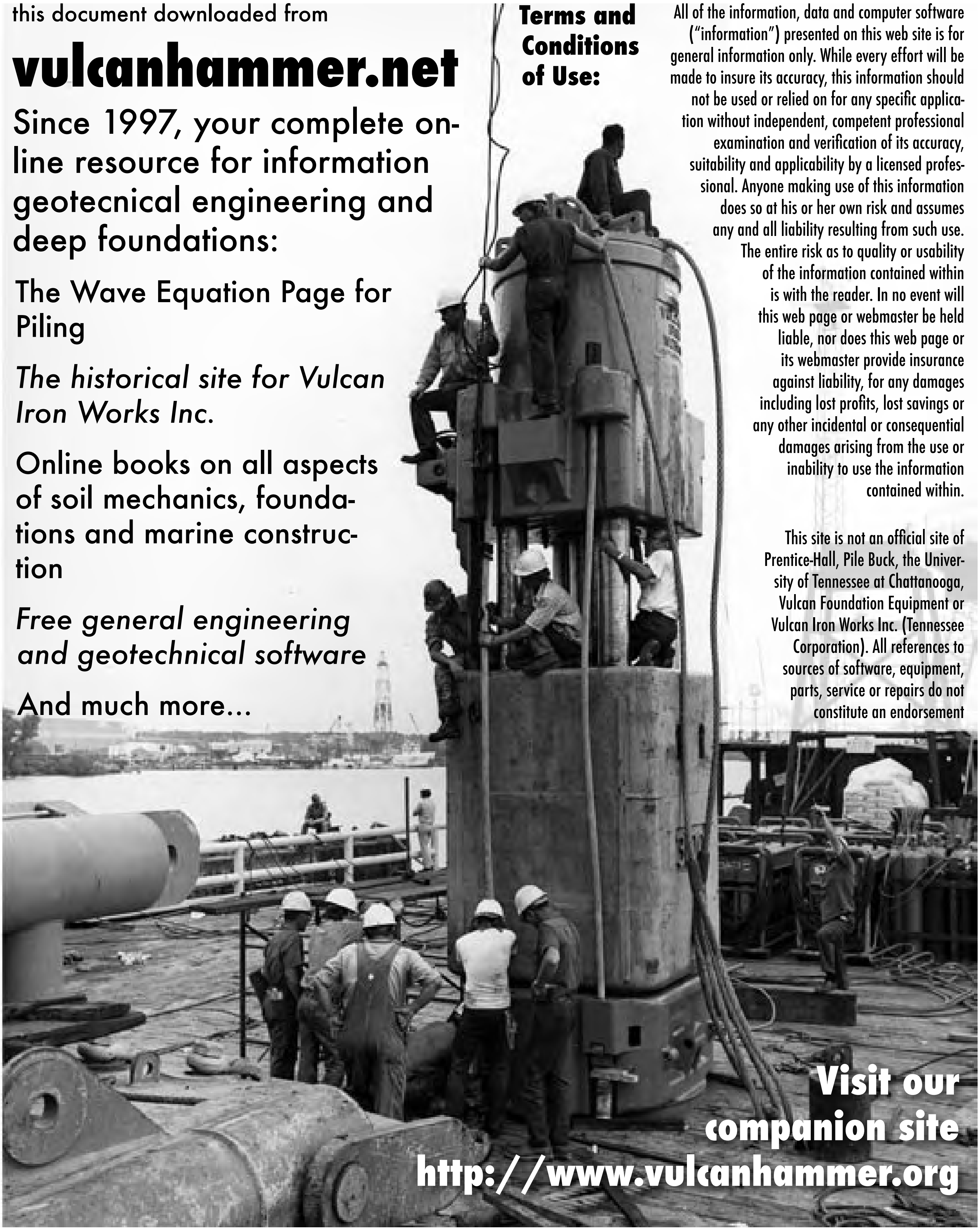

NORTHWESTERN UNIVERSITY

SPECIFICATIONS
FOR CONTROL OF VIBRATIONS
DURING BLASTING AND PILE DRIVING

THESIS

SUBMITTED TO THE DEPARTMENT OF CIVIL ENGINEERING

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS

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MASTER OF SCIENCE

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by

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ABSTRACT

Controlling environmental effects of civil engineering operations has always been of concern to all parties involved in the construction process. Since control is exercised through the responsibilities outlined in contract specifications, these details are important. This work specifically addresses specifications that incorporate recent developments in the control of external construction vibration effects. These technical vibration specifications are intended to establish controls for the protection of nearby structures from ground vibrations, permanent ground deformation, emission of projectiles, and low frequency air overpressures. Annoyance of neighbors from noise and vibration intrusion also must be taken into account.

