equal volumes of explosives. An arbitrary scale is used to compare the weight of a fixed volume of the explosive being rated to a fixed volume of ANFO. Normally, these rating numbers are given as either decimal fractions, or by arbitrarily setting the weight of ANFO as 100 and comparing other explosives against ANFO. Therefore, their values would be either somewhat greater or less than 100.

e. Cohesiveness. Cohesiveness is defined as the ability of the explosive to maintain its original shape. There are times when explosive must maintain its original shape and others when it should flow freely. For example, when blasting in cracked or broken ground, one definitely wants to use an explosive that will not flow into the cracked area causing holes to be overloaded. Conversely, in other applications such as in bulk loading, explosives should flow freely and should not bridge the borehole nor form gaps in the explosive column.

2-6. Selection of Explosives.

a. General.

(1) The explosives used in blasting need to function safely and reliably under the environmental conditions of the proposed use, as discussed in Section 2-4, but ultimately the explosives selected need to meet the objectives and goals of the overall Master Blasting Plan. Chapter 9, Section 9-3.a gives further detail on the content and requirements of one of these plans.

(2) The first and foremost goal is to break rock. However, some other objectives that may need to be considered are: (1) a specific fragment size, (2) future handling of rock, (3) minimum damage to remaining rock, (4) rock displacement, (5) diggability, (6) vibration, (7) air blast, and (8) cost. It is important to understand that each site is different and may involve multiple stakeholders.

The Master Blasting Plan must be tailored to meet the site specific goals and objectives as defined by these stakeholders and reflected in the plans and specifications.

(3) In the explosive selection process, the objectives and goals of the Master Blasting Plan can eliminate certain types of explosives from consideration on a particular project. After the objectives and goals have been considered, one must consider the limitations of blast site factors. Limitations of main concern are: (1) blast site location, (2) geology, (3) project specifications, (4) available explosives, and (5) available drill types.

b. Blast Site. The blast site can limit the selection of the explosives for a Master Blasting Plan. Concerns such as allowable blast size, proximity to sensitive locations, water conditions, and topography of site will all have an impact on the selection of the explosives. If the blast site is located near urban areas or sensitive structures where excessive vibrations are not tolerated the blast size (amount of explosives) will have to be reduced. As discussed earlier water greatly impacts the selection of explosives. The topography of a site may limit equipment mobility and could limit the selection of explosives by, for example, not allowing an explosives pump truck on site.

c. Geology. Geology greatly impacts the selection of explosives for a Master Blasting Plan. One of the first things to consider is the hardness of the rock and its resistance to blasting. ANFO will most likely work well on limestone, but it may have difficulty achieving proper fragmentation on a harder gneiss. Other geological considerations that may limit explosive selection are bedding planes, faults, joints, voids, and caverns. Chapter 3, “Geologic Considerations,” goes into detail on geological features that can influence a blast at the site.

d. Project Specifications. The project specifications will impact the selection of explosives for a Master Blasting Plan. Project specifications are usually developed by the primary stakeholder and can be very prescriptive. Prescriptive specifications can greatly limit the selection of explosives by specifying a particular type of explosive of minimum density of explosive. Performance-based specification such as fragmentation size and blast size will also have an impact on selection.

e. Available Explosives. The availability of explosives will impact the selection of explosives for a Master Blasting Plan. If a particular explosive is readily available, making it cheaper, it will most likely be used. Also if a blasting contractor has an inventory of a particular type of explosive, it will probably be used. Certain explosives may not be available for use for the particular project. Always consult controlling regulations applicable at the site before final selection of explosive product. Special permits for some products may require additional time or cost and this must also be factored into the selection of an appropriate product.

f. Available Drill Types. The availability of drilling equipment will impact the selection of explosives for a Master Blasting Plan. If the available drill equipment for a particular site can only drill 3-in. blastholes, the selection of an explosive like some heavy ANFO would not be a good choice since some heavy ANFO has a critical diameter of over 3-in. See Chapter 4, “Drilling Methods and Considerations for Blasting Operations,” for a review of commonly used drilling equipment.

2-7. Initiation Systems.

a. General.

(1) The initiation system transfers the detonation signal from hole-to-hole at a precise time and the selection of an initiation system is critical for the success of a blast. The initiation system not only controls the sequencing of blastholes, but also affects the amount of vibration generated from a blast, the amount of fragmentation produced, as well as the backbreak and violence that will occur.

(2) Although the cost of the system is an important consideration, it should always be a secondary consideration, especially if the most economical initiation system causes problems with backbreak, excessive ground vibration, or fragmentation. Often these negative issues can be much more costly than the savings that might be realized with using the cheaper system. An initiation system should be chosen first to achieve the needed results in the blasting program and only after that on comparing costs.

(3) Initiators can be broken down into two broad classifications: electric and non-electric. Electric initiators use an electric charge to initiate the detonation. Non-electric (NONEL) methods include the use of blasting caps, detonating cord, delay primers, shock tubes, and boosters.

b. Electric and Electronic Initiation Systems. There are several different types of electric and electronic initiation systems: (1) electric blasting caps without delay, (2) electric blasting caps with delay, (3) electronic delay systems, and (4) the sequential blasting machine.

(1) Electric Blasting Caps with delay

(a) The electric blasting cap (EB cap) consists of a cylindrical aluminum or copper shell containing a series of powder charges (Figure 2-20). Electric current is supplied to the cap by means of two leg wires that are internally connected by a small length of high-resistance wire known as the bridge wire. The bridge wire serves a function similar to the filament in an electric light bulb. When a current of sufficient intensity is passed through the bridge wire, the wire heats to incandescence and ignites a heat-sensitive flash compound. Once ignition occurs, it sets off a primer charge and base charge in the cap near instantaneously. Instantaneous EB caps are made to fire within a few milliseconds (ms) after current is applied. Instantaneous caps contain no delay tube or delay element.

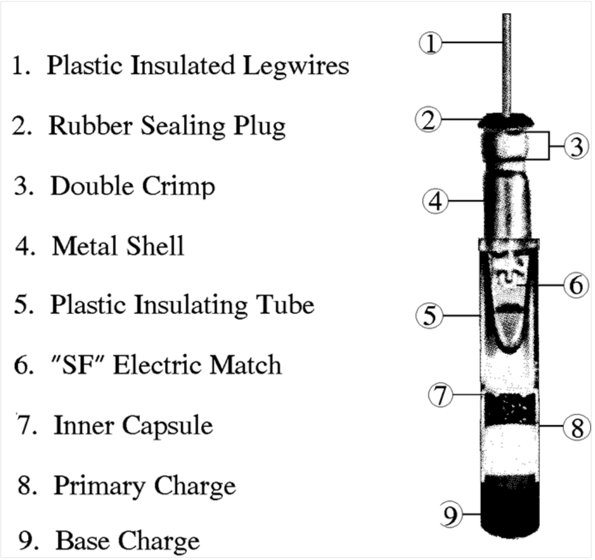

Figure 2-20. Instantaneous EB Cap.

(2) Electric blasting caps with delays

(a) A delay blasting cap contains a delay element that acts as an internal fuse. A delay element provides a time delay before the base charge fires (Figure 2-21). The leg wires on EB caps are made of either iron or copper. Each leg wire on an EB cap is a different color and all caps in a series have the same two colors of leg wires, which serve as an aid in hooking up. The leg wires enter the EB cap through the open end of the cap. To avoid contamination by foreign material or water, a rubber plug seals the opening so that only the leg wires pass through the plug.

(b) Millisecond delay EB caps are commonly used for surface blasting applications (Figure 2-21). These delays vary between periods depending on the manufacturer. However, the most common increments are 25 and 50 milliseconds (ms). Long period delays caps are also used and have intervals ranging from a hundred ms to over a half second delay. They provide time for rock movement under tight shooting conditions. They are generally used in tunnel driving, shaft sinking, and underground mining.

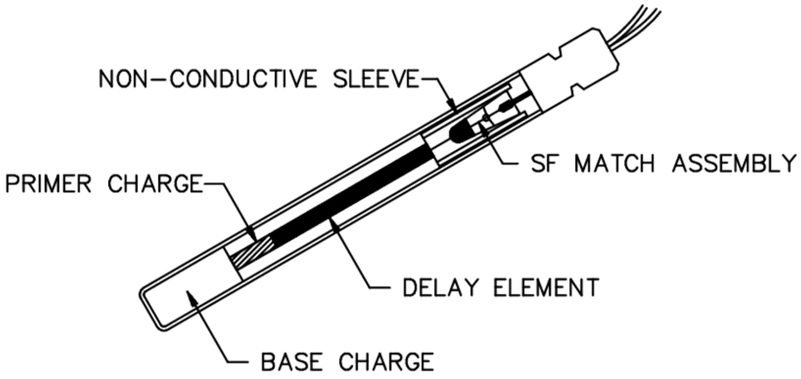

Figure 2-21. Delay EB Caps.

(3) Electronic Delay Initiation Systems

(a) The most recent development in blasting initiators is the electronic delay blasting cap. These devices allow for more accurate and precise timing than can be achieved with other initiation systems. Electronic detonators contain an integrated circuit chip and a capacitor that control the initiation time and provide voltage to the bridge wire. This provides the blaster much better control over ground vibration, flyrock, air blast, and fragmentation. These initiators virtually eliminate the problems of cap scatter times, inaccurate firing, and out-of-sequence shooting. The systems allow for both very small delays with an accuracy of ± 1 ms and for long delays up to 20,000 ms. These systems have been used on surface, underground, mining, and demolition projects. These systems also allow for the blaster to simultaneously initiate two or more primers in a single column.

(b) Electronic systems can allow a blaster to set delay timings that may be contrary to regulatory intervals (<8 ms) and regulations that control at a site should be consulted before these timings are used. Additionally, these short delay times should only be used with caution and where the blaster has significant experience with these systems and tight delays. More sophisticated blast analysis tools are also recommended where very short delays are used.

(c) However, communication within the system can be disrupted due to stray current, leakage, or static electricity. This can result in failed or incorrect communications or commands. Low battery levels are a particular problem and should be avoided. Manufacturers often require training and certification before these systems can be used to minimize these kinds of problems and troubleshooting can be difficult for untrained personnel.

(4) Sequential Blasting Machine.

(a) The sequential blasting machine was first developed by Research Energy of Ohio, Inc. It is solid state condenser-discharge blasting machine with a sequential timer that permits the detonation of many electric caps. The machine is capable of firing up to 225 ohms per circuit, at different, precisely timed intervals. The machine consists of 10 different firing circuits that are programmed to fire one after another at selected intervals. The combination of 10 different circuits, or intervals, in conjunction with delay blasting caps, can yield many independent blasts

(b) Sequential timers are used in construction as well as mining applications. The timers allow the use of many delays within a blast. The weight of explosives fired per delay period can be significantly reduced to control noise and vibration effects since there are many delays available. The sequential blasting machine can be set to fire from 5 to 199 ms in increments of 1 ms.

(c) The programmable sequential timer allows the machine to be set with nine different delay increments. The machine also allows for the use of four slave units with the master unit. Using slaves and the master unit, one can get 50 different delays that are fully adjustable.

(d) Electronic Delay Blasting Caps
Over the years, a definite need has surfaced for extremely-accurate delays. Electronic technology has advanced to the point that technology exists to create these accurate electronic delays at a reasonable cost. An electronic detonator with extremely-accurate firing times and the ability to

have infinite delay periods at any interval of time can revolutionize the blasting industry. This initiation system would virtually eliminate the problems of cap scatter times, inaccurate firing and out-of-sequence shooting.

There are approximately a dozen different electronic detonator systems either in development or in use today. There are many differences in construction, timing precision, and methods of hookup and use. Electronic detonators can be grouped into two categories: Field programmed systems and factory programmed units. The factory programmed systems can be further grouped into electrically wired systems and systems, which use shock tube lines to energize electronic detonator.

Electronic Detonators are used at some quarries on a production basis despite of their high cost. Users claim that fragmentation is more uniform, muckpiles are predicable in shape, back walls are less damaged and vibration can be significantly lower and more predictable than when using other non-electronic detonators (Figure 2-22).

Figure 2-22. DavyFire Electronic Blasting Cap.

c. Non-Electric Initiation Methods (NONEL).

(1) Non-electric initiation systems (NONEL) have been used in the explosive industry for many years. Cap and fuse, the first method of non-electric initiation, provided a low cost, but hazard prone system. The cap and fuse system has declined in use with the introduction of more sophisticated, less dangerous methods. Truly accurate timing with cap and fuse is impossible. The cap and fuse system has no place in a modern construction industry and must not be used on USACE projects.

(2) Some frequently used non-electric initiation systems are available: (1) Detonating Cords and Systems, (2) Delayed Primers, and (3) Shock Tube Initiation Systems. All are used in the construction industry. To increase the number of delays available, individuals often combine the use of more than one non-electric system on a blast. Often electric and non-electric system components are combined to give a larger selection of delays and specific delay times.

(3) Detonating Cord and Compatible Delay Systems. Detonating cord is a round, flexible cord containing a center core of high explosive, usually PETN (Pentaerythratol tetranitrate), within a reinforced waterproofing covering. Detonating cord is relatively insensitive and requires a proper detonator, such as No. 6 strength cap, for initiation. It has a very high velocity of detonation approximately equal to 21,000 ft/s. The cord's detonation pressure fires cap sensitive high explosives with which it comes into contact. Detonating cord is insensitive to ordinary shock and friction. Surface as well as in-hole delays can be achieved by proper delay devices attached to detonating cord. A major disadvantage in the use of detonating cord on the surface is the loud crack as the cord detonates, and the possibility of grass and brush fires in dry areas.

(4) Shock Tube Initiation Systems. A shock tube is a non-electric detonator in the form of a small diameter hollow plastic tube. This tube shocks the explosive through the use of a percussive wave traveling down the length of the tube. It usually contains a small amount of Octahydro-1,3,5,7-Tetranitro-1,3,5,7-Tetrazocine (HMX)/aluminum explosive powder on the tubes inner diameter, which detonates at great speed. These systems take a precise energy input to initiate the reaction inside the tube. It may be initiated by detonating cord, EB cap, cap and fuse, or a starter consisting of a shotgun primer in a firing device. The unique aspects of shock tube systems are:

- They are safe from some electrical hazards and radio frequency hazards.
- They are noiseless on the surface.
- They will not initiate cap sensitive explosives in the blastholes.
- They will propagate a reaction through and around tight kinks and knots.

(5) Long Period Shock Tube Initiators provide precise non-electric delay initiation for all underground mining, shaft sinking, and special construction needs. The delay caps are available in different lengths of the shock tube. Shock tube detonators are suited for use with commercially available dynamites, cap sensitive water gels, or emulsion type high explosives because the tube will not initiate or disrupt these explosives. Shock tube initiators can be used for initiation of non-cap sensitive blasting agents with a suitable primer.

(6) Long length, heavy duty (LLHD) millisecond initiators are similar to the Long Period (LP) initiators except that their delays are of shorter intervals. The LLHD unit has a long length tube that extends to the collar of the blasthole. The long length tube eliminates the need for any detonating cord in the blasthole that allows the use of cap sensitive explosives in the hole. Trunkline delays are usually used in place of detonating cord trunklines. All units contain built-in delays to replace conventional millisecond connectors used with detonating cord. Trunkline delays are factory assembled units with five main components, the shock tube, the blasting cap, the connector, the delay tag, and the plastic sleeve.

d. Lightning is a hazard to both surface and underground blasting. Should a lightning bolt strike the blasting circuit, a detonation would most probably result with either electric, non-electric or electronic initiators. The probability that a direct hit would occur is remote, but a lightning bolt striking a faraway object could induce enough current into an electric circuit to cause a detonation. The danger from lightning is increased if a fence, stream, or power transmission line exists between the blasting site and the storm. Underground blasting is not safe from lightning hazards since induced currents large enough to cause detonations can and have been transmitted through the ground. All blasting operations should cease and the area should be guarded when a storm is approaching. Commercially available lightning detectors can be purchase in areas where electrical storms are common. Lightning Detectors are required on every construction project where blasting is required. . Equipment must be equivalent or better than the Safety Devices Model SD-250 Elk 11 (Figure 2-23) or the SkyScan EWSP EWS-PRO lightening detector (Figure 2-24).

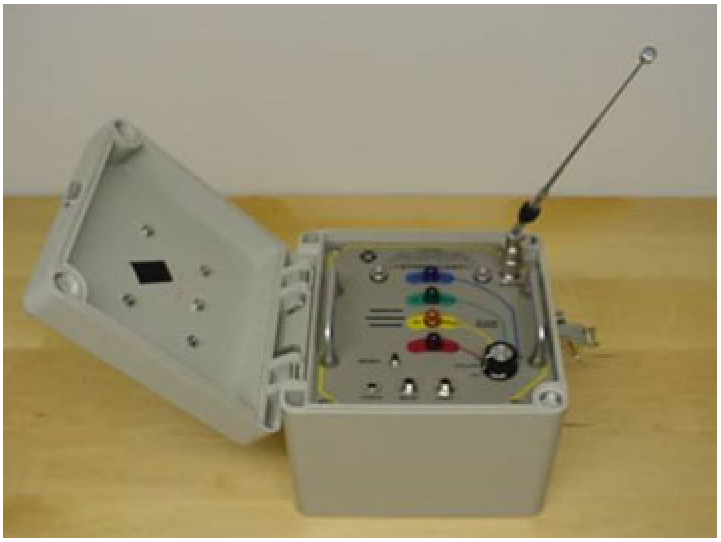

Figure 2-23. Lightning Detector Model SD-250B (Courtesy of Safety Devices, Inc.).

Actual Size: 9"H x 10"W x 5"D

Figure 2-24. SkyScan EWSP EWS-PRO Lightning Detector.

e. Primer and Boosters.

(1) The difference between a primer and booster is in its use, rather than in its physical composition or makeup. A primer is defined as an explosive unit that contains an initiator. For example, if a blasting cap is placed into a cartridge of dynamite, that cartridge with initiator becomes the primer. A booster, on the other hand, is an explosive unit of different composition than the borehole charge and does not contain a firing device. The booster is initiated by the column charge adjacent to it. A booster is used to put additional energy into a hard or tough rock layer (Figure 2-25).

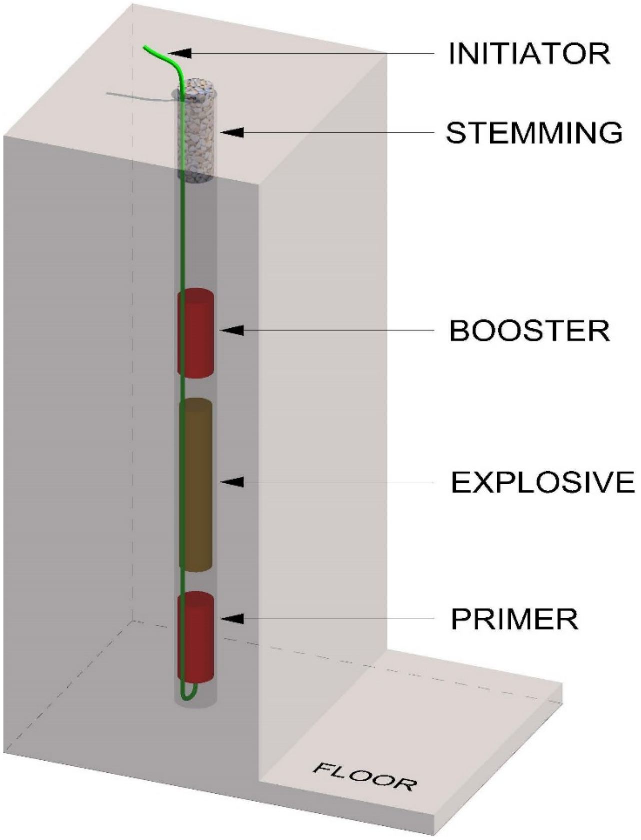

Figure 2-25. Primers and Boosters in a Borehole

(2) The number of primers that placed in a blasthole is dependent on several factors. There is no one method of priming that is a universally accepted procedure. It is common practice for some operators to routinely put two primers into a blasthole regardless of the borehole length. This is done where the blaster is concerned about the possibility of getting a poor blasting cap, which may not fire, or may have a concern for cutoffs of the hole due to shifting rock caused by a previous delay firing. In either case, the rationale is that using a second primer provides insurance against problems. If a rock mass contains considerable numbers of mud seams or open joints, confinement on the main charge could be lost during the detonation process. In this case it is common to find operators placing additional primers in the blasthole to cause the explosive charge to fire more rapidly, thereby reducing possible problems due to loss of confinement. If the blaster is working in a rock that contains mud seams, it may require a second primer to get efficient detonation throughout the total length of the charge. Conversely, in most cases from a purely technical standpoint for competent rock only

one primer is needed for a single column charge of explosive. In these cases where more than one primer is used, it would be assumed that the bottom primer would be firing first.

(3) If two or more primers are being placed in a blasthole, normally the second primer would be placed on a later delay period since the first primer location may be critical for the shot to perform properly. The second delayed primer would act only as a backup unit should the first one fail to initiate at the proper time.

(4) Primers can be found in many sizes and in many varying compositions. Primer diameters can vary in size (Figure 2-26) and come in many different compositions. Various grades of dynamite are used as primers as well as water gels, emulsions, and densified AN compounds. Various types of cast explosives of high density, high velocity, and high costs are also used for priming. Because of the vast number of sizes and compositions of primers, it is confusing for the operator. Improper selections are often made that can cause less than optimum results. Figure 2-27 shows a typical primer.

Figure 2-26. Primers (Courtesy of the Austin Powder Company).

Figure 2-27. Primers with Caps Inserted Ready to Be Loaded Into Blastholes.

(5) The two most critical criteria in primer selection are primer composition and primer size. The primer composition determines the detonation pressure that is directly responsible for the initiation of the main charge. Research conducted by Norm Junk at the Atlas Powder Company has demonstrated that primer composition significantly affected the performance of ANFO charges. Figure 2-28 shows the effect of detonation pressure for a 30 in. diameter ANFO charge and the response of the ANFO at various distances from the primer. Thermal primers of low detonation pressure caused a burning reaction to start rather than a detonation. All primers producing detonation velocities above steady state are acceptable

(6) Primer size is also important to obtain a proper reaction. Very small diameter primers are not as efficient as large diameter units. Figure 2-29 shows the effect of primer diameter on ANFO response in 30 in. diameter charges at various distances from the primers. This research conducted by Atlas Powder Company (Junk, 1968 and Morhard, 1987), decades ago, indicated that small diameter primers become inefficient regardless of the composition of the material used.

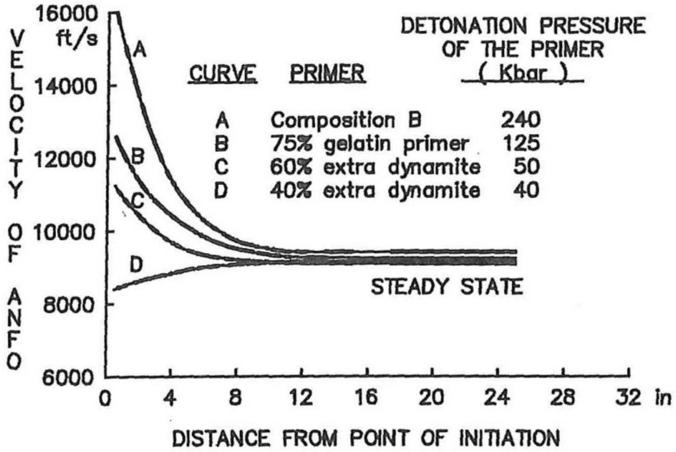

Figure 2-28. Velocity of ANFO with Different Primer Detonation Pressures and Distance from the Primer (Konya and Walter, 2006; after Junk).

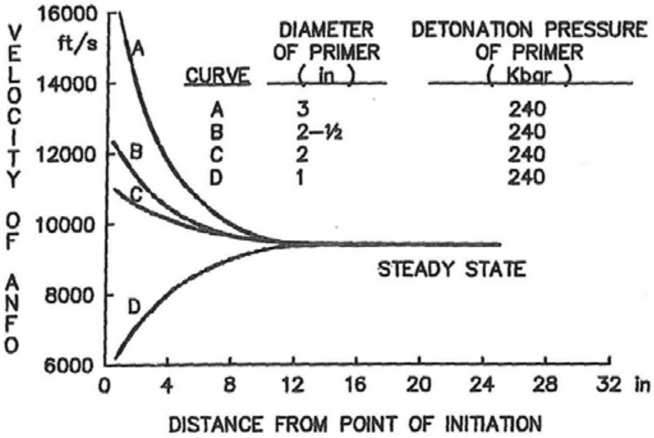

Figure 2-29. Velocity of ANFO with Different Diameter of Primers and Distance from the Primer (Konya and Walter, 2006; after Junk).

(7) General guidelines for selection of a primer are:

(a) The detonation pressure of a primer must be above the level necessary to cause the main charge to detonate at or above its normal velocity. The density and confined detonation velocity can be used as indicators of detonation pressure if detonation pressure values are not available. A primer that has a density of approximately 1.2 g/cc with a confined detonation velocity greater than 15,000 ft/s will normally be adequate when priming non-cap sensitive explosives, materials such as ANFOs, blasting agents, and most water gels. This combination of density and velocity produces a detonation pressure of about 60 kbar. For explosives such as emulsions, which detonate at higher velocities, more energetic primers will produce better results. A density of primer of 1.3 g/cc with a confined detonation velocity greater than 17,000 ft/s will be adequate to more quickly achieve the explosive's normal velocity. This combination of density and velocity produces a detonation pressure of about 80 kbar.

(b) The diameter of the primer should be larger than the critical diameter of the explosive used for the main column charge.

(c) The primer must be sensitive to the initiator. A wide variety of the products are used as primers and each have different sensitivities. Some may be initiated by low energy detonating cord, while others may be insensitive to these initiators. It is important that the operator understand the sensitivity of the primer to ensure that detonation in the main column charge will properly occur.

(d) The explosive in the primer must reach its rated velocity of detonation within the length of the cartridge. That is, the primer length should be sufficient so that the steady state velocity can be reached. If this is achieved, then additional cartridges of primer explosive serve no useful purpose.

(e) For most blasting applications, where there is no decking, no more than two primers per blasthole are needed. The second primers, although technically not needed, is commonly used as a backup system should the first primer fail or fail to shoot the entire charge.

(8) Boosters are used to intensify the explosive reaction at a particular location within the explosive column. Boosters are sometimes used between each cartridge of detonating explosive to ensure a detonation transfer across the ties of the cartridge, but this is normally a poor use of a booster as it is seldom needed and adds to the cost. The selection of an explosive in a cartridge that would not require a booster between each cartridge may be a more economical solution.

(9) In general, boosters are used to put more energy into a hard layer within the rock column. They are sometimes also used to intensify the reaction around the primer, which will put more energy at the primer location. This is commonly used when primers are near the bottom of the hole, since the bottom of the hole is the hardest place to break. Using a booster at the hole bottom normally allows the increase in the burden dimension and better breakage at the toe of the shot. Boosters can be made of similar explosive materials as primers. Their sole function is to place more energy at point locations within the explosive column.

(10) Effects of detonating cord on energy release.

(a) Cap sensitive explosives, such as dynamite, are initiated by detonating cord. Non-cap-sensitive explosives such as ammonium nitrate, emulsions, and water gels can be affected in many ways by detonating cord passing through the explosive column. If the detonating cord has sufficient energy, non-cap-sensitive explosives may detonate or burn. A burning reaction, rather than a detonation, releases only a fraction of the explosives available energy. The blast becomes underloaded because of this low energy release and it can result in ground vibration levels increasing while blastholes may vent and produce flyrock.

(b) To prevent the main explosive charge from burning or deflagrating, detonating cord should not be not too large for the borehole diameter. Acceptable cord grain loads that are not predicted to cause deflagration are given in Table 2-11.

Table 2-11. Maximum Cord Load.

Borehole Diameter (in)	Maximum Cord Load (grain/ft)
2 – 5	10
5 - 8	25
8 – 15	50

(c) If the detonating cord is too small to cause an appropriate reaction in the explosive, it can cause the explosive to be damaged. The damage that results is called dead pressing or pre-compression. Dead pressing increases the explosive density causing it not to detonate. This occurs when the detonating cord is of sufficient energy to crush out the air spaces within the explosive or to break the air-filled microspheres placed in some products. These air pockets are needed to provide locations to form hot spots for detonation. The adiabatic compression of air is necessary for detonation to proceed throughout the explosive.

(d) When the explosive is partially compressed or damaged by pre-compression, it may detonate or burn releasing only a fraction of the available energy. This effect can be confusing since the explosive may be totally consumed yet little rock breakage results. Commonly, the blaster who suffers this type of problem believes that the problem is because of hard, tough rock. To obtain a better understanding of this problem, look at the energy loss that results from passing a detonating cord though an explosive column in Figure 2-30.

(e) Figure 2-30 (Bhushan. Konya, Lukovic. 1986) shows the energy loss for ANFO, which is damaged by detonating cord. Slurry can also suffer similar damage. Even a four-grain detonating cord can cause a significant energy loss in ANFO with approximately 38% of the useful energy is lost with as little as a four-grain cord in a 2-in. diameter blasthole.

(f) The general recommendation is not to use any detonating cord in small diameter holes unless the holes are loaded with Dynamite.

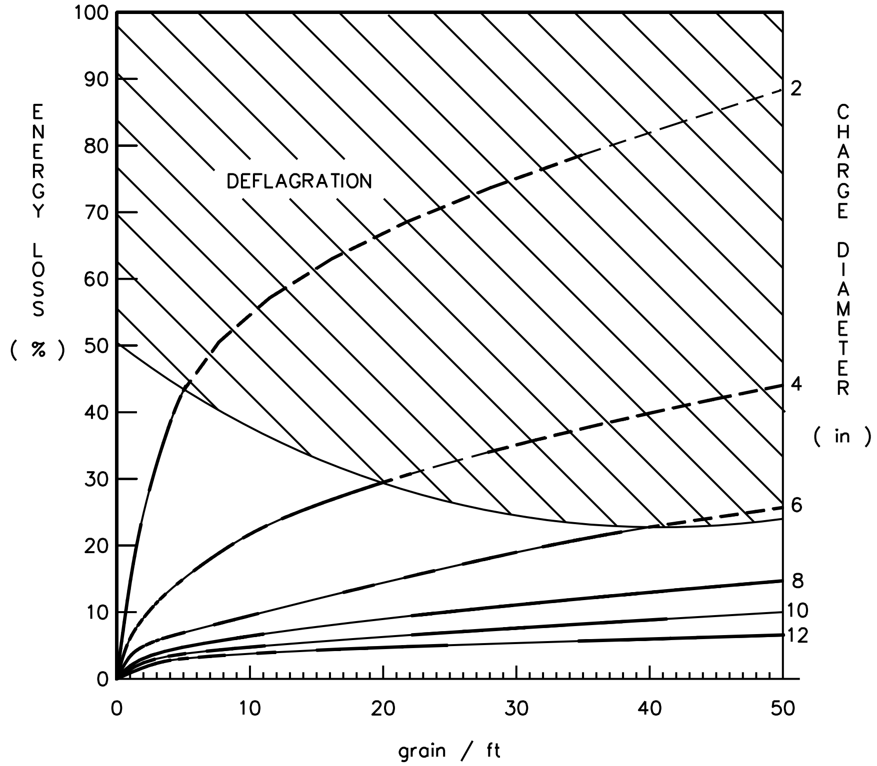

Figure 2-30. Energy Loss Caused by Detonating Cord (Bhushan, 1986).

2-8. Handling, Storage, and Transportation Issues.

a. Handling, storage, and transportation of explosives must be in line with the prescribed Federal regulations, per the USACE EM 385-1-1, Safety and Health Requirements, applicable state laws and regulations, and any local restrictions. All USACE projects as of the 2014 edition of EM 385-1-1 require that an Explosive Safety Site Plan be filed and approved with the Department of Defense Explosive Safety Board. These laws and regulations are needed to protect the safety and welfare of the public and of all personnel involved in the handling, storage, or transportation of explosives.

b. These regulations and requirements change based on the location of the project and may change over time. The following are a list of the Federal regulatory agencies and industry standards that should be consulted when dealing with explosives:

(1) Bureau of Alcohol, Tobacco, Firearms and Explosives (ATF).

(2) 27 Code of the Federal Regulations (CFR) 555 – ATF Commerce in Explosives.

(3) Occupational Safety & Health Administration (OSHA).

(4) 29 CFR 1910.109 – OSHA Explosives and Blasting Agents.

(5) 29 CFR 1926 Subpart U – OSHA Blasting and the Use of Explosives.

(6) Department of Transportation (DOT).

(7) U.S. Coast Guard (USCG).

(8) Federal Aviation Administration (FAA).

(9) Department of Defense (DoD).

(10) DoD 6055.9-STD – Ammunition and Explosives Safety Standards.

(11) U.S. Army Corps of Engineers (USACE).

(12) EM 385-1-1 Section 29 Blasting.

(13) EM 385-1-97, Chapter II, “Explosive Safety for Construction Activities.”

(14) American Society of Safety Engineers (ASSE).

(15) American National Standards Institute (ANSI)/ASSE A10.7 – Safety Requirements for Transportation, Storage, Handling and Use of Commercial Explosives.

(16) Institute of Makers of Explosives (IME).

(17) Safety Library Publications.

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CHAPTER 3

Geologic Considerations

3-1. Introduction to Geology and Blasting.

A thorough understanding of the geology and rock mass structure at any blasting site is fundamental to well-engineered blast design. Rock type, change in lithology, the presence of voids and the presence of discontinuities, and in rare cases the in-situ stress in the rock can all affect a blast and, when unanticipated, can affect the success of the project. Good characterization of the rock at the site and checks on that understanding by review of blasthole drilling are needed to ensure that the blast design is appropriate for the site. This chapter covers some of the geologic considerations for blasting, including the effects of rock type, rock mass structure, weathering, and groundwater. It assumes good familiarity with geology including rock types and structural geological conditions that can be expected at a site where a blasting program may be executed. It concludes with a discussion of the exploration and site characterization needed to support blasting projects.

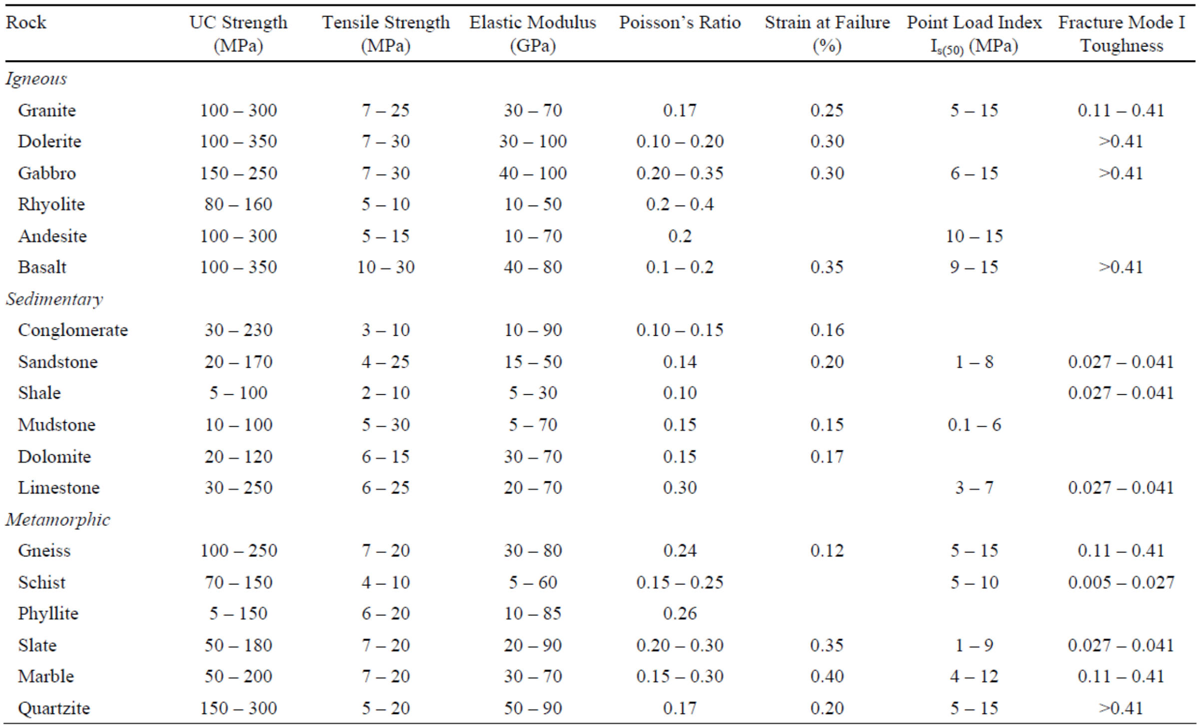
3-2. Effects of Rock Type.

a. Rock type can have an effect on blasting operations in that different rock types have different strengths and densities, and thus require a different blast design to achieve good results. One very interesting property of rock is that, like concrete, it is stronger in compression than in tension. Therefore, a goal of efficient blast design will be to place the rock in tension rather than compression. However, with increasing confinement, the rock becomes very strong. Thus, to move the rock by blasting, it must have a small enough burden to be displaced by the explosive. Chapter 5 discusses this issue in more detail.

b. The intact rock describes the fundamental rock type and properties (e.g., limestone and compressive strength of 5500 psi). The rock mass includes the intact rock along with all discontinuities, joints, faults, bedding, voids, etc. that occur within a volume of rock to be studied or blasted. These breaks in the rock have a significant effect on blasting operations and are discussed in Section 3-3.

c. While the rock mass properties are often of much more importance, the intact rock values should also be taken into account during blast design. Samples of rock, taken by diamond core drilling without the discontinuities or structure of the rock mass are generally used to determine these properties. A word of caution on rock sampling of this type, as is described in many textbooks on the subject; there can be considerable variation in samples from location to location and these are very small samples when compared to the overall quantity of rock present at a site. Where limited testing is performed, more variability of results can be expected. Charts and tables for approximate values based on the rock type (e.g., granite, limestone, sandstone, shale etc.) are readily available, though the values can have a wide range and laboratory testing will better reflect actual site conditions. However, for initial estimation where laboratory tests have not yet been performed, these can be of considerable value to the designer as the first estimate of the properties. Table 3-1 lists some typical intact rock sample values. The following sections describe several testing methods to determine commonly used intact rock properties as prescribed by the American Society for Testing and Materials (ASTM 2008a,b).

Table 3-1. Typical Intact Rock Values (Zhou, 2008).



Rock	UC Strength (MPa)	Tensile Strength (MPa)	Elastic Modulus (GPa)	Poisson's Ratio	Strain at Failure (%)	Point Load Index $I_{s(50)}$ (MPa)	Fracture Mode I Toughness
Igneous							
Granite	100 – 300	7 – 25	30 – 70	0.17	0.25	5 – 15	0.11 – 0.41
Dolerite	100 – 350	7 – 30	30 – 100	0.10 – 0.20	0.30		>0.41
Gabbro	150 – 250	7 – 30	40 – 100	0.20 – 0.35	0.30	6 – 15	>0.41
Rhyolite	80 – 160	5 – 10	10 – 50	0.2 – 0.4			
Andesite	100 – 300	5 – 15	10 – 70	0.2		10 – 15	
Basalt	100 – 350	10 – 30	40 – 80	0.1 – 0.2	0.35	9 – 15	>0.41
Sedimentary							
Conglomerate	30 – 230	3 – 10	10 – 90	0.10 – 0.15	0.16		
Sandstone	20 – 170	4 – 25	15 – 50	0.14	0.20	1 – 8	0.027 – 0.041
Shale	5 – 100	2 – 10	5 – 30	0.10			0.027 – 0.041
Mudstone	10 – 100	5 – 30	5 – 70	0.15	0.15	0.1 – 6	
Dolomite	20 – 120	6 – 15	30 – 70	0.15	0.17		
Limestone	30 – 250	6 – 25	20 – 70	0.30		3 – 7	0.027 – 0.041
Metamorphic							
Gneiss	100 – 250	7 – 20	30 – 80	0.24	0.12	5 – 15	0.11 – 0.41
Schist	70 – 150	4 – 10	5 – 60	0.15 – 0.25		5 – 10	0.005 – 0.027
Phyllite	5 – 150	6 – 20	10 – 85	0.26			
Slate	50 – 180	7 – 20	20 – 90	0.20 – 0.30	0.35	1 – 9	0.027 – 0.041
Marble	50 – 200	7 – 20	30 – 70	0.15 – 0.30	0.40	4 – 12	0.11 – 0.41
Quartzite	150 – 300	5 – 20	50 – 90	0.17	0.20	5 – 15	>0.41

d. The density of rock is perhaps the most commonly used property as it can be used in empirical formulas to determine design powder factors. In general, the higher the bulk density of the rock, the more explosive energy will be needed for desired fragmentation. The sonic wave velocity is also typically higher for competent rock that has greater density.

e. Strength of the rock is usually described by the relatively simple and inexpensive unconfined compression test (ASTM D7012, Method C 2014). While the compressive strength of the rock is greater than in tension or shear, empirical values and ratios can be used to obtain the desired strength based on the rock type where only unconfined compression tests are performed. These are less accurate than actual laboratory tests.

f. Tensile strength is usually determined by the Brazilian Disk Tension test (ASTM 3967). Direct shear tests (ASTM 5607-08) can also be performed. However, the ease of rock breakage in tension is only partly due to rock being weaker in tension than in compression. It is also due to the fact that the rock is easier to fracture in tension as it is a brittle material. Explosive gases in a borehole, where there is a free face, load the rock mainly in tension, thus using far less energy than would be required if breaking the rock primarily in compression.

g. Tests to determine the elastic modulus (Young's Modulus) and Poisson's Ratio (ASTM D7012, Methods B and D 2014) are performed and have been used to determine the blastability of rock.

3-3. Effects of Rock Mass Structure.

a. While laboratory samples may test the intact rock, the actual strength of the rock mass and its resistance to blasting are usually far less than the intact rock values would indicate. This is due to the naturally occurring network of joints, bedding, faults, cavities, voids, and breaks within the rock. These flaws in the rock play an important role as they can create planes of weakness within the rock mass that will influence the fragmentation of the rock. Where a rock mass contains multiple rock types, or different facies, these too can influence the blast as different rock types may require different blasting design. Cavities and voids, which are a weathering feature, will be discussed below in Section 3-4.a.

b. Structural discontinuities such as joints, faults, and bedding planes are all breaks that subdivide the rock. Their spacing, orientation, and persistence in the rock mass are the most important geologic consideration that will affect blast performance. Good mapping and site characterization is essential as the characteristics of these features will need to be communicated to the blast designer. The strike, dip, and spacing of these structural features should be well understood by the geologist before blasting design begins. The simple block diagram in Figure 3-1 shows how the terms are used.

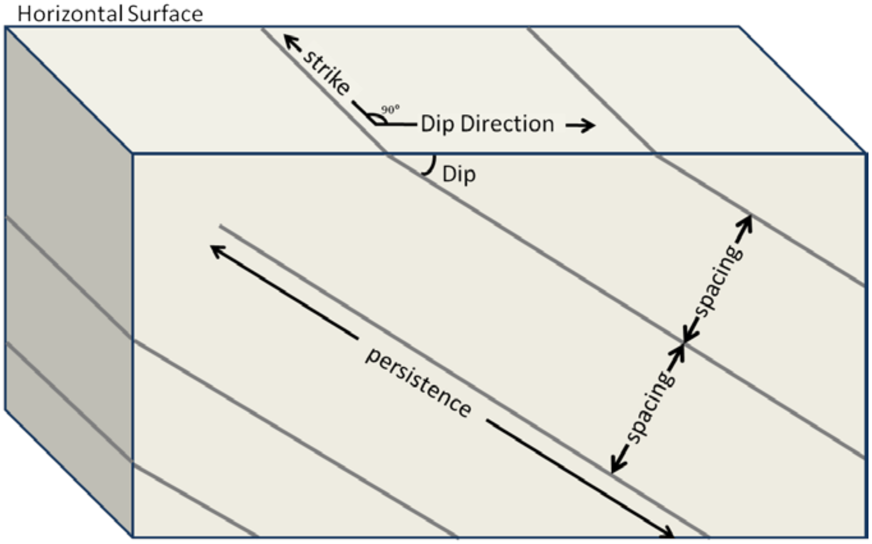
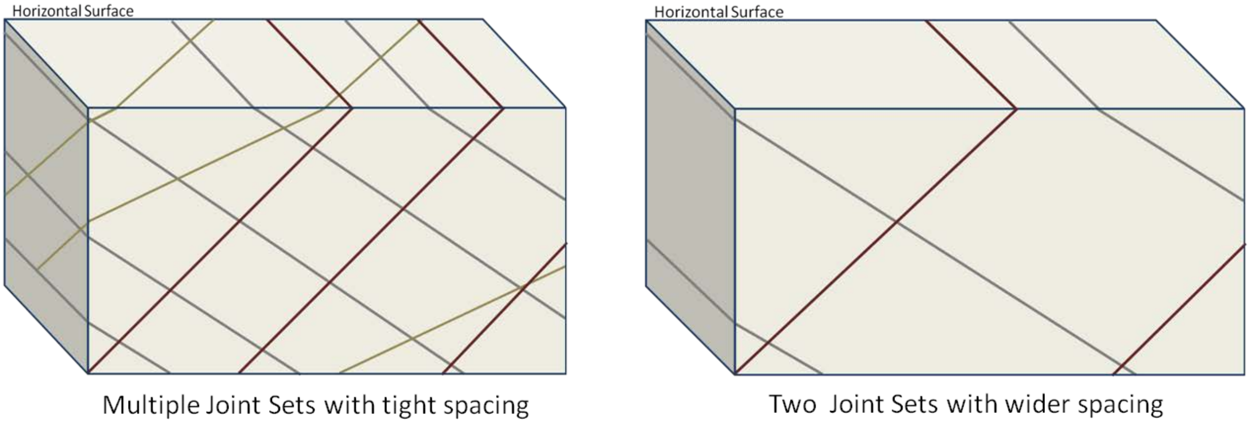


Figure 3-1. Strike, Dip, Spacing, and Persistence of Structural Features in Rock.

c. Structural discontinuities can have an aperture (opening) and infilling of material such as clay. Where the aperture is small and there is little infilling, this may be less important than the spacing. However, as will be discussed in Section 3-4, these features can serve as a conduit for water, and weathering effects can widen them to significant features.

d. The block size and fragmentation characteristics of the rock mass are heavily influenced by the spacing of these discontinuities (Figure 3-2.). Explosive energy will not be well distributed through the rock mass when the borehole patterns are larger than the discontinuity spacing. When the borehole separation is 2 to 4 times the block size, much larger boulders with inadequate fragmentation that are difficult to handle can be expected. More effective fragmentation is accomplished where explosive charges lie within the solid blocks bounded by joints. This is typically adjusted by tightening the pattern and using a smaller blasthole diameter.



Multiple Joint Sets with tight spacing

Two Joint Sets with wider spacing

Figure 3-2. Comparison on Block Size in Rock Mass with Different Joint or Discontinuity Sets and Spacing.

e. Additionally, the tensile strength across a structural discontinuity is considerably weaker than the tensile strength of the intact rock. Thus, where borehole spacing is too wide, instead of forming the tensile cracks through the intact rock, the mass splits along the discontinuity instead of the desired rock face. This can lead to a widening of the aperture of the discontinuity, leaving a structural feature in the remaining rock mass that can contribute to long term stability problems.

f. This can be particularly problematic for presplit faces. Where discontinuities are nearly vertical and strike parallel or within around 15 degrees of the direction of the final rock face, it can be extremely difficult to create a presplit face that does not follow these discontinuities.

g. The overall dip of the structural features present in the rock mass in relationship to the desired bench or final wall face can make a difference in the final wall produced. Blasting with the dip or against the dip can both leave rock slope stability vulnerabilities in the final rock wall. Blasting with the dip can allow for the use of lesser explosive charges, or use larger burdens as the rock moves more readily down the slope. However, this can produce much greater backbreak at the top of the slope. Where the discontinuities may intersect the top of the slope or next higher bench behind the desired face, the rock may be removed along the dip, rather than at the design face location. Figure 3-3 shows backbreak where rock is removed at the top of the slope beyond the design face. Blasting against the dip generally requires more explosive charge as the blast must work against the overall rock mass structure. However, this can produce more overhangs.

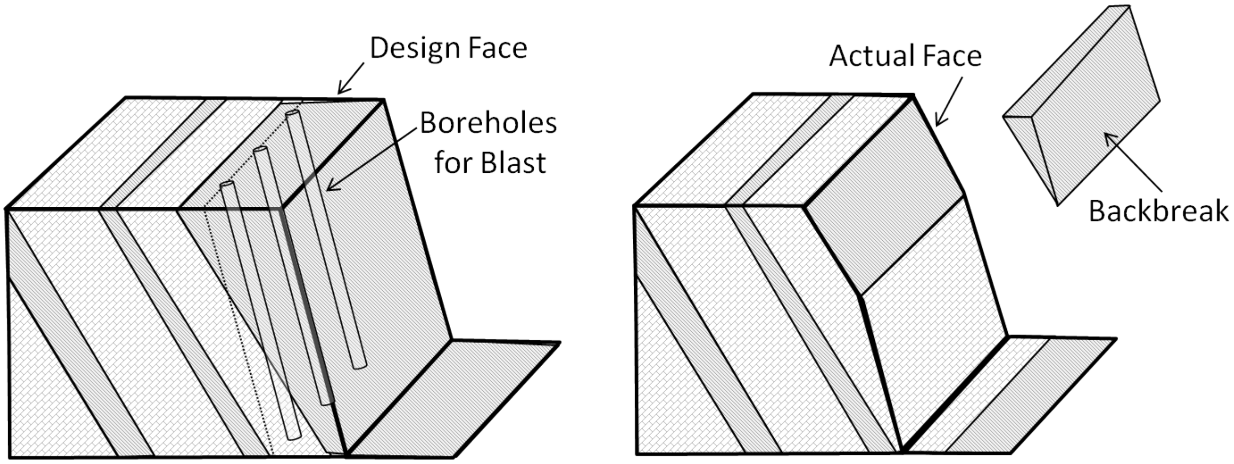


Figure 3-3. Blasting with the Dip Where Backbreak Removes Additional Material at the Top of the Slope.

h. Figure 3-4 shows overhang that can occur from backbreak of material removed at the bottom of the slope when blasting against dip. Where more lightly loaded to prevent the backbreak at the toe, additional material can be left on the slope at the toe. Blasting can also be executed against strike, though where multiple rock types are present in the face, the results can be somewhat unpredictable. The block diagram in Figure 3-5 illustrates this.

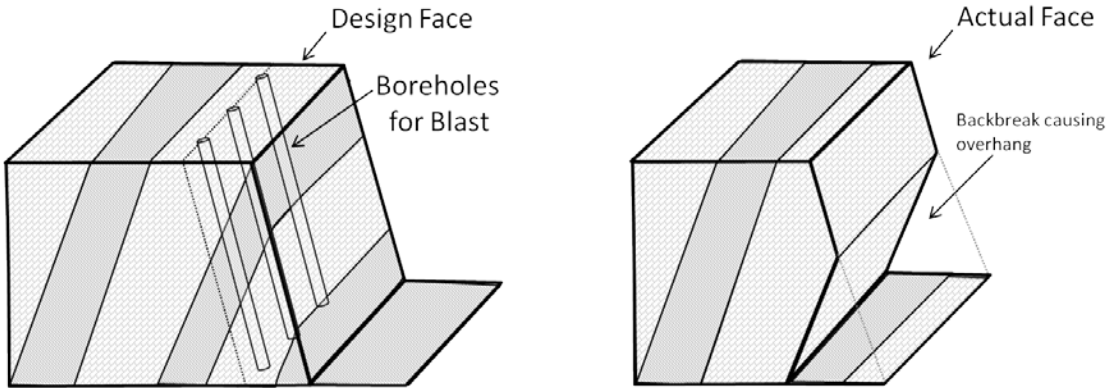


Figure 3-4. Blasting against Dip Where Backbreak Occurs at the Toe of the Slope Causing and Overhang.

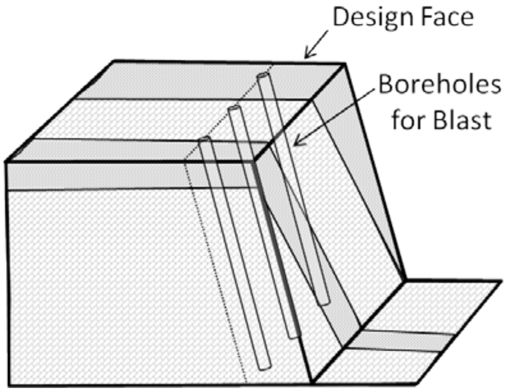


Figure 3-5. Blasting Against Strike.

i. Figures 3-3 to 3-5 show that the structure of the rock should be taken into account when planning a blast design because the structure can have a strong influence on the stability of the wall. Kinematic analysis of the rock structural features should be completed during the design phase of a project where rock excavation is planned to identify problem features that may develop in the design rock wall or excavation.

j. Figure 3-6 shows rock stability failure modes that can be created by rock removal and exposure of rock structural discontinuities. Design of the site should incorporate a thorough understanding of the rock structure and problems that can develop during construction. A review of the boreholes used for blasting as the project progresses should be used to check the original geological model for the site. A final wall should always be inspected after a blast to assess the rock slope stability and determine the need for any additional blasting, mitigation, or reinforcement.

k. Where a rock mass to be blasted contains more than one rock type, blasting can become more complicated as each material may require a different powder factor and design to achieve good results. The stratigraphy of the site should be well understood during the design process as the blasting techniques may need to be modified for each rock type present. Deck loading is often used to accommodate changes in stratigraphy. Chapter 5 gives further detail on this issue.

a. Circular failure in overburden soil, waste rock or heavily fractured rock with no identifiable structural pattern.

b. Plane failure in rock with highly ordered structure, such as slate.

c. Wedge failure on two intersecting discontinuities.

d. Toppling failure in hard rock which can form columnar structures seperated by steeply dipping discontinuities.

Figure 3-6. Rock Failure Modes Due to Structure within a Rock Mass.

l. Removal of the confining rock can also cause problems in the remaining rock mass, particularly where the in-situ horizontal stress is high. Figure 3-7 shows a tension crack along a presplit wall and Figure 3-8 shows heave in a quarry floor. These features are often also structurally controlled as they occur most easily along the weaker discontinuities in the rock and perpendicular to the major principal stress.

m. Fault zones also present a problem, particularly where they enclose breccias. Blasting conducted near faults will often break to the fault surface. Venting of gases can also occur along permeable breccias or fault zones, causing a loss in the blasting energy and poor results unless deck loading is used. Porous faults and breccias constitute potentially weak zones that may be of utmost importance in stability considerations.

Figure 3-7. Tension Crack in Rock Mass after Presplit Blasting.

Figure 3-8. Heave in Quarry Floor Due to Unloading of the Rock by Blasting and Excavation.

3-4. Effects of Weathering on Blasting Operations.

a. Voids (openings, cavities, and caves in rock) can have a deleterious effect on blasting. These voids can be naturally occurring as in karst rocks such as limestone, or they may be manmade due to tunnels, shafts, pipes, or abandoned mines. Where any karst sensitive rock such as limestone, gypsum, anhydrite, or dolomite are expected at an excavation site, the geologist assessing the site should provide a description of the solutioning activity expected. Figures 3-9 and 3-10 show some problem karst features encountered during a blasting project.

Figure 3-9. View of Karst Feature at Base of Presplit with Concrete Added at Cave Mouth.

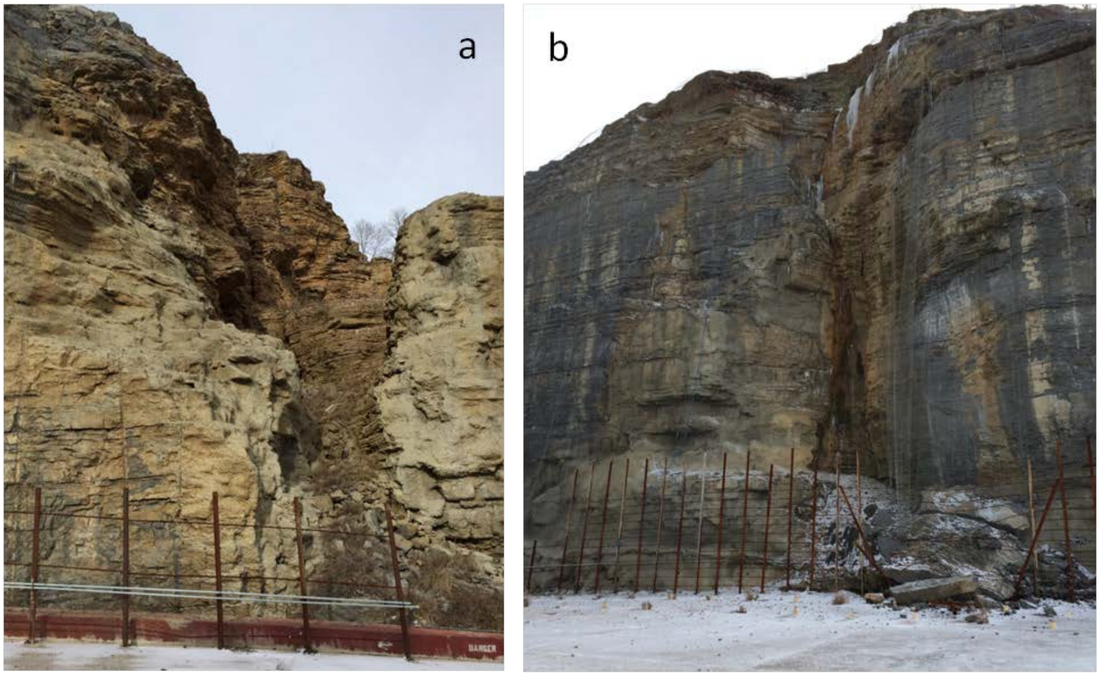


Figure 3-10. Vertical Karst Features in Presplit Face.

b. Careful attention will be needed to drilling for the blasting boreholes as it is seldom possible to fully map a site and describe the location of every possible void and cavity. Furthermore, while the karst development at the site may be described, solutioning can be expected to occur along structural features in the rock. It is not unusual for cavities to occur along bedding or along joints. Where two joints intersect, a karst shaft may develop. This information along with the drill logs will be of great value to the blaster. However, to assess the effects of blasting on surrounding structures and the final wall excavation, a geologist or engineer assigned to monitor the construction should also review all of this data before the holes are loaded.

c. Explosives can be lost into a void, particularly those in bulk or slurry form resulting in overloading. The air space can decouple the explosive and rock, decreasing the deficiency of the blast. Voids can cause a blast to have inadequate confinement, which can lead to additional fly rock. Where voids, either manmade or natural, are connected to the surface, unexpected air overpressure may be broadcast out of the void and onto the surface.

d. Where bulk explosives and slurries are used, the blaster should keep a careful account of the amount of explosive material that went into the hole. Drilling and blasting records are key to recognizing these conditions before loading of holes. Drillers will often record voids as “rod drops” that is a zone where there was little or no resistance to drilling. If loss of explosives into a void is suspected, the zone should be located and corrective measures taken to seal it. Special handling of the loading will be required where cavities are encountered; the loading may be plugged in the borehole above and below the cavity, or it may be sealed with sand, stemming material, or grouting. It may be necessary to prohibit use of bulk explosives on projects where there are numerous voids and cavities. This can be addressed through the plans and specifications.

e. Likewise, zones of intact but weathered rock can present difficulties to the blaster. Mud seams and weathered zones have different properties than the unaltered and intact rock. Weathered rock will blast more easily than a massive intact rock, so blasting techniques should be adjusted. Typically, the blaster may lower the powder factor when working in this type of material. Figure 3-11 shows some weathered limestone layers uncovered by excavation during a blasting project. The limestone in this photograph is substantially weathered, and numerous karst features are present.

f. One way of simplifying the handling of weathered material is to blast it separately from the intact material below. By partially excavating down to the lower limit of a weathered zone, the mass is simplified to one with fairly uniform properties. The type of explosives used for excavating weathered material will vary based on the extent and degree of weathering, but generally, the blaster may use cartridged rather than bulk explosives in this type of formation. The normal situation is that the weathered zone is at or near top of rock. The difficulty in producing a good final face is compounded here by the poorer quality of rock and the lower confining pressure. Therefore, the topmost presplit bench usually requires extra care in design and execution.

Figure 3-11. Weathered Limestone Layers Uncovered by Excavation during a Blasting Project.

g. Some weathered rock is decomposed to the extent that it may be ripped (removed mechanically) or treated like a soil, negating the need for blasting. The design engineer should check the specifications of the available equipment (usually obtained from the manufacturer or supplier) before determining if the rock should be blasted or ripped. For comparison, Table 3-2 lists basic rock hardness properties and their relation to excavation techniques. Also, the designer should consider that other factors such labor, equipment costs, and total project time might be involved in determining whether rock can be ripped economically.

h. Mixed ground conditions, where rock “floaters” and intact rock are surrounded by soil or more weathered rock can present significant problems as these may be difficult to excavate with conventional equipment and problematic to blast. The depth and lateral extent of mixed conditions should be mapped before the blast design, and this information provided to the contractor in the specifications. Typically all overburden will be removed from the rock before blasting starts in order to design and use appropriate blasting techniques. A blaster should not be allowed to blindly drill blast patterns in areas of mixed ground conditions.

i. These ground conditions will affect not only the design of the mass blasting, but also how the final walls are approached by the blaster. See Chapter 6, “Specialty Blasting Techniques,” for final wall methods that can be used. However, a few points are important to discuss here. Pre-splitting will typically be used to provide a relatively smooth finished wall. The loading of the presplit holes may need to be changed or eliminated based on the drilling and encountering voids. Typically line drilling or precision pre-splitting will be employed at certain distances on either side of the void or other geologic feature. This will provide a finished surface.

Keeping the explosives away from the feature will prevent gases from escaping into the feature, thereby preventing unwanted effects.

Table 3-2. Rock Hardness and Excavation Characteristics (after Hatheway 1997).

Rock hardness description	Identification criteria	Unconfined compressive strength (psi)	Seismic wave velocity (ft/s)	Excavation properties
Very soft rock	Material crumbles under firm blows with sharp end of geologic pick; can be peeled with a knife; too hard to cut a triaxial sample by hand. Pieces up to 3 cm thick can be broken by finger pressure. Standard Penetration Test (SPT) will refuse.	250 – 440	1,500 – 4,000	Easy ripping
Soft rock	Can be just scraped with a knife; indentations 1 mm to 3 mm show in the specimen with firm blows of the pick point; has dull sound under hammer.	440 – 1,500	4,000 – 5,000	Hard ripping
Hard rock	Cannot be scraped with a knife; hand specimen can be broken by pick with a single firm blow; rock rings under hammer.	1,500 – 2,900	5,000 – 5,900	Very hard ripping
Very hard rock	Hand specimen breaks with pick after more than one blow; rock rings under hammer.	2,900 – 10,000	5,900 – 7,000	Extremely hard ripping or blasting
Extremely hard rock	Specimen requires many blows with geological pick to break through intact material; rock rings under hammer.	> 10,000	> 7,000	Blasting

3-5. Effects of Ground Water on Blasting Operations.

a. Ideally, every blaster would prefer that all boreholes be dry. However, this is seldom the case. Water in a borehole creates problems in that it limits the explosive products that can be used. Explosive products that float or are not water resistant will interfere with blasting operations where water can be expected in the blasting boreholes. Where the blaster uses low water resistance explosives, the boreholes must be dewatered before loading and protected from water reentry. Even small amounts of water can degrade most ANFO products. The blastholes may be loaded with water resistant ANFO or can be redesigned and loaded with pumped bulk emulsion. Water resistant cartridged explosives could also be used but will increase costs.

b. Where excavations are deep or underground, entire dewatering systems may need to be set up and protected during blasting operations. The need for site dewatering should be addressed during the site characterization and should be included in the plans and specifications. As of 2015, the most common way of dealing with dewatering at a site is to require a contractor to assess the dewatering necessary and propose a plan to USACE personnel in the form of a submittal. This method has certainly been used with great success on many projects. However, the need for dewatering and the extent of the dewatering expected should also be quantified to the extent possible during the design process and the information gathered communicated to the contractor. Inclusion of measurement and payment and separate contract line item numbers (CLINs) for dewatering should be very carefully formulated as they have resulted in excessive and unnecessary costs on some projects.

c. Pre-blast well surveys are often needed where wells are used for water supply near a blasting site. These are usually conducted by the contractor before blasting, but well surveys completed before construction can give the geologist or engineer a good idea of the surrounding groundwater conditions. Where artesian conditions are expected, this information should be communicated to the contractor in the plans and specifications.

3-6. <u>Site Exploration and Characterization for Rock Blasting Projects</u>. Good site characterization of a potential blasting excavation is essential to the success of the project. There are many excellent references available on this topic, but a few important points follow.

a. Defining the Rock Mass

(1) As the structure of the rock can have such a significant effect on the success of a blasting program, care should be taken to fully define the structural characteristics of the rock. This will usually involve drilling, mapping, laboratory testing, and exploration while a project is in the design phase and before plans and specifications are completed. Rock structure exists in three dimensions and any exploratory program should keep that well in mind.

(2) Design checks will need to be made for final wall stability and to assess the potential to undermine any surrounding structures by daylighting a structural feature that could cause a rock failure mode. Kinematic analysis and rock stability analysis should always be performed if critical structures are to be located near or beside a rock excavation, even where blasting is not used.

(3) All rock types, stratification, voids, and water conditions should be assessed for the project and information provided to the contractor and to the blaster to allow for good blast design. Many of these features can have detrimental effects on blasting that cannot be mitigated in design if they are unexpected.

b. There will be a need for laboratory testing of samples. Intact rock samples should be tested in the laboratory to provide information for the blaster. ASTM laboratory testing methods listed in this chapter should be used to provide the data. Published tables give a good place to begin a design, but intact rock values can be highly variable, even across a site. A published table is not adequate for final blast design.

c. Drilling Documentation.

(1) Drilling is vitally important to support almost all rock excavation projects and blasting operations. Subsurface characterization is very difficult without drilling unless there are already existing rock walls that can be mapped and conditions that can be projected back into the rock mass. Angled drilling may be more effective at locating potential problems in the rock mass. Consult Engineer Technical Letter (ETL) 1110-2-581 for information on directional drilling.

(2) It is important that all exploratory boreholes be accurately surveyed and completely backfilled, and that all lost tools be carefully documented. The presence and condition of exploratory boreholes will need to be accounted for in the design. Poorly backfilled or open holes can destroy a shot, leading to damages and claims.

(3) While it is seldom possible to completely replace the information from drilling with geophysics, many geophysical tools can be used to extract the maximum amount of information from each borehole. Although it is an older method, gamma-gamma has been used successfully for many years to located shales and clay seams. Newer camera based methods such as the Optical and Acoustical Televiewer can be of great benefit to the geologist who assesses the site because these methods reveal the true in-situ conditions of the rock. Additionally, these methods can be used to get orientations of structural features encountered in the borehole, replacing the far more cumbersome oriented core methods. Although these methods are likely impractical for use in boreholes intended as part of the blast design, thy can give invaluable site characterization data to the geologist during an exploratory program. Many other methods are available with extensive information available in published literature.

(4) Drilling information will also be gathered during construction as the blasting program is executed. Chapter 10, “Documentation and Monitoring During Construction,” will cover this topic in detail. However, the boreholes drilled as the blasting proceeds should be reviewed not only by the blaster, but also by other qualified personnel such as the geologist or engineer assessing the site to determine that site conditions are as expected based on the exploration and the design. This can be particularly crucial in karst conditions where additional voids and cavities are frequently located during blasting even when the site characterization is excellent. The rock-quality designation (RQD) values, the percent recovery and the length of intact core pieces can give the blaster important information about the formation and how to load the blastholes. The blaster should review the core boxes pre-bid to be able to give a realistic blasting price.

d. Reports and Documents. All information gathered in the site exploration should be used to create a report that explains all of the pertinent data and conclusions based on that data. This data must be included in the Design Documentation Report (DDR) and should be incorporated to the extent possible into the plans and specifications or in attached data provided to the contractor. The particular vehicle used to convey this information to the contractor may vary based on the contracting method. However, as has been discussed in this chapter, it is vitally important that the blaster understand the geological conditions of the site. Site characterization information that is more interpretive may be more appropriate to include in the Engineering Considerations and Instructions to Field Personnel (ECIFP) to provide the Government Quality Assurance (QA) staff the benefit of the design rationale.

e. Drilling Logs. The blaster is required to keep a drilling log to be able to identify unusual geologic features such a voids and soft seams in each blasthole. This is essential so that the blaster can properly load the holes. The blaster must be required to use the drilling log to prevent overloading weak areas ,which can result in blow outs, violence, flyrock, excessive air overpressure and overbreak in the final walls. The drilling log should be compared to the blasthole loading diagrams to be sure that the blaster is properly loading the blastholes.

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CHAPTER 4

Drilling Methods and Considerations for Blasting Operations

4-1. Introduction.

a. Drilling for blasting can be the most expensive single component of the overall excavation program. Blasting agents are typically less expensive per hole than the drilling. If the shot design is done properly, removal of shot rock is also less expensive than drilling because it requires less specialized equipment. The manner in which drilling is performed can result in conflict between Government and Contractor objectives. For example, the greatest economy of hole spacing for the contractor may not produce adequate fragmentation or proper perimeter control for the Government. This being said, it is generally preferable to use performance-based contract requirements for drilling. More prescriptive requirements are only advisable where site conditions or special considerations warrant them, for example, when the shot rock must meet strict gradation requirements for a rock fill, but where shot rock is only available in a limited quantity. Special requirements on drilling also may be needed for grade or invert control.

b. Drilling contract costs are most commonly set by the foot of borehole. Such costs are proportional to the borehole diameter and are often bracketed by depths, e.g., one cost per foot for depths of 1 to 50 ft., and an incrementally higher cost for depths 50 to 100 ft. The cost of presplit or other perimeter blastholes may be paid for per foot, or may be included in a unit cost per square yard or square foot of face produced. If the latter is chosen, a maximum hole spacing should be specified. Drilling for blasting requires consideration of the site conditions and also of the purpose for which the blasting is being performed. Logistics (mobility, and ability to mobilize and demobilize efficiently) are as important in drilling blastholes as in exploration drilling. The terrain over which the drill is moved from hole-to-hole as well as the ease with which it is removed to a safe location during the shot is also important. Depending on the design of blasts, it may be necessary to have a drill or drills capable of borings of varying sizes. However, a single size hole is typically used on a site for production blasting even if a different design is used in a preliminary phase.

c. Drilling not only provides a hole to contain the explosive agents, but the holes themselves are used in evaluating the effectiveness of the blast. Boreholes may also be left open and act in the propagation of the crack separating intact rock from the rock to be removed. The efficiency and quality of a blast is assessed through examining the rock face that remains and looking for the remnants of the last line of drill holes. In an ideal presplit blast, the rock will break away from the face along a line connecting diameters of the last line of blastholes exposing a section of half of the blastholes circumference, leaving behind what are referred to as “half casts” (Figure 4-1). A blast that is overloaded will leave fewer half casts behind. A blast that is underloaded will result in rock left behind with portions of blastholes entire circumference remaining as “full casts” or “whole casts” on the wall of the excavation. (Figure 4-2).

Figure 4-1. View of “Half Casts” on Rock Slope after Blasting at Kentucky Lock.

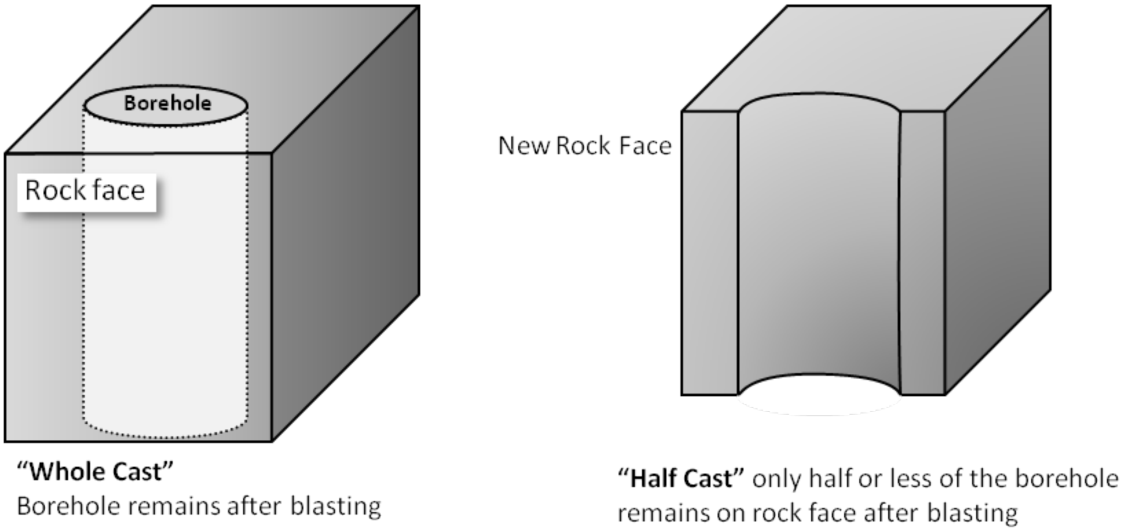


Figure 4-2. Comparison of “Half Casts” and “Whole Casts.”

4-2. Equipment and Types of Drilling.

a. General.

(1) Designation of drilling equipment is typically not within the specifications of contracts for drill and blast excavations. However, good familiarity with the equipment that may be used to execute a blasting program during construction is useful in design, cost estimating, and evaluating the contractor's blasting work plans.

(2) Where there are special circumstances, projects may include restrictions on drilling equipment. This is particularly true for underground blasting, where internal combustion engines are not permitted. There may be circumstances where drilling fluids are disallowed for reasons of water management. Drilling equipment may be specified in the contract documents that specify very tight requirements for extreme depth or borehole deviation, or that require the use of specialized equipment and tooling.

(3) The actual make and model as well as the technical specifications of the drills to be used should be included in the submittals of contractors, where this work is performed during construction under contract. Appropriate entities familiar with the project needs and the work being performed should review these specifications for approval. If more than one type of drill is proposed for usage, the circumstances and rationale for selecting the piece of equipment to be used should be described in the work plan/submittals, along with the potential sequences of work and any expectations of impacts to the schedule and quality of the work from using one piece of equipment over another. Care should be taken to review that equipment the contractor plans to use on site is sufficiently accurate and sized for the needs of the project. Contractor furnished documentation should include appropriate inspection and maintenance records. Drilling equipment deemed unsafe or in need of repair should not be permitted.

b. Factors in Selection of Drilling Equipment.

(1) Selection of drilling equipment is based on considerations of many factors, both technical and economical. The technical suitability of one piece of equipment may be superseded by its availability in the area or the contractor's fleet of equipment, and sometimes by the familiarity of one kind of drill over another. The primary factors considered in selecting the appropriate drilling equipment for blasting are:

(a) Logistics and power source.

(b) Physical constraints.

(c) Subsurface characteristics.

(d) Drill capacity, i.e., hole diameter and depth.

(e) Drill accuracy.

(f) Production rates.

(2) Logistics and Power Source. Logistical and power source considerations include the means of transportation on site and around site between drill-hole locations, and the compatibility of drills with other onsite equipment and activities. Underground drilling requires the use of non-internal-combustion engines (diesel), air driven equipment, or (rarely) electrically-powered drills. Some drills use one source of energy for transportation and another for operating the drill itself, e.g., truck-mounted drills with separate drive engines for the truck and the drill, or drills that use an engine-driven vehicle and an air-powered drill. Where air is used there should be considerations for damage to air lines by blasting or normal construction activities.

(3) Physical Constraints. Site conditions may limit the selection of drilling equipment. Uneven terrain, muddy conditions, or awkward close spaces may preclude the use of truck-mounted drills. "Cultural constraints" such as noise and vibration can influence the type of drill to be used in places where the noise from scheduled blasts might be tolerated better than ongoing noise of percussion drilling or the noise of a large diesel engine. Track mounted or all-terrain vehicle mounted drills may be required where terrain challenges exist. Close or difficult to reach spaces may require the use of small portable equipment such as "jack leg," pneumatic, or small air rock drills (Figure 4-3), at least until larger areas are opened up to allow larger equipment to access the area.

Figure 4-3. Photograph of Air Rock Drill Used for Blasting of Boulders on a Rock Slope.

(4) Subsurface Characteristics. The subsurface characteristics that influence selection of drilling equipment for blastholes are lithology and structure. A majority of drilling for large scale blasting is done using percussion drills, and the lithology is not a major consideration in the selection of the drill, except that the capacity and drill bits must be appropriate to the site conditions. Bit wear/consumption is largely dependent on how abrasive the rock is. The Cerchar Abrasivity Index (CAI) test is generally accepted for this determination. However, for most projects, it is best to

leave this estimation up to the contractor. Rotary drilling equipment and bits depend more on the rock type than does percussion drilling equipment. The structure of the rock —including considerations of jointing, folding, bedding planes or foliation planes, and considerations of weathering— are important in planning the drill and blasting program for a site. These features will have influences on the design of drill patterns and the progress of excavation. Changes in lithology and non-rock (voids, clay-filled joints, or soil) intervals can result in "walking" of the drill steel, which can result in less accurate placement of holes for blasting.

(5) Drill Capacity – Hole Diameter and Depth. It is important that the drill have the capacity to accomplish borings of the diameter and depths necessary, and that it can do so without taxing their efficiency. A drill that is under-powered or under-fit for the diameter and depth required may be able to achieve acceptable results in ideal circumstances, but unforeseen variations in subsurface conditions can be just enough to cause problems in achieving the desired depth, problems caused by borehole deviation, or problems that simply result from slowed progress. Drills that are used beyond their ideal capacity will typically result in more frequent down-time for repairs and maintenance.

(6) Drill Accuracy. For roadway cut or commercial excavation projects, most drill rigs will be able to maintain acceptable accuracy in drilling, particularly for holes that are not deep. However, there are circumstances where high accuracy is required (e.g., line drilling next to lock wall, see Figure 4-4). Drilling rates, drilling operator, drill rig chosen, and drill bits can all affect the accuracy of the drilling. Where drill holes are expected to be deep and where high accuracy is important, it is essential to review of the equipment to be used.

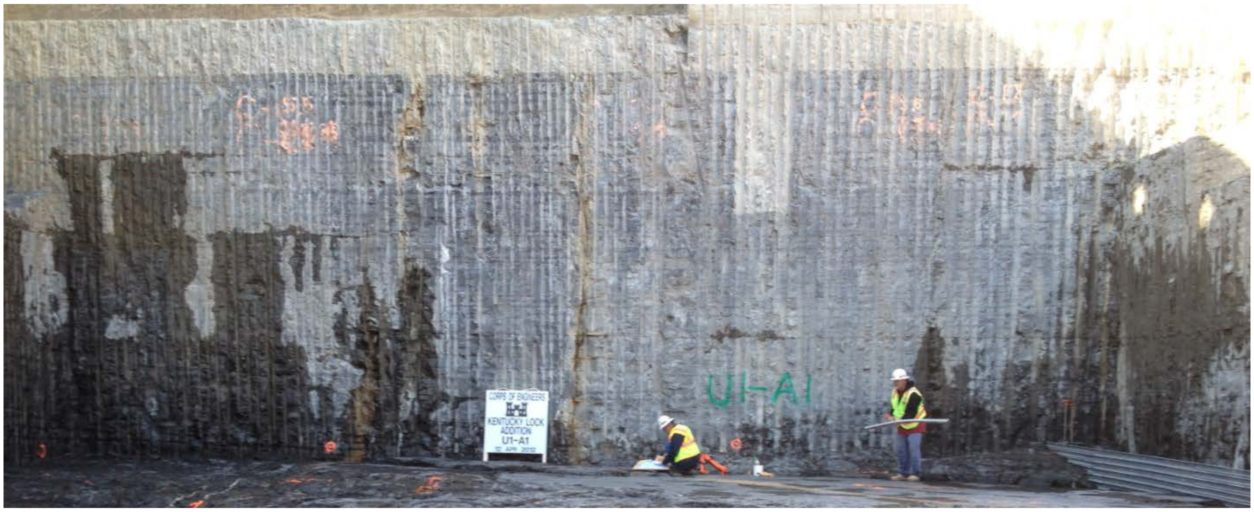


Figure 4-4. Line Drilling for a Lock Construction Project Showing Accurate Drill-Hole Locations.

(7) Production Rates. Production rates for drilling equipment vary widely based on the type of drilling, the type of material being drilled, and the diameter of the drill hole. Small 3-in. blastholes can be drilled with percussion equipment at rates in the range of tens of feet per hour in competent limestone; whereas larger diameter rotary tri-cone or diamond rotary drilling may take an hour to drill 10 ft. Production rate has a direct impact on the overall costs of the excavation, and so it makes

sense that percussion methods are the most commonly used for blastholes. Within the family of percussion drills there is wide variation in production rates with the highest rates achieved by hydraulic percussion rock drills (see Down-the-Hole Driven [DHD]).

c. Types of Drills.

(1) Drills are categorized based on the method of advancing the hole and the configuration of the drill machine. The two principle methods of advancing the hole are percussion (in which a bit or chisel is hammered into the ground) and rotary (in which a bit is spun and its teeth or abrasives in the bit cut the material to advance the hole).

(2) Percussion. Percussion bits use the earliest approach to advancing a hole through hard material by pounding a chisel or relatively pointed object into the ground. Mechanical hammers or vibrators now drive the bit, which is rotated between blows to make a more uniform circular hole, while water, air, or a mixture thereof are injected to remove the fragments (drill cuttings). Rotation and downward pressure are minimal. The differences among the percussion methods are in the design of hammer used and the method used to remove the cuttings.

(a) Out-of-the-Hole-Drill (OHD) (or Topdrill). The designation OHD refers either to "Out-of-the-Hole Drills" "or Over-Head-Drive Drills," in which the driving hammer is outside the borehole and the impact occurs outside the hole via a slide hammer or vibration as the bit is turned in the hole (Figure 4-5). Generally, these drills are restricted to hole sizes of 5-in or less to maintain economical production rates.

(b) The primary advantage of this method is twofold: it is the least expensive method, and the mechanism, which can be large, remains outside the hole. This results in a smaller hole than needed for other percussion drills.

(c) The disadvantages of these drills is that because the impact occurs at the top of the hole, as the hole deepens, the energy transfer through the drill rods is less efficient, and so the production rates slow as depth increases. Another disadvantage is that, because the impact occurs outside the hole, there may be a tendency for the drill stem to bend and for the boreholes to deviate from their intended trajectory, more so as depth increases. This makes the OHD drill one of the least accurate for drill-hole alignment. In fact, older models were commonly called "drifter drills." Also, as the percussion occurs outside the hole, these drills tend to be among the noisiest. These drills are exclusively air driven, regardless of the vehicle on which they are mounted.

Figure 4-5. Two Air-Percussion OHD Drill Rigs. Note Pile of Rock Fines (Drill Cuttings) in Front of the Rigs Removed from the Hole.

(d) Down-the-Hole Driven Drills (DHD). Down-the-Hole-Drills use a design that puts the hammer piston in the hole at the bit, removing both the disadvantage of dissipated energy and the deviation caused by the distance between the piston and the bit (Figure 4-6). Because the percussion occurs within the borehole, these drills tend be less noisy. Because of the distance between the piston and the top of the hole, higher pressures are needed to operate these drills, so some of the lower noise levels of the drills themselves may be offset by the noise of a high capacity compressor or water pump. The requirement for high-strength components inside the drill stem calls for more expensive steel and machining. Consequently, DHD bits and mechanical components also tend to be relatively expensive. The requirement for moving parts of a durable design necessitates somewhat larger holes. The minimum size for these drills in production is therefore slightly larger than that of OHD drills. Because the design of the drill tools includes the hammer, if the drill is lost in the hole and cannot be recovered, the overall loss (of the tooling plus the hole) is greater than a similar loss involving an OHD drill.