An attempt is made in this thesis to present suitable specifications for all types of blasting encountered today in civil engineering projects: production rounds, controlled, close-in and demolition blasting, as well as blast densification of sands. Special chapters deal with vibrations and soil displacement caused by pile driving, and with air overpressures created by both blasting and piling engineering.

The following conclusions are advanced, among others, concerning the geotechnical, the procedural, and the management aspects of vibration control specifications. It is necessary to take vibration considerations into account in the design of the project. This can be accomplished by making preconstruction surveys, by incorporating frequency considerations, and by setting realistic particle velocity limits. The specification should ask the contractor to meet given requirements, but should leave the choice of the method to his ingenuity. Specialists of the operations carried out on the site should be hired by the contractor, and test programs should always be performed before the start of full scale activities. Monitoring of vibration effects, such as peak particle velocity and air overpressures, requires special schemes, especially for pile driving, where two threshold values of particle velocity should be introduced. The engineer should not be considered only as the control authority, but also as a skilled person whose advise on specific problems can be valuable.

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V = vibration peak particle velocity, in ips (mm/s),

I = intercept, vibration particle velocity when $(R/\sqrt[i]{W})=1$,

R = distance from the blast, in ft (m),

W = charge weight per delay, in lbs (kg),

n = attenuation slope,

i = 2 or 3, respectively for square or cubic root scaling,

f = frequency, in Hz,

δ = displacement, in inches (mm),

g = acceleration of the gravity,

D = distance from the pile driving activity, in m,

I = intercept, vibration particle velocity when D = 1m,

j = seismic component,

L_{NP} = noise pollution level, in dB,

L_{eq} = mean intensity of the noise over a specific time period, in dB,

σ = standard deviation of instantaneous noise pollution level

INTRODUCTION

Controlling environmental effects of civil engineering operations has always been of concern to all parties involved in the construction process. Since control is exercised through the responsibilities outlined in contract specifications, these details are important. This work specifically addresses specifications that incorporate recent developments in the control of external construction vibration effects. These technical vibration specifications are intended to establish controls for the protection of nearby structures from ground vibrations, permanent ground deformation, emission of projectiles, and low frequency air overpressures. Annoyance of neighbors from noise and vibration intrusion also must be taken into account.

Excavation of rock by production or controlled blasting methods is the main cause of ground vibrations. Moreover, today's use of explosives as an engineering tool challenges contractors to blast in immediate proximity to existing structures, to explosively demolish entire buildings, and to blast densify loose sands. Specifications must therefore be updated to follow these special needs.

Pile driving operations produce ground motions and soil movement. Nevertheless, the concern is more focused on controlling the permanent displacement of the soil than limiting the ground motions. It appears that piling vibration specifications are rare, if not non-existent; the general practice being to refer to blasting specifications without any modification or comment.

Both piling and blasting engineering induce air overpressures. The nature of the control depends on the frequency of the excitation, and distinction must be made in the text of the specification.

The following specifications are intended to establish controls for ground vibrations and soil / rock permanent displacement caused by all types of blasting operations: production rounds, controlled, close-in and demolition blasting, as well as blast densification of sands. An attempt is made to present a piling vibration specification, and a special chapter deals with air overpressures.

These specifications are written to stress equally geotechnical, procedural, and management aspects of the problem, including measures to be taken before the writing of the specification. Segments can be extracted for use as special project provisions, to supplement other more general specifications, or to aid in updating existing texts. A special effort has been made to provide comments useful for the contractor to ascertain the nature of the procedures required, therefore allowing for an accurate bidding of the project. Finally, the intent of the text as a performance specification promotes any contribution the contractor may make to the job from his past experience and ingenuity.

CHAPTER 1

BLASTING AND VIBRATIONS

SOURCES

The following list comports the existing specifications used in the writing of the specification part of this text. The complete details of these references, as well as the literature used for the comments, feature in appendix A.