Figure 4-6. Large Water Hammer Down Hole Drill.

(e) Rotary Drilling: As the name implies, rotary drilling advances the hole not by fracturing the rock or hard materials in an impact mode, but by abrading the rock and advancing the hole by applying downward pressure while rotating the cutting bit. As with percussion drilling, air and or water are used to remove cuttings. Unlike percussion drilling, downward pressure and rotation are more important. Rotary drilling uses three kinds of bits:

- Roller Bit Drilling. Roller bit drilling uses bi-cone or more commonly tri-cone bits made with abrasive rotating cones arranged to roll as downward pressure is applied and the bit is rotated. Typically the cones are roughened with button-shaped projections that are hardened steel or carbide. Although air can be used alone to remove cuttings, water, or drilling fluid may be necessary in deeper holes both to remove cuttings and cool the bit as frictional heating may cause it to weaken or to prematurely wear.
- Blade or Drag-Bit Drilling. In softer material or shale, it may be possible to rotary drill using bits that are configured with one or more chisel-shaped blades that are commonly carbide-tipped to scrape and gouge the material to advance the hole. As in roller bit drilling, air or water may be used to remove cuttings, but water or drilling fluid may be necessary to cool the bit and remove cuttings from deeper holes.
- In some instances, it may be necessary to use diamond-embedded or diamond-impregnated bits to rotary drill holes. They have the advantage of providing a smooth borehole and also may be used with coring tools to provide representative core of the material. Diamond rotary drilling is significantly more expensive and more time consuming than other types of drilling.

(f) Table 4-1 lists the characteristics of OHD and DHD methods, for comparison.

Table 4-1. Characteristics of OHD and DHD Methods.

Parameter	OHD	DHD	Rotary Drilling
Depth	Relatively shallow, typically most effective at depths <30 ft.	Relatively deep	Deep Holes
Accuracy	Least Accurate	Straighter holes	More accurate than OHD
Rock Hardness	Works in all rock types and rock hardness	Works in all rock types and rock hardness	Works in all rock types and rock hardness
Hole Size	5-in. diameter max economical size	Minimum hole size 3.0-in.	Hole sizes generally 3.5 – 6 in.
Noise	Noisiest	Noisy as hammer is down hole	Less noisy
Expense	Least expensive	More expensive than OHD	Most expensive
Logging Accuracy for rock conditions	Destructive drilling, least accurate picture	Destructive Drilling, least accurate picture	Destructive drilling if roller cone, samples and best method for logging if wireline
Production Rate	Fast at top of hole decreasing with depth	Fastest overall	Slowest in most lithologies

4-3. Drilling Accuracy.

a. Drilling accuracy in blasting is more important as the pattern of boreholes tightens or become closer. However it is important for achieving acceptable, predictable, and repeatable results for all blasting. The starting setup of the rig is a critical first step in controlling accuracy. Specifications should include the maximum allowable deviations for top of hole location and verticality/orientation of the drill mast. If boreholes are closely spaced, or (in the extreme) if they intersect, the effectiveness of blasting will be compromised. Accuracy includes deviation from the designed orientation, as well as the depth to which boreholes are advanced. Underdrilling, with the same charge per hole, may result in loading holes to the extent that stemming may be inadequate resulting in rifling or flyrock projection. In a worst case scenario, a loaded hole may be intersected during drilling. Nevertheless, a best practice is to finish drilling all holes for a shot before loading begins. Loading holes while still drilling is, in some cases an unsafe practice that has led to deadly accidents OSHA and the EM385-1-1 do not allow drilling within 50 ft. of a loaded hole. If deviation results in holes being farther apart at depth than desired, the shot can produce poor fragmentation and leave rock in place that was intended to be removed. For underwater blasting, the drilling requirements near loaded holes are different and the EM385-1-1 should be consulting when planning and executing the underwater blasting program.

b. Blastholes are typically not deep enough to make intersection of holes a major concern. However, if a program of high benches is being designed, it may be appropriate to consider a test program of drilling to determine the range of deviations typical of the equipment to be used. Borehole deviation can be measured before loading using down hole instruments. The contractor should be required to install electronic alignment devices on the drill to assist in drilling straight holes.

4-4. Logging of Blastholes.

a. A driller's log must be required for all blastholes as part of the blast records that are kept by the contractor and made available to the engineer. These drill logs must be included with the blast report. These logs should always be reviewed by the blaster in charge before holes are loaded. Chapter 10, "Documentation and Monitoring During Construction," gives further detail. However, all drilling logs must include date and time of drilling, location, blasthole number, elevation of collar, location and length of voids and soft seems, applicable records of down pressure, rotation speed or other drill settings used while drilling as well as relevant observations of air/fluid and cuttings. Key observations include but are not limited to:

(1) Discontinuities and cavities, which may indicate where blasting gases can escape and negatively affect a blast.

(2) Water bearing zones, which are relevant for the types of explosives that can be used.

(3) Fluid or air loss or gain, which are relevant for indicating potential discontinuities, cavities, or water bearing zones.

(4) Odors and color changes, which may indicate a change in the lithology or geological layer at the site. Any change in drilling action or cuttings should be logged.

(5) Rapid change in penetration rate of drill.

b. The depths of these features are critical as the presence of water and changes in lithology, voids, and discontinuities can seriously affect blast design. Measurement while drilling (MWD) systems that record relevant data may be required in critical blasting operations. Chapter 3, "Geologic Considerations," further discusses these features and how they can affect blast design and performance.

c. The drillers' logs of holes and MWD records must be provided to the blaster, who will review them before loading the holes to determine if the drillers' assumptions are correct and if adjustments are necessary as to quantities of materials needed, stemming, decking, etc. The conditions of the rock and the presence of groundwater or other concerns must be communicated by the log and by direct communication between the driller and the blaster whenever conditions may impact the appropriate loading and stemming of holes. A final checked depth should be recorded on the log along with the date, time, and initials of the person checking the depth so that the person loading the hole knows how long the hole has been open, its actual depth, and the depth to water (if water was present at that time). A subsequent check should be performed immediately before loading the hole. This is particularly important where subdrilling is prohibited.

CHAPTER 5

Surface and Underground Blast Design

5-1. Introduction.

a. The design of blasts should always start with fundamental concepts of ideal blast design, and then modified as necessary to account for local geologic conditions (see Chapter 4 for further discussion on this topic). However, there are a number of variables involved in evaluating a blasting plan. This chapter lays out a step-by-step procedure for the analysis of a blasting plan, and examines methods to determine whether design variables are within normally acceptable ranges.

b. Discussion of patterns, timing and designs in this chapter are not intended to be sufficient education for the reader to design blasts. Actual loadings are not shown and these patterns are presented for “ideal” rock conditions. Adjustments are to be expected in order to best fit the onsite conditions. Some differences should also be expected in order to optimize designs once actual blasting data are available. The information in this chapter is provided in order to facilitate understanding of why the blaster may choose different patterns and timings to achieve particular goals on a blasting project.

5-2. Principles of Blast Pattern Design.

a. Burden.

(1) Burden distance is defined as the shortest distance to relief at the time the hole detonates (Figure 5-1). Relief is normally considered to be either a ledge face or the internal face created by a row of holes that have previously shot on an earlier delay as with a presplit.

(2) The selection of the proper burden is one of the most important decisions made in any blast design. Of all the design dimensions in blasting, it is the most critical and has the least allowable error. Other variables are more flexible and will not produce the drastic differences in results with the same proportion of error. If burdens are too small, rock is thrown a considerable distance from the face, air blast levels are high and the fragmentation may be excessively fine. If burdens are too large, severe backbreak and back shattering occur on the back wall.

(3) Excessive burdens can also cause over confinement, which may cause blastholes to “geyser,” throwing flyrock for considerable distances (Figure 5-2). This may result vertical cratering of the rock and high levels of air blast when blastholes relieve by blowing out. Over confinement of the blastholes also results in significantly higher levels of ground vibration per pound of explosive used. Rock breakage can be extremely coarse and bottom or toe problems often result.

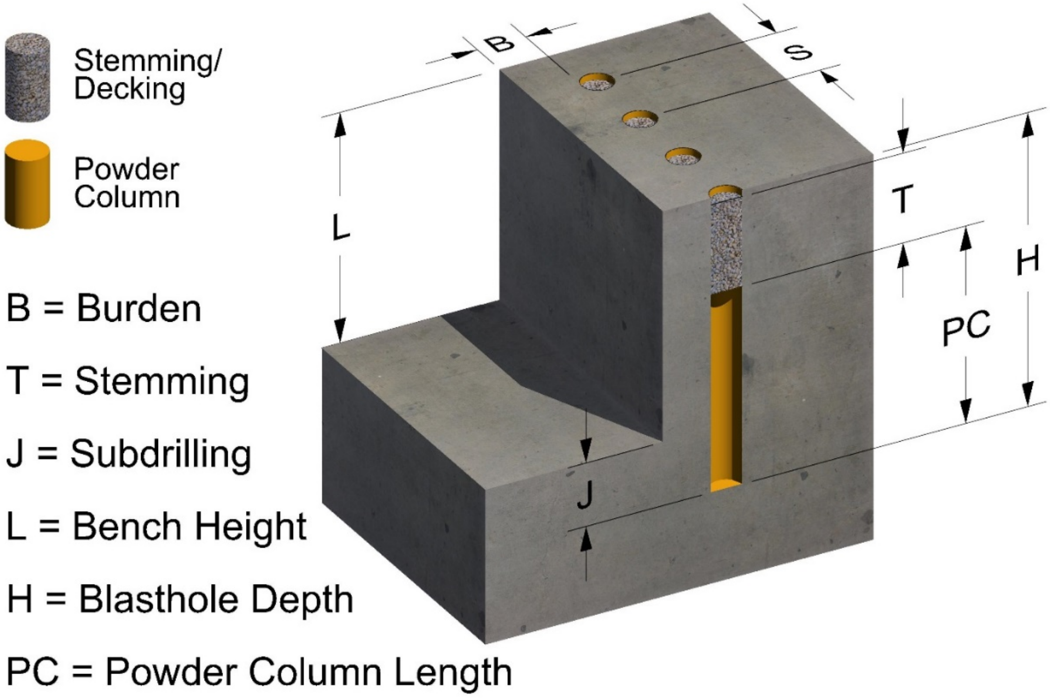


Figure 5-1. Symbols for Blast Design.

Figure 5-2. Flyrock Produced by a Blast with Excessive Burden and Over Confinement.

(4) If the operator has selected a burden and used it successfully for a drill hole of another size and wants to determine a burden for a drill hole that is either larger or smaller, the following simple ratio can be used as long as only the blasthole diameter is varied:

$$B_2 = B_1 * \left({}^{D_{e2}}\!/_{D_{e1}} \right) \tag{5-1}$$

where:

B_1 = Burden successfully used on previous blasts.

D_{e1} = Diameter of explosive for B_1.

B_2 = New burden.

D_{e2} = New diameter of explosive for B_2.

b. Adjustments for Rock and Explosive Type.

(1) When a blaster is moving into a new area general rock and explosive characteristics are the initial guide. When moving into a new area, especially one where there are residents nearby, it is essential that the first shot not be a disaster. The Konya formula helps to estimate burden under these situations:

$$B = \left(2 \, {}^{SG_e}\!/_{SG_r} + 1.5 \right) * D_e \tag{5-2}$$

where:

B = Burden (ft).

SG_e = Specific Gravity or Density of Explosive.

SG_r = Specific Gravity or Density of Rock.

D_e = Diameter of Explosive (in.).

(2) In the general case, burdens, which are used on the job, will be reasonable if they are within ±10% of the value obtained from Equation 5-2. Rock density is used in Equation 5-2 as an indication of matrix strength.

(3) Geologic Considerations, there is a relationship between rock density and rock strength. The denser the rock, the more energy needed to overcome its tensile strength and to cause breakage to occur. There is also a relationship to the amount of energy needed to move rock. The denser the rock, the more energy needed to move it.

(4) Explosive strength characteristics can be approximated using specific gravity/density because the stronger the explosive, the denser the explosive. Table 5-1 lists common rock types and their specific gravity. Chapter 3 provides further data.

Table 5-1. Common Rock Specific Gravities.

Rock Type	Specific Gravity
Basalt	2.8 – 3.0
Diabase	2.6 – 3.0
Diorite	2.8 – 3.0
Dolomite	2.8 – 2.9
Gneiss	2.6 – 2.9
Granite	2.6 – 2.9
Hematite	4.5 – 5.3
Limestone	2.4 – 2.9
Marble	2.1 – 2.9
Mica schist	2.5 – 2.9
Quartzite	2.0 – 2.8
Sandstone	2.0 – 2.8
Shale	2.4 – 2.8
Slate	2.5 – 2.8
Trap Rock	2.6 – 3.0

(5) The previous equations proposed for burden selection used the density of the explosives as an indicator of energy. The new generation of slurry explosives, called "emulsions," have somewhat different energies, but near constant density. The burden equations thus far proposed will define a reasonable burden, but will not differentiate between the energy levels of some explosives such as emulsions. To more closely approximate the burden for a test blast, one can use an equation that uses relative bulk strength rather than explosive density. Relative bulk strength is the energy level at constant volume as compared to a standard explosive.

(6) The standard explosive is ANFO, which is defined to have an energy level of 100. To use the energy equation, one would consider the relative bulk strength (relative volume strength) of the explosive. It has been found that the relative bulk strength values determined from underwater bubble energy tests normally produce reasonable results. Working with relative energies can be somewhat misleading since relative energies may be calculated rather than obtained from bubble energy test data. The explosive in the borehole environment may not be as efficient as would have been expected from the underwater test data. Equation 5-3 expresses the Konya equation using relative energy:

$$B = 0.67 * D_e * \sqrt[3]{St_v / SG_r} \qquad (5\text{-}3)$$

where:

B = Burden (ft).

D_e = Diameter of Explosive (in).

St_V = Relative Bulk Strength (ANFO = 100).

SG_r = Specific Gravity of the Rock.

c. Geologic Correction Factors.

(1) No one number will suffice as the exact burden in a particular rock type because of the variable nature of geology. Even when strength characteristics are unchanged, the manner of rock deposition and geologic structure must also be considered in the blast design. The manner in which the beds are dipping influences the design of the burden in the pattern. Chapter 3, "Geologic Considerations," discusses these issues, but specific formulas and correction factors are addressed here.

(2) Explosive energy must overcome two rock strengths: the tensile strength of the rock matrix and the tensile strength of the rock mass. The tensile strength of the matrix is measured using the Brazilian, modulus, or rupture test conducted on a uniaxial testing machine. The test may have biased results because it tests the intact rock rather than the rock mass. The mass strength can be very weak while the matrix strength can be strong. For example, a very strong rock matrix that is highly fractured, broken, foliated, and laminated may result in a rock mass on the verge of collapse simply due to the rock structure.

(3) To estimate the deviation from the normal burden formula for unusual rock structure, two constants are incorporated into the formula: Kd, which is a correction for the rock deposition, and Ks, which is a correction for the geologic structure. Kd values, which range from 0.95 to 1.18, describe the dipping of the beds (Table 5-2). The classification method is broken into three general cases of deposition: (1) beds steeply dipping into the cut, (2) beds steeply dipping into the face or into the massive rock, and (3) other cases of deposition.

Table 5-2. Correction for Bedding Orientation.

Bedding Orientation	Kd
Bedding steeply dipping into cut	1.18
Bedding steeply dipping into face	0.95
Other cases of deposition	1.00

(4) The correction for the geologic structure takes into account the fractured nature of the rock in place, the joint strength and frequency, and cementation between layers of rock. The correction factors for rock structure ranges from 0.95 to 1.30 (Table 5-3). Massive intact rock would have a Ks value of 0.95 while heavily broken fractured rock could have a Ks value of about 1.3.

Table 5-3. Correction for Geologic Structure.

Geologic Structure	Ks
Heavily cracked, frequent weak joints weakly cemented layers	1.30
Thin well cemented layers with tight joints	1.10
Massive intact rock	0.95

d. The Konya Burden equation can be adjusted for geologic structure by multiplying the standard equation by geologic correction factors.

$$B = \left(2^{SG_e}/_{SG_r} + 1.5\right) * D_e * \ Kd * \ Ks \qquad (5\text{-}4)$$

e. Stemming Distance.

(1) Stemming distance refers to the top portion of the blasthole normally filled with inert material to confine the explosive gases. The charge must be confined in the borehole for a high explosive charge to function properly and to release the maximum energy. Adequate confinement is also necessary to control air blast and flyrock. The common relationship for stemming determination is:

$$T = 0.7 * B \qquad (5\text{-}5)$$

where:

T = Stemming (ft).

B = Burden (ft).

(2) In most cases of bench blasting, a stemming distance of 0.7 times burden is adequate to keep material from ejecting prematurely from the hole. Stemming distance is proportional to the burden; therefore, the charge diameter, density of explosive, and density of rock are all needed to determine the burden. Stemming distance is also a function of these variables.

(3) If the blast is poorly designed, a stemming distance equal 0.7 x B may not be adequate to keep the stemming from blowing out. In fact, under conditions of poor design doubling, tripling, and quadrupling the stemming distance may not ensure that the holes will function properly. Therefore, the average stemming distance previously discussed is only valid if the shot is functioning properly.

(4) It has been common practice on commercial projects to use drill cutting for stemming as they are conveniently located at the collar of the blasthole. This is not allowed on USACE projects. Very fine cuttings commonly called “drilling dust” make poor stemming material. When using drill cuttings heavy with drilling dust, approximately 30% or 0.3 x B additional stemming will have to be used than if the crushed stone were used for the stemming material. In instances where solid rock is located near the surface of the bench (cap rock), operators often bring the main explosive column as high as possible to break this massive zone.

(5) Crushed stone stemming material assists in the prevention of blow out, flyrock, and air overpressure. In Equation 5-5, where the stemming distance was calculated, if drilling dust were used instead of crushed stone or drilling chips, it may be necessary to increase the stemming depth to equal burden distance. Drilling dust makes poor stemming material since it will not lock into bore-hole walls and is easily ejected. It has been standard practice on USACE projects to forbid the use of drill cuttings and to require crushed stone that has been appropriately sized.

(6) The stemming distance commonly used for construction blasting near structures that can be damaged by flyrock is equal to the burden distance or 1.1 times the burden distance to avoid flyrock. The stemming material would be crushed stone. One would rather need to hoe-ram larger rock on top of the pile than face the higher probability of flyrock from insufficient stemming.

(7) If the blast total design is not reasonable no amount of stemming will protect from possible flyrock.

(8) If stemming distances are excessive, poor top breakage will result and the amount of back-break will increase. When a blast functions properly, the stemming zone will gently lift and slowly drop onto the broken rock pile after the burden has moved out. Figure 5-3 shows this action.

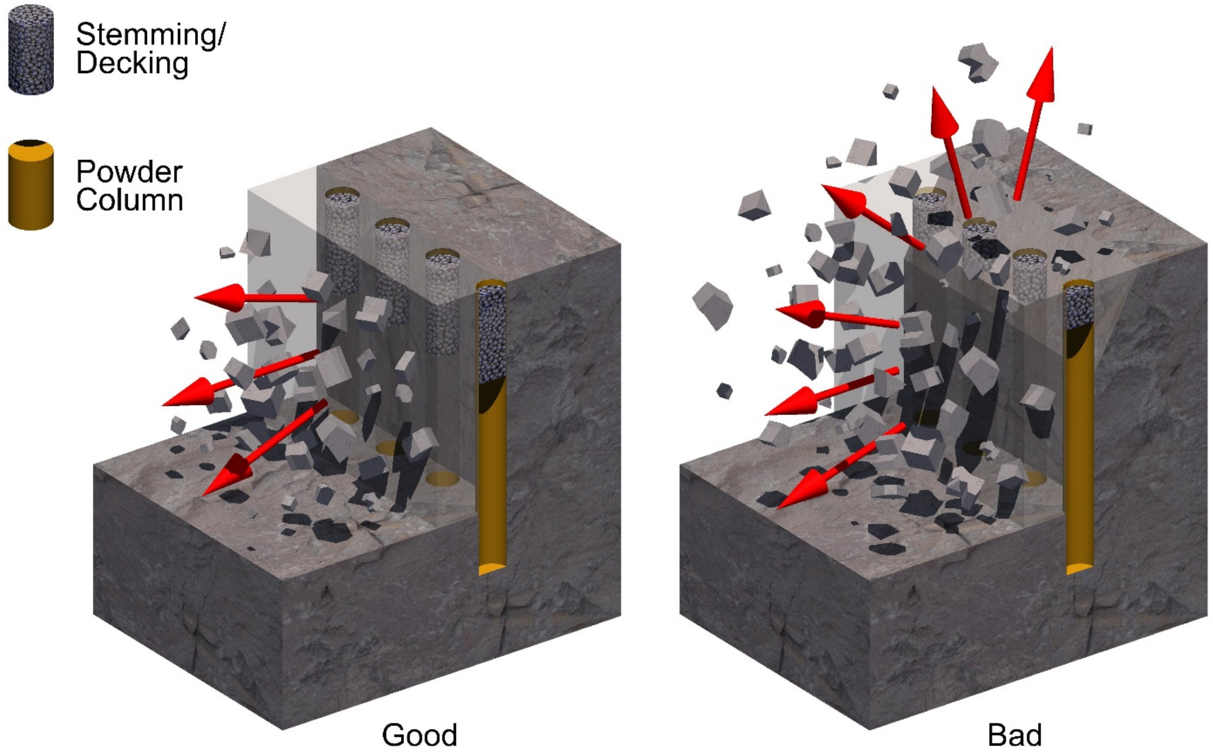


Figure 5-3. Stemming Zone Performance.

(9) Selection of the proper size of stemming material is important to minimize the stemming depth to break cap rock. Very fine drilling dust will not lock into the blasthole. Very coarse stemming materials have the tendency to bridge the hole when loading and may be ejected like golf balls. The optimum size of stemming material is material that has an average diameter of

approximately 0.05 times the diameter of the blasthole. Material must be angular to function properly. The best size is determined as follows:

$$S_z = {D_h}/{20} \tag{5-6}$$

where:

Sz = Particle size (in.).

Dh = Blasthole diameter (in.).

(10) River gravel of this size, which has become rounded, will not function as well as crushed stone. On detonation of the explosive in the blasthole, stemming particles will be compressed to mortar consistency for a short distance above the charge (Figures 5-4 and 5-5).

Figure 5-4. Stemming Material Compaction Immediately Above Charge Before (left) and After (right).

Figure 5-5. Stemming Material Compaction Immediately Above Charge in Borehole.

(11) Stemming plugs are either used to retain the stemming at a specific location in the blasthole or to channel the forces from a blast in a specific manner into the stemming material. The

plugs that hold the stemming in a particular location in a blasthole are normally made of polyethylene shells, gas bags, or polyurethane foam plugs. These plugs can be used to support charges or stemming in the blasthole or to support the stemming above a charge or air gap in the blasthole.

(12) The plugs that are made to channel forces into the stemming are normally either conical or spherical in shape (Figure 5-6). These plugs are placed into the stemming zone with the intent of causing the stemming material to bridge and lock into the blasthole walls more efficiently as gas pressure from the detonating explosive exerts force against the plug. It is claimed that these plugs will reduce the amount of stemming needed or will eliminate blow out or stemming ejection from the blasthole. These devices seem to be effective in underground rounds or where poor quality stemming materials such as drill cuttings are used. No definitive data is known that stemming plugs are more effective in situations where the proper crushed stone stemming is employed under the same blasting circumstances.

Figure 5-6. Plugs to Channel Forces into Stemming.

f. Subdrilling.

(1) Subdrilling is a common term to denote the depth to which a blasthole will be drilled below the proposed grade to ensure that breakage will occur to the grade line. Blastholes normally do not break to full depth. On most construction projects, subdrilling is used unless, by coincidence, there is either a soft seam or a distinct bedding plane located at the grade line. If this occurs, no subdrilling would be used.

(2) Blastholes may be backfilled a distance of 6 to 12 charge diameters to confine the gases and keep them away from a soft seam (Figure 5-7). On the other hand, if there is a soft seam located a short distance above the grade line and massive material below, it is not uncommon to have to subdrill considerably deeper to break the material below the soft seam. Figure 5-7, for example, shows a soft seam 1ft. above the grade. In this case, a subdrilling approximately equal to the burden

distance was required below the grade to ensure breakage to grade. In most instances, subdrilling is approximated as follows:

$$J = 0.3 * B \tag{5-7}$$

where:

J = Subdrilling (ft).

B = Burden (ft).

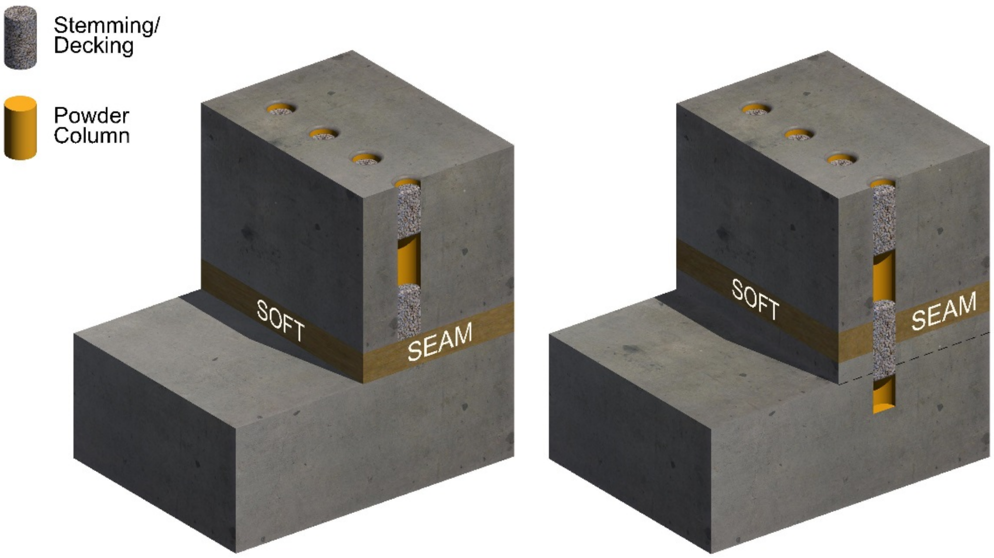


Figure 5-7. Backfill Borehole to Soft Seam (Left) and Problem of Soft Seam Off Bottom (Right).

(3) The subdrilling must not contain drill cuttings, mud, or any rock materials. If borehole walls naturally slough and fill in, drilling must be deeper than the subdrilling previously discussed so that, at the time of loading, the calculated amount of subdrilling is open and will contain explosives.

(4) To get a flat bottom in an excavation, it makes good economic sense to drill to a depth below grade, which, in spite of random drilling depth errors and sloughing holes, ensures that all hole bottoms will be down to the proper depth at the time of loading. If drilling is done slightly deeper than required and some holes are too deep at the time of loading, the blaster can always place drill cuttings in the bottom of those holes to bring them up to the desired height. However, at the time of loading, the blaster does not have the ability to remove excessive cuttings or materials that have fallen into the hole.

(5) Figure 5-8 shows the function of subdrilling. The lines on the figure represent stress contours or zones where the stresses in the rock are equal. The zone that is cross-hatched indicated the zone of maximum tension in the rock. Figure 5-8 shows where subdrilling is used there is a larger zone of maximum tension. This occurs closer to floor level or the area that must be sheared.

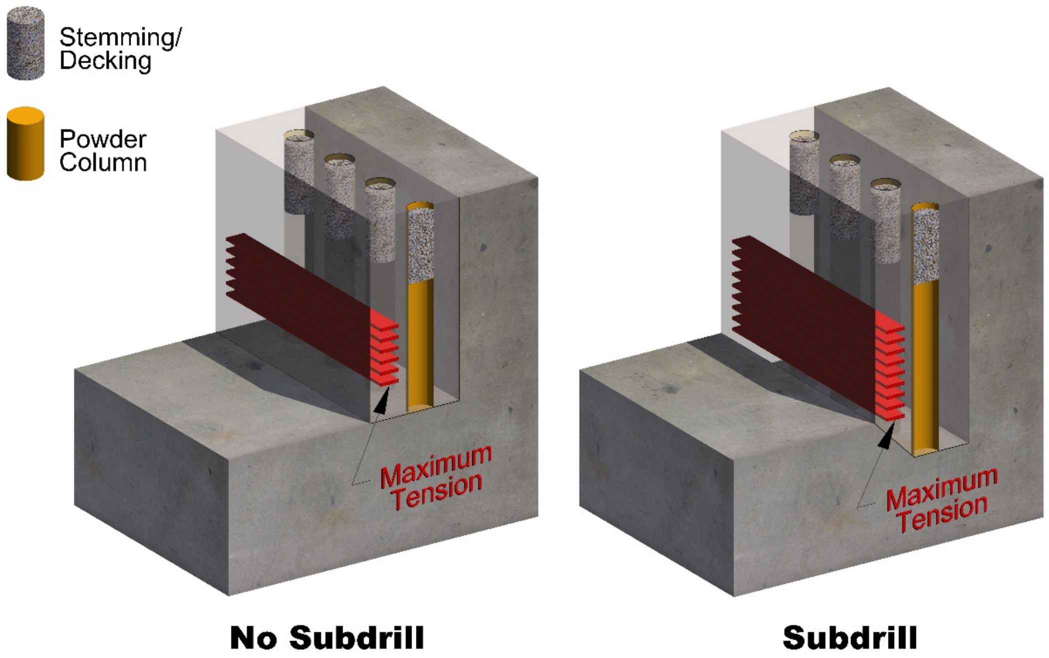


Figure 5-8. Subdrilling and Maximum Tensile Stress Levels.

(6) Subdrilling should be carefully evaluated for structural foundations because damage within the subdrilled zone will result in loss of strength that is hard to quantify. Specifications often disallow subdrilling for structural foundations. Careful attention to foundation preparation before concrete placement is always important, but especially so when subdrilling is permitted.

g. Selection of a Blasthole Size.

(1) The selection of the proper size blasthole for any job requires a two-part evaluation. The first part considers the effect of the drill-hole size on fragmentation, air blast, flyrock, and ground vibration. The second considers drilling economics.

(2) Fragmentation, air blast, flyrock, and ground vibration all have to be assessed. In general, the larger the hole size, the more problems are possible with air overpressure, flyrock, ground vibration, and fragmentation. To gain insight into the potential problems that can result requires the consideration of the stiffness ratio, which is the bench height, L, divided by the burden distance, or L/B. Konya defined this term and the corresponding effects. Table 5-4 summarizes potential problems related to the stiffness ratio.

(3) With the help of the data in Table 5-4, the operator can determine the potential for unwanted effects, and how much of a tradeoff should be made with the drilling and loading economics and these factors. A general rule of thumb is that: the more massive the rock in a production blast, the more probable the outcome listed in Table 5-4.

Table 5-4. Potential Problems as Related to Stiffness Ratio (L/B) (Konya).

Stiffness Ratio	1	2	3	4
Fragmentation	Poor	Fair	Good	Excellent
Air blast	Severe	Fair	Good	Excellent
Flyrock	Severe	Fair	Good	Excellent
Ground vibration	Severe	Fair	Good	Excellent
Comments	Severe backbreak and toe problems. Do not shoot. REDESIGN!	Redesign if possible.	Good control and fragmentation.	No increased benefit by increasing stiffness ratio above 4.

(4) A simple method used to approximate a blasthole length where the stiffness ratio is above 2, is the so-called the "Rule of Five" (Figure 5-9). The minimum length of blasthole in feet is approximated by multiplying the hole diameter in inches by 5 and the result is given in feet, as calculated in Equation 5-8:

$$L_H = 5 * D_e \qquad (5\text{-}8)$$

where:

L_H = Minimum Bench Height (ft).

D_e = Diameter of Explosive (in.).

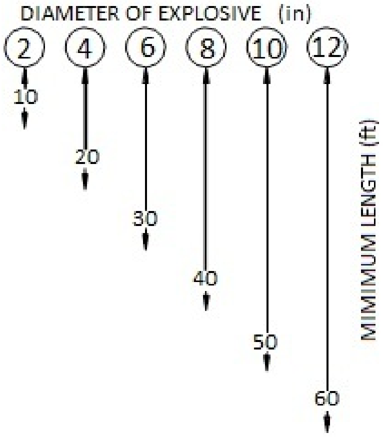


Figure 5-9. Rule of Five.

5-3. Initiation Sequence.

a. Initiation Timing.

(1) Selection of the proper initiation timing is as important as the selection of the proper physical dimensions, such as burden and spacing. This section discusses two general conditions of initiation timing: 1) where holes within a row are fired instantaneously or 2) fired simultaneously. Simultaneous initiation along a row mandates a larger spacing. Therefore, since holes are spaced further apart, the cost per yard or per ton of the broken material is reduced. However, larger spacing

with simultaneous initiation can result in undesirable ground vibrations. Although more yardage is produced by instantaneous initiation, the fragmentation distribution is coarser than those produced by proper delay initiation timing with shorter blasthole spacing. Delay initiation timing along a row reduces ground vibration and produces finer fragmentation. To assess or complete blast designs, some relatively simple rules on delay initiation timing can be established. The data in Table 5-5 can be used along with the Equation 5-9 to calculate appropriate hole-to-hole delays.

Table 5-5. Time Delay Between Blastholes in a Row (for Bench Blasting).

Rock Type	T_H Constant (ms/ft)
Sands, loams, marls, coals	1.8 – 2.1
Some limestone, rock salt, some shales	1.5 – 1.8
Compact limestones and marbles, some granites and basalts, quartzite rocks, some gneiss and gabbro	1.2 – 1.5
Diabase, diabase porphyrites, compact gneisses and micashists, magnetites	0.9 – 1.2

(2) Delays between holes within a row are estimated by Equation 5-9.

$$t_H = T_H * S \tag{5-9}$$

where:

t_H = Hole-to-hole delay in a row (ms).

T_H = Delay constant hole-to-hole from Table 5-5 (ms/ft).

S = Spacing (ft).

(3) Row-to-Row Delays

(a) Guidelines for row-to-row initiation (t_r) are:

- Short delay times cause higher rock piles closer to the face.
- Short delay times cause more endbreak.
- Short delay times cause more violence, air overpressure, and ground vibration.
- Short delay times have more potential for flyrock.
- Long delay times decrease levels of ground vibration.
- Long delay times decrease the amount of backbreak.

(b) Table 5-6 lists the general guidelines to determine the delay time to be used between rows in production blasts.

Table 5-6. Time Delay between Rows.

t_R Constant (ms/ft)	Result
2	Violence, excessive air blast, backbreak, etc.
2-3	High pile close to face, moderate air blast, backbreak
3-4	Average pile height, average air blast, and backbreak
4-6	Scattered pile with minimum backbreak
7-14	Overburden casting

(c) Delayed times should not be less than 2 ms/ft of burden between rows. Delay times should normally be no greater than 6 ms/ft of burden between rows. When the stiffness ratio is near 2 and wall control is critical in multi-row shots (6 or more rows), row-to-row delays may be expanded to as much as 14 ms/ft of burden to obtain low muck piles and overburden casting. Equation 5-10 calculates the delay time between rows.

$$t_r = T_R * B \tag{5-10}$$

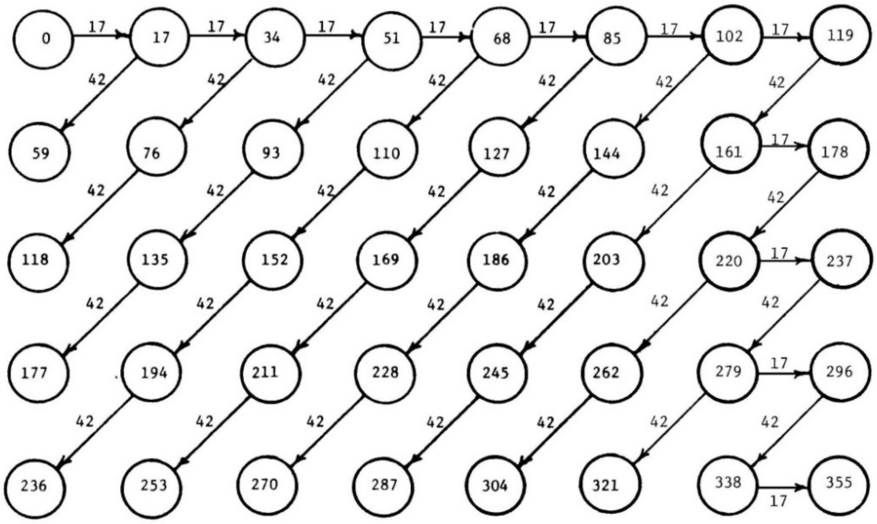
where:

t_r = Time delay between rows (ms).

T_R = Time factor between rows (Table 5-6) (ms/ft).

B = Burden (ft).

(d) The selection of an estimated time in ms can be easily calculated from these equations. However, the values obtained may be difficult if not impossible to implement in the field because of the limitations in hardware selected or available. Therefore, longer delays than estimated will often be used for this reason and to reduce vibration effects. In any case, obtaining as accurate a delay time is critical to predicting the blasting effects. These should be clearly documented before blasting actually occurs. Figure 5-10 shows an example of a delay timing diagram showing the location of the surface delays as well as the blasthole firing time.



Note: Third row overlaps beginning 8th hole in first row and thereafter. Additional rows will also overlap. (Less than 8 MS delay considered to overlap)

Figure 5-10. General Sample Layout of a Production Shot That Shows the Timing Sequence.

(e) A significant portion of blasting problems (e.g., air overpressure, flyrock, excessive vibration, and poor fragmentation) is directly related to the initiation timing (Figure 5-11). The calculations above give approximate appropriate ms delays. However, timing must also be considered for its potential to cause ground vibration. In general shorter delays will cause increased vibration. However, face motion and rock movement occurs more rapidly on high benches than they do on low benches (see Section 5-4.a(5)) for a discussion of low benches, high benches and the stiffness ratio) and this must also be considered when designing delays . It takes time to overcome the inertia of the rock material and on low benches commonly one-half to one-third of the bench depth is unloaded and contains stemming. There is a greater time lag for bench movement on a low bench than there is on benches with higher L/B ratios (see Figure 5-1 for the definition of L/B). To produce the forward motion of the rock toward the face, reduce backbreak and to reduce boulders it is recommended to increase the timing between rows to as much as double the values calculated by Equation 5-10 using constant values given in Table 5-6.

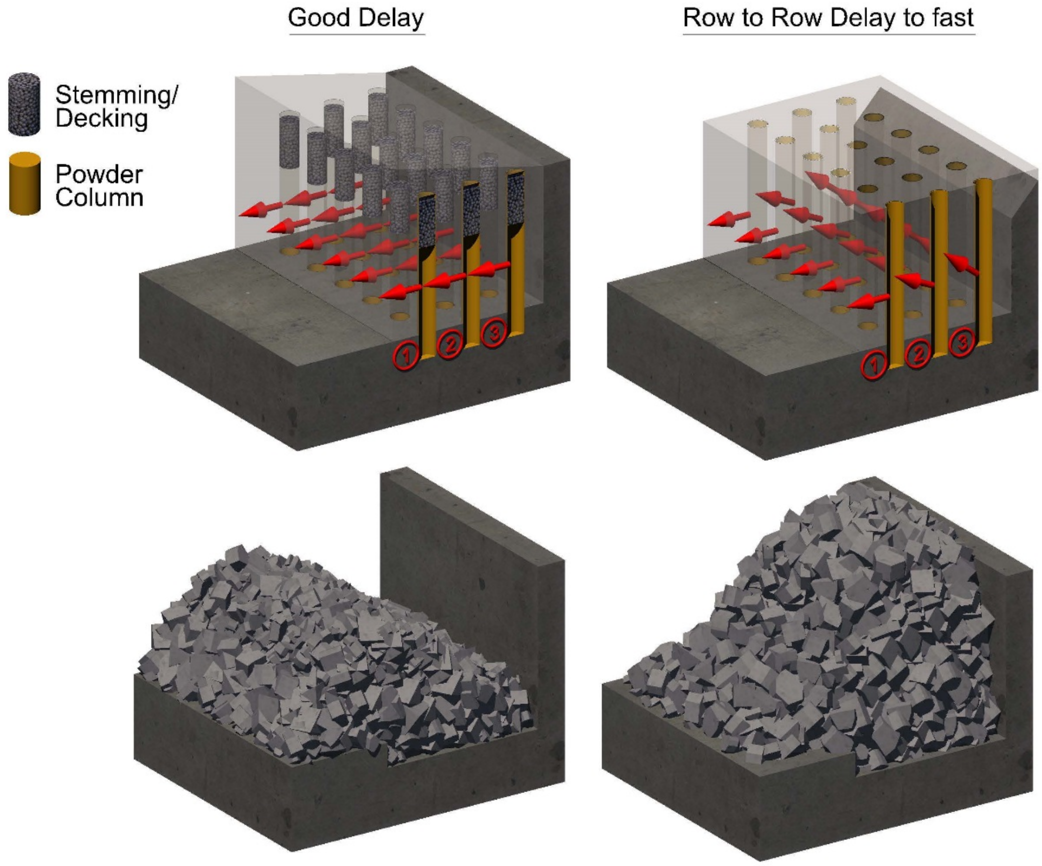


Figure 5-11. Piling and Uplift Resulting from Timing.

(f) Regulatory agencies often require that charges be fired on an 8 ms delay if they are to be considered separate events from the standpoint of ground vibration. Both the vibration character and the blasting performance time previously discussed must be looked at from a realistic standpoint. Damaging levels of ground vibration have been determined using the 8 millisecond rule. The rule states that the weight of all explosives charges fired within 8 milliseconds must be added together and those fired at greater than 8 milliseconds act separately. This rule encompasses the blasting cap tolerances. The rule has been used for the last 50 years. Some blasters state that the more accurate electronic delays can be fired on shorted intervals such as 4 ms delays and that the vibration will not be additive. This is not true for many reasons and also no damage criteria exists for 4 ms delay. For all USACE blasting projects the use of the 8 ms rule is mandatory.

b. Borehole Timing Effects. Blasters have recognized the need for sequencing blastholes. The need for proper sequencing is even more pronounced in underground work. If holes do not sequence properly, boot legs result and rounds do not pull to full depth. Sequencing holes has been used for many years. Unfortunately, there is a lot more to timing than just sequencing holes. If a pattern is properly drilled and loaded, the initiation timing controls the fragmentation size, piling of the broken material, maximum vibration level, amount of air overpressure created, amount of flyrock produced, backbreak, endbreak, and general overbreak. Timing is one of the most important blast design variables and, unfortunately, it is most often neglected.

Poor timing in combination with other design inadequacies are responsible for most blasting problems.

(1) Fragmentation Size. The size to which the rock is broken from the blast depends on the way the blasting energy works both between the holes and between rows. The spacing of the holes also depends on the timing. Breakage will suffer if the spacing and timing are wrong. In the past 40 years, a great deal of research has been done in many different countries investigating the effects of hole-to-hole timing on breakage and there are many different recommendations in the literature for optimal timing. It is a recognized that initiation within a certain timing window will produce better results with no additional explosives used.

(2) Piling or Casting Material. The timing between rows in a blast controls the piling or casting of the broken material. If delays are too short, row-to-row, the rock will be thrown vertically into the air and may even create flyrock on the bench. If longer times are used, the material can peel away, row by row, allowing forward motion of the broken rock. Operators who use explosive casting in coal mining operations know that timing controls the amount of materials that can be put into the spoil pile.

(3) Air Overpressure (Blast) and Flyrock.

(a) Air overpressure and flyrock are also influenced by the timing. A good shot can go bad with a change of nothing more than the cap periods in the hole. In general, row-to-row timing that is too fast will increase the air overpressure and flyrock problems. For example, if the row-to-row timing is too fast and the previous row has not had a chance to move, there is added resistance on that second row. The hole, in fact, senses a much larger burden and cannot relieve itself laterally and tends to blow out vertically. This blowout can be very difficult to control.

(b) Another source of air overpressure is the concussion, sub-audible sound produced by the falling wall. If the initiation rate along a face equals the velocity or sound in air, airwaves can be superimposed causing increased air blast, which under some circumstances can have directional effects.

(4) Maximum Vibration. Ground vibration is also controlled by the timing. The timing effects the ground vibration in two separate ways. For example, if the row-to-row timing is too fast, there is added resistance on the blastholes. Less breakage occurs and more of the total energy becomes seismic energy, which causes problems with ground vibration. Heavy confinement is known to raise vibration levels by as much as 500%. Hole-to-hole timing can effect ground vibration also, since increased relief on a blasthole, at the time it fire, increases breakage and decreases seismic effects. The following paragraphs illustrate an even more critical effect of the timing on vibration, both hole-to-hole and row-to-row.

(5) Overbreak, Backbreak and Endbreak. Breakage beyond the excavation limits is common in many types of blasting. The increased backbreak and endbreak, in general, can be controlled by the selection of the proper timing. It is often common, on operations, to give the last row and sometimes the end holes in a row more time before they fire to allow earlier firing rows to

move out of the way. This reduces the resistance on those holes and reduces the pressure on the back walls, whereby cleaner breaks with less endbreak and backbreak will occur.

c. Cap Scatter.

(1) General

(a) All initiation systems used today, except electronic delays, have scatter times of initiation, which means that the blasting cap will not fire exactly on the rated delay. In general, unless told otherwise by the manufacturer, one could assume that the rated cap delay period has a maximum scatter time of approximately ±10% of the rated firing time. This scatter time contains the shifting of the average firing time (mean value) as well as the scatter time around this average value (two standard deviations). This is to say, for example, that either an electric or non-electric cap that is rated as a 200 ms delay will fire between 180 and 220 ms. If the subsequent hole is due to fire at 210 ms, the probability of having a true 10 ms delay time between the two holes is relatively small.

(b) If good wall control and low vibration and violence is to be achieved, sequential movement of rows is necessary. Serious consideration of the effect of scatter time especially on row-to-row delays must be made when designing the blast.

(c) Cap scatter time has been responsible for backbreak, flyrock, air overpressure, and excessive ground vibration.

5-4. Principles of Production Blasting Patterns.

a. Geometry and Initiation.

(1) A blasting pattern consists of placing properly designed single blastholes into a geometrical relationship with one another and with the open face. The spacing between blastholes in a single row depends on two variables, the initiation timing of the adjacent holes and the stiffness ratio, L/B. The Konya method of determining blasthole spacing calculates spacing depending on the stiffness ratio and the blasthole timing.

(2) If holes are initiated simultaneously, spacing must be spread further apart than if holes are timed on a delay. If holes are spaced too close together and fired instantaneously, a number of undesirable effects will occur. Cracks from the closely spaced blastholes will link prematurely causing a shattered zone in the wall between holes (Figure 5-12). The premature linking will form a plane whereby gases will be vented prematurely to the atmosphere causing air overpressure and flyrock. The venting process will reduce the available amount of energy and in effect the holes will become overconfined. The overconfinement condition will increase the amount of ground vibration. In spite of the close spacing and the large amount of energy per unit volume of rock, fragmentation of the burden rock will usually be poor. Conversely, it is obvious that, if blastholes are spaced too far apart for either delay or instantaneous initiation, fragmentation will become coarse and rough walls will result (Figure 5-13).

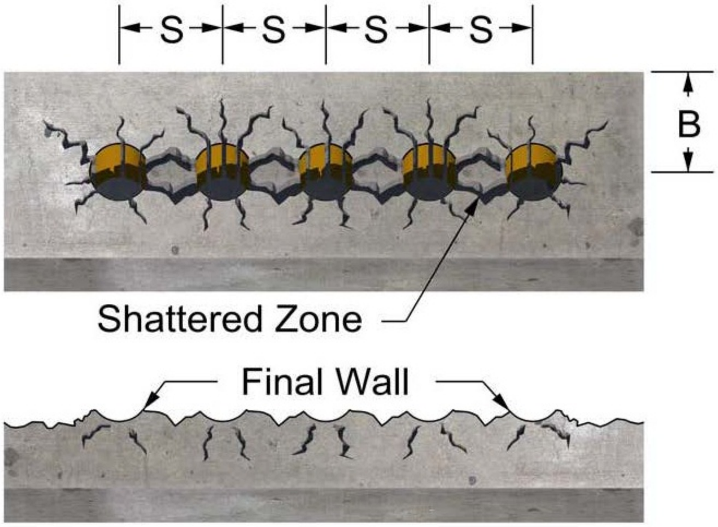


Figure 5-12. Shattered Zone from Close Spacing.

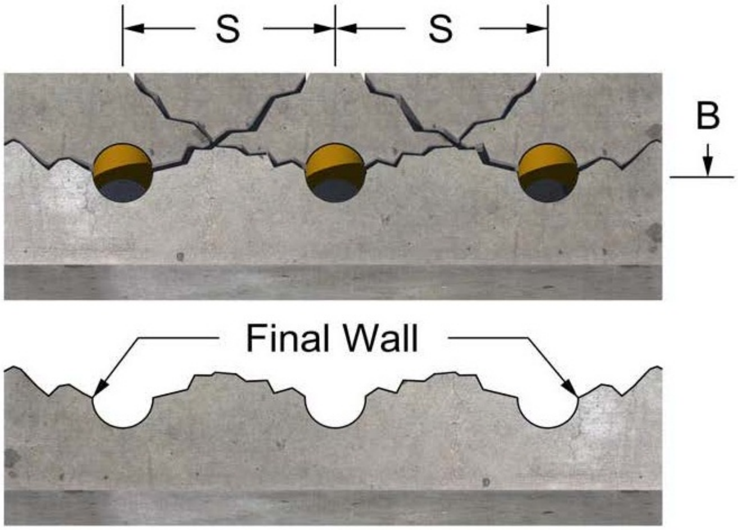


Figure 5-13. Rough Walls from Excessive Spacing.

(3) Blasthole spacing must be normalized to overcome problems with stiffness. Therefore, when benches are low compared to the burden, stiffness is a factor that must be considered. When benches are high, stiffness is no longer a consideration (Table 5-7).

(4) Two factors must be considered for hole spacing. The first is to determine if blastholes function either instantaneously or with delays. The second is whether benches are classified as low or high as compared to the burden.

(5) The first decision as to whether holes function simultaneously or delayed is obvious. The second must be tied to physical dimensions such as the burden and the bench height. The stiffness ratio or L/B is used to make this determination. If L/B is less than 4 and greater than 1,

benches are considered low and stiffness must be considered. On the other hand, if L/B is greater than 4, stiffness is no longer a concern. There are, therefore, four separate conditions that must be discussed: (1) instantaneous initiation low benches, (2) instantaneous initiation high benches, (3) delayed initiation low benches, and (4) delayed initiation high. Table 5-8 summarizes the spacing equations.

Table 5-7. Potential Problems As Related To Stiffness Ratio (L/B)

Stiffness Ratio	1	2	3	4 or Higher
Fragmentation	Poor	Fair	Good	Excellent
Airblast	Severe	Fair	Good	Excellent
Flyrock	Severe	Fair	Good	Excellent
Ground Vibration	Severe	Fair	Good	Excellent
Comments	Severe backbreak and toe problems. Do not shoot. REDESIGN!	Redesign if possible.	Good control and fragmentation.	No increased benefit by increasing stiffness ratio above 4.

Table 5-8. Summary of Spacing Equations (Konya).

	Low Bench (L / B < 4)	High Bench (L / B => 4)
Instantaneous	S = (L + 2B)/3	S = 2B
Delay	S = (L + 7B)/8	S = 1.4B

b. Instantaneous Initiation Low Benches.

(1) Equation 5-11 may be used to check the blasting plan and determine if spacing is within normal limits:

$$S = {}^{(L + 2B)}/_{3} \tag{5-11}$$

where:

S = Spacing (ft).
L = Bench height (ft).
B = Burden (ft).

(2) If the conditions from the particular blast are placed in this equation and if the actual spacing is within ±15% of the calculated spacing, then the spacing is considered within reasonable limits. In no case should the spacing be less than the burden.

c. Instantaneous Initiation High Benches. To function as a high bench, the bench height to burden ratio must be 4 or more. With instantaneous initiation between holes, calculated spacing is within reasonable limits if it is within 15% of the actual spacing, as calculated by:

$$S = 2B \tag{5-12}$$

d. Delayed Initiation Low Benches. When the stiffness ratio is between 1 and 4 with delayed initiation between holes, Equation 5-13 is used to check spacing. Calculated spacing is within reasonable limits if is within ±15% of the actual spacing when substituting the designed parameters:

$$S = {}^{(L + 7B)}\!/_{8} \tag{5-13}$$

where:

S = Spacing (ft).

L = Bench height (ft).

B = Burden (ft).

e. Delayed Initiation High Benches. When the L/B stiffness ratio is 4 or more and holes in a row are delayed, Equation 5-14 is used to check the spacing. Calculated spacing is within reasonable limits if it is within ±15% of the actual spacing, as calculated by:

$$S = 1.4 * B \tag{5-14}$$

where:

S = Spacing (ft).

B = Burden (ft).

f. Pattern Design.

(1) To maximize fragmentation and minimize unwanted side effects from blasting, the design variables of burden, stemming, subdrilling, spacing, and timing must be selected such that all variables are working together. To better explain the relationship between the variables, figures will be used to illustrate the effects of having properly matched variables and improperly matched variables. For this example, it is assumed that there are no geologic complications and all bench heights are at least four times the burden.

(2) When a blasting pattern is constructed, every hole must be analyzed to determine if it will respond properly. Analyzing spacing or drill burden without consideration for initiation timing does not produce a true picture of what will occur when the hole is fired. If a pattern is properly designed, there is a repetitive sequence in the crater forms that are broken per hole. For example, depending on the relationship between the blasthole and the free face, different crater shapes will be created from independent holes firing (Figure 5-14). To simplify this analysis, assume that the breakage angle between the burden line and the edge of the crater is approximately 45°. If a blasthole has more than one burden direction at the time of its detonation, the distance to the free face along both burden directions should be equal.

(3) Figure 5-14A shows the breakage angle formed when there is one vertical free face. For the purposes of this analysis, the horizontal free face or the bench top will not be considered since from the previous discussion it was evident that explosives preferentially function radially away from the blastholes.

(4) Figure 5-14B shows two vertical free faces that form a 90° angle, in which breakage patterns would be different from those in Figure 5-14A. In Figure 5-14F, a corner cut would experience a different area of breakage because of the orientation of the face. If the blasthole is on a corner with two vertical free faces, the breakage area is equivalent to two craters of area shown in Figure 5-14A. In Figure 5-14E, the crater will be considerably larger than that shown in Figure 5-14A through Figure 5-14D.

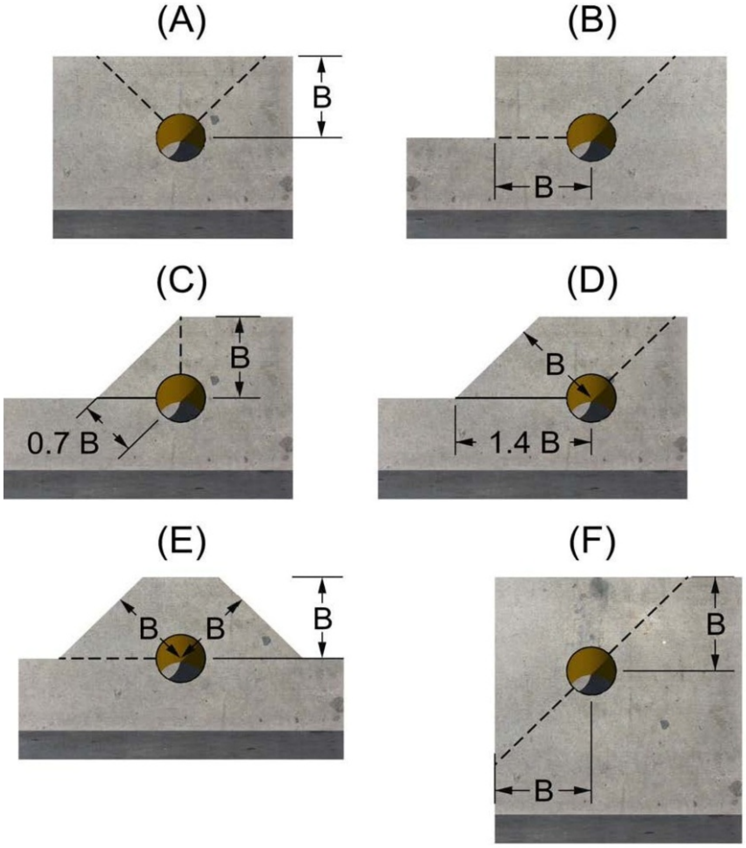


Figure 5-14. Typical Crater Forms (Plan View).

(5) It is apparent that, even if the same amount of explosive is used in each blasthole in the above examples, different volumes of rock are fragmented depending on the blasthole orientation to the free face. This simple example shows that powder factor or the amount of explosive used per volume of blasted rock is not a constant number within a shot, even if the rock type and explosive type are identical.

(6) To actually design the blasting pattern, a number of factors must be considered. The first factor must be the direction in which the rock is to move. The lowest period delays will be placed

in that direction. As the lower period delays fire, they create additional free faces and relief. In this way, the rock is moved toward the direction of the lowest period delays.

(7) Another important consideration is fragmentation sizing and vibration. Fragmentation sizing varies with bench height, delays, and spacing.

(8) To better understand blasting patterns, whether they are electric or non-electric, it is necessary to follow the following steps:

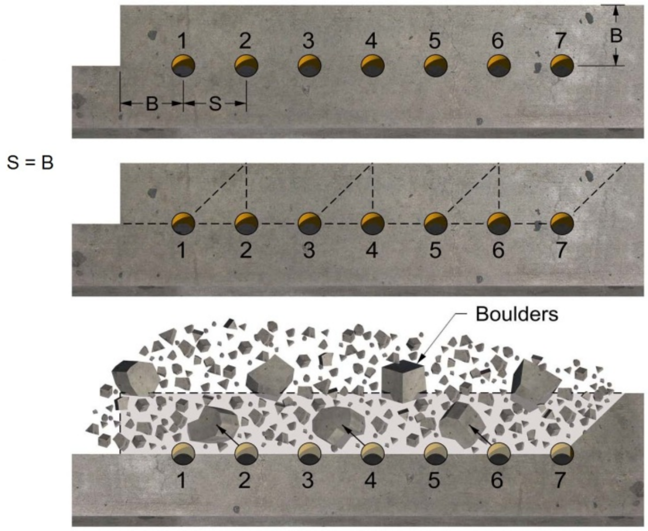
- Draw the pattern and show the appropriate surface and downhole delays.
- Draw the identical pattern and show the actual firing time of each blasthole or each deck.
- Determine the sequence of firing. Instead of using only the firing time of the holes, add a third drawing that shows the actual sequence of hole firing. This is very important, especially with complex electric or non-electric patterns. Without the third drawing showing actual sequence, very often the blaster or engineer does not truly realize how the holes are sequencing.

5-5. <u>Rock Piling Considerations</u>.

a. The function of the blasting pattern is not only to fracture the rock to the desired size distribution, but also to pile or place the rock in a manner that is most economic to handle in the next step of the operation. The type of equipment that will do the digging, the blasted material is an important consideration when the blast is designed. If the benches are relatively low and a shovel is used for loading, one may want to stack the rock to ensure a high bucket-fill factor. On the other hand, if benches are high and an end loader will do the digging, there should be an intentional scattering of the broken rock. To ensure the proper piling of material, the following principles should be considered in the design process:

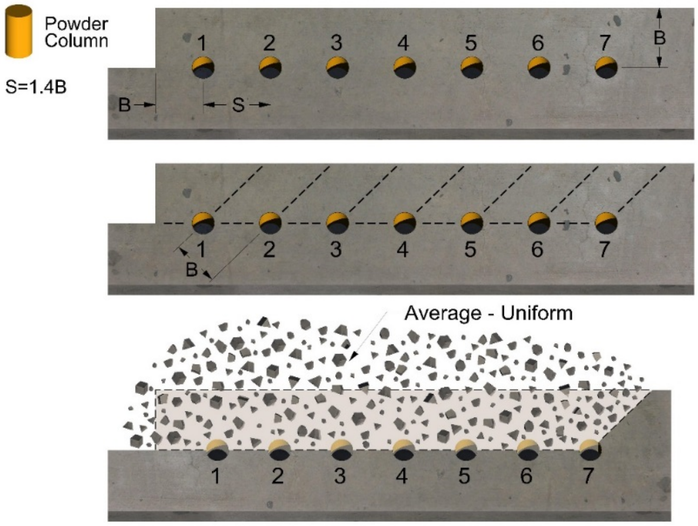
- Rock movement will be parallel to the burden dimension.
- Instantaneous initiation along a row causes more displacement than delayed initiation.
- Shots delayed row by row scatter the rock more than shots arranged in a V-cut.
- Shots designed in a V-cut give maximum piling close to the face.

b. Figures 5-15 through 5-21 show the type of piling and fragmentation anticipated from different patterns.



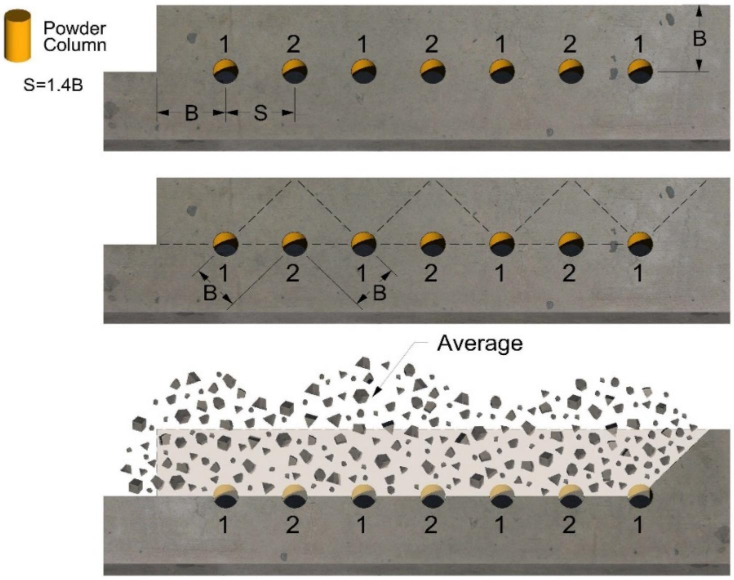
Conditions:	Drill pattern:	All holes spaced at burden distance
	Initiation Timing:	Progressive MS Delays
	Vibration Level:	Low, each hole on a separate delay
	Fragmentation:	Two separate distributions. Fines and some boulders
	High Bench:	L / B > 4

Figure 5-15. Single Row Progressive Delays, S = B.



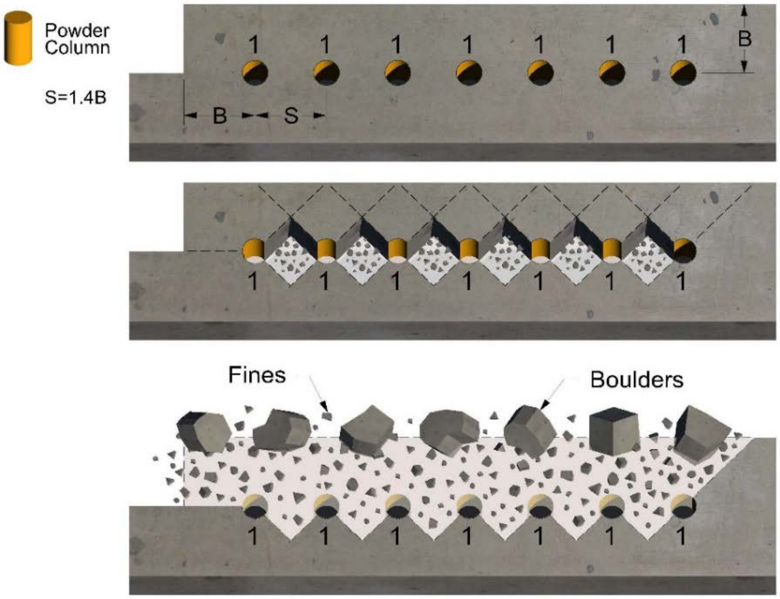
Conditions:	Drill pattern:	First hole, burden distance from face. Spacing is 1.4 B for L / B ¾ 4
	Initiation Timing:	Progressive MS Delays
	Vibration Level:	Low, each hole on a separate delay
	Fragmentation:	Uniform, one tight distribution
	High Bench:	L / B > 4

Figure 5-16. Single Row Progressive Delays, S =1.4B.



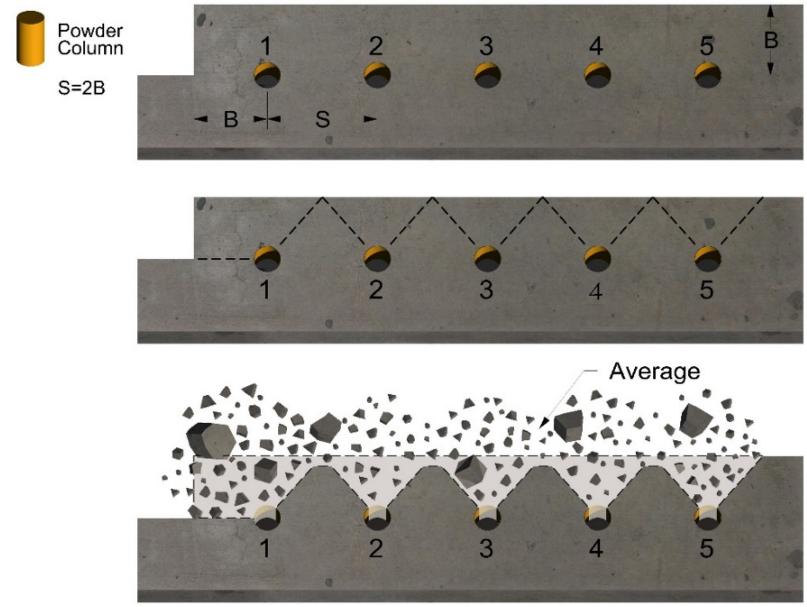
Conditions:	Drill pattern:	First hole, burden distance from face. Spacing is 1.4 B for L / B ¾ 4
	Initiation Timing:	Alternating MS Delays
	Vibration Level:	High, since one-half ot total holes firing on one delay
	Fragmentation:	Majority of rock in two different size distribution.
	High Bench:	L / B > 4

Figure 5-17. Single Row Alternating Delays, S = 1.4B.



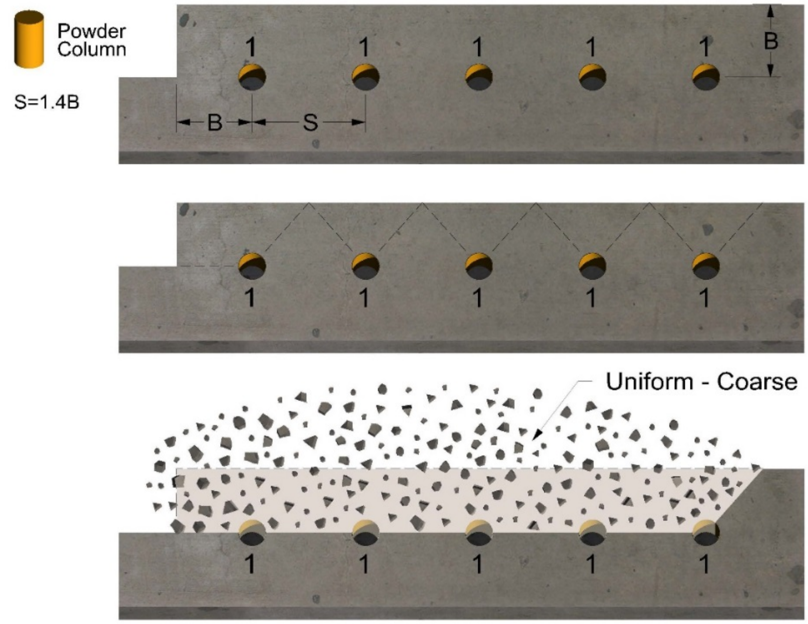
Conditions:	Drill pattern:	First hole, burden distance from face. Spacing is 1.4 B for L / B
	Initiation Timing:	Instantaneous.
	Vibration Level:	High, since all holes firing on one delay
	Fragmentation:	Majority of rock in two different size distribution (fines and boulders).
	High Bench:	L / B > 4

Figure 5-18. Single Row Instantaneous, S = 1.4B.



Conditions:	Drill pattern:	First hole, burden distance from face. Spacing is 2B.
	Initiation Timing:	Progressive Delays.
	Vibration Level:	Low, each hole on separate delay.
	Fragmentation:	Average, some boulders, rough face.
	High Bench:	L / B > 4

Figure 5-19. Progressive Delays, S = 2B.



Conditions:	Drill pattern:	First hole, burden distance from face. Spacing is 2B for L/B¾4.
	Initiation Timing:	Instantaneous row.
	Vibration Level:	High
	Fragmentation:	Uniform, coarse.
	High Bench:	L / B > 4

Figure 5-20. Single Row Instantaneous, S = 2B.

c. Whenever a new bench is started, a box cut is needed to open the bench. Box cuts begin with only one vertical face for relief. For that reason they are often more prone to result in violence, especially from the corner holes marked No. 6 in Figure 5-21. One often hears rules of thumb in the field indicating that blow out of corner holes can be controlled by skipping a delay or doubling the delay in the corner holes. This may or may not be effective depending on which delay period (in ms) is actually used in the corner holes. Figure 5-22 shows how a more effective solution to the problem is to design the blast so that the corner holes are totally eliminated.

d. In both Figures 5-21 and 5-22, the rock is piled in the center and rock movement is perpendicular to the break lines shown in the diagrams. A major disadvantage of this type of pattern is that many holes fire on the same period, thereby creating higher vibration levels. The major advantage of the pattern is that it reduces drilling and explosive costs since blastholes, behind the first row, are drilled on a spacing equal to 1.4 times the burden. The distance between rows is also 1.4 times the burden. Since the rows are fired on echelon the distance to relief between holes is the true design burden.

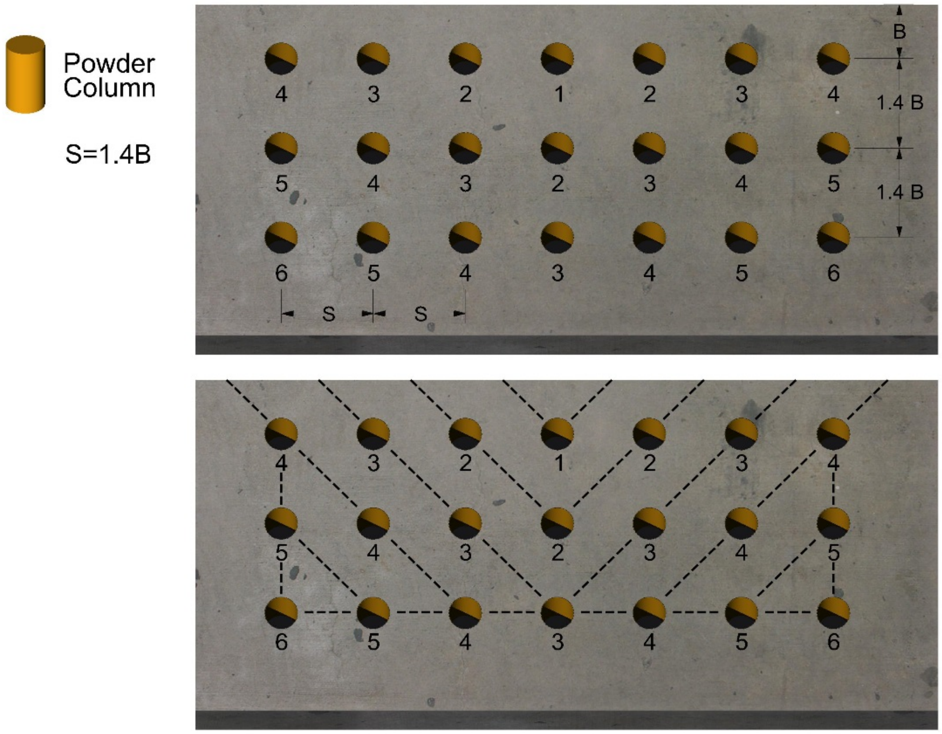


Figure 5-21. V-Cut (Square Corner, Box Cut Used to Open a Bench), Progressive Delays, S = 1.4B: More Violence Prone in the Corners at the Holes Marked Number 6.

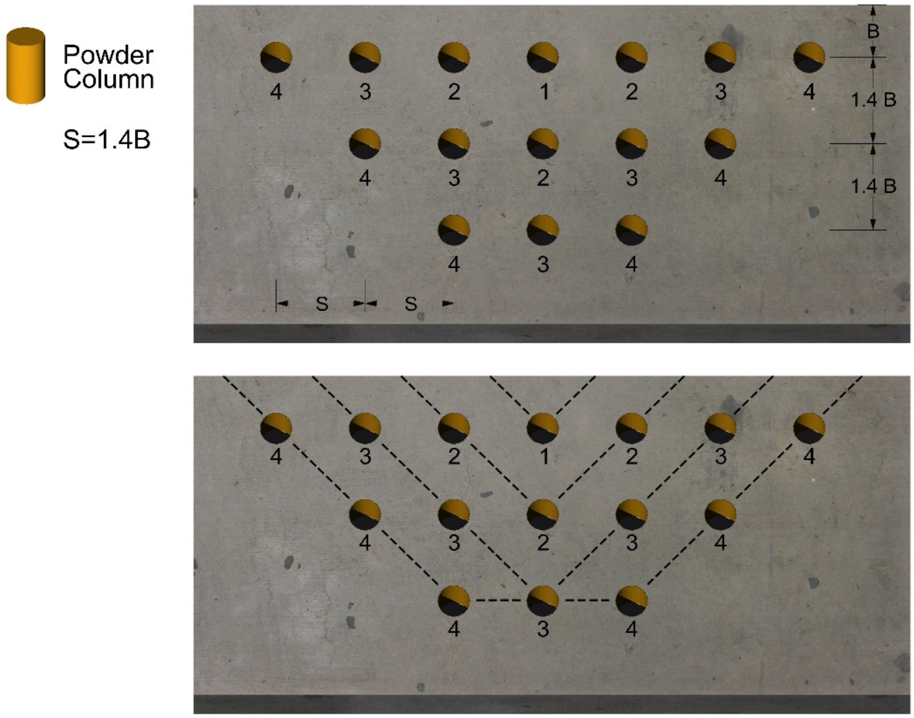


Figure 5-22. V-Cut (Angle Corner, Box Cut Used To Open a Bench), Progressive Delays, S = 1.4B, Better Design for Prevention of Corner Problems.

e. In situations where lower vibration levels are required or where it is desired to break the rock somewhat more finely, the pattern shown in Figure 5-23 could be used. The cost per volume would increase with the use of this pattern. In this delayed pattern, no blasthole reinforces a neighboring blasthole. Delay periods different from those shown in Figure 5-23 could be considered. If vibration is a concern, each blasthole within the pattern could be fired independently. Figure 5-24 shows an example of a different timing sequence, which would result in a change in smaller size distribution.

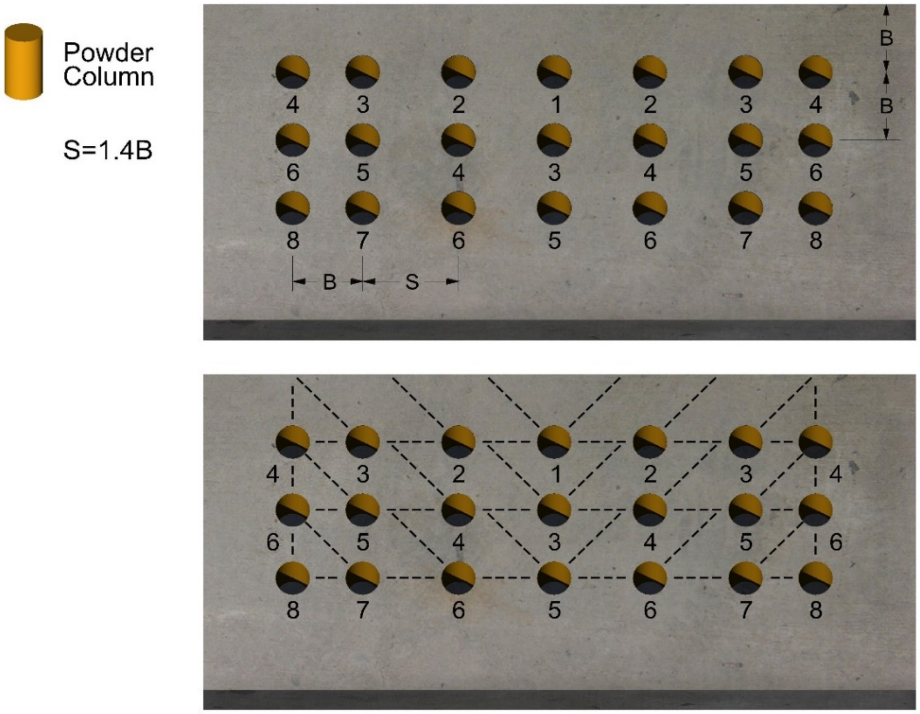


Figure 5-23. Box Cut, Progressive Delays, S = 1.4B.

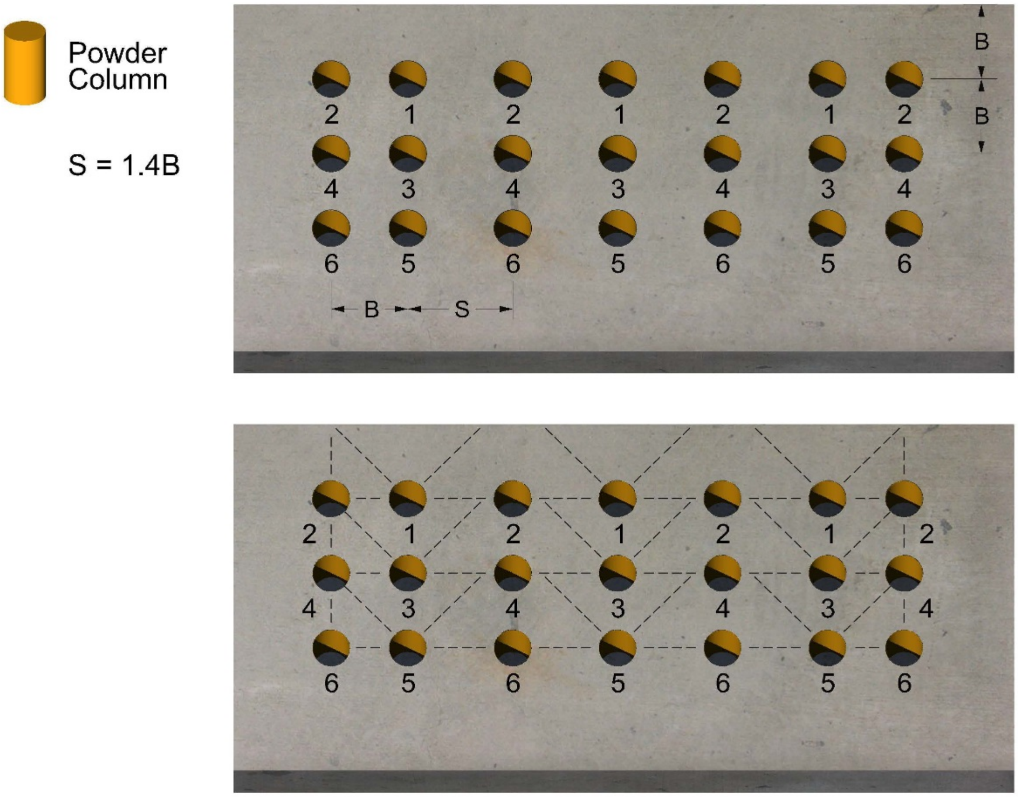


Figure 5-24. Box Cut Alternating Delays, S = 1.4B.

f. If the box cuts shown in Figures 5-23 and 5-24 were used to open a bench, the corner cut shown in Figure 5-25 could be used to continue production along this bench. As in the box cut, each hole could be fired on a separate delay to reduce vibration. It should be noted that the edge holes in a row are not spaced at 1.4 times the burden. They are spaced at 1.0 times the burden and often loaded lighter than the remainder of the production holes. This is done to change the direction the holes move away from the side walls, which also reduces the end break at the end of each row. If the V-cut as shown in Figure 5-22 were used, it could be followed by the corner cut shown in Figure 5-26. If the operator desires to change the direction of rock movement in Figure 5-26 (movement perpendicular to break line), the pattern could be designed as shown in Figure 5-27.

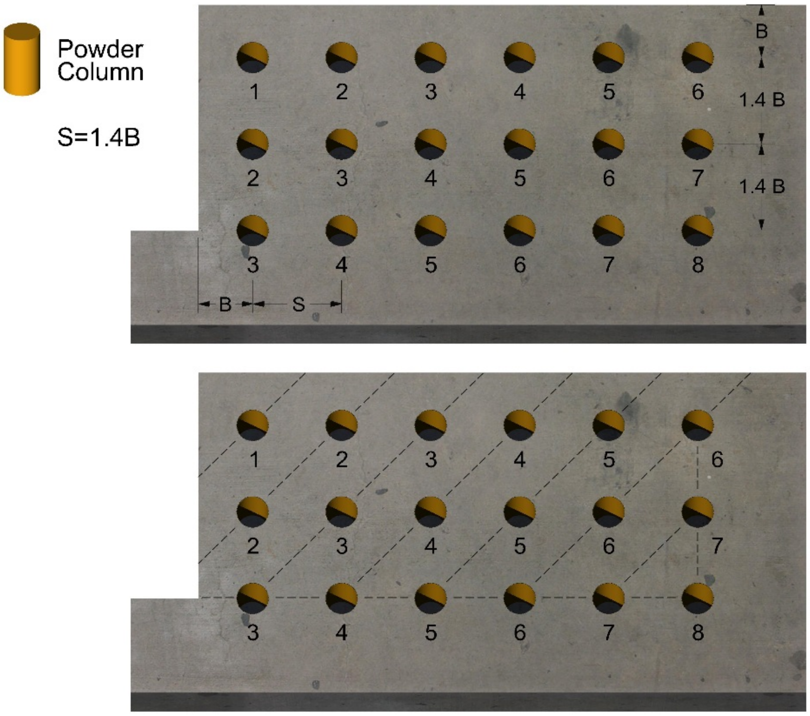


Figure 5-25. Square Corner, Cut Fired on Echelon, S = 1.4 B.

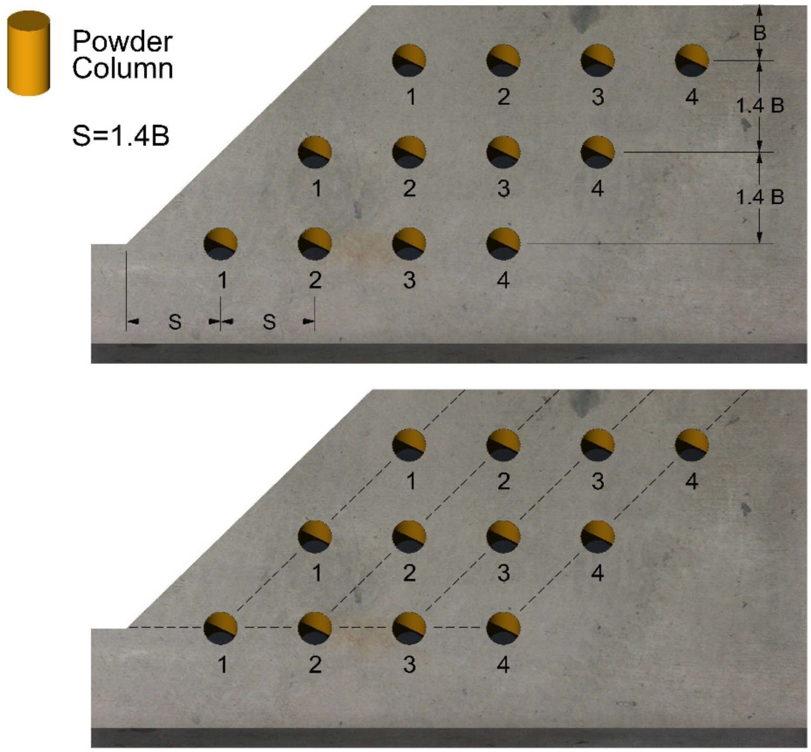


Figure 5-26. Angle Corner, Fired on Echelon, S = 1.4 B.