(1) Federal Highway Administration (FHWA), Controlled Blasting Specification, 1985,
(2) Wiss, Janney, Elstner, Associates, Inc. (WJE), Blast Vibration Protection Guidelines for various projects, 1987 to 1991,
(3) Hendron and Oriard, Specifications for Controlled Blasting in Civil Engineering Projects, 1972,
(4) Stone and Webster Engineering Corporation, Technical Specifications for different projects, 1974, 1975,
(5) US Army Corps of Engineers, Typical CE Blasting Specifications, 1972
(6) Dowding, Blast Vibration Controls for Lyceum Theater, 1986,
(7) US Department of the Interior, Office of Surface Mining Reclamation and Enforcement Regulations, 1987.

CUSTOMIZING AND USE OF THESE SPECIFICATIONS

Format

The text consists of two parts written both in bold and normal fonts. The bold parts represent the specification itself, while the normal, and indented, parts are comments on the specification paragraph immediately above.

Performance Specification

As far as possible, these specifications emphasize the performance necessary to fulfill the given requirements, rather than the method used to meet them. This makes it a **performance specification,** rather than a **methods specification.**

Customizing and Use

Different methods are generally given in comments, and it is necessary for the person in charge of the project to customize this text, to fit as best the specific characteristics of each project. This "tailoring" operation requires full cooperation between the Owner, the Engineer / Designer, and ultimately the Contractor. An important part of this customizing phase is the preconstruction survey, described below.

Preconstruction Survey

A preconstruction survey of all buildings within a radius of 400 ft (120 m) of the future blasting activities, or out to a distance at which vibration of 0.1 ips (2 mm/s) occurs should be undertaken by the Engineer prior to the start of any activity on the site, including the test blast program. The objective of this survey is to determine the buildings' susceptibility to disruption from blast vibrations. Disruption includes impact on sensitive equipment and operation, as well as cosmetic cracking, and effect on the surrounding geologic materials. The results of this study will be made available to the Contractor.

Susceptibility Ratings of Structures

The Engineer should classify the buildings inspected under the requirements of this specification into different categories, as a function of a building's susceptibility to cracking during blasting vibrations. Each building inspected should be placed into one of these categories.

Usually, and as developed by Wiss, Janney, Elstner, Associates, Inc. (WJE, 1990), three different categories are considered: "low susceptibility", "moderate susceptibility", and "high susceptibility" to cracking. "Cracking" is the threshold of cosmetic cracking, as defined below.

A building identified as having "high susceptibility" has already experienced a significant amount of degradation to its primary structural and / or non structural systems. Blasting vibrations may result in further degradation of these elements, possibly resulting in injuries to personnel in the vicinity of the building. Buildings with loose or unstable elements, such as loose bricks or structurally cracked terra cotta cornices, are considered to fall into this category. Buildings with significant quantities of fragile, potentially unstable contents, which may be damaged during blasting, are also included in this category.

A building identified as having a "moderate susceptibility" has not yet experienced significant degradation to its primary structure, or its non structural systems, which would lead to further building degradation due to blasting; however some building deterioration has occurred prior to blasting. Buildings identified as having bricks that may possibly be loose, as determined by visual inspection, are considered to fall into this category. Buildings with small to moderate quantities of fragile, potentially unstable contents, which may be damaged during blasting, are also included in this category.

A building identified as having a "low susceptibility" is not expected to experience cosmetic cracking when subjected to blasting.

Microvibrations and Sensitive Equipment and / or Operations

An important part of the preconstruction survey should deal with the possible nearby presence of sensitive equipment and / or operations, such as hospitals, computerized industries or banks, industrial machinery,... It is necessary to take theses information into account for the establishment of the controls.

Surrounding Rock / Soil Densification and Backbreak

One of the objectives of the preconstruction survey is to check for static stability of the geologic material surrounding the site. Densification of loose material, slope movement, and / or backbreak of existing slopes can occur during blasting operations, and this possibility must be considered when establishing control limits of ground vibrations.

PRODUCTION BLASTING: GENERAL BLASTING PROVISIONS (Section 1) (4)

This specification is intended to establish controls for use of explosives in the interest of life, health, and safety of employees and the public, as wel'l as the protection of nearby structures, property, and rock that is to remain in place. All of the Contractor's responsibilities apply equally to any Subcontractor involved in blasting activities. Blasting shall be allowed only during a specific period of time every day, as determined by the Engineer on site, according to locally applicable codes and necessary operational restrictions.

Explosives (Section 1.1) (2, 4)

Transportation, handling, storage, and use of explosives shall be subject to all state and local ordinances concerning this matter, as well as to appropriate federal safety guides. The Contractor shall maintain an inventory record of storage and withdrawal of all explosives. This record shall be available to the contracting officer, and he shall be promptly notified of any loss or theft of explosives. The Contractor shall provide such reasonable and adequate protective facilities as are necessary to prevent loss or theft of explosives. Overnight storage of explosives and detonators outside of the magazines will not be permitted. Caps or others exploders

(4) Refers to list on page 1

or fuses shall in no case be stored, transported, or kept in the same place in which dynamite or other explosives are stored, transported or kept.

> The object of this paragraph is to make clear that the Contractor is entirely responsible for the use of explosives on the construction site. The appropriate federal safety guides (in the United States) for reference in this section are usually the Subpart U -Blasting and the Use of Explosives- of the Department of Labor "Safety and Health Regulations for Construction", and the regulations of the Department of Treasury contained in 26 CFR 181, Commerce in Explosives.

Blasting Procedures (Section 1.2)

Controlled Perimeter Blasting Techniques (1, 2, 4)

Where blasting is used for excavation, the best modern practice of controlled blasting method shall be employed. Acceptable controlled perimeter techniques include the so-called smooth wall, cushion, pre splitting or line drilling blasting. Controlled blasting refers to the controlled use of explosives and blasting accessories, in carefully spaced and aligned drill holes, to produce a uniform free surface, or shear plane, in the rock along the specified backslope.

> Since this is a performance specification, as opposed to a method specification, the choice of the blasting technique is left entirely to the Contractor. Moreover, details of controlled blasting will be treated in a special chapter.

Blasting Mats / Flyrock Control (1, 2, 4)

Before the firing of any blast, the rock to be blasted shall be covered with blasting mats, as approved by the Engineer. Mats shall be placed for every blast over the entire loaded area and shall restrict all fly rock from leaving the site. If

blasted rock is permitted to escape the blasting mats, all blast-related activities, including drilling operations, shall be stopped by the Engineer. The Contractor shall prepare a report describing why rock was allowed to be ejected, and how such events will be prevented in the future. This report shall be submitted to the Engineer. In order to proceed with any further blast-related activity, written permission shall be obtained from the Engineer. These provisions do not relieve the Contractor from all responsibility for the safety of his own personnel, the safety of the general public, as well as damage to structures.

> The paragraph notifies that the Contractor will be held liable for all claims resulting from personal injury and damage to property or equipment due to excessive flying rock. Blasting mats are usually made of steel-wire rope, or rubber tires, or a combination of both.

Blasting Specialists (Section 1.3)   (2, 4)

The Contractor shall engage a blasting specialist as required to establish satisfactory blasting techniques. The specialist shall have had considerable experience in the use of explosives . His qualifications shall be subject to the approval of the Engineer (with the concurrence of the Geotechnical Engineer, if any). As a minimum, he must be a licensed blaster in the state where blasting operations take place. He shall be responsible for the design of all blasting operations, and his services shall be continued as long as the Engineer deems them to be necessary.

> In some cases, and where the size of the project is of enough importance, the Contractor shall assign to the blasting operations, and maintain on a full time basis during the time that blasting is in progress, a supervisor of mature experience specialized in the use of explosives. His qualifications shall be subject to the same approval as for the blasting specialist. This requirement is necessary to ensure that an appropriately trained person designs and continues the work.

Blasting Plan (Section 1.4)   (1, 2, 3, 4, 5, 7)

General

No less than three weeks prior to commencing the test blast program, or at the preconstruction conference (whichever is earliest), or at any time the Contractor proposes to change the drilling and blasting methods, the Contractor shall submit a blasting plan to the Engineer for review. The blasting plan shall contain the full details of the drilling and blasting patterns and controls the Contractor proposes to use for both the production and controlled blasting. The blasting plan shall contain the following minimum information:

- **station limits of proposed shots,**
- **plan and section view of proposed drill pattern including free face, burden, blast hole spacing, blast hole diameters, blast hole angles, lift height, and sub drill depth,**
- **loading diagrams for each blast showing type and amount of explosives, primers, initiators, and location and depth of stemming,**
- **form for reporting the vibration results for each blast,**
- **initiation sequence of blast holes, including delay times and delay system,**
- **identification of explosives suppliers and blasting specialists,**
- **manufacturers data sheets for all explosives, primers, and initiators to be employed,**
- **procedures to inform and protect the public and adjacent property,**
- **plan for de-initiation in case of misfire.**

The blasting plan submittal is for quality control and record keeping purposes. Review of the blast plan by the Engineer does not relieve the Contractor from his responsibility for the accuracy and adequacy of the plan when implemented in the field.