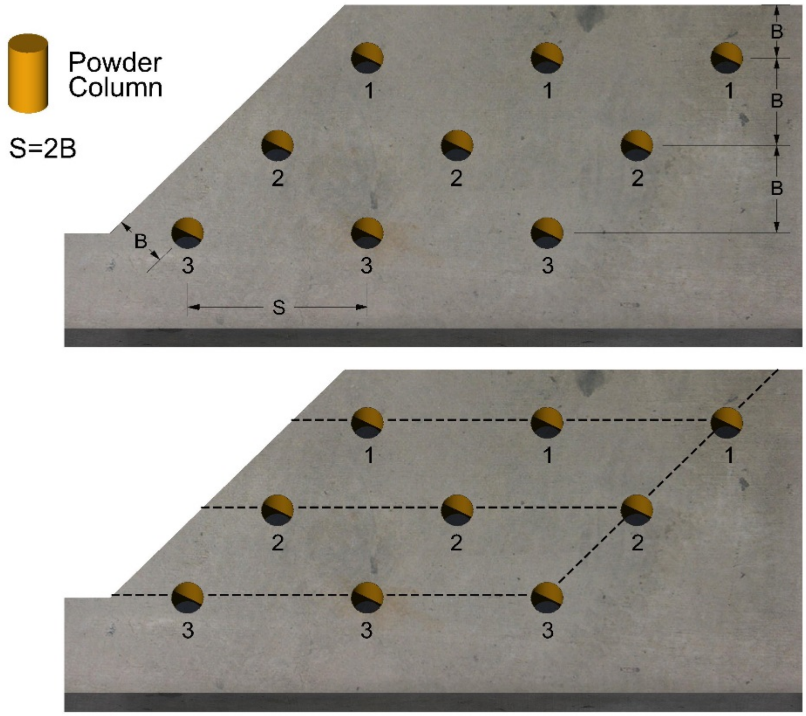


Figure 5-27. Angle Corner, Instantaneous Rows, S = 2 B.

g. The methods of pattern construction previously discussed have indicated general timing sequence or the sequencing of blastholes. The actual time in ms to be used in these patterns will also control scatter or piling along with the air overpressure, flyrock, and ground vibration. The general guidelines for producing proper timing were given in Section 5-3. These must be considered in the selection of the actual timing in ms both hole-to-hole and row-to-row in the shots described in the previous section. The combination of blasting pattern sequencing, along with actual timing, further controls scatter or heaping of the pile.

5-6. Rock Fragmentation and Wall Control.

a. To control fragmentation, two important principles must be correctly applied. The proper amount of energy must be applied at strategic locations within the rock mass, and energy must also be released at a precise time to allow the proper interactions to occur.

b. The energy distribution within the rock mass is further broken down into two distinct areas. First there must be sufficient energy, achieved by using the proper amount of explosives. To break the rock mass, the explosive must also be placed in a geometric configuration where the energy is maximized for fragmentation. This geometric configuration is commonly called the blasting pattern.

c. The release of the energy at the wrong time can change the end result, even though the proper amount of energy is strategically placed throughout the rock mass in the proper pattern. If the initiation timing is not correct, differences in breakage, vibration, air overpressure, flyrock, and backbreak can occur. This discussion does not consider the effects of the timing of the release of the energy. This section considers only the strategic placement of the proper amount of energy in a correct blasting pattern.

d. The study of the concerns of fragmentation goes back to the early days of blasting. Blasters realized that on some blasts, the energy was very efficiently used in the breakage process. On others, very little energy was used in an efficient manner and instead a great deal of noise, ground vibration, air overpressure, and flyrock resulted with little breakage. There have been many empirical methods that have surfaced over the decades, suggesting methods of design that would more efficiently use this energy. These design methods would also give the blaster a way of producing consistent results by applying similar techniques under different circumstances and in different rock masses.

5-7. Rip-Rap Production (see also Chapter 6, "Specialty Blasting Techniques"). Rip-rap is larger size rock normally used to protect banks or slopes from the effect of water and erosion. Rip-rap can weigh a few kilograms or a few tons each depending on the end use of the product. Small size rip-rap can be produced in production blasts by increasing the burden distance and reducing the spacing distance. On the other hand, large size rip-rap weighing thousands of kilograms must be produced using a different technique. Large stone for breakwater walls must be undamaged so that the action of waves and freezing will not deteriorate the rock prematurely. Extreme care must be taken to produce un-fractured rock. This can be accomplished by using principles of controlled blasting along with the production blast. For example, blastholes can be drilled with excessive burdens and minimum spacing. Blastholes are loaded lightly to prevent major damage from occurring around the borehole. When the blast is fired, large pieces of unfractured rock are produced (Figure 5-28). Not every rock can be used for rip-rap production. Geologically speaking, the rock must be either massive or inter-bedded with considerable cohesion across the bedding planes.

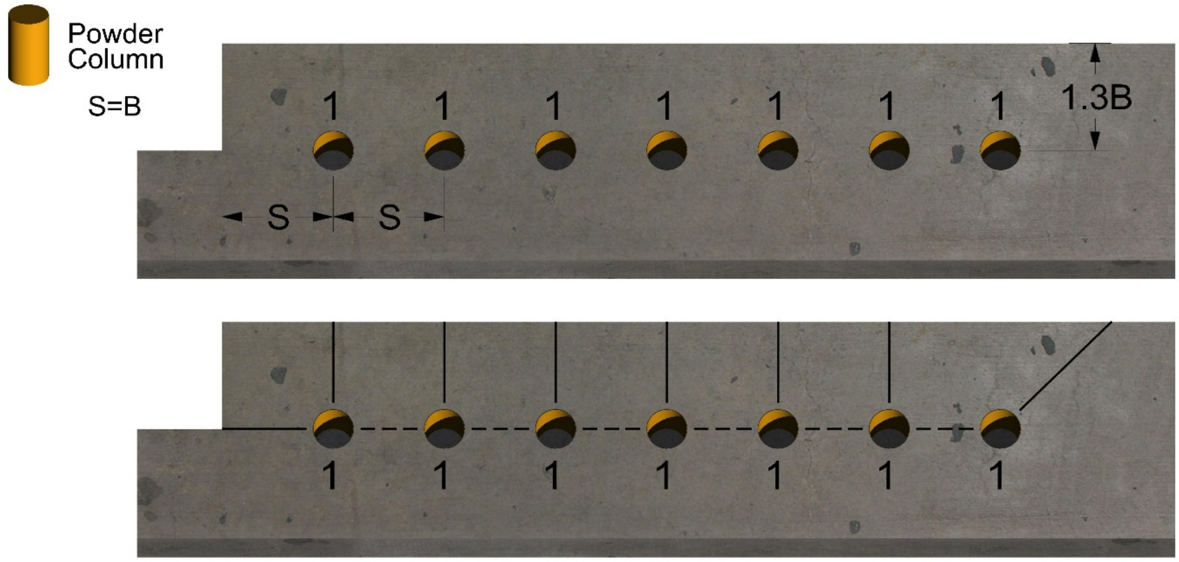


Figure 5-28. Production of Large Rip-Rap, S = B.

5-8. Sinking Cuts.

a. When starting off from a flat rock surface and dropping down to a lower level, such as in highway construction, foundation placement, or blasting for a bridge pier, a blasting pattern commonly called a sinking cut, drop shot, or drop cut will be used. This shot is different from production blasting patterns previously discussed in that there is only one free face, the horizontal top surface of the rock, at the time the shot is initiated.

The first holes to fire in this type of shot function entirely different from those previously discussed. These opening holes must create the second free face toward which the rock can push, bend, or move. Timing of these holes is critical in that, if the time is too short between the initiation of the first or center holes and the subsequent holes, poor breakage results along with extreme violence.

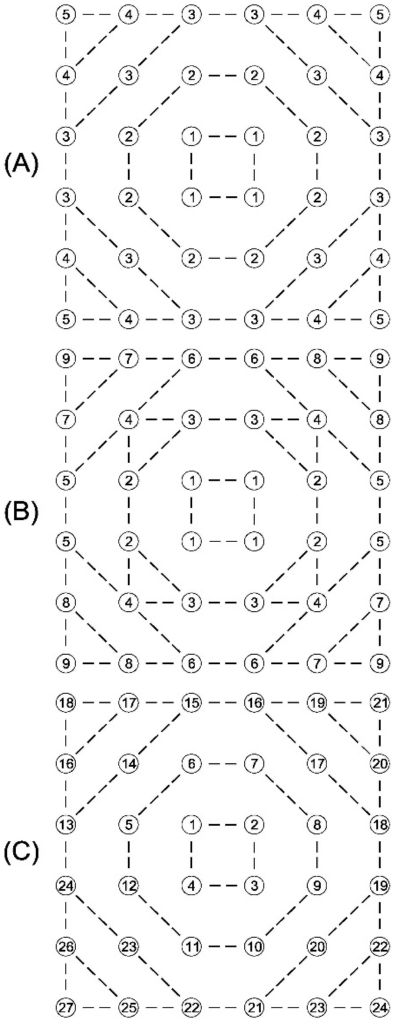


Figure 5-29. Sinking Cuts, Square Pattern, S = B.

b. In Figure 5-29A Sequencing is from row-to-row with only one cap period between each hole. This is a poor pattern because too much rock is broken at one time and the holes are firing too fast. However, the pattern in Figure 5-29B shows different firing sequence, which allows additional movement before each subsequent delay fires. Figure 5-29A also has many holes firing on the same delay period, which will increase the vibration level. Vibration from this type of shot will be higher than from other production rounds because the first holes to fire are heavily confined at the time they detonate.

c. To better explain the functioning of a sinking cut, this section discusses pattern the pattern in Figure 5-29B in detail. In the analysis of pattern it is evident in this example that there are only four holes firing per delay period. This is important, especially near the center of the shot, since if too much rock moves into the center of the shot at one time, the center of the pattern may stick and not move. If this occurs, the remainder of the holes in the pattern will rifle causing poor breakage and excessive flyrock and air overpressure. Sinking cuts can also be delayed so that only one hole or a fraction of a hole fires at one time.

(1) The first holes to fire in the pattern function differently from the rest of the holes in the pattern. For example, the No. 1 holes are functioning on area A, as shown in the diagram, with a tremendous concentration of energy within the zone. No. 2 holes and others, thereafter, use half the number of holes and approximately half the explosive to break a similar volume of rock. Holes marked No. 1 radially crack the rock, but cannot bend or displace it since there is no place for this type of motion to occur. Instead, the radial cracks are pressurized by the gases and begin to lift as in a cratering shot.

(2) The No. 2 holes function differently. No. 1 holes are lifting and No. 2 holes function toward a free face outlined by the break line of No. 1 holes. They, therefore, radially crack and displace into the crater produced by No. 1 holes. Subsequent holes in the shot all have a vertical free face to work toward as did the No. 2 holes. Pattern Figure 5.29B is somewhat different from other patterns previously discussed because the physical direction of the burden changes with each hole firing. If the pattern is laid out in a north and south direction as indicated, holes No. 2 sense a burden in an east-west direction where No. 3 holes sense a burden in a north-south direction. The burden is the most important dimension in a blast. To ensure that all holes have the same maximum distance as the burden, the pattern will be drilled square with an equal burden and spacing.

(3) The No. 1 holes must break to grade to ensure that the subsequent holes can break to grade. If No. 1 hole breaks only partially to the grade line, the entire bottom of the shot will be high and above grade level. To ensure that No. 1 holes break properly, they should be drilled deeper than those in the remainder of the shot. The No. 1 holes should be subdrilled approximately twice as deep as others in the blast or to a depth of 0.5 x burden.

(4) No. 1 holes function differently from the remainder of the holes in the shot and are designed to crater. To control flyrock from the shot, the No. 1 holes should be stemmed equal to the burden distance. The remainder of the holes will be stemmed to a depth of approximately 0.7 burden.

(5) The final dimension in a sinking cut, which needs to be considered, is the depth of the shot. It is obvious that unlimited depth is not a realistic assumption. Gravity effects cause problems with rock motion necessary to produce the desired results.

d. There are two rules of thumb that are considered when designing sinking cuts. The first states that the depth of holes should not be greater than half the dimension across the pattern. This is to say that the cut depth will be one-half the distance obtained if spacing between blastholes in a row are added together. For example, if the pattern width was 60 ft., the depth of the cut should be no more than half that, or 30 ft. A second rule of thumb states that the maximum L/B or bench height to burden ratio for a sinking cut to function properly should not be greater than 4. For example, if the burden between holes in a pattern would be 5 ft., a practical sinking cut depth of 20 ft. would be realistic. On the other hand, if 6 in. diameter holes were being used for sinking cuts with burdens of 15 ft., than practical depth of the cut might be as great as 60 ft. It must be remembered that the greater the depth in a sinking cut, the greater the probability that the cut will not function properly and will not break totally to grade. Laminated rock with closely spaced bedding planes is more forgiving of errors in judgment than is massive rock. In massive rock, these ratios should be clearly followed, while in laminated rock, additional depth is often obtained. The timing sequence in Figure 5-30B is more easily achieved with electric or electronic caps. The timing sequence for non-electric shock tube can be done using dual delays as shown in Figure 5-30C.

5-9. Hillside and Sliver Cuts.

a. Hillside or sliver cuts can be difficult to control, since in most instances the rock cannot be thrown from the hillside. If the purpose of the blasting was to scatter the rock down the hillside, there would be no problem is designing the blast. When it is the intent of the operator to keep as much rock as possible in the cut itself, procedures can be used that are similar to a modified V-cut. The method of timing of the blastholes will ensure rock movement in a manner to keep the rock pushing toward the bank rather than pushing toward the slope. Figure 5-30 shows an example of this type of cut.

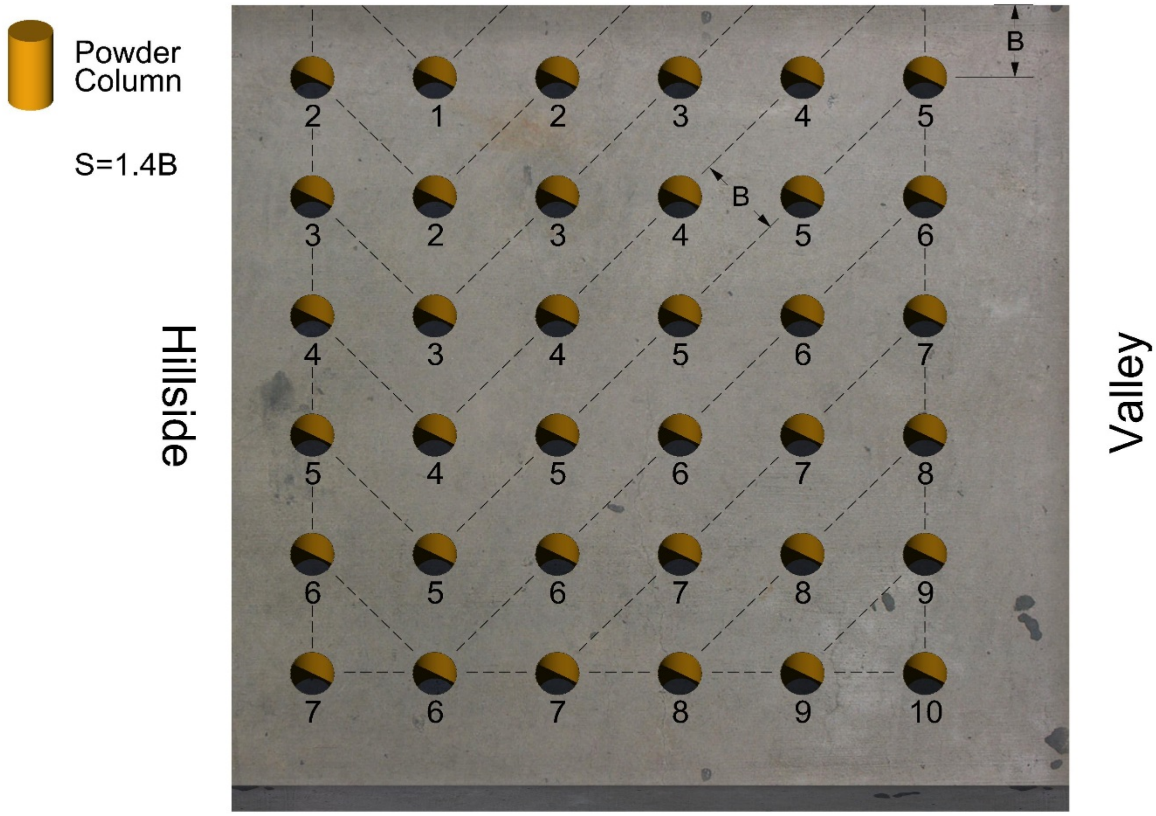


Figure 5-30. Hillside Sliver Cut, S = 1.4B.

b. On steeply sloping hillsides, the outer row of holes has very little depth. To produce the proper fragmentation, displacement, and piling, especially in massive rock, the operator must consider the general principles of rock breakage as described in Chapter 2. The L/B ratio must never be less than 1. If large diameter holes are used where considerable depth is available, blasthole size and related burdens and spacings must be reduced on the outer edges of the slope. Air track drilling with smaller drills and smaller diameter explosive loads may be necessary to produce the proper controlled results.

5-10. Trenching.

a. There are many considerations when designing a utility trench. The size of pipe or utility that will go into the trench, of course, is one of the prime considerations. One does not want to blast a 6-ft wide trench if only an 8-in. line is going into the ground. On the other hand, the size of the excavation equipment bucket is also an important consideration, since it will be used to remove the material from the shot. In no instance can one design a shot, regardless of the size of the utility line that has a width less than the excavator bucket.

b. In trench blasting, the local geology is extremely important. Trenches are at the surface of the earth, where one can encounter the most weathered, unstable type of rock. Often there has been significant decomposition of the rock resulting in clay or mud pockets and seams within the rock mass. The overburden, whether it is weathered rock or soil, may not be flat-lying and this is an important consideration when the holes are loaded. One does not place explosives in the overburden (soil) above the solid rock. Therefore, it is imperative that the blaster know the actual depth to rock within each hole. This is done by keeping a drilling log. To blast efficiently, explosives would be loaded in the hole and stemming must be placed within the rock itself, not only in the overburden.

c. In utility trench blasting, techniques that are used in bedded weak rock may not function in solid massive material. Bedding planes will allow gas migration into the rock mass allowing more cratering action. On the other hand, similar techniques used in massive rock may not cause cratering. Instead, blastholes may rifle with little, if any, resulting breakage.

d. In the following discussion, the difference in blasting techniques between massive, hard materials and inter-bedded, weaker rock will be reviewed. If a narrow trench is needed in an inner-bedded rock mass, one can often use a single row of holes down the center of the trench line. The burden distance or spacing between these single row holes would be similar to that indicated in Equation 5-2 above. A minimum L/B ratio of 1 must be used in all types of blasting.

e. If the trench is to be shallow, smaller diameter holes will be needed than if the trench is to be deep. The timing should be such that holes will sequence down the row. If blastholes are all fired instantaneously, considerable rock will be scattered in the nearby area. As bench heights are reduced, the probability of scatter will increase and blasting mats may be necessary. The single row technique is not applicable in massive hard rock. Normally blastholes will rifle with little, if any, breakage between holes. In massive material, a double row trench is normally used.

f. Figure 5-31 shows the design of a double row trench. In massive materials, the blasthole should be placed at the excavation limit. In highly bedded weaker materials, on the other hand, it is often recommended that the blastholes be placed about 12 in. within the excavation limit since considerable overbreak usually results. Placing the blastholes within 12 in. of the excavation limit, in massive materials, will produce poor results. To determine if a utility trench pattern is within reasonable limits, the following guideline is used.

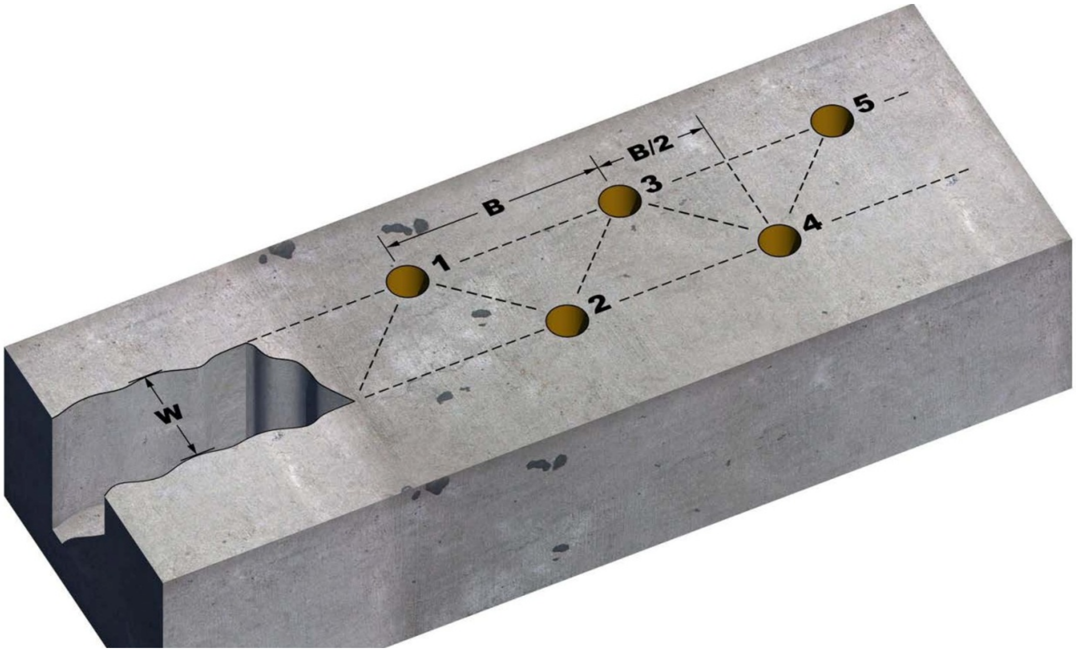


Figure 5-31. Two-Row Trench Design.

g. The burden distance should be as approximated by Equation 5-2 and that burden is placed at the location shown in Figure 5-31. Note that this is not the true burden or the perpendicular distance from the hole to the face at the time the hole detonates is less.

h. The width of the trench must be between 0.75B and 1.25B. If trench widths must be less than 0.75B, then smaller holes and smaller diameter powder charges should be used with burdens that are appropriate for these smaller charges. On the other hand, if trench widths must be greater than 1.25B, either a larger borehole would be needed with its appropriate burden, or a three-row trench (Figure 5-32) could be used. The L/B ratio must be greater than 1.

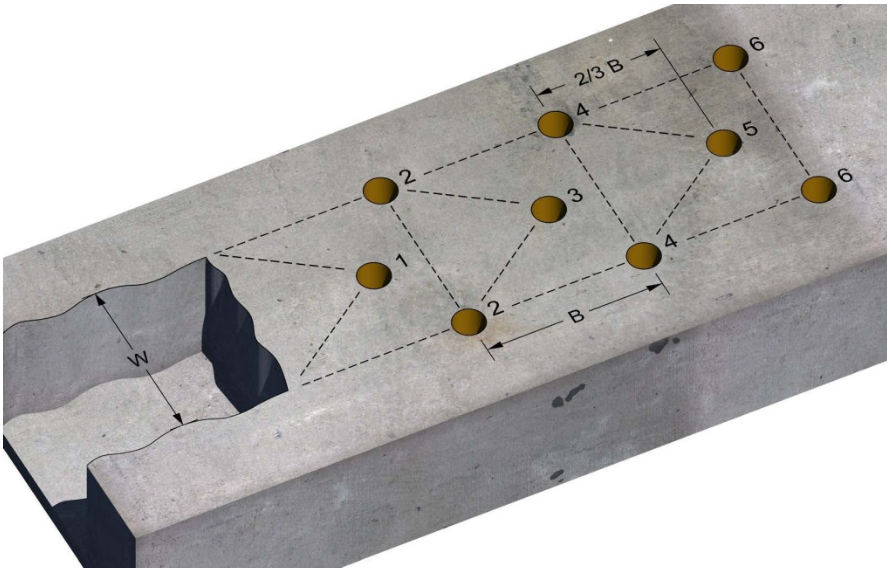
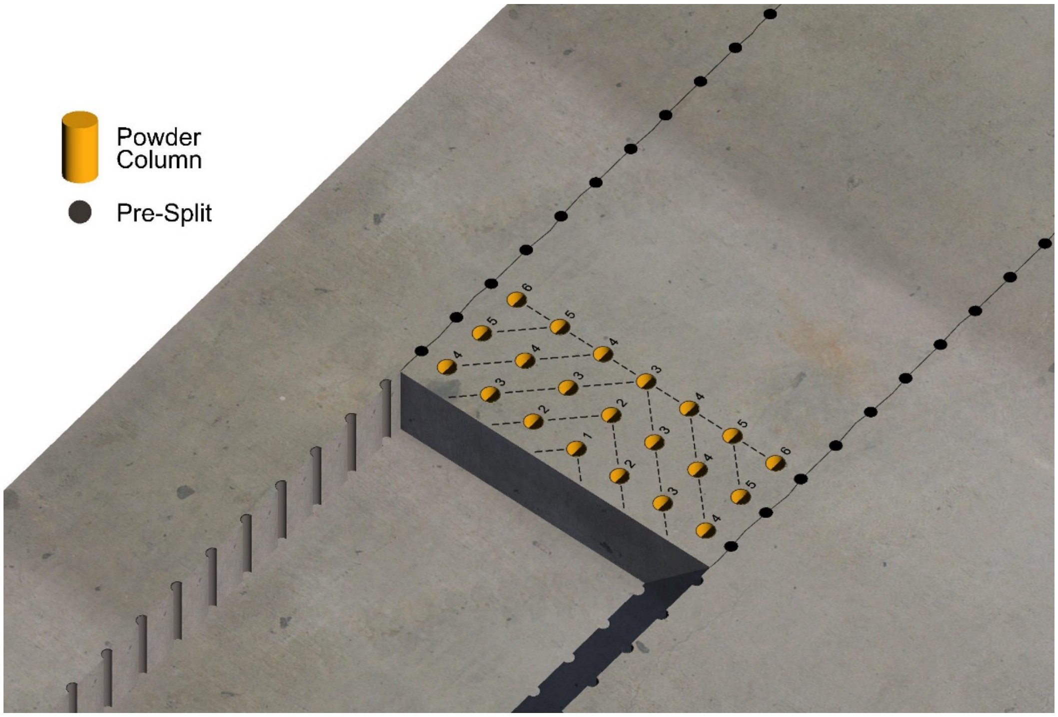


Figure 5-32. Three-Row Trench Design.

5-11. Cut and Cover.

a. Cut and cover is a method of construction for shallow tunnels in which a trench is excavated, then a roof system is constructed. Excavation in rock for cut and cover may incorporate either standard blasting patterns or patterns used for trench design, depending on excavation dimensions and geology. Typical patterns used are “V” and “box cut” patterns shown in Figures 5-21 through 5-24.



b. Figure 5-33 shows a typical blasting pattern in a cut and cover tunneling project. The use of pre-splitting or line drilling along the side walls of the trench, in advance of the production blasts, will be necessary to maintain good wall control and prevent overbreak, see Section 6-2.

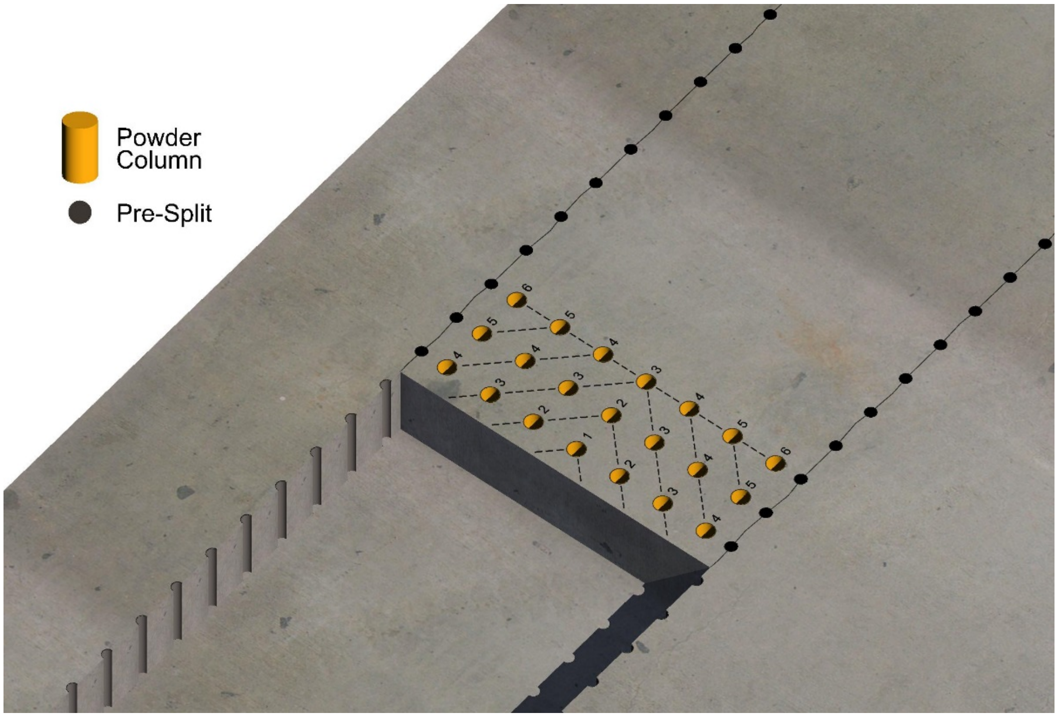


Figure 5-33. Typical Cut and Cover Blasting Pattern.

5-12. Underground Blasting.

a. General.

(1) Underground blasting operations differ from surface operations because they lack the additional face of relief that is normal to many surface blasting jobs. In underground operations, engineers have only one face into which they must drill so they can create relief perpendicular to that face by using the first drill holes to fire. If proper relief is not created when the first blastholes fire, the rest of the blasting round may do little breakage and may rifle out of the collar of the holes.

(2) An additional difference in underground operations is the fact that blasting parameters must conform to a specific contour. This can be quite different from mass blasting or mining operations on the surface where the exact size of any blast is not normally critical. This chapter reviews many of the common underground blast designs used for shaft sinking and tunneling.

b. Shafts.

(1) In both mining and construction operations, vertical or inclined shafts provide access underground. Shafts are used to provide access from the surface to underground entries or from one level to another in a mining operation.

(2) Shaft sinking is difficult because the work area is normally small, noisy, and commonly wet. The job can be dangerous because exposed walls above the drilling and blasting crews can ravel and rocks may fall with little warning. Advance is slow because the drilling, blasting, and

mucking are cyclic operations. The blasted rock must be well fragmented to be removed by the excavation equipment. Today, most shafts are made with a circular cross section, which gives better distribution of rock pressures and decreases the need for reinforcement.

(3) There are three common methods used for blasting circular shafts: ring drilling with vertical holes (Figure 5-34), pyramid cuts (Figure 5-35) and bench rounds (Figure 5-36). Some operations also use modified burn cuts to provide the second face of relief in a shaft round (Figure 5-37).

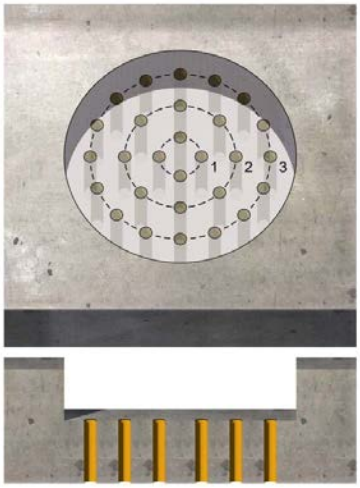


Figure 5-34. Ring Drill.

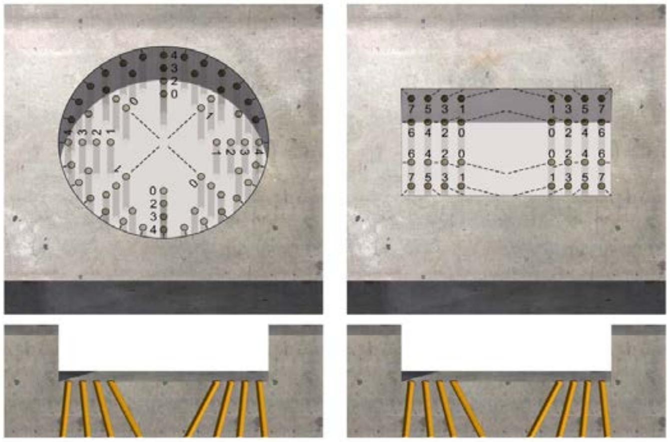


Figure 5-35. Pyramid Cuts.

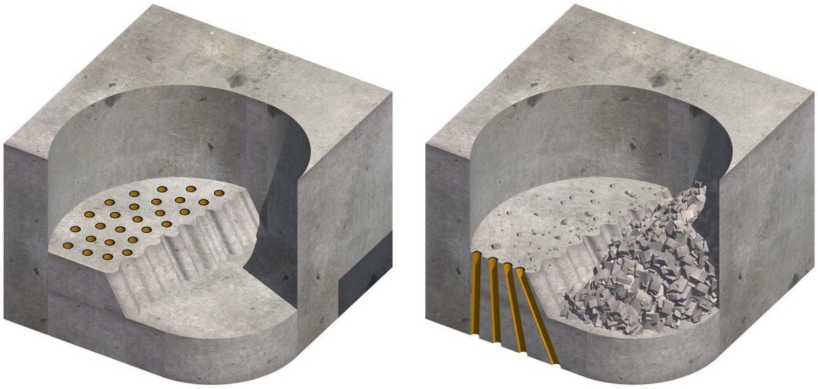


Figure 5-36. Bench Round.

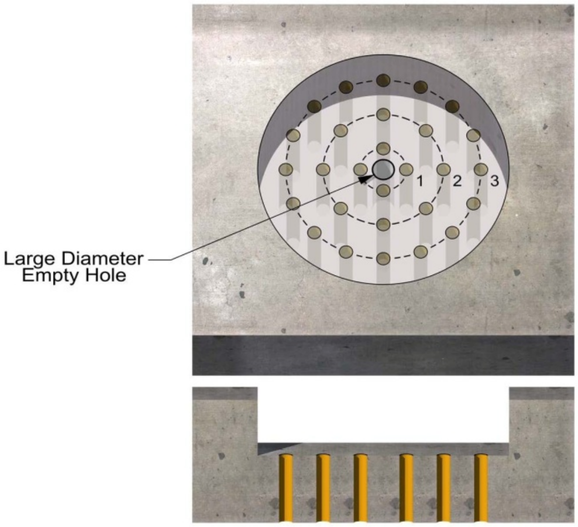


Figure 5-37. Ring Drilling with Burn Cut Center.

c. Ring Drilled Vertical Hole Design.

The following section will go through a step-by-step procedure to design this type of shaft.

(1) Burden Determination

The burden for the shaft round is found in the same manner as for surface blasting operation:

$$B = \left(\frac{2SG_e}{SG_R} + 1.5 \right) D_e \tag{5-15}$$

where:

B = Burden (ft)

SG_e = Specific Gravity or Density of Explosive (g/cm³)

SG_r = Specific Gravity or Density of Rock (g/cm³)
D_e = Diameter of Explosive (in)

(2) Number of Rings

$$N_R = \frac{\left(R_{SH} - \frac{B}{2}\right)}{B} + 1 \tag{5-16}$$

where:

N_R = Number of Rings
R_{SH} = Shaft Radius (ft)
B = Burden (ft)
D_e = Diameter of Explosive (in)

(3) Burden Actual

$$B_A = \frac{2\,R_{SH}}{2\,N_R - 1} \tag{5-17}$$

(4) Spacing of Holes in Ring (Estimate)

$$S = B \tag{5-18}$$

where:

S = Spacing (ft)
B = Burden (ft)

(5) Number of Holes per Ring

$$N_H = \frac{2\,R_R \pi}{S} \tag{5-19}$$

where:

N_H = Number of Holes/Ring
R_R = Ring Radius (ft)
S = Spacing (ft)
D_e = Diameter of Explosive (in)

(6) Spacing Actual / Ring

$$S = \frac{2\,R_R \pi}{N_H} \tag{5-20}$$

(7) Depth of Advance

$$L = 2\,B \tag{5-21}$$

where:

L = Advance (ft)

B = Burden (ft)

(8) Subdrill

$$J = 0.3\,B \tag{5-22}$$

(9) Stemming

$$T = 0.5\,B \tag{5-23}$$

(10) Look Out

$$\begin{aligned} LO &= 3.281(0.1 + (H/3.281)\,(\text{TAN } 2°) \\ LO &= 3.281(0.1 + (H/3.281)\,0.03492 \end{aligned} \tag{5-24}$$

where:

LO = Look out (ft)

H = Hole Depth (ft)

(11) Timing
Minimum 100-150 ms or LP Delays per ring or spiral delays outward.

d. Tunneling.

(1) Tunnel blasting is different from bench blasting because it is done toward one free surface while bench blasting is done toward two or more free faces. In bench blasting, there is a great deal of natural relief in the pattern resulting from the additional free faces. In tunneling, however, the rock is more confined and a second free face must be created parallel to the axis of the boreholes.

(2) The second free face is produced by a cut in the tunnel face that can either be a parallel hole cut, a V-cut, or a fan cut. After the cut is made, the stoping holes push the rock toward relief created by the cut. The stoping holes can be compared in some respects with bench blasting. In general, tunnel blasts are somewhat overcharged to produce fine fragmentation because the disastrous effects of overloading are negated by the confinement given in the tunnel.

(3) As a result of the additional confinement and lack of developed free faces, the timing between delays being fired must be longer than in surface blasting to allow for rock movement and

for the development of the additional free face before subsequent holes fire. In tunnel blasting, long period delays are generally used. If ms delays are used, cap periods are skipped to provide between 75-150 ms (at minimum) between holes firing. This increased time is absolutely essential to allow tunnel blasts to function properly.

(4) A number of different types of holes must be discussed when blasting in tunnels. Figure 5-38 shows some of the types of holes that must be considered. The blastholes can be divided into the following categories (numbers correspond to those in Figure 5-38):

(a) Lifter (floor) holes (1).

(b) Rib (wall) holes (2).

(c) Back (roof) holes (3).

(d) Stoping (horizontal) holes (4).

(e) Stoping (vertical) holes (5).

(f) Cut holes (6).

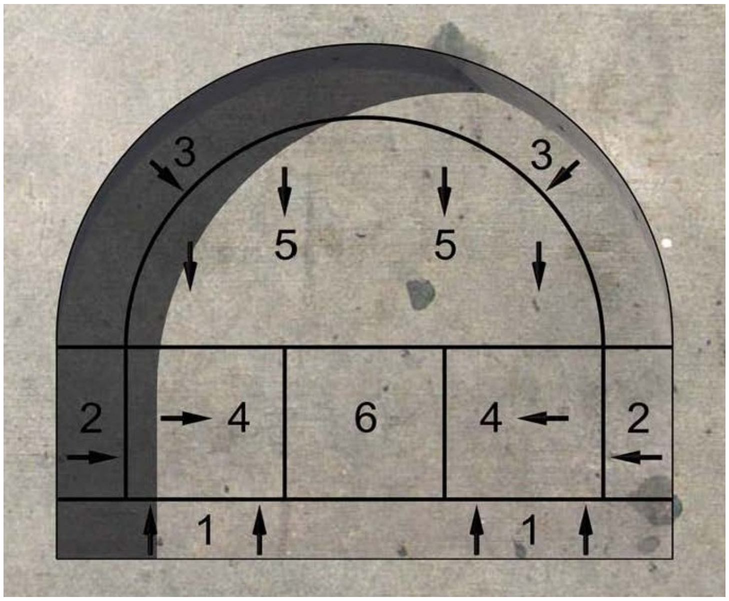


Figure 5-38. Types of Holes Used in Tunneling.

(5) The perimeter holes on the tunnel must be angled outward to keep the tunnel profile from changing as the tunnel is advanced. This outward angling is called the “look out.” Figure 5-39 shows the “look out” angles. The “look out” (LO) is commonly taken to be LO = 3.281*(0.1+(H/3.281)(TAN 2°). The LO and H are in Feet. Burdens for all tunneling rounds are calculated and measured at the bottom of the holes. The “look out” must be taken into account when determining true burdens at hole bottoms.

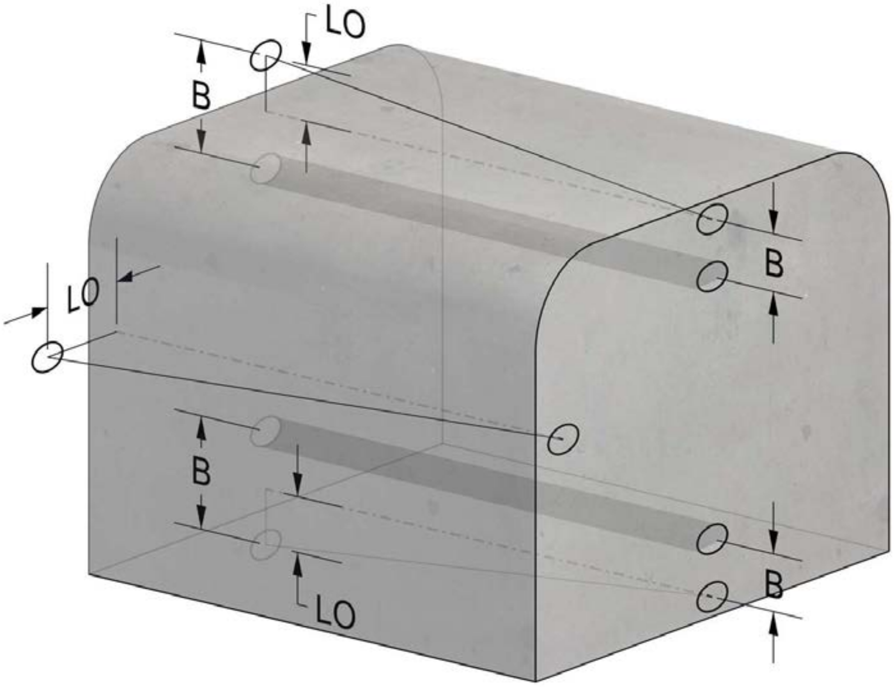


Figure 5-39. Look Out Angles.

(6) The perimeter holes in the rib and back are commonly drilled on close spacing and are lightly loaded. They may also be trim blasted to provide a contour that requires little reinforcement. Figure 5-40 shows the minimum extent of damage zones if trim blasting (vs. production blasting) methods are used on the perimeters.

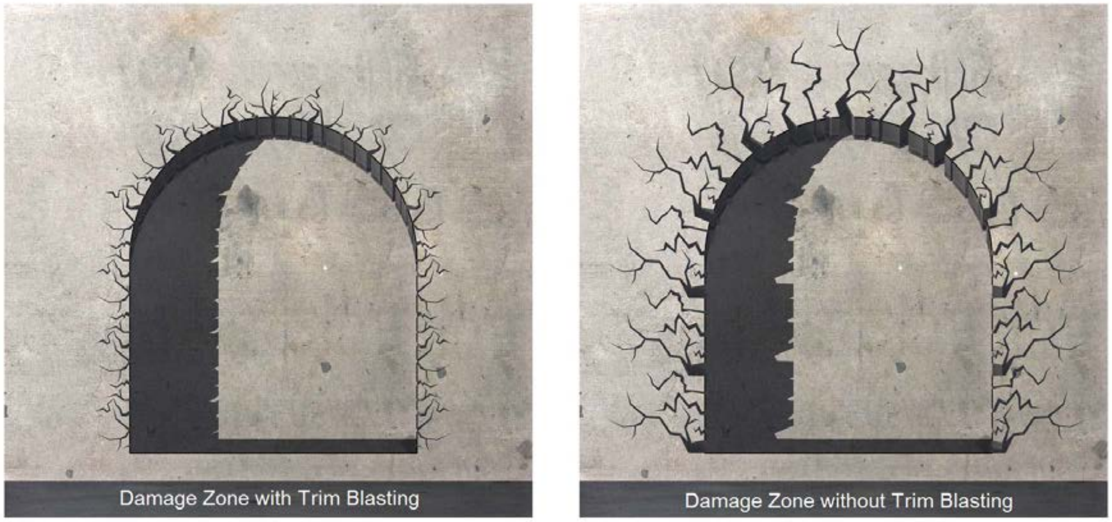


Figure 5-40. Damage Zone.

(7) Burn Cut

(a) The most commonly used cut today is the large hole burn cut. The name “burn cut” originates from a type of blast where the holes are drilled parallel to one another. One or more holes in the cut are left empty to act as a face of relief toward which the other holes can break.

(b) Traditionally, the burn cut was drilled where the empty and loaded holes were all the same diameter. It was later found that using empty holes of a larger diameter than the loaded holes provided additional relief in the pattern and reduced the number of drill holes needed. The large empty holes also allowed for additional advance per round. A variety of names resulted from the hybrid of the burn cut that used larger, empty holes. For the purposes of clarity, this type of blast will be called burn cut.

(c) The cut holes can be placed in any location in the tunnel face. However, the location of the cut influences the amount of throw, the number of drill holes, and the total cost per cubic meter. For example, if the cut holes are placed close to the wall as shown in Figure 5-41A&B, the pattern will require fewer drill holes, yet the broken rock will not be displaced as far down the tunnel. The cut is alternated from the right to the left side walls to ensure that bootlegs (or high spots) from previous rounds are not drilled into on subsequent rounds.

(d) To obtain good forward motion of the muck pile, the cut may be placed in the middle of the face and toward the bottom of the cut. In this position, throw will be minimized (Figure 5-41C). If additional throw is required, the cut holes can be placed higher in the center of the face (Figure 5-41D).

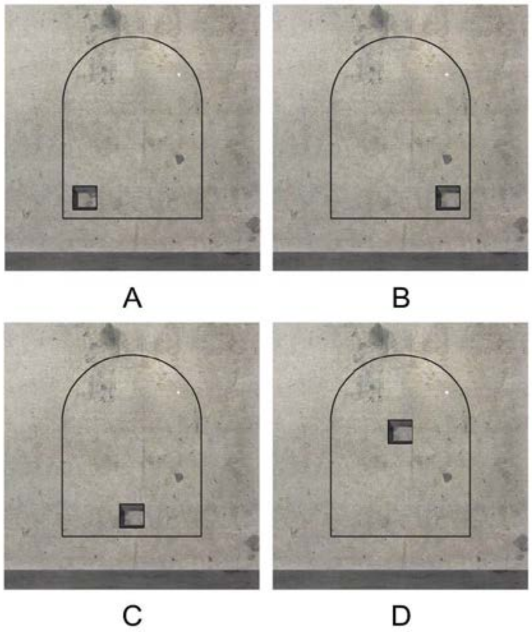


Figure 5-41. Locations for Cut Holes

(e) The overriding principle of all burn cut designs is as follows. Burdens on loaded holes are selected so the volume of rock broken by any hole cannot be greater than what would occupy the void space created by either the burn hole or subsequent holes firing. In this calculation, one must also consider the fact that when the rock web breaks between holes, it will occupy a larger space then it did before firing. In other words, the swell factor of the rock must be considered.

(f) If blastholes within the cut break a larger volume than can fit in the previously developed crater volume, the cut “freezes,” which means it becomes blocked by the rock that can no longer be ejected. If this occurs, the relief parallel to the axis of the boreholes is lost and blastholes will no longer break properly. In fact, they will begin to rifle out of their collars and shatter the adjacent rock, but will not allow the mechanism of flexural failure to cause breakage in the third dimension. Therefore, in the cut itself, distances must be accurately designed and drilled. The timing must also be sufficiently slowed to allow rock to begin to eject from the blasted area before subsequent holes fire. Figure 5-42 shows the general layout of a burn cut.

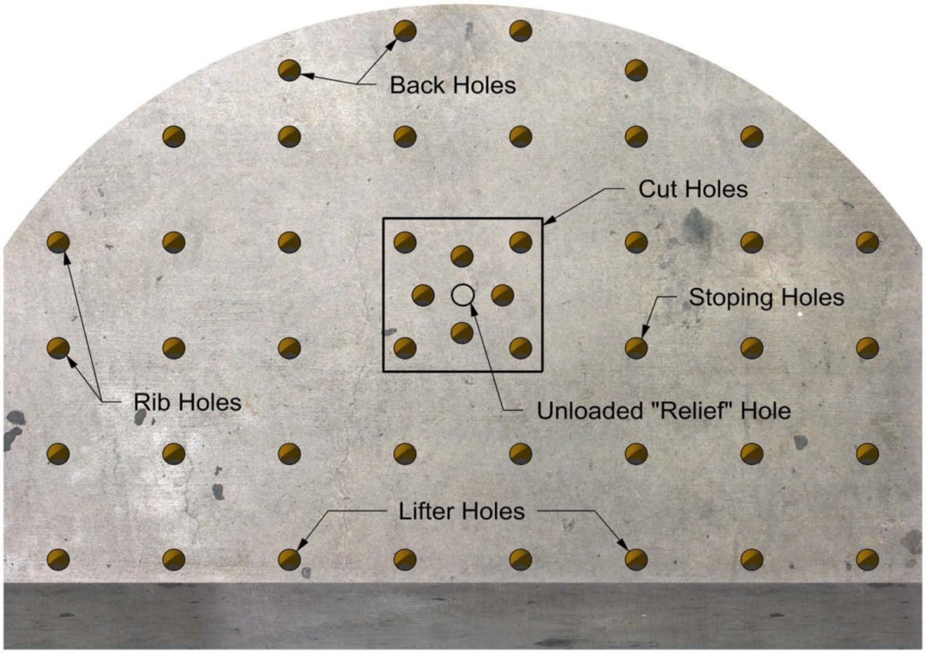


Figure 5-42. General Burn Cut Design

(8) Burn or Parallel Hole Cuts

- The most commonly used cut today is the large hole burn cut. The name “burn cut” originates from a type of blast where the holes are drilled parallel to one another. One or more holes in the cut are left empty to act as a face of relief toward which the other holes can break.

- Traditionally, the burn cut was drilled where the empty and loaded holes were all the same diameter. It was later found that using empty holes of a larger diameter than the loaded holes provided additional relief in the pattern and reduced the number of drill holes needed. The large empty holes also allowed for additional advance per round. Figure 5-43 shows the relationship between the advance per round and the empty hole diameters. A variety of names resulted from the hybrid of the burn cut, which used larger, empty holes. For the purposes of clarity, this type of blast will be called a burn cut. Figure 5-44 shows the general timing sequence of a burn cut.

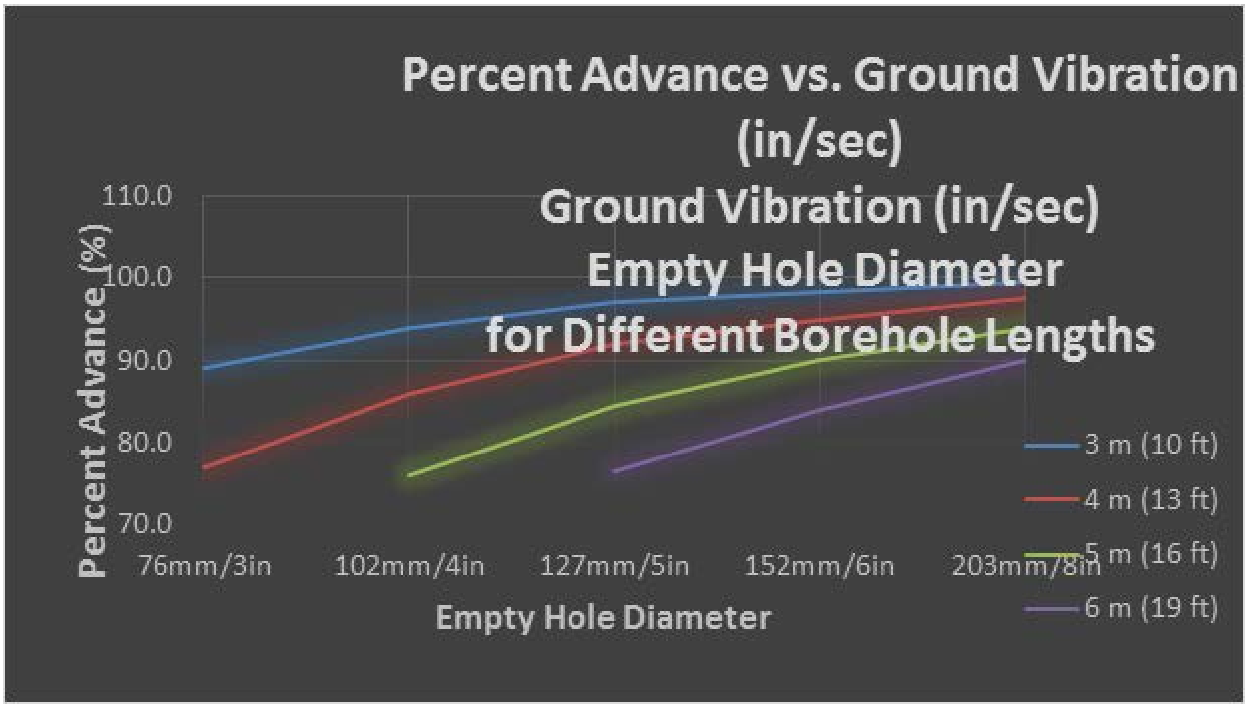


Figure 5-43. Percent Advance vs. Hole Diameter.

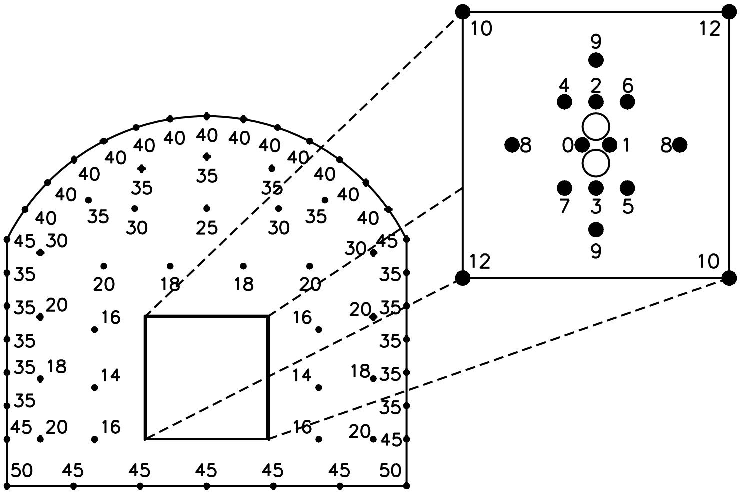


Figure 5-44. General Timing Sequence of the Burn Cut.

e. Calculations of Burn Cut Dimensions.

(1) Empty Holes(s) (D_H). Figure 5-45 shows a typical design of a burn cut. The unloaded “relief” hole diameter is designated D_H. If the burden is too large or too small the burn cut will not function properly. Figure 5-46 shows whether the rock will be plastically deformed, filled with broken rock or clean blasted. If more than one empty hole is used, the equivalent diameter of a single empty hole, which contains the volume of all empty holes must be calculated. This can be done using the following equation.

$$D_H = d_H \sqrt{N} \qquad (5\text{-}25)$$

where:

D_H = Diameter of equivalent single empty hole (in)

d_H = Diameter of empty holes (in)

N = Number of empty holes

(2) Example: Find the equivalent D_H for three empty holes of 3-in. diameter.

$$D_H = 3\sqrt{3} = 5.2 \text{ in} \qquad (5\text{-}26)$$

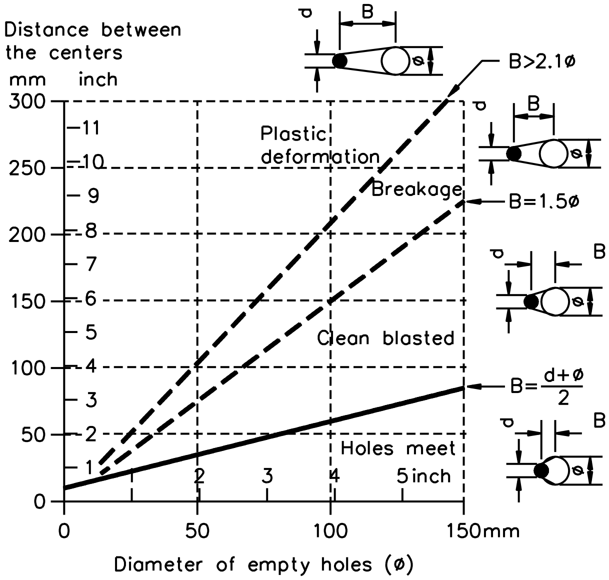


Figure 5-45. Hole Spacings in Burn Cut (Swedes)

(3) Calculation of B_1 for Square 1
The first square of holes is located B_1 distance from the center (Figure 5-46).

$$B_1 = 1.5\, D_H \qquad (5\text{-}27)$$

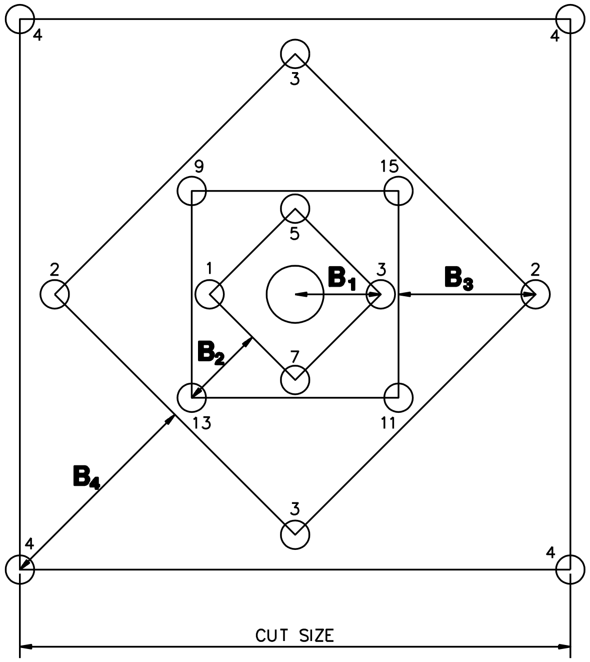


Figure 5-46. Burn Cut Showing Burden Distances.

- The distance or radius from the exact center of the cut will be called R (Figure 5-47).

$$R_1 = B_1 \tag{5-28}$$

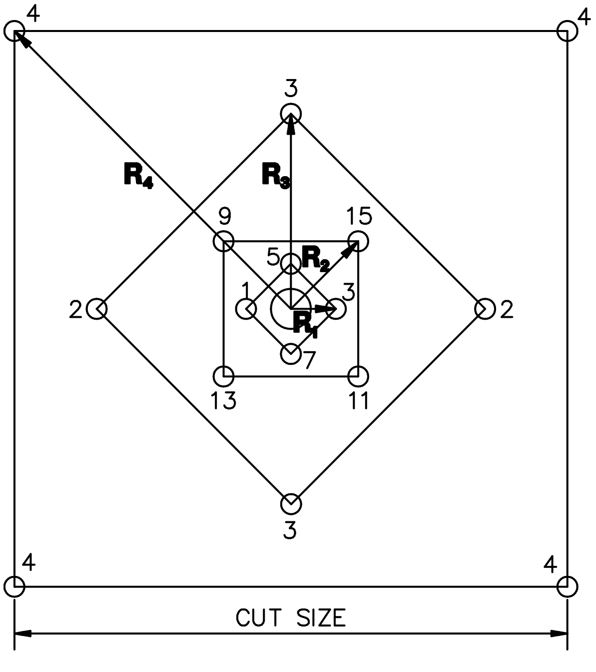


Figure 5-47. Distance from Center to Cut Holes

- The Sc value denotes the cut size or the distance between blastholes in the square (Figure 5-48). Table 5-9 lists some simplified burn cut calculations.

$$Sc_1 = B_1\sqrt{2} \tag{5-29}$$

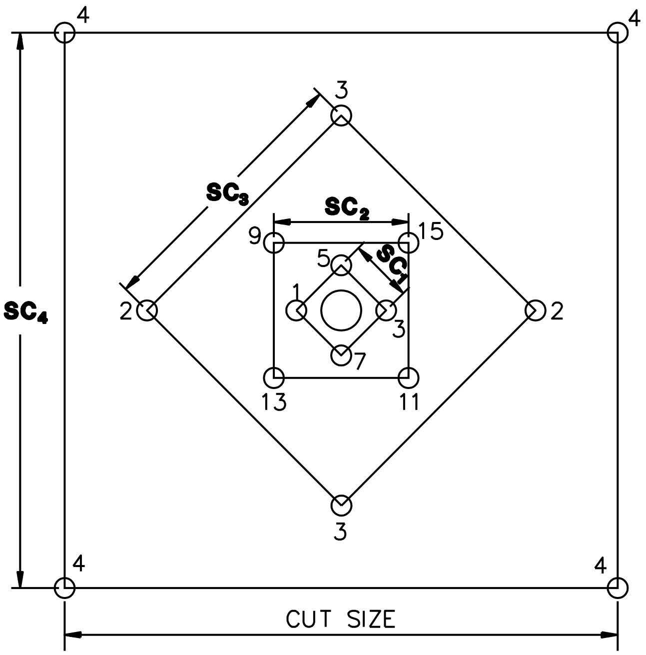


Figure 5-48. Distances Between Cut Holes.

Table 5-9. Simplified Burn Cut Calculations.

Square No	1	2	3	4
B=	1.50 D_H	2.12 D_H	4.50 D_H	9.54 D_H
R=	1.50 D_H	3.18 D_H	6.75 D_H	14.31 D_H
Sc=	2.12 D_H	4.5 D_H	9.54 D_H	20.23 D_H
T=	1.50 D_H	1.06 D_H	2.25 D_H	4.77 D_H
Check	$S_c \geq \sqrt{L}$	$S_c \geq \sqrt{L}$	$S_c \geq \sqrt{L}$	$S_c \geq \sqrt{L}$

(4) Depth of Blasthole (H). The depth of the blasthole, which will break to 95% or more of their depth, can be found from Equation 5-30:

$$H = \frac{(D_H x25.4) + 16.51}{12.7} \tag{5-30}$$

where:

H = Depth (ft)

D_H = Hole diameter (in)

- Depth of Advance (L) (Expect)

$$L = 0.95\ H \qquad (5\text{-}31)$$

(5) Check if charge can break burdens in each square. Use burden formula:

$$B = \left(\frac{2\ SG_e}{SG_R} + 1.5 \right) D_e \qquad (5\text{-}32)$$

- Stopping Holes

$$B = \left(\frac{2\ SG_e}{SG_R} + 1.5 \right) D_e \qquad (5\text{-}33)$$

$$S = 1.1\ B$$

$$T = 0.5\ B$$

where:

S = Spacing (ft)

B = Burden (ft)

T = Stemming (ft)

(6) Lifter Holes

$$B = \left(\frac{2\ SG_e}{SG_R} + 1.5 \right) D_e \qquad (5\text{-}34)$$

$$S = 1.1\ B$$

$$T = 0.2\ B$$

(7) Contour Holes (Rib and Back Holes)

Commonly trim blasted with holes on 0.045 m to 0.6 m centers, otherwise:

$$B = \left(\frac{2\ SG_e}{SG_R} + 1.5 \right) D_e \qquad (5\text{-}35)$$

$$S = 1.1\ B$$

$$T = B$$

- Blasthole Timing. Cut holes fired with delays at least 50 ms between periods. Stoping holes delayed at least 100 ms or LP delays. Contour holes (trim blasted) fired on same delay. Lifters shot last.
- Initiator. Always placed on bottom of blastholes.

(a) The most common cut used in underground work with angle drill holes is the V-cut. The V-cut differs from the burn cut in that fewer holes are drilled and less advance can be made per round with a V-cut when compared to a burn cut. The advance per round is also limited by tunnel width. In general, the advance per round increases with width, and an advance of up to 50% of the tunnel width is attainable. The angle of the V must not be acute and should not be less than 60°. More acute angles require higher energy charges for the amount of burden used. A cut normally consists of two Vs, but in deeper rounds, a cut may consist of as many as four Vs (Figure 5-49).

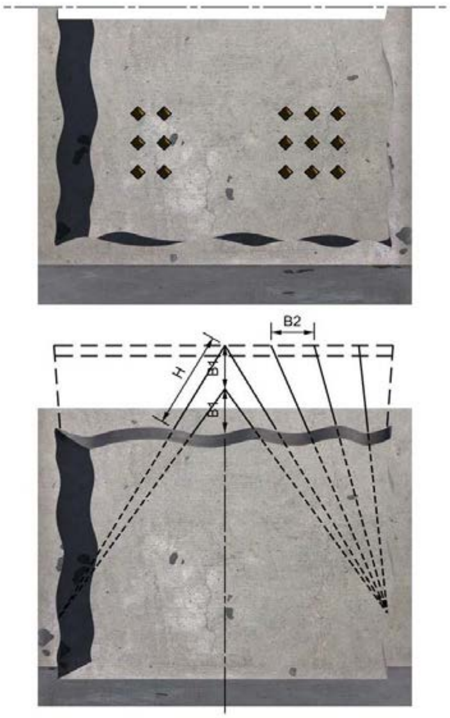


Figure 5-49. Basic V-Cut.

f. V-cut Design.

(1) Determination of Burden.

(a) The burden is always measured at the very bottom of the blasthole and is placed as shown in Figure 5-49. It is realized that this is not the exact true burden and holes with greater angles (those that approach V) have a smaller true burden. This, however, is done to simplify design. When one considers drilling error and other factors, the reduction in true burden can actually be beneficial.

(b) The burden can be determined by using the same equation that we have used before.

$$B = \left(\frac{2\,SG_e}{SG_R} + 1.5 \right) D_e \tag{5-36}$$

(c) The distance between V's is shown in Figure 5-49 as distance B_1 is calculated as follows.

$$B_1 = 2B \tag{5-37}$$

where:

B = Burden (ft.)

B_1 = Burden (ft.)

(2) Spacing Between Holes (vertically). The vertical spacing between V's is:

$$S = 1.2\ B \tag{5-38}$$

where:

S = Spacing (ft.)

B = Burden (ft.)

(3) The normal angle in the apex of the V is about 60°. For small narrow tunnels, V angles of less than 60° have been used. However, the explosive loading density in each hole must be increased.

(4) Depth of Cut or Advance (L). In general, the depth of the cut will vary from 2B to a maximum 50% of the tunnel width. Blastholes normally will not break to the bottoms and advance can be assured to be between 90%-95% of drill depth.

(5) Stemming Distance. Blastholes are normally loaded to within 0.3B - 0.5B to the collar depending on the strength of the materials to be blasted. Collars are either left open or clay stemming plugs are sometimes used.

(6) Lifter and Stoping Holes. The same design procedure is used as previously discussed with the burn cut.

(7) Contour (Rib and Back) Holes. The same procedure is used as previously discussed with the burn cut.

(8) Look Out. Same procedure is used as in design of burn cut.

(9) Blasthole Loading. It is important to have initiators placed at the bottom of the blastholes. The loading density can be reduced near the collar when explosive cartridges are used, rather than pneumatically loaded ANFO. The loading density reductions can begin after 1/3 of the hole is loaded with the designated amount to achieve proper burdens.

(10) Timing Sequence. The timing in V-cuts should be at least 50 ms between V's where multiple V's occur one behind the other. The timing must be so designed to allow movement of

rock to begin before subsequent holes fire. For this reason, minimum delays should be 75 to 100 ms as shown in Figure 5-50.

(a) Each V in the cut should be fired with the same delay period using ms detonators to ensure minimal cap tolerance between each leg of the V as it fires. Delay time between adjacent Vs should be at least 75 ms (minimum). Figure 5-49 shows the basic layout of the Vs.

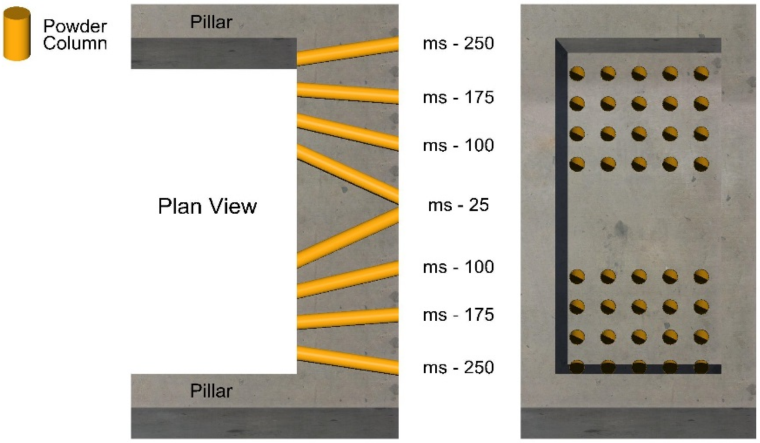


Figure 5-50. Timing for V-Cut.

(b) Figure 5-49 above shows two burdens, the burden at the back of all holes and the burden between the Vs. The distance indicated as B-1 (Figure 5-49) that is located between Vs is twice the normal burden of a 60° angle that is used in the apex of the V. In some cases, an additional blasthole is drilled perpendicular to the face following the line of B-1, which is called the “Breaker hole.” This is used if the fragmentation originating within the V is too large.

(c) Figure 5-51 shows the dimension needed to drill a proper V-cut. Three sets of specific dimensions are needed for each hole. These are: (1) the distance at which the hole is collared from the center of the entry, (2) the angle at which the hole enters the rock mass, and (3) the length of the particular blasthole.

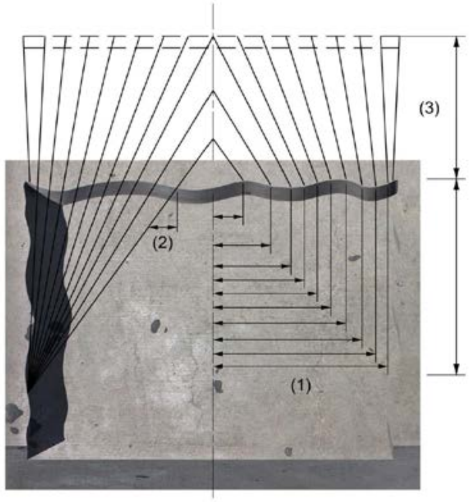


Figure 5-51. V-Cut Dimensions.

(11) Fan Cuts. The fan cut is similar in design and method of operation to the V-cut. Both the fan and V-cut must create relief as holes fire toward the one open face. There is no additional relief created by empty holes as is done in the burn cut. Figure 5-52 shows a typical fan cut. Dimensions are determined using the same methods and formulas as in the V-cut.

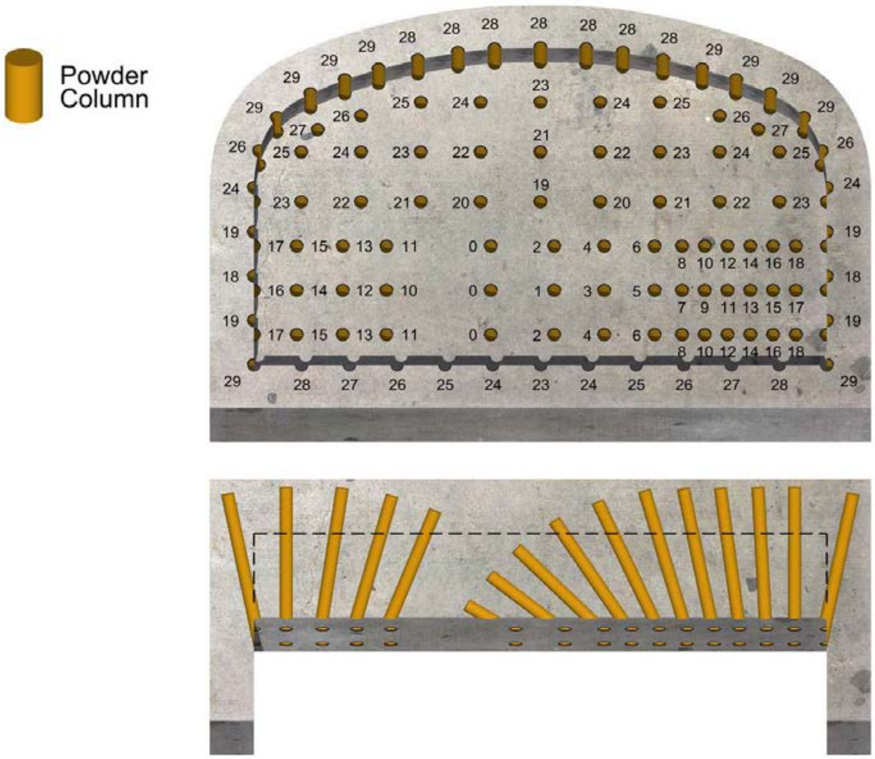


Figure 5-52. Fan Cut.

(12) Heading and Bench Methods. The Heading and Bench Method (Figures 5-53 and 5-54) is a combination of an underground tunnel round and a surface bench blast. The top heading is driven ahead of the bench. Any of the cuts or tunnel rounds discussed could be used to develop the heading. The bench is designed using the same principles as previously discussed for bench blasting.

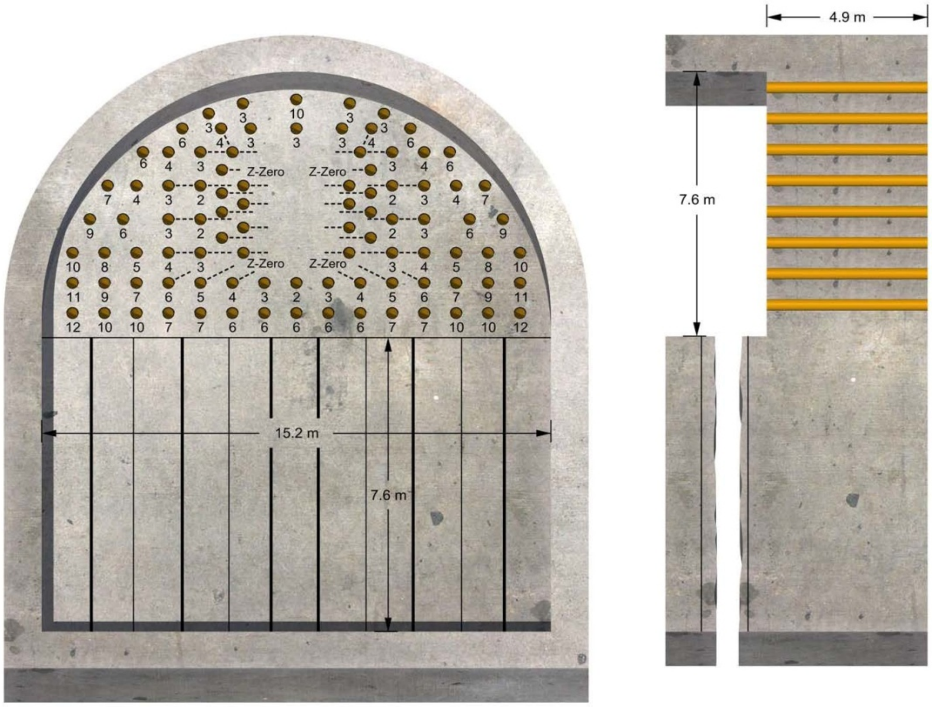


Figure 5-53. Heading and Bench Method.

Figure 5-54. Photo of Heading and Bench Method in a Tunnel.

5-13. Blast Design Documentation. Blasting patterns are not typically designed by USACE personnel. That responsibility is left to the contractor’s blasting specialists. The pattern design of a blast should be included in the blasting plan submitted by the contractor. Chapter 9, Paragraph 9-3a discuss details of what should be included in a blasting plan submittal. The methods shown in this section and be used to check the contractor’s design and determine if they are reasonable. These methods can also aid in the calculation of the government estimate.

CHAPTER 6

Specialty Blasting Techniques

6-1. Introduction. Blasting tools and methods continue to develop, and no manual can hope to encompass all techniques that could be employed on a site in the future. However, a short overview of some of the methods that can be used during execution of blasting projects can be useful. This chapter covers some of these additional methods and provides further details on a few methods mentioned in previous chapters.

6-2. Controlled Blasting Techniques for Creating a Final Rock Face.

a. All blasting that is planned and executed with care is “controlled blasting” in that it involves the controlled use of explosives. The term “Controlled Blasting” refers to wall control using pre-splitting or trim (cushion) blasting. The mining and construction industry uses this term for the tools and techniques employed to reduce overbreak and produce a stable competent final rock wall. Unlike production blasts, the goal here is not the fracturing of the rock into appropriate size for removal. Instead the goal is to leave a relatively smooth final face with as little fracturing of the remaining rock mass as possible. The holes drilled for these techniques are much more closely spaced than those for production blasts and are generally lightly loaded. There are a number of controlled blasting techniques in common use for producing a final wall: presplit blasting, trim blasting (cushion blasting), and line drilling — all of which can be used with or without production blasting.

b. None of these techniques are perfect and the geological characteristics as well as the production blast design will control the success of the blast. Where rock is both hard and competent, with few discontinuities or changes in lithology even modified production blasting techniques may produce satisfactory results. Where rock is softer and less competent, these final face wall techniques are needed to produce a good final rock face. As with all other blasting technique, adjustments may need to be made after a trial area to produce the best results.

c. A relatively smooth, competent final rock face may not be needed for all construction projects. However, where people and equipment are likely to be located beneath the new wall, particularly where the remaining face is above a roadway, parking area, building, switchyard, or other long term facility, a competent final rock face is needed for long term rockfall control. Production blasts often leave a ragged rock face, with numerous large boulders still on the slope, and with fractures extending up to 50 ft. or more into the final slope face, Because of the fracturing, it can leave as one practitioner put it “…a nearly infinite supply of rockfall.” Rockfalls are not the only issue. Excessive excavation quantities and severe overbreak, which can increase concrete placement volumes, can also severely increase costs.

d. A problematic final wall that exposes people and property to rockfall can develop over time even with the use of these techniques, depending on the geology of the site and on how well the blasting is executed. Final walls that develop rockfall issues can become maintenance headaches or significant safety threats (Figure 6-1). Where the final wall will be covered after construction (e.g., for lock monolith construction), this may not be a problem. However, where a rock will remain exposed to the elements over time, the designer needs to consider the long term condition of the rock wall. While no blasting program is a guarantee against weathering, a better face may be needed than for slopes that will remain exposed to the elements.

Figure 6-1. View of Rock Slope Next to Switchyard with a Problem Face. Note that the Fence Was Installed To Protect People and Switchyard Equipment from Rocks Falling from the Wall.

e. This may require lighter loading and more careful execution of these techniques, including (where possible) the use of trial blasts to test the effectiveness under actual field conditions. For certain geological conditions, where longer term differential weathering of the slope may occur, the designer may want to consider a ¼:1 (H:V) final slope rather than a vertical slope.

f. Table 6-1 lists final wall methods and gives a brief description of each method along with typical advantages and disadvantages. Subsequent sections will discuss each of these methods in more detail.

Table 6-1. Comparison of Final Wall Controlled Blasting Methods.

Procedure	Description	Advantages	Limitations
Presplit Blasting	A row of tightly spaced holes are located at the final wall face, lightly loaded, and detonated before production blast.	This procedure yields excellent results in hard rock on surface blasting operations. It is less expensive than line drilling, and better than cushion blasting for a long term rock face.	Results cannot be seen until excavation has been removed to the presplit line.

Procedure	Description	Advantages	Limitations
Precision Pre-splitting	A row of holes are located at the final wall face, that may be spaced 12 to 30 in. and extremely light explosive loads, and are then lightly loaded shot before the main excavation.	This procedure can be used in weak and heavily jointed rock and little overbreak results. Requires closer spacing than standard presplit.	This procedure does limit damage to rock mass from production blasts. However. It performs well in weak or highly fractured rock.
Trim Blasting (Cushion Blasting)	A row of tightly spaced holes are located at the final wall face, and are then lightly loaded and detonated after production blast. The annulus around the explosive is not filled with crushed rock. Preferred for underground use.	This procedure may reduce the half cast appearance of the presplit. This more ragged face may be an advantage for certain cosmetic applications. This procedure may be of good use as trim blasting to remove smaller rock.	This procedure produces a more ragged face with more radial fractures than presplit or smooth wall blasting. The slope face is more prone to long term raveling of the rock.
Line Drilling	A row of very tightly spaced unloaded holes is located at the final wall face. This procedure was in common usage on USACE projects before presplit was introduced. It is still used where rock gives problematic results with presplit blasting and where very careful control is needed.	This procedure gives very good control of final wall face. It is typically only used where even light loads may cause too much overbreak. It has been used very effectively in lock construction when blasting next to and below an existing lock wall.	This procedure is very expensive as drilling costs are high due to the number of boreholes. It can give unpredictable results in non-homogenous rock slopes.

g. Presplit Blasting.

(1) Presplit blasting uses a single row of holes that are spaced more tightly than production blastholes along the line where the final face is to be located on the new slope. These are generally produced by holes with diameters of 3 to 4 in. This row is detonated before the adjoining production blastholes are detonated. This can be done either as a completely separate shot or shot first with the production shot delayed after the final presplit hole (i.e., 100 m/s delay attached from final presplit hole to first production hole). Subdrilling is normally not used. Pre-splitting works well for vertical slopes and for slope ratios up to ½:1 (H:V) although better results are generally seen from vertical and ¼:1 slope operations. The angled final slope face can often give better long term wall conditions than the vertical, especially where the rock is not massive and is somewhat susceptible to weathering. It is particularly effective where weaker layers are located below more competent layers and where differential weathering of the rock layers can produce long term rock slope stability problems. Pre-splitting is the preferred method of wall control on surface operations. Trim (cushion) blasting is the preferred method for underground blasting because of the in-situ stress fields.

(2) One unique feature of presplit blastholes is that there is an intentional empty annulus around the explosive inside the borehole. Another method is to have an airdeck about the explosive that does not have an empty annulus around the explosive. However, the airdeck presplit method is not allowed by USACE because it can damage the toe of the slope due to the loading. The function of the presplit is to cushion the shock wave and drop the gas pressure on the walls of the blasthole, which reduces, but does not totally eliminate, the crushing and radial cracking seen in production boreholes. The pressure confined in the borehole due to the explosion must be greater than the tensile strength of the rock. A crack forms along row of these boreholes due to the pressure of the expanding gases and the relatively tightly spaced boreholes producing the final face. It has the effect of terminating the blasting shock, stress, and pressure of the production blast at this crack.

(3) Pre-splitting can be produced with a number of different products. Cartridge dynamites, coiled water gels, and emulsions in coils and special rigid tubes have all been used. Detonation cord can, depending on the project, also be used as the primary explosive load and can be particularly effective in difficult limestone formations when used with tightly spaced holes with precision pre-splitting. Figure 6-2 shows typical loading for presplit holes. Pre-splitting allows for more stable rock cuts than most other blasting techniques, with the exception of line drilling. Cuts can be steeper, and with a well-executed presplit half casts are visible along the length of the drilled boreholes along the final rock face. As with production blasting, the presence of voids, joints, faults, fractured zones, and other discontinuities makes achieving a good face more difficult. Where there are near vertical joints or discontinuities that intersect the face at less than 15 degrees, it is extremely difficult to produce a crack with pre-splitting holes that does not travel along this feature. A smooth face may still be difficult to achieve where these near vertical joints intersect from 15 to 30 degrees. See Chapter 3, "Geologic Considerations" for further detail.

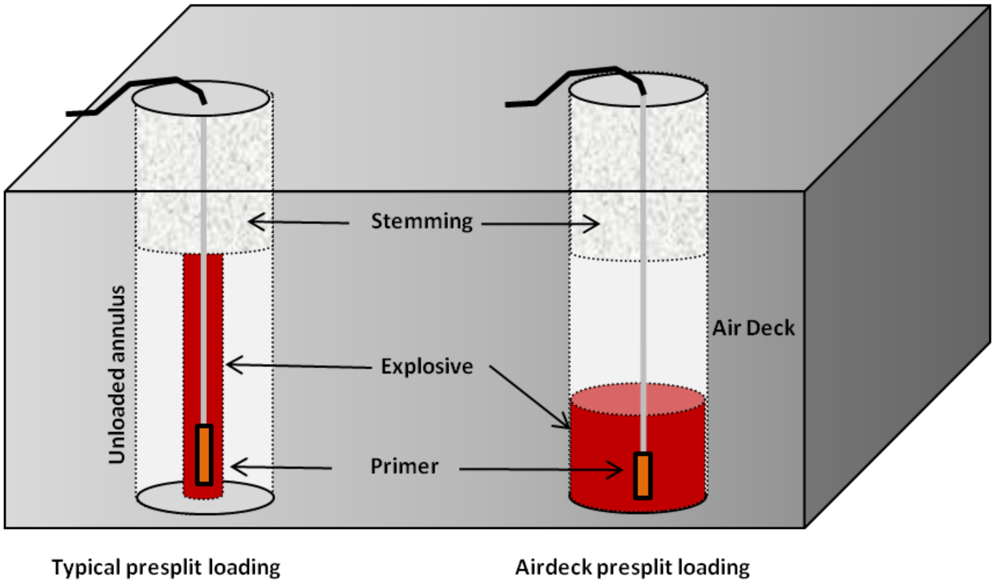


Figure 6-2. Typical Loading for Presplit Holes.

(4) Borehole alignment is particularly important and holes that deviate can cause significant problems (Figure 6-3). Where boreholes deviate together, the face may be overloaded. Where they deviate apart, the face may be underloaded. Neither situation is ideal for good blasting results. The overloaded zone results in increased radial cracking and damage to the rock face causing overbreak. The underloaded zone may not crack along final slope face, leaving whole casts and boulders protruding from the face. The deeper the holes are drilled, the more significant this problem becomes. Hydraulic or air track drills can, with good drilling technique and collaring, be used for presplit drilling, but particular attention to borehole alignment needs to be paid by the driller. Likewise, the blaster in charge needs to know of any deviation noted in the boreholes as it may require modification of the blast design. Pre-splitting lifts are typically performed on no more than 50-ft lifts although many contractors and agencies still prefer a maximum of 30-ft lift height. Deeper lifts have been successfully executed, but depend greatly on the accuracy of the drilling and the skill of the blaster. If it is anticipated that a project will use lift thicknesses of more than 50-ft, these items should demand close attention during both the specifications and execution phases of the work.

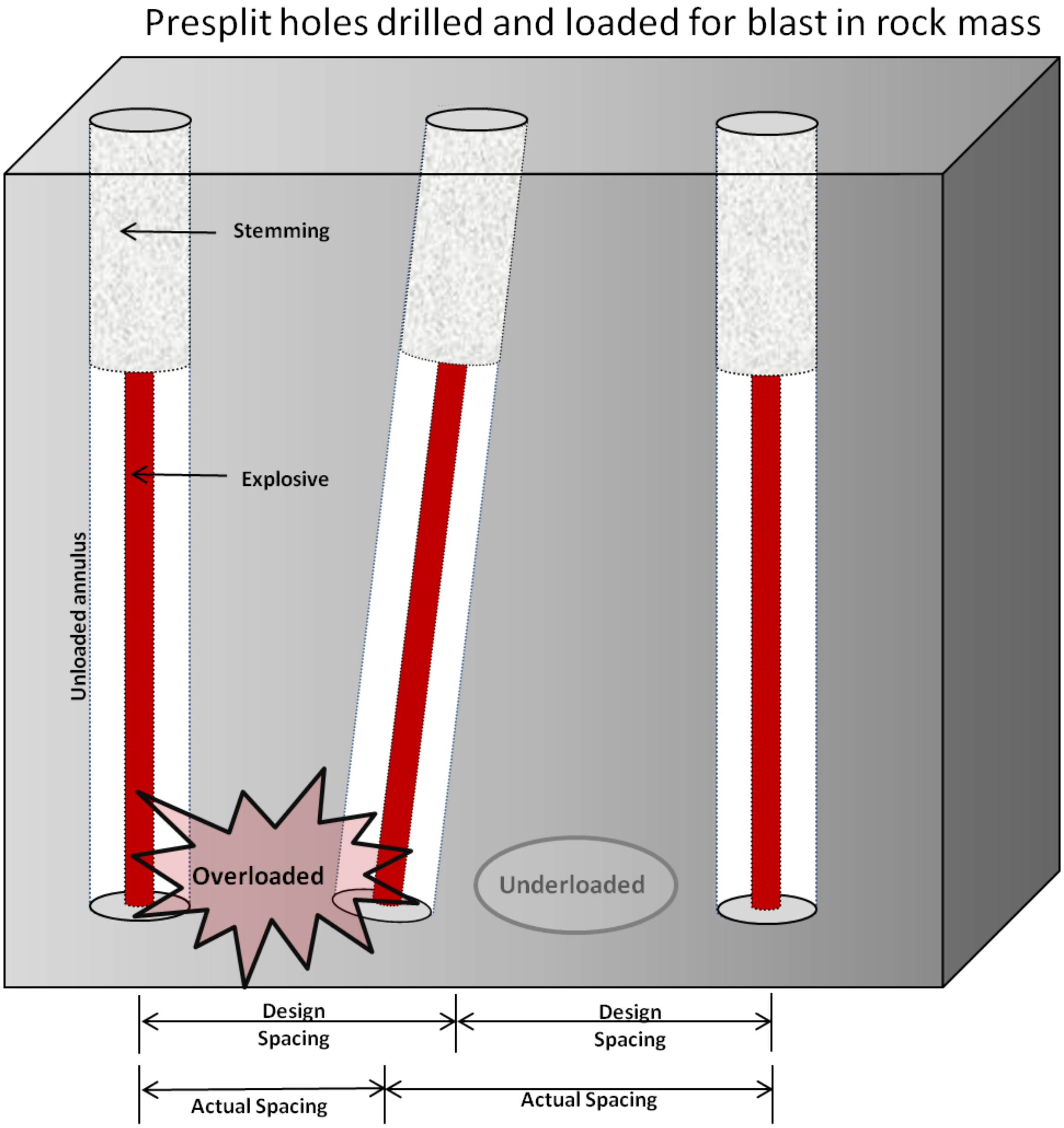


Figure 6-3. Problems Caused by Borehole Deviation in Presplit Blasting.

(5) Boreholes can deviate in three dimensions as well, causing rock to be left on the slope that was intended to be removed by presplit. Figure 6-4 shows a slope with two intersecting boreholes. The borehole to the left deviated into an adjacent borehole. Careful inspection shows that this borehole was also deviation out of the plane of the intended presplit. Other boreholes on this face also deviated into and out of the face, leaving areas where no half casts can be seen and leaving rock on the slope. This photo shows why drilling should <u>never</u> be allowed near a loaded borehole. If a drill intersects a loaded hole, the explosion can be set off as soon as the loaded hole is penetrated.

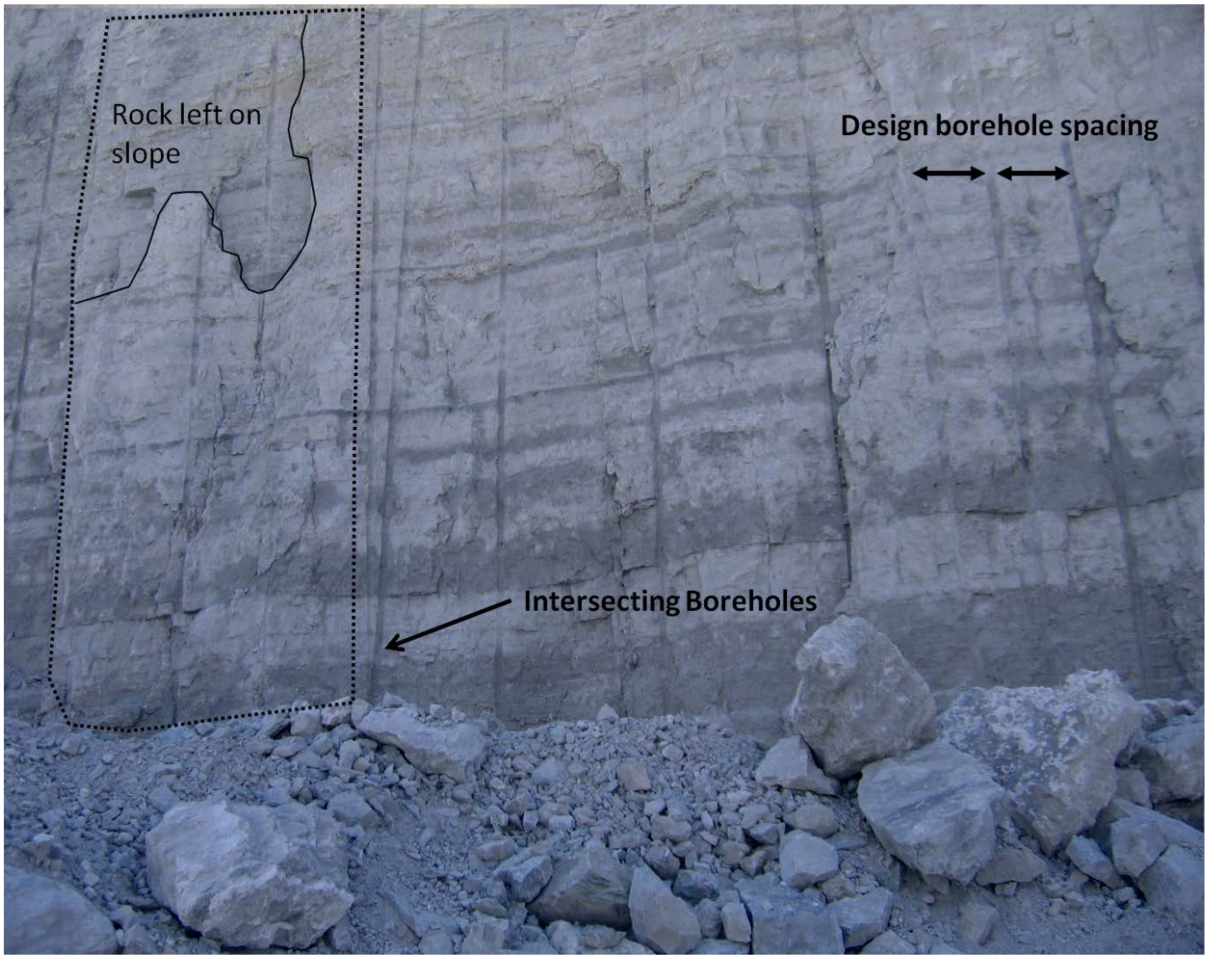


Figure 6-4. Intersecting Boreholes and Boreholes Deviating in Three Dimensions, Leaving Material on Rock Slope.

(6) Figure 6-5 shows the successful use of presplit blasting techniques on a high wall excavation in limestone. Each lift is shown by arrows. The top two presplit lifts are quite tall at 125-ft and have produced a good face. The upper presplit consisted of two benches that were removed at the presplit line. The lowest lift marked has a visible offset in this photograph. This offset is due to the presence of the upper wall. Drilling equipment cannot set up perfectly on the same plane as the upper holes. Particular care should be taken to make sure this offset is not too large as it can be a launching feature, allowing falling rock from the slope above to gain a more horizontal trajectory, extending the rockfall zone beneath the slope. Specifications usually call for no more than 18-in of offset.

(7) While there are a number of empirical formulas for presplit blasting have been published in the literature, most do not take into account the rock mass strength because the tensile strength of most rock is so low when compared to its crushing strength. The goal when pre-splitting is to apply a pressure above the tensile strength, but well below the crushing strength to minimize damage to the face. Sufficient burden for the presplit blast is essential since a burden that is too small can result in violent flyrock.

Figure 6-5. View of Highwall Excavation in Limestone Using Presplit Blasting with up to 125 ft Presplit Lifts.

(8) Konya gives the following empirical equation to estimate the powder load per foot and spacing that can be used to evaluate a pre-splitting plan. However, good agreement with these does not negate the need to conduct trial blasts and adjust to the conditions of the site:

$$d_{ec} = \frac{D_h^2}{28} \tag{6-1}$$

where:

d_{ec} = Explosive load (pounds/ft).

D_h = Diameter of the empty hole (in).

(9) When this equation is used to determine the load, the spacing can then be estimated by:

$$S = 10 \times D_h \tag{6-2}$$

where:

S = spacing of the presplit holes (in).

(10) The constant 10 in the above formula is conservative. It is meant to make sure that the presplit distance is not excessive and that the presplit will occur on the test blast. Field experience indicates that often this value can be increased to 12 and sometimes 14.

(11) However, pre-splitting is not a form of vibration control. The crack that propagates along the line of presplit boreholes has little to no effect in reducing the vibration from the production blast. Depending on the situation, and the explosive products used, presplit blasting may produce more vibration per unit weight of explosive used than other blasting technique.

h. Trim Blasting (Cushion Blasting).

(1) This method was developed in Sweden and is most effective in underground applications, where pre-splitting has more disadvantages. It is widely used for controlling overbreak in tunnel headings and stopes. It is used as a surface excavation method, though typically pre-splitting is more effective in this case. In trim blasting, the row of blasting holes are detonated after the main production blast, either on a delay or well after the production blasting is complete and the rock has been excavated. Typically trim blasting holes have a spacing of no more than 16 times the diameter of the empty hole for the charge weight calculated above. Trim blasting (cushion blasting) does not protect the final wall from the impacts of the production blast and are only used on surface excavations if presplit methods fail as a result of high residual stresses in the rock. All site design including a rock cut should be designed with rockfall and final rock slope stability in mind, but trim blasting slopes require particular care to provide an adequate rockfall catchment area beneath the cut as they are more prone to long term raveling. As with all other controlled methods, borehole alignment is critical for good results. Trim blasting, which is used to remove sections of rock, is considered a type of cushion blasting, and is further described Section 6-5, “Trim Blasting.”

i. Line Drilling.

(1) Line drilling is an older method for final wall control commonly employed by USACE before the adoption of presplit blasting techniques. Many of the foundation excavations completed in the 1930s and 1940s by USACE employed this technique. While presplit most often produces excellent results, and is the most common method used by USACE, line drilling still has use in certain circumstances. It is used primarily where presplit trials have not produced good results and where extremely careful work is needed to prevent overbreak where rock slopes are located adjacent to and below an existing structure (e.g., for construction of a new lock where the neatline excavation line is adjacent to and below an existing lock wall). Its primary difference from other controlled blasting methods is that the row of tightly drilled holes are not loaded. The wall is protected from damage by the production blast in two ways: (1) the last line of production boreholes is typically more lightly loaded than the remainder of the production boreholes and (2) the very tight spacing creates a plane of weakness, thus the blast creates the split between adjacent boreholes that produces the final face. Boreholes are commonly small diameter (3-in or less) and spaced 2 to 4 times the borehole diameters. Occasionally, larger diameters (e.g., 6-in) are used.

(2) Line drilling can also be used to help protect geologic features and other critical structures from blasting gases from escaping into karst features or faults. Keeping the blastholes away from the final face will help prevent gases from escaping into these features. Line drilling will also help protect the finished corners as discussed below.

(3) This method can produce poorer results than presplit blasting where the rock mass is not heterogeneous and where it is more geologically complex. The 18th Edition of the Blasters Handbook (ISEE 2011) notes that "… thin bedded, sedimentary, foliated metamorphic formations are not well suited to line drilling for overbreak control unless drilling can be done perpendicular to the strike of the rock." USACE experience has shown that medium to thin bedded limestone and dolomite have been successfully line drilled on numerous projects, but for most of these applications, the bedding of the rock was less than 20 degrees. Where more conventional line drilling spacing is employed along with an very light explosive such as detonation cord, it is more properly classified as a type of presplit blasting (precision), though it may be called line drilling on a project to denote the additional drilling expense.

(4) Figure 6-6 shows line drilling as used on the construction of a new lock chamber at Kentucky Lock. The foundation of the existing lock wall is visible in the top portion of the photograph and the new rock cut is located below. This blast removed a small amount of the existing rock foundation on the outside of the old lock chamber monoliths. Extremely careful blasting control was needed to successfully make this cut.

Figure 6-6. Line Drilling at Kentucky Lock Project Used for Construction of Excavation for New Lock Chamber Located Adjacent to and Immediately below the Existing Lock Wall.

j. Precision Pre-splitting (Konya, 2015 and 2016).

(1) Explosive Loads. Explosive Loads are the amount of explosive used as a column load placed in each hole in order to achieve the desired results. Many rock properties were considered to help predict the explosive load necessary. Figures 6-7 and 6-8 show examples of jointing and presplitting results. Some of the properties considered were: Tensile Strength, Shear Strength, Compressive Strength, Young's Modulus, and Poisson's Ratio. These were all computed at a fixed 24 in. (61cm) spacing.

Figure 6-7. Precision Presplit Test.

Figure 6-8. Over 1.5 Million Feet of Detonating Cord used on USACE Precision Presplit Project, Grundy, VA.

(2) The only property that seems to have a large influence on the explosive load was Young's Modulus or the Modulus of Elasticity.

$$(E) = \text{stress} / \text{strain} = \sigma / \varepsilon. \qquad (6\text{-}3)$$

where:

E = Young's modulus (N/m^2), (lb/in^2), (GPa)

(3) The Young's Modulus seems to have a linear relationship with explosive loads for Precision Pre-splitting. Young's Modulus is defined as the forced needed per unit area to stretch or compress a material. In terms of blasting mechanics, we can think of the explosive load as providing a set amount of force and the rock is the material we want to stretch. When we look at the blast in this these terms, it makes sense that explosive load would correlate well with the Young's Modulus.

(4) Konya Equations for Determining Explosive Load for 24-in. spacing. The results of precision presplit blast conducted on construction projects were used to develop the precision presplit column load prediction equations shown below (U.S. units with detonating cord loads).

$$Grains\ per\ foot = 18.78 * \left(Young's\ Modulus(GPa)\right) - 32.76 \qquad (6\text{-}4)$$

(5) The first Precision Presplit was fired by Dr. Konya in sandstone. The blasthole spacing was 24 in. The results of this test blast are shown in Figure 6-5. When explosive column loads are small such as 100 to 500 grains per foot of explosive it is necessary and convenient to use multiple strands of detonating cord for the explosive load. Many large projects are now completed using Precision Pre-splitting methods for both mining and construction. The USACE Grundy Remediation Project in Grundy, VA, used over 1.5 million feet of detonating cord for the Precision Presplit blasts (Figure 6-7).

(6) Geologic Conditions.

(a) With these equations, the values for the explosive column loads for test blasts can be calculated. These will be for the average Young's Modulus for the rock, but the Young's Modulus may vary at every site. Table 6-2 lists the beginning values for test blasts in different rock types when blasthole spacing is 24 in.

Table 6-2. Rock Type Calculations (Konya, 2016).

Rock Type	Young's Modulus (GPa)	Explosive Load (grains/ft)	Explosive Load (kg/m)
Siltstone	8.5	100	0.021
Sandstone	15	250	0.053
Shale	20	300	0.064
Limestone	30	550	0.117
Granite	40	700	0.149

(b) Figure 6-9 shows how Young's Modulus relates to the explosive load in kilograms per meter. While this equation would work well for determining explosive loads, precision pre-splitting's explosive loads are normally determined in grains of detonating cord per foot of cord in the United States.

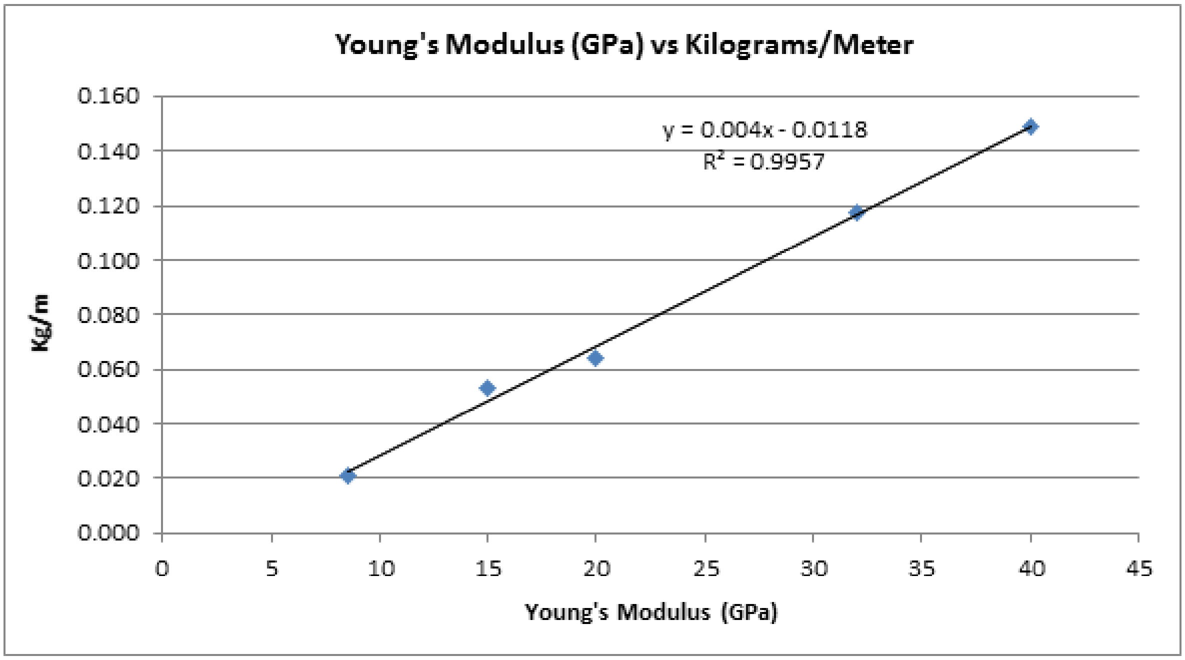


Figure 6-9. Young's Modulus vs. Kilograms/Meter – For Precision Pre-splitting at 24-in (Konya, 2016).

(c) Kilograms per meter can be converted to grains of detonating cord per foot by using Equation 6-5:

$$Grains\ of\ Detonating\ Cord = \frac{Kilograms\ of\ Explosive}{0.000213} \tag{6-5}$$

k. Precision Trim (Cushion) Blasting.

(1) "Precision trim blasting" means adjusting the strength of the explosive to match the strength requirements to cause the web of rock between holes to fail in tension with the minimum energy needed and to create the split without damaging the rock surface on the perimeter.

(2) In some applications where trim holes must be drilled at very close spacings, normal chargers are too large and cause overbreak around the holes. The use of closely spaced holes, on 12- to 24-in. centers, may be necessary in some geologic formations and for concrete removal in some structures. In some cases, it is necessary to drill larger holes than normally would be used, however, the spacings are small. Additional airspace around the charges is not normally detrimental to the formation of the split. If one uses the equation based on the hole diameter to calculate the loads, the charges would be too large for the spacings. On these close spacings, use the Konya precision trimming Equation 6-6 to estimate the amount of explosive that would be necessary for a fixed close

spacing for the test $d_{ec} = 7000\left(\frac{S}{85}\right)^2$ (6-6blast. It is often convenient to use detonating cord to provide this small distributed load.

$$d_{ec} = 7000\left(\frac{S}{85}\right)^2 \tag{6-6}$$

where:

dc = loading density (grain/ft)

S = spacing (in)

(3) Example: Three-inch diameter blastholes will be drilled on 18-in. centers and 20 ft. deep. Determine the grain loading of detonating cord needed to shear the rock web on the trim blast.

$$d_{ec} = 7000\left(\frac{S}{85}\right)^2 = 7000\left(\frac{18}{85}\right)^2 = 314\text{grain / ft}$$

l. Integrating Final Wall Blasting into Overall Blasting Plan. No plan to prevent blasting damage to the final wall will be successful if the goal of this final wall is not taken into account with the overall blast design. The degree of confinement adjacent to the final wall plays a large part in the damage to the final rock mass. As production blasts can damage a rock mass well beyond the final row of blastholes, if this damage is not taken into account and the final wall method is employed too late in the sequence of construction, the rock face may not suit the goals of the project. These techniques are intended to provide a means to transition from the well fragmented rock of the production blast area to a mostly undamaged final wall face over as short a distance as possible to make the blasting most economically efficient. The goal of good fragmentation for ease of removal cannot trump the needs of the final wall as it often becomes part of the permanent features of the project. Rock wall faces that are expected to be exposed to the elements as a permanent feature of the construction will need more care than a wall that needs to be safe only in the short term. However, where these methods are well executed and integrated into the overall blasting plan, excellent results can be achieved.

m. Assessing Final Wall Blasting Results.

(1) In general, the final wall should be as smooth as possible, with little overbreak and damage to the remaining rock mass. Where rock is left on the slope, or excessive damage occurs to the remaining rock mass, adjustments to the blasting plan will be needed. Chapter 3, “Geologic Considerations” provides further detail. However, a few practical points on an achievable face given certain rock discontinuities are needed here.

(2) Where near vertical discontinuities and joints in the rock are perpendicular or nearly perpendicular to the final face and the joints are tight, a good result can generally be expected and the slope face should be relatively planar. This can be seen both in Figure 6-10, which shows the joint trace as a brown discoloration near the sign, and in Figure 6-11, which shows the expected final wall results.

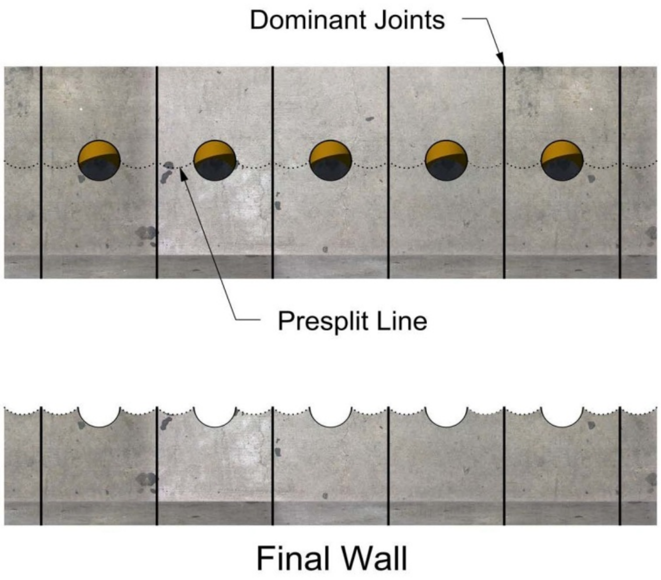


Figure 6-10. Presplit with Joints at 90 Degrees.

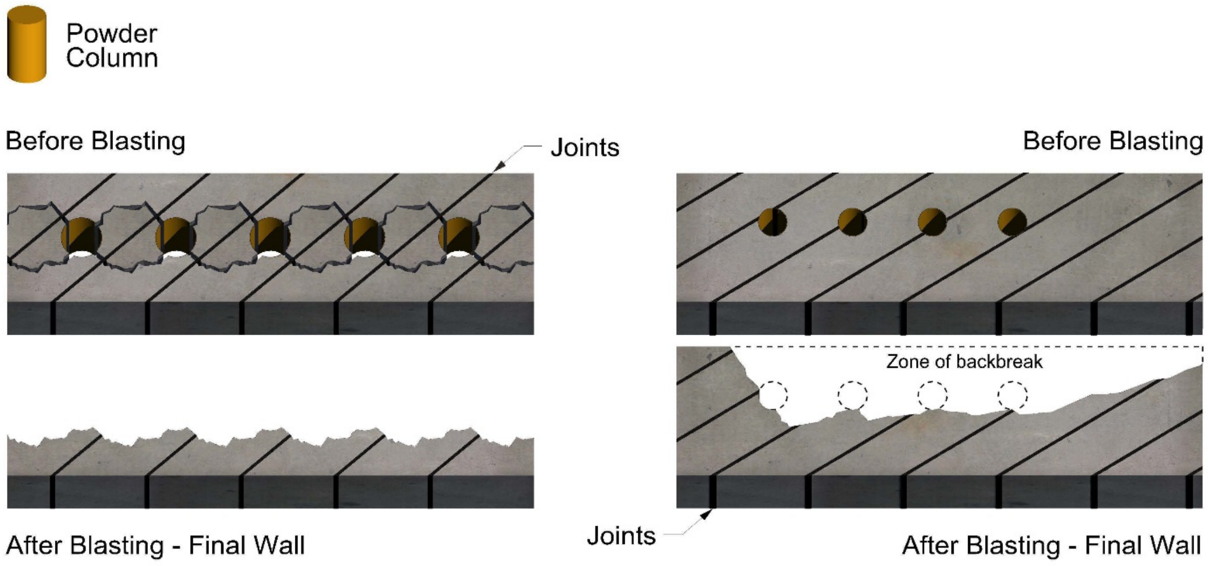


Figure 6-11. Final Wall Face Where Near Vertical Joints or Discontinuities Intersect the Face.

(3) Where near vertical holes and joints are more oblique to the final face, the remaining wall can appear more ragged (Figure 6-11). This should not be an unexpected result, though it may involve more overbreak than was originally anticipated in the blast design. Cracking may occur less neatly, thus leaving the face rougher and zones of backbreak may be seen on the slope. This is not necessarily an indication that the blast was overloaded.

(4) The most difficult condition is where the weak joints intersect the face at less than 30 degrees. In this case, the half casts may not be present on the final wall and the plane of the slope will often follow the joint orientation at that location. Where these are less than 15 degrees, this is almost impossible to prevent and should be considered during blast design. This may still result in a very successful final wall face. Figure 6-12 shows a nearly parallel joint that was intersected by the final wall. The presplit lift above broke behind this face, but the lower lift shows its trace on the face. No half casts are present where this parallel joint face is daylighting on the slope.

Figure 6-12. Successful Presplit Rock Face with a Nearly Parallel Intersecting Joint. Rock Was Removed Back to Joint Face and No Half Casts Are Visible at Joint Face.

(5) If there are 90-degree outside and inside corners designed in a project, then line drilling can be used to protect those corners. The line drilling of an inside corner a certain length from the intersection, e.g., 24 in., will assist in keeping the shape of the corner and allow for the rock to be removed if any remains (Figure 6-13). Outside corners are much harder to protect. The orientation of the joints/fractures will dictate the length from the corner that should be line drilled. Typically, that distance will be much longer than inside corners. This will protect the corner from damage (Figure 6-13). The specific site geology and contract specifications will determine the amount of line drilling required at corners or other locations.

Figure 6-13. Line Drilling Holes on an inside and outside Corner. Crew Checking the Depths to Quality Control (QC) the Drillers Work.

6-3. Cast Blasting. The cast blasting method, which is primarily employed in the coal mining industry, is used to cast significant amounts of rock from the blast into a previously mined pit. Blasts are designed for rock to have a high velocity from the face and it uses a much higher powder factor than other controlled blasts. This method is unlikely to be of use for USACE projects as it is a mining method, and does not control damage to the remaining rock mass. It is included here only because mining operations sometimes can have effects on USACE projects. The 18th Edition of the Blasters' Handbook (ISEE 2011) has an entire chapter on the subject.

6-4. Boulder Blasting (Secondary Blasting).

a. Boulder blasting is used to break up larger material that is too oversized for handling. Other forms of secondary blasting are mud capping, blockholing and air cushion blasting. This can be used on single boulders or on multiple boulders and is often employed to reduce large rockfall to smaller sizes. It can also be employed during blasting operations where the production blast did not reduce the rock fragments to the point where they can be handled with onsite construction equipment. There are many reasons why insufficient fragmentation may be achieved: improper design, geologic considerations, explosives malfunctions, and misfires. Also, this is often disallowed on USACE projects in the specification because secondary blasting is much more likely to cause flyrock than other kinds of blasting.

b. Where blasting has already occurred, careful consideration of the cause of the oversized rock needs to be evaluated before accessing the site. If undetonated explosives are possible, the blaster in charge will need time to assess the site, and no personnel or equipment should enter the area until the blaster in charge has given the all clear. If Government personnel suspect undetonated explosives, no personnel or equipment should enter the site until the situation has been fully discussed and evaluated. Failure to take adequate safety precautions in these kinds of events produces fatalities.

c. Secondary blasting is more expensive and requires greater skill for loading and design than production blasting. Apart from the issue of undetonated explosives from a production pile, secondary blasting can also be hazardous. Fly rock is much more of a concern and the air blast will be far more noticeable compared to other blasting techniques. Flyrock does not have to be large to cause damage. Figure 6-14 shows two small gravel sized pieces of rock embedded in a post after boulder blasting. A companion rock that came down from the slope at the same time is shown in the background.

Figure 6-14. Flyrock Embedded in Wooden Post after Boulder Blasting.

d. Access to the site can also be a concern. Transporting drilling equipment to the boulders on a rock pile can be difficult. Getting drilling access up on a slope where boulders are located on top of a slope, with a drill suspended from a crane is even more difficult and expensive.

e. There are three basic methods to reducing boulders and oversized boulder piles to smaller rocks: internal charge placement, external charge placement, and snakeholing. The blaster can use one or all of these methods depending on the situation. With all of these methods the direction fragments of the boulder will fly is not really controllable by the blaster as we are using the blasting charges to more as cratering charges and the block will break what appears to be randomly due to the path of least resistance in the material.

f. For internal charge placement (also called blockholing), a holes or holes are drilled directly in the boulder; the explosive charge is placed and stemmed. Care should be taken with setup as these are often are drilled with hand equipment, rather than a drill rig. Where a boulder is large, or located up on a slope, the driller and blaster may need a safety harness and other equipment for access. Likewise, stemming may require extra attention as these holes are typically smaller and considerably shallower than production blastholes, particularly when drilled with a hand pneumatic or hydraulic drill. Here, there may be reason to deviate from the standard USACE practice and specifications to allow clay, drill cuttings or other fine material to be used as the stemming material. This is done for two reasons: 1) material is less harmful if it is ejected from the hole and 2) crushed stone would typically need to move some distance up the column in order to lock into place here we have much smaller depths of blasting holes than in more typical designs. Drill holes should be no deeper than 2/3rds of the depth of the boulder being drilled and should be as close to 90-degrees from the drill face as possible. Low powder factors are used to minimize the amount of flyrock. The Blasters Handbook (ISEE 2011) recommends charges be limited to no more than a ½ lb/yd^3, Konya recommends a much smaller 1/8th lb/yd^3. The goal of blockholing is to crack the boulder, rather than to move the boulder so larger changes should be used with caution. The load is approximately two ounces per cubic yard for the Test Shot, and thereafter, either increased or decreased depending on the type of rock being blasted. If the boulder is not spherical in shape and instead is rectangular, many small holes may have to be drilled and the powder load distributed between those smaller holes. Blockholing techniques use much less explosive than mud capping; however, the degree of fragmentation and the direction in which the fragments fly is not controllable by the blaster, since the charges are functioning as cratering charges and breaking randomly in the direction of least resistance.

g. The air cushion method of breaking boulders, which is commonly used, works in a similar manner to the water cushion method described by Schmidt and Worsey as an alternative method from the Missouri University of Science and Technology. The major difference between the two techniques is that water is used in the blasthole rather than air. The blasthole is drilled in the boulder to 2/3 of the depth of the bolder, inserting a primer at ⅓ of the depth, filling the hole with water and then detonating to reduce the powder factor needed and to reduce flyrock see Figure 6-15 (Schmidt and Worsey 2000). . A charge, that equals approximately 2 ounces per cubic yard, is used for the Test Shot. Blastholes are stemmed to a minimum of 1/3 the depth of the hole. Common stemming materials are clay rather than crushed stone. The reason clay is used rather than crushed stone is that crushed stone must have distance to move up the hole and lock into place to function properly. In general, in air cushion blasting the length of the stemming zone is not sufficient to allow material to lock into place. Therefore, clay is used, which will not lock into the hole but will provide a time lag between the time the hole is pressurized and the clay is ejected. The minimum depth of stemming with this type of blasting should be approximately 12 in. If stemming depths are less, holes may rifle with little breakage resulting. Internal charge placement is the most predictable means of boulder blasting, but still involves far more uncertainty than with more standard blast design. Always approach a boulder blasting job with due caution, no matter which method is chosen.

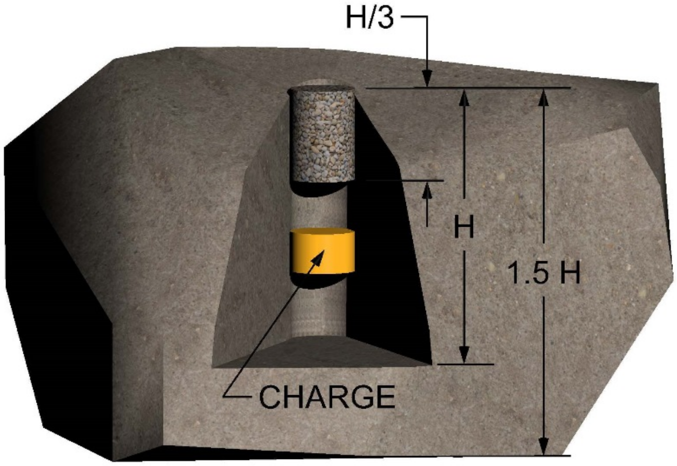


Figure 6-15. Air Cushion Blasting.

h. If the minimum amount of stemming is used, the maximum air cushion occurs. The rock will break into the minimum number of pieces. Often, in massive materials an operator can predict with fair accuracy whether the rock will break into two or three pieces, or three or four pieces. When air cushion techniques are used, the minimum amount of flyrock will occur with the rock normally popping open and laying in its original location with little, if any, throw. If more fragments are desired, the air cushion can be reduced by increasing the amount of stemming in the hole. The more stemming placed into the blasthole, the more fragments will result and more violence will occur.

i. For external charge placement, no hole is drilled. This is the most dangerous method of boulder blasting, though it usually the fastest and least expensive method. Mudcapping, the practice of placing mud, or other containment (e.g., sandbags,) on top of the charge is the most commonly used method for external charge placement. When mudcapping is used, between 0.5 to 1 pound of explosive per cubic yard of boulder are normally sufficient. Occasionally bags of water are placed for containment, but this is not recommended. In no case should aggregates or larger rock be used for mudcapping due to the potential for this material to become a projectile at detonation. Other methods in common use involves shaping ANFO, or a cartridge explosive product into a cone and initiation the detonation from the top of the cone. The explosive force is then directed toward the boulder. As with mudcapping, these methods should be expected to produce flyrock.

j. Snakeholing involves placement of the explosive underneath the rock that is to be blasted. A hole is dug or boreholes are drilled near or at the base of the boulder pile. Explosives are placed and detonated. Sometimes used along with lifters (explosive charges placed in nearly horizontal boreholes to excavate a rock slope), this method would not be preferred over final wall techniques as it produces much more damage to the slope. Where used at a rock slope, snakeholes are placed at the toe, and lifters would be drilled in a row or several rows above the toe. Snakehole boreholes are usually placed on a down angle. While more common for quarrying operations and boulder breaking, this method would seldom be used for structural excavations.

k. Seam blasting is used where a crack, seam, or geologic discontinuity is present. Explosives can be placed in these seams to remove rock from the slope, or less commonly, to fragment a boulder that has already fallen off of a slope. This is a very common method to use for rockfall stabilization projects where a boulder needs to be dislodged from the rock face.

l. The "boulder buster" is another development that involves the use of a cartridge that resembles a shotgun shell and a column of water to break the boulder. When the shell is fired, it causes a high impulse pressure wave to break apart the rock. While still using a small cartridge-based explosive, this method cracks boulders while significantly reducing or eliminating flyrock. While technically a blasting method, this use of explosive does not generally require a blasting license.

m. It may be advantageous to avoid this type of blasting and employ mechanical means such as with a hoe-ram or expansive grouts as discussed in Section 6-7 "Alternatives to Blasting."

6-5. Trim Blasting. Trim blasting is used to trim rocks and boulders from a face after a production blast or where blocks need to be removed from a rock face due to potential instability. This method is sometimes called "cushion blasting," where boreholes use crushed rock placed around the explosive. These terms are often used interchangeably in the literature. In common construction usage, trim blasting does not refer as much to the blasting technique as it does to the smaller scale trimming or removal of rock from a slope face. Most of the secondary blasting methods listed above can be used. Trim blasting typically involves much smaller burden than pre-splitting and smooth blasting. As with the secondary blasting, more flyrock and airblast can be expected than with production blasting. Trim blasting on a slope can result in flyrock that can travel large distances, and a substantial clear zone is recommended where this flyrock cannot be very carefully controlled.

6-6. Blasting for Rock Stability and Rockfall Control.

a. Most of the methods mentioned in this and the previous chapter can be used to stabilize a slope that has a rock stability or rockfall problem, provided that they are used as part of an overall stabilization design. Even production blasting can be useful because sometimes the most economical means to prevent rockfall and rock stability problems may be to simply re-cut the slope. All too often access roads, parking areas, switchyards, and other critical infrastructure were not built with rockfall protection in mind. Access roads to facilities along natural rock slopes can present particular problems as these were often designed to a lesser standard than would be required on a larger roadway. Natural rock slopes located along a river below a dam can be a particular problem as the roadway design often never took rockfall into account. While one of the most cost effective means to control rockfall is to provide a sufficiently sized rockfall catchment ditch below the slope, many access roads have little to no clear zone from the edge of the traveled roadway to the base of the slope. Where rock slopes are high, this can pose a rockfall threat to personnel and the public even where the slope is otherwise stable.

b. Trim blasting and secondary blasting techniques are most commonly used to aid in the scaling or removal of unsatisfactory and potentially unstable rock from a slope. It can be an effective means to support the mechanical and hand scaling of a slope where re-cutting the slope is not an option. Other methods to remove rock are discussed below, but blasting should always be considered one of the important tools in the toolbox for rockfall control. Figure 6-16 shows a trim blast used to support a scaling operation to remove unstable boulders in a slope above a dam access road.

Figure 6-16. Trim Blasting to Remove Unstable Boulders from a Rock Slope.

c. Likewise, blasting techniques have been successfully used to remove sometimes large unstable areas of rock to prevent or mitigate rock slides. Here presplit and smooth blasting can be of particular effectiveness, but the blasting design must take into account the particulars of the structural features of the slope and the rock that needs to be removed. Vertical slopes are not always preferred, and very careful blasting design may be needed to break the rock back to a particular discontinuity. Where possible, blasting should be used along with other methods to design the final slope to work with the geological situation to leave the slope with as few structural additions as possible (e.g., rock bolts, rockfall drapery, rockfall fences). Where these structural additions to the rock slope are needed, the blast design should support their most effective application. An example of this can be seen on the U.S. 64 Rockslide that occurred in the Ocoee River Gorge across from Ocoee Dam No. 2 in 2009. At this location, a large slide covered a roadway, but left surrounding rock that could slide along the same plane. Mechanical scaling, trim blasting, and secondary blasting techniques were used to remove the unstable rock back to a more stable face, which was then rock bolted. Figures 6-17 and 6-18 show before and after photographs of the site. Few halfcasts can be seen on the slope as the goal was to fragment and remove the rock back to an already existing surface in the rock slope. Therefore, little presplit blasting was used.

Figure 6-17. Rock Slide along US64 in the Ocoee River Gorge across from Parksville Dam, Immediately after the Slide.

Figure 6-18. View of US64 Slide after Remediation

d. Drilling access for rockfall and rock slope stability can be extremely difficult and require more planning, expense, and coordination than drilling at a quarry or a foundation excavation. Drills mounted on hanging platforms have been successfully used to drill boreholes for blasting (Figure 6-19). Another innovation involves the use of a wagon drill that is lowered to the appropriate portion of the slope by cabling. Where blastholes can be small, or site access is extremely difficult, hand drills can be used.

Figure 6-19. View of Drill Attachment with Button Bit Used for Drilling Small Blastholes to Perform Trim Blasting on a Rock Slope.

6-7. <u>Alternatives to Blasting</u>.

a. Mechanical excavation of rock can always be considered as an alternative to blasting, but it is not often the most economical one. Rammers attached to a track excavator can be an effective means to excavate a small slope where the rock is soft or thin bedded. Hoe rammers can also be effective for breaking boulders into pieces that can be handled with more standard excavation equipment.

b. Another mechanical means of rock removal is through the use of a large saw. While this may be far less common, and generally not economical when compared to blasting, these tools are available. Figure 6-20 shows a saw used to cut blocks of oolitic limestone.

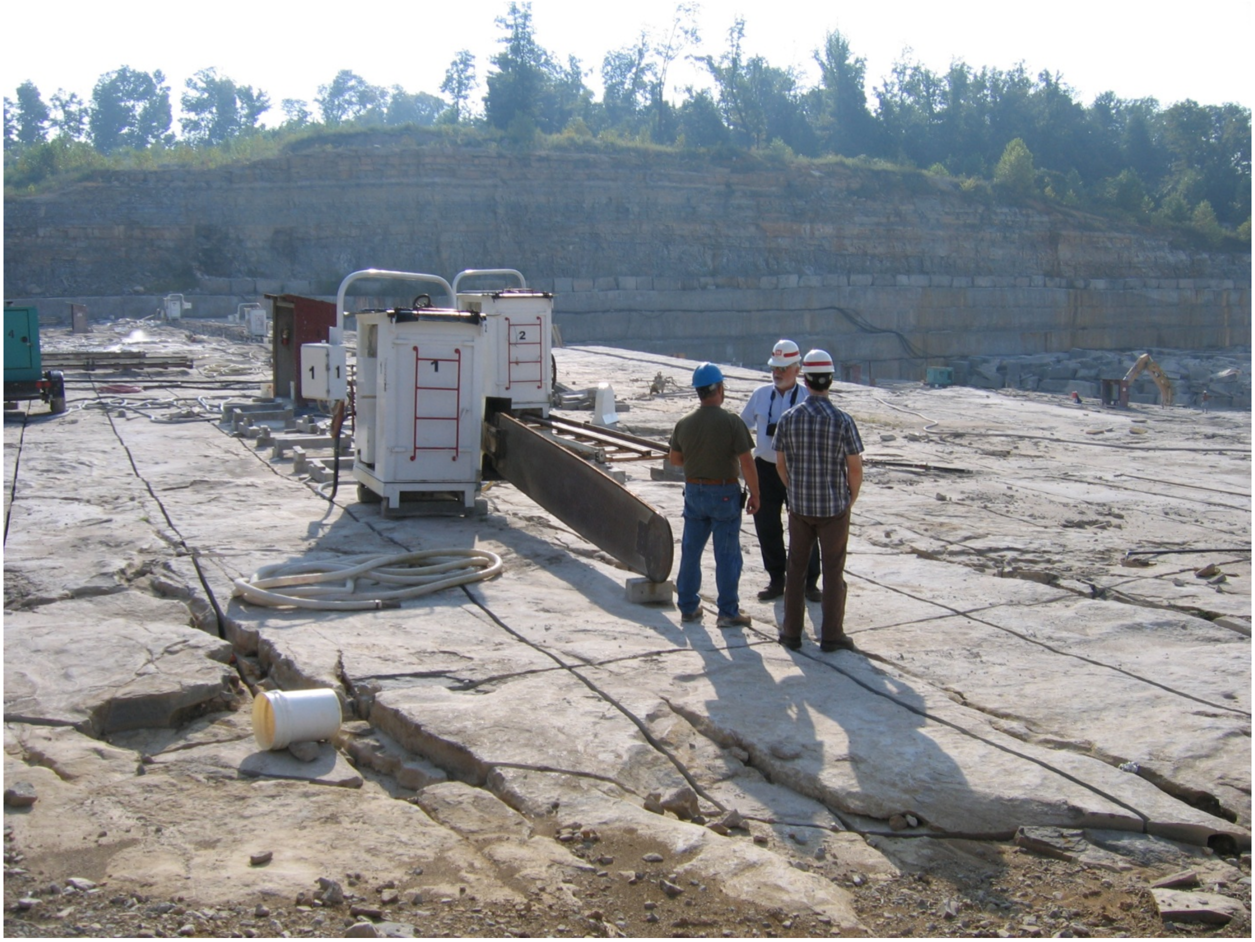


Figure 6-20. Sawing Oolitic Limestone as an Alternative to Blasting.

c. Using an airbag placed in seams or discontinuities in rock has had great success without the need for blasting. This is primarily useful for rockfall stabilization projects. Flat bags are placed in an open seam and then inflated to move the rock away from the wall face. While this may take several attempts where the geometry allows, large boulders can be removed from a slope without blasting. Figures 6-21 and 6-22 show examples where airbags were used for scaling on an access road to Cordell Hull Dam, TN.

Figure 6-21. Airbag with Scalers in a Man Lift before Being Placed behind a Large Unstable Column of Rock to Be Removed from a Slope.

Figure 6-22. Boulder Removed from Slope Using Airbags Shown in Fig 6-21.

d. Chemical demolition agents such as expansive grouts or rock splitting mortar have also been successfully used to break boulders instead blasting. Holes are drilled into the rock to be broken and the grout is poured into or injected into the hole. This chemical grout is allowed to expand within the boulder, producing rock stresses up to 18,000 psi of pressure that will break apart the rock. The process is much slower than drilling and can take up to 2-12 hours to produce results. However, there is very little noise and no flyrock produced. This method is generally more expensive than blasting for large scale fragmentation, but for smaller scale boulder cracking, expansive grouts can be quite cost effective.

(1) There are circumstances on projects where blasting with explosives cannot be used effectively. The reasons that blasting may not be used is because of local regulations, proximity to protected structures, and in areas where it is not practical to shut down vehicular or pedestrian traffic to allow for blasting. During the past few decades expanding mortar has been used to break both rock and concrete in these circumstances.

(2) The use of close spaced drilling and rock splitting mortar is many times more expensive per cubic yard than normal drilling and blasting but there are also many advantages of using these products such as: no blast vibration or airblast, no unexpected blast fractures, no flyrock hazard, no explosive transport, no explosive storage, no security problems. Holes are drilled on close spacing and filled with the rock splitting mortar in a matter of hours the mortar expands as it cures causing the rock or concrete to crack (Figure 6-23).

Figure 6-23. Fractures in Rock Created by Rock Splitting Mortar (Courtesy of Da-Mite).

e. Breaking tool. Figure 6-24 shows a device (a Magnum Buster) that can be used when rock or concrete must be removed in or near protected structures. It is a non-explosive breaking tool that can be used for fragmenting rock or concrete in confined areas where conventional explosives are not allowed or appropriate. The Boulder Buster uses a propellant, gunpowder, as the power source. The expanding gases from shotgun shell size cartridges generate a rapid pressure impulse upon a column of water in a drill hole. This causes controlled tensile fracturing in rock or concrete. The device is placed in a water filled drill hole, held down with a flexible mat, and mechanically initiated with a short lanyard. It is safe to use in close quarters since fly rock is negligible, noxious fumes are nonexistent, and ground vibrations are minimal. It can enables simple breaking operations to be carried out without the hassles and restrictions placed on conventional explosive use in crowded areas. These products are still available on a limited basis.

Figure 6-24. Magnum Buster.

(1) Propellant based boulder breaking devices. There are a number of propellants that are currently used for breaking boulders and mass rock or concrete. Some of these propellants are placed in plastic cartridges and some also contain initiators. These products do not contain high explosives. These propellants provide a slower, less violent reaction. These propellant materials also can be stored and shipped less stringently than high explosives. One such product in the United States is called NxBurst (Figure 6-25).

Figure 6-25. Propellant Cartridges (Courtesy of Nxco).

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CHAPTER 7

Underwater Blasting

7-1. General.

a. The intent of this chapter is to give the reader an introduction to the principles of underwater blasting and an appreciation for the differences involved in underwater blasting project. Like Chapter 5, the information is included to aid in the understanding of blasting plans and activities for underwater blasting and should not be considered sufficient education for the reader to design blasts. The information in this chapter is provided to facilitate understanding of blasting plans, specifications, monitoring and activities that may be different from conventional land-based blasting projects.

b. Explosives can be used on underwater construction projects for many activities such as demolition, excavation and geophysical exploration. Underwater blasting uses the same physical and chemical principles as in conventional land-based or terrestrial blasting and the properties of the rock and/or concrete are substantially the same. Thus, many of the principles discussed earlier in this manual are directly applicable. However, there are some significant differences that must be addressed and these may impact both design and monitoring of the blasting:

(1) Logistical and Monitoring Challenges. The logistical challenges and equipment associated with underwater blasting are also quite different from land-based blasting. Blasting underwater is often more difficult because the blasting is less easily directly observed. Thus instrumentation and surveys become even more critical than in land-based blasting. Drilling is often done from on top of the water column, rather than with submerged drills located directly on top of the drill holes to be loaded. Where divers are used there may be limitations on the time underwater for each diver.

(2) Water Properties are Different than Air. Most obviously, the compressibility and density of the two are quite different and this can result additional considerations than are needed when blasting above water. Pressure waves are generated in water are often much more significant than those generated in the air with terrestrial blasting. Transmission of wave energy through water is also more efficient, and when not accounted for in design this can cause additional unwanted damage. Available oxygen and the cooling effect of water must also be considered and these can have an impact of the effect of blasting. Water properties also affects the trajectory and throw distance of material blasted underwater as it provides increasing resistance to rapidly moving objects with a phenomenon called viscous damping. This results in blasted material with smaller displacements than would be expected on land-based projects. Where water is deep, this phenomenon damps the movement of flyrock. However, this effect should be evaluated for every blast as shallow water may be insufficient to prevent damaging flyrock particularly where there are sensitive structures located close to the blasting site.

(3) Flora and Fauna. Blasting underwater has different potential impacts on the flora and fauna in the surrounding area and these must be considered during blasting design. Typically in the blasting industry, “environment” considers the impacts upon humans and structures, while “natural resources” refers to impacts upon flora and fauna. These can be from pressure waves generated by blasting or from other effects such as the migration of silts, sediment or rock dust. Air pressure

waves typically do not have the same effect on wildlife as underwater blasting and these differences must be taken into account.

7-2. Equipment and Logistics of Underwater Blasting.

a. Mobilization. Access to the location where underwater blasting is to be performed requires boats and/or barges of an appropriate configuration and suitable mobility for the work. Safety on board barges and decks and for overwater work in general is prescribed by EM 385-1-1 and U.S. Coast Guard regulations. Properly licensed and certified personnel are required to meet all local, state and Federal regulations. Smaller boats and barges may be better suited for shallower water bodies, and larger boats are necessary for deeper water or in areas where moving water is more of a concern.

(1) Provisions must be made for the specialized materials, equipment and activities involved in underwater blasting, including ordinary mechanical tools, drilling equipment, survey and monitoring equipment, day storage magazines for explosive components, blasting controls and detonators, as well as onboard sanitary and first aid.

(2) Anchorage systems or spuds are necessary to maintain position of the barge and also must be of a design to make movement practical and minimize navigational impacts where other users require access around the area of work.

(3) An auxiliary boat may be necessary to provide rapid evacuation of a work barge for emergencies or for ease of transport to shore for brief intervals, such as breaks or change of shift.

(4) It is important to plan and include contingencies for every aspect of the work that is performed overwater such that trips ashore are kept to a minimum, as the costs of delays overwater are much greater than they are for land-based work, owing to the additional personnel and equipment involved. Redundancy in equipment and materials is one way of accomplishing this.

b. Barges. Barges differ from boats in the simplicity of their design and typically do not have their own mode of locomotion on water, although some have small motors for small-scale movements. Multiple barges can be lashed together in an almost modular fashion to achieve the desired work area and facilitate mobility.

(1) Anchorage systems may consist of conventional anchors, cables and winches, or spuds. Spuds are legs that extend from the barge to the substrate. Spuds may either be free-moving, in such a way that the barge will rise and fall in response to waves or changes in water level; or rigid, such that once in place they act as legs and the work deck is then like a table that remains in firm connection to the legs and thus the substrate.

(2) Jack-up barges are specialized barges with the ability to raise and lower the work barge on the legs or spuds by means of jacks or winches connected to the spuds. Jack-up barges are considerably more costly to use and are not as readily available as conventional work barges. Barge capacity should consider the weight of all equipment, supplies and personnel that will be onboard, with contingency.

(3) For use where space permits, barges provide ideal work platforms and can be readily configured for this type of work. A typical work deck barge has a flat steel work surface with lashing points to tie down equipment and may have either permanent or temporary enclosure(s) for storage and/or onboard work.

(4) Depending upon the size and scope of the work, an onboard generator may be used with the barge. Although blasting is not normally performed at night, there may be other activities related to the work such as surveying, dredging or removing blasted materials, or drilling, that may be performed at night, and these activities will require onboard lighting.

(5) Work barges are constructed as hollow wafer-shaped structures to render them buoyant and to keep the work surface high enough above water to minimize wave splash. Barges may have internal “wet wells” or through-going holes that are sealed so that the barge maintains its internal air-filled chamber, but the well is open as a kind of donut hole through which drill rods, casing, sampling, charge placement and fuse connections can be run. Alternatively, if multiple barges are lashed together, spacers or casings can be placed between barges to allow this to be done between the barges.

(6) Steel pipes/casings are driven down into the mud above the location of blastholes. The drilling is done through the steel pipe. The steel pipe/casing is absolutely essential to keep holes from plugging and filling with debris. After drilling is completed PVC pipe may be inserted into the drill holes and the steel pipe/casing can be removed. After the drilling is completed, the initiators, explosives, and stemming are all loaded through the PVC pipe into the rock. The initiator leads are affixed to the shooting line.

(7) Both cartridged and bulk products have been used for underwater blasting. Normally in underwater blasting a clamshell or dipper bucket dredge is used to extract the broken rock. The rock must be blasted to proper depth and of a size to make for easy digging. In underwater blasting applications, high spots or not breaking to grade causes project delays and high costs to go back and reshoot the rock. For this reason in underwater blasting applications the rock is shot deeper and harder than the intended grade to make sure the intended grade can be achieved with no remedial action.

c. Boats. Whenever barges are used, a tow appropriately sized for moving, locating and stabilizing the barges will be necessary. The boat may be needed to stabilize floating work platforms, depending upon the configuration, and will otherwise be necessary to move from location to location. Additionally, it may be necessary or prudent to have a smaller runabout boat for more expedient trips ashore and for added safety.

d. Drilling Equipment. As with any work involving drilling, the capacity of the drill will depend upon the size (diameter), depth and material to be drilled.

(1) Drilling from a barge (Figure 7-1) poses unique challenges, the most significant is in the potential for water level to change while drilling. This changes the drill’s impact pressure, if the drill is a top-drive type, as the downpressure will be intensified when the barge drops in elevation relative to the substrate through which the bit is cutting.

Figure 7-1. Photo of Drill Barge.

(2) If the barge is not a rigid "jack-up" barge, even minor waves can cause problems such as drill tooling will shearing off under compression resulting in lost tooling and a lost hole. A jack-up barge eliminates this concern, but jack-up barges are far more expensive to operate and are not as readily available.

(3) Rigs that are capable of rotating the drill stem with little or no downpressure by means of a kelly bar that slides through chucks that can be loosened or disengaged are preferable, as the drill stem will provide enough weight to penetrate most materials. Additionally, because the limited size and carrying capacity of barges, drills for underwater blasting are typically skid-mounted so they do not require a truck, which reduces their weight and footprint on the barge.

(4) Other considerations may include the fuel or power supply, as some drills are more efficient using air (pneumatic), whereas others are more effective when powered by an engine (either diesel or gasoline.) The type of drill is usually left up to the contractor to size this equipment to the needs of the job, but the overall Underwater Master Blasting Plan should provide justification for the selection.

(5) Drill holes must have casing from the work deck to the substrate and orientation of drill holes is critical. The size of drill tooling is an important consideration in maintaining the proper orientation of drill holes, as is the overall configuration of drill rig, barge and anchorage system. The large drill barges used in underwater blasting have the capacity to have drill-hole diameters of 4.5-in. Some smaller drill barges use 3.5-in. drill bits. Small barges in the past have used 2.0 drill bit diameters. Maintenance and repair of drilling equipment can be time consuming, and it is important that equipment be brought up to optimal working condition before mobilizing it overwater, and that contingencies be included in the Underwater Master Blasting Plan, including consideration for having redundant equipment at the ready.

e. Miscellaneous Materials. Loading tubes and casings must be of similar metals in order to reduce the risk of electrical transient currents developing from galvanic action of the metals in water, or from moving water in contact with the metals. Floats should be anchored within each submerged stemming, in such a manner as to be released when properly detonated. These floats may remain connected in the event of a misfire of a particular hole. Remaining floats in the shot pattern are a useful indicator of problems with the shot.

f. Personnel. Because the considerable delays that can result from unanticipated conditions or occurrences overwater, it may be advisable for personnel to be familiar with multiple aspects of the operation, as well as to consider the potential need for additional personnel for this work who may be available on short notice. Although it is recommended that personnel be familiar with different aspects of the work, the same designations and limitations of responsibilities should be assigned as are done in land-based blasting. It is important to keep the number of people on board the vessel and barges to a minimum for safety and practical reasons, but there must be a balance between having the necessary personnel on hand to accomplish the work efficiently and having backup resources on land, but ready to be deployed when needed. The need for trained and specialized personnel will add cost to this type of work and should be considered when planning underwater blasting.

7-3. Underwater Pressure Waves. The properties of water make the effects of the pressure waves somewhat different than those in the air.

a. Waveforms in solid media and air. As with terrestrial blasting, underwater blasting produces the same kinds of body and surface waves and the general behavior of those waves in soil and rock can be expected to be the same. Although vibrations in the rock or concrete may be at the upper bound for a given charge due to saturation of the materials and better confinement and coupling of the explosive (Oriard, 2002) waves passing through water behave somewhat differently than through air. See Section 8-3 for a discussion of passage through soil, rock, and air.

b. Airblast and Vibrations from Waves Due to Underwater Blasting.

(1) Airblast are the overpressure waveforms that move though air as audible and sub-audible sound waves. These are also called compression waves. Airblast may be greatly reduced or eliminated in underwater blasting applications, depending upon water depth and confinement of the blasting agents. Air blast still may remain a concern where the project is near an urban area or when the water depth above the material being shot is very shallow (i.e., less than 5 ft. of water depth). Additional information on airblast or air over pressure, even for underwater blasting, is contained in Chapter 8, Section 8-4.

(2) Depending upon the size and scope of the project, there may be a need to assess vibrations on surrounding structures due to underwater blasting. Additional information on vibrations due to body and surface waves, even for underwater blasting, is contained in Chapter 8, Section 8-8.

c. Pressure Waves Generated by Underwater Blasting. Compression waves or pressure waves, also called overpressure waves, are transmitted through fluids (liquids and gases). The differences in compressibility and density between water and air result in differences in the transmission and effects of these waves.

(1) The Water Body. Compared to rock formations and soils, water is much more uniform in its physical properties and there is relatively little variation from one site to another. Thus, the pressures generated by a specific charge suspended in water is much more repeatable than those in rock, which are far less homogeneous. It is standard procedure to provide a check on monitoring procedures and equipment to detonate one or small test charges suspended in the water before proceeding with other blasting on the project.

(2) The most common field condition of interest is the impact upon a structure(s) or organisms located close to the blasting site. For close ranges impacts due to blasting, distance becomes more important than site conditions.

(3) Where pressure waves are carried to greater distances, water temperatures, salinity, current, carried sediments, layering, and bottom contours become increasingly more important in determining the transmitted pressure levels or audibility of the sound. At very great distances, the site conditions play an ever-more important role, with more variation in the results.

(4) Open-water detonations. A charge detonated in open water, suspended in water beneath a buoy, may allow the gas products to oscillate before reaching the air-water surface and being liberated into the air. The bubbles in the water rapidly expand due the high pressure of the explosive gas. These can oscillate and collapse underwater causing damages to structures. These cyclic bubble oscillations produce a secondary pressure waves that occurs after the initial shock wave. They can be eliminated or reduced when the charge is near the air-water surface.

(5) Embedded detonations. Confining a charge causes the work by the detonation gases produced by the charge to be confined within rock or a concrete structure rather than moving through the water. This also prevents or reduces bubble oscillation and its attendant pressure wave. The explosive must be well confined both by stemming in the shot hole and by the medium being blasted, in order that the gases perform work and are then not vented easily into the surrounding water

(6) Depth of Water. The depth of water is another important parameter. For most uses related to engineering features the water depth is shallow, less than 75 ft. of depth, compared to the great depths that were of interest in prior work such as Cole (1948), which were focused on military applications. Shallow water reduces the gas bubble oscillation cycles and wave channeling.

(a) When the water is shallow and there is a firm rock floor to the water body, the pressure wave in the water a short distance from the source is reflected back into the water from both the air-water surface and the water-rock surface. This causes the pressure wave beyond a certain lateral distance from the source to be captured within the water. This channeled wave does not release much energy either to the air above or rock below. The dominant factor in a channeled pressure wave’s attenuation is spreading of the wavefront area.

(b) The channeled wave’s wavefront may also no longer expand hemispherically. The channeled wavefront is restricted effectively to a cylindrical wavefront with an expanding radius of the distance from the detonated source and cylinder height of the shallow water depth. The result is lessened attenuation, thus greater amplitude pressure waves at distance relative to shots releasing less pressure-wave energy into the water. Therefore, the charges must be well confined in rock do perform its intended work and to reduce to as small as possible the energy reaching the overlying water.

(7) The Pressure Wave. Depending upon the size, scope and potential water-borne impacts of the project, there may be need to assess water-borne pressure waves, also called overpressures. Background data for normal and extremes of water-borne pressure waves should be collected and reviewed to consider whether blasting may contribute to overpressure impacts. The impacts of underwater blasting, other than vibratory transmission through sediment and rock, are largely dependent upon the behavior of pressure waves' transit through the water volume above and/or surrounding the blast site.

7-4. Peak Pressure.

a. While the peak pressure of the water pulse generated by an explosion is not the only parameter that can predict damage, it is a parameter that is used to assess potential impacts at a site. This was focus of early theoretical work in the area of pressures generated underwater by explosives, which began during World War II for military applications including submarine warfare (Kirkwood, and Bethe, 1942). While much of this work was classified and the time, some of their results are reported by Cole (1948) along with Cole's own test measurements. This work is still of use to the modern practitioner understanding peak pressures.

b. Cole's Experiments. Cole's experiments were completed with TNT and other military explosives, rather than more common explosives used on engineering projects. For his measurements with TNT, Cole calculated peak pressure, P_P, in psi, as Equation 7-1, which can also be written in its' inverted form as Equation 7-2 (as per Oriard, 2002):

$$P_p = 2.25\mathrm{E}4 \left(\frac{W^{\frac{1}{3}}}{R}\right)^{1.13} \tag{7-1}$$

$$P_p = 2.25\mathrm{E}4 \left(\frac{R}{W^{\frac{1}{3}}}\right)^{-1.13} \tag{7-2}$$

where:

W = Charge weight in pounds.

R = Range or distance in feet.

c. The more common form of the expression in the literature is Equation 7-2, where R / $W^{1/3}$, called the normalized or scaled distance. While the exponent of -1.13 fits Cole's data for TNT and Pentolite, other explosives may produce a different value. Cole's (1948) formula for P_P is particularly useful to natural resource testing in the field. Charge may easily be suspended in water from a buoy and the aquatic organisms being tested are suspended in a cage(s) at an appropriate lateral distance(s) from the detonation. Pressure-wave records at the cages may be converted to varied pressure-wave measures.

d. P_P in its general form. P_P is the equation of a straight line on a log-log graph of scaled distance on the x axis and peak pressure on the y axis. It is a line produced by regression of experimental data. The general form, useful for any type of submerged detonation, is:

$$P_p = c * CRSD^{-a} \tag{7-3}$$

where:

c = the coefficient, is the P_P-intercept at a cube-root scaled distance (CRSD) of 1.0

$CRSD$ = $R / W^{1/3}$

-a = the slope of the log-log regression line.

(1) With a negative exponent, the regression line slopes downward to the right as scaled distance increases. The equation represents the decay slope or rate of attenuation. Typically this is less than the conventional value of 1.6 used for most conditions on land.

(2) There are three sources for the coefficients of Equation 7-3 for charges detonated in water. Cole (1948) found the coefficient, c, to be 2.25E4 and the exponent, a, to be -1.13 for varied water depths, particularly deep water. Two other sources, USACE ETL (1991) and Soloway and Dahl (2014), the latter being for shallow water specifically, have two slightly lower values of c, 2.16E4 and 2.13E4, respectively, and the same “a” exponent of -1.13. These three open-water (OW) equations are provided in Table 7-1, and plotted on Figure 7-2. The three open-water, or suspended charge, equations have such similar coefficients that they overplot one another in Figure 7-2. Cole (1948) found that the value of W for Equation 7-1 should be multiplied by a strength factor for varied types of explosives in military applications and when suspended in water. For rock excavation or structures demolition in shallow water, however, this weight-strength factor is relatively unimportant. This is particularly true when monitoring pressure waves at a single project with a similar type of explosive material for all shots.

Table 7-1. Equations for Equations for Estimating Peak Pressures (P_P) from Underwater Blasting.

Charge Position	P_P Estimate (psi)	Source
Single, Suspended Charge, Open-water Blasting	$P_P = 22{,}500\ CRSD^{-1.13}$	Cole (1948)
Single, Suspended Charge, Open-water Blasting	$P_P = 21{,}600\ CRSD^{-1.13}$	USACE ETL (1991)
Single, Suspended Charge, Open-water Blasting	$P_P = 21{,}300\ CRSD^{-1.13}$	Soloway and Dahl (2014)
Less confined Charge(s) within Rock or Concrete	$P_P = 7{,}500\ CRSD^{-1.13}$	Oriard (2002)
More confined Charge(s) within Rock or Concrete	$P_P = 2{,}250\ CRSD^{-1.13}$	Oriard (2002)
Charge(s) within Low strength Rock	$P_P = 5{,}460\ CRSD^{-1.23}$	Hempen et al. (2007)
RSD = R / $W^{1/3}$, Cubed-root Scaled Distance, for R, the range, in feet, and W, the charge weight in pounds of a single charge or the shot pattern’s maximum charge weight per delay (where the delay is longer than 8 ms within a row or longer than 25 ms between rows).		

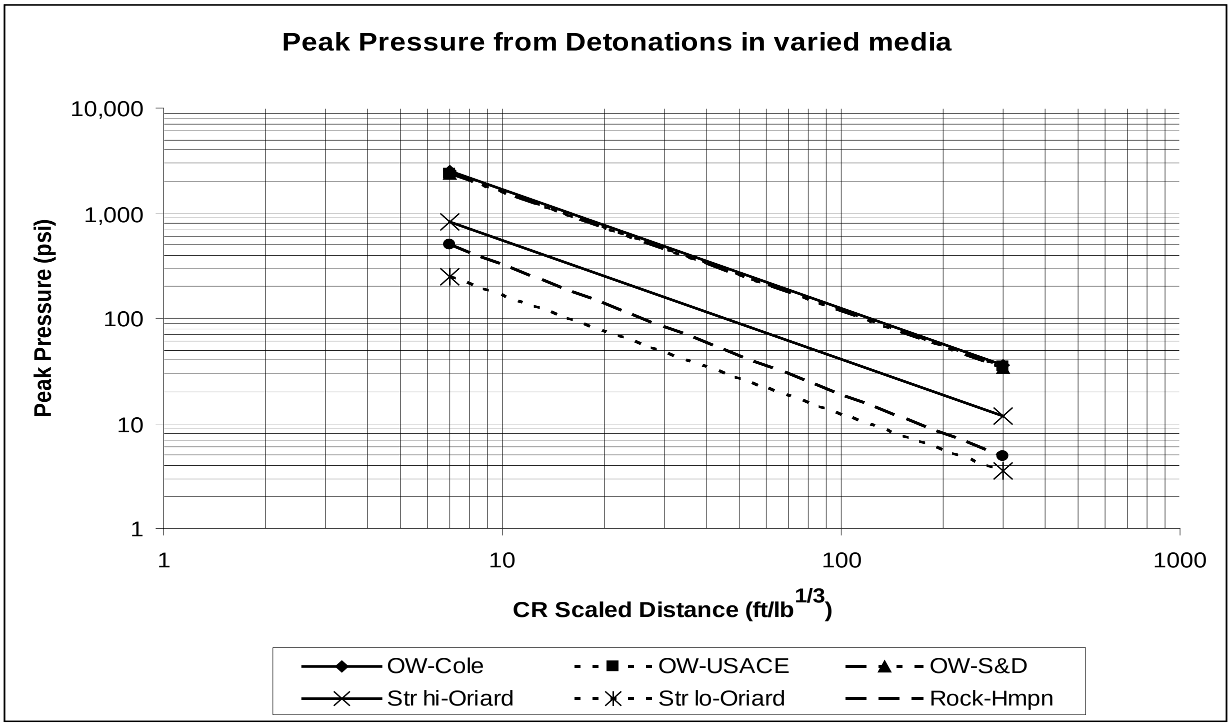

Figure 7-2. Estimated Peak Pressures Generated by Underwater Blasting for Open-water (OW) or within a Structure (Str) or Rock for the Equations of Table 7-1.

(3) Oriard (2002) provides some data for blasting of structures surrounded by water. The P_P data for underwater blasting (Oriard, 2002) of rock and large structures is developed without considering how near charges are detonated to the surrounding water and without evaluation of the radiation into rock beneath the structure. Oriard (2002) provides two figures (Figure 7-3, p 240, and Figure 7-23, p 275) for blast demolition of structures and the removal of columns surrounded by water. Oriard (2002) gives no parameters for using either of his equations shown in Table 7-1 and depicted in Figure 7-2. A linear charge within a structure, but very close to the exterior surface in contact with the surrounding water body, could have P_P values much closer to the equations for open-water blasts. Therefore the P_P could plot above Oriard's higher amplitude (less confined) equation in Figure 7-2. Alternately, a shot pattern from demolition of a massive structure founded in rock or from blast excavation of rock with a short vertical face exposed to a water body may produce P_P values that are well below his lower-amplitude (more confined) equation. Care should be taken when using Oriard's more confined equation as it is likely not sufficiently conservative for underwater blasting with important structures nearby or with natural resources to be protected.

(4) Hempen et al. (2007) determined a different set of P_P equations in the form of Equation 7-1 for rock excavation at Miami's Harbor in Florida. This is shown in Table 7-1 as the equation for Charge(s) within low strength rock. The rock at Miami Harbor could not be dredged productively, yet the rock properties were not as strong as most sedimentary rock or mass concrete. Further, the rock had weathering and other flaws that could cause lack of confinement down the length of an otherwise properly stemmed shot hole. The site did have the ability to radiate energy into the subsurface, which reduced the energy that was transmitted into the water body. Other locations of stronger continuous rock units may have greater reduction of P_P (a smaller coefficient and a more negative

exponent) with distance than exhibited by this testing. The lessons of this blasting are that the actual equation for any submerged rock excavation site may only be obtained by comparing recorded values for that blasting at that site. Both the coefficient and the exponent were higher due to conditions of the rock at the site. Conditions were poor enough that for most estimations of P_P for a submerged rock excavation site one may use the Hempen et al. (2007) equation of Table 7-1 as the upper bound. With poor strength rock and poor confinement it should provide a good estimate of the maximum generation of P_P in the water for rock blasting. The P_P estimate from Hempen et al. (2007) should not be preferred to the lower estimate of Oriard (2002), as Oriard may be more appropriate for more competent rock with well confined blasting. However, it may be appropriate to use the Hempen et al. (2007) estimate for important mitigation issues until testing shows that a lower estimate for the particular site or the lower estimate of Oriard (2002) is appropriate.

e. Factors and Considerations that modify the waveform from theoretical P_P.

(1) Equation 7-1 is the base equation for P_P estimates for all underwater blasting, including multiple charges on delays in open water or within rock being excavated or structure being removed. Consider that when the explosive is being used to demolish a submerged structure or to excavate rock below the water surface, the P_P and the entire waveform is modified by the energy consumed in work accomplished in the medium and the radiation of the wave through the structure or rock.

(2) Two other factors modify the waveform from that produced with single, suspended or open-water explosions: (1) there are multiple charges shot with millisecond delay timing, and (2) the gaseous phase of the detonations in the structure or rock has reduced potential for the oscillation of a single gas bubble rising to the surface. Multiple charges on delays cause the sources of the shock and gaseous phases to be spread throughout the pattern separating them by delay and travel time. The shock phase passes in some directions through the undisturbed structure or rock and is slightly modified. In other directions the expanding waveform transits through the medium previously shot in the pattern and its bubble field, and is significantly modified. The gaseous phase, having its energy consumed by displacement of the mass being shot and the cooling effect of the ambient water, is disbursed into disassociated bubbles without the energy to oscillate and form their own shock wave pulses. The last important factor is the possible connection of the structure or rock to the radiating property of massive rock beneath the shot mass. Massive founding rock transmits energy into the subsurface and little of that energy passing downward returns to the water body surrounding or above medium containing the shot pattern's explosives.

(3) Deeply buried and confined charges in rock will generate higher levels of vibration in the rock, but they will generate lower levels of pressure waves in the adjacent body of water. This would also be true in adjacent air. Water pressure can vary considerably with the depth of charge burial, an important concept in the design of underwater blasts. When charges are loaded to the collar of the hole and are thus vented directly into the water (called rifling), the water pressures will be much higher. It is the errant shot hole with the least confinement, or the shot holes within a flawed medium allowing venting, that produce the greatest water-borne P_P. With poorly confined holes we expect to see a P_P value closer to that of a suspended charge. Additionally, such charges generate much stronger-acting gas bubbles that can have more damage potential than the peak pressure of the water-borne pressure pulses.

(4) Care should also be taken when using these P_P Equations of Table 7-1 for piers and columns surrounded by water or for mass concrete founded in soil. If the P_P is important, err toward higher values of open-water charges. The shot hole nearest to the surrounding water or shot hole with the little confinement due to defects in the medium produce the greatest water-borne peak pressure. Recording the pressure waveform in water is the better, but more expensive, means to resolve the actual waveform and its parameters. The pressure wave may be recorded at important projects to assess the site's conditions and blasting parameters effect on the water-borne waveform.

(5) Amplitudes of P_P may easily be compared at a single project site by considering the form of Equation 7-1. The P_P will remain approximately the same at a project for constant values of CRSD (= R / $W^{1/3}$). As the distance is decreased to an important submerged feature of a project covering a sizable area, the $W^{1/3}$ must be proportionally decreased to retain the P_P at a previously acceptable level. Vibration from land-based blasting decreases more rapidly with distance.

(6) Sound Pressure Level. The other form of P_P for hydroacoustics is the Sound Pressure Level (SPL). P_P, are given in units of pressure: pounds per square inch (lb/in^2, psi), millibars (mb), Pascals (Pa); or, as SPL in units, dB, of decibels relative to a reference level (1 micropascal = 7.25E-12 psi) for water with conversions as follows.

$$\text{In PSI, } SPL_{dB,water} = 20 * \text{Log}P_{p,psi} + 196.8 \tag{7-4}$$

$$\text{In mb, } SPL_{dB,water} = 20 * \text{Log}P_{p,mb} + 160.1 \tag{7-5}$$

$$\text{In Pa, } SPL_{dB,water} = 20 * \text{Log}P_{p,Pa} + 120.0 \tag{7-6}$$

7-5. Pressure Wave Parameters.

a. The recorded time history of a pressure wave, the full waveform, is more important than the single measure of P_P. Other measures, which consider time, and the frequency of varied portions of the waveform are also useful. Particular impacts may require strength or energy measures from the waveform. Environmental Compliance also may require the recording of the pressure wave and the calculation of strength or energy parameters to evaluate metrics provided by resource agencies.

(1) Impulse is the strength parameter of the pressure waveform, which is cited by some researchers as relating to damage. Impulse is represented by the area under the pressure time-history curve. Impulse cannot be properly estimated before the detonation, as there is insufficient research providing a number of cases with details of the site, detonation and procedures. Impulse is the time integral of the recorded pressure waveform and results in units of pressure time, such as pounds per square inch-milliseconds (psi-ms) or pascal-seconds (Pa-s). The impulse is commonly provided by researchers for the entire time history, whether for a single, open-water detonation or a large, delayed shot pattern for rock excavation. The total impulse of the time history is not a useful parameter as it is the action of the impulse over a period of time that is related to potential damage. The smallest sustained negative impulse may be a useful parameter (Keevin and Hempen, 1997) in assessing im-

pacts to aquatic life. This sustained negative impulse expands air-filled organs of aquatic life, causing the organ to burst. The negative impact is more likely important, when it immediately follows a large positive pulse.

(2) Some researchers have recommended that the energy of the pressure time history is an important consideration. The two common measures are Energy Flux Density (EFD) and Sound Exposure Level (SEL). Soloway and Dahl (2014) provide an estimating equation for SEL for single, open-water detonations in shallow water. Neither measure has adequately been provided in literature to estimate the energy measure for excavating rock underwater or removing a submerged concrete structure. Both measures can be digitally assessed from the recorded pressure time history of a recording. EFD may be provided in many different energy units. SEL is provided in decibels (dB) relative to a reference energy level for water. For acoustic studies, SEL is graphically compared to frequency content of the waveform. The total EFD of a time history is not a useful parameter, particularly for a shot pattern with many charges detonated on delays. The few cycles of energy near the resonant frequency of an important structure or structural component or near frequencies damaging aquatic species being protected, or their organs, are the important energy parameter.

b. Measurement of Pressure Waves. The full pressure waveform or overpressure due to underwater blasting may be recorded for processing the variety of overpressure parameters that travel through the water. The waveform may be recorded by two different systems with separate system attributes. When recording of the pressure waveform is required, the chosen recording system must be resolved by its attributes. Both systems could be needed for some projects with broad requirements.

(1) Pressure Transducer Systems. One type of recording system involves a pressure transducer(s) and the amplification of the voltage response to water-borne pressures impacting the transducer in time. The advantages of the transducer system are: very high pressures may be recorded at very high frequencies within the range of the system's flat response; and, multiple sensors may be deployed by cables to the amplifier and recording devices. The primary disadvantages of this system are: its inability to accurately record small peak pressures below 25 psi; and, the system must be connected by cable to the amplifier and recording system and has a limited length of cable, perhaps 700 ft., for very high frequency measurements. The system has a limited recording time dependent on the recording system, which may require careful initiation of the system with triggering of the blast detonation's firing.

(2) Hydrophone Systems. The other type of recording system uses a single or multiple hydrophones with limited cabling from an independent processing/recording system. The advantages of newer hydrophone systems are: the ability to record small pressures over a broad frequency range; and, its compact system that records a single sensor location through a cable to the surface recording device independent of other sensor positions. The primary disadvantages of a hydrophone system are: its inability to record high peak pressures near the blast location; multiple systems must be deployed to record at separate locations; and, accurate clock timing or a timing mark on the records is required between hydrophone recorders to compare hydrophone records, since hydrophones are recorded by separate systems. Hydrophone systems have the ability to record for long periods, yet only a limited recording time is needed to record even a large blasting pattern. Multiple hydrophone locations, may require an advanced start of the hydrophone systems with some timing mark near the triggering of the blast detonation's firing.

c. Field Deployment for Pressure-wave Recording. Monitoring an underwater blast for the pressure waveform is more complex than recording airblast and vibrations on land. The deployed system requires a skilled subcontractor familiar with recording and processing pressure waveforms from underwater blasting. The recording subcontractor may be hired by, but should be independent of, the blasting and general contractors for the site.

d. Pressure Wave Monitoring in Contracts. The contract must detail the overall requirements of the pressure-wave monitoring. Any overpressure limitations on the project must be resolved with permitting or negotiating agencies in advance of developing the specifications. The specifications should detail the following requirements of the pressure-wave monitoring.