Shot by Shot

The Contractor shall submit records identified in the blasting plan for each individual shot, on forms approved / supplied by the Engineer. The shot record reports must be transmitted to the Engineer by the Contractor, within 24 hours of the shot, in the case when the vibration level exceeds 80% of the control limit. This requirement will be developed in section 2.6 of this specification.

When the contract requires the Contractor to retain a blasting consultant to assist with the blast design, all blasting plan submittals must be approved by the blasting consultant. The approval of the detailed plans by the Engineer does in no way relieve the Contractor of his responsibility and liability for injury to persons, or damage to property, or other responsibilities under this contract. The Contractor may also make his own measurements, to ensure that the blasting is within safe limits. Nevertheless, these measurements are not justification for using charges per delay greater than those calculated by the Engineer.

A blank Shot Record Report can be found in Appendix B.

Test Blast Program (Section 1.4) (1, 2, 4)

Definition / Responsible Party

The Contractor shall provide any necessary cooperation with the Engineer for conducting a test blast program. While the Engineer will take the lead role in this program, the Contractor shall concur in the intent , design and process of the testing. This program shall be performed prior to the start of any construction blasting, including presplitting. It shall be performed to show how the vibrations decrease with increasing distances from the blast, and increase with increasing amounts of explosives. This program is intended to provide subsequent guidance for a correct blast design, conducted for this particular project, and not to define any envelope or relationship to be used as a control.

Velocity control limits will not be raised on the basis of data obtained from the test blast program. If, during the test blast program or during the course of construction, it becomes evident that the limits established are too high for safe blasting, more restrictive limits may be established.

The program should be designed to include a range in the blast parameters. The first blast should be conservatively designed to produce air pressures and ground vibrations well below the controls established for the project. Charge weight per delay and the number of holes should then be increased until near-production rounds are detonated (Linehan and Dowding, 1986). Ordinarily, the tests include three to seven blasts, and should be completed in one to three days. The Contractor will be held responsible for any consequences resulting from this program in terms of damage to structures and/or to persons, on the same basis as for any other blasting activity conducted on the site.

Monitoring

At least six blast monitors shall be used. Their number, type, and location shall be approved by the Engineer. They shall be aligned in two linear arrays, perpendicular to one another. For each linear instrument array, a wide range of instrument distances shall be used. The far position shall be at least a hundred times farther from the blast than the closest. Properly spaced instrument positions should be established in log distance increments, rather than additive distance increments, to reach out three logarithmic units.

Analysis of Results

A statistical analysis of the test data will be performed by the Engineer. The results of this analysis shall be given to the Contractor within three weeks of the completion of the test blast program. This information is for general guidance information only, and does not relieve the Contractor from designing future blasts that meet the ground vibration controls.

Statistical analyses for evaluating test blast data are based on methods that have been accepted for the last several years. The maxima of three-component peak particle velocities, measured at varying distances from the blast with various charge sizes, are employed to develop an attenuation relationship. The resulting attenuation relationship, based on the accepted practice of square or cubic root scaling and a power equation, takes the following form (Linehan and Dowding, 1986):

$$V = I(R / \sqrt[i]{W})^{-n}$$

where:

V = vibration peak particle velocity, in ips (mm/s)
I = intercept, vibration particle velocity when $(R/\sqrt[i]{W})=1$
R = distance from the blast, in ft (m)
W = charge weight per delay, in lbs (kg)
n = attenuation slope
i = 2 or 3, respectively for square or cubic root scaling.

This attenuation relationship should be established such that 95% of the measurements will fall below its bound. There are other methods of allowing for variations in blast amplitude at a particular site. The important point is that the attenuation relationship should be conservative to allow for variations in geology and blast parameters.

Blast Warning Procedures (Section 1.6) (2, 4)

General

The Contractor, at his own expense, shall erect proper, durable signs of adequate size stating that blasting operations are being carried out in the area. Such signs shall be posted at points clearly visible to all traffic approaching the area. A system of reliable, audible warnings shall