(1) Each sensor must have a recent Manufacturer's calibration within the past 12 months. The monitoring system(s) must follow the Navy' requirements for calibration. USACE ETL (1991) provides a useful reference for underwater blast monitoring.

(2) All pressure-wave monitoring systems for the project must have an initiation and sensor comparison check before the first underwater blast to be recorded, with any change of sensors, and after the last blast. The purpose of the check is to both assure the full system properly records at every sensor for the first blast and that each sensor compares well in recording similar pressure amplitudes at varied frequencies. The check should be conducted with all sensors at the same distance from a broad frequency range source, like a blasting cap. Each sensor's processed record should provide peak pressure values that are within 5% at the same time and frequency of all other sensors.

(3) The limits of peak pressure to be applied to the blasting and the distance from the blast or the specific location to apply those limits should be clearly and concisely stated. Other parameters may be cited by regulators. Impulse or energy parameters of the pressure wave must be resolved from processed pressure wave records, well after the blast occurred. Because P_P may be quickly resolved from a record immediately following the shot, estimating a P_P goal consistent with other parameters may be useful to remaining near the other parameter limits being requested.

e. Pressure-wave Propagation and Prediction.

(1) Pressure-wave Propagation. Pressure waves pass spherically from compaction charges or conically from a column charge in a shot hole into the medium that contains the charge. As noted earlier, only the detonation's shock wave produces a pressure wave for a properly confined set of hole in a shot pattern to excavate rock or remove a structure underwater. For a well confined charge, the detonation gases can produce no pressure wave of their own.

(2) Much of the pressure-wave's energy pass into the subsurface when the purpose is removing rock or a massive structure on rock. The energy is attenuated into the subsurface and mostly continues downward. When the structure is a column or pier surrounded by water, particularly when rock is much deeper than the base of the mass concrete, significant amount of energy may be transmitted directly into the water or maybe diffracted through the soil media back into the water.

(3) The pressure waveform that enters the water dominantly remains in the shallow water, regardless of the purpose of the blasting or type of blasting. The waveform in the water can become a channeled wave with low attenuation, when the rock forms the floor of the water body.

(4) Pressure-wave prediction. Estimates of impulse or energy parameters due to underwater blasting for excavating rock or removing a structure underwater are not accurate into 2017. Insufficient pressure-wave monitoring has been conducted on too few projects to develop models for parameters other than P_P. The equations of Table 7-1 provide a means to estimate P_P from a shot pattern's blasting. All the parameters of the pressure wave may be resolved after the blast from the recording of the water-borne waveform

7-6. Considerations for Underwater Blasting.

a. Introduction. For the evaluation of blasting effects in water, there are important aspects of the explosion process and placement of explosive materials for the intended purpose that should be reviewed. As with terrestrial blasting there are two primary elements of energy release that are important in underwater blasting: (1) Brisant energy and (2) expansion of gases within the blasthole that does work on the material being blasted Brisant energy develops from shock of detonation and begins the process of crushing or fracturing the material immediately surrounding the explosive. The increasing pressure from, and expansion of, gases lengthens and expands discontinuities within the surrounding mass. The gas expansion displaces the damaged materials to great distances. As variation in strata, wind, air pressure, humidity and temperature can influence the transmission through air of energy in land-based blasting, analogous variable properties of water can influence the transmission of energy and the way materials and water respond to underwater blasting.

Important underwater blasting parameters include, but are not limited to: types of explosives and their properties; energy releases from underwater explosions -amplitude, duration, frequency, pressure, impulse, EFD; charge weight and explosive gas diameter versus water column depth; unconfined test explosion properties versus confined blasting to perform work; scaling laws of underwater blasting; wave mechanisms - spherical, cylindrical and planar wave propagation; and measuring equipment and its calibration (Keevin and Hempen, 1997).

b. Shock Waves. Detonation produces an initial shock wave in underwater blasting just as in land-based blasting. Underwater shock waves propagate spherically from a compact source producing pressures in the range from 1 to 10 GPa or higher, especially in deep water. The shock wave initially expands rapidly closest to the source with high amplitude with peak overpressure in excess of 15,000 psi and velocity of approximately 5,000 ft/s or many times the acoustic velocity. The amplitude and velocity of the wave decrease independently of each other as the wavefront radius increases. The wave eventually becomes a typical acoustic wave. Although the general phenomena mimic those of conventional land-based blasting, the difference in compressibility between air and water is responsible for greater impacts at further distances in water than are produced by air blast.

(1) Characteristics of material alters behavior of shock waves. Most underwater blasting involves loaded boreholes in the substrate or within a concrete structure. The behavior of waves is related to the characteristics of the media through which they travel or propagate. Waves moving across boundaries of significantly different materials are altered by the angle of incidence between the direction of propagation and the boundary and change through diffraction and reflection. The contrasts between soil, rock or concrete and water are significant enough to alter the wave forms and

reduce the energy from blasting. Oriard (1985) produced a graphical representation between the angle of incidence and the energy ratio of blasts that shows the differences between blasts on land adjacent to water and in material beneath water. Oriard concluded that the energy from blasts not beneath the water or at an extreme grazing angle (nearly parallel to the rock/water surface) transmitted to water would result in wave amplitude about 1/40 to 1/400 of the case where the propagation is nearly perpendicular to the rock/water boundary. He also concluded that the shock wave energy transferred from blasts directly beneath water would range from 30% to almost 40% of the generated energy. The larger the distance from the boundary and the lower the angle of incidence, the lower the shock wave energy will be upon entering the water.

(2) Wave propagation. From the understanding of reflection and refraction, it is evident that the direction of wave propagation is important, as it is in land-based blasting. The intensity of blast energy in water can be altered (reduced or increased) by orienting the detonation and changing the direction of shock wave propagation in both the blasted medium and the water. Detonation typically begins at the deepest point in the blasthole, progressing upward. This results in a somewhat focused release to the water directly above the blasthole. The case of a borehole normal to the boundary maximizes the transmission of the energy to the 37% level. It would be safer to initiate at the top and bottom of the hole to assure detonation of the charge column, but the added advantage is there will be less energy going up the hole toward the water body.

c. Expansion of Gases. As is the case with land-based blasting, the detonation results in the production of hot, expanding gases that radiate outward in the wake of the shock wave. Unlike blasting in air, or at least in dry holes, however, the presence of water in the vicinity results in water vapor from the heat being released. This adds to the other gases from the ignition phase. This combination produces a small hot and pressurized bubble that expands against the confining pressure in rock. Once the gas exits the substrate, only the hydrostatic pressure of water contains the gas volume.

(1) The gas phase of the detonation must be well confined to provide the effective work of displacing the mass toward the free face. While performing this displacement work in the confined condition, the gases are cooled and disseminated into the water rushing into the opening as the medium displaces out past the prior free face. The loss of energy, the cooling of the gases, and their dissemination into the water as small bubbles do not allow the escaping gases to act as an energetic, oscillating single volume, like a detonation suspended in water.

(2) When the gas vents to the water after displacing the rock in underwater blasting, the gases form a myriad of low energy bubbles rising to the surface. When there is a lack of confinement, the gas production will exit at high velocity, or rifle, out of the top of the shot hole or from any fractures or flaws of the medium being shot. The lack of confinement may be due factors such as weakened or degraded portions of the rock mass, loading of shot holes that have no sound rock, loading holes above the top of sound rock, poor stemming material, rock discontinuities, improper stemming placement, as well as other less common causes. Shot holes that rifle ejecta produce little or no mass displacement and contribute a great deal of energy into the water column. These rifling holes cause high amplitude overpressure waves to enter the water column. Even the occasional rifling of an underwater hole produces extremely adverse pressure waves. Rifling or otherwise unconfined detonations do not displace the medium and do not produce much vibration at surrounding structures.

Overconfined shot holes produce adverse vibrations, but contribute little energy as pressure waves into the water body.

(3) For unconfined detonations with very shallow water, the escaping gas may vent at the air-water surface as a columnar gas plume with a very loud airblast as with unconfined terrestrial blasting.

(4) At greater water depths the gas bubble from an unconfined detonation, like an open-water charge, does not immediately breach to the air/water surface, but may undergo cyclical oscillations as it rises toward the surface. The gas bubble oscillations may be as significant as those from open-water detonations. In deep water the gas bubble may have many oscillation with smaller pressure-wave amplitudes with each succeeding oscillation. Yet for projects in shallow water vented gas may have only a few oscillations. The oscillations for deep, open-water detonation have the following mechanics.

(5) Transmission of shock by the expanding gas volume to the water depletes some of the energy within the bubble. The gases continue to expand and the bubble continues to grow in size. This expansion continues to push the water outward in a radial direction, also aided slightly by afterflow from the passage of the shock. At a critical point the inertia of the radial flow causes the bubble to over expand to a level where the internal gas pressure is exceeded by the local hydrostatic pressure, and then the cooled gases are no longer in dynamic equilibrium. The vertical rise of the bubble slows as the bubble's volume increases. Cole (1949) and Bjarnholt (1978) describe the limiting controls on the size of the expanding gas bubble. This phenomenon establishes an oscillation of the bubble over-expanding and overcontracting, as the bubble volume rises.

(6) The bubble collapses to a much smaller size, but has several times the volume of the original solid or liquid explosive material. The bubble accelerates in its vertical rise, as the bubble contracts. As the bubble collapses in size, inward flow continues. The inward compression builds before the bubble over-compresses and again produces an outward pulse. The resulting outward shockwave from this over-compression is significant, but much less than the initial shock because there is no chemical energy release of expanding gases at this stage.

(7) The cycle is repeated, each time with energy losses from friction and dissipation, until either the bubble vents to the air/water surface or the pulsation essentially stops from lack of energy (Mellor, 1986). The size and associated energy of the bubble in its oscillation is a function of the number of cycles that occur between detonation and when the bubble reaches the water surface. Cole (1949) reported the energy of the cycles is reduced such that after the first oscillation the bubble has only 14 percent of its total initial energy and after a second oscillation the energy is reduced to less than 8 percent.

d. Effects of Temperature, Pressure/Depth and Salinity. Beyond the zone of overpressurization, where the energy wave from the blast behaves as an acoustic wave, the character is more susceptible to variables of temperature, pressure and salinity. Acoustic velocity in water increases in direct proportion to increases in temperature, pressure and salinity. This becomes a consideration particularly in seawater, where zones or stratification may occur with varying salinity and temperature, and where depth may also vary significantly near an area of blasting. In areas where temperature and depth of water are influenced by tides and length of solar heating, the acoustic velocity will vary diurnally, particularly at shallower depths.

(1) Whether or not discreet strata develop in the water column, acoustic waves will be refracted by water with varying properties, influencing the velocity of the wave front. Rays representing direction normal to the wave in the direction of propagation refract such that they are bent downward in instances where the velocity increases toward the air-water interface; i.e., as the wave moves up in the water column, its velocity is directed more and more horizontally. It is possible in deep enough water for the wave to refract enough that the direction trend eventually reverses and moves downward at great distance from the source. If that distance is not reached, and the ray normal to the wave reaches the water's surface the wave will be reflected. At the radial limit of surface reflection a shadow zone develops that is not traversed by the pressure wave.

(2) The terms shallow and deep water as they pertain to blasting may be defined by varied considerations. Shallow water may be thought of as water of depth insufficient for the development of a gas bubble, if the detonation was not contained by a sound material. Shallow water may be related to temperature and seasonal water stratification. Shallow may be compared to Natural Resource habitat depths, food source depths, or other species related depths. Shallow or deep may refer to depths of adverse impacts. Shallow may be related project issues. The designation of shallow or deep for underwater blasting has little importance. Typically, projects with water depths around 60 to 75 ft. or less are considered shallow. Projects that require blasting beneath more than 500 ft. of water may be considered deep.

e. Effects of Reflections at the Air-Water Surface. A primary impact for organisms containing air volumes in their organs are the inversions of pressure waves due to the pressure wave's reflection at the air-water surface. As stresses cannot be passes into air from water, the compression amplitude is converted from compression to tensile waves of equal magnitude up to the tensile capacity of the water. This inversion causes the extreme pressure rises of blasting to be converted to tensile waves, usually of a much lower truncated tensile (negative) amplitude near the detonation source.

(1) Natural resource impacts may occur due to tensile wave development. This tensile wave causes expansion of air-filled organs after being sharply compressed. If the duration of the tensile wave is long enough, the frequency having some match to the resonant frequency of the air-filled organ, then air in the organ will rapidly expand beyond the organ's ability to contain it, rupturing and damaging surrounding organs. Keevin (1995) noted damage to fish from a single, open-water shot was due solely to expansion (not compression) of air-containing organs where the amplitude and duration of the tensile wave from reflection of the pressure wave off the air-water surface caused the damage. The extent of the tensile wave's impact due to the reflection can produce morbidity and mortality in the organism impacted. Minor effects on structures may also be caused by these tensile waves.

(2) A similar effect to the tensile wave can produce spalling of concrete. Spalling occurs due to the expansion of air bubbles in shallow cracks close to the surface of the concrete exposed to underwater tensile waves. Spalling rarely has a structural impact, but can lead to maintenance concerns that short the useful life of the structure.

f. Effects of Ice. Ice may have a greater effect on underwater blasting related to its impacts on drilling than on the blasting itself, but all its effects can be difficult to quantify. Ice may also significantly impede navigation that is required to locate the overwater plant and equipment involved. For thick enough ice and sustained low temperatures drilling may be possible without need of boats or barges to drill, and the ice may be sufficient to remain intact following blasting. It is clear that an intact ice cover would more efficiently reflect shock waves. Even intact ice has properties that are variable and will likewise alter the manner of wave transmission. Among the more important variables would be thickness, temperature/hardness, constituents of the ice, whether or not there is snow on it and air entrainment. In general, ice will dampen and diminish surface waves or eruptions of gases, and even noise that may or may not be of importance to the project. Because the initial shock and the expansion of gases are responsible for the bulk of the work done by blasting, the presence of ice may be of minor significance to blasting compared to other aspects.

g. Effects of Charge Placement and Confinement.

(1) A confined detonation for excavating rock underwater or removing a submerged concrete structure causes the detonation's shock wave to be dominantly passed into the rock or massive structure, greatly reducing the Brisant energy from entering the water. Being confined the detonation product's gases produce work in displacing the rock or concrete, which eliminates any pressure wave from the gas phase. The pressure wave entering the water from excavating rock underwater or removing a submerged concrete structure is greatly reduced. The waveform that does enter the water does not attenuate greatly as an expanding cylindrical (channeled) wave in shallow water. Proper confinement will produce less adverse impacts than a similar, but poorly confined, shot. Overconfinement of charges will prevent successive rows of shot holes from breaking the mass to the full depth and will increase vibrations received at surrounding structures. If the explosive materials are underconfined, then the detonation gases will escape before performing productive work and will increase peak pressure amplitudes in the water.

(2) The founding media of the structure being removed may affect the pressure wave entering the water. If the structure is massive and founded on rock, a great amount of the shock energy will be passed into the foundation and not enter the water at any point. If the structure is founded in soil or pile-founded, some of the detonation's shock energy will be diffracted into the soil and into water above the soil.

(3) Blasting for removal of a column or pier or caisson, which is surrounded by water, is an intermediate case between open-water detonations and blasting for excavating rock underwater or removing a submerged concrete structure. Estimates of the pressure parameters for water-surrounded structure may be less accurate. Recording of the pressure wave should be conducted, if pressure parameters need to be resolved.

(4) The explosive materials must be confined by stemming in the shot holes for either excavating rock underwater and removing a submerged concrete structure, or for removal of a column or pier or caisson, which is surrounded by water. This confinement will both properly work on the rock or structure and have a considerable reduction in water pressure, compared to charges that are detonated directly in the water. Where reasonable effort is made to stem the blastholes and to keep the charges well below the hole collars, the water pressures will often be reduced by a factor of 3 to 5, compared to charges suspended in water. However, if underwater demolition is to take place, such as the removal of concrete or steel sections, there may be very little stemming in the holes, no stemming at all, or the charges may be simply attached to the structural exteriors where they are in direct contact with the water. In these latter cases, estimated water pressures should be similar to charges

suspended in open water. The same would be true for those cases where large charges are laid on a rock surface at the bottom of the water body in preference to placing the explosives in drilled holes confined by stemming. Water pressures for any blasting where the charge is exposed directly to water produce the same pressure waves as those for charges suspended in open water.

(5) Some blasting contractors working on certain types of blasting projects, such as cross-country trenching operations, may wish to detonate long lines of charges simultaneously. This procedure might be used to cross a water body, where the charges are placed on the bottom rock surface in open water or in drilled holes below the water. The practice of charge placement on the rock surface should be prohibited. For placement in drilled shot holes, the maximum charge weight per delay with the simultaneous firing will cause extreme estimates of peak pressure. Like vibrations from land-based blasting of simultaneous shot holes, the maximum charge weight per delay may be estimated as the amount of explosives in a portion of the line that is approximately equal to the perpendicular distance between the simultaneous shot hole line and the location for estimating peak pressure.

(6) Contractors may wish to load underwater blastholes to the hole collars, which must be prohibited. There may be the confused incentive that the cost of additional extra explosive materials loaded into the full hole depth compared to the use of proper stemming will more productively displace the rock at a lower cost. Blasting without confinement from stemming causes greatly lessened work by the explosives materials and produces rifling of the detonation products into the water, which in turn produces large increases of peak pressures.

(7) Blasting Delay Pattern. For loaded shot holes in underwater blasting, the number of holes and choice of delay pattern is similar to land-based blasting. Properly selected delays will effectively excavate rock or remove the portion of the structure that has loaded shot holes. Proper delay selection will also lessen all adverse impacts. Delays between rows that are too long may lead to under-confined charges, if the burden and delay timing are not adequately designed. When the delay periods between charges contribute to poor confinement, the shock wave or excess gas release may cause greatly increase peak pressures without doing the intended work. When the burden and delay periods between rows are mismatched to cause excess confinement, less breakage will occur in the later rows of the shot and excessive vibrations will be produced.

(8) Delays between rows for underwater blasting should have at minimum 25 milliseconds of delay time. In-row delays should be a minimum of 9 milliseconds between holes. Delays may be adjusted for better production, as long as no prescribed limits are exceeded or other damage is noted.

(9) The initiation point for simultaneously detonated shot holes will have a varying impact close to the ends of the shot holes and offset from the shot holes along their length. The peak pressure amplitudes will be: lowest near the initiated end of the simultaneously detonated row of shot holes; moderate offset from the line of shot holes; and, greatest near the end concluding the detonation.

(10) Detrimental Compounds. Blasting products can leave detrimental compounds in the water after blasting. These detrimental compounds may be of concern for drinking water supply or Public Use of the water body or for a potential harm to aquatic species. Blasting Agents have been selected to lessen manmade compounds for reducing aquatic species' impacts such as replacements to ANFO, where the fuel oil components (FO) was a replaced with a citric product.

7-7. Natural Resource Considerations.

a. Impact Assessment. A number of Federal laws require coordination with Federal regulatory agencies (i.e., U.S. Fish and Wildlife Service and National Marine Fisheries Service) and natural resource impact analysis of projects requiring blasting. For example, the National Environmental Policy Act, Endangered Species Act, and Marine Mammal Protection Act all require interagency coordination and environmental (natural resource) impact reviews. Current listings of species covered by the Endangered and Threatened Species regulations may be obtained by reviewing 50 CFR 17.11 and 17.12, which is updated daily whenever species are added or removed from the listing.

b. State Permitting. In addition, many states require permits for use of explosives (Keevin, 1998). Many of the state natural resource reviews are extensive. For example, in Oregon, for in-water blasting projects, the blaster is required to provide information concerning projects impacts and proposed mitigation measures, including fish and wildlife species that occur in the blast area and predicted effects of the blasting on those species; fish and wildlife habitat within the affected area and the predicted effects of blasting on those habitats; estimated distance of impacts and area affected; and measures that the blaster (before and after construction) will use to prevent injury to fish and wildlife and their habitats, including an analysis of their effectiveness under the environmental conditions at the project site. This Oregon-state analysis is comparable to an impact analysis conducted under Federal laws.

c. Mechanism of Impacts to National Resources. Blasting in water presents unique natural resource problems. Blast overpressures in water do not attenuate as rapidly as in the atmosphere and can cause injury and mortality to aquatic organisms at much greater distances than in air (Keevin and Hempen, 1997). Blast overpressure is the sharp instantaneous rise in ambient pressure resulting from an explosion. Occupationally, it is also described as high energy impulse noise. Blast-induced injury is traditionally divided into three broad categories (Elsayed, 1997; Lavonas, 2000).

(1) First, primary blast injury may be caused by the direct effect of blast overpressure on the organism. Air is easily compressible by pressure, while water is not. As a result, a primary blast injury almost always affects air-filled structures such as the lung, ear, and gastrointestinal tract of water-submerged species. Some species, such as birds or mammals, in close proximity to the blast may be impacted by the air-borne wave.

(2) Second, blast injury may be caused by flying objects (flyrock) that strike an organism.

(3) Third, blast injury may occur when an organism in transit is impacted due to alarm, e.g., a bird in flight. For the purposes of impact analysis, each of these three broad categories should be considered although primary blast injury is usually of greatest concern. Generally, primary blast injury has the greatest impact on water-submerged organisms for blasts within, below, or near the water body. However, organisms on the water surface, on and beneath the land surface, and in flight may also need consideration for blast impacts.

(4) Blast overpressure also attenuates rapidly in air (Mellor, 1985) and terrestrial organisms have to be very close to the blast to suffer primary blast injuries. Generally, it is possible to establish

"safe zones" for terrestrial organisms. If organisms are within a predetermined area, the blast can be put on hold until the organism moves from the area. Blasting contractors are often required to restrict the overpressure from blasting to protect structures. This has an added benefit of protecting terrestrial organisms. For example, a 133 dB level is a standard safety level established by the U.S. Bureau of Mines (Siskind et al., 1980) and this same level is required in USACE EM 385-1-1 (2014): Safety and Health Requirements Manual. These levels are far below levels responsible for mortality (i.e., 20 psi or 196 dB for birds [Damon et al. 1974, as reviewed in O'Keeffe and Young, 1984; Yelverton et al., 1973]) or injury in terrestrial organisms. Blasters routinely calculate "structure safe zones" that can be applied to terrestrial organism "safe zones." Disturbance (i.e., harassment, scaring) of terrestrial organisms by explosions remains a potential problem. Larkin et al. (1996) provide the best literature review on the effects of noise on terrestrial wildlife, available at URL: http://nhsbig.inhs.uiuc.edu/bioacoustics/noise_and_wildlife.txt

d. Blasting Effects on Natural Resources on USACE Projects.

(1) Explosives have been used both near water and underwater by the Corps of Engineers for structure demolition; channel and harbor construction; channel deepening; navigation obstruction removal; and pipeline trench crossings of lakes, rivers, and streams. The potential for injury and mortality to aquatic organisms resulting from underwater blasts has been well documented (Lewis, 1996; Keevin and Hempen, 1997). The assessment of project impacts requires a thorough understanding of the natural resource effects of underwater explosions. The literature on blasting effects is often published in obscure journals and governmental reports and is difficult to gather in a timely fashion by environmental planners and resource managers attempting to practice good stewardship of the Nation's water resources. Currently, four publications summarize the literature on the natural resource impacts of underwater explosives use on aquatic organisms: Keevin and Hempen (1997), Lewis (1996), O' Keeffe and Young (1984), and Wright (1982). Lewis (1996) and Keevin and Hempen (1997).

(2) Although a considerable amount of information is available on the natural resource's effects of underwater explosions, there are still major data gaps that require further research (Keevin et al., 1999). Some explosives use projects may require some level of basic research before blasting can proceed.

e. Blasting Effects on Aquatic Species.

(1) Several considerations occur with respect to blasting impacts upon aquatic species. Social and political perceptions of a project that will impact aquatic life may be serious enough to stop a project. More state agencies are assigning greater socio-economic value to aquatic species of fish and especially mammals. Even where blasting is not expected to impact threatened or endangered species, there will likely be a requirement to assess and mitigate impacts to any aquatic life. There may be situations where replacement for fish kills is unacceptable to the public, recreational or commercial interests, and mitigation by replacement of fish will not be adequate by itself.

(2) Threatened or endangered species requirements to avoid harm to the species' population(s) may be disruptive to the schedule, may cause procedural changes to the blasting, may require additional mitigation measures, and usually requires environment or physical monitoring of the blasting.

(3) Pressure-wave impacts upon aquatic species or the general public from underwater blasting is based upon submerged delay timing (delay times should be greater than 25 milliseconds between the nearest holes of adjacent rows), maximum submerged charge weight per delay (maximum total charge weight within the shot pattern within any 25 millisecond interval over the total delay period), and CRSD.

(4) Pressure-wave Parameters for Evaluating Natural Resource Impacts. The literature cites peak pressure, impulse and energy measures, often associated with frequency, for mortality or morbidity or specific organ damage to varied aquatic organisms. Peak pressure is the only parameter that may be estimated approximately. Impulse and energy parameters cannot be assessed for the first few shots of a project's underwater blasting. After several shots have properly taken pressure-wave records, impulse and energy measures may be approximated for future shots, when the structure or organism, geologic environment, and blasting procedures remain similar.

7-8. Mortality Modeling.

a. Predictive mortality models give an approximation of the injury or kill radius of a given explosive charge (Hempen and Keevin, 1995). Mortality models are useful for bounding the mortality radius and are good first-order tools to make assessment of natural resource impacts due to submerged explosions. Such model predictions are extremely useful to natural resource managers in assessing the potential impacts from a proposed project. Modeling does require blast design information (i.e., charge size, delays) that is required as model input. Based on the quality of the aquatic resource(s) in the blasting area and predicted impacts, it is possible to make rational decisions concerning compensation (in the case of fish), or concerning the use of appropriate techniques to mitigate impacts (Keevin, 1998; Keevin and Hempen, 1995, 1997).

b. Injury/Harassment Modeling. Under both the Endangered Species Act and Marine Mammal Protection Act, harming or harassing species is considered a "take." Regulatory agencies often provide criteria levels (i.e., peak pressure, SEL) for the taking of protected species involving injury or harassment. The goal is normally not to exceed these levels at various distances from the blast. The criteria are evolving at the time of preparation of this EM. Therefore, coordination with the U.S. Fish and Wildlife Service and/or the National Marine Fisheries Service is critical during the early project planning phases of projects requiring underwater blasting. Items to take under consideration when evaluating injury or harassment of species include:

(1) Explosives in open water that are not contained completely by rigid structures will produce both higher amplitude and higher frequency shock waves than contained detonations. Thus, the use of blasting in structure demolition or rock removal will result in lower aquatic organism mortality than the same explosive detonated in open water.

(2) The variation between open water and contained detonations is important because most mortality models were developed using open water shot data that will overestimate demolition or embedded shots' impacts. For example, Nedwell and Thandavamoorthy (1992) compared the pressure time histories from the detonation of small explosive charges in both free water and embedded explosions. They found that the impulse of the water-borne shock wave following the detonation of an explosive charge embedded in a borehole was about 30% of that occurring for the same charge at the same distance, when it was freely suspended in water. The peak pressure value resulting from the

confined charge was reduced to about 6% of the peak pressure from the same size charge detonated in open water. The 30% value has been widely accepted by the international blasting industry and was used in the development of their “Guidelines for the Safe Use of Explosives under Water” (Marine Technology Directorate Ltd., 1996). The user should review carefully how the mortality models were developed and modify them for embedded shots, if necessary. There are many variables not fully developed by Nedwell and Thandavamoorthy (1992) that affect the water-borne wave’s parameter for contained detonations.

7-9. Mitigation Planning.

a. Development of effective mitigation strategies requires two components: a working knowledge of explosives and their impacts, and information on viable mitigation techniques related to explosives. Lewis (1996) and Keevin and Hempen (1997) provide information on the effects of underwater explosions. Keevin (1998), Keevin and Hempen (1997) and Jordan et al. (2007) provide comprehensive reviews of mitigation techniques.

b. Introduction. Keevin and Hempen (1995) developed a tiered mitigation approach for fish that is modified here to include sea turtles and marine mammals, based on: (1) the blasting design; (2) biological criteria; and, (3) use of physical mitigation features. Each tier requires progressively more mitigation measures to avoid impacts to aquatic resources. The tiered mitigation planning process will require a cooperative spirit between the blaster and natural resource agencies.

c. Tier I Mitigation Planning. Tier I Planning involves the development of a blasting design by the explosive engineer who attempts to reduce or limit the amount of explosives being used. It also involves an assessment of potential natural resource effects, based on the existing aquatic resources in the blast area (this may involve survey work) and mathematical mortality modeling by natural resource personnel. An initial coordinated effort is required between the blaster and the natural resource agency.

(1) Blast design parameters that are considered for Tier I Planning:

(a) Evaluate the need to use explosives. If practical alternatives are available, use non-explosive techniques.

(b) Plan the blasting program to minimize the weight of explosive charges per delay and the number of days of explosive exposure.

(2) Biological parameters that are assessed for Tier I Planning:

(a) Evaluate the quality of the aquatic resource based on existing information. If there have been no previous resource surveys of the blast area and there is reason for natural resource concern, require or conduct the survey. Based on the quality of resources, make a decision concerning magnitude of potential impacts.

(b) Conduct mathematical mortality modeling to determine potential aquatic impacts. Based on predicted impacts, make a rational decision concerning compensation (for fishery resources), or use of other mitigation techniques.

d. Tier II Mitigation Planning. Should the development of an explosive design and environmental assessment of potential impacts result in a determination that "important" aquatic resources are at risk, then Tier II Planning should be implemented. Tier II blast design mitigation measures involve the use of delays, stemming, decking, etc., to reduce water-borne shock waves entering the aquatic environment. Many of these types of features would be part of good explosives design to reduce peak overpressure or ground vibration. Biological parameters include such measures as seasonal blasting limits to avoid spawning fish, large migrations, or periods of larval drift.

(1) Blast design parameters are considered for Tier II Planning:

(a) Use adequate lengths of angular stemming material in drill holes to reduce energy dispersal to the aquatic environment.

(b) Subdivide the explosives deployment using delays to reduce total pressure. Carefully consider detonating cord in the firing system, as greater mortality could result.

(c) When possible, use decking in drill holes to reduce total pressure.

(d) Use shaped charges for surficial charges to focus the blast energy, thereby reducing energy released to the aquatic environment during demolition.

(2) Biological parameters are assessed for Tier II Planning.

(a) Recommend the presence of an agency observer with authority to resolve revised blast parameters, or to halt blasting or require the use of mitigation techniques if mortality is excessive based on predetermined mortality levels.

(b) If applicable, limit the season of explosive use to avoid major migration periods, spawning seasons, spawning beds, or larval drift.

(c) If there is a concern with migrating fish, use sampling techniques (e.g., hydroacoustics) to avoid impacting large congregations.

(d) Blasting can be planned during time periods of low sea turtle or marine mammal abundance.

(e) Aerial surveys can be conducted before and after detonation. If sea turtles or marine mammals are observed, detonations can be delayed until they have left the area (Jordan et al., 2007).

(f) Use non-explosive scare techniques to move organisms from the immediate blast zone.

e. Tier III Mitigation Planning. Should there still be environmental concerns after Tier I and II planning efforts, Tier III measures can be employed. If important commercial or sport species are being impacted, there is always the option to give monetary compensation for fish losses based on replacement values developed by the American Fisheries Society (1992, 1993).

Threatened and endangered species can present special problems with regulatory permitting requirements. Bubble curtains or other physical barriers can be used to avoid mortality of these species (Keevin and Hempen, 1997). If injury or mortality is excessive, based on predetermined mortality levels or observation, state, or Federal fish and wildlife agencies can require compensation for fishery resources.

7-10. Damage Prediction, Prevention and Control and Monitoring.

a. Impacts of Underwater Blasting. The optimized blasting design will maximize intended production, while minimizing adverse impacts. Some consequences of blasting may be considered to have no immediate consequence, yet these consequences may have long term or unforeseen impacts at a later date.

(1) Minor impacts, those deemed of little or no significance, may be the easiest to assess first and either dismiss or make minor adjustments to mitigate. Among the minor considerations may be the particle size distribution of the displaced material from blasting. In some cases there may be concerns for the production of fine-grained materials that might cause secondary impacts or degradation of habitats. Associated with these might be short and medium-term considerations for turbidity. Even the use of containment measures, such as blast mats and turbidity screens, are not extremely effective in limiting the spread of fines within water from underwater blasting.

(2) Other relatively minor impacts of underwater blasting are of no more significance than with land-based blasting, such as brief sensation of vibration and related noise. Beyond the area where these impacts are outside of tolerable ranges, scheduling the blasts at times when the nuisance effects are minimized may be the best means of mitigation.

b. Mitigation of Underwater Blasting Impacts. Mitigating underwater blasting’s impacts must begin with the comprehension of the structure(s), public use and natural resources being impacted. Many impacts may be mitigated to some extent by the contractor’s adjustment of the blasting program. It is the contractor’s responsibility to reduce the impacts, and this must be clearly cited in the specifications and contract documents. This may require study during the design phase and agreements with Natural Resource agencies on blasting constraints necessary to minimize impacts during construction.

(1) Limitations on Underwater Blasting. Some impacts may not be easily mitigated, but the impacts may be lessened by having seasonal or temporal limitations on the blasting. For example, residential complaints about blasting may be diminished merely by requiring the blasting only on week days at regular times of the day. Avoiding the season of highest population may be the primary means of lessening blasting impacts either for public use or upon aquatic organisms.

(2) Restricting public access or purchasing the fry of an impacted species may be the next procedure to lessen the severity of blasting impacts. Natural Resource agencies usually do not allow frightening of marine mammals to keep them away from the blast zone. Objectionable noise in air for birds or in water for aquatic organisms may be allowed in some cases. Repelling charges immediately before the blast has been allowed at some projects in the hope of causing fish to move from the area.

(3) Controlling the blasting impacts by monitoring may be a more costly means to avoid impacts. Land-based blasting controls vibration impacts upon structures by monitoring. Underwater blasting may require vibration monitoring for structures or hydroacoustic monitoring to control the blasting impacts of pressure waves. The contractor would be obligated to revise the blasting program by whatever means necessary to remain within spec-established limits by amplitude and distance.

c. General Types of Mitigation and Monitoring.

(1) Mitigating measures may include air-bubble curtains, solid walls, or other types of barricades. The decision to use mitigating measures should be made carefully keeping in mind cost and schedule impacts to the project as well as blasting impacts.

(2) For some projects that can tolerate delays, monitoring of the established criteria and beginning the blasting with a test blast program can allow the blasting to be adjusted during the testing period. Such monitoring during the test blast program and the production blasting may show the blasting impacts remain below the established criteria. Those projects that have a designed mitigation may use the cost of the system as “insurance,” in the hope that the migration may not be needed.

(3) For projects that are not tolerant of delays, or where impacts are known to be too high there may be projects where a well-designed mitigating measure is necessary for every submerged blast. Projects with a continuous use mitigation will need monitoring at the beginning of changes to the blasting program, but may be able to avoid continuous monitoring of the blasting program.

(4) Some mitigations for established criteria could be as simple as conducting the blasting when a lake was low or the lake level is drawn below a critical elevation. Some projects may be able to easily create a berm in shallow water that contains the entire area of blasting still in the wet. Such a berm would need some simple design criteria to prevent pressure-wave passage through, or being diffracted beneath, the berm to the adjacent water body. A berm will not be effective when it is not founded on rock, unless some other features are added to create a boundary within the soil beneath the berm.

(5) The most expensive procedure for mitigating underwater blasting impacts is the requirement for the contractor’s placement of an attenuation/reflection system for the water-borne pressure waves. These systems, typically called air curtains or air-bubble curtains or bubble curtains or bubblers, may need to be designed before the specifications are completed or during the contracting process or conducted by a specialist/specialty firm under the prime contractor. There are proprietary systems that also perform well. Proprietary systems may be more expensive than a mitigation designed for the project or may not meet the needs of the project for its purpose, site conditions or criteria to be mitigated. Any mitigating device, whether proprietary or deigned for the project, must be monitoring for the established criteria to be mitigated. Any air curtain must be designed for: the specific project and its blasting purpose; the properties of the mass being removed; the water body’s depths, tidal flow, maximum velocity and turbulence; the structures or organisms possibly being impacted and their key impact parameters; and, its target limitations for the key impact parameters. Some systems may be used for a single blast, while other systems may be transported, maintained and repaired for use on programs with many blasts.

(6) Which factors might be of interest depends on the nature of the work and the sensitivity of nearby structures or facilities or organisms, which are being protected. Blasting within a water body, below the water bottom or near a body of water can take place for a number of purposes and involve different types of blasting procedures. Two of the most common activities are undertaken for channel excavation in rock and for the demolition of existing concrete such as bridge piers or portions of existing dams. A closely related situation occurs where there will be an interest in water-borne pulses when the explosives charges are not directly vented to the water. This condition exists, for example, when blasting takes place on a land surface adjacent to a body of water, or in a tunnel located below a body of water. These cases are sometimes of interest relative to marine life. At relatively high pressure levels, there is an interest in the potential for physical injury to marine life. At lower levels, where physical injury would not be possible, there has been some interest in the characteristics of the transmitted sound and the potential of annoyance or disturbance to certain marine mammals such as whales.

d. The Use of Air Curtains to Reduce Water Pressures.

(1) It is well known that it is possible to reduce the pressures in sonic waves in any material including water, air, or solids by forcing those waves to pass through sonic barriers. That is the function of acoustical materials in buildings. The same principles apply to sonic waves in water. The barriers become more effective if their physical properties are far different from those of the water. Experience has demonstrated that well-designed barriers in the form of air curtains are easily constructed, moderately expensive, and fairly effective in reducing water pressures. The greater the air fraction to water and the smaller the bubbles in size for an air curtain, the greater will be the reduction in water pressure (Hempen, 1993). The air fraction needs to be at least 3% and the orifice diameter creating the bubbles should be smaller than 1/8-in. It is common to note a reduction in pressure-wave amplitude by a factor of 10 or more for an effective air curtain.

(2) An air curtain must be properly designed for: the project requiring blasting, the submerged medium to be blasted, the founding media’s (soil, pile-founded, or rock) properties, the water depth and its variability through the blasting project, and the established criteria to be mitigated. Only a previously successful designer of an air curtain system should develop the components of an air curtain.

(3) A few useful references are available as of March 2017 that cover the breadth of air curtain system design.

- Oriard (2002), which is often cited for varied blasting information, provides some useful information concerning air curtain system. Use this reference carefully, as some of its material is outdated and now incorrect.
- CalTrans (2017) provides very useful air curtain data and the monitoring of air curtain mitigation of pier removals for natural resource concerns in San Francisco Bay.
- The Navy has a very useful report on the testing of an air curtain for open-water (suspended) detonations, which should be available in 2017.

e. Monitoring of Underwater Blasting

(1) Monitoring during blasting involves both the use of instruments to detect and quantify physical impacts of blasting and the observations made by personnel on hand, or the visual monitoring of blasts either by witnesses or video recording. The latter is far more effective in discerning the need to make adjustments in land-based blasting, because the blast and its after effects are far more readily observable. The audible evidence, displacement immediately following detonation, and the manner in which materials are thrown is much easier to see on land. The color and quantity of gases released are also much more evident in air. Water's dampening of acoustic waves and turbidity impair our abilities to use our own senses to assess the blasts. Underwater blasting may include a greater reliance upon measurements of parameters by instrumentation and data collected from the water.

(2) Measurements taken of water-related parameters (turbidity, dissolved oxygen content, temperature, constituents of concern, etc.) in pre-blast surveys should be included in the monitoring during blasting or immediately following blasts.

(3) Monitoring during blasting should include the same kinds of measurements as with land-based blasting, and also may include hydroacoustic measurements of pressure waveform at locations for aquatic species and/or sensitive structures. The pressure waveform analysis of each blast should assist in modifying the layout and design parameters of the blasts to lessen the blasting impacts.

(4) In cases where sensitive species of concern, be they commercially significant or designated as Threatened or Endangered, it may be necessary to develop a hydroacoustic monitoring plan. The plan should assess a pressure-wave parameter, which will be monitored to assure the blasting remains below the defined limiting value without harm to the species. In some cases it may be possible to physically displace the species with seines or nets that does not harm them or their habitat. In others, there may be ways of protecting them near the shot pattern with mitigation measures. The mitigation procedures would need to be monitored to assure that adjustments to either the blasting itself or the mitigation procedure remained below an established limiting value of a hydroacoustic parameter.

(5) In addition to measures related to species of concern, it may be useful to monitor impacts on other species by conducting population assessments prior to blasting and surveying mortality after blasts. Mortality is difficult to evaluate accurately. Such population assessments should relate a hydroacoustic parameter, which is being monitored, to mortality of the determined population.

7-11. Design of Underwater Blasting.

a. Introduction. The means and methods that will optimize underwater blasting are important to consider more so than with land-based blasting, because the relative costs are higher for underwater blasting and the movement or removal of blasted material is more difficult. It is also far more difficult and expensive to make corrections and perform supplemental blasting underwater than on land, let alone discern the causes for deficiencies or identify the areas where there is a need to perform additional blasting. Lastly, the public use and natural resource impacts of underwater blasting are more difficult to assess, control and mitigate. It is far easier to control access and monitor wildlife in the vicinity of land-based blasts than it is underwater. The impacts from blasting are far easier to evaluate on land than it is underwater, because we move about and breathe freely on land and are limited in our ability to do so underwater.

b. Optimized Blasting. The primary goals of optimized blasting are similar to those of controlled blasting, but the terms are not synonymous nor mutually exclusive. Optimized blasting includes many elements of controlled blasting with minimizing overbreak, being perhaps the most important. Optimized blasting also includes minimizing blast energy in order to reduce the impacts to the surrounding media, i.e., the substrate beyond the limits of desired excavation, and reduce impacts (shock and pressure pulse) in the water surrounding the area to be excavated.

(1) Shock Energy and Charge Weight. In order to optimize underwater blasting, the shock energy should be reduced and the charge weight increased. This may be intuitively contrary to the assumption that greater shock energy is required to crush or fracture material (rock, concrete, etc.) under the additional confinement of water, but the same confinement and reflective characteristics of water on the energy make it possible for less shock energy to perform the same amount of work, in combination with the confined gas energy released during the combustion phase. It is the rapid release of high shock energy and its transmission that is more responsible for undesired damage to structures and injuries to aquatic life, so minimizing this phase minimizes unintended collateral damage.

(2) Stemming. When a blast occurs in a medium underwater the gas energy is released directly above the blast to the water, as discussed above. Premature venting of the expanding gases from a blast diminishes the effectiveness of the blast and releases excessive amounts of energy to the overlying water body. Stemming is necessary in the design of a blast in order to control and contain the energy and maximize its effectiveness.

(a) A source of large boulders in any type of blasting is the stemming zone. In surface applications, where flyrock and noise are always a great concern, stemming depths of 0.7 times the burden to 1.1 times the burden are commonly used to control flyrock and noise. When blasting under 10 or more feet of water, the water itself acts to pressurize the stemming material and the water helps to contain and control both flyrock and noise. For this reason in underwater blasting less stemming distance may be used than for land-based applications, typically the tamped stemming depth is 5. times the diameter of the shot hole from below the top of firm rock or concrete.

(b) It is common practice in deep underwater blasting to reduce the amount off stemming to approximately 0.25B in deep water. This stemming reduction allows higher explosive loading in the rock that will better shatter the collar area and reduce boulders. The water above the shot will keep flyrock from occurring and keep noise at reasonable levels.

(c) If impulse is of concern, then the stemming should be 1.0B and 0.7B. The stemming material should be 0.25- to 0.375-in. crushed stone. Larger stemming distance may reduce impulse but increase fragmentation size in the collar area.

(3) Blasting Parameters. Some parameters used in designing underwater blasts are the same as those used in land-based blasting; however, the relationships between them are different because the differences between air and water. Other design variables are different and these will be addressed in this chapter.

c. Underwater Blasting Design Guidance.

(1) Underwater blasting is commonly used for river crossings, harbor deepening projects, water intake structures, and reservoirs, and for other construction applications. Water depths may range from a few tens of feet up to approximately 200 ft. It is common in river crossings and harbor deepening projects to do blasting routinely in water 35 to 55 ft. deep.

(2) Blast Design for Underwater Blasting. In underwater blasting, hole diameters are generally less than 4½ in. Conservative burden and spacing values are used to ensure that the proper rock fragmentation is achieved to make easy digging of the broken rock. The methods previously discussed for determining burden and spacing for bench blasts also apply to underwater blasting. The powder factor for underwater blasting is commonly approximately 2 lbs per cubic yard of material blasted.

d. Underwater Blasting Equations.

Burden:

$$B = \left(\left(\frac{2*SG_e}{SG_r}\right) + 1.5\right)De \qquad (7\text{-}7)$$

where:

B = Burden in feet;

SG_e = Specific Gravity of explosive

SG_r = Specific Gravity of rock;

De = Diameter of explosive in inches

Stemming length (minimum for impulse control):

$$T = 0.7B \qquad (7\text{-}8)$$

where:

T = Stemming in feet

B = Burden in feet;

Subdrilling:

$$J = 0.7B(min) \text{ to } 1.0 * B \qquad (7\text{-}9)$$

where:

J = Subdrilling in feet

B = Burden in feet;

Spacing:

$$S = \frac{(L+7B)}{8} \qquad (7\text{-}10)$$

where:

S = Spacing in feet

L = Bench height in feet

Volume:

$$Vol = \frac{(B*S*L)}{27} \qquad (7\text{-}11)$$

where:

Vol = volume of blast in cubic yards

B = Burden in feet

S = Spacing in feet

L = Bench height in feet

Powder Column:

$$PC = L + J - T \qquad (7\text{-}12)$$

where:

PC = Powder Column in feet

L = Bench height in feet

J = Subdrilling in feet

T = Stemming in feet

Loading Density:

$$de = 0.3405 * SG_e * De^2 \qquad (7\text{-}13)$$

where:

de = Loading Density, in pounds per foot of borehole;

SG_e = Specific Gravity of explosive

De = Diameter of explosive in inches

T = Stemming in feet

Explosive per hole:

$$Exp = de * PC \qquad (7\text{-}14)$$

where:

Exp = Explosive per hole in pounds

de = Loading Density in pounds per foot of borehole;

PC = Powder Column in feet

Powder Factor:

$$PF = \frac{Exp}{Vol} \qquad (7\text{-}15)$$

where:

PF = Powder Factor in pounds per cubic yard

Exp = Explosive per hole in pounds

Vol = volume of blast in cubic yards

Timing along the Row:

$$tH = TH * S \qquad (7\text{-}16)$$

where:

tH = Timing along the row, delay time in miliseconds – 9 ms min

TH = 1.6 ms/ft

S = Spacing in feet

Timing between the Rows:

$$tR = TH * B \qquad (7\text{-}17)$$

where:

tR = Timing between the row, delay time in miliseconds – 25 ms min

TR = 5.0 ms/ft

B = Burden in feet

Anticipated Airblast for Confined blasts, submerged in water less than 10 feet in depth. For water greater than 10 feet in depth there is no anticipated airblast:

$$POP = (0.61 * CRSD)^{-0.96} \qquad (7\text{-}18)$$

$$CRSD = \frac{R}{(W^{1/3})} \qquad (7\text{-}19)$$

where:

POP = Peak Overpressure (USBM) in psi

CRSD = Cube root scaled distance

R = Distance from closest blast pattern's shot hole, in feet, to the location of interest

W = Maximum Charge Weight, in pounds, per delay (with a minimum delay of 9 ms)

Peak Overpressure, in decibels referenced to air:

$$POP_{dB} = 20 * Log * \left(\frac{POP}{2.9*10^{-9}}\right) \quad (7\text{-}20)$$

where:

POP_{dB} = Peak Overpressure in dB referenced to air

POP = Peak Overpressure (USBM) in psi

Anticipated Vibration of Peak Particle Velocity (PPV): (see Chapter 8, Section 8-8)

Peak Particle Velocity:

$$PPV = 50\left(\frac{R}{W^{0.5}}\right)^{-1.15} \quad (7\text{-}21)$$

where:

PPV = Peak Particle Velocity in inches/sec

R = Distance from closest blast pattern's shot hole, in feet, to the location of interest

W = Maximum Charge Weight, in pounds, per delay (with a minimum delay of 9 ms)

Peak Pressure for excavation of submerged low strength rock:

Peak Particle Velocity:

$$PP = (5{,}460 * CRSD)^{-1.23} \quad (7\text{-}22)$$

where:

PP = Peak Pressure in psi

CRSD = Cube Root Scaled Distance

e. Example Underwater Blasting Design Problem.

(1) The rock to be blasted underwater is a sandstone, with well cemented beds. The sandstone has a density of 2.5 g/cc. The rock layer to be removed is 10 to 26 ft thick. The water depth is 40 ft deep. The blasthole diameter is 4.5 in. The diameter of the cartridged emulsion explosive SGe = 1.15) is 3.75 in. The blast will consist of four rows of holes with eight holes per row:

- Design the blast. Find the burden, stemming, subdrilling, spacing and timing along the row and between rows for the 26 ft depth.
- Find the anticipated vibration level at 400 ft from the blast for the maximum charge weight.
- Find the anticipated airblast level at 400 ft from the blast for the maximum charge.
- Find the anticipated underwater peak pressure at 400 ft for confined low strength rock.

(2) Resulting calculations are:

Burden: $B = \left(\left(\frac{2*SG_e}{SG_r}\right) + 1.5\right)De = \left(\left(\frac{2*1.15}{2.5}\right) + 1.5\right)3.75 = 9ft$

Stemming: $T = 0.7B = 0.7 * 9 = 6.3ft$

Round to 6.5 ft (Round to nearest ½ foot for practical spacing units)

Subdrilling: $J = 0.7 * 9 = 6.3\ ft$ to $J = 1.0 * 9 = 9\ ft$

Use 9ft

Spacing for 10-ft bench: $S = \frac{(L+7B)}{8} = \frac{(10+7*9)}{8} = 9.1\ ft$

Spacing for 26-ft bench, $S = \frac{(L+7B)}{8} = \frac{(26+7*9)}{8} = 11.1\ ft$

Powder Column (minimum) 10-ft bench:

$$PC = L + J + T = 10 + 9 - 6.5 = 12.5\ ft$$

Powder Column (minimum) 26-ft bench,

$$PC = L + J + T = 26 + 9 - 6.5 = 28.5\ ft$$

Loading density:

$$de = 0.3405 * SG_e * De^2 = 0.3405 * 1.15 * 3.752 = 5.5\ lbs/ft$$

Explosive/Hole (10-ft bench): $Exp = 5.5 * 12.5 = 68.75\ lbs$

Explosive/Hole (26-ft bench): $Exp = 5.5 * 28.5 = 156.75\ lbs$

Volume (10-ft bench): $Vol = \frac{(9*9.1*10)}{27} = 30.4\ yd^3$

Volume (26-ft bench): $Vol = \frac{(9*11.1*26)}{27} = 96.4\ yd^3$

Powder Factor (10-ft bench): $PF = \frac{68.75}{30.4} = 2.26\ lbs/yd^3$

Powder Factor (26-ft bench): $PF = \frac{156.75}{96.4} = 1.63\ lbs/yd^3$

Timing along row (with 9-ft spacing): $tH = TH * S = 1.6 * 9 = 14.4\ ms$

OK, exceeds the 9-ms minimum delay)

Timing along row with 11-ft spacing): $tH = TH * S = 1.6 * 11 = 17.6\ ms$

OK, exceeds the 9-ms minimum delay)

Timing between rows: $tR = 5 * 9 = 45\ ms$

Timing delay with non-electric shock tube would be 25 ms along a row and 42 ms between rows.

There is no Anticipated Airblast with the rock submerged below 15 ft water depth.

Anticipated Vibration, PPV, for 26-ft bench at a position 400 ft away from the nearest shot hole,

$$PPV = 50\left(\frac{R}{W^{0.5}}\right)^{-1.15} = 50\left(\frac{400}{156.75^{0.5}}\right)^{-1.15} = 0.93psi$$

Anticipated PP, for detonations within low strength rock at 400 ft

$$PP = (5{,}460 * CRSD)^{-1.23} = \left(5{,}460 * \frac{R}{(W^{1/3})}\right)^{-1.23}$$

$$PP = \left(5{,}460 * \frac{400}{\left(156.75^{\frac{1}{3}}\right)}\right)^{-1.23} = 27.33psi$$

7-12. <u>Contractual Considerations for Underwater Blasting</u>.

a. General. Most of the considerations that go into designing a conventional or terrestrial blasting program are applicable to underwater blasting. There are aspects of those considerations that are unique to underwater blasting (e.g., air blast, noise and impacts to surrounding fauna), as well as the ability to visually inspect and analyze the success of blasts.

b. Program Development. Both the office contracting for blasting services and the Blaster (or Blasting firm) need to recognize the unique circumstances of underwater blasting. The office contracting for underwater water excavation should recognize prior to developing the specifications: whether any provisions of the Safety Manual (EM 385-1-1) will limit the conduct of the underwater rock excavation; natural resource issues and agreements for natural resource or public use precautions must be completely resolved; underwater pressure-wave monitoring, if required, is a specialty that few contractors conduct well; and, hiring a consultant may be advisable to the office for either or both development of the specifications and/or during the underwater blasting.

(1) Only Blasters with successful underwater blasting experience for several projects should be considered for underwater excavation projects.

(2) Successful underwater rock excavation blasters would typically recognize: limitations of the Safety Manual (EM 385-1-1); moving the rock face beneath the water surface requires more time to develop a free face than when only air is resisting the rock displacement; the concern for water sensitivity of the blasting agent; the maximum, allowable vibrational and/or pressure-wave impacts; the greatest vibrational (structural) impacts are due to overconfinement of the blasting agent; the greatest pressure-wave impacts are due to possibly rare underconfinement of the blasting agent; detonation cord should not be used, if natural resource concerns are an issue; and, the initiation system may have special requirements for underwater blasting.

c. Safety. USACE EM 385-1-1 Safety and Health Requirements Manual includes Section 29 addressing Blasting, specifically Subsection 29.J: Underwater Blasting.

(1) Among its requirements are that no blast be fired while any vessel under way is closer than 1,500 ft. to the underwater blast area, and any moored vessels and passengers on board be notified before a blast is fired and appropriate blasting flags displayed.

(2) Transportation and handling of explosives for blasting underwater must be done according to all Federal state and local ordinances, and U.S. Coast Guard Regulations contained in 49 CFR 176. OSHA regulations regarding underwater blasting are contained in 29CFR 1926.912.

(3) There are provisions in EM 385-1-1 (2014 edition) regarding underwater blasting that may, if implemented on particular projects, prohibit blasting or reduce its efficiency. Among these are the limitations on drilling near loaded holes, typically disallowed in terrestrial applications and the requirement that holes be measured for alignment at frequent intervals during drilling. These limitations can be inconsistent with technical and feasibility constraints of recent drilling and surveying advances. Variances to EM 385-1-1 are not to be undertaken lightly and do not happen quickly. Further interaction with HQ Safety Office, MSC Safety Office and District Safety Office would needed before considering changes to these requirements. This will add coordination time and labor to a project and may not be approved. Any project considering variations in the requirements of the EM will need to take this coordination time and effort into consideration. This could cause considerable financial risk to a project if this was not done until construction was underway.

d. Permitting. No single Federal set of regulations governs mitigation of explosive effects on land or under water. State agencies were canvassed by Keevin and Hempen (1997) to track those state agencies that issued permits for this work. At that time it was found that 33 states had permit requirements managed in their respective natural resource agencies (by various names, but essentially the agencies responsible for environmental management related to surface waters, fish, wildlife and plants.) Some states had multiple agencies involved in permitting for underwater blasting or use of explosives in waterways or wetlands. Seventeen states in the survey reported that while their natural resource agencies did not specifically issue permits related to underwater blasting, they may provide input to other agencies within their state and to Federal agencies. In addition, the Federal Fish and Wildlife Coordination Act provides for state agencies review and comment on applications for USACE Section 404 Clean Water Act permits.

(1) Any Federal projects using explosives also fall under the provisions of the National Environmental Policy Act (NEPA) and the Endangered Species Act (ESA). As such NEPA requires Environmental Assessments of project impacts and possibly may trigger requirements for an Environmental Impact Statement. The ESA requires a Biological Assessment of potential impacts to Federally Threatened and Endangered Species, and species proposed for listing under the Act.

(2) A thorough preparatory search of applicable regulations and regulatory agencies is necessary before underwater blasting specifications are considered. Failure to obtain necessary permits can cause shutdowns, delays, fines, contractor claims and political concerns, and ultimately result in significant cost and schedule impacts to projects. Liberal time allowances should be included in project schedules for work involving underwater blasting, because agencies may not have enough familiarity with this kind of work to give realistic predictions of what is required and how much time the permitting processes will take. Permit limitations must be anticipated, developed and finalized prior to underwater blasting specifications being developed. Bidding and awarding contracts prior to full understanding of natural resource permit limitations will likely require many costly contract revisions and work delays.

e. Navigational Impacts. Underwater blasting is used as a method to remove materials from harbors, canals and navigational channels; however, during blasting there are impacts to ongoing navigation in existing waterways in terms of closures or restrictions on vessels where navigation continues. Typically, blasting allows excavation much more rapidly than mechanical means. Preparatory informational meetings with the public and commercial groups using navigational waters are necessary before and often during construction of longer projects to keep appropriate parties informed of conditions. Coordination with the U.S. Coast Guard and appropriate state agencies, highway departments (in the event there are bridges nearby), and any other organizations connected with public and commercial navigation may also be necessary.

f. Structures. As with any blasting program, the potential impacts to existing nearby structures, whether submerged or on adjacent land, must be considered in the design and implementation of underwater blasting projects. In cases where blasting is being used to demolish or alter structures in water, there may also be nearby structures that are intended to remain unaltered. A detailed survey of surrounding structures both in the water body and on land within the area of impact is required. After considering the potential impacts to structures, a program to establish pre-blast conditions should be undertaken, similar to land-based blasting, and a program of monitoring during and a post-blasting survey conducted. Mitigation measures may be necessary to address impacts. These surveying, monitoring and mitigation efforts may or may not be complicated by the differences between terrestrial and underwater blasting. Vibration from blasting is based upon delay timing (delay times should be greater than 8 milliseconds), maximum charge weight per delay (maximum total charge weight within the shot pattern within any 8 millisecond interval over the total delay period), and square root scaled distance.

g. Public Notice and Public Meetings. Many of the aspects of public notice and public meetings are not specific to underwater blasting and apply to all blasting projects. Public notice may or may not be required depending upon the size and scope of the project and proximity to areas of public interest or use, or the jurisdiction of the water body. Public notice may include published notice of the scope and schedule of work and/or may involve public meetings. Adequate materials in a readily understood format should be prepared where necessary for public meetings. Illustrations should be used where appropriate, and citation of any ordinances regarding limitations of energy, vibration and restricted periods, hourly, weekly, holiday, seasonal times when blasting is prohibited, should be provided. As with many instances where public meetings are held, presenters should anticipate a variety of concerns for noise, aesthetic issues and nuisance issues, in addition to more well defined concerns. Explaining safety and controlling procedures should be clear and concise and describe measures to avoid impacts, and provide transparency to prevent perceptions of secrecy or deception. Such actions with contact information for inquiries and perceptions of damage will foster trust and allay fear. Only realistic and attainable commitments should be made – and should be either developed ahead of time as part of the Technical Analysis, or where more involved, afterwards by the Design Team in response to legitimate concerns raised. Avoid making spontaneous commitments in public forums without appropriate technical review to verify that such agreements are technically measurable, relevant and achievable. A public-meeting rehearsal, including proxy questions, may be considered to prepare speakers and minimize the potential of unforeseen occurrences. Detailed minutes of public meetings should be prepared and all questions documented along with responses. The documentation associated with public notice and public meetings should be included in the permanent record of the project.

h. Blast Vibration and Pressure Waves. Depending upon the size and scope of the project there may be need to assess water-borne pressure waves, also called overpressures (both in air and water), and vibrations. Background data for normal and extremes of water pressure waves should be collected and reviewed to consider whether blasting may contribute to overpressure impacts. The impacts of underwater blasting, other than vibratory transmission through sediment and rock, are largely dependent upon the behavior of pressure waves transit through the water volume above or surrounding the blasted feature. The wave behavior is affected in turn by factors related to the site characteristics (sediment, rock, geology, water body bathymetry and properties, and nearby structures) and overall design of the blast.

i. Types of Explosive Materials. Blasting agents operate optimally in reactions that are balanced with respect to oxygen, i.e., neither a deficiency nor surplus of oxygen exists. So the formulation of blasting agents in aquatic environments may be more important than in land-based blasting, because of the need to balance the fuel and the oxygen available for combustion. In addition to considering the oxygen deficiency, water also has a cooling effect on the reaction, and the cooling may reduce the detonation’s effectiveness or strength of the gas expansion. The gas expansion enables the detonation to develop the free face for the next row of rock to move. Finally, there are regulatory concerns. In order to comply with OSHA regulations in 29 CFR 1926.912, all components (agents, and detonators) must be designed and suitable for wet environments. Blasting caps and detonation cord must be water resistant. Emulsions and dynamites are well-rated for underwater blasting and cartridge ANFO are better suited for usage in underwater blasting, provided adequate sized holes are used to ensure full detonation. EM 385-1-1 limits the use of electric blasting caps, which may be potentially initiated by marine radios and, therefore, should be prohibited. Detonation cord tends to have a greater kill radius for fish and is noisier in general than other methods. Detonation cord should be prohibited, when fish kill is an important adverse impact. Shock tubes or similar detonation systems are often considered the least problematic.

7-13. Developing Underwater Blasting Contract Specifications.

a. Site Considerations.

(1) Determining Substrate Characteristics. Previously performed investigations (dredging records, geologic mapping, harbor or channel construction records) may provide valuable information on the material at the lake or stream bottom. Records of marine incidents related to vessels contacting the harbor or channel bottom or reports of wrecks may be useful as well. If no information is available, a program of exploration using borings and/or geophysics may be necessary to define the substrate and physical properties necessary to design an underwater blasting program. Drilling blastholes from overwater into the substrate is more complicated than on land. If non-sampling drilling methods are used it is more difficult to identify changes in strata or to discern softer or harder seams or discontinuities in the substrate. Closer attention to drilling action can help compensate for these difficulties, but loading and installation of decking or stemming should consider the greater uncertainty.

(2) Survey of Pre-Blast Topography. Underwater blasting requires somewhat different surveys, owing to the relative limitations on visibility and accessibility to underwater structures or features in general. Additionally pre- and post-blast surveys of conditions, which might include aquatic species (if performed), will have to consider seasonal fluctuations and statistical variation of populations in order to prevent unwarranted conclusions and explain implied population growth or reductions that may not be blast related.

(3) Multi-beam hydrographic or similar high resolution digital surveys are useful tools for identifying and documenting pre-blast topography. Three-dimensional survey services are readily available and are far more precise than 2-dimensional profiles to document the conditions underwater as well as to provide a basis for quantity-based payment once materials are removed.

(4) Water. In cases where turbidity of mobilized materials within the substrate are of concern, as well as areas where the dissolved oxygen levels may be impacted, a program of monitoring turbidity and dissolved oxygen should be considered. Background parameter measurements should be taken under a variety of conditions with respect to weather, wave height and water temperature to determine a reasonable range of background values.

b. Structures. A review of documented underwater structures and their most recent reported conditions may be combined with underwater surveys. Construction reports will help in assessing the potential sensitivity of structures to underwater blasting as well.

(1) As with conventional land-based blasting, more rigid or brittle structures are likely to be more susceptible to damage from blasting underwater. Wave transmission underwater may have a greater affect than air blast and that possible impact will have to be taken into account.

(2) Where there are terrestrial structures of concern, which may suffer impacts from blasting, measurements of background vibrations caused by a range of normally-occurring events such as storms, boat traffic, tidal fluctuation, etc. should be established before proceeding so that conditions caused by blasting that are beyond these ranges can be considered with the appropriate level of concern.

c. Marine Natural Resources (Fish, Mammals, Plants). A thorough assessment of the marine and aquatic species and biological inventory of populations of aquatic species will be necessary for most underwater blasting programs in open water. State agencies may require a survey of fish in the vicinity of an underwater blasting project, and depending upon the location, there may be amphibians, reptiles, birds, or aquatic mammals in the area that require attention. The presence of threatened or endangered species (fish or aquatic mammals) or fish of economic significance may necessitate mitigation measures. A review of species of concern, Threatened or endangered species must be performed in order to prepare mitigation measures before an underwater blasting program can be initiated. Refer to Section 7-3.b.

d. Review of Marine and Weather Data. It is essential to designing an underwater blasting plan that the marine conditions on site be as well-known as possible. Daily, as well as seasonal, fluctuations of the water level are part of the considerations used in planning the logistical as well as the direct blasting design. Climatic data, tidal data, water temperature fluctuations and information relative to currents, flood stages, wave heights should all be considered in the process of designing a blasting Underwater Master Blasting Plan. The designation of criteria important to the ongoing project should be identified and a means of regularly monitoring these conditions should be included in the Underwater Master Blasting Plan. Conditions that require special attention, mitigation measures or that may suspend operations, as well as decision logic trees and personnel involved, should be defined ahead of time.

e. Other Logistics. A review of the surrounding waterway to determine access and potential alternative routes for travel should be considered. Changing water elevations, currents, storms or changing marine traffic patterns can alter routes to and from the site. A location for tying up overnight or during periods of shutdown may need to be considered – either near the site or at some safe harbor in the event of potential impacts from waves or storms. Contingency measures for alternative transportation of personnel and equipment should be considered in the Underwater Master Blasting Plan.

f. Underwater Blasting Restrictions. There are some restrictions on all blasting programs. All underwater blasting programs are required to be initiated during day light hours to be certain the area is clear of personnel before detonation. There may be other contract restrictions for a variety of reasons other than excavation limits. Some restrictions are specified in the contract and may related to permits or agreements with agencies. Some controls may be imposed by the contractor to assure personnel safety and assuring orderly loading, wiring, communication and initiation procedures. The following are typical restrictions that may be specifically detailed within the contract.

(1) Project Operational or Structural Restrictions. The project may require continuity of work or limitations upon operational impacts. Certain features of the project may require monitoring and/or significant vibration limitations. Pre- and post-blast surveys may be required.

(2) Structural Restrictions for the property of others. The property surrounding the site may require monitoring and/or vibration limitations. Pre- and post-blast surveys may be required.

(3) Natural Resource Restrictions. Agreements or permits from Natural Resource agencies may require certain hydroacoustic restrictions. Seasonal limitations and/or blast initiation delays may be needed, while a specified species is near the shot pattern. Limitation of the maximum charge weight per delay, other blasting adjustments or limitations, and/or specialized pressure-wave monitoring by an independent third party may be required.

(4) Public Use Restrictions. There may be potential impacts upon the public from the blasting. Some types of potential impacts include: important roads/highways near the blasting zone; public use areas, which may require curtailment of public use by time periods or property constraints or use restrictions; and, partial or full closure of public areas for periods during the project's blasting.

g. Hydroacoustic Impacts from the Underwater Blasting and its' Monitoring. Vibration impacts upon structures is very similar to land-based blasting. Structural and vibration impacts and its monitoring is developed in Chapter 8, Section 8-8.

(1) Hydroacoustic or Underwater Pressure-wave (compression-wave) or Underwater Overpressure Impacts may be assessed for an underwater blasting project. These hydroacoustic impacts require careful deliberation before being accepted. A project with significant public use concerns or natural resource protective measures may have a need for hydroacoustic monitoring. Such monitoring is difficult to conduct properly and requires processing to determine the necessary parameters.

(2) Accepted parameter(s), Allowable Magnitude and Position Range of Hydroacoustic Impacts. Public use concerns may be assessed between the appropriate agencies for recreational uses of the water body within one mile, or less, of the blasting. Agreements with, or permits from, natural resource agencies may require protective measures for threatened or endangered or commercially-important species. Significant evaluation should be conducted before resolving the physical parameter(s), its(their) allowable amplitude(s), and the nearest lateral distance from the blasting to avoid impacts to either the public or indigenous species. Such hydroacoustic limitations may require specialized consultation to best determine reasonable parameters prior to agreement with outside agencies. Only when important water-borne restrictions are required for blasting may hydroacoustic monitoring be needed. Hydroacoustic monitoring may be considered, if there are important water-borne restrictions for public use concerns or for Natural Resource protective measures. Such underwater monitoring is not easily conducted, so monitoring should not be required lightly. Hydroacoustic monitoring may be the only means to assure that blasting is not producing adverse impacts in the accepted parameter(s).

(3) Specialized Underwater Hydroacoustic Monitoring Equipment. The primary types of hydroacoustic equipment are either hydrophones or pressure transducers. The project's water-borne limitations may resolve, which of the two types of equipment may be needed. Hydrophone systems are easier to use and record pressure waves, but hydrophone systems record at lower pressure amplitudes and are not as hardy as transducer systems. Pressure transducer systems require more equipment than hydrophone systems to record the pressure waves, but transducer systems can record very high pressure amplitudes near the shot. Both system types will require processing of the raw records to provide the parameter(s) of interest.

(4) Selection of the Hydroacoustic Monitoring Subcontractor. An independent third party should be required to conduct the necessary hydroacoustic monitoring. Such monitoring is difficult to conduct properly and is occasionally unsuccessful for a given shot, even with a well-practiced and previously effective hydroacoustic monitoring Consultant. The specifications must provide criteria for the main contractor's selection of the hydroacoustic monitoring subcontractor. The capabilities and prior successful underwater monitoring of the hydroacoustic monitoring subcontractor must be provided in the Underwater Master Blasting Plan. The hydroacoustic monitoring subcontractor will be subject to the approval of the Contracting Officer.

(5) Project Hydroacoustic Monitoring. The specification will detail the required underwater impact parameter(s) to be measured, the allowable maximum amplitude of the parameter(s), and the distance from the nearest point within the shot pattern to the maximum allowable parameter amplitude. The number of monitoring positions may be established in the specifications or determined within the discussion of the Underwater Master Blasting Plan. It will be required for the raw hydroacoustic records to be processed. Specific testing will be required to assure that the monitoring is recording the actual and precise pressure-wave measures. Two tests are required to assure a uniform comparison among all hydroacoustic devices. A manufacture's calibration is required for each hydroacoustic device within the last 12 months of its anticipated use. Water-borne comparative tests of all hydroacoustic devices are required before deployment, when different devices will be used, and after the last deployment of Hydroacoustic Monitoring. Each water-borne comparative test records the results of all hydrophone and/or pressure transducer systems being deployed at the same distance from a noise source. These water-borne comparative tests resolve the variation between devices in overpressure amplitude at different frequencies. The manufacturer's calibration and the water-borne comparative tests provide the data to understand the accuracy and precision in processing the raw hydroacoustic overpressure records. A brief report in the Shot Record is required to detail the accepted parameter(s) at each monitoring position for every underwater shot with hydroacoustic monitoring. The data from both the manufacturer's calibration and the water-borne comparative tests, and the raw and processed hydroacoustic records must be provided digitally following each shot.

h. Recommended Contract Provisions.

(1) Underwater Master Blasting Plan. The Master Plan for an underwater blasting program, as with any construction activity, must contain enough detail to explain the process with respect to personnel, equipment, sequence of operation, materials, monitoring, natural resource controls, ventilation (where applicable), logistics, and communication. The Underwater Master Blasting Plan is submitted for the review and approval of the Contracting Officer. The Master Blasting Plan must include all elements, as noted in Chapter 9, Section 9-3.a. A Gant Chart identifying the Critical Path and subordinate tasks associated with the work may be a part of the Master Plan or may be linked to it as a separate submittal. In general, minimizing the numbers of separate submittals is advisable. Scheduling of overall project work may determine whether it is best to have the Gant Chart as part of the Underwater Master Blasting Plan or not. Underwater Master Blasting Plan also must include descriptions of the anticipated water conditions, such as currents, temperature and waves, and how the overall blasting program will accommodate variations anticipated. Expectations of the schedule of blasts and removal of spoils should be included with the understanding that circumstances may affect the day-to-day blasting schedule. Schematic drawings of blast arrays as well as the general conceptual assumptions, bench heights, the configuration of blasts showing the sequence of excavation, haul methods, and routes and disposition of spoils should be included. Sample calculations for important blast parameters should be provided to demonstrate a basis for the overall blasting design. The exact design of each blast cannot be given in the Underwater Master Blasting Plan, because blasts are typically adjusted in some manner based on results of previous blasts with respect to loading, delays, hole pattern, and burden. The Master Blasting Plan must provide the rationale that will be used in this process of adjustment. Safety aspects, while of utmost importance, are typically addressed in the detailed Site Specific Health and Safety Plan whether by this exact name or another. Similarly, a

separate Natural Resources Plan should be prepared to access and describe mitigation of natural resource impacts of blasting, including, but not limited to the impacts of pressure waves for underwater blasting on aquatic life and measures included to mitigate these impacts.

(2) Test Blasting for Underwater Blasting Contracts. If Test Blasting (see Chapter 9, Section 9-3.b is required for the specific contract/project, the specifications should detail whether any Natural Resource or Public use impacts or their monitoring are elements of the Test Blasting's determination of a successful Test Shot or Test Blasting program.

(3) Required Elements of the Underwater Master Blasting Plan. Include all elements of the Master Blasting Plan, Chapter 9, Section 9-3.

(4) Monitoring. Structural monitoring of vibrations must follow procedures noted Chapter 8, Section 8-8, "Ground Vibration." Pressure wave monitoring may be required. Underwater pressure-wave monitoring developed in this chapter, Section 7-5.d.

(5) Underwater methods and procedures. The programs to conduct underwater rock excavation must recognize the differences from land-based blasting in safety, overwater positioning, drilling with potentially variable current and wave conditions, loading holes immediately following drilling of the shot holes, effective overwater blasting procedures, water sensitivity of explosive materials, avoiding particular types of explosive materials and initiators and firing lines, delay timing, adequate stemming, vibrational impacts upon structures from overconfinement, natural resource impacts from pressure waves due to underconfinement or loss of confinement, natural resource limitations and agreements, and hydroacoustic monitoring. A section describing the conduct of the Test Blasting Program, the area for the Test Blasting, its sequencing, execution, and the Test Blasting's application to subsequent production blasting. The Underwater Master Blasting Plan should detail these specific underwater differences. Added discussion should be provided for noting underwater delay timing, underwater charge weight per delay, and CRSD in regard to both shot plan design, effective of the rock blasting, and avoiding both public use and natural resource impacts.

(6) Pre-Shot Plans. The Underwater Pre-Shot Plans, which detail the proposed shot pattern data, must be separate submittals and are provided for Information Only. An Underwater Pre-Shot Plan must include all elements as noted in Chapter 9, Section 9-3.b.

(7) Underwater Pre-Shot Plans' Data. Additional data are required for an underwater shot, relative to a land-based blast.

(8) Underwater Delay Timing. The development of a free face between rows of submerged holes consumes more time as rock attempts to displace water, relative to the faster movement of rock displacing air in land-based blasting. The delay time between close holes in any two adjacent rows should be 25 milliseconds, or longer, for underwater blasting. Delays between two adjacent holes in the same row should exceed 8 milliseconds. Delay timing may be adjusted for better productivity, if structural vibrations and/or natural resource pressure waves will not be adversely impacted, or if no adverse impacts have developed.

(9) Underwater Maximum Charge Weights Per Delay. There are two maximum charge weights per delay for underwater blasting that are independent variables separately for structural vibrations and natural resource pressure waves. For structural vibration estimates, the maximum charge weight per delay (Str) is the largest explosive materials' weight within any 9 millisecond interval over the total delay time. For Natural Resource pressure-wave assessment, the maximum charge weight per delay (NR) is the largest explosive materials' weight within any 25 millisecond interval over the total delay time.

(10) Scaled Distance for Monitoring of Underwater Blasting. Similar to maximum charge weights per delay, there are two independent scaled distances for underwater blasting. For structural vibration estimates and graphing particle velocity, the square root scaled distance (SRSD) is assessed. The SRSD is closest approach in feet of the assessment location from the shot pattern divided by the square root of the maximum charge weight per delay (Str). For Natural Resource pressure-wave estimates and graphing peak overpressure, the CRSD is assessed. The CRSD is closest approach in feet of the assessment location from the shot pattern divided by the cube root of the maximum charge weight per delay (NR).

(11) Required Elements of the Underwater Blasting's Shot Plans. A section should develop whether the shot was within the Test Blasting or production blasting phase of the contract. The section would describe in narrative the success and effectiveness of the shot and its ability to avoid both land-based and underwater impacts.

(12) Post-Shot Records. The Underwater Post-Shot Records, which detail the information of the installed explosive materials and outcome of the shot pattern's detonation, must be separate submittals and may be provided for Information Only. The Shot Record is the reporting of the detailed development of each shot and its specific outcomes. An Underwater Shot Record will include all elements as noted in Chapter 9, Section 9-3.c.

(a) Underwater Post-Shot Records' Data. The Post-Shot Record will provide all the actual data from the underwater shot, including the assessed or estimated data of the Underwater Pre-Shot Plan's Data.

(b) Required Elements of the Underwater Blasting's Post-Shot Records. The Shot Record must revise or recreate each of the forms provided in the Underwater Pre-Shot Plan (Section 7-13.h(6)) for the same shot pattern. The following are additional material required on the forms or other material required for the Post-Shot Record.

(c) The Post-Shot Record. The Post-Shot Record for an underwater shot will provide all the requirements of the Chapter 9, Section 9-3.c, "Post-Shot Record." The narrative must include any underwater monitoring or impact parameters related to the shot's results and success, regardless of the shot being a Test Shot or production blast. If this underwater blast was a Test Shot, the results and success narrative must include any of the prescribed Test Shot parameters related to underwater monitoring or impacts.

(d) The Monitoring Data Table. The table for an underwater shot shall provide all the requirements of the Monitoring Data Table, Chapter 9, Section 9-3.b(2)(b). The concise table must include all Underwater Shot Plan's estimated parameters and the actual parameters for the underwater monitoring.

(e) The Seismograph and Hydroacoustic Monitoring Report. The report for an underwater shot will provide all the requirements of the Seismograph Report, Chapter 9, Section 9-3.c(2)(c). The report must include all hydroacoustic estimates from before the shot, assessment, actual data, narrative and records, as required from Chapter 7, Section 7-4. e. (6) for all underwater monitoring of the underwater blast.

(f) Adverse Impacts Report. The report for an underwater shot will provide all the requirements of the Adverse Impacts Report, Chapter 9, Section 9-3.c(2)(d). The report must include any and all impacts, concerns and exceeded monitoring parameters for the project's public use and natural resource issues.

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CHAPTER 8

Damage Prediction, Prevention and Control

8-1. Introduction. A necessary part of all blasting operations is the estimation of potential damage to nearby life and structures. Although potential blasting impacts are generally classified as "environmental impacts," certain types of impacts are classified separately for purposes of clarity. In blasting, for example, commonly anticipated structural and human life impacts are also considered environmental impacts. Potential blasting impact on wildlife and wildlife habitat are termed "natural resource impacts," even though some would include these under environmental impacts. One of the common unintended effects of blasting is possible damage to nearby structures that can result from flyrock, airblast, ground vibrations, and water-borne pressure waves. This chapter discusses structural response, induced strains, and resulting crack damage as basic information necessary when addressing public concerns with blasting. In the case of air or ground vibrations, threshold damage to one- and two-story residential structures occurs as cosmetic hairline cracking in plaster, wallboard, and masonry walls. This chapter lists airblast and ground vibration damage criteria that specify thresholds, which if avoided, provide protection against the development of these cracks. When blasting must be done in areas near residential or business structures, home or business owners may anticipate potential damages. To allay those fears and to accurately document pre-existing conditions versus actual damages caused by contract blasting, pre-blast inspections should be conducted for most to all, nearby homeowners or many to most businesses depending upon site conditions and the scaled distance to the structures. An important part in developing good public relations program and in minimizing complaints and legal claims is to provide home or business owners with information on blast schedules, the need for blasting, and the relative harmlessness of blasting relative to natural and cultural stresses. Documenting cracks with pre-blast and post-blast inspections, maintaining accurate blast records, and cataloging vibration levels and complaints are essential elements for public understanding and potentially in providing evidence in litigation.

8-2. Advanced Studies and Surveys.

a. General.

(1) Study Use. A variety of specialty studies will enable the project to achieve the best possible design, or to obtain required/useful data. Some contracts will not require any specialized studies. Those contracts with prior blasting of a similar nature that will meet the contract's limitations may not require any added resolutions. Other contracts may require types of studies referenced here or other assessments not referenced in this chapter. Some contracts may warrant these or other evaluations within the contract, rather than before the publication of the specifications.

(2) Varied Types of Studies. A broad variety of assessments may be considered to aid in the design or contracting work. A Detailed Site Investigation may be done to evaluate the site, e.g., the geologic nature of the bedrock or qualities of the structure targeted for demolition. Site geology and topography may vary over short distances. The prudent designer will need to know the spatial variations of geologic factors among the rock formations impacted by the design. In some cases, blasting may be done to remove a structure. Even the dimensions of the structure may be well known, the

quality of the concrete and the associated percussion drilling rate may not be well understood. A better set of bids may be obtained, if such pertinent information, e.g., drilling rates, bit size to be used in the demolition or excavation blasting, etc., were known and provided with bid documents.

(3) Blast Attenuation Studies. They may be required if important structures, government or private, are near the blast location. The attenuation study will calculate the rate of decay of particle velocity (the most useful parameter to predict damage) with varied explosive charge weights per delay for affected areas.

(4) Structural Inventories. They are evaluations of any governmental and nongovernmental (private or commercial or residential) structures that may be impacted by blasting. Trained inspectors create these inventories by doing surveys of the structures before the blast and after blasting, if necessary. Pre-blast inventories are conducted before the blasting and may be conducted either before the contract is let, or through the contract as part of the blasting services. Post-blast surveys may be required for; all Pre-blast inventory structures or for specified important structures or only those structures meeting a specified criterion. Post-blast inventories may only be conducted for structures that have a complaint pertaining to a particular blast's alleged damage. The blasting contractor typically conducts post-blast surveys at the time of the complaint.

(5) Natural Resource Habitat Assessments. These are done to ensure compliance with Federal, state, and/or local environmental laws and regulations. These Natural Resource assessments determine whether a potential exists to impact a particular species.

(6) Engineering Assessments for Water-Borne Pressure Waves. They are studies done to assess potential natural resource impacts on aquatic or marine organisms or structural impacts on submerged structures. These impacts develop from blasting in, beneath, or adjacent to water bodies. The assessments resolve both potential impact and possible mitigation measures to be taken. Refer to Chapter 7, Section 7-4.

(7) Study Abstracts. Precontracting studies should be abstracted, summarized, or otherwise noted in specifications. If the study is important enough to be conducted, the study is important enough for a prominent notice in the specifications. A short abstract or summary should be included in the specifications, so that any interested bidder may acquire the full reports of the studies.

b. Site Investigations.

(1) Purpose. Some high level projects, e.g., work on the existing foundation of a dam site, may already have had site geologic evaluations. Other projects, e.g., the development of a quarry for stone production or rock removal from a navigation channel, may have had no detailed site description or evaluation of site geology for drilling. A Detailed Site Investigation or Test Drilling may be needed to evaluate the geologic nature of the bedrock at the site, or to determine the qualities of the structure for demolition.

(2) Need. All known data should be available to all bidders and the winning contractor. For some contracts, there may be a considerable advantage in doing preliminary specialized studies that reduce the number of unknown factors before bidding begins. This can to help increase the number

of potential bidders (to stimulate competition and lower bids), and also to resolve unanticipated issues that the winning contractor might encounter during the project, which reduces the potential for changed-site-condition issues.

(3) Site Investigations or Test Drilling. It would be warranted to develop adequate data for Chapter 5, “Surface and Underground Blast Design.” The extent of a site appraisal is subjective. The risk of changed-site-condition concerns should provide motivation to perform sufficient studies of a site with inadequate data on the site’s geology. A study should provide geologic information that will not “change” its conditions between the conclusion of the study and the date the contract is awarded. A Blasting Consultant could determine the extent of information sufficient for a given site. No opinions or deductions should be provided with these studies or reports. Only factual data should be determined in the reporting.

(4) Test Drilling is occasionally conducted to develop drilling rates. Drilling rates are a significant portion of blasting costs. Percussion drilling, or other types of drilling that would be used with blasting, may be helpful to indicate actual conditions. Sites that have had no drilling that may be used to gauge production-drilling rates, either on the site or nearby, would benefit from test drilling. A test percussion drilling program may potentially lower bid costs for drilling, because the risk to the contractor is lessened.

(5) Sites that may have difficult drilling conditions can significantly benefit if the likely rate of drilling and bit wear can be demonstrated, e.g., sites with difficult rock conditions, very dense or abrasive units, etc. Overwater drilling can be quite expensive for an underwater blasting program (see Chapter 7, Section 7-5). A short percussion drilling program overwater for a channel rock removal project could significantly modify bids for many contracts, particularly large projects.

(6) Structures requiring blast demolition benefit from test percussion drilling, if the concrete contains hard aggregate, or if there are uncertainties about whether the concrete contains reinforcement or about the size or location or reinforcement. The most beneficial test drilling will have a drill holes in several locations. Test drilling should use either a range of bit sizes or the approximate bit size likely for the blastholes.

c. Blast Attenuation Studies.

(1) Purpose. Sites requiring blasting in an urban or commercial locale will require care to avoid blast impacts on surrounding structures. The public and property owners usually do not adequately understand blast mitigation. Attenuation studies may be required to determine if the needed explosive necessary to accomplish the contract will impact surrounding nongovernmental properties. Attenuation studies usually develop ground vibration of varying scaled distances for charge weights per delay.

(2) Need. Attenuation studies are only needed when there are specific site or blasting constraints. For most sites, the charge weights per delay or production shooting may be varied adequately, or the project duration may be lengthened to avoid impacts without precontracted studies. Attenuation studies are warranted for sites very close to sensitive structures. A specialist that has previously conducted and used attenuation studies should develop the attenuation study.

d. Structural Inventories.

(1) Purpose. Structural inventories should be conducted when blasting may impact nongovernmental or governmental properties. The distance to nongovernmental structures requiring pre-blast surveys depends on the charge weight per delay likely to be used. If different contractors vary in their assessments of blast attenuation, it usually indicates that a structural inventory should be included in the contract with specified requirements. While precontracted structural inventories are not common, some blasting projects may need to perform the structural inventories before the contract is established.

(2) Need. Structural inventories, commonly termed “pre-blast” and “post-blast” surveys, are typical for most projects requiring blasting. Most structural inventories are not undertaken as precontracted studies; they are more typically conducted by the contractor. Pre-blast and post-blast surveys should be done by independent subcontractors, who regularly do such surveys and evaluate blast damage.

(3) The pre-blast surveys are inventories before any blasting has occurred. The pre-blast surveys allow some communication with owners to allay concerns of blasting and to heighten the owner’s interest in the present condition of the structure. Both are significant advantages. The pre-blast survey provides the benchmark of the structure’s condition before any blasting. Governmental structures of importance within the survey range should have pre-blast surveys.

(4) Post-blast surveys are commonly conducted only for structures that have a damage complaint related to a particular blasting event or that have monitoring that exceeded potentially damaging blast-vibration thresholds. In some cases, post-blast surveys may be required following the completion of the blasting program for the site, of all structures that have had pre-blast surveys. The same person that conducted the pre-blast survey, if one was made for the structure, should conduct the post-blast survey.

(5) A predetermined form should be used for every structural inventory. At a minimum, the inventory form should include: the owner’s name and mailing address; the location of the structure; the date the survey was conducted; the name and the address of the person performing the survey, and the signature of the surveyor; the name, address, and signature of the person allowing entry to the structure or denying entry; and the format of the inventory description. The form should resolve the type(s) of description for each property. The inventory should include written and/or photographs and/or video recordings of all the rooms, exterior, foundation, and pertinent features that may be impacted by blasting. The Government must receive a copy of all forms and all descriptions of all structures having inventories shortly after the survey is conducted. Each property owner should also receive, at minimum, a summary of the survey. The better practice is to provide the property owner with a full copy of the inventory report. Blank example forms are included in Appendix C of this manual.

(6) The distance within which structures should be inventoried is variable. Structures often have pre-blast surveys within 500 to 1,000 ft. of any blasting. Every structure does not require a pre-blast survey. Typically, the closest structure, which lies within the range being surveyed for all azi-

muths about the blasting zone, will have a pre-blast survey. Important or sensitive structures are often surveyed, even when they lie just beyond the range of pre-blast surveys. The Government should typically obtain the rights-of-entry for all the structures to be surveyed.

e. Natural Resource Assessment. There may be requirements to conduct Impact Assessment for species that may be harmed by land-based blasting. Impact Assessments or Mortality Modeling for Underwater Blasting are provided in Chapter 7.

8-3. Waves Due to Blasting and Their Recording.

a. Seismic waves are waves that travel through the earth. These waves represent the transmission of energy through the solid earth or near the surface of the earth. Other types of wave transmission of energy are sound waves, light waves, and radio waves. Earthquakes generate seismic waves. The science that studies earthquakes is Seismology, the name being derived from the Greek word "seismos" meaning to shake. In addition to the naturally generated seismic waves, there are many manmade sources of seismic waves. When these manmade seismic waves are sensible, that is when they can be felt, and they are referred to as "vibration."

b. The "Vibration Problem." Some human activities such as blasting, pile driving, etc., produce seismic waves that people can feel. They are disturbed, concerned, perhaps fearful, and begin inquiring about what is happening. Thus begins a confrontation known as the "Vibration Problem." The reaction of the public to these vibrations, because they are noticeable, can be out of proportion to any actual damage resulting from blasting operations. Airblast effects, discussed in more detail below, are similar in that the sound is very noticeable even where the decibel level is within tolerable guidelines. These effects should be considered when communications planning for a project.

c. The vibration problem has been thoroughly investigated in the past and continues to be the subject of ongoing research. Since the subject starts with seismic energy and seismic waves, a brief discussion of these waves is in order.

d. The detonation of explosive materials produces different waveforms in solids than in fluids (liquids and gases). No waves are produced in a vacuum. Waves generated by blasting include.

e. Body Waves are waves that travel through the mass of rock, penetrating down into the interior of the rock mass or structure in which the explosives are placed. Body waves occur as compression waves that have particle movement in the same direction as the wave propagates and shear waves that have particle movement normal to the direction of wave propagation. There are two kinds of body waves: compressional waves and shear waves. The compressional wave is a push-pull type wave that produces alternating compression and dilatation in the direction of wave travel, such as occurs in a stretched spring. The shear wave is a transverse wave that vibrates at right angles to the direction of wave travel. The motion of a shear wave can be seen in a rope that is strongly flexed at one end. The rope moves up and down, but the wave travels outward toward the other end. Soil materials transmit shear and compression waves; whereas, fluids (including liquids and gases) transmit compression waves, but do not support shear wave transmission.

f. Surface Waves are waves that travel along the surface boundaries of dissimilar solids (sediment and rock), even at the interface of air or water but do not travel through it. Deformations from surface waves are generated by body waves and are constrained by physical conditions from traveling much greater than one wavelength into the interior of the rock mass, sediments or structures. Surface waves are generated by body waves that are restrained by physical and geometrical conditions from traveling into the interior of the rock mass. Surface waves produce the largest ground motions and are the large energy carriers.

g. Overpressure or compression waves or pressure waves are transmitted through fluids. Physical effects of underwater blasting are the production of overpressure through water and air. Refer to Chapter 7, Section 7-3 for the pressure waves in water due to underwater or near water body blasting. Airblast are the overpressure waveforms through air as audible and sub-audible sound (or noise) waves or compression waves. Airblast may be greatly reduced depending confinement of the explosive materials.

8-4. Air Overpressure.

a. Airblast Generated by Blasting.

(1) In addition to ground vibrations, blasting produces air-borne energy called air overpressure or impulsive sound. There are many good references for theory and background on Air overpressure such as USBM RI 8485 (1980), Rock Blasting and Overbreak, 5th Edition (2015) as well as books written by Charles Dowding and Lewis Oriard. This manual was designed to provide the knowledge necessary to understand the use and measurement of air overpressure data and air overpressure potential. Severe Air overpressure can cause serious damage to structures. Figure 8-1 shows the damage that occurred from severe airblast at the explosion at the West, Texas agriculture feed store from the detonation of ammonium nitrate.

Figure 8-1. Airblast Damage at West, Texas Explosion.

(2) The decibel scale is most commonly used. It is logarithmic with values representing pressure changes above or below a standardized reference pressure. A change of 6 dB represents a doubling of the pressure in psi. Air overpressure frequencies are both audible and sub-audible and peak air overpressure measurements were used to correlate with window breakage and structural cracking similar to peak ground particle velocity measurements. Occupants cannot usually identify if the vibration and rattling is from the ground vibration and/or the air overpressure. Annoyance can often be attributed to airblast. If airblast is likely, it is important to discuss its impacts as part of any public relations program.

b. Measurement. Airblast is measured with sound level meters, pressure transducers, or wide-response microphones in blasting seismograph. To accurately measure the amplitude, especially with low frequency microphones, a windscreen is recommended to cut down on the background noise level. The microphone should be placed 3-ft above the ground and 5-ft to one side of the structure to prevent reflections distorting the record. The frequency response of the microphone has a great effect on the measured response.

c. Regions Of Potential Damage For Airblast. There are two distinct regions of potential airblast damage that are quite different. They are referred to as Near Field and Far Field.

8-5. Near Field Air Overpressure.

a. This is the region around the blast site where there is direct transmission of the pressure pulse. The potential for damage in the near field is considered small with reasonable blast design. The details of spacing, burden, stemming, explosive charge, delays, covering of detonating cord trunklines and use of cord with minimal core load can minimize air overpressure. Proper execution of the design insures a very low probability of glass breakage. The reason the U.S. Air Overpressure Standards are set at 134 dB is because the current air overpressure standards apply to single strength glass that is under strain from being improperly set.

b. Overpressure and Decibels. Air overpressure waveform is most commonly measured for its peak value in decibels (dB_a), referenced to a base level for air. Air overpressure is commonly recorded by specialized absolute reading microphone in units of pounds per square inch (psi). Peak overpressure, P_{Pa}, the maximum value for the entire waveform, is converted to dB_a by the following equation:

$$P_{Pa}\,(dB_a) = 20 \log\left(P_{Pa}\,(psi) / P_o \right) \quad (8\text{-}1)$$

where

$P_{Pa}\,(dB_a)$ is the Peak Air Overpressure being converted to dB_a,

P_{Pa} (psi) is the Peak Air Overpressure measured in psi,

P_o is the reference or base level of overpressure in psi for air, and

$P_o = 2.9 \times 10^{-9}$ psi (lb/in^2) ~ 3×10^{-9} psi.

$$dB = 20 * Log\left(\frac{P}{Po}\right)$$

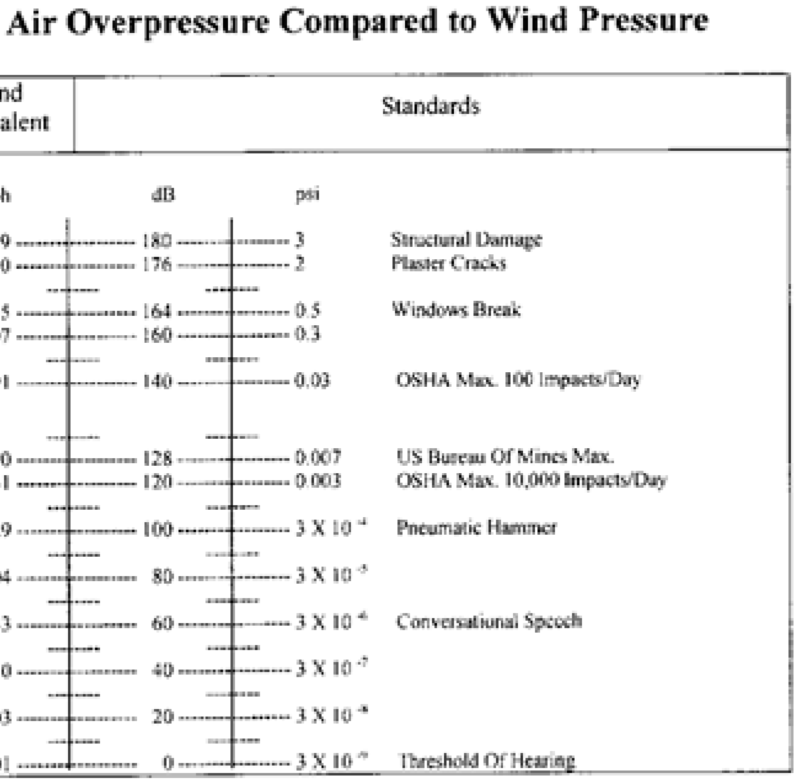
c. The other form of P_{Pa} for airblast is the Sound Pressure Level, $SPL_{dB,air}$. $P_{Pa,}$ are given in units of pressure: pounds per square inch (lb/in^2, psi), millibars (mb), Pascals (Pa); or, as SPL in units, dB, of decibels relative to a reference level (1 micropascal = 2.9E-9 psi) for air with conversions as follows.

$$SPL\ dB_a = 20\ Log\ P_{Pa\ mb} + 134.1 \quad (8\text{-}2)$$

$$SPL\ dB_a = 20\ Log\ P_{Pa\ Pa} + 94.0 \quad (8\text{-}3)$$

$$SPL\ dB_a = 20\ Log\ P_{Pa\ psi} + 170.8 \quad (8\text{-}4)$$

d. Air overpressure can also be expressed in equivalent wind velocity (Figure 8-2). It is often more understandable to the general public to relate these pressures as wind velocity because this is a unit that they understand where decibels and psi may be foreign and unknown.



Air Overpressure Compared to Wind Pressure

Wind Equivalent	Standards		
mph	dB	psi	
329.09	180	3	Structural Damage
268.70	176	2	Plaster Cracks
134.35	164	0.5	Windows Break
104.07	160	0.3	
32.91	140	0.03	OSHA Max. 100 Impacts/Day
15.90	128	0.007	US Bureau Of Mines Max.
10.41	120	0.003	OSHA Max. 10,000 Impacts/Day
3.29	100	$3 X 10^{-4}$	Pneumatic Hammer
1.04	80	$3 X 10^{-5}$	
0.33	60	$3 X 10^{-6}$	Conversational Speech
0.10	40	$3 X 10^{-7}$	
0.03	20	$3 X 10^{-8}$	
0.01	0	$3 X 10^{-9}$	Threshold Of Hearing

Figure 8-2. Comparison of Air Overpressure Standards.

e. Scaled Distance for Air Overpressure. Air Overpressure is scaled according to the cube root of the charge weight similar to underwater blasting (Table 8-1). Cubed-root Scaled Distance, $CRSD = SD_3 = R / W^{1/3}$, for R, the range, in feet, and W, the charge weight in pounds of a single charge or the shot pattern's maximum charge weight per delay (where the delay is longer than 8 ms). (Airblast does not use the square root of the charge weight used for ground vibration.)

$$Air\ Overpressure\ Scaled\ Distance = \frac{Distance\ (ft)}{\sqrt[3]{Pounds\ per\ Delay}} \tag{8-5}$$

If detonating cord is used as the column charge for precision pre-splitting then the air overpressure scaled distance is calculated as shown below.

$$Air\ Overpressure\ Scaled\ Distance = \frac{Distance\ (ft)}{\sqrt[3]{Grains\ per\ Delay/_{7000}}} \tag{8-6}$$

Table 8-1. Equations For (Near Field) Prediction of Air Overpressure (ISEE Blasters Handbook 2011).

Blast Type	Airblast Pressure (AP) (psi) U.S. Equation	Source
Open Air (no confinement)	$P=187 \times SD_3^{-1.38}$	Perkins
Coal Mines (parting)	$P=169 \times SD_3^{-1.62}$	USBM RI 8485
Coal Mines (high wall)	$P=0.162 \times SD_3^{-0.79}$	USBM RI 8485
Quarry Face	$P=1.32 \times SD_3^{-0.97}$	USBM RI 8485
Metal Mine	$P=0.401 \times SD_3^{-0.71}$	USBM RI 8485
Construction (average)	$P=1 \times SD_3^{-1.1}$	Oriard (2005)
Construction (highly confined)	$P=0.1 \times SD_3^{-1.1}$	Oriard (2005)
Buried (total confinement)	$P=0.061 \times SD_3^{-0.96}$	USBM RI 8485
Construction (Konya)	$P=0.95 \times SD_3^{-0.89}$	Konya (2015)

a. Propagation and Prediction.

(1) As with ground vibrations, airblast dissipates with distance and loses energy as distance increases from the blast to the monitoring location. Also, as with ground vibrations, explosive charge weight per delay and distances are important prediction parameters for airblasts. In addition to the size of a blast, the degree of confinement is critical for airblast generation. “Confinement” describes how well the blast is contained within the rock being blasted. (“Relief” is the inverse of confinement and is a function of the shot geometry and delay timing used). A “poorly confined” blast may result in excessive airblast noise (airblast changes may be increased on the order of 10- to 100-times, or more), but may also reduce ground vibration amplitudes by a factor of less than half.

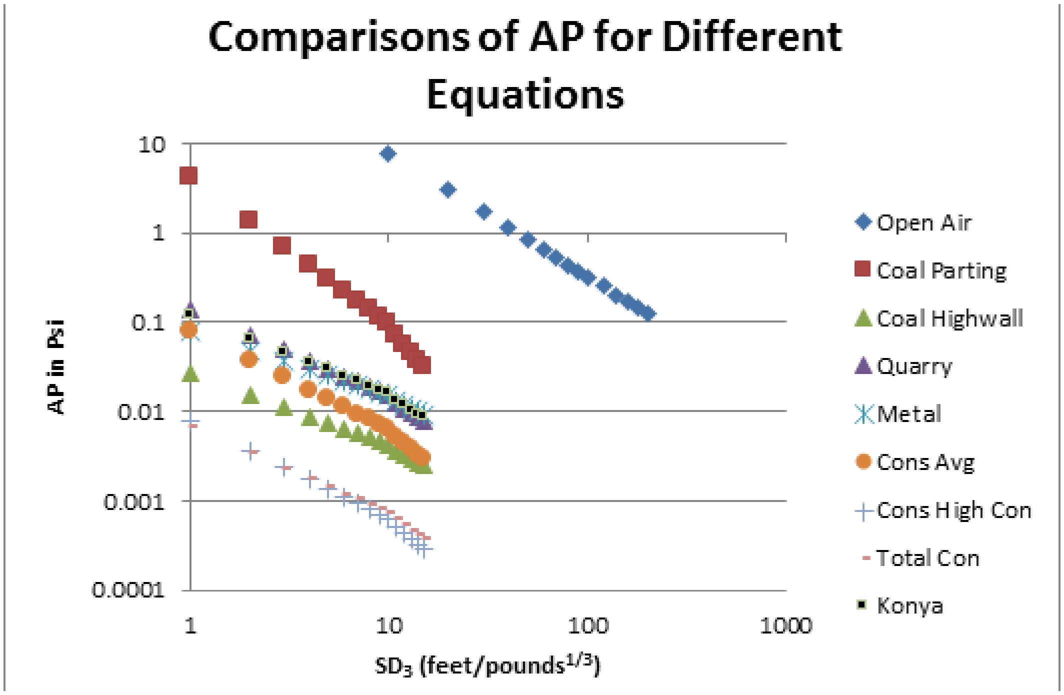


Figure 8-3. Comparison of AP for All Equations Including Konya.

(2) Recent research has produced an equation for air overpressure, AP, for construction projects using 3- to 4-in. diameter blastholes. The equation for normal air overpressure for construction blasting is given below. Both the average values and the 95% confidence level equations are shown. It has often been reported that the normal presplit blasting would produce airblast levels that exceed those generated by construction production blasts. Figure 8-3 shows a comparison of AP for all equations, including Konya.

$$\text{[Mean value] AP (psi)} = 0.14(d/(W^{1/3}))^{-0.89}$$
$$\text{[95\% confidence] AP (psi)} = 0.95(d/(W^{1/3}))^{-0.89} \qquad (8\text{-}7)$$

where:

d = distance in feet

W = charge weight in pounds per 8 ms delay.

(3) The expected air overpressure for Precision Pre-splitting is given below. Both the average values and the 95% confidence level equations are shown.

$$\text{[Mean value] AP(dB)} = -17.81*\text{LOG}\ (d/(W^{1/3}) + 153.71$$
$$\text{[95\% confidence] AP(dB)} = -17.81*\text{LOG}\ (d/(W^{1/3}) + 170.34 \qquad (8\text{-}8)$$

where:

d = distance in feet

W = charge weight in pounds per delay

(4) USBM Bulletin 656 proposed an overpressure of 0.5 psi (164 dB) as a safe level for prevention of glass breakage and indicated that blasting, which generated ground vibration below 2 in/s, automatically limited air overpressures to safe levels, that is, less than 0.5 psi (164 dB). Siskind and Summers, Bureau of Mines TPS 78 (1974), proposed safe levels for preventing glass breakage. These levels also helped reduce annoyance. Table 8-2 lists these values. These limits reduced the dB from 164 to 134 dB. This is a pressure reduction from 0.5 psi to 0.018 psi or a reduction to 3.6 % of the limit shown in USBM Bulletin 656. It should be noted that the standards for damage criteria has been changed in the United States to accommodate the weakest single strength glass that is poorly set and under strain. Toughened glass has five times the strength of annealed glass. Hurricane proof glass (Dade County Building Code) for example must have a strength to withstand a 120 mph wind velocity at minimum. This value is near 0.4 psi. Single strength glass is commonly 1/16th in. thick. Double strength glass is twice as thick.

Table 8-2. Sound Level Limits.

	Linear peak		C-peak or C-fast	A-peak or A-fast
	dB	psi	dB	dB
Safe	128	0.007	120	95
Caution	128	0.007	120	95
	to	to	to	To
	134	0.018	130	115
Limit	134	0.018	130	115
	Recommended		Not Recommended	

(5) Siskind et al. (1980a) and ANSI S2.20-1983 reported weather influences on airblast propagation. Two atmospheric conditions are significant: temperature inversions and wind (direction and strength). Both of these conditions can increase airblast levels above what would be expected in their absence at a given scaled distance. They do not produce additional airblast energy, but only affect its distribution. In temperature inversions, warm air overlies cooler air. This is the reverse of the normal situation of steadily falling temperature with increasing altitude about 35,000 ft. Under normal conditions, airblast ray paths are bent away from the earth’s surface by the process of acoustic refraction (analogous to optical refraction of light). When an inversion exists, by contrast, these rays are bent downward in the inversion layer and can produce one or more focus points at large distances from the blast. A focus location will be an area of abnormally high airblast, with a relatively silent zone between it and the source.

(6) RI 8485 describes inversion-produced sound intensification of up to three times and averaging 1.8 times (5.1 dB). The American National Standards Institute (ANSI) standard also reports some tests of atmospheric focusing with a 1% chance of amplification two times above the standard curves. Temperature inversions are common in the mornings and evenings as the ground surface and air heat and cool at different rates. One reason that surface mines tend to blast near the middle of the day is to avoid these types of inversions. The DuPont Blasters’ Handbook (E.I. DuPont 1977) in-

cludes examples of inversion effects on airblast waves. Wind is the second significant weather influence on airblast propagation. Examples of wind effects are 10- to 15-dB increases of sound level downwind compared with levels in cross- or upwind conditions for quarry blasts, and a change of the propagation decay exponent proportional to wind velocity (Siskind et al. 1980a).

8-6. Far Field and Airblast Focusing.

a. Far Field (Airblast Focusing).

(1) Far field represents the region far from the blast site (i.e., 4 to 20 miles) where direct transmission cannot account for the effects produced. It represents a focusing or concentration of sound waves in a narrow region. These waves have traveled up into the atmosphere and have been refracted back to the earth, producing an intense overpressure in a narrow focal region.

(2) The cause of airblast focusing is the presence of an atmospheric inversion. The more severe the inversion, the more intense the focusing may be. Wind can also be a significant factor adding to the inversion effect.

b. Atmospheric Inversion.

(1) An atmospheric inversion is an abnormal, but not uncommon phenomenon. Normally temperature decreases with height in the atmosphere, cooling at the normal lapse rate of 3.5°F for each 1,000 ft of height. For example, assume a surface air temperature of 70°F, then under normal lapse rate conditions, the air temperature at 4,000 ft would be:

$$70°\text{F} - 4{,}000\text{ ft }(3.5°\text{F}/1{,}000\text{ ft}) = 56°\text{F}$$

(2) The velocity of sound in air is temperature dependent, increasing as temperature rises and gets warmer or decreasing as temperature falls and gets colder. The change is approximately 1 ft/second for a temperature change of 1°F. Under normal atmospheric conditions, the air temperature decreases with height so the velocity of sound decreases, causing the sound waves to curve upward away from the ground. The sound is absorbed in the atmosphere. Figure 8-4 shows this effect.

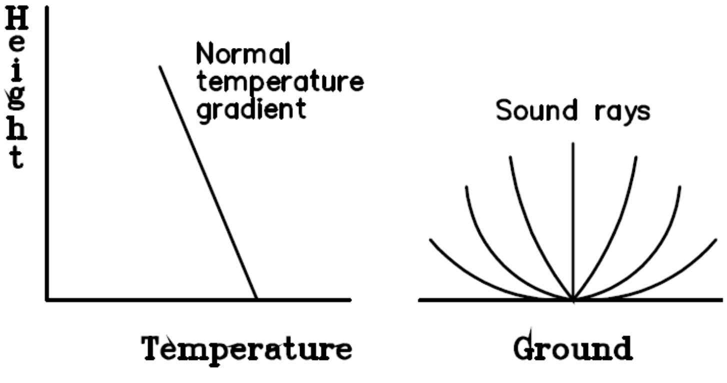


Figure 8-4. Normal Atmospheric Conditions (Konya and Walter, 2006).

(3) In an atmospheric inversion, the air temperature increases with height, so the velocity of sound increased, causing the sound waves to curve downward toward the ground. Thus, the sound may return to the earth, but at some distance from its point or origin. Figure 8-5 illustrates the inversion condition and the curving downward of the sound rays in the atmosphere.

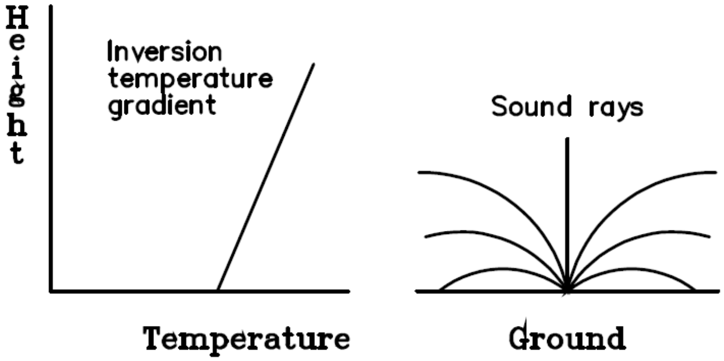


Figure 8-5. Atmospheric Inversion (Konya and Walter, 2006).

(4) When the sound returns to the earth as just described, it may under appropriate conditions concentrate or focus in a narrow region and produce much higher sound levels than in adjacent regions on either side. This effect is shown in Figure 8-6.

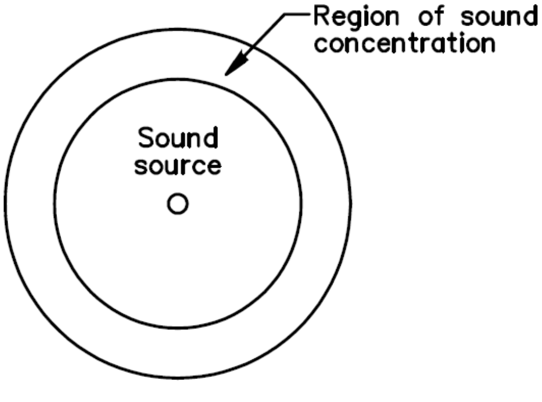


Figure 8-6. Sound Focusing-Inversion Effect (Konya and Walter, 2006).

c. Wind Effect.

(1) Wind may contribute significantly to causing airblast focusing. On the downwind side, the wind will add to the velocity effect produced by the inversion and increase the sound velocity. On the upwind side, the wind will oppose the velocity effect and decrease the sound velocity. If the wind is strong enough, the sound may be completely blown away from the upwind side. Figure 8-7 shows the wind effect.

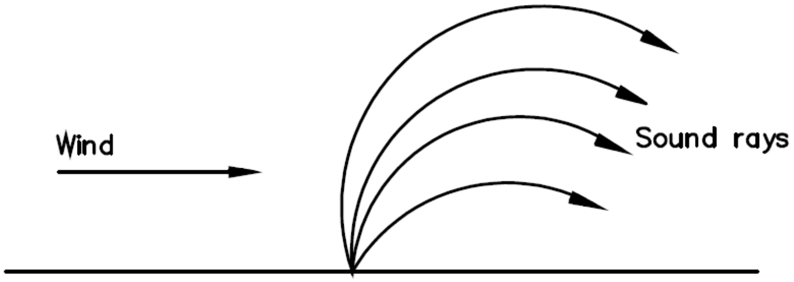


Figure 8-7. Wind Effect (Konya and Walter, 2006).

(2) The focal region previously shown as a circular region with sound source at the center may be reduced to a crescent shape by the wind effect, resulting in a higher sound intensity in the focal region (Figure 8-8).

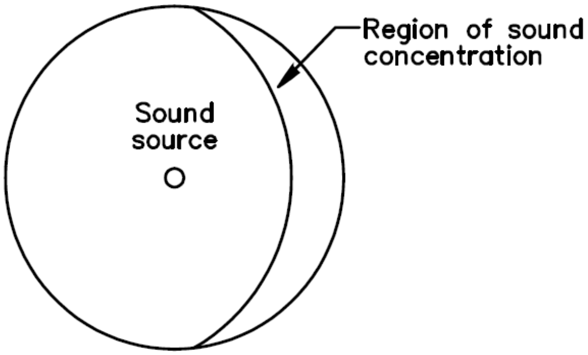


Figure 8-8. Airblast Focusing Plus Wind Effect (Konya and Walter, 2006).

(3) Airblast focusing is produced by the combination of an atmospheric temperature inversion and wind. The effect varies with height and must be evaluated at successive elevation (approximately every 1,000 ft.). This requires meteorological data and a sophisticated computer program to process it. This is not feasible for normal day-to-day operations. A diagram of intense airblast focusing is shown in Figure 8-9.

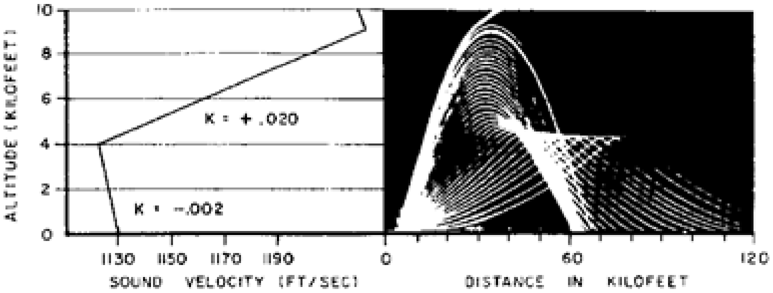


Figure 8-9. Airblast Focusing (Konya and Walter, 2006).

d. Procedures to Avoid Airblast Focusing:

(1) Do not shoot if there is an atmospheric inversion.

(2) Contact the local weather bureau to find out if there is an inversion.

(3) Radiation inversions commonly exist in the mornings, but normally disappear by noon. Hold the shot until the inversion has been dissipated. Frontal and air mass inversions tend to persist and do not go away.

(4) Obtain wind information from the Weather Bureau. If the downwind direction is a populated sensitive area, avoid shooting, if it is unpopulated or industrial shooting may be feasible.

8-7. Structural Responses Caused by Both Ground Vibration and Airblast.

a. Normal Damage.

(1) Normal to structures is considered if either the ground vibration or the air overpressure exceed specified limits. When blasting is close to structures the air overpressure can arrive before the ground vibration has been eliminated. In this case both ground vibration levels and air overpressure levels if considered independently could both be in safe zone.

(2) When these two forces interact and superimpose on the structural movement the vibration in the structure can be much greater than the measured ground vibration. This additional movement is due to the racking response of the building as a result of the additional stress caused by the air overpressure. The example shown in Figure 8-10 is from USBM RI. 8485. The normal blasting vibration and air overpressure limit on damage are not applicable when these forces superimpose.

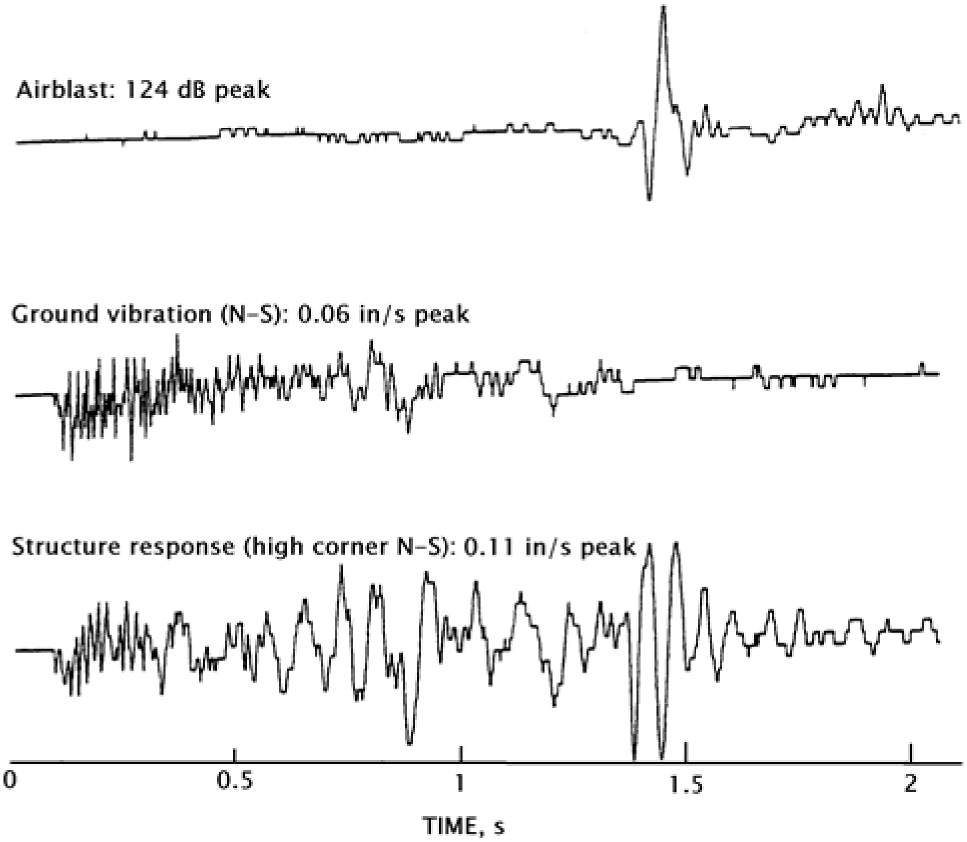


Figure 8-10. Structural Responses Caused by Both Ground Vibration and Airblast (Konya and Walter, 2006).

b. Comparison to Sonic Booms and Wind Pressure. Much research has been done on sonic boom-produced structure response. RI 8485 discusses six sonic boom studies in relation to mining airblast effects and concluded that responses were roughly comparable for equivalent overpressures. Winds of 25 miles per hour can produce similar effects (pressures of 1.6 lb/ft^2 or 131.7 dB) as discussed in Sutherland's study of sonic boom impacts. Wind-induced pressures on a planer wall are given by the relationship, $P= 0.00256 V^2$, where P is pressure in pounds per square foot and V is wind speed in miles per hour. Some researchers use a higher coefficient than 0.00256 based on assumptions of wind vs. height, gusts, and structure shape. Although such a wind is comparable in amplitude to a strong airblast, its effects are not as noticeable. This is because of the relatively slow rate of pressure changes caused by wind and the correspondingly minor or nonexistent rattling, in contrast to the relatively rapid pressure changes produced from airblast waves.

c. Safe Level Criteria. Table 8-3 lists the four recommended limits, depending on how the airblast is measured and analyzed. A good blasting relations program will require airblast levels be maintained far below the criteria. Siskind et al. (1980b) and Dick et al. (1983) discuss techniques of reducing airblast levels. EM 385-1-1 (2014) requires airblast levels to not exceed 133 dB on structures.

Table 8-3. Safe Level Airblast Criteria For Residential Structures.

Measurement system	Amplitude
0.1-Hz high-pass system	134 dB
2-Hz high-pass system	133 dB
5- or 6-Hz high-pass system	129 dB
C-slow (events not exceeding 2-sec duration)	105 dB
After Siskind, et al. (1980a)	

8-8. Ground Vibration.

a. Ground Vibrations Generated by Blasting.

(1) Measurement - Ground vibrations from blasting are typically measured with motion sensing transducers attached to either digital or analog recorders. The geophones or transducers are similar to seismic geophones except they are calibrated to perform over a specified frequency and amplitude range. Specialized “blasting seismographs” are self-contained devices shown in Figure 8-11, usually self-triggered and 4-channel (three ground vibration and one airblast). Figure 8-12 shows the time history for one channel and describes the wave parameters. In this chapter, the term “seismograph” will denote a blasting seismograph. Seismographs usually measure the ground movement in three mutually orthogonal (mutually perpendicular) directions. These “components of motion” have two axes in the horizontal plane and one vertical. The horizontal components are traditionally labeled “longitudinal” or “radial” (if the axis is pointing in the direction of the blast) and “transverse” (perpendicular to the direction of the blast).

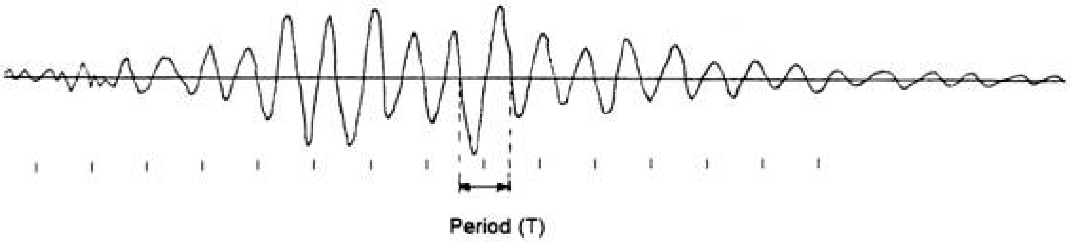
Figure 8-11. Seismograph with Attached Geophone.

GV-BLAST TIME HISTORY RECORD EXAMPLE

BLASTING TIME HISTORY
Amplitude versus time.
For this record, it is particle velocity amplitude. Vibration records could also be acceleration or displacement time histories depending on the devices used to measure the motion.

Period (T) is the time in seconds for one complete vibration cycle or "seconds per cycle."

Frequency (f) is 1/T or "cycles per second" also "Hz"



Period (and frequency) can usually be estimated by measuring the time between zero crossings, particularly for a record which has a uniform or one dominant frequency.

In this example, the timing marks represent 0.1 sec (100 ms) and the measured period is about 88 percent of the time between marks

Period (T): 0.88 x 0.1 sec = .088 sec
Frequency (f): 1/.088 = 11.4 Hz

Figure 8-12. Example of Ground Vibration Time History Record (Konya and Walter, 2006).

(2) Ground vibration measurements of velocity (V), displacement (D) or acceleration (A) are made at a point in the ground. Current practice specifies measuring velocity for damage assessment. Displacement, velocity, and acceleration are related through differentiation and integration, but can often be approximated by sine waves or parts of sine waves making simple conversions, as:

$$A = 2\pi f V = (2\pi f)^2 D \tag{8-9}$$

where f is the frequency in Hz (cycles per second). For accelerations in g's, the value in in/s^2 must be divided by 386 in/s^2/g. Unless otherwise specified, peak particle velocity (peak ground vibration) is defined as the highest particle velocity of all three components of motion without respect to a "plus or minus" sign.

(3) Vibration frequency can be determined in a variety of ways, including Fourier techniques and inversion of the periods read between zero crossings on the records. The fast Fourier transform provides the frequency distribution of the vibration history. It does not preserve amplitude information, but is an aid good for filtering, allowing the time signal to be reconstructed after filtering. Periods measured from the records are less rigorous, but maintain the intrinsic relationship between frequency and time history amplitude. The frequency is computed as the inverse of the period, or time needed for one cycle of oscillation:

$$f = 1/T \tag{8-10}$$

where T is the period in seconds. Analysis on peak particle velocity and the associated frequency is commonly used in blasting regulation because they correlate with observations of cracking (Nichols et al. 1971, Siskind et al. 1980b).

(4) Seismographs may record the peak amplitude or provide a time history record or waveform. Care should be taken when selecting seismographs. Peak recording instruments may also provide the vector sum of the three orthogonal components. Vector sum peak amplitudes will be higher by about 10 to 25%, and while appropriate for regulatory compliance monitoring, are seldom used since damage standards are based on the highest value of any single directional time history and not vector sum. In all cases, especially near-to-source monitoring, peak amplitude, frequency range, and mounting of the transducers need to be considered. Any time there is a question on vibration levels and or the possibility of tampering, a full waveform reading seismograph should be used. Normal operations would have the transducer package buried in soil, or hot glued or bolted on hard surfaces, this is critical when the expected vibration levels approach 0.2 g. Just placing the sensors on the ground (spiked or not), on a slab, or with sandbags is not sufficient as slippage and rotation can occur. Note: 0.2 g corresponds to 0.61 ips at 20 Hz, 1.2 ips at 10 Hz and 2.5 ips at 5 Hz. Transducer placement is intended to assess the vibration impacting a structure and should be measuring input. For this reason, and to be consistent with the structure response and damage, the transducer should be placed on solid ground or on a basement concrete slab and not on an upper story.

b. Propagation and Prediction.

(1) Propagation effects and geology change the amplitude and frequency character of ground vibrations as they travel from the blast region to measured locations. Dissipation or geometric spreading is generally characterized by an exponential decrease in amplitude with distance from the source. Generally, the strongest influence on amplitude is distance and the charge weight per delay.

(2) Distance and geology also influence ground vibration frequencies. Close to the blast (<1000 ft.), vibrations are dominated by high frequencies created by the time-delayed detonations of the blastholes. At distances beyond a few hundred feet, “surface waves” tend to dominate. Surface waves are particular types of low- frequency seismic waves generated by and characteristic of the geological structure and composition. At large distances from the blast (e.g., 1,000 ft.), changes in shot design will have little effect on the vibration frequency but will affect the peak particle velocity.

(3) The Bureau of Mines in RI 8507 distinguished frequencies associated with coal mine blasting, quarry blasting and construction blasting. Coal mine blasting produced the lowest frequencies, quarry blasting was next followed by construction blasting that produced the highest frequencies (shown graphically in Figure 8-13).

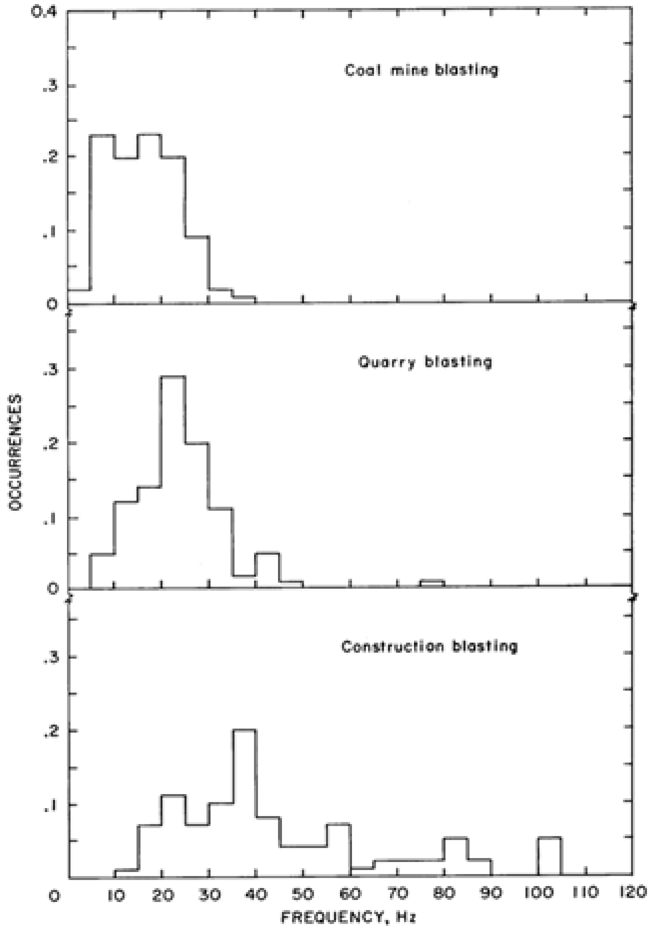


Figure 8-13. Predominant Frequency Histogram of Coal, Quarry, and Construction Blasts (USBM RI-1807)

(4) Although these frequencies are labeled as coal mine, quarry and construction the differences are due to shot size, distance, and rock properties that are characteristic of the operation. Distance is probably the most important factor since low frequency vibration will appear on any blast record if the distance is large enough. High frequency vibration attenuates rapidly because it requires much more energy than low frequency, the energy required varying as the square of the frequency. Thus, low frequency energy propagates to large distances.

c. Ground Vibration Scaled Distance (Ds).

(1) The formula for ground vibration scaled distance is:

$$Scaled\ Distance = \frac{Distance\ from\ Blast}{\sqrt{Pounds\ per\ delay}}$$

(2) Precision Pre-splitting produces different vibration levels than normal production blasting with the same size blastholes. With standard pre-splitting methods it has been found that the vibration can be as much as five times greater than a production blast using the same diameter blasthole

and the same scaled distance. This is because all holes are confined at the time they fire, producing greater particle velocity than a normal blast would at the same scaled distance' precision.

(3) Precision Pre-splitting is normally done using very light explosive loads or detonating cord. The scaled distance equation can be changed to the equation below for detonating cord with values in grains per foot:

$$Scaled\ Distance = \frac{Distance\ from\ Blast}{\sqrt{Grains\ per\ delay/_{7000}}}$$

(4) Using this scaled distance we can evaluate the ground vibration produced by a Precision Presplit.

d. Ground Vibration Analysis.

(1) Construction blasthole sizes are most commonly between 3.5 and 4.0 in diameter. Data from USACE projects in granite, limestone and shales were used to produce equations for vibration prediction in production blasting and precision pre-splitting with a 95 % confidence level. These equations can be used to predict the maximum ground vibration levels for a precision presplit blast with similar conditions. Equations for predicting Ground Vibration from Production blasts using 3.5- to 4.0-in. diameter blastholes (95% confidence level) (Konya) (U.S. Units):

$$PPV\ \left(\frac{in}{s}\right) = 50.87 * (Scaled\ Distance)^{-1.15} \qquad (8\text{-}11)$$

(2) Equations for predicting Ground Vibration from Precision Presplit blasts using 3.5- to 4.0-in. diameter blastholes (95% confidence level) (Konya) (U.S. Units):

$$PPV\ \left(\frac{in}{s}\right) = 26.79 * (Scaled\ Distance)^{-0.92}$$

(3) Figure 8-14 shows how precision pre-splitting compares to production blasting in terms of ground vibration (in/sec). For lower scaled distances precision presplitting actually produces lower vibration levels than a production blast. At the larger scale distances, precision presplitting produces more vibration, but significantly less than standard presplit blasting.

(4) These equations and the data in Table 8-4 indicate that when precision presplitting is used, the ground vibration is similar to that which results from the same scaled distance from production blasts (Figure 8-15). Standard pre-splitting methods cause the vibration to increase by as much as a factor of 5 because more energy is used than is needed to form the presplit crack. This additional energy causes an increase in the seismic energy (vibration) produced.

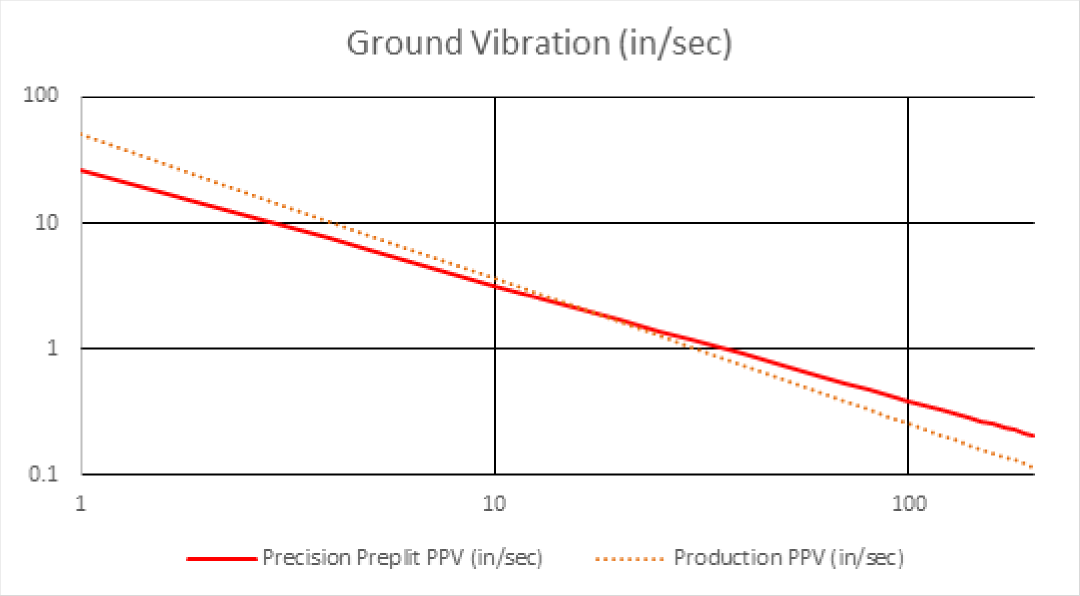


Figure 8-14. Ground Vibration Graph.

Table 8-4. Ground Vibration (Presplit and Production).

Ds	PPV (in/sec) (Presplit)	PPV (in/sec) (Production)
10	3.22	3.60
20	1.70	1.62
30	1.17	1.02
40	0.90	0.73
50	0.73	0.57
75	0.50	0.35
100	0.39	0.25
200	0.20	0.11
400	0.11	0.05

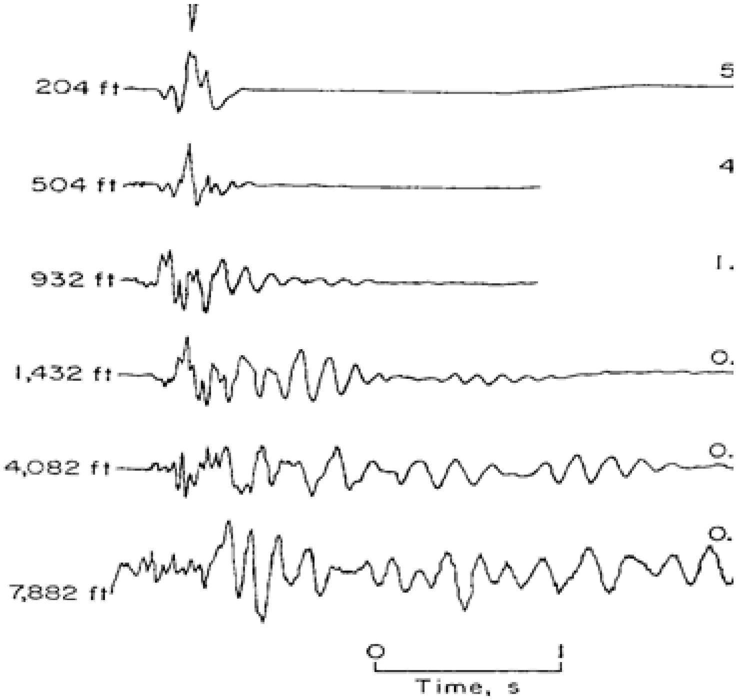


Figure 8-15. Sets of Waveforms from a Propagation Array of Seven Seismographs at Different Distances (from USBM RI 9226 1989).

(5) Recommendations for safe blasting and the regulations based on those recommendations apply to vibrations measured outside and close to the structures of concern. The regulations include effects of structure response where the blast frequency matches the structures natural frequency. Consequently, safe guidelines for such low-rise and lightweight structures will not necessarily apply to other structures such as large-span or high-rise buildings unless they have similar response frequencies and maximum structure response amplifications as those studied. In practice, most blasting damage issues involve one- and two-story residences (Figure 8-16).

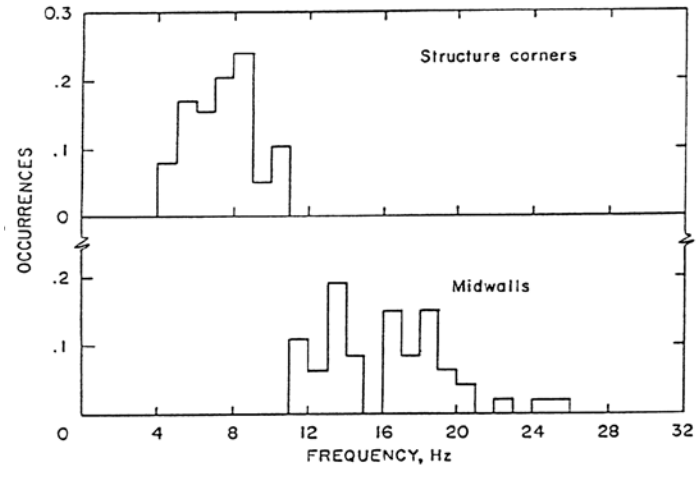


Figure 8-16. Natural Frequencies of Residential Structures as Reported in USBM RI 8507 (1980).

e. Vibration Scale (Konya).

(1) It is often difficult for the public to understand the magnitudes of vibration from blasting and relate this to normal environmental vibration that they sense every day. Since blast vibration is A-Cultural and triggers response people become concerned about vibration levels from blasting while they are not concerned about the same vibration levels from Cultural vibration ,which occurs every day in their lives. To put vibration in the proper perspective we can compare both the A-Cultural and Cultural vibration magnitudes. To do this in a simple understandable manner, use the Konya Scale where we can divide the vibration levels into 20 different classes (Table 8-5). We can start with a peak particle velocity of 0.001 to less than 0.002 in. per second and put all vibration less than 0.002 in. class one. Class one is the level at which some (very few) people can perceive vibration. We then double the previous number from 0.001 to 0.002. Class two vibration would be 0.002 to less than 0.004. Class three would double again to 0.004 but less than 0.008 and so on.

(2) This class method can be used for both blast effects and separately for environmental vibration. The two charts can then be easily compared without confusion. Konya's Blast Effects Scale shows the PPV levels and the class numbers for Human perception and potential damage ,which can result at high vibration levels. Konya's Environmental Vibration Scale shows vibration levels from normal activities.

(3) For example, class five vibration is the level where most people perceive vibration (Table 8-6, which lists Konya's Blast Effects Scale) and some become concerned that the vibration will damage their home. Class five on Konya's Environmental Vibration Scale shows that all normal activities on the chart produce vibration at class five or greater. In general most regulatory bodies allow vibration to at least class 10 because they understand that no structural damage can occur in homes at these vibration levels.

Table 8-5. Environmental Vibration Scale (Konya).

	Vibration Scale, Class 1 To 20																			
Activity	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Walking	X	X	X	X	X															
Train Nearby	X	X	X	X	X	X														
Walking On Wood Floor	X	X	X	X	X	X	X													
Pile Driving, Punch Barge	X	X	X	X	X	X	X	X												
Garbage Disposal	X	X	X	X	X	X	X	X	X											
Jumping	X	X	X	X	X	X	X	X	X											
Door Slams	X	X	X	X	X	X	X	X	X											
Pounding Nails	X	X	X	X	X	X	X	X	X	X										
Daily Environmental Change	X	X	X	X	X	X	X	X	X	X	X	X								
Riding In Automobile	X	X	X	X	X	X	X	X	X	X	X	X	X							
Peak Particle Velocity (Ips) (Threshold Values)	0.001	0.002	0.004	0.008	0.016	0.032	0.064	0.128	0.256	0.512	1.024	2.048	4.096	8.192	16.38	32.77	65.54	131.0	262.1	524.2

Table 8-6. Blast Effects Scale (Konya).

Effects	Vibration Scale, Class 1 To 20																			
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Perception By Older Population	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Perception By All					X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Water Ripples						X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Pipes Rattle						X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Loose Objects Rattle						X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Crack Extensions In Plaster (Invisible)											X	X	X	X	X	X	X	X	X	X
Crack Extensions (Visible)												X	X	X	X	X	X	X	X	X
New Crack Formation (Plaster)													X	X	X	X	X	X	X	X
Fine Cracks In Masonry													X	X	X	X	X	X	X	X
Broken Windows													X	X	X	X	X	X	X	X
Chimney Damage														X	X	X	X	X	X	X
Large Cracks In Masonry Walls														X	X	X	X	X	X	X
Cracks Concrete Walls																		X	X	X
Cracks Concrete Slabs																			X	X
Cracks Massive Concrete																				X
Peak Particle Velocity (Ips) (Threshold Values)	0.001	0.002	0.004	0.008	0.016	0.032	0.064	0.128	0.256	0.512	1.024	2.048	4.096	8.192	16.38	32.77	65.54	131.07	262.14	524.29

f. Factors Effecting Vibration.

(1) If blasting operations were conducted with 100% efficiency, one would expect that if the same type of blast was done many times, the same particle velocity would result. It is obvious from the previous sections that there is a great deal of variability in vibration levels even if the same thing is done each time. It is not uncommon for two blasts that are designed theoretically identically to perform quite differently in the field. This is especially confusing when two blasts are side by side in what appears to be uniform rock material and the vibrations are measured at a particular home thousands of feet from the blast. It would seem that the vibration should be very similar since the energy is following almost the identical path through the ground from the blast area to the home. Then why

then is there such a great difference in our blasting vibration. How do frequencies change from blast to blast? There are many factors that affect vibration transmission. Table 8-7 lists these factors.

Table 8-7. Factors Effecting Vibration.

1. Burden
2. Spacing
3. Subdrilling
4. Stemming depth
5. Type of stemming
6. Bench height
7. Number of decks
8. Charge geometry
9. Powder column length
10. Rock type
11. Rock physical properties
12. Explosive energy
13. Actual delivered energy
14. Number of primers
15. Primer Composition
16. Boosters
17. Geologic factors
18. Number of holes in a row
19. Number of rows
20. Type of initiator
21. Row-to-row delays
22. In-hole delays
23. Initiator accuracy
24. Distance to structure
25. Face angle to structure

(2) The above listing indicates the importance of the execution of the blast design in the field. Changes in burden, spacing, stemming, powder column length, number of rows, number of holes, or types of delays can change the vibration produced. Precise execution of the blast design with limitations of the tolerances and deviations from the design hole-to-hole will drastically reduce vibration. Vibration records will begin to resemble one another if the variability in the design parameter is controlled.

g. Vibration Standards.

(1) The present vibration standards are the result of more than a half century of research and investigation by concerned scientists. The first significant investigation was initiated by the U.S. Bureau of Mines in 1930, and culminated in 1942 with publication of Bulletin 442, Seismic Effects of Quarry Blasting. This and other programs will be briefly described.

(2) Per Thoenen and Windes. 1942. <u>Seismic Effects of Quarry Blasting</u> U.S. Bureau of Mines, Bulletin 442:

<u>Acceleration</u> <u>Index</u>
Safe zone - less than 0.1 g
Caution zone - between 0.1 and 1.0 g
Damage zone - greater than 1.0 g

(3) Per Crandell, F.J. 1949. Ground Vibration Due to Blasting and Its Effect Upon Structures. Journal of the Boston Society of Civil Engineers:

$$\textit{Energy Ratio Index}\ (\mathrm{ER}) = \left(\frac{a}{f}\right)^2 \qquad (8\text{-}12)$$

where:

a = Acceleration (ft/s^2)

f = Frequency (Hz)

Safe zone = ER less than 3

Caution zone = ER between 3 and 6

Damage zone = ER greater than 6

Energy Ratio has the dimension of velocity and an ER = 1 is equivalent to a particle velocity = 1.9 in/s

(4) Per Langefors, Westerberg, and Kihlstrom. 1958. Ground Vibration in Blasting, Parts I-III, Water Power, 1958:

Velocity Index
No damage - less than 2.8 in/s
Fine cracks - 4.3 in/s
Cracking - 6.3 in/s
Serious cracking - 9.1 in/s

(5) Per Edwards and Northwood. 1959. Experimental Blasting Studies on Structures. National Research Council. Ottawa: Canada:

Velocity Index
Safe zone - Less than 2.0 in/s
Damage - 4.0 to 5.0 in/s

(6) Per Nichols, Johnson, and Duvall. 1971. Blasting Vibration and Their Effects on Structures. U. S. Bureau of Mines, Bulletin:

Velocity Index
Safe zone - less than 2.0 in/s
Damage zone - greater than 2.0 in/s

(7) In addition to the Bureau's own work, Bulletin 656 is also a synthesis of the work of the number of other investigators. Particle velocity is considered to be the best measure of damage potential. The safe vibration criterion was specified in Bulletin 656 as follows:

(a) The safe vibration criterion is based on the measurement of individual components, and if the particle velocity of any component exceeds 2 in/s damage is likely to occur.

(b) Damage means the development of fine cracks in plaster. Very quickly the particle velocity, 2 in/s, became known as the "safe limit." Many regulations were and continue to be still based on this value. Additional levels of vibration based on the results of other investigations used in Bulletin 656 are:

- Threshold of damage (4 in/s).
    - Opening of old cracks.
    - Formation of new cracks.
    - Dislodging of loose objects.
- Minor damage (5.4 in/s).
    - Fallen plaster.
    - Broken windows.
    - Fine cracks in masonry.
    - No weakening structure.
- Major damage (7.6 in/s).
    - Large cracks in masonry.
    - Shifting of foundation-bearing walls.
    - Serious weakening of structure.

(c) The major damage zone correlates reasonably well with the beginning damage level for natural earthquakes.

h. Recent Damage Criteria.

(1) In 1980, the U.S. Bureau of Mines reported on its most recent investigation of surface mine blasting in RI 8507 (Siskind, et al.). Structural resonance responding to low frequency ground vibration, resulting in increased displacement and strain, was found to be a serious problem.

(2) This reintroduced the dependence of damage on frequency. Prior to this, the safe limit particle velocity was independent of frequency. Also, measurements were made inside structures rather than just by ground measurements. Inside measurement seems quite reasonable and logical, but data from previous investigations of structural vibration yielded very poor results, hence, the emphasis on ground measurement.

(3) The threshold of damage used in RI 8507 was specified as cosmetic damage of the most superficial type, of interior cracking that develops in all homes, independent of blasting.

(4) The safe vibration level was defined as levels unlikely to produce interior cracking or other damages in residences.

(5) Safe vibration levels as specified in RI 8507 are listed in Table 8-8 and shown in Figure 8-17. These criteria are based on a 5% probability of damage.

Table 8-8. Safe Peak Particle Velocity For Residential Structures (RI 8507).

Type of Structure	f < 40 Hz	f > 40 Hz
Modern homes - drywall interiors	0.75 in/s	2 in/s
Older homes - plaster on wood lath for interior walls	0.50 in/s	2 in/s

(6) These safe vibration levels represent a conservative approach to damage after the U.S. Bureau of Mines changed the definition of damage.

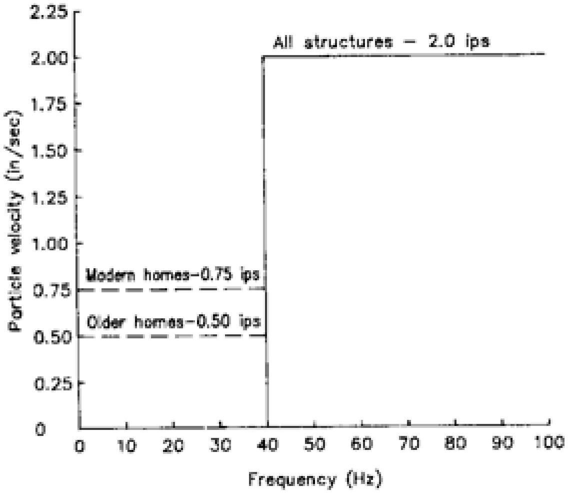


Figure 8-17. Safe Vibration Levels (RI 8507).

i. Alternative Blasting Criteria.

(1) RI 8507 also proposed alternative blasting criteria using a combination of displacement and velocity criteria applied over several frequency ranges. These alternative criteria are shown in Figure 8-18.

(2) These criteria using both displacement and velocity over respective frequency ranges have not been accepted by all concerned. Instrumentation will need frequency reading capability in addition to the capability of reading both displacement and velocity in order to cover all ranges. This indicates the state of flux in which the question of safe vibration standards existed, which still exists today.

(3) The problem is associated with the concept of what really constitutes vibration damage. The most superficial type of cracking advocated in RI 8507 is scarcely a realistic guide for control. Limiting vibration to a level with a low probability of producing the most superficial type of cracking will cost industry untold millions of dollars. What is the alternative? Damage of this description, if it occurs could be handled through insurance adjustment.

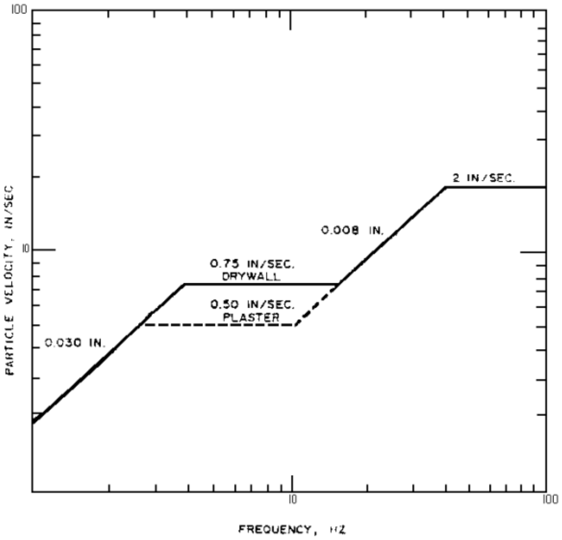


Figure 8-18. Alternative Blasting Level Criteria (RI 8507, U.S. Bureau of Mines).

(4) An important consideration to be noted is that there probably is no lower limit beyond which damage will not occur, since there will always be structures at the point of failure due to normal environmental stresses. It is not unusual to read of a structure collapsing for no apparent reason.

(5) In RI 8896, (1984), "Effects of Repeated Blasting on a Wood-Frame House" U.S. Bureau of Mines, it indicates that cosmetic cracks occurred during construction of a test house and also during periods when no blasts were detonated. It was further noticed that human activity, temperature, and humidity changes caused strains equivalent to ground particle velocity of 1.2 in/s to 3.0 in/sec.

j. The Office of Surface Mining Regulations.

(1) The Office of Surface Mining, in preparing its regulations, modified the Bureau of Mines proposed criteria based on counter proposals that it received and came up with a less stringent standard similar to the Bureau of Mines alternative safe blasting criteria. Recognizing a frequency dependence for vibration associated with distance, the Office of Surface Mining Presented its regulation as listed in Table 8-9.

Table 8-9. Office of Surface Mining's Required Ground Vibration Limits.

Distance from the Blasting site (ft)	Maximum allowable peak particle velocity (in/s)	Scaled distance factor to be applied without seismic monitoring
0 to 300	1.25	50
301 to 5000	1.00	55
5001 and beyond	0.75	65

(2) Table 8-9 combines the effects of distance and frequency. At short distances, high frequency vibration predominates. At larger distances, the high frequency vibration has attenuated or died out and low frequency vibration predominates. Buildings have low frequency response characteristics and will resonate and may sustain damage. Therefore, at large distances a lower peak particle velocity, 0.75 in/s, and a larger scaled distance, Ds = 65, are mandated. At the shorter distances, a higher peak particle velocity, 1.25 in/s, and a smaller scaled distance, Ds = 50, are permitted.

(3) The displacement and velocity values and the frequency ranges over which each applies as specified by the Office of Surface Mining are shown in Figure 8-19.

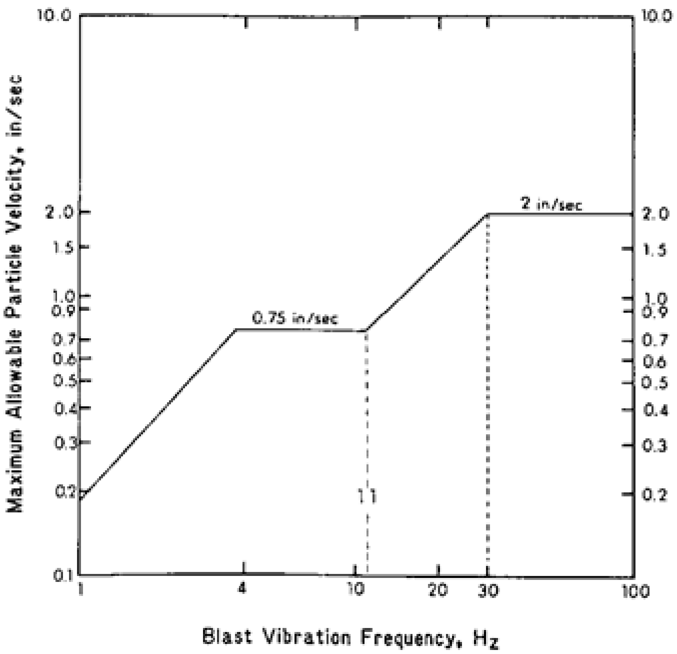


Figure 8-19. OSM Alternative Blasting Level Criteria (Modified from Figure B 1, RI 8507 U.S. Bureau of Mines).

k. Long Term Vibration and Fatigue.

(1) Blasting vibration is a short term phenomenon. The question of repeated blasting effects arises regularly as a point of concern. These could be included with the effects from pile driving and recurring industrial operations. Generally, the effects are relatively low level vibrations, which individually fall below recommended levels of safe vibration and are not considered as potentially damaging.

(2) There is not much information available on this topic, which is generally not regarded as an important problem.

(3) One investigation by Walter, 1967, used impact vibration continuously generated in a structure for approximately 13 months, 24 hours a day. The structure was an ordinary room approximately 8 x 8 x 8 ft. of dry wall construction. The vibrator was mounted on the ceiling, generating motion that was transmitted throughout the structure and surrounding area.

(4) The natural frequency of the wall panels was 12.5 Hz and the ceiling panel was 60 Hz. Vibration frequencies measured in the wall panels ranged from 10 to 18 Hz. with particle velocity ranging from 0.05 to 0.16 in/s.

(5) The total time of vibration was of the order of 30 million seconds. No noticeable effects resulted from this extended vibration. It was concluded that low level vibration even in the natural frequency response range of the structure has practically zero potential for causing damage.

(6) The U.S. Army Corp. of Engineers, Civil Engineering Research Laboratory, CERL, conducted a fatigue test for the U.S. Bureau of Mines using a biaxial shake table on which was mounted a typical residential room, 8 x 8 x 8 ft. The shake table was programmed with one horizontal component and the vertical component of a quarry blast from Bulletin 656 whose predominant frequencies were 26 and 30 Hz respectively.

(7) Vibration test levels were 0.1, 0.5, 1.0, 2.0, 4.0, 8.0, and 16.0 in/s. Each was run a series of times starting with one run, then five runs, then 10, 50, 100, and 500 runs with inspection after each series. No damage occurred until the sixth run at 4.0 in/s. This sixth run was preceded by 2669 prior runs with no damage. In fact, there were 666 runs at 2.0 in/s and five at 4.0 in/s. with no damage. It is significant to note that when damage occurred it occurred at a particle velocity in excess of 2.0 in/s.

(8) Koerner tested 1/10 scale block masonry walls at resonant frequencies. Failure was observed after approximately 10,000 cycles at particle velocities of 1.2 to 2.0 in/s. Later tests on 1/4 scale block walls showed cracking after 60,000 to 400,000 cycles at particle velocities 1.69 to 1.95 in/s.

(9) These studies show that fatigue effects such as cracking may occur at vibration levels that are relatively high.

l. Vibration Effects. Cracks produced in structures by natural earthquakes, which are low intensity effects, have a characteristic pattern called the X - crack or vibration crack. These cracks result from the fact that the top of a structure, due to its inertia, lags behind. The structure is deformed from a regular rectangular shape into a parallelogram, with one of its diagonals elongated and the other compressed. If the elongation exceeds the strength of the material, it will fail producing a tension crack. As the earth vibration reverses, the same thing will occur in reverse, with the opposite diagonals being elongated and compressed with the possible formation of another tension crack. When both cracks occur they form an X - crack pattern. Figure 8-20 illustrates the process. If it occurs, the X - crack pattern is most likely to be associated with large blasts.

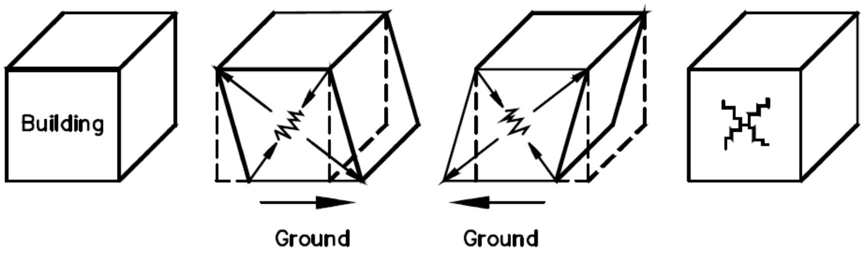


Figure 8-20. Vibration X – Crack Pattern.

m. Directional Vibration Effects.

(1) The energy that moves out from the source of the blast, measured in terms of ground vibration and peak particle velocity, moves out in all directions from the source. If the ground would transmit vibration in the same manner in all directions and if all other factors remain constant, then theoretically at the same distance in any direction from a blast, the vibration levels would be equal. Unfortunately, on true job conditions, vibration transmission is not ideal and because of changes in the earth structure, vibration is transferred differently in different directions. The geologic structure, joints and faults, will change vibration levels and frequency in different directions of the source. Other factors dealing with blasting pattern design can also contribute to these directional vibration effects.

(2) In the past, it was common practice to monitor behind the blast at the nearest structure since it was assumed that in this direction vibration levels would be greatest. Recommendations for monitoring practice have changed and research has shown that the highest vibration levels are commonly, not behind the shot, but to the sides of the blast. In particular, vibration levels are commonly highest in the direction toward which the delays are progressing. For example, if a blast is fired with the first hole on the left hand side of the pattern and the delays are progressing toward the right hand side of the pattern, then in the direction toward the right hand side of the pattern one would commonly find the highest vibration levels.

(3) In order to calibrate the ground and determine site specific transmission characteristics, it is recommended that at least two seismographs be used when blasting in close proximity to structures. One seismograph placed on the end of the shot and one at 90 degrees. For example, behind the blast. After test shooting is completed and the transmission characteristics are known, the second seismograph may be unnecessary since the ground has already been calibrated and vibration levels in one direction can be related to vibration levels in the other direction.

n. Frequency Wave Length Effects.

(1) When a line of increased motion occurs, what are its dimensions and how large an area is affected? It will cover a space of the order of one to two wavelengths. Wavelength is defined as propagation velocity multiplied by the wave period:

$$L = V\ T \qquad (8\text{-}13)$$

where:

L = Wavelength (ft.)

V = Propagation velocity (ft/s)

T = Wave period (s)

For a wave of period 1/10 second and propagation velocity 2,000 ft/second, the wavelength is 200 ft.

Assuming the waves are approximately the same (Figure 8-21), at maximum coincidence, the motion would be doubled but the wave length will be that of either wave since they are the same (Figure 8-22).

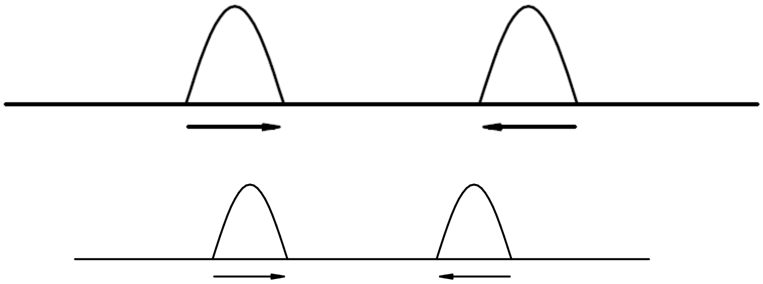


Figure 8-21. Converging Equal Wavelets.

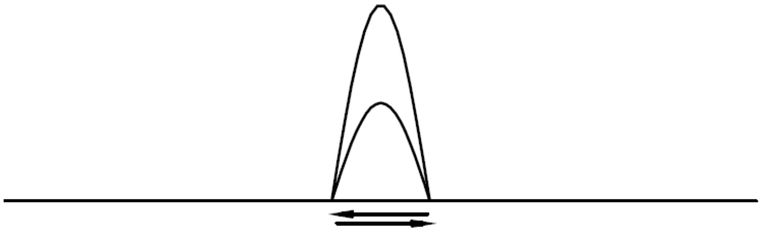


Figure 8-22. Composite Wave Motion at Maximum Coincidence.

(2) This form will be repeated after the maximum has occurred when the waves pass complete coincidence and begin to separate each into its own distinct form. Thus, there is a periodicity whose wavelength approaches the sum of the two wavelengths. Also, the wavelength of the composite motion varies from a single wavelength to approximately double the single wavelength. The converging and diverging wavelets are shown in Figure 8-23.

(3) The wave period and the frequency are both effected. At the point of maximum coincidence the period and frequency are those of the single wave. Since the period may approach double that of a single wave, the frequency will be cut approximately in half.

(4) The significant points here are that they can exist:

(a) A region of increased seismic motion and hence increased peak particle velocity with maximum at the center, minimum at the edges of the resultant combined waves.

(b) The region in which this occurs, the order of two wave lengths wide approximately 400 to 800 ft. depending on propagation velocity and wave period.

(c) Wave periods will be increased to approximately double with a corresponding lowering of the frequency to half.

(d) A region of high-seismic risk because of the increased motion and reduced frequency of vibration.

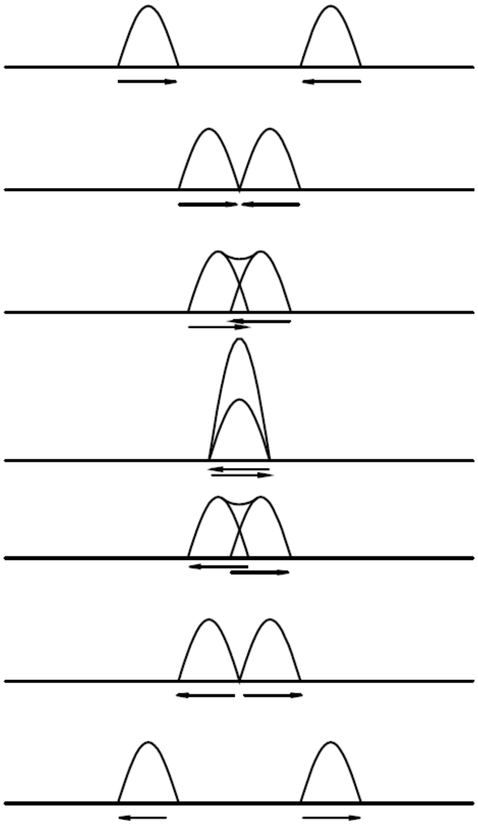


Figure 8-23. Converging and Diverging Wave Interaction.

o. Non-Damage Effects. Damage producing vibration seldom occurs, but many other effects occur that are disconcerting and alarming to persons who feel and hear the vibration. Some of these effects are:

- Walls and floors vibrate and make noise.
- Pipes and duct work may rattle.
- Loose objects, plates, etc., may rattle.
- Objects may slide over a table or shelf, and may fall off.
- Chandeliers and hanging objects may swing.

- Water may ripple and oscillate.
- Noise inside a structure is greatly amplified over noise outside.
- Vibration is very disturbing to occupants.

p. Causes for Cracks Other Than Blasting. Cracking is a normal occurrence in the walls and ceilings of structures, and the causes are multiple, ranging from poor construction to normal environmental stress, such as thermal stresses, wind, etc. The Small Home,* published by the Architects Small House Service Bureau of the United States, Inc. 1925, gave a list of reasons for the development of cracks, which included:

- Building a house on a hill.
- Failure to make the footings wide enough.
- Failure to carry the footings below the frost line.
- Width of footings not made proportional to the loads they carry.
- The posts in the basement not provided with separate footings.
- Failure to provide a base above the basement floor line for the setting of wooden posts.
- Not enough cement used in the concrete.
- Dirty sand or gravel used in the concrete.
- Failure to protect beams and sills form rotting through dampness.
- Setting floor joists one end on masonry and the other end on wood.
- Wooden beams used to support masonry over openings.
- Mortar, plaster, or concrete work allowed to freeze before setting.
- Braces omitted in wooden walls.
- Sheathing omitted in wooden walls (excepting in “back- plastered” construction).
- Drainage water from roof not carried away from foundations.
- Floor joists not bridged.
- Supporting posts too small.
- Cross beams too light.
- Sub-flooring omitted.
- Wooden walls not framed so as to equalize shrinkage.
- Poor materials used in plaster.

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*Published in Monthly Service Bulletin 44 of the Architects’ Small House Service Bureau of the United States, Inc.

- Plaster applied too thin.
- Lath placed to close together.
- Lath run behind studs at corners.
- Metal reinforcement omitted in plaster at corners.
- Metal lath omitted where wooden walls join masonry.
- Metal lath omitted on wide expanses of ceiling.
- Plaster applied directly on masonry at chimney stack.
- Plaster applied on lath that is too dry.
- Too much cement in the stucco.
- Stucco not kept wet until set.
- Subsoil drainage not carried away from walls.
- First coat of plaster not properly keyed to backing.
- Floor joists placed too far apart.
- Wood beams spanned too long between posts.
- Failure to use double joists under unsupported partitions.
- Too few nails used.
- Rafters too light or too far apart.
- Failure to erect trusses over wide wooden openings.

q. Blast Design Adjustment to Reduce Vibration Levels. When vibration levels are too high and it becomes desirable and even necessary to reduce them, there are a number of options.

(1) Charge Reduction. The maximum charge per delay may be reduced by decreasing the number of holes per delay. If the number of holes per delay cannot be reduced then it may be possible to deck load and fire each hole with two or more delays.

(2) Blast Design. The vibration level can be reduced by redesigning the blast so that less energy per hole is necessary to fragment the rock. This may require changing the hole spacing, the burden and even the hole size. A change in explosive may be helpful also. This requires going back to square one and starting over. This is an extreme circumstance and not likely to be necessary.

r. Blasting Standard for Non-Residential Structures. Vibration standards can be divided into two other groups in addition to the normal building standards, high level vibration structures and low level vibration sensitive components.

s. Blasting Near Concrete Structures. On many demolition projects, old concrete is near the blasting operation. In fact, it is not uncommon to blast away part of a structure, leaving the other structure intact. This is a common procedure when locks along rivers need to be refurbished. When locks become eroded due to the water and the environmental conditions, approximately 2 ft. of old concrete is blasted away and new concrete is poured in its place. It is obvious that the concrete that remains from the original structure has been subjected to very high peak particle velocity. Oriard measured values of strain and peak particle velocity that produced various types of failure in concrete. His results are given in Table 8-10 (Oriard).

t. Green Concrete. Concrete and bridges fall into the high level vibration structures. Green concrete, however, is not in this group. Different types of concrete exist. Therefore, general conservative guidelines for concrete may be given. Since concrete acquires about one-third its strength in 72 hours, after this time a peak particle velocity of 1.0 in/s is a reasonable maximum until the concrete reaches full strength at 28 days. Before 72 hours it is not advisable to blast.

u. Blasting Near Green Concrete. It is not uncommon to have blasting operations in one section of a project and the pouring of concrete in another. Contractors do have concern as to what effect the blasting vibration has on the integrity of the new structure being poured. Table 8-10 lists some guidelines for peak particle velocities related to time after pouring. Previous studies conducted by Oriard and the Tennessee Valley Authority (TVA) in 1976 and the Portland Cement Association (PCA) have recommended limits. Table 8-11 incorporates the PCA limits and is more conservative than the Oriard TVA limits. As discussed above, it is not advisable to blast within 72 hours of concrete placement.

Table 8-10. Failure In Concrete Due To Vibration.

Type	Strain (µin/in)	PPV (in/s)
Static	140	20
Grout Spall	700	100
Skin Spall	1300	200
Cracking	2400	375

Table 8-11. Recommended Vibration Levels for Green Concrete.

Time After Placement		PPV (in/s)
0 - 10	Hours	0.1
10 - 24	Hours	2.0
24 - 48	Hours	3.0
2 - 3	Days	4.00
4 - 7	Days	6.00
8 - 10	Days	8.00
> 10	Days	10.00

v. Grout Curtain.

(1) A grout curtain is a mortar mix that is injected under high pressure into the formation and becomes a part of the formation. The grout curtain moves with the formation. Past research shows that the minimum particle velocity to break the weakest rock members is 10 to 20 ips.

(2) A grout curtain does not function as a concrete column or as shotcrete in a tunnel because there is no flexure or spalling occurring with the grout curtain as would occur in a concrete column or concrete walls or with shotcrete tunnel lining. The grout curtain instead moves with the rock mass similar to mass concrete.

(3) Konya therefore suggests the conservative "Vibration Levels for Grout Curtains" listed in Table 8-12. These vibration limits fit the actual field data. These are in my opinion conservative limits that are reported from real field data and should supersede the earlier recommendations that were not supported by actual field measurements.

Table 8-12. Vibration Levels For Grout Curtains (Konya).

Time After Placement		PPV (in/s)
0 – 24	Hours	2.0
24 - 48	Hours	3.0
2 - 3	Days	5.00
4 - 7	Days	7.00
8 - 10	Days	9.00
> 10	Days	10.00

w. Bridges. Bridges present a variety of sizes, types, construction, age, etc. A steel structure and reinforced concrete structure would minimally be covered by 2.0 in/s and might go to 5.0 in/s.

x. Buried Pipelines. Buried pipelines such as gas and oil transmission lines are normally fabricated of steel, which has a much greater strength than the rock or soil in which it is buried. The primary consideration is that the pipe should be in the elastic zone and never in the fracture zone. This can be accomplished by employing a standoff distance from the blasthole equal to 3 to 5 times the hole spacing. If the hole spacing is 6 ft. then the standoff distance is 18 to 30 ft.

y. Computers and Hospitals. Computers and hospitals fall into the low level sensitive category. It is usually not the hospital structure that is of concern but instrumentation employed therein. It is usually not possible to get vibration specifications for the delicate instrumentation used in the hospital. A practical procedure is to measure the ambient background vibration in the sensitive areas of the hospital and compare this with a Test Shot.

z. Computer Specifications. Computer specifications are usually frequency dependent changing with the frequency range. One computer manufacturer has specifications listed in Table 8-13.

Table 8-13. Floor Vibration.

Frequency Hz	Double Amplitude	Acceleration
5-25	0.001 in / 0.0254 mm	
25-100	0.0005 in / 0.0127 mm	
100-300		0.25 g / 2.45 m/s^2

8-9. Sensitivity to Vibration.

a. Human beings are remarkably sensitive to vibration. If this were not so, the vibration problem would scarcely exist. The explosive technology of today insures that most operations are conducted in a safe manner. In relatively few cases is there a significant probability of damage.

b. Since vibration is felt in practically all cases, the reaction to this sensation is one of curiosity, concern, and even fear. Hence, it is important to understand something about human response to vibration that depends on vibration levels, frequency and duration. In addition to these physical factors, it is important to keep in mind that human response is a highly subjective phenomenon.

c. Human response has been investigated by many researchers. One of the early investigations was by Reiher and Meister, Berlin, 1931. Other investigations were made by Goldman, 1948, and Wiss and Parmelee, 1974. A composite of these investigators’ results was presented graphically in the U.S. Bureau of Mines RI 8507, Siskind, et al., 1980. This composite is represented here in Figure 8-24.

d. The human response curves are all similar and highly subjective in that the response is a mixture of physiological and psychological factors individual to each person. Based on these curves, a very simple and practical set of human responses can be designated as listed in Table 8-14.

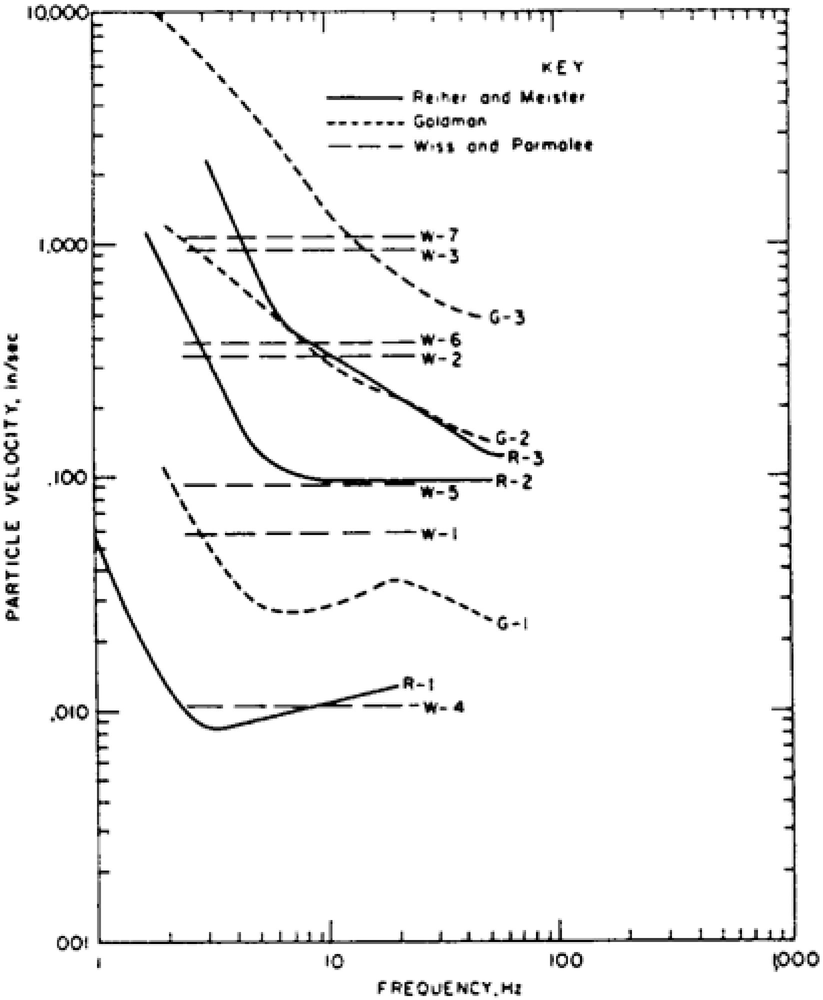

Figure 8-24. Human Response to Vibration (RI 8507).

Table 8-14. Human Response.

Response	Particle velocity	Displacement at 10 Hz	Displacement at 40 Hz
Noticeable	0.02 in/s	0.00032 in	0.00008 in
Troublesome	0.2 in/s	0.0032 in	0.0008 in
Severe	0.7 in/s	0.011 in	0.0028 in

e. Vibration is a fact of daily life, which one regularly experiences but is seldom aware of. This type of vibration has been designated Cultural vibration. Generally, it elicits no reaction from the person affected.

f. Other vibration that contrasts sharply, because it is not part of the daily experience but is unusual, has been designated A-Cultural. It surprises a person, is disturbing, and causes an acute awareness. Table 8-15 lists some examples of Cultural and A-Cultural vibration.

Table 8-15. Cultural and A-Cultural Vibration.

Cultural Vibration	A-Cultural Vibration
Automobile	Blasting
Commuter Train	Pile Driving
Household	Impact Machinery
Industrial Plant or Office	Jack Hammer
Airplane	Forging Hammers
Common Denominator:	Common Denominator:
No reaction	Persons react because these vibrations are unfamiliar, disturbing

g. Blasting is definitely a A-Cultural vibration for the average person as the annoyance and fear associated with it begin at levels much lower that the damage level for structures.

8-10. Flyrock. Every blasting operation identifies its own blasting zone based on experience, the purpose of the blasting, and local issues such as rock hardness and the blast layout. One extreme is the difficult blasting on Minnesota's Mesabi Iron Range. There, the rock is hard and blasting is very energetic with large holes and low benches. Their blast zones are defined in miles. The other extreme is represented by a totally confined blast such as a presplit or a trench excavation where small amounts of explosive are involved. In such cases, the geometry or mats prevent much rock movement. In a mining operation (as in cast blasting in surface strip coal mines), the blast zone is defined as an area where rock throw is expected and sometimes specifically planned. Flyrock would then be defined as material thrown outside this specified zone.

a. Causes of Flyrock.

(1) There are two causes of flyrock: too much and too little relief. Relief is the path that explosive energy takes to escape from the rock mass. Good blasting consists of having the explosive do useful work in: (1) breaking up the rock; (2) in most cases, providing moderate rock throw to spread out the material; and (3) enabling efficient handling. For flyrock purposes in bench blasting, there are two relief directions, in front of the face, and on top around the blasthole collar region. These will be addressed separately.

(2) As a generalization, too much relief leads to excessive front-face flyrock. This simply means that the explosive has caused too much displacement for the rock being blasted. Causes include, for example, too little burden, fissures, seams and voids, overloaded holes, and broken up bench. Another generalization is that too little relief leads to high angle flyrock from top collar venting. This venting can result from insufficient or ineffective stemming, broken up cap rock, and too little time for horizontal relief in back rows of holes. These same mechanisms also lead to high airblast. The two different sources of flyrock require two mitigating approaches.

b. Controlling Flyrock.

(1) Bench Face

(a) Burdens must be sufficient to contain the explosive energy. This means that the effective burdens should be at least 25 times the blasthole diameter. The exact amount depends on the rock toughness, weight, explosive type, and minor factors as described in various blasting texts such as Dick et al. (1983) and Atlas (1987). Compromising the burdens are irregular and sloping faces, drilling inaccuracy, and voids leading to excessive explosive loads. Soft seams and weak rock in the face also leads to blowout and flyrock.

(b) Explosive weights should be monitored to avoid overloading into void space. Fissures, mud seams, and weaknesses should be stemmed through rather than loaded with explosive. Additional burden may be needed if the face is broken up or irregular. If the face is sloping, angled holes may help maintain the proper burden along the blasthole length. If angled holes are not possible, the explosive column may have to be shortened to avoid the lightly-burdened collar region. Special care may be needed to control drilling accuracy at some sites. In general, burden to diameter ratios of 14.2 or more should limit flyrock to a manageable initial velocity of 100 ft/second and a range of 300 ft. (Workman and Clader 1994).

(2) Bench Top

(a) Violence from the top of the bench and around the collar typically occurs from two different causes: (1) excessive explosive and/or not enough relief and (2) ineffective stemming and/or cratering and far too much relief. Burdens should be optimized for the same reasons as required to avoid face-produced flyrock. Additionally, sufficient time must be provided to allow relief of later-firing rows of blastholes. This means that delay timing between rows should be at least 2 milliseconds per foot of burden. Some mines have found that back rows of blastholes in a multi-row array need even longer times to allow some movement and unburdening for both flyrock and backbreak control. Far worse than delays that are too short are delays that are out of sequence. Delays out of sequence create too little relief initially and are followed by holes with too much relief. Misfires are serious flyrock generators.

(b) Cratering results when explosive breaks out to the top surface. One recommendation is for a “scaled depth of burial” of at least 2.0 ft/lb1/3 (Roth 1979). Depth of burial is defined as the distance from surface to the center of the charge divided by the cube root of the explosive weight. The charge size for cylindrical boreholes usually does not equate to the total length, but is limited to only the first six to eight charge diameters. Effective stemming is required to contain the explosive energy until it has done its useful work. This means a stemming length of about 0.7 times the burden and coarse angular material, which will interlock and hold against explosive gas pressure. This means that drill cuttings are insufficient and that crushed aggregate must be provided. Stemming that does not hold results in pieces of material from around the collar zone being thrown at a high angle and in all directions. It also usually means high airblast, ground vibration and leaving a toe of unbroken rock above grade.

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CHAPTER 9

Preparation of Contract Specifications

9-1. Acquisition Strategy/Contracting Type.

a. General. The acquisition strategy and decision as to the contract type is often based on considerations of the overall project and the complexities of various activities involved. Blasting seldom occurs in work that is separate from other activities. The strategy should consider whether the design and subsequent contract should mandate the use of blasting, or if blasting is simply one potential method of excavation or removal of material. When removal of rock is involved and mechanical excavation is presumed to be prohibitively tedious or impossible, blasting may be assumed. However, the role of blasting in the total contract may have a bearing on what strategy is applied. The decisions in the acquisition strategy are developed by the Contracting Officer in consultation with the Design Team and the Project Manager, but the Contracting Officer is the governing authority.

b. Prescriptive vs. Performance-Based Specifications.

(1) Prescriptive specifications mandate that the contractor perform the work in a particular way, often with prescribed equipment, means, and methods. The use of prescriptive specifications implies that the means and methods and equipment specified will achieve the intended results; anything less is open to claims. While there may be circumstances where this is necessary for reasons of compatibility with other operations, other equipment or conditions on site, it is normally preferable to allow the contractors to choose the method (a performance-based contract) of removing the material or creating the excavation that is most efficient within their capability, thereby minimizing the costs. The basic premise is that the contractor is told what to achieve (i.e., in a performance-based contract), or the contractor is told how to do the work (i.e., in a prescriptive contract), but not both. As blasting is somewhat of an art that requires recent experiences, knowledge of varied procedures and the aptitude to both work efficiently and safely, most offices should avoid prescriptive contracts. All blasting must be performed within the restrictions of applicable Federal, state, and local ordinances and the provisions of EM 385-1-1. However, there will usually be site conditions or concurrent operations or environmental and public concerns that add restrictions not accounted for by regulations. Limitations and/or restrictions and monitoring requirements will need to be developed before considering the contract vehicle.

(2) To be able to get the results desired it is necessary to provide guidance to the Contractor in the way of blasting specifications if wall control, invert or bottom roughness are a concern. If no guidance is given poor blasting results are often blamed on geology instead of the low cost blasting methods employed. The means and methods, within limits, can be determined by the Contractor but blast design considerations that are known to cause problems must be identified in the specifications. For example, one would not want a Contractor to use a 6-in. diameter blasthole loaded with ANFO with a 6-ft bench height adjacent to a final wall. This will cause cratering and destroy the wall. It is necessary to instruct the Contractor that on benches less than 10 ft. deep the maximum explosive diameter is 1.25 in. This distributed charge will break in a controlled manner without cratering and destroying an adjacent wall. The Contractor has his choice of means and methods as long as a 1.25 in.

diameter charge is used. Good blasting companies want guidelines and detailed blasting specifications otherwise they are required to use the lowest cost methods to bid the contract in a manner anticipated by the competition. They cannot do the job properly or their cost will be too high as compared to other bids. It is not uncommon that a blasting Contractor will bid the job very low and then claim geologic changed conditions to get the desired result at a significantly higher price. If bids are too low they should be rejected.

c. Low Bid Contract. If the blasting (or excavation or demolition assumed to involve blasting) is a relatively minor or very simple part of a much larger contract that still lends itself well to a Low Bid type of procurement, then if wall control, rock size distribution or invert or bottom roughness are not a concern then a Low Bid contract may be the most cost effective and satisfactory vehicle. In such a case, submittal requirements for Blasting Consultant/Blasting Specialist, Blasting Plans, and monitoring and controls can be included in the specifications such that the work will be performed with appropriate controls and precautions. The advantages of a Low Bid contract are that it is relatively simple to prepare, simple to solicit, and simple to evaluate and award. There is no negotiation. The bidders provide their bid prices for the job, and by doing so, commit to being able to perform the specified work within that overall bid price and within the specified time and scope. For this type of acquisition, the pricing is evaluated before award to ensure that an imbalanced bid was not submitted. Imbalanced bids in blasting contracts must never be accepted because they lead to poor results, overbreak and changed conditions claims. The contract must require performance benchmarks where the Government can stop the blasting should major problems result. Low bid contracts, although simple to evaluate and award, often lead to inferior workmanship and claims.

d. Best Value Lowest Price Technically Acceptable Contract. Bidder in a Best Value Lowest Price Technically Acceptable solicitation are provided with criteria they must satisfy for their bid to be considered acceptable. When using the lowest price, technically acceptable evaluation method, offerors must satisfy ALL technical evaluation factors for their technical proposals to be considered accepted. This type of procurement strategy is somewhat more constraining in that it requires a level of technical expertise, and that it requires the offerors' submittal to demonstrate that they meet the minimum qualifications stipulated in the solicitation. There is a simple analysis with a yes/no screening applied to each submittal package indicating whether it adequately demonstrates that the submitting entity meets the criteria in the solicitation. The lowest priced proposal among those meeting the minimum criteria for each evaluation factor is then selected. The requirements must be plainly set forth in the solicitation and cannot be so restrictive that they exclude competent contractors from bidding. However, the criteria must also be relevant and justified by the needs of the design and the project purpose in general. This procurement strategy has the advantage over simple Low Bid procurement in that it screens potentially under-qualified or un-qualified offerors who might submit a proposal without being able to successfully complete the contract, or those whose limitations might result in under-performing or significant hardships on the part of the Government, or of the contractor, or of both to achieve the goals. It is somewhat more time consuming to prepare a solicitation that will be procured using this evaluation method because the criteria must be developed to meet the specific needs of the project, in a way that is otherwise objective and does not eliminate qualified offerors. This method requires a two-component proposal, including information that documents the technical qualifications that demonstrate the offeror's capabilities with respect to the stated criteria, and the proposal itself. The determination of technical acceptability adds a step to the selection process, but presumably eliminates some risks, most significantly that of accepting a proposal from a firm ill-prepared or incapable of completing the work. Exchanges with offerors are limited in this type of procurement and the offerors are not obligated to describe their approach to the project beyond the stated criteria.

e. Best Value Tradeoff Contract. In a Best Value Tradeoff evaluation method, the solicitation states the purpose of the project and defines the requirements in plans and specifications, as with other methods. The solicitation consists of the plans and specifications, the selection criteria, and the basis of the tradeoff used in selection. It differs from Low Bid and Lowest Priced, Technically Acceptable Proposal contracts, in that offerors are instructed to provide greater detail in their proposals regarding the means and methods they will use to accomplish the end results. Criteria are given in the solicitation to provide the offeror with the aspects of the work that the proposal must address in sufficient detail to evaluate it. Criteria are carefully determined because failure to address criteria in a proposal may cause a qualified or even superior offeror to be rejected. The criteria should be developed to reflect the priorities of the project such that criteria may be ranked as major and secondary criteria. Although a typical tradeoff includes the evaluation of cost/price and technical factors, the technical factors may be considered more important than price. In some cases, price may be less important than the manner in which the proposal demonstrates a superior approach that ensures the likelihood of successfully performing the work in a manner that offers the Government significantly greater value than the other proposals. Under this method, it is possible to accept a higher priced offer if that offer is determined to be “worth the premium price” for its superior qualities. This method of procurement is advantageous for complex projects with high risks where the offerors’ expertise and their abilities to provide greater value to the Government than might otherwise have been anticipated. Value may be reflected in a number of ways, including more expeditious completion, lower operational costs, lower costs of follow-on contracts, greater efficiency of the project, greater compatibility with other elements of the project, proven expertise to meet an important project limitation/restriction, or a safer overall project. Greater value or benefits may also be revealed in a proposal in an area not even considered during design. This method permits negotiations. This method does require greater attention to detail in establishing selection criteria and instructions to proposers. The selection process consists of four steps: (1) compliance reviews, (2) technical evaluations, (3) price evaluations, and (4) trade off analysis.

9-2. Contract Documents – Plans and Specifications. The conventional plans and specifications for work that is either focused on blasting or that involves blasting as a smaller component of the work should be prepared concisely and as clearly as possible. Even if blasting or rock removal is a relatively small part of the overall project, blasting has inherent risks and protocols that require attention.

a. Bid Schedule. The bid schedule for contracts involving drilling and blasting should minimize the number of bid items to those necessary to result in a fair bid. However, to evaluate the bids or cost proposals, the bid schedule should include a representative list of items anticipated to execute the work that are important enough to assign costs/prices. It will also be necessary to establish the criteria for payment, typically either a line item per cubic yard excavated or a lump sum for excavation of a given part of the project. Having bid items that represent a more detailed breakdown of the work may complicate the administration of the contract. In the event the contract is modified, a more detailed breakdown will help to establish an appropriate and fair adjustment of the contract costs. If blasting or rock removal in one area or type of material is significantly different from another, it will make the bidding more logical to separate those areas or parts of the work from each other as separate CLINs because the costs will be different.

b. Bid Items.

(1) For jobs in which blasting or rock excavation that may involve blasting are relatively small parts of the project, it may be appropriate to use a "job" or lump sum approach if the quantity to excavate is well defined. If, on the other hand, blasting or rock excavation is a major part of the work covered by the plans and specifications, it is more appropriate to develop CLINs with quantities that can be adjusted as the actual work progresses. Among the most common descriptive CLINs in such cases are bid items for rock excavation by ton or cubic yard (measured pre-blast or in bank). It may be appropriate to break these out by categories of removal if materials differ in their characteristics enough to alter the level of effort. If these types of materials are different in their material properties, they should be cited and referenced to the Geotechnical Baseline Report (GBR).

(2) Where there are different levels of precision or control of the impacts of blasting, such as a perimeter or trim line, higher costs may make it necessary to delineate this type (controlled blasting, trim blasting or presplit blasting) as a separate line item from production blasting, where the extent of impacts is less critical so long as the impacts are contained within the material to be removed. Although the measurement of separate parts of the work or different materials may be broken out, the unit of measure should be kept constant unless there is a significant reason to do otherwise. For example, production blasting should be measured in cubic yards or tons or Presplit blasting measured in square feet or square yard of face. In situations where drilling forms a greater part of the costs than other activities, e.g., where there may be line drilling or large amounts of presplit or highly precise blasting, it may even be appropriate to include a separate bid item for drilling of blastholes, measured by the linear foot, or presplit face measured by the square yard. However, care should be taken in mixing units of measure for the same work to avoid paying twice for things like drilling. That is to say, it is important to be sure that the costs for drilling are not included elsewhere if they are measured separately for payment. Presplitting includes the cost of drilling, explosive agents, labor, removal of the rock within 6 ft. laterally from the presplit face (not included in the production blasting volume), and scaling; however because the face and its condition are the important aspects of this type of blasting, the area of the face is often considered a more appropriate way of looking at the costs. Because bulk excavations are considered more on the basis of making a space, volume or tonnage of materials removed are often considered more appropriate ways of considering costs. For example, do not pay for both the square yard of a presplit face and for the cubic yard or ton of rock removed to make that face unless these are specifically addressed in the contract. Pre-splitting forms the crack on the perimeter but does not fracture the rock for production purposes.

c. Pay Line. Plans should illustrate the "pay line," or design slopes, grades, excavation boundaries, or the minimum and/or maximum tolerances. It will be necessary to establish the boundaries of the rock/material faces that the design requires, as well as the extent to which the contractor will be allowed to exceed these lines or dimensions. The tolerances should be noted on the drawings (Plans) and also described within the Specifications. The consequences or impacts for excavation beyond tolerances should also be specified in terms of notification, payment, and mitigation measures. When tolerances are exceeded, the Contract Officer Representative (COR) should be notified as soon as possible to implement any remedial measures necessary. It is generally in the best interests of both the project and the contractor to minimize the amount of overbreak beyond the pay lines, as removal of such material adds costs and impacts beyond the pay lines that may adversely affect the project. Perimeter control is dependent on the quality of drilling. If the drilling accuracy is poor, money penalties often do not work because the Contractor wants to keep the excavation moving ahead and losing some money as a penalty for poor drilling is often more economical than taking the time to do proper drill alignment. The following statement in blasting specifications produces good drilling results: “Presplit holes must be drilled within 3 in. of the staked collar location. If presplit holes are outside of the 3-in. tolerance, they will be filled with crushed stone, lean concrete or stemmed and re-drilled at the proper location.”

d. Material Disposal. Although many jobs can be specified in a manner that includes disposal of the excavated/blasted material as incidental to excavation/blasting, it is sometimes necessary to include a separate item for disposal. If the material is less marketable or has properties that limit where it may be disposed (contaminants, mineral properties, weathering, or inclusions of undesirable constituents like chert), disposal costs may vary from one part of the project to another so it may be appropriate to include a CLIN for disposal of materials. If contamination or other constituents are present that limit disposal, laboratory testing may be necessary to determine the disposition of the material. Such costs may be either included in disposal costs or specified by a separate CLIN. For more complex testing requirements these costs are better managed separate from the disposal costs. If constituents of the material being excavated are of significant concern, the materials and the constituents should be identified and highlighted in the GBR. If, on the other hand, the material is a marketable aggregate or stone product, a CLIN for disposal is more likely to be inappropriate. The swell factor should be considered when developing disposal quantities.

e. Control of Water. The groundwater conditions should be clearly presented in the GBR/Geotechnical Data Report (GDR) or similar documentation provided to prospective contractors before they submit their bids or proposals. If groundwater in an excavation is anticipated to impact operations or means and methods, it may be appropriate to include considerations for management of water. Federal, state, and local regulations may mandate the disposition of waters from construction sites, and the Environmental Protection portion of the specifications may describe the measures necessary. A separate CLIN may be appropriate to cover and track the costs of management of water. Such a CLIN would typically be in units of time (days of pumping/dewatering) or volume of water (often rounded to the nearest thousand gallons of water) and included in pay vouchers incrementally as the work progresses. Permitting may be covered within that CLIN, or may be more expeditiously managed by the COR/Government depending on conditions. The explosives used in wet blastholes are generally more costly than explosives used in dry blastholes. It is important to supply this environmental information in the blasting specifications.

f. Scaling. Scaling is the removal of loose, detached, or separated rock from the blast face. It is often necessary to use a variety of means and methods to achieve this task. Scaling of a face to remove materials that could potentially fall and injure personnel or damage equipment or other components of the project is an important matter both during production blasting and at the end of the project when all blasting is complete. Scaling may be considered part of the blasting job and as such, is not measured separately for payment. On the other hand, it may be considered important enough to specify and to be assigned a CLIN. Scaling of temporary faces such as those between rounds of blasting should not be measured for payment, as this is done more for the safety of the contractor during construction and does not represent a permanent feature of the project. Payment for scaling of the final faces of the excavation may be measured for payment based on either the time required in hours or fractions of shift, or by square yard of face. On the other hand, it may be advantageous to consider scaling part of the incidental costs of excavating, thereby motivating the contractor(s) to design their blasting programs to reduce the amount of scaling necessary. In any event, there should be clearly manageable acceptance criteria stated in the contract that makes it easier for the contractor(s) to estimate their costs and also making it easier for construction representatives/inspectors to determine if the scaling requirements have been met. Additionally, it may be appropriate to consider defining types of scaling, i.e., manual scaling, which denotes scaling that can be performed by workers with hand held tools, or equipment or mechanical scaling, which requires heavy equipment such as rippers, pneumatic rams, or backhoes. Separate CLINs for each may be in order. Likewise, if areas are readily accessible from level ground, one CLIN might be appropriate, but if there are some areas accessible from a bench or level ground but others that require rope access or high-lift access, then those may warrant a separate CLIN or CLINs.

g. Rock Reinforcement. Rock reinforcement is typically considered a separate item and is addressed in a separate section of the plans and specifications where needed. The provisions for rock reinforcement may be an issue of contractor’s safety, means, and methods, and would not be measured for payment, but would be installed after submittal of appropriate work plan as its installation may impact other elements of the project. Some types of rock reinforcement or rock support installed by contractor(s) as part of their temporary support may remain in place and alter subsequent work or design, so it is important that the type of support and its location and design be properly documented even though it may not be a separate pay item.

h. Foundation Preparation. The level of effort required to adequately prepare a foundation can be significantly affected by the contractor’s blasting. Poor blasting practices can result in significant damage to foundations that will require significant effort for preparation. Specifications should be written such that the contractor is not relieved of the responsibility to minimize the damage resulting from the means and methods that were used. The test blasting should include test “to grade” shots to evaluate if the blaster can provide a satisfactory bottom that will not require extensive preliminary clean-ups and foundation preparation. This can help the blaster in planning better foundation grade shots.

i. Size of Explosives and Elevations of lifts within excavation. The specifications should address the size of explosive charges at the foundation level. The larger the charge diameter the poorer the results. If high benches and large diameter explosives with the resulting large burdens and spacing are used at grade the foundation will be rough and jagged, in many rock types. The final bench above the foundation is commonly restricted to no more than 10 ft. high. In order to get the best controlled breakage at the foundation level the following limitation at grade have proven beneficial. Below are listed typical lift heights with specified explosive diameters. Charge compression (charge tamping) in these blastholes will not be allowed. Charge compression forces the smaller diameter explosive charge to equal the diameter of the blasthole.

(1) Lifts up to 10 Feet Deep. Production blastholes that are designed for lifts or hole depths of 10 ft. or less must be loaded with explosive cartridges no larger than 1.25-inches in diameter. On cut slopes of 1:0.25 (V:H) or greater there may be some short blastholes. The Contractor will be required to follow this specification as to explosive diameter as it relates to bench height. This may require the use of mixed drilling for maximum production efficiency.

(2) Lifts from 10 to 15 Feet Deep. Production blastholes that are designed for lifts of 10 to 15 ft. deep must be loaded with explosive cartridges no larger than 1.5-inches in diameter.

(3) Lifts from 15 to 20 Feet Deep or More. Production blastholes that are designed for lifts of 15 to 20 ft. deep must be loaded with explosive cartridges no larger than 2.5-inches in diameter. If blasthole alignment restrictions can be met and geological conditions permit, the lift depth may be increased to a maximum of 35 ft. at the option of the COR.

j. GBR/ GDR.

(1) The GBR provides information relevant to subsurface conditions, referred to as the baseline conditions. The purpose of the GBR is to:

(a) Set baselines for geotechnical conditions and material behavior assumed to be encountered during construction. Site conditions that may affect the blasting program should be noted clearly and completely.

(b) Identify important construction considerations, key project constraints, and selected requirements to be addressed by the Contractors during bid preparation and construction.

(2) The contractual baselines do not represent warranties by the Government of the actual subsurface conditions that will be encountered by the Contractor. Rather, the purpose of the baselines is to translate the results of geotechnical investigations into clear descriptions of subsurface conditions. Nothing in this GBR limits the rights of the Government should a claim arise for differing site conditions.

(3) The GBR is based on several assumptions regarding the sequence of construction, the means and methods, and workmanship to be employed by the Contractor. The anticipated behavior of subsurface materials as described in the GBR will be influenced by the means and methods selected and used during construction by the Contractor, and behavior may therefore vary from that described in the report. The Contractor must evaluate the soil and groundwater conditions described in the GBR as they relate to, and interact with, the means and methods selected by the Contractor for construction.

(4) The GDR should contain baseline conditions including overburden depth and properties, bedrock types, joint patterns, bedding thickness, schistosity, texture, stratigraphy, rock mechanical properties, groundwater conditions and hydraulic conductivity, regional and local geology, and any other geological or geotechnical properties that could impact the cost.

(5) The GBR references the GDR. The GDRs present details of the project field investigation and results of previous investigations completed at or near the site. Also included as part of the GDR are the results of the laboratory testing performed on soil and rock samples collected during the in-

vestigation(s), including detailed descriptions of the field and laboratory testing data and detailed descriptions of methods. Boring logs and a summary table of laboratory test results are often presented in the GDR. The GBR and the GDR are provided as information for the Contractor and are included in the Contract Documents. If there are any inconsistencies between the GBR and the GDR, the GBR will take precedence.

(6) The GBR is not intended to present the minimum required design and standards of construction contained in the plans and specifications. Nothing in this GBR should be construed as amending or altering the plans and specifications or applicable Federal Acquisition Regulation clauses, or relaxing the standards of construction

(7) The technical concepts, terms, and descriptions in the GBR follow standards commonly used in geotechnical engineering/engineering geology that have specific meaning pertaining to the work. Bidders or Offerors should have a qualified geotechnical engineer or qualified engineering geologist carefully review the GBR so that a complete understanding of the information presented in this report is developed before submitting a bid.

(8) Pre-bid / Pre-submittal Site Visits. Depending on the complexity of the project and the role of blasting within a project, it may be appropriate to encourage prospective bidders or offerors of proposals (depending on the type of solicitation) to conduct or attend a preliminary site visit. This will permit them to visually assess any logistical considerations and to evaluate the environment in which the site exists. The site visit also encourages the Contractor to review the core boxes that give valuable information for future blast design and costing. It also permits them to consider questions before submitting a bid or proposal in a more informed light. If bidders or offerors make inquiries or submit questions to the Contracting Officer or Technical points of contact, it is required that the questions and the responses be provided to all other bidders or offerors. Site visits may be established for individual firms or may be considered as part of a pre-bid or pre-proposal onsite conference with all interested entities. If a site visit is required by the solicitation, it may not be required on a specific date or time and provisions should be made to conduct such visits at times arranged by offerors or bidders.

(9) Special studies. For some sites there may be an advantage to include special studies within the GBR to reduce the uncertainties in the bid or offer. Such special studies may include: information on nearby quarry or road-cut blasting; conducting test drilling with drilling rigs similar to those likely to be used in the blasting for drilling rates and bit wear; geologic assessments that provide data on possible project karst or other factors that may affect pre-splitting, scaling or foundation damage; studies to anticipate blasting impacts on nearby government, public or private structures or environmental concerns. Such special studies should present factual data and not estimate/theorize the application of the data to the proposed blasting. Special studies for prior projects have provided significant reductions in bid or offer costs, as compared to the cost of the study.

9-3. Proposals and Submittals. Proposals are the materials provided by offerors in response to a Request for Proposals (RFPs) such as solicitations for Best Value Lowest Cost Technically Acceptable or Best Value Tradeoff contracts. The documents contained in a proposal are prepared in direct answer to the requirements of a solicitation, and include items such as resumes, organizational charts, project experience summaries, equipment lists, subcontractor associations, endorsements, and work plans or statements of how a contractor plans to approach the work under the contract. Submittals are those supplemental documents and drawings provided after award as specified in the contract. Submittals should include resumes of key personnel not identified in the proposal, if there was one, as well as work plans, product data, equipment lists, schedules, test data, monitoring data, QC reports, and any other submittals identified in the specifications. A register is included in the specifications listing each submittal required and the section of the specifications where requirements and details are identified.

a. Master Blasting Plan.

(1) A comprehensive Master Blasting Plan should be included either as a portion of a proposal or as a preconstruction submittal depending on the type of solicitation for the contract. In some cases, a preliminary plan may be part of a proposal submitted in response to an RFP. If the offeror is successful, a final updated Master Blasting Plan will be required before the work begins for approval of the Contracting Officer. The plan should be submitted for the sake of clarity as a whole rather than piecemeal. The plan should include:

(a) Safety issues and the blasting limitations required in the contract should be addressed, as the contractor explains all the issues below.

(b) All authorities having jurisdiction over operations involving the transportation, storage, handling and use of explosives; a printed copy of all applicable Federal, state and local regulations governing the use and storage of explosives for this contract; copies of all required blasting permits regarding explosive use and storage; and, copies of necessary blasting licenses or authorization obtained from the state and pertinent localities

(c) Means and methods for drilling, blasting, material handling, explosive materials' transport and onsite storage, and disposal.

(d) Type(s) of explosives, primers, delays, initiators, and any other components and detonators to be used.

(e) Figures depicting the areas of blasts, and typical burden, and bench heights,

(f) Calculations used to design the blasts, vibration and airblast control and regression analysis to be used.

(g) Size, configuration, and approximate number of blasts planned.

(h) Whether pre-blast surveys are available for any properties; and the subcontractor or personnel, equipment, and procedures for monitoring the blasting program.

(i) Examples of all forms used in the contractor's submissions. Individual forms may require revision for the Contracting Officer's approval.

(j) Evaluation procedures for individual shots, Quality Control aspects, and corrective measures to be employed as the work progresses.

(k) Worker, site and public safety procedures, means to control environmental and natural resource restrictions, shot communication procedures, signage, and equipment details.

(l) Typical labor, specific personnel and subcontractors to be used.

(m) Basic schedule of work (a detailed schedule of work is required as a separate submittal).

(n) A section describing the test blasting area sequencing, execution, and application to subsequent blasting. The test blasting section of the specifications only provides goals and the definition of a successful Test Shot (allowing the contractor to continue to a larger Test Shot or production blasting).

(o) Technical data sheets for all blasting materials to be used on the project attached as an appendix.

(2) The plan should include a narrative and flow chart of the sequence and procedures to be employed to execute ongoing work: drill, blast, muck/remove of spoils and the size, number of shifts, and the equipment anticipated to accomplish the work. Drilling should be described in terms of the type of drill, size and type of bit, anticipated subdrill depths, hole spacing, decking, stemming, and plans and sections showing the lift/bench height, sequences, delays, including any blank or unloaded holes. A separate appendix or appendices should include descriptions and manufacturers' specifications for all equipment, mitigation devices (mats, mesh, or netting), monitoring devices, blast initiation devices, and materials used, credentials of key personnel, plans for control of water, disposal of spoils, and other significant aspects of the work related to drilling and blasting.

(3) The Master Blasting Plan contains an organizational chart identifying the Key Personnel and points of contact for the portion of the work involving drilling and blasting. The organizational chart should also list both contractor and USACE personnel, emergency notification procedures, design personnel, key construction personnel, local sponsors, and relevant regulatory agencies. Applicable Activity Hazard Analyses and Safety provisions specific to blasting should be detailed and referenced appropriately to the overall project Health and Safety Plan.

(4) A concise section of the Master Blasting Plan should identify potential sensitive structures and receptors that might be impacted by blasting. These potential impact receptors or structures should be tabulated by distance and linked to the locations identified on a figure. The table should describe the types of potential impacts (air blast, fly rock, vibration, noise, etc.). Where appropriate, mitigation measures should be identified for each of these impacts. For more sensitive receptors or structures, a scaled response tree should be included that indicates stepped measures and points at which the COR should be notified in the event an impact occurs.

(5) The Master Blasting Plan should properly develop the following topics.

(a) Delay Timing. Delay timing for land-based blasting may need to have longer delay periods, if particle velocity limits are being approached or exceeded at monitoring locations. The most important factors for vibration impacts are delay timing, azimuthal orientation of shot holes relative to the monitoring locations, and the maximum charge weight per 8 millisecond delay. Typically, delays should be longer than 8 milliseconds for land-based blasting.

(b) Bench Height. The dimensions of benches (height, configuration, etc.) are important in considering the logistics of the operations, the energy required for the blasts, the handling of muck and any water, and the coordination with other onsite activities. If the design of the benches may be inconsequential to the overall design, this matter is left to the contractor, provided that, when it is presented in the Drilling and Blasting Work Plan, it presents no unacceptable risks to project scope, schedule, or safety. If there are pre-existing constraints for bench heights or if the bench heights are pre-designed for specific project features, they must be presented in the plans and specifications. Any unusual or unique aspects may be included in the GBR.

(c) Hole Diameter and Spacing and Delay Timing. Hole diameter and spacing are aspects of the design of blasts that are typically left to the contractor's Blasting Specialist and the blaster on site. These aspects should be included in the Drilling and Blasting Work Plan to assist in evaluating the plan or schedule.

(d) Drilling Equipment. Unless drilling is performed underground, there are typically no restrictions on the type of drilling equipment to be used in blasting. Confined space conditions, or underground blasting may require the use of non-internal-combustion drills (either diesel or compressed air or both). Other environmental considerations may preclude the use of water or drilling fluids. Any such restrictions must be specified as they will have impacts on schedule and cost. While typically, there are no restrictions on drilling equipment, the performance by the equipment should be considered.

b. Pre-Shot Plan.

(1) The contractor must prepare a Pre-Shot Plan for each proposed blast for information only and must be provided before loading any explosive materials for the shot pattern, which is described by that Pre-Shot Plan. The purpose of the Pre-Shot Plan is to detail how the contractor prefers to: develop the shot pattern and its delay timing; accomplish this phase of the work; and, estimates the likely maximum values for monitoring stations, if any.

(2) The Pre-Shot Plan must include at least the follow topics anticipated for the blast.

(a) The general Pre-Shot Plan [form] must be signed by the licensed explosive user-blaster and will include the following: the estimated date, order number and the estimated time of the shot; whether this coming shot is a Test Blast, production shot or other type of special blast; the total number of holes to be shot; the GPS horizontal location of the outermost (corner) shot holes and the lift elevations; availability of Drilling Logs; the total weight of explosives placed; the powder factors both in charge weight per cubic yard of material shot and in charge weight per foot of total shot hole depth; the maximum charge weight per delay, which is the largest weight within any 8 millisecond interval over the total delay time; the general delay time between holes within a row and the general delay time between the closest holes of adjacent rows; whether decking or delays within a single hole will be used; any procedures for controlling air blast, flyrock or vibrations; and, a section on method's or procedural changes, if any, for this shot to rectify blasting problems of prior shots. The expected vibration and airblast at protected should be estimated. The equations used for estimating airblast and ground vibration must be indicated in the Master Blasting Plan.

(b) A monitoring data table [form] is required with each monitoring location as a row in the table. The data table must provide for each monitoring location: the monitoring position's name or number, the closest approach distance from the monitoring location to the blast pattern, square root scaled distance for each monitoring location, and for each seismograph channel. The, reports will also show the peak particle velocity time history, the maximum acceleration, maximum displacement and the peak air blast overpressure.

(c) A shot hole data table [form] is required with one row for each shot hole in the descending hole and row number. Each row of the table is specific to a single drill hole and must provide: the number/title of the hole, the top of sound rock's depth, top and bottom depths of stemming, whether other stemming intervals were required and their lengths in that hole, length of rock in the hole, total hole depth, total charge weight within the hole, and total delay firing time for that hole.

(d) A small-scale plan map [form] is required of proper scale to show the project's, or this phase of the project's area. The map must provide: a consistent orientation for a number of shot patterns, a north arrow, a scale, the linear perimeter of the blast pattern's GPS locations, and each monitoring locations' GPS locations. This is commonly called a "Grid Map" because there is a horizontal and vertical grid with letters and numbers designating a location of the blast on the grid map.

(e) A large scale plan map or sketch [form] is required of proper scale to show the anticipated shot hole pattern and delay timing. The plan map or sketch must provide: a north arrow, a scale, the each of the shot hole locations that will be loaded, and each shot hole's name/number and total delay timing.

(f) A generalized elevation sketch [form] is required for the coming shot pattern. The sketch must depict the total vertical length of a typical hole with its subdrilling, decking charges, locations of explosives and stemming, and the locations of primers and boosters.

c. Post-Shot Record.

(1) The contractor must prepare a Post-Shot Record following each shot. The Post-Shot Record provides corrections of the data for what explosive materials were actually loaded and the results of the shot. The purpose of the Post-Shot Record is to fully document all elements of the shot pattern and the impacts from it.

(2) The Post-Shot Record must revise or recreate each of the forms provided in the Pre-Shot Plan for the same shot pattern. The following are additional material required on the forms or other material required for the Post-Shot Record.

(a) The general Post-Shot Record [form] must be signed by the licensed explosive user-blaster with the time and date of the signing. The general Post-Shot Record must provide all the same data and forms using the actual values, instead of the anticipated or estimated values, as provided in the Pre-Shot Plan. The Post-Shot Record must provide a brief narrative on the results and success of the shot. If the blast was a Test Shot, the narrative must include the prescribed parameters for determining the success of the Test Shot, whether the Test was successful, and the allowable parameters of the subsequent Test Shot or that the Test Blasting program has been concluded by this Test Shot.

(b) A monitoring data table [form] for the Post-Shot Record is required with each monitoring location as a row in the table. The monitoring data table provides the same data as the Pre-Shot Plan's monitoring data table and adds for each monitoring location: both the actual component and total vector sum peak particle velocities, and the actual peak airblast overpressure. Drill Logs [form] of all the shot holes within the shot pattern, including those holes that were not loaded with explosive materials. The shot hole drill logs that indicate the known voids and soft seams encountered during drilling. The drill log must at least include the following: name/number of the drill hole; date drilled, top of hole elevation; depth to sound rock; depth interval of any soft, weathered, highly fractured zones or voids, and description of the material or whether the void has soft material, water or air filling; changes in the rock type by drilling action or cuttings; and, total depth of the hole. The licensed regulated explosive use-operator must review the drill logs and must acknowledge review by initialing the first page of each drill log sheet.

(c) Seismograph Report [form] is required for every shot, which has monitoring conducted for the shot._ Each seismograph report must be signed by the person in responsible charge of the monitoring and must include the following: the date and name/number of the shot; a narrative description of the shot's monitoring and comparison of the actual monitored parameters to the estimated parameters; reference to the Post-Shot Record's small-scale plan map; the monitoring equipment's' manufacturer, model, serial number, and the last calibration date by location; a single graph (in log-log scales) for each monitoring location of component peak particle velocities versus the frequency of each specific component peak particle velocity value for values of this shot; a single graph (in log-log scales) for each monitoring location of each component's largest peak particle velocity versus square root scaled distance for the values all prior shots; any of additional data pertinent to the monitoring; and, the name of all digital files of the furnished monitoring records for the shot. The projected air blast and ground vibration from the Pre-Shot Plan will be compared to the actual measured vibration. A new regression for airblast and ground vibration will be prepared with the new data and new equations will be used for prediction of expected air blast and ground vibration for the next blast

(d) Adverse Impacts Report [form] is required for every shot. For the typical case, in which no adverse conditions were recognized or reported, make that statement. A revised or updated Adverse Impacts Report may need to be furnished days or weeks after a specific shot, when the exceeded condition is noted or alleged damage is claimed._The conditions requiring an Adverse Impacts Report's completion include: an injury or a complaint of damage due to blasting; a flyrock projectile thrown a sizable distance or endangering either personnel or property; a shot that either exceeded maximum particle velocity or airblast overpressure limits, or recorded maximum particle velocity or airblast overpressure 25% greater than that estimated for the shot; a misfire, including any portion of the pattern not firing or a delay being skipped; vibration and airblast data that exceeded contract limits or that were 25% greater than the pre-shot plan's estimate. A brief narrative must describe the cause of each exceeded condition and alleged damage. The methods or procedural changes must document how to rectify the foregoing adversity in future shots.

d. Structure Monitoring Plan.

(1) Blasting contractors are responsible for resolving damage claims related to their activities. To defend against frivolous claims and to document possible adverse impacts from their activities, pre-blast surveys and structural monitoring plans are necessary. Pre-blast survey reports must be furnished as copies to the government and the property owner prior to initiating blasting. Private property owners cannot be required to permit a contractor to access their property to document pre-blast conditions, but if they decline to participate in pre-blast surveys, claims of damages are much more difficult for them to present. It may be advantageous for the government to acquire rights-of-entry for the contractor to conduct pre-blast surveys. Regardless of whether such properties participate in pre-blast assessments, sensitive or potentially sensitive receptors of blast impacts should be identified ahead of time. Monitoring blast impacts between the blasting locations and sensitive receptors will assist in evaluating any claims. The contractor's Structural Monitoring Plan may be a standalone plan or part of the Master Blasting Plan, depending on the size and scope of the overall project and the review schedule.

(2) The inspection of structures should be carefully documented and records should be kept free of subjective or vague terms. They should include the date, time, participants, owner/occupant, and detailed physical description of the structures. Whenever possible, a pre-blast inspection should be conducted of sensitive receptor locations. Interior and exterior walls should be numbered sequentially in clockwise fashion, and rooms within the structure identified on a detailed floor plan. Any recent dust or crumbs of plaster, composition materials or splinters should be noted and photographed. Inspections of stress points such as the corners of doorways and archways should be examined for potential evidence of settlement. Inspections should include the tightness of window panes, indications of cracking of glass, wall cracking, separation or cracking of masonry or concrete, floorboard separation as indicated by cracks or openings in wall and floor covering or finishes, plumbness of walls and doors, and gaps between walls, floors, and moldings. The type of wall and floor covering should be addressed in the report. Displacement across areas of stains or accumulations of dust or items in the structure showing displacement should also be noted. If walls or other areas are observed to be free of signs of distress, they should be labeled "free" indicating free of impacts. Basements and attics should be included in the inspections. In these areas, the inspection should focus on potential impacts to utilities, especially gas and water lines. Indications of impacts may include freshly crumbled plaster or masonry below the points where pipes or conduits pass through walls.

e. Organizational Chart. The proposal or submittals should include a clear and concise organizational chart identifying the people and roles of key personnel and any subcontractors to be involved in the work. Each person or entity identified should provide a corresponding resume or statement of qualifications in the case of subcontractors, indicating their suitability and the manner in which they fulfill any applicable requirements specified. the Technical Evaluation Team should review the organizational chart to verify that the required elements are addressed, and to verify that no one person is either overloaded with responsibilities and roles to the point where they are irreplaceable or that they cannot meet all the requirements, and to verify that their roles are exclusive of all other duties, i.e., that they do not have other significant responsibilities. The provided organization chart should clearly show the structure of the firm and the chain of command on site.

f. Resumes of Key Personnel. Any individual whose name appears on the organizational chart, whether an employee of the prime contractor, a subcontractor, or a consultant, should provide a resume. The resumes should be clear and concise, should identify the knowledge, skills, and experiences of the person relevant to their role in the project, and should address any applicable specified requirements such as certification, professional registration, formal training, years of specified experience, and number and brief identification of relevant projects and their role in those projects.

(1) Blasting Specialist.

(a) Among the key personnel, one of the most important individuals in the proposal for a Best Value solicitation or included in the submittals of a Low Bid contract is the Blasting Specialist, Blasting Consultant or Blasting Engineer, and Blaster in Charge depending on the wording in the specifications. The credentials, resume and work history should be available for review by the Technical Evaluation Team or the Submittal Reviewer before approval. A web-based search of both the individual and any associated employers should be performed to identify any mishaps, legal issues, or problems that may have occurred and that might cause their suitability to come into question. The Blasting Specialist is identified as a person who has experience and academic knowledge of commercial blasting, blasting vibration, and air overpressure control monitoring. The Blasting Specialist must be professionally involved in the planning, supervision, and use of blast monitoring equipment to maintain compliance with regulations and safety protocols, and must be familiar with and capable of implementing measures to mitigate damages from blast vibrations and air overpressure. The Blasting Specialist should not have any other responsibilities. Additionally the Blasting Specialist(s) should have at a minimum:

- Current Alcohol Tobacco and Firearms licensing.
- Hands-on experience as a blaster for at least 3 years of work or one year hands-on experience and an advance University Degree in Explosives Engineering.
- A complete understanding of blast vibration impacts with an emphasis on vibration frequency, acceleration, and ground strain/displacement.
- Have attended at least five blasting seminars, short courses or blasting conferences in the last 10 years.
- A working knowledge of drilling and drilling equipment used to prepare blastholes.
- Familiarity with Federal, state, and local regulations regarding blasting.

(b) The Blasting Specialist should have also read the GBR before developing the Master Blasting Plan.

(c) Depending on the scope of the project and the amount of documentation it may be necessary to require a Blasting Administrator to work with the Blasting Specialist to handle the documentation and office work. It has been learned on large blasting projects that the Blasting Specialist can be overwhelmed by the documentation requirements and the schedule. Having a Blasting Administrator reporting to the Blasting Specialist will allow the Blasting Specialist to attend to his duties onsite with the Blaster in Charge. The Blasting Administrator should have similar qualifications as the Blasting Specialist.

(2) Certifications and Professional Registration. The proposal must document that those key personnel identified in the specifications are either certified, licensed or registered professionals, and

must verify that their certifications or registrations are current. Where required by the solicitation and/or specifications, the proposals or submittals must include equipment and material certifications.

(3) Site Safety and Health Officer (SSHO). In addition to the General Requirements for the position, The SSHO should have a minimum of 5 years' experience as a Safety Officer on blasting projects.

(4) Subcontracting Plan and Subcontractors' Credentials. The contractor(s) or offeror(s) should provide a plan indicating the intended portions of the work that they anticipate will be performed by subcontractors. Prospective subcontractors should be identified, as well as any past experiences the prime and subcontractors might have had with them. The percentage of work to be subcontracted should be estimated, and the chains of command of each organization should be clearly explained, graphically and in a narrative. The corporate resumes and credentials of any subcontractors should be submitted and should be subject to the same requirements as the prime contractor for those aspects of the work in which they will participate. Although it may not be binding, it may provide a level of assurance to require a letter from each subcontractor indicating that they have agreed to be a part of the contractor's team on the project and that they commit to participating for the duration of those tasks in which they will be involved. This may discourage contractors or offerors from submitting a proposal that contains assumed participation by subcontractors who are recognized experts or have a reputation that would reflect favorably on the submittal, but who do not actually have any intention of participating in the contract.

g. Schedule. A detailed project schedule and Gantt chart identifying the Critical Path, schedule float, and subordinate tasks involved in the work is a required submittal. The schedule must indicate those items in the Critical Path clearly. A narrative should accompany the schedule that presents the logic of the Critical Path, that explains where potential slippage may be most likely to occur, and that specifies what measures may be implemented to minimize the risk of schedule slippage. The schedule should be provided in a specified software format to ensure that it is electronically accessible to both the contractor and the COR.

9-4. Definitions and References.

a. Part 1 of the Specifications for blasting should include definitions of terminology used in the specifications, particularly for those terms that have multiple meanings, e.g., "precision blasting" and "controlled blasting." The intent here is not to provide a glossary, but rather to clearly and concisely clarify the exact meanings of terms used in the specifications.

b. References should be carefully selected as there is potential for definitions and circumstances in the referenced material to substantially differ from, or contradict those of, the specifications. When using references, especially from other agencies, organizations, or technical sources, these materials should be reviewed before inclusion to verify relevance and beneficial use. The benefit of a given reference should be weighed against the potential for confusion or contradiction with the designer's intent. Whenever this potential exists, it should be emphasized that the specifications take precedence over references.

9-5. Considerations of Alternatives to Blasting. Whenever there are sensitive receptors or controversial aspects of the areas surrounding the site, alternatives to blasting should be considered.

Manual or mechanical excavation or expansive grouts not involving blasting may be conducted in some materials in a manner that is less disturbing to people in the area. If the project schedule permits these alternatives without significant adverse impact to cost, schedule, or scope, they should be allowed.

9-6. Considerations of Types of Blasting. Although it is typically not the intent of contract specifications to mandate types of blasting, specifications should include the maximum PPV and permitted air overpressure in: sensitive areas, areas where close excavation tolerances are required, or areas where structures may be present that require extra care or precision (pipelines, buildings, power plants, etc.). Whenever this is the case, the means and methods to be used in this type of blasting should be identified separately in the Specifications and described separately from other kinds of blasting in the contractor's Master Blasting Plan.

9-7. Special Limitations.

a. Contract Special Provisions should be used to identify site specific features of the work or work area that may pose challenges or are of particular importance to the successful completion of the project. These items may or may not be appropriate to include or cross reference in other sections of the plans and specifications.

b. The identification of known areas of concern or special conditions on or near the site does not relieve the contractor(s) from performing their own survey of conditions. However, it may be appropriate to point out the known areas of concern or conditions on site or in the vicinity, as a means of assuring that the contractor(s) take appropriate measures. There may also be conditions of a time-dependent nature or scheduled activities that are not obvious or may not otherwise be known to the contractor(s) as they prepare their work plan. The locations of underground features of the area including utility structures (even though all states require drillers to use an underground utility locator before commencing drilling,), and unique geologic considerations should be clearly stated, so the contractor is not required to discover such features in the course of their own preparations. Site access and site control details may be unique and should be clarified. If there are specific PPV, air overpressure, scheduling, or other limitations within specific areas, these should be clearly stated. Special habitats should also be identified before preparing the Master Blasting Plan. If there are traffic limitations, they should be made clear to the contractor. In the case of blasting in or near water bodies, there may be special considerations for boaters, swimmers, or other recreational users. It is important to inform the contractor(s) that notifying them of these concerns does not imply they (the recreational users) are not the only ones requiring this consideration.

9-8. PermitsTypically, the contractor is required to obtain any permits necessary to perform the work. These may include permits form the state natural resources agency, as well as county and local agencies overseeing construction and excavation or blasting specifically. It may be necessary to obtain a National Pollutant Discharge Elimination System (NPDES) permit for the discharge of water from the project. This may be done either by USACE or the contractor, depending on the complexity or scope of the project. It may be appropriate for the contractor to obtain this permit if the construction may produce specific wastewater characteristics that are more familiar. However such a process can be time consuming, and it may be more time-efficient to make assumptions about the wastewater characteristics (or to perform tests before construction) and for USACE to obtain an NPDES permit ahead of the work.

9-9. Regulatory Agencies. Ordinarily OSHA oversees civil works construction projects. However, if the project activity is considered to be "mining" (the definition of which amounts to the purpose of the excavation, not its size, dimensions, or the means and methods used to construct it), the Mine Safety and Health Administration (MSHA) may have jurisdiction. Contractor(s) should be informed that they are responsible for performing the work within the regulation of the specific agency that has oversight authority.

9-10. Contractor Documentation/Submittals During Construction.

a. Blasting Records. Careful documentation is necessary for all activities involving blasting. Regulations require the Blasting Specialist or Certified Blaster to prepare and maintain records of blasting materials and activities. The format of each of the following documents should be provided in advance for review and approval of the COR.

(1) Inventories. Records must be kept of all explosives received, detonated, returned, or disposed of in any way. If explosives are delivered daily or for each blast and any excess removed from the site, then inventory records are not required for the site, but must be maintained by the provider. If onsite inventory is not required, the contractor must maintain and provide copies of invoices, delivery tickets or other documentation of explosives received on site in completely legible form, and noted with date and time of delivery. If onsite storage of any type of explosive, blasting agent or initiator, an inventory required to be maintained on site. The onsite inventory records must be clear and separate for each explosive material, and must include the dates, times, and quantities (starting and subsequent deliveries, amounts used, and final balances each day or shift explosives are used). The inventory must be maintained in duplicate, such that one copy is always at the storage location and the end-of-day duplicate may be copied with a daily change of inventory copy being provided to the COR. The explosives storage should be offsite whenever possible, otherwise the project engineer will also be responsible for compliance to all explosive storage regulations.

(2) Project or Contract Safety and Blasting Work Plan. Project Blasting Plan describe all the materials, procedures, limitations, permits, personnel and subcontracted firms that the contractor will use or develop to achieve the requirements of the contract.

(3) Pre-Shot Plans. Pre-Shot Plans document the intention of the contractor in deciding each shot pattern to drill, load and initiate. Pre-Shot Plans should be required before either the shot holes are drilled or the shot holes are loaded. Pre-Shot Plans do not need to be required for all projects. Pre-Shot Plans are required for projects that have significant impacts that are required to be monitored or have an important contract provision(s) that must be met. It documents: the contractor's anticipated blasting result for the monitoring or contract provision(s), and adjustment of the coming shot from experience on previous test or production blasts.

(4) Drill-hole Logs. If Pre-Shot Plans are required, Drill-hole Logs are required for information only. Copies of Drill-hole Logs must be provided to the COR by 8 am of the next workday following the drilling of any holes of a shot pattern or at least 24 hours before shot loading begins. The purpose of the Drill-hole Logs is to provide sufficient data from drilling to fully understand

changes of media with depth for proper design of the shot pattern and for using the physical Drill-hole Log during loading of the blasting agents in each individual hole. The Drill-hole Logs must be available to the Blaster for the final loading and delay timing design of the shot pattern, and to the person loading each hole. Drill-hole Logs must depict to the nearest 0.1 ft. all of the following: some designation of the hole name; the elevation of the top of the hole; the description of the first material encountered; a driller's description of each unit (from cuttings and downward rod pressure) encountered and the depth to the top of the unit; the top of sound rock's depth or a note that no sound rock was reached to the full depth of the hole; the driller's description of all soft or weak materials or voids (whether mud-, or water-, or air-filled) or bit drops and the depth extent of such zones; and, the bottom (total) depth of the hole.

(5) Post-Shot Reports. Blasting Reports must be maintained for each blast at the time of the blasting. These records provide information as to the date of the blast, the details of how the blast was designed and loaded. They provide documentation of how the blast occurred, including measurements of vibration, fragmentation, airblast, and flyrock, and a record of any safety incidents. At a minimum, the information must include:

(a) Name of permit holder.

(b) Location, date, and time of the blast.

(c) Name, signature, and certificate number of blaster.

(d) Direction and distance to nearest dwelling, building, or structure not owned or operated by the permit holder.

(e) Weather conditions.

(f) Type of material blasted (rock type, concrete, etc.).

(g) Number of holes.

(h) Diameter and depth of each hole, burden, spacing stemming, subdrill, explosive load (size and weight) and timing of each blasthole.

(i) Types of explosives used.

(j) Total weight of explosives used.

(k) Maximum weight of explosives detonated in any eight millisecond interval.

(l) Method of firing and type of circuit.

(m) Type and locations of stemming.

(n) Use of mats or netting.

(o) Type of delay and time of delays.

(p) Drawings of blast pattern layout and of the hole/deck delay timing, and typical shot hole loading section.

(q) Seismograph records showing vibration and airblast time histories.

(r) Seismograph reading, location, and distance from blast.

(s) Anticipated vibration and airblast and how calculated

(t) Regression equations used

(u) Instrument calibration data.

(v) Name of instrument reader.

(w) Name of firm or individual interpreting reading.

(x) Shot location.

(y) Location of video cameras on map or plan

(z) Reason for delaying the blast, if any.

(aa) Comments and remarks, including assessment of blast success, any adverse impacts, reports of damage, and required blasting adjustments in future shots due to any of these issues.

(6) Blasting Monitoring Records. Blasting monitoring reports must be submitted in a timely manner, so that any adverse impacts they reflect can be mitigated before subsequent blasting. Peak monitoring values should be processed immediately for review following each blast. Monitoring Records must be furnished promptly for inclusion with the Blast Report. The contractor should be required to submit both hard copy and digital versions of the seismograph and vibration records following each blast, annotated with any appropriate remarks or observations of flyrock, air blast impacts, as well as the distance from the seismograph and the pounds of explosive fired per 8 ms delay, or any other relevant information from each blast.

b. Adjustments to Blasting Plans. Modifications of the Blasting Plan from the Master Blasting Plan or subsequent revisions must be provided for approval of the COR.

(1) Any significant adjustments to the Master Blasting Plan must be submitted for approval by the COR. Minor adjustments may be made and should be furnished as they are made and documented by both the contractor and the COR as addenda to the Drilling and Blasting Plan or in some fashion so that they can be evaluated if the need arises. Adjustments that might be considered significant would include bench height, widths, size of holes or changes in explosives, delays, equipment, or work cycle.

(2) Test Blasting is typically required for projects where the potential of adverse impacts exist, and production blasting is expected both to have many shot holes in some shot patterns and to con-

tinue over a protracted period of time. The specifications should detail a variety of information concerning conducting the early Test Blasting phase of the contract. The specification should establish for the Test Blasting Program: its goal; the first Test Shot's criteria, which may include the maximum number of holes and rows, the total charge weight, the Maximum Charge Weight per 8 millisecond Delay, the minimum Square root Scaled Distance to the nearest structure or feature of importance, and the maximum Particle Velocity and air blast or other measure at the nearest structure or feature of importance; the means to state the particular Test Shot was successful to continue to the next larger Test Shot or move to production blasting; the criteria for increasing a subsequent Test Shot's parameters from the prior successful Test Shot; the criteria for completing a successful Test Blasting Program to begin the production blasting; and, any criteria for adverse impacts during production blasting that would require the contractor to return to some phase of the Test Blasting program to steadily increase in success before returning to production blasting.

c. Blasting Specialist Evaluations. The Blasting Specialist should be required to evaluate the effectiveness of the blasting as it continues. A written evaluation may not be necessary for smaller programs, but for extensive or particularly complex blasting, periodic and ad hoc evaluations may be necessary. These evaluations should include appropriate recommendations as well as narrative discussion of any minor and major adjustments and observations. The Blasting Specialist should provide a brief monthly report to show awareness of the project details, review of Blast Reports and Video recordings and proposed blasting methods.

d. Photos and Video / Web camera. Two videos of each blast should be required of all blasting operation by the permitting authority, each shot should also be documented with "before" and "after" photographs. Web camera recording should be considered on large and long duration projects. The specifics of this requirement will be site specific, and technology advancements should be used as they become feasible.

e. ECIFPs. Consistent with other construction, Engineering Considerations and Instructions for Field Personnel documents are required for projects where blasting is involved. These should include a notification chain of communication to convey any events where tolerances are exceeded in blasting and any adverse actions that result, and also notification of appropriate safety and contracting violations to the office of counsel in the event of complaints from offsite property owners or others. This document should include site condition information that can help the Construction Quality Assurance staff anticipate areas of special concern or difficulty. The document may explain the original design intent, the reasoning behind the bid schedule, and measurement and payment items, and it may also list those CLINs that contain the greatest risk from a time and cost growth standpoint. The ECIFP does not need to rehash topics already well explained in the specifications.

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CHAPTER 10

Documentation and Monitoring During Construction

10-1. Purpose and Need for Documentation.

a. General

(1) Documentation is key to a successful blasting program. The need for documentation must be understood and incorporated in the work activities from the time the specifications are written, through contract award and execution, and as subsequent completion reports are written. This is vital, as most USACE projects rely on the Contractor to do the actual blast design. Most specifications require submittals of this plan for Government review. However, as will be discussed in this chapter, there is more to successful monitoring of construction programs than simply reviewing early submittals. Blast designs, as discussed in Chapter 5, are iterative and must be updated as shots proceed to best fit the conditions of the site and to meet the project goals in a safe and cost efficient manner. It is strongly recommended that, if the Resident Office and/or District Office does not have the blasting expertise to properly evaluate the blasting, it would beneficial to reach out to the Regional Technical Expert and the Geotechnical, Geology and Materials Center of Practice for help.

(2) Specifications, as discussed in Chapter 9, "Preparation of Contract Specifications," set the ground rules for the expectations of the Government and the activities of the Contractor. With blasting, the Government will have the need to review products, methods, and data generated by blasting, and this should be included in the specifications. It is also important to build time and resources into the project to evaluate critical aspects of a blasting program in real time, so that corrective mitigation can be implemented immediately when and where necessary. Where projects have adjacent infrastructure and facilities that need to be protected (e.g., construction of a new lock adjacent to an operating lock), the Government will need to assess the potential for damage by fly rock, excessive vibrations, overbreak, and movement within a rock slope. This assessment cannot be done without appropriate documentation of the blasting program as it proceeds. The assessment includes both the contractor's initial Pre-Shot Plans and the Post-Shot Results as those Shot Plans are executed.

(3) Wherever possible, documents for the project should be generated or converted into electronic form. Hand written documents can be easily scanned and are easier to share with a central office than the original paper documents. Almost all video and photography equipment in use on a project will be in a digital form. Items that may be included in the specification that should be reviewed by the construction office to assess these plans are:

(a) Qualification of personnel involved in blasting.

(b) Master Blasting Plan.

(c) Preconstruction surveys.

(d) Drilling Logs, for each shot are provided before the shot is fired.

(e) Hole surveys, which are of particular value in high consequence shots.

(f) Pre- and post-shot documentation including maps, layouts, timing, and loading records.

(g) Video(s) of shot, which are necessary where there are critical structures. Slow motion view of the video can give the blaster and Government a better view of how a shot developed, any potential adjustments that should be made, and what might have caused particular problems.

(h) Seismograph readings.

(i) Incident reports and damage assessments, if any.

(j) Meeting minutes, where agreements and understandings are reached.

(4) Timeliness of the data may also be an issue. It does little good to review Pre-Shot plans after several shots have already been executed. Specifications should be in place to establish the expectation of when data is to be delivered. Where this is found to be insufficient on a project (e.g., where no time limits are given), and where they are later found to be needed to execute the project efficiently, the contract will likely require a modification. Time limits must be backed up by consequences. For example, if blast reports or video recordings are not produced at the time required then the contractor must cease all drilling and blasting activities until the reports or videos are submitted.

(5) The value of this assessment documentation will be easily illustrated where there are problems on a project, particularly if they involve misfires. When a misfire occurs, leaving explosive in the ground, having an accurate location of the blastholes, the original drill logs, and the hole loading information can save lives.

(6) Such documentation is also a necessary part of follow-on Foundation Reports prepared to capture lessons learned, as well as to document construction history beyond simple as-builts. Foundation Reports are a required element for unique and major construction projects.

b. Blast Design Adjustment.

(1) As discussed in Chapter 5, blast design should be expected to change as the blaster adjusts the plan to better meet the site conditions. Blast designs should always be considered as “living documents” and work plans should be adjusted to meet the site conditions and project goals.

(2) The Master Blasting Plan should include a sequence of test blasting with some criteria allowing the increase of subsequent test blasts to determine what kind of vibrations the site will experience with different shots. Site vibration and air overpressure attenuation curves will be developed by the vibration consultant from the test blasting and used to supplement design of future blasts. Once the site attenuation curve is developed and the seismograph data is collected on test blasting and ramped up, it may be possible to fire more holes in sequence and to keep vibrations within acceptable limits.

c. Drilling and Blasting Work Plan.

(1) The Contractor will need to develop their detailed Rock Excavation Plan in coordination with the blaster in concert with the Master Blasting Plan. The Master Blasting Plan should be included in the Excavation Plan to allow the Government to ability to evaluate the blasting plans and

whether it is sufficient to complete the excavation. The Government frequently requires test shots of pre-splits, line drilling, and sinking shots on a site-by-site basis and where there is a change in rock formations. The Contractor(s) can plan to have this done in a way that will not hinder their Rock Excavation Plan. For example, a Contractor may want the blaster to "blow and go" with large mass production shots to get rock removed. However the blaster will need to prove that the critical shots to grade and near sensitive structures, presplit shots to grade, etc. can be executed to contract specifications. This proof is provided by the test shots building to the production shots' parameters. If the blaster can prove that these test shots can be successfully executed in an area where there is more room for error and learning, then it can be done near the sensitive structure. A contractor should include the test blasting sequence with the plans and schedules submitted. The Resident Geologist and QA personnel should expect to review the blasting plan for every shot and to assess the results of the test shots before further blasting proceeds.

(2) Blasters typically prefer to shoot the presplit before and have a delay to start the production shot. During the test blasting and ramp up, the test presplit shots should be shot as their own shot to evaluate the results of the loading. The goal is to crack the rock between the holes to create the face. This is done to evaluate the loading of the presplit holes and the resultant breakage. If presplit holes are too heavily loaded they could cause breakage into the rock in front or behind the perimeter. The production shot may then be changed by rock that has already broken. At this point, the production holes may be overloaded and may cause more potential damage and/or fly rock/vibration, or may cause cut offs in the production shot such that not all the holes will fire. Depending on the project, the Blaster may need to show success in pre-splitting by breaking the plane before being allowed to shoot the production shot on delay. It is good practice to shoot the presplit as a separate blast even during production on critical slopes because should a problem occur with the presplit it gives the Contractor a "second chance" to produce a presplit before the production blast fires and damages the slope.

(3) The importance of the rRock Excavation Plan is that well planned and executed blasting will experience fewer contract problems. This minimizes damaged rock and the need for potential remedial actions to fix problems of rock stability during blasting. In the Rock Excavation Plan, the contractor should include not only the sequence of line drilling, pre-splitting, blasting, and rock removal, but also time allowances to evaluate, remediate, and stabilize walls to keep the blasting moving forward. Each project site will be different, but generally there will be advance knowledge by the orientation of the rock and/or geologic features in the rock such as clay-filled solution features or large bentonite seams. In such cases, treatment and stabilization will typically be specified to include rock bolts, etc.

(4) Good blasting can lessen the need for slope stabilization and will reduce the amount of mechanical excavation to grade. Less blast damaged rock means less rock to remove to provide an adequate foundation surface for the structure. The submittal should be detailed, showing expected shots, presplit lines, line drilling, and other features.

(5) Pre-Shot Blast Plans should always detail the borehole pattern, loading, and timing that will be used for each shot. These are addenda to the Master Blasting Plan and should be added for every shot. These Pre-Shot Plans should be reviewed by QA personnel before blasting for that shot proceeds. Likewise, Post-Shot Reports should be submitted and reviewed before the next shot proceeds. Where there are inefficiencies in the schedule, or difficulties in the blasting due to geologic

considerations, the review of the Pre-Shot Plan along with assessments of the Post-Shot Record's results will allow the Resident Geologist and QA personnel to understand why and how the contractor needs to make adjustments to the blasting plans. It should be clearly understood that review of the Pre-Shot Plan does not in any way negate the Contractor's responsibilities on the project.

(6) The Resident Office and District Office (usually a Geology or Geotechnical Section) should coordinate the review of the Master Blasting Plan and Rock Excavation Plan and related submittals. Where necessary, this may involve reviews with an A/E-hired Blasting Consultant. A procedure should be in place before the contract is awarded to coordinate these reviews expeditiously. (The Resident Engineer (RE) office typically only has 30 days to return submittals.) This procedure should also be in place, minimally, by the start of the blasting program. If a Resident Geologist at the RE office is sufficiently experienced, later reviews can be handled in the RE office and data can be collected and transmitted electronically to design geologists.

10-2. Quality Control/Quality Assurance for Blasting Projects.

a. General

(1) Each project ECIFP will have far greater detail that what QA and QC need to maintain their awareness on particular projects. The Resident Office staff should be familiar with the ECIFP and design staff should pay particular attention to the preparation of this document.

(2) Duties of Government Construction Personnel:

(a) Resident Engineer. The REs usually bears ultimate responsibility for major decisions, but relies on the project geologist and inspectors for information and advice.

(b) Resident Geologist. The project geologist should be intimately familiar with blasting in rock and understand the site geologic properties and be involved in the day-to-day oversight of the blasting program. Inform and assist the REs in making blasting progress and addressing any problems that arise.

(c) Construction Inspector: The construction inspector will determine that blasting methods used by the contractor are in compliance with the requirements of the plans and specifications and also that the work complies with the blasting program and methods submitted by the contractor to the Contracting Officer Representative. Significant deviations will be reported to the Resident Engineer/Resident Geologist for a decision. The inspector will report on information concerning the program and blasting method, as discussed in Chapter 9 of this manual. The inspector also should report daily observations and progress of the job to the project geologist.

(3) A cooperative spirit should be maintained among Government and Contractor personnel, drillers, and blasting crew, if the best results are to be obtained. Although inspectors monitor the drilling and blasting operations, they do not take over the role of foreman for the contractor, e.g., they should refrain from giving orders directly to workers. A thorough knowledge of drilling and blasting techniques is the best assurance of a satisfactory job. Chapters 2 through 6 of this manual in particular are intended to help in this regard.

(4) Engineer Pamphlet (EP) 415-1-261 (1992), Quality Assurance Representative's Guide Pile Driving, Dams, Levees, and Related Items, gives basic items for QA Reps to be aware of, and lists recordkeeping requirements for excavation in which blasting is employed. Good practice for QAs on a blasting project include:

(a) Checking the contractor's blasting pattern against the contractor's approved plan. This includes the need to check the as-drilled holes against the plan. If there is more than two diameters of deviation between two blastholes, poor results can be achieved and the blast may not be as designed. It is critical to verify driller execution of the plan.

(b) Verifying drilling records by checking locations of marked significant features such as mud seams and voids.

(c) Maintaining survey control. Ensure that the surveyor takes shots on the blastholes and that the cut sheets are used by the drillers of the blastholes.

(d) Checking the use of test blasts before starting a full scale blasting program. Monitor the test blast program before full scale blasting, if required in the contract.

(e) Keeping a record of quantity of powder used per blast, delays used, blasting caps, and the depth and spacing, subdrilling and stemming of the holes.

(f) Verifying hole stemming, loading, etc. are accurately recorded on the blasting log.

(g) Checking the finished surfaces in the blasting area for fractures due to over blasting.

(h) Checking size of blasted rock.

(i) Checking on the need to change the blasting pattern.

(j) Check out that requirements for monitoring blasts are carried out.

(k) QA activities for dredging drilling and blasting:

(l) Checking operators of plant for conformance.

(m) Verifying quantity of explosives on hand at start of watch.

(n) Checking contractor compliance to state, county, municipal, and Coast Guard regulations relative to use, storage, and transporting of explosives. Verify contractor blasting plan.

(o) Requiring strict adherence to safety regulations and blasting plan.

b. Blast Records. The specifications should require the contractor to furnish the Contracting Officer with complete information on every blast. Where a proposed general blasting plan is required before the start of blasting, the individual blast reports may be submitted after the blast. On other projects, proposed blast data have been required before drilling starts on each blast with a final report required after the shot is fired. Information should include location of blast by station and range; elevation of top of blast; depth, spacing, burden, number, and diameter of holes; type and quantities of explosives; quantities of detonating cord used; type and quantities and delay periods of blasting caps; maximum quantity of explosive detonated in a single 8 millisecond delay period; a sketch of drill-hole pattern; number of cubic yards blasted; and powder factor. See Appendix C for examples of blast records.

c. Sequence of Operations. Where there are technical reasons for excavation to proceed in a particular sequence, this requirement should be clearly defined in either the plans or specifications. The contractor's Rock Excavation Plan and Master Blasting Plan should comply with the specified sequence, if there is one.

d. Specifying Methods to Obtain Sound Final Walls. Where experience and geologic data indicate that a method such as pre-splitting is necessary to obtain the desired results, specify the method, or methods if an option can be given. Each method should be described in sufficient detail so that no item is omitted that might prove to be essential for its success. Allow enough latitude that the method can be adjusted to the field conditions and to contractor's proposals. Any contractor's proposal must be described in detail and demonstrated to give equal and satisfactory results. When specifying pre-splitting, recognize that in some rock, right-angle, outside corners of excavations are not often successfully obtained. Therefore, where special problems exist, the contractor may propose alternate methods. A review of this manual and other sources with the contractor's plans should be undertaken to understand why a contractor may propose a change at these locations, before any change should be considered. Methods such as line drilling outside corners have been successfully used where presplit blasting was not giving good results.

e. Obtaining Final Grade. The use of angle holes, smaller blastholes and explosives and limitation on the depth of a final lift should be considered, if they will be helpful in obtaining the final grade without damaging the underlying rock.

f. Specifying and Prohibiting Certain Practices. It is sometimes beneficial to provide in the specification for the use of such measures as deck loaded and small diameter holes that may be deemed necessary later. Undesirable practices, such as subdrilling below specified tolerances in structural excavations, should also be prohibited.

g. Requiring Gradation Ranges in Blasted Rock. When blasting results are desired to produce certain fragmentation, the contractor(s) should perform test blasting to demonstrate that they will produce the desired product.

h. Monitoring Progress.

(1) Inspectors should be aware of the problems that can occur with blasting on the construction site. They must be sure that the contractor is following the blasting plan is sending modifications and change orders to the project engineer if these plans are to be modified.

(2) Blastholes should be drilled reasonably close to the location given on the blasting plans as required in the specifications. Improper drilling will cause improper blasting results. If problems oc-

cur as a result of the blasting, they are best to be corrected near the time that they occur and not in litigation or mediation at the end of the project. Many projects have been successfully completed, because both the Government and the contractor personnel understood there was a problem, had the ability to consider the options for the solution to the problem, and jointly selected options that completed the project without any cost overruns.

(3) Blasting coordination meetings have proved to be useful on some projects. These meetings are usually held weekly with the contractor, the Government, blasting subcontractor, vibration consultant, and the Government's blasting consultant. A general outline of these meetings would include:

(a) Purpose.

(b) Responsibilities.

(c) Quality Control.

(d) Pre-Shot Plans.

(e) Drill logs.

(f) Post-Shot Reports.

(g) Videos.

(h) Test shots/ramp up.

(i) Specialty Shots (e.g., sinking shot).

(j) Blasting Operations Overview Report.

(k) Conclusion.

(l) Weekly schedule of drilling/blasting, in list and map form showing locations of shots, issues, geology, drawings with upcoming work, and scheduling of special meetings for critical shots.

10-3. Pre and Post-Blasting Surveys.

a. The pre- and post-blast surveys or vibration surveys are required to document the condition of nearby structures before and after a blasting program is performed. This is to reduce claims by nearby property owners by showing what the condition is before and after. These surveys are typically conducted by the contractor, though some may have been performed in the design phase of the project. The construction staff's role will be to make sure these investigations are conducted and submitted in a timely manner.

b. Structural inventories should be conducted when blasting will occur and nongovernmental or governmental properties may be impacted. The distance to nongovernmental structures requiring pre-blast surveys is dependent on the charge weight per delay likely to be used. Variability between differing contractors will usually suggest that a structural inventory should be included within the contract with specified requirements. Precontract structural inventories are not common, but some blasting projects may need to perform the structural inventories before the contract is established. This is not desirable since the contractors should always retain the risk and responsibility for their operations.

c. Some situations require more prescriptive direction of pre-blast surveys and vibration monitoring and control. These would include structures with critical mechanical or electrical components that are susceptible to vibrations and/or locations that have restrictive access due to security concerns. The specifications should include a list of structures that need this special monitoring especially any specific instructions that are beyond the typical industry standards, and also should define limited access locations. For example, access to a Power Company's Powerhouse Control Room/Generator Room must be scheduled a week in advance and an escort from the customer and Government must be present for the entire monitoring period. Additionally, some components such as breakers have manufacturer's data on allowable vibration levels. Some situations may limit the amount of documentation allowed. For example, some locations prohibit video and photography so the vibration consultant will needs to do all documentation by hand, which will slow the process and add cost.

d. The pre-blast survey may also help determine where additional instrumentation needs to be set up. Establish allowable vibrations and specify them in the contract. Know the reasons for the limits and what to do and who to notify if those limits are reached or exceeded. For example, suppose that thresholds were specified for a class of structures' instrumentation, and this threshold was exceeded, but it was not known what it meant. Will the contractor be required to stop work, perform remedial action, adjust blasting, or revert to mechanical excavation? There should be an effort to answer these questions before blasting starts even if there will always be unknowns.

e. Structural inventories, commonly termed pre-blast and post-blast surveys, are typical for most projects requiring blasting. Most structural inventories are conducted by the contractor and are not undertaken as precontracted studies. Pre-blast and post-blast surveys should be conducted by subcontractors, who: are independent of the blasting contractor, regularly perform such surveys, and evaluate blast damage.

f. The pre-blast surveys are conducted before any blasting has occurred. The pre-blast survey allows some communication with owners to allay concerns of blasting and to heighten the owner's interest in the present condition of the structure. Both are significant advantages. The pre-blast survey is the benchmark of the structure's condition before any blasting. Governmental structures of importance within the survey range should have pre-blast surveys. A copy of the pre-blast survey should be provided to the owner of the assessed structure.

g. Post-blast surveys are commonly conducted only for structures that have a damage complaint relative to a particular blasting event. Post-blast surveys may be required of all structures having pre-blast surveys, following the completion of the blasting program for the site. The same person that conducted the pre-blast survey, if one was made for the structure, should conduct the post-blast survey.

h. A predetermined form should be used for every structural inventory. The inventory form, at minimum, should include: the owner's name and mailing address; the location of the structure; the date the survey was conducted; the name and the address of the person performing the survey, and the signature of the surveyor; the name, address, and signature of the person allowing or denying entry to the structure; and the format of the inventory description. The form should resolve the type(s) of description for each property. The inventory should include written and/or photographic and/or videographic descriptions of all the rooms, exterior, foundation, and pertinent features that may be impacted by blasting. The Government must receive a copy of all forms and all descriptions of all structures having inventories within a short period of the survey being conducted. Each property owner should receive, at minimum, a summary of the survey.

i. The distance within which structures should be inventoried is variable. Structures often have pre-blast surveys within 150 m to 300 m (500 to 1,000 ft) of any blasting. Every structure does not require a pre-blast survey. Typically, the closest structure, which lies within the range being surveyed for all azimuths about the blasting zone, has a pre-blast survey. Important or sensitive structures are often surveyed, even when they are located just beyond the range of pre-blast surveys. The Government will usually obtain the rights-of-entry for all structures to be surveyed.

j. The Resident Office will need to make sure the contractor conducts the required surveys in a timely manner before the start of blasting and engage the vibration subcontractor as needed if complains arise during blasting. Upon completion of the blasting program the post-blasting vibration surveys will be conducted, if required, in a timely manner. This will capture any changes that have occurred during the blasting and determine if it related to the blasting. It may be advantageous for the Quality Assurance Representatives to observe the contractor conducting the surveys to ensure they are completed to specifications.

10-4. Blasting Records.

a. The main records needed are:

(1) Pre-blast survey, discussed above,

(2) Drilling logs

(3) Pre-Shot Plans,

(4) Post-Shot Reports,

(5) Blasting Operations Overview Report, and

(6) Post-blast survey, discussed above.

b. What is needed for good records:

(1) Completeness.

(2) Timely submission. Specifications require timeframes. Note if contractors cannot keep up. Consider whether to add a position Blasting Administrator to handle all the paperwork. Anticipate variances.

(3) Check calculations and shot timing sequence.

c. Learning. Document shot such that another blaster could duplicate the blast without a need for any further documentation.

d. Project Blasting Records.

(1) Recordkeeping is vital on blasting contracts as without accurate records, problem shots cannot be accurately assessed. Detailed recordkeeping on site (Figure 10-1) is not the same thing as specifying methods or results related to the design items that appear in the blasting records. Accurate records serve as the long term documents that allows the blaster, contractor, and the Government to accurately assess the effectiveness of blasting methods that the contractor has chosen. The records can be used for forensic investigations when a shot does not go as expected. They are also vital to build an understanding of the means and methods that work well. Items that should appear in the written record should be specified in the contract. Sample forms should be furnished in the Master Blasting Plan for government approval. The contract should specify that a particular form be revised for the remainder of the contract, when an important item has not been addressed. Note also that some “standard” blasting report forms are not complete in some respects. For example, one form may not include the maximum charge per delay, quite often an important item.

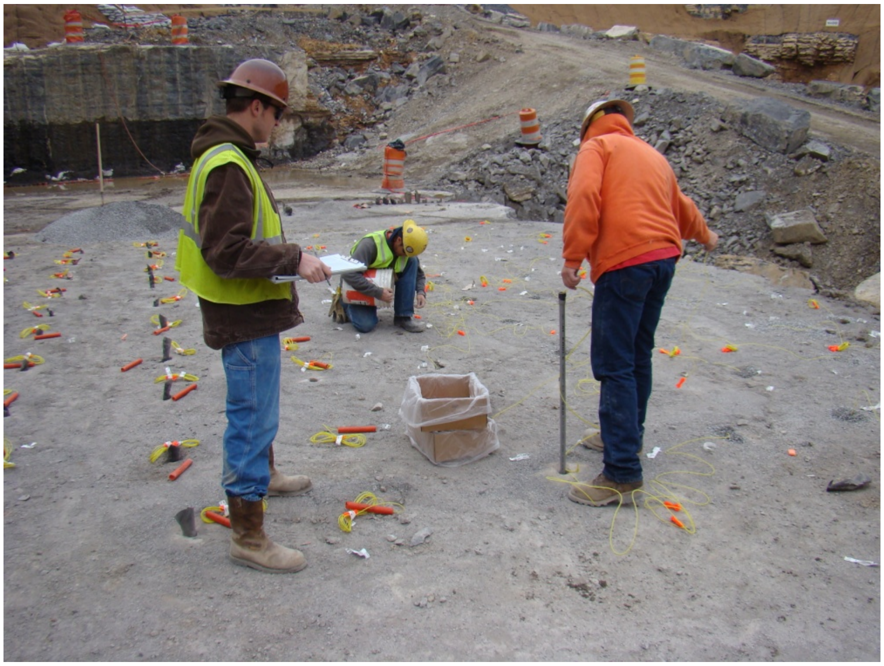

Figure 10-1. Blaster Keeping Records While Loading Shot.

(2) It is also very common to provide some type of ongoing instrumental monitoring of all work. There should be some contractual understanding of what monitoring will be done and who

will do it, the Engineer or the contractor. The choice depends on the nature of the work and the nature of the concerns. Most common are simple, general purpose, ground vibration and air blast overpressure measurements, as they might be applied to offsite residences. That type of monitoring is technically simple and easily arranged, but care should be taken to meet the need for accurate recordkeeping. For onsite structures, it may be wise to include measurements of water pressure, strain, displacement, acceleration, or other data that might be useful in evaluating the response of structural components related to their design criteria. This type of monitoring is technically more sophisticated and may require the services of outside instrumentation specialists. It is usually done by the Engineer, and the results are passed on to the contractor(s) for their information and guidance. For marine life, it may be useful to monitor water pressures and water quality. On past projects, such monitoring has been done by either party to the contract.

e. Test Blasts.

(1) Test blasts are frequently desirable, whether they be related to rock breakage or perimeter control or blast effects on nearby facilities. If test blasts are to be required, the contract documents should specify that test blasts will be required and some criteria must be met to increase the subsequent Test Shot in any way. For example, a minimum of two or three test blasts might be required. The number of blastholes, the number of rows the depth of the holes may all be specified in the specifications for the test blast. They might be located away from the item of concern. The actual project work would not be allowed until the test blasts produced results satisfactory to the Engineer. Bidders would not usually expect to perform these tests or to provide funds for them unless they are specified.

(2) For special cases of blasting near unusually delicate or critical items, there may be doubts about the accuracy of predicted responses. It is then wise to begin with small test blasts while monitoring the response(s) accurately with sensitive, precise instruments. The blasting operations can then be increased incrementally with further monitoring until full scale blasting is achieved or until full scale responses can be accurately predicted. A useful example is the blasting done directly in front of the underwater powerhouse walls at Guri Dam, Venezuela. Theoretically, strains should have reached damaging levels. However, small blasts were increased incrementally while strains and other parameters were carefully measured (also included were acceleration, velocity, and water pressure). Strains never reached potentially harmful levels, and the work was completed successfully despite the fact that sophisticated mathematical models predicted damage (Oriard 1983, 1991) such unusual and delicate work required complete control on the part of the Engineer. The contractor was directed in every detail and was paid on the basis of time and materials. Both reward and risk were perceived initially to be extremely high, but the risks were virtually eliminated by sensitive response monitoring and by starting with very small test shots.

(3) For blasting to remove rock underwater, it is best to avoid directing the number of lifts (stage of blasting and excavation) where possible. Also, there may be great savings in time and cost to design and contract for as much work as possible to be conducted “in the dry,” that is, working from a solid surface above water. One example for a deep harbor excavation was to bring the rock excavation down to a horizontal bench about 1 ft. above high tide level. From that level, the remainder was drilled and blasted in a single operation. See Chapter 7, “Underwater Blasting,” for more information on design and methods of blasting underwater.

(4) If the work must take place close to existing facilities, it may require smaller blasthole diameters on closer centers, so that the smaller charges are not potentially damaging to those facilities. In some cases where the full load in a single hole could be potentially damaging, it may require deck loading. If holes are of small diameter, but will have to be drilled to great depths, and there may be a serious problem with the accuracy of the drilling. The holes may deviate from their initial alignment. Larger diameters can be drilled to better control accuracy, but may lead to unacceptably heavy charges. One possible solution is deck loading.

(5) Blasting demolition near existing structures has taken place many times for the removal of cofferdams after the completion of structural work. One unusual example was the removal of a 50 ft. high solid rock cofferdam in front of the intake structure at the Manapouri Project in New Zealand, even though the base of the rock dam was only 3 ft. from the base of the intake structure. This was done in a single lift without damage to the structure (see Oriard 1991).

(6) A number of projects have come to a halt, when it was discovered that the desired work could not be accomplished within the specified vibration limits. These usually come about because "standard" specifications are written without the benefit of experienced review or field testing in advance of preparing contracts. For example, several projects have involved the partial removal of concrete structures, with a vibration limit of 4.0 ips imposed at the demarcation line between concrete to be removed and concrete to remain. Because it is impossible to break concrete at 4.0 ips it was similarly impossible to accomplish the work, and work was halted. One such case is reported by Oriard (1998). There was no technical difficulty in using controlled blasting methods to remove concrete to the demarcation line, without causing damage to the concrete that would remain. This is a common practice. The difficulty was the contract narrative, not conducting the work.

(7) Most engineered structures are far more able to tolerate nearby blasting activities than is generally supposed. When there is doubt, incremental tests and careful monitoring can answer most of the questions.

(8) In summary, there is a general rule for most major projects: Be prepared for the unexpected. It will probably occur. It is wise to prepare some contractual mechanism for handling the unexpected.

f. Blast Bookkeeping Forms. Sample Blasting Forms (Appendix C) gives an example of many different types of blasting forms that can be used on blasting projects. These forms should include:

(1) Pre-Shot Plan Form.

(2) Drill Log Form.

(3) Post-Shot Report Form.

(4) Pre-blast Inspection Form.

(5) Seismic Monitoring Form.

(6) Drill Pattern Inspection Form.

(7) Presplit Drill-hole Evaluation Form.

g. Evaluation of Proposed Pre-Shot Blast Plan.

(1) When evaluating a proposed Pre-Shot Blast Plan, the following items should be checked:

(a) Drill patterns.

(b) Survey.

(c) Hole depth.

(d) Explosives used.

(e) Loading.

(f) Initiation System.

(g) Delay timing

(h) Presplit pattern.

(i) Presplit holes.

(j) Line drilling.

(k) Explosive.

(2) Test blasting and early blasts. Blasts near critical structures should be reviewed by the Vibration specialist and this should be included in the blasting plans. This will aid in the governments review since the data will have already been reviewed. It may be prudent to require the Government Blasting Consultant to review report as well.

(3) The following items should be checked on the plan. Chapter 5 gives guidance and formulas that can be used to evaluate the plan. Some offices have developed MS Excel® tools to input data from pre-shot plans into standard formulas from this manual and other references that can assist in evaluation of plans. Reach out to the Geotechnical, Geology, and Materials Center of Practice blasting experts for assistance. If there are questions when reviewing the Pre-Shot Plan it is best to meet with the Blasting Specialist and ask questions. The Government's blasting consultant must be used for the review of all blasting submittals and the shot plans. If there are concerns on timing and related matters, the plan can be changed. No drilling should start until approval of the Pre-Shot Plan. The blaster can make revisions to the plan based on conditions encountered during drilling, but these changes have to be noted and reasons given in the Post-Shot Report. By law, the magazine keeper must keep a strict accounting of explosives used and what is stored in the magazine. He does this partly by comparing the Pre-Shot and Post-Shot Reports to make sure the amount of explosives used adds up to what was described as being in each hole, etc. This requirement also includes:

(a) Determine drilling equipment capabilities.

(b) Check explosive selection for specific site conditions.

(c) Determine specific gravity of rock and explosives.

(d) Check burden dimension.

(e) Check stiffness ratio.

(f) Check stemming material and depth.

(g) Check subdrilling depth (is subdrilling allowed?).

(h) Determine loading density.

(i) Determine powder column length.

(j) Determine total weight of explosives per boreholes.

(k) Check Scaled distance formula (vibration control).

(l) Check timing sequence.

(m) Check spacing.

(n) Determine potential of violence utilizing stiffness ratio.

(o) Determine proposed drill-hole size for presplit.

(p) Check loading density and charge diameter for presplit.

(q) Check blasthole spacing (production and presplit).

(r) Check burden.

(s) Survey.

(t) Notifications.

(u) Seismograph locations.

(v) Drill logs.

(w) Typical loading diagram.

h. Damage Control and Verification

(1) By the use of the proper specifications and proper inspection during the project, the amount of damage should be minimized. For example, the alignment of presplit or trim blastholes can be checked using a laser profiler with boretrack unit attached. In this manner, before any blasts are

fired, the alignment of the blastholes can be checked on an ongoing basis to be sure that the contractor is drilling holes within proper accuracy limits. It is too late once the holes are drilled and fired to check the alignment of those holes. However, if those holes are checked before blasting and are found to be out of alignment, other holes can be drilled to help maintain alignment of slopes.

(2) If damage or alleged damage begins to occur, the contractor should immediately be put on notice. Contracts, which required approval of the contractor's Blasting Consultant, can have the contractor seek an assessment by the Blasting Consultant to properly adjust the blasting. For those contracts without advanced approval of a Blasting Consultant, the Contractor should bring his blasting consultant from the outside. The blasting consultant should be brought in to record, document, and verify the damage, and to determine methods to prevent damage to occur on subsequent blasts. The blasting consultant for the Government should verify and review the report generated from the Contractor's blasting consultant.

(3) One example is the Harlan Diversion Project where both the Corps and the contractor realized the problems with the controlled blasting on the site. The problems with the controlled blasting could have resulted in a multi-million dollar cost overrun on the project. Both the Corps and the contractor jointly hired a consultant who quickly came in and within a few days had the problem solved and eliminated the potential multi-million dollar cost overrun.

(4) Carefully check the Master Blasting Plan that planned items are as specified in contract:

(a) Make sure all personnel are qualified for their position.

(b) Verify resumes and reference projects by calling listed names and projects.

(c) Do not allow submission of the Master Blasting Plan until qualified personnel are approved by the Government and author the plan.

10-5. Video and Photographic Documentation.

a. All blasting conducted must be documented by digital video records. Digital video records should be taken of each blast from a minimum of two designated locations. The recordings should be labeled to identify the blast and location of camera (i.e., Shot 35a – Position A). The labeling is critical to correlate with actual shots. The proposed locations of the recorder should be submitted with the Pre-Shot Plan and subject to approval by COR/Project Geologist. On occasion, it will be necessary to adjust recording locations based on location of shot, weather, and lighting. The Government should be notified and paperwork should reflect this. Depending on the project, it may be advantageous to either specify and approve locations officially, or to require two cameras and coordinate with the contractor verbally the day of the blast. For example, on one project in a deep excavation, the QC in charge of setting up the cameras would simply stop by the Resident Office and discuss the locations for the cameras for the day's blast. The location of the cameras should be shown or referenced on the blast report. Still digital photos should be taken before and after the blasts and after mucking the shot rock to see the resulting walls and foundation. These photos would be separate from the final foundation photographs taken during mapping prior to concrete placement.

b. Recordings should be made available within a specified timeframe, typically within 24 hours, ideally on the same day. Recordings should be in a viewable format on the electronic database or contract required delivery. These videos will be critical for the blaster(s) to learn about their blasting design. Moreover, if there are problems with the shot, the Government can request the videos be provided before the specified timeframe.

c. The two camera location should be a minimum (the more cameras, the better). The contractor or Government may have webcams to monitor the site continuously, and the Government may want to set up their own cameras (especially if there are problems with the blasting) to serve as a backup to the contractor's recordings.

d. Digital photography should be required, especially on critical blast locations. Before and after photographs are always useful. Taking pictures of the shot timing hookup is also helpful. The blaster(s) will want to take photos for their resumes and marketing. Photographs are second only to video as learning tools. Both good and bad photographic results are useful for forensic analysis and to show work progress. Photographs are important to also document the construction progress, as it will be changing every day with blasting and some excavations will only be open for a limited time before concreting operations cover the foundation and walls.

Figure 10-2. Photograph of Drilled Shot Pattern Also Showing Line Drilled Walls.

e. Labeling required in specification and organization on electronic database. The submitted Post-Shot Report should always have a digital video disk attached for the final record/submittal. It is a good idea (and not much added effort) to enter each day's videos in an electronic database for all to view.

10-6. Data Management.

(1) The blasting program will create a significant amount of data. The specifications will require reports containing both raw and analyzed data. The construction contracts now require paperless contract files. This means that all submittals must be in electronic form. Construction is required to use the paperless contracting, which will make documents more readily available, typically as portable document file (PDF) scans of the hard copies that the contractor produces. For further information, consult Engineering and Construction Bulletin No. 2013-1, Implementing Virtual Contracting Enterprise (VCE) Paperless Contract File Initiative. ProjectWise, the current document management standard at the time of publication, or equivalent future system should be used to store permanent contract records.

(2) If specific files such as spreadsheets or drawings are required, then they should specified in the contract. It will be most beneficial to the Government and designers to require as much of the data as possible to be electronic, depending on the project. Since the contractor is likely already using all the data to their full benefit, the Government should require the contractor to share their data so the Government can also benefit from its use, and also reduce its efforts to turn analog data into digital. The submittals received will typically be organized by submittal numbers. The project should require a secure file transfer protocol (sFTP) site where data can be organized by shot number contain pre-shot, post-shot, videos, vibration and air overpressure data, etc.

(a) It may be necessary to require real time data from the contractor. The important information after a blast is determining whether the blast has caused any excessive vibrations in critical structures. The seismographs are typically being monitored via a call-in system or online retrieval of records. It may be beneficial to require that an online interface be made available to the Government and the customer so that readings can be retrieved after a blast. Note that it may be best for the Government to have access. It may also be useful to give customers access if they have the knowledge to understand and interpret the raw electronic data. All blasts will cause vibrations/air blasts, but the thresholds need to be clearly defined in the specifications for each structure. Do not monitor a structure simply for the sake of monitoring, or because there is no threshold given; this practice might make the customer think there is damage when there is no reason to be concerned. Some cases may require analysis. In other cases, a clearly indicated threshold may be helpful. For example, 2 in/s is the max allowable vibration of a maintenance shop foundation. On the display for the readings, it would be useful to note the maximum allowable reading, and below this, the actual reading. The values could also be written out or shown on a chart. If they will be involved in the work, The Resident Office QAs should be trained to do or monitor this activity.

(b) The designers should consider requiring the use or creation of a Geographic Information System (GIS) database for managing large blasting projects. The survey of hole locations, depths, powder loads, etc. could be recorded as featureclasses and used in GIS models of the site. Some powder companies provide programs or mobile applications for smart phone for blast design and checking calculations used in the Pre-Shot Blast Plan. These programs are sometimes free to blasters who purchase product from them.

10-7. Instrumentation and Monitoring.

a. The contract specifications will determine the seismograph locations. The contract should also allow for two or more seismographs for locations determined by the COR/Project Geologist. For example, if seismographs are specified to be located in basements of Buildings A and B and bridge foundation Piers 23 and 25, the contract should allow for two additional seismographs to be placed at the discretion of the Government. These two could then be placed in Building C and Pier 28, which are further away from the project site. After the test blasting, if it is reported that Building C and Pier 28 seismograph do not trigger as a result of any of the blasting, the contractor may request to remove the seismographs or they could decide that it may be more beneficial to move the Building C seismograph to Pier 24 and leave the Pier 25 location for the time being and evaluate later.

b. The QC/QA inspectors should have a basic understanding of how the seismograph works, and in what condition it should be set up. For example, the geophone is glued to the floor, or attached to a welded plate on a sheet pile. The QC/QA inspector should be able to judge at a glance whether the seismograph is improperly placed. They should be able to read the screen and determine the last reading. They should know the thresholds and inform others if these have been passed. They will need to know who to notify if thresholds have been exceeded. It is helpful to have a list of the instruments, their respective trigger levels, and the maximum threshold for the location along with a plan view drawing that notes the locations of the instruments. In some cases, instruments may be located in areas with limited access for safety or security concerns. A plan should be put in place to access that data remotely and to periodically inspect the instruments.

c. There may be other instruments besides seismographs that could detect performance issues because of nearby blasting. Each project will have different instruments. This manual will not address the need or use for these. However blasting near existing projects that may have instruments such as Relative Block Movement Devices (RBMDs), inclinometers, joint meters, crack gauges, etc. should include a monitoring plan for these instruments that outlines the roles, responsibilities, thresholds, and responses that are required. The inspectors should know where instruments are located, how they are monitored, and the given thresholds of concern. Typically these instruments will be installed and monitored before blasting because they are designed to monitor movement in structures independent of any blasting, but could result in movement due to blasting. Crack gauges may be installed in areas that have settled, or were damaged due to blasting, and that need further monitoring. Typically instrumentation will be a contractor responsibility. A subcontractor is often hired to handle this. However, the Construction Inspectors should also understand the system.

d. Refer to Chapter 8 for information regarding vibrations and monitoring. Evaluating the results from instrumentation to assess blasting effects will be an ongoing process by the vibration consultant, Blasting Specialist, and the Government. Results will be discussed in post-shot reports, vibration reports, and the Blasting Operations Overview Report (BOOR).

10-8. Data Needs for Completion Reports Following Construction.

a. Once the blasting and foundation work is completed, the project geologist can start compiling information and reports to incorporate into the overall project completion report. Completion reports are required per the Engineer Regulation (ER) 1110-1-1901. Completion reports for foundation construction section require that “if blasting is employed in connection with excavation, the blasting system should be described including information on the kinds and the quantities of explosives used, the sizes of charges, the depths and the spacing of holes, delays used, descriptions of any overbreak, special procedures such as smooth wall blasting or pre-splitting, and other pertinent data.”

b. The “other pertinent data” should include vibration data such as the site attenuation curve, photographic and video data, problems encountered, and results of any remediation. The project geologist and QA staff will be collecting data such as spreadsheets of the blasts and results in addition to the daily quality assurance reports (QAR) entered into Resident Management System (RMS). This data is helpful to the Administrative Contracting Officer and/or COR in documenting progress of work in event there is a claim, but also may be handy in the completion report to understand how the work was carried out from the Resident Office’s point of view.

c. ER 1110-1-1901 also requires, that on projects that include aggregate production and stockpiling for concrete materials, “[i]n case of quarry, the most commonly used blasting pattern should be detailed to include blasthole spacing and depth, powder types and requirements, delay timing and power factor.”

d. The main components related to the blasting will be further description of the geology in relation to the blasting conducted. There will be a summary of changes, if any, between the Pre-blast and Post-blast surveys, which should include whether there was any damage to surrounding structures as a result of the blasting, when was this discovered, and what was done about it. The summary should also list lessons learned for future projects.

e. The contract should require the contractor to submit a BOOR at various periods during the construction. For example, there should be a BOOR after test blasting, after critical shots, other times requested by COR, and a final BOOR for the project. This final report can be used to supplement the completion report. This is where the Blasting Specialist and vibration specialist, using the data collected during the course of blasting, will describe the test blasting and ramp up. (This may already be a report submitted immediately after the above is completed for government review, and may be contingent on the Government allowing the contactor to proceed with more blasting.)

f. The important data needed in the BOOR and useful in the completion report will describe: the line drilling that was conducted; the spacing and any loading; the results; the precision pre-splitted that was conducted; and the spacing, loading, results achieved; production blasting, buffer shots, and sinking and special shots conducted, and their results. There will be vibration data and site attenuation curve, videos, and other pertinent information. The report will also describe: the resulting to grade shots and results; whether subdrilling was allowed and the results; whether there was extensive blast damage and subsequent mechanical excavation, and whether these resulted claims. The report should conclude with lessons learned that can be taken away from this project to help future projects work better.

g. If there will be follow-on work on the particular project (such as a base plus options), or if a project will be bid in phases, there will be much to gain by studying the work of the blasting and/or first phase. The data collected can be used to improve the specifications for the future work and to allow for “knowns” to set the next contractor on a better footing. For example, suppose a lock project is separated into different phases. If the first phase contract consisted of upstream monoliths and the blasting program was very successful and produced some very useful information, then this documented information will allow a specification in the next phases to be written with more detail and allowances for the blaster to change methods based on the previously documented performance. If there was very little response from seismographs in certain locations, then there may be no need to incur that extra cost on the following phases. Most projects will be a fully complete project and will need documentation for the permanent record.

APPENDIX A

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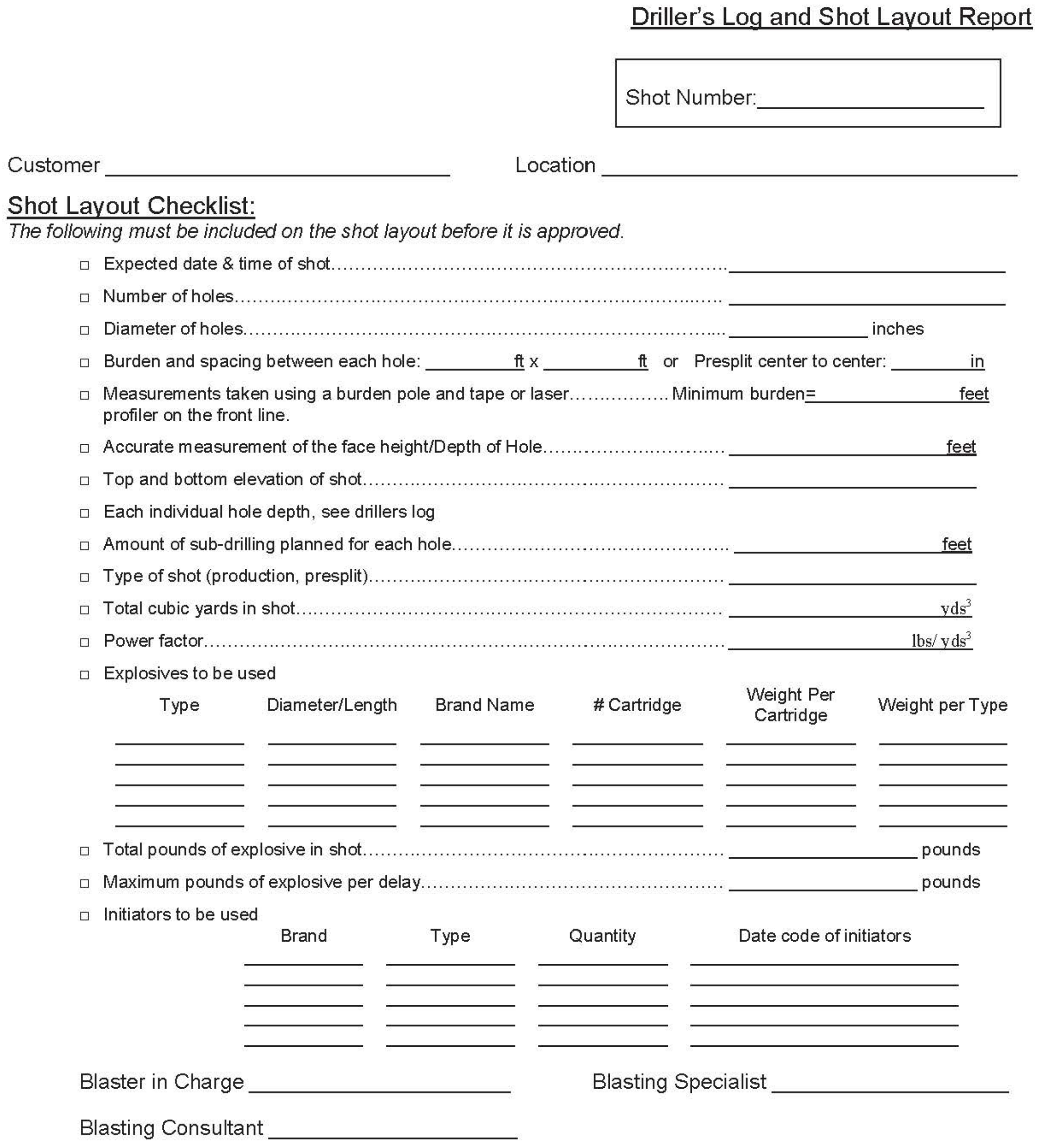
APPENDIX B

SAMPLE BLASTING FORMS



Driller's Log and Shot Layout Report

Shot Number:____________________

Customer ______________________________ Location ____________________________________

Shot Layout Checklist:

The following must be included on the shot layout before it is approved.

- ☐ Expected date & time of shot……………………………………………………________________________
- ☐ Number of holes……………………………………………………………………… ________________________
- ☐ Diameter of holes………………………………………………………………….... ____________ inches
- ☐ Burden and spacing between each hole: ________ft x ________ft or Presplit center to center: _______in
- ☐ Measurements taken using a burden pole and tape or laser profiler on the front line.……………. Minimum burden=____________feet
- ☐ Accurate measurement of the face height/Depth of Hole.…………………….… __________________feet
- ☐ Top and bottom elevation of shot……………………………………………… ____________________
- ☐ Each individual hole depth, see drillers log
- ☐ Amount of sub-drilling planned for each hole.……………………………………. ________________feet
- ☐ Type of shot (production, presplit)…………………………………………………… ____________________
- ☐ Total cubic yards in shot…………………………………………………………… ________________yds^3
- ☐ Power factor…………………………………………………………………………… ________________lbs/ yds^3
- ☐ Explosives to be used

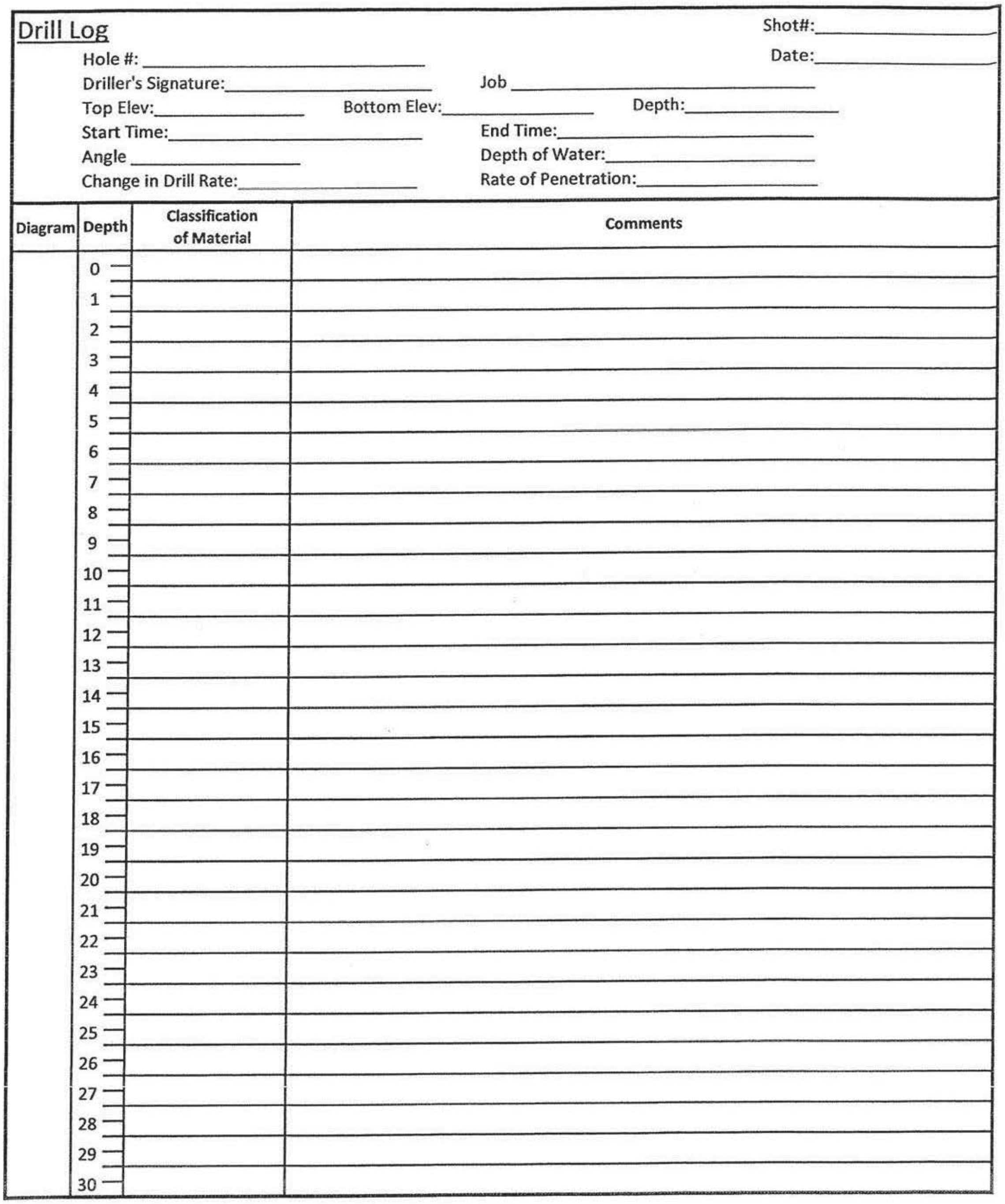
Type	Diameter/Length	Brand Name	# Cartridge	Weight Per Cartridge	Weight per Type

- ☐ Total pounds of explosive in shot……………………………………………… ______________ pounds
- ☐ Maximum pounds of explosive per delay……………………………………… ______________ pounds
- ☐ Initiators to be used

Brand	Type	Quantity	Date code of initiators

Blaster in Charge ______________________ Blasting Specialist ____________________

Blasting Consultant _____________________



Drill Log

Shot#:________________

Hole #: ________________________

Date:________________

Driller's Signature:__________________

Job ________________________

Top Elev:____________

Bottom Elev:____________

Depth:____________

Start Time:____________________

End Time:____________________

Angle ______________

Depth of Water:__________________

Change in Drill Rate:______________

Rate of Penetration:________________

Diagram	Depth	Classification of Material	Comments
	0		
	1		
	2		
	3		
	4		
	5		
	6		
	7		
	8		
	9		
	10		
	11		
	12		
	13		
	14		
	15		
	16		
	17		
	18		
	19		
	20		
	21		
	22		
	23		
	24		
	25		
	26		
	27		
	28		
	29		
	30		

Shot Grid (PROPOSED)

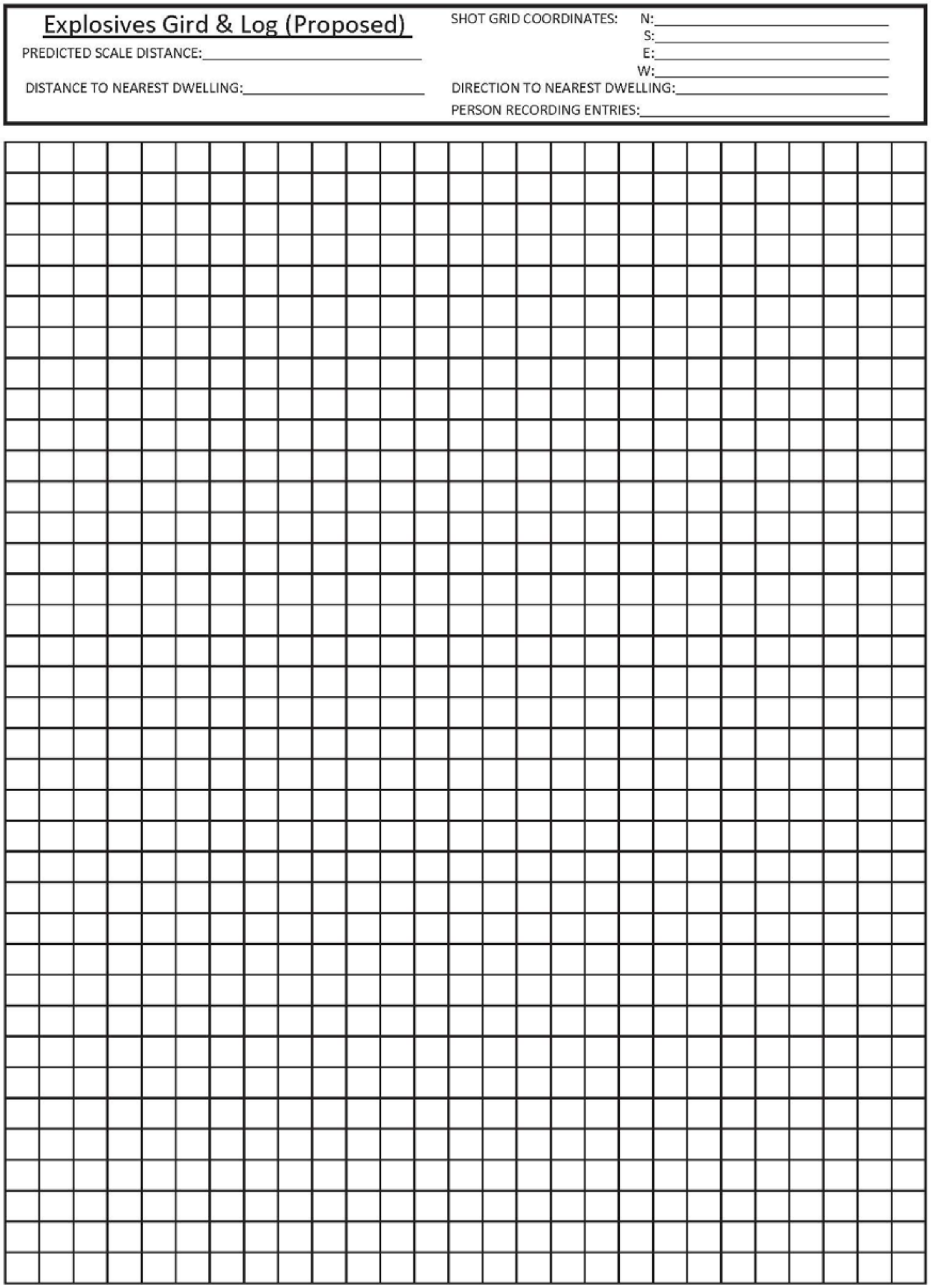
Plan View Diagram - Show point of initiation -POI

Include Hole location, hole pattern, delay periods, and relative location of structures
Hole Firing Times should be listed with top deck at top of list & deck timing descending in order of decks in hole.

Shot Grid (Actual)

Plan View Diagram - Show point of initiation -POI

Includes Hole location, hole pattern, delay periods, and relative location of structures
Hole Firing Times should be listed with top deck at top of list & deck timing descending in order of decks in hole.



Explosives Gird & Log (Proposed)

SHOT GRID COORDINATES: N:____________________________
S:____________________________
E:____________________________
W:____________________________

PREDICTED SCALE DISTANCE:____________________________

DISTANCE TO NEAREST DWELLING:________________________

DIRECTION TO NEAREST DWELLING:________________________

PERSON RECORDING ENTRIES:____________________________

Explosives Gird & Log (Actual)

PREDICTED SCALE DISTANCE:____________________________

DISTANCE TO NEAREST DWELLING:__________________________

SHOT GRID COORDINATES:
N:________________________________
S:________________________________
E:________________________________
W:________________________________

DIRECTION TO NEAREST DWELLING:____________________________

PERSON RECORDING ENTRIES:__________________________________

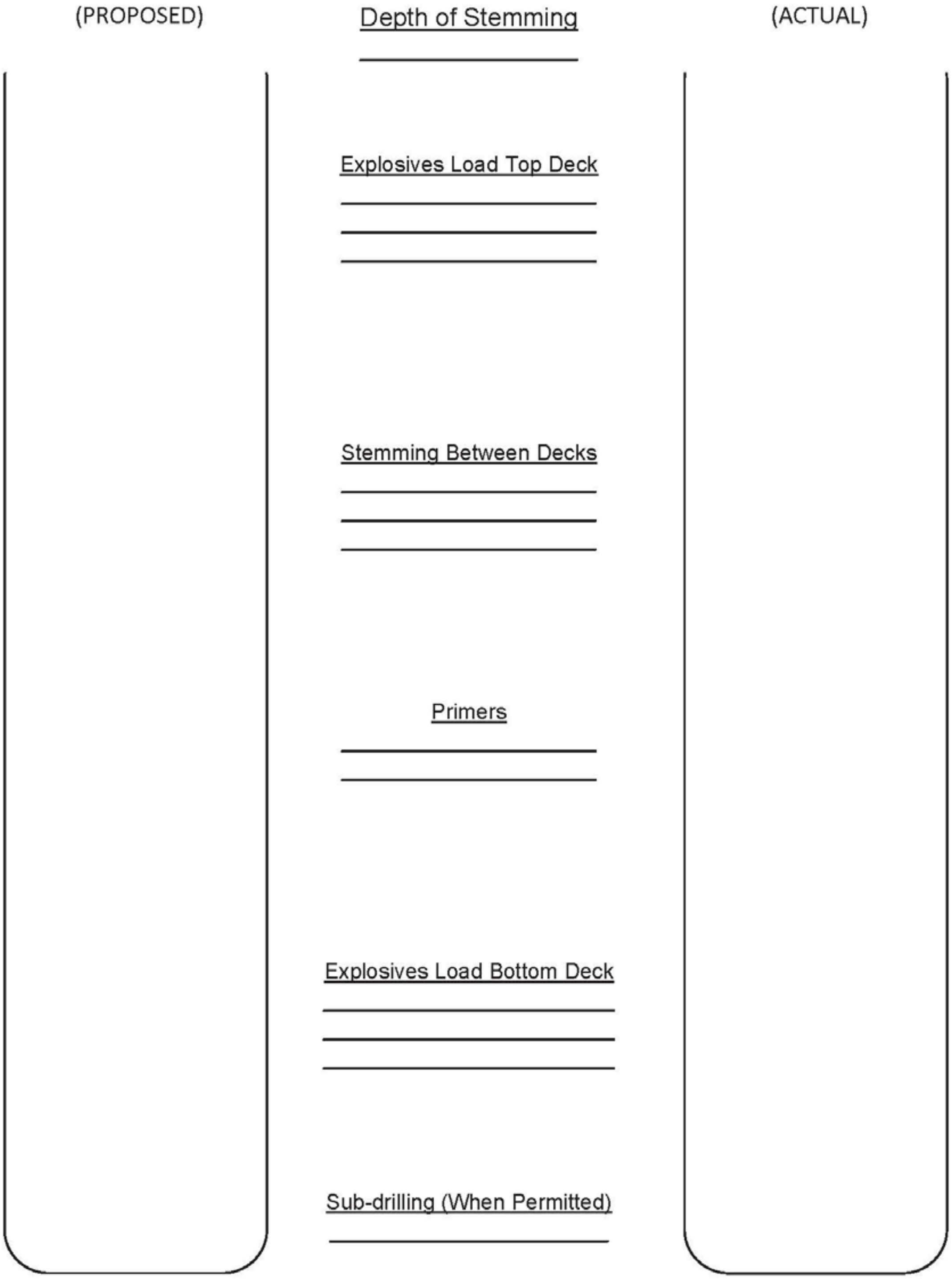
Explosive Log

JOB:______________________________ ENTERED BY:___________________________________

Hole #	Hole Depth	Explosives Load	Depth of Stemming	Decks	Primers	Hole #	Hole Depth	Explosives Load	Depth of Stemming	Decks	Primers
1						31					
2						32					
3						33					
4						34					
5						35					
6						36					
7						37					
8						38					
9						39					
10						40					
11						41					
12						42					
13						43					
14						44					
15						45					
16						46					
17						47					
18						48					
19						49					
20						50					
21						51					
22						52					
23						53					
24						54					
25						55					
26						56					
27						57					
28						58					
29						59					
30						60					

Total Number of Holes Loaded:__________________ Total Pounds of Explosvies:_______________________

Blasting Specialist:_____________________________ Blaster in Charger______________________________



(PROPOSED)

Depth of Stemming
____

(ACTUAL)

Explosives Load Top Deck
____
____
____

Stemming Between Decks
____
____
____

Primers
____
____

Explosives Load Bottom Deck
____
____
____

Sub-drilling (When Permitted)
____

Seismograph Locations:

Unit No: ____________________
Location: ____________________
Coordinates: ____________________
Elevation: ____________________
Distance to Blast: ____________________
Trigger level: ____________________
Seismic reading: ______NT or SA__________

Unit No: ____________________
Location: ____________________
Coordinates: ____________________
Elevation: ____________________
Distance to Blast: ____________________
Trigger level: ____________________
Seismic reading: ______NT or SA__________

Unit No: ____________________
Location: ____________________
Coordinates: ____________________
Elevation: ____________________
Distance to Blast: ____________________
Trigger level: ____________________
Seismic reading: ______NT or SA__________

Unit No: ____________________
Location: ____________________
Coordinates: ____________________
Elevation: ____________________
Distance to Blast: ____________________
Trigger level: ____________________
Seismic reading: ______NT or SA__________

Unit No: ____________________
Location: ____________________
Coordinates: ____________________
Elevation: ____________________
Distance to Blast: ____________________
Trigger level: ____________________
Seismic reading: ______NT or SA__________

Unit No: ____________________
Location: ____________________
Coordinates: ____________________
Elevation: ____________________
Distance to Blast: ____________________
Trigger level: ____________________
Seismic reading: ______NT or SA__________

Unit No: ____________________
Location: ____________________
Coordinates: ____________________
Elevation: ____________________
Distance to Blast: ____________________
Trigger level: ____________________
Seismic reading: ______NT or SA__________

Unit No: ____________________
Location: ____________________
Coordinates: ____________________
Elevation: ____________________
Distance to Blast: ____________________
Trigger level: ____________________
Seismic reading: ______NT or SA__________

Personnel on Shot Crew:

____
____
____
____
____

NT = Seismograph did not trigger
SA = See Attached Seismograph Report

BLASTING REPORT

Consumer ________________________ Operation ________________________
Address ________________________ Job Address ________________________
Delivery ticket # ________________________ Purchase Order # ________________________
BLAST DATA: Shot Number ________________ Date ______________ Time __________
No. Holes ____________________ Diameter __________in. Depth __________ft.
Burden __________ft., Spacing __________ft., Sub-drilling ________ft., Total stemming depth______ ft.
Material used to stem ________________________ Type of shot ________________________
Material being blasted ________________________
Blasters name ________________________ Signature ________________________
Blasters license No. ________________________ State ________________________

Explosives used:

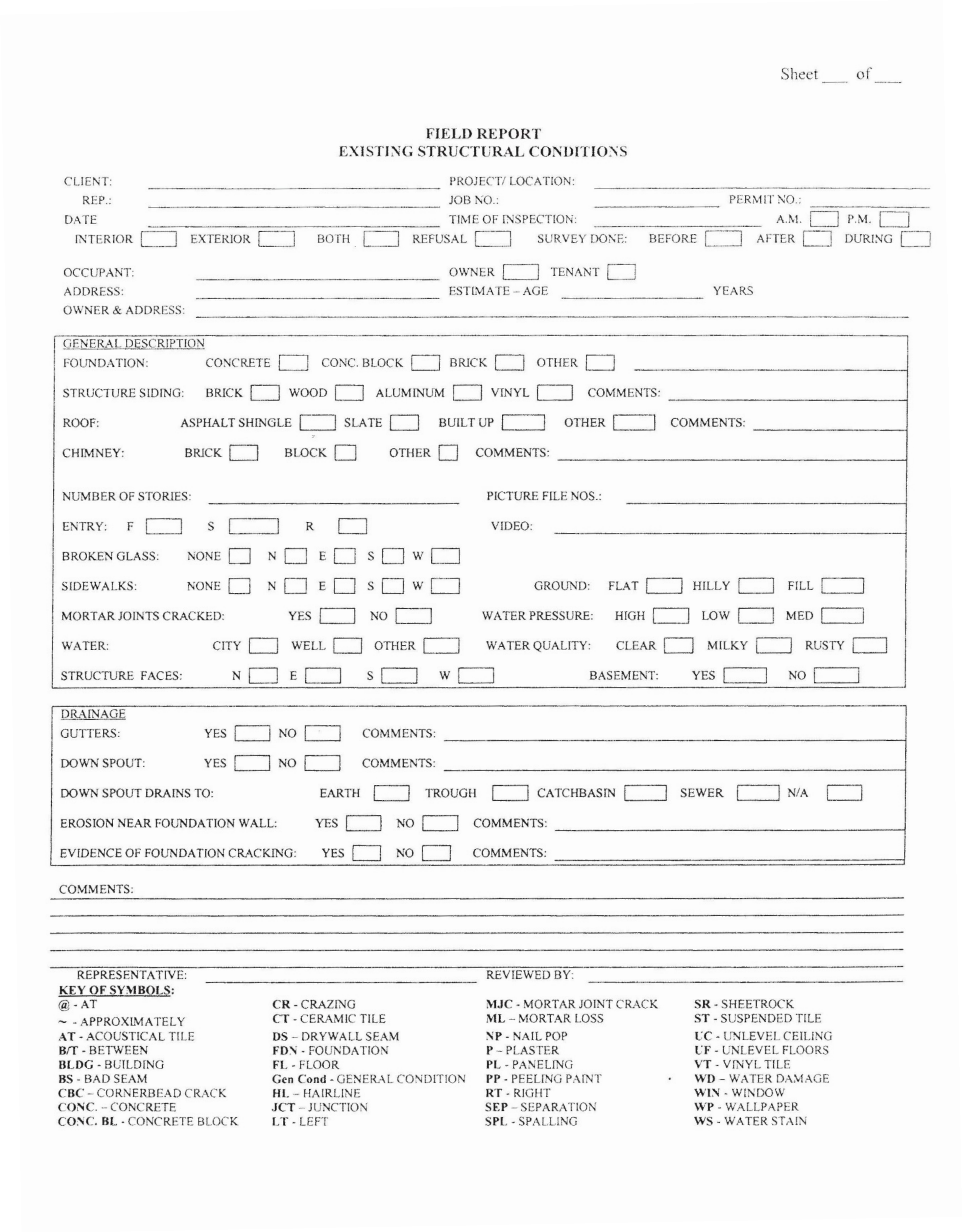
Type	Diameter/Length	Brand Name	# Cartridge	Weight Per Cartridge	Weight per Type

Estimated yds^3 ________ Powder factor __________lbs/ yds^3 Non-electric firing device ________________________
Maximum weight of explosives detonated within any 8 millisecond period ________________________
Maximum number of holes or decks detonated within any 8 millisecond period ________________________

Initiators used:

Brand	Type	Quantity	Date code of initiators

Weather ____________________ Temp. ______________ Wind direction ______________ Velocity ________mph
Actual Scaled distance ________________________ Were mats or other protection used _______yes _______no
Special conditions ____
____
____
Blasting Specialists evaluation of the blast result____
____
____
____



Sheet ___ of ___

FIELD REPORT
EXISTING STRUCTURAL CONDITIONS

CLIENT: ____________ PROJECT/ LOCATION: ____________
REP.: ____________ JOB NO.: ____________ PERMIT NO.: ____________
DATE ____________ TIME OF INSPECTION: ____________ A.M. ☐ P.M. ☐
INTERIOR ☐ EXTERIOR ☐ BOTH ☐ REFUSAL ☐ SURVEY DONE: BEFORE ☐ AFTER ☐ DURING ☐

OCCUPANT: ____________ OWNER ☐ TENANT ☐
ADDRESS: ____________ ESTIMATE – AGE ____________ YEARS
OWNER & ADDRESS: ____________

GENERAL DESCRIPTION
FOUNDATION: CONCRETE ☐ CONC. BLOCK ☐ BRICK ☐ OTHER ☐ ____________
STRUCTURE SIDING: BRICK ☐ WOOD ☐ ALUMINUM ☐ VINYL ☐ COMMENTS: ____________
ROOF: ASPHALT SHINGLE ☐ SLATE ☐ BUILT UP ☐ OTHER ☐ COMMENTS: ____________
CHIMNEY: BRICK ☐ BLOCK ☐ OTHER ☐ COMMENTS: ____________

NUMBER OF STORIES: ____________ PICTURE FILE NOS.: ____________
ENTRY: F ☐ S ☐ R ☐ VIDEO: ____________
BROKEN GLASS: NONE ☐ N ☐ E ☐ S ☐ W ☐
SIDEWALKS: NONE ☐ N ☐ E ☐ S ☐ W ☐ GROUND: FLAT ☐ HILLY ☐ FILL ☐
MORTAR JOINTS CRACKED: YES ☐ NO ☐ WATER PRESSURE: HIGH ☐ LOW ☐ MED ☐
WATER: CITY ☐ WELL ☐ OTHER ☐ WATER QUALITY: CLEAR ☐ MILKY ☐ RUSTY ☐
STRUCTURE FACES: N ☐ E ☐ S ☐ W ☐ BASEMENT: YES ☐ NO ☐

DRAINAGE
GUTTERS: YES ☐ NO ☐ COMMENTS: ____________
DOWN SPOUT: YES ☐ NO ☐ COMMENTS: ____________
DOWN SPOUT DRAINS TO: EARTH ☐ TROUGH ☐ CATCHBASIN ☐ SEWER ☐ N/A ☐
EROSION NEAR FOUNDATION WALL: YES ☐ NO ☐ COMMENTS: ____________
EVIDENCE OF FOUNDATION CRACKING: YES ☐ NO ☐ COMMENTS: ____________

COMMENTS: ____________

REPRESENTATIVE: ____________ REVIEWED BY: ____________

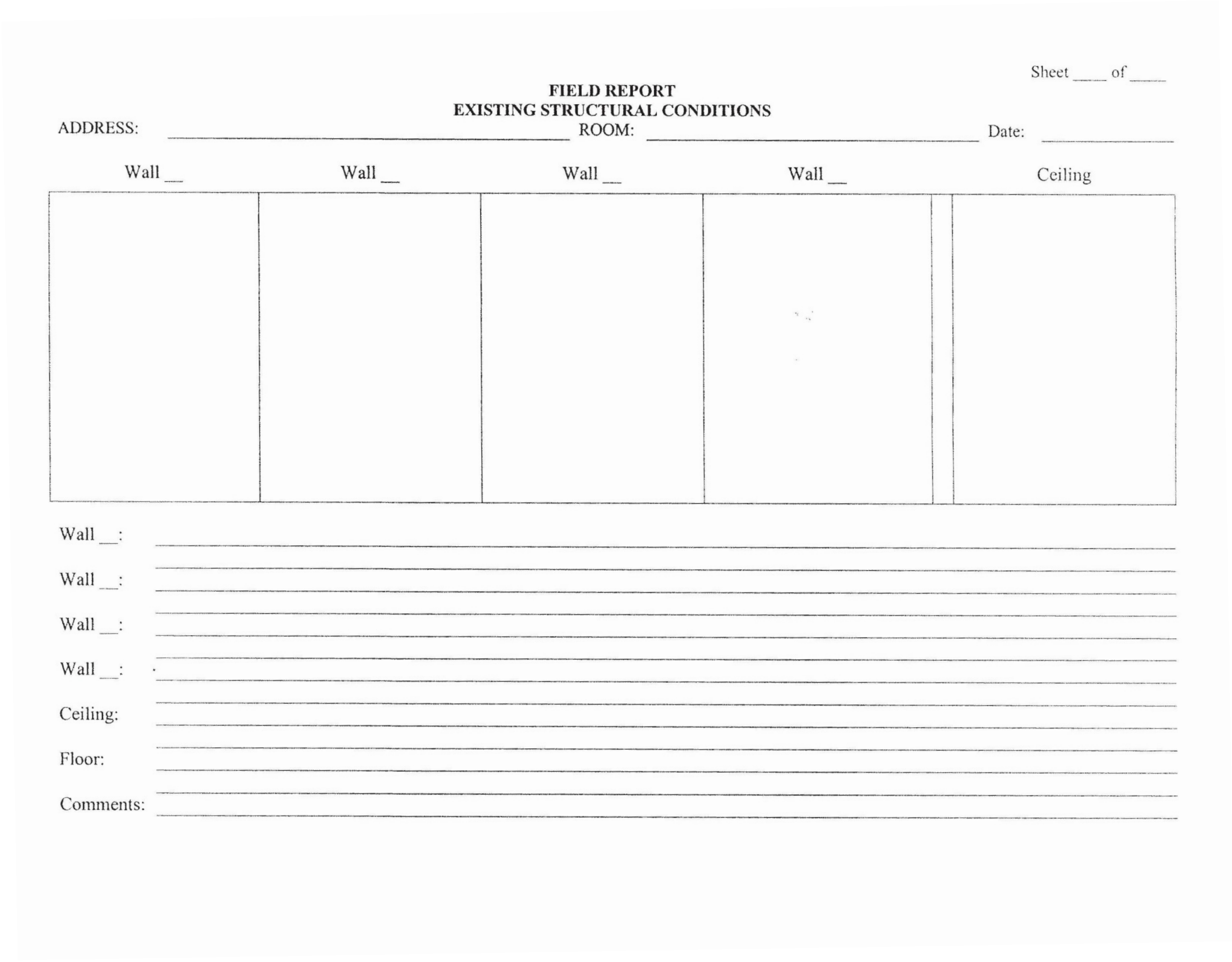
KEY OF SYMBOLS:

@ - AT
~ - APPROXIMATELY
AT - ACOUSTICAL TILE
B/T - BETWEEN
BLDG - BUILDING
BS - BAD SEAM
CBC – CORNERBEAD CRACK
CONC. – CONCRETE
CONC. BL - CONCRETE BLOCK

CR - CRAZING
CT - CERAMIC TILE
DS – DRYWALL SEAM
FDN - FOUNDATION
FL - FLOOR
Gen Cond - GENERAL CONDITION
HL – HAIRLINE
JCT – JUNCTION
LT - LEFT

MJC - MORTAR JOINT CRACK
ML – MORTAR LOSS
NP - NAIL POP
P – PLASTER
PL - PANELING
PP - PEELING PAINT
RT - RIGHT
SEP – SEPARATION
SPL - SPALLING

SR - SHEETROCK
ST - SUSPENDED TILE
UC - UNLEVEL CEILING
UF - UNLEVEL FLOORS
VT - VINYL TILE
WD – WATER DAMAGE
WIN - WINDOW
WP - WALLPAPER
WS - WATER STAIN



Sheet ____ of ____

FIELD REPORT
EXISTING STRUCTURAL CONDITIONS

ADDRESS: ____________________ ROOM: ____________________ Date: __________

Wall __	Wall __	Wall __	Wall __		Ceiling

Wall __: ______________________________

Wall __: ______________________________

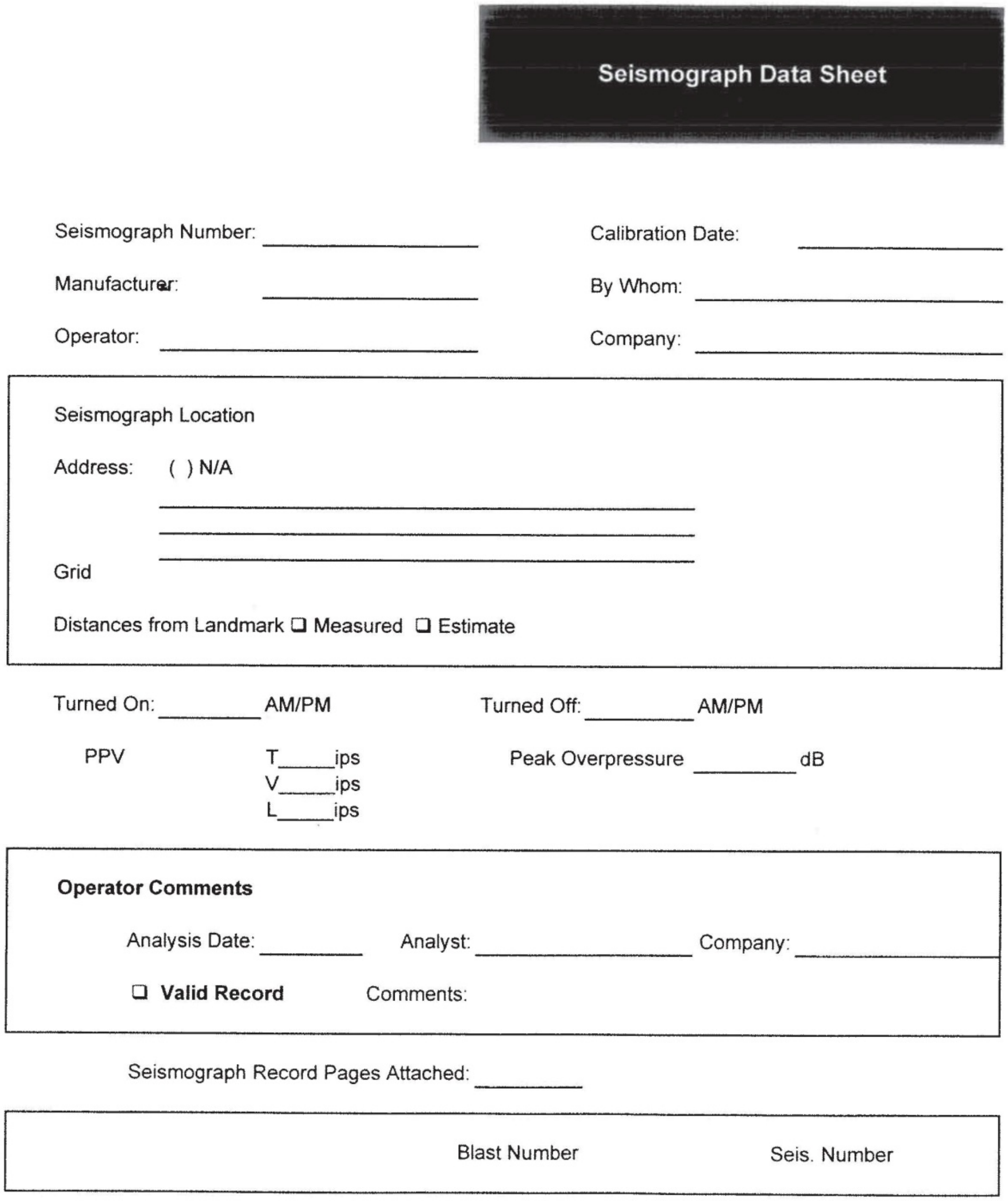
Wall __: ______________________________

Wall __: ______________________________

Ceiling: ______________________________

Floor: ______________________________

Comments: ______________________________



Seismograph Data Sheet

Seismograph Number: ____________________ Calibration Date: ____________________

Manufacturer: ____________________ By Whom: ____________________

Operator: ____________________ Company: ____________________

Seismograph Location

Address: ( ) N/A
____
____
____

Grid

Distances from Landmark ☐ Measured ☐ Estimate

Turned On: __________ AM/PM Turned Off: __________ AM/PM

PPV
T______ips
V______ips
L______ips

Peak Overpressure __________ dB

Operator Comments

Analysis Date: __________ Analyst: ____________________ Company: ____________________

☐ **Valid Record** Comments:

Seismograph Record Pages Attached: __________

Blast Number Seis. Number

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GLOSSARY

Table 1. Technical Terms Used in this Manual.

Term	Definition
Air bagging	A non-blasting method for rock removal involving the inflation of bags within a crack or crevice behind a boulder on a rock face to destabilize the rock and force it to fall off the slope.
Air blast	See air overpressure
Air overpressure	The air pressure caused by a shockwave induced by blasting over and above ambient air pressure.
Ammonium nitrate cycling	The ability of ammonium nitrate (AN) to change its crystal form with temperature.
ANFO	Ammonium nitrate (AN) and fuel oil (FO) a blasting agent. It is the most commonly used explosive on construction projects.
ATF	Alcohol, Tobacco and Firearms
Backbreak	A type of overbreak where rock is broken and/or displaced beyond the intended line of the blast.
Bedding	A break in sedimentary rock, the smallest division of a geological formation bounded by well-defined planes that separate the layer from other layers.
Bench height	Height of rock bench that will be blasted
Binary explosives	Two-component explosives that require the mixing of two ingredients, usually on site before the material becomes cap sensitive.
Blade or Drag-Bits	In softer material or shale it may be possible to rotary drill using bits that are configured with one or more chisel-shaped blades that are commonly carbide-tipped to scrape and gouge the material to advance the hole. Like roller bit drilling air or water may be used to remove cuttings, but water or drilling fluid may be necessary to cool the bit and remove cuttings from deeper holes.
Blasting Agents	A mixture of a fuel and an oxidizer that is intended for blasting, but is otherwise not an explosive and cannot be detonated using a No. 8 blasting cap. These are also called cap-insensitive or non-cap sensitive materials. They require a booster to detonate. The most common blasting agent is ANFO.
Blasting Caps	Small, sensitive explosive devices that are generally used to detonate a larger, more powerful and less sensitive explosive such as TNT, dynamite, or plastic explosive.

Term	Definition
Blasting mats	Used to help control flyrock. These are very heavy mats usually made from rubber tires, conveyor belts or other similar materials. While not practical to cover large blast areas, blast mats are of particular use in confined areas where flyrock may damage buildings or other structures.
Brisance	The capacity of an explosive to shatter rock. This capacity is mainly controlled by the detonation pressure of the explosive.
Booster	An additional explosive used to intensify the explosive reaction of an explosive. These are used with blasting agents that require a booster to initiate detonation.
Bootleg	A portion of a blasthole remaining in the rock mass after a blast. These can be dangerous where explosives are left in the hole due to a misfire or other blasting mishap.
Boreholes	Holes drilled into rock into which explosives are placed. These are generally drilled using “destructive” drilling techniques that do not leave a rock sample such as core behind.
Bulk Strength	Is the energy level at a constant volume as compared to a standard explosive. ANFO is used as the standard and has an energy level of 100.
Burden	The volume of rock to be fragmented and displace by blasting. There are two kinds, the drilled burden and the shot burden.
Burden distance	The shortest distance from the blastholes to the nearest free face.
Cap sensitive	The property of an explosive that describes its sensitivity to being initiated by a blasting cap. A blasting agent also requires a booster to initiate.
Cap scatter	The excessive delay or uncertainly produced by the error rate of the initiation system resulting in blasting caps that detonate sooner or later than the design.
Cartridge slurry	A slurry explosive product contained in a cartridge for easier transportation and loading.
Cohesiveness	The ability of the explosive to maintain its original shape.
Combustion	The exothermic chemical decomposition of a compound. It is a reaction between a fuel and an oxidizer.
Competent Rock	A rock that is intact and in a generally unweathered to slightly weathered state.

Term	Definition
Confinement	The restriction of the ability of an explosive charge to escape before performing work on the rock it is supplied by the burden. Boreholes are drilled in a rock mass to provide confinement for the explosive. More of the blasting energy is directed toward work in the rock mass where the explosive is confined.
Critical Diameter	Is the minimum diameter at which a particular explosive will reliably detonate.
Decking	Method to create unloaded zones. Often this is created by using stemming to separate several layers of explosives in a loaded hole. Decks may be used to increase the efficiency of the blast, to limit the amount of explosives at any given delay or may be used where a weak layer or void has been encountered in the rock.
Deflagration	Deflagration or burning, occurs when the combustion of the explosive compound occurs at less than the speed of sound. It propagates through the explosive material through a flame front (heat transfer).
Delay	The time interval between successive detonations. These are used by the blaster to provide a free face for rock to displace.
Depth of advance	The total length of the borehole down to the intended grade of the blast.
Detonating cord	A round, flexible cord containing a center core of high explosive, usually PETN, within a reinforced waterproofing covering.
Detonation	Occurs when the combustion of the explosive compound occurs more rapidly than the speed of sound. It propagates through the explosive material by a detonation, or shock wave. The speed of this wave through the surrounding rock will vary by explosive used, properties of the rock, and appropriate design of a blast.
Detonating cord	Also called Det Cord. It is a round, flexible cord containing a center core of high explosive, usually PETN, within a reinforced waterproofing covering. Detonating cord is relatively insensitive and requires a proper detonator, such as No. 6 strength cap, for initiation
Detonation pressure	The pressure produced by the shock energy of a detonation.
Detonation velocity	The speed that the detonation, once it has reached a steady state travels through the explosive.
Detonator	A device, either electric or non-electric that is inserted into an explosive and used to cause the detonation.

Term	Definition
DHD	Down-the-hole drill percussion drill rig sometimes used to drill holes for blasting. The hammer providing the percussive force is located in the borehole and boreholes are generally somewhat larger than OHD's where the hammer is located outside the borehole.
Diamond Rotary Drilling	In some instances it may be necessary to use diamond-embedded or diamond-impregnated bits to rotary drill holes. These bits come in a limited number of sizes and configurations because of the expense involved in their manufacture. They have the advantage of providing a smooth borehole and also may be used with coring tools to provide representative core of the material. Diamond rotary drilling is significantly more expensive than other types of drilling.
Dirt Ditching	Dirt ditching is the use of explosives to excavate a ditch or trench in soil.
Drifter drill	See OHD
Drill cuttings	Material removed from a borehole by drilling action usually of a percussive drill. These are chips, sand, or gravel sized bits of rock removed by the flushing action of air or water.
Drilled burden	Defined as the distance between a row of boreholes and the nearest free face. It is always measured perpendicular to a row. It is also the distance between any two rows of boreholes. When laying out a blasting pattern for a shot, this is the term usually meant when using the word burden.
Drilling dust	Very fine drill cuttings, usually unsuitable for use as stemming.
Dry Blasting Agent	See ANFO.
Dynamite	A high explosive made from the combination of nitroglycerine stabilized with diatomaceous earth (or other absorbent substance such as powdered shells or clay) and including a small amount of sodium carbonate. Dynamite is generally formed in small sticks covered with a protective coating.
Electric blasting (EB) caps	An electric initiation system.
Electronic delay Initiation Systems	An electronic based initiation system. These systems allow more accuracy and precision than other systems.
Emulsion	An explosive mixture with a similar composition to slurry explosives. These products have higher detonation velocities than most slurries.
Endbreak	Overbreak from the end of a cut after a blast.

Term	Definition
Explosives	Chemical mixtures or compounds that when subjected to shock, impact, or heat produces a rapid chemical reaction that results in the sudden release of energy through the process of detonation. This sudden release of energy, mostly in the form of hot gas, when properly confined and initiated can be used to perform mechanical work on the surrounding material. There are four basic components in explosives: carbon, hydrogen, nitrogen, and oxygen. These components are combined so that the explosive mixtures are part oxidizer and part fuel or sensitizer
Facies	For rock: A group of rock units. Facies are generally a subdivision of a formation that describes a subset of the formation. It is defined by the particular rock type and its characteristics.
Flyrock	The rock that is launched into the air and travels further than was intended by the blast design. Flyrock can cause considerable damage.
Free face	Defined as the nearest open face and it marks a boundary of a rock mass that is relatively uniform in its properties. In rock blasting this is the edge of the rock face or at a row of blastholes that is uncovered during blasting to provide room for expansion and movement after detonation has occurred. It is also the top surface of the rock that will be blasted. Features such as joints, faults, bedding planes, voids, and other discontinuities are not considered free faces because they do not allow for relief.
Full Cast	See whole cast
Fume	A toxic gas produced during the detonation process.
Half Cast	Part of the borehole used for blasting left on a rock cut face after blasting. Where good pre-splitting technique is used, these should be visible on the face.
Heave	The amount the rock displaces from the in-situ condition due to blasting.
Heavy ANFO	An ammonium nitrate blend of ammonium nitrate prills, fuel oil, and an explosive slurry.
High Explosives	Those that when unconfined can be can be detonated using a No. 8 blasting cap. Dynamite is a type of high explosive.
Initiation system	The entire system used to initiate the blast. This includes the detonator (electric or non-electric), boosters, starters, delay devices, and all their connecting parts.

Term	Definition
Intact rock	The rock type (e.g., limestone, sandstone, granite, basalt) in its intact condition without the discontinuities, joints, bedding, and other features that describe the whole rock mass. Laboratory samples of rock are generally samples of the rock material and do not necessarily reflect the properties of the rock mass.
Kinematic Analysis	Analysis of the faults, fractures, joints, bedding, and other structural features within a rock mass that can results in a rock failure mode such as: plane shear, wedge failure or toppling.
Lithology	Geology term for indicate a zone or layer of rock that has relatively consistent geological features.
Low Explosives	An explosive material that deflagrates (or burns) when unconfined. The most common example is black powder.
MSHA	Mine Safety and Health Administration
Mudcapping	The use of mud to couple and explosive charge to a boulder to fragment the rock, this is a method of secondary blasting.
MWD	Measurement While Drilling
No. 8 Blasting Cap	An industry standard blasting cap used as a detonator. It contains two grams of a mixture of 80% mercury fulminate (a secondary explosive) and 20% cent potassium chlorate (a primary explosive), or a blasting cap of equivalent strength. An equivalent strength cap comprises 0.014-.016 oz of PETN base charge pressed in an aluminum shell with bottom thickness not to exceed 0.03 in., to a specific gravity of not less than 0.8 oz/in^3., and primed with standard weights of primer depending on the manufacturer. It is the most common type of blasting cap in use as of 2014.
Nomograph	A graph representing the relationship between three or more variables arranged so that the relationship between each variable can be determined from a straight line.
NONEL	Non-electric initiation systems. Early systems were caps and fuses, but now currently include detonating cord systems, delayed primers, and shock tube initiation systems.
OHD	An over-the-head percussion drill rig also called a topdrill or drifter drill often used to drill boreholes used for rock blasting. The hammer is located outside the drill hole.
OSHA	Occupational Safety and Health Administration
Overbreak	Is rock that has been removed further than was intended on a rock wall face by the blasting operations. Also called backbreak.

Term	Definition
Overconfinement	Where too much confinement of the explosive occurs (e.g., where there is too much burden). This can cause excessive airblast, flyrock, and vibrations.
Percussion Drill	A drill rig that uses a bit to pound or chisel rock down in a borehole. The drive rotates the bit, producing a uniform circular hole. Water or air is used to flush out cuttings. There are two types of rigs, depending on the location of the hammer used to provide the percussive force: Over-the-Head Driven, where the hammer is located outside the hole and DHD (Down-the-Hole Driven), where the hammer is located within the hole itself.
PETN	Pentaerythritol Tetranitrate, a high explosive that is a nitrate ester of pentaerythritol. First created in 1891 by Bernhard Tollens and P. Wigand and patented by DuPont in 1945 it has a high brisance and is primarily used as a booster. It has the explosive power of 1.24 x that of TNT.
Powder column length	The length of the borehole where explosive charge(s) has been placed.
Powder factor	The ratio between the weight of explosives that have been detonated and the total volume of rock that was blasted. For construction practice, this volume is measures in cubic yards. Shot powder factor, the total weight of explosives, and the total volume of rock (including the subdrilling zone) should always be reported on construction monitoring documents.
Presplit blasting	A cautious blasting procedure that is used to produce a shear plane within the rock mass. Most often used to produce a clean, and relatively solid rock cut face, presplit blasting involves the use of boreholes that are more closely spaced than production blastholes. These more lightly loaded holes are detonated ahead of the main production blast and it propagates a crack along these holes. The crack is intended to protect the new rock cut face, or some other perimeter, by allowing the blasting gases an escape point. This has the effect of reducing back break, or overbreak, in the new rock wall. This method is used extensively for roadway rock cuts and any other cuts where a solid wall with little to no backbreak is needed. It is used to reduce the amount of rockfall that can occur from the exposed face than could be expected using production blasting alone. When executed well, the exposed rock face should contain “half casts” of the boreholes used for blasting.
Prill	A small dry sphere made from melted liquid. Bulk ANFO is prilled ammonium nitrate and fuel oil.

Term	Definition
Primer	An explosive device used to initiate detonation in a more insensitive explosive. A No. 8 blasting cap is a type of primer.
Production Blasting	Is a blast that is intended to fragment and displace a designed volume of rock. The focus of this blast is the maximum volume of rock fragmented per amount of explosive used. This blasting technique by itself will produce a ragged rock face and does not provide protection against back break or overbreak at the new rock face. It also tends to create radial fractures around the boreholes, which reduce the strength of the remaining rock mass if techniques such as presplit blasting are not used along with production blasting.
Relief	Presence of a free face in the rock mass such that the blasted rock can displace into that space as it displaces and expands due to the detonation.
Rock blasting	The science and art of the use of controlled explosive energy to fragment, displace, and shear, thus facilitating the removal of rock. It can be used both for surface and subsurface rock excavation and for rock removal underwater. When this explosive energy is released inside rock, it produces both fragmentation of the rock and heave (displacing the rock from its in-situ condition). Blasts can be designed to fragment rock only for ease of removal, but can also be designed to fragment rock into smaller sizes useful for the production of rock products such as rip-rap.
Rockfall	Is rock that falls off of a slope onto an undesirable location.
Rock Mass	Describes the entire mass of rock to be removed or considered. It includes the rock type, but also all joints, fractures, bedding, faults, voids, discontinuities, and other features that may affect the behavior of the rock as a whole. Thus, the properties of the rock mass may be considerably different from those of the rock material.
Roller Bit Drilling	Bi-cone or more commonly tri-cone bits are made with abrasive rotating cones arranged to roll as downward pressure is applied and the bit is rotated. Typically the cones are roughened with button-shaped projections of hardened steel or carbide. Although air can be used alone to remove cuttings, water, or drilling fluid may be necessary in deeper holes both to remove cuttings and cook the bit as frictional heating may cause t to weaken or prematurely wear.
Rotary Drilling	Rotary drilling advances the hole not by abrasion and advances the hole by applying downward pressure while rotating the cutting bit.
Scaling	The removal of loose, detached, or separated rock from a rock slope face.

Term	Definition
Secondary Blasting	A secondary blast used to fragment rock that was not adequately fragmented by the initial production blast.
Sensitivity	The property of an explosive that defines how easily the reaction can be initiated. Highly sensitive explosives can, under the correct circumstances self-initiate.
Sensitiveness	The characteristic of an explosive that defines its ability to propagate through the entire length of the column charge and controls the minimum diameter for practical use. If bore hole diameter is smaller than this critical diameter for the material, detonation of the explosive material will not occur. Note: unconfined critical diameter for a particular product is usually different than the confined critical diameter.
Sequential Blasting Machine	Is a solid state condenser-discharge blasting machine with a sequential timer that permits the detonation of many electric caps.
Shock tube	Is a non-electric detonator in the form of a small diameter hollow plastic tube. This tube shocks the explosive through the use of a percussive wave traveling down the length of the tube. It usually contains a small amount of HMX/aluminum explosive powder on the tubes inner diameter that detonates at great speed.
Shot burden	Defined as the distance between a single borehole containing explosives and the nearest free face.
Sinking Cut blasting	Where a blast must be designed that has no vertical or sloped free face and it must penetrate into the rock below. Rock cannot be displaced sideways in this type of blasting and thus it must be expelled upwards. Flyrock is a particular problem with this type of blast as it is not possible to direct the blasting energy in any direction but up. This must be accounted for during design and monitoring.
Slurry	A mixture of AN or other nitrates and a fuel sensitizer. This sensitizer is usually a hydrocarbon or hydrocarbon and aluminum. Occasionally TNT or nitrocellulose is used along with water.
Smooth blasting	Similar to presplit blasting, but the holes are detonated after the production blastholes are detonated. The purpose is to blast loose remaining burden with lighter charges while not causing any additional damage to the new rock wall face. Smooth blasting has been used effectively where there is a joint or discontinuity in the rock that already exists at the desired new rock face.
Spacing	Defined as the distance between holes that are located in a row. Drilling patterns are always defined as this spacing and the burden (e.g., for a 5 x 6 pattern, the blast design has a burden of 5 ft. and a spacing between boreholes of 6 ft.).

Term	Definition
Stemming	The inert material put in a borehole along with the explosive to provide confinement along the axis of the borehole. Material used for stemming is commonly small angular sized aggregate or drill cuttings, though it is not recommended to use drill cuttings.
Subdrill	The length of borehole below the bottom grade of the intended blast.
Swell	The term used to account for the increase in volume of rock that has been blasted or otherwise excavated. The volume increases from the in-situ condition because the piled rock fragments take up more space as intact rock is much denser.
Swell factor	The percentage of increase in volume expected due to blasting or excavation.
Temperature resistance	The ability of an explosive compound to resist decomposition, initiation, or other problems due to changes in the explosives temperature.
Throw	See heave
Topdrill	See OHD
TNT	2,4,6-trinitrotoluene, a high explosive that was first invented in 1863 by Joseph Wilbrand for use as a yellow dye. Due to its high activation energy and stable characteristics, this compound was not used as an explosive for years after its initial manufacture. TNT is used as a standard for explosive energy and has been used in construction, though its primary use has been for military ordinance and industrial applications.
Water gel	See slurry
Water resistance	Is the ability of an explosive to withstand exposure to water without it suffering detrimental effects in performance.
Whole Cast	The blasting borehole remains intact after blasting operations have been completed. These are most often due to blasting or drilling error.

Table 2. Acronyms and Abbreviations Used in this Manual.

Term	Definition
ACO/COR	Administrative Contracting Officer/Contract Officer Representative
ANFO	Ammonium Nitrate and Fuel Oil
ANSI	American National Standards Institute
ASSE	American Society of Safety Engineers
ASTM	American Society for Testing and Materials
ATF	(U.S. Department of Justice) Bureau of Alcohol, Tobacco, Firearms, and Explosives
BOOR	Blasting Operations Overview Report
CECW	Directorate of Civil Works, U.S. Army Corps of Engineers
CFR	Code of the Federal Regulations
CLIN	Contract Line Item Number
COR	Contract Officer Representative
CRSD	Cube-Root Scaled Distance
DHD	Down-the-Hole Driven Drills
DoD	U.S. Department of Defense
DOT	Department of Transportation
EB	Electric Blasting
ECIFP	Engineering Considerations and Instructions for Field Personnel
EM	Engineer Manual
EP	Engineer Pamphlet
ER	Engineer Regulation
ETL	Engineer Technical Letter
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FO	Fuel Oil
GBR	Geotechnical Baseline Report
GDR	Geotechnical Data Report
GIS	Geographic Information System
HMX	Octahydro-1,3,5,7-Tetranitro-1,3,5,7-Tetrazocine
HQUSACE	Headquarters, U.S. Army Corps of Engineers

Term	Definition
IME	Institute of Makers of Explosives
ips	Inches per second, (in/s)
ISEE	International Society of Explosives Engineers
LLHD	Long Length, Heavy Duty
LP	Long period
ms	Millisecond
MSC	Major Subordinate Command
MSHA	Mine Safety and Health Administration
MWD	Measurement While Drilling
NA	Not Applicable
NG	Nitroglycerine
NONEL	Non-Electric
NPDES	National Pollutant Discharge Elimination System
OHD	Out-of-the-Hole-Drill
OSHA	Occupational Safety and Health Administration
OSM	Office of Surface Mining
PC	Powder Column (length)
PDF	Portable Document Format
PETN	Pentaerythritol Tetranitrate
POI	Point of initiation
PPV	Peak Particle Velocity
QA	Quality Assurance
QAR	Quality Assurance Report
QC	Quality Control
RBMD	Relative Block Movement Device
RE	Resident Engineer
RFP	Request for Proposal
RI	Report of Investigations
RMS	Resident Management System
RQD	Rock-Quality Designation
SDOF	Single Degree of Freedom

Term	Definition
SES	Senior Executive Service
SPL	Sound Pressure Level
SPT	Standard Penetration Test
SQRD	Square root scaled distance
SSHO	Site Safety and Health Officer
STD	Standard
TAN	Tangent
TNT	trinitrotoluene
TR	Technical Report
TVA	Tennessee Valley Authority
U.S.	United States
USACE	U.S. Army Corps of Engineers
USBM	U.S. Bureau of Mines
USCG	U.S. Coast Guard
USGS	U.S. Geological Survey
VCE	Virtual Contracting Enterprise

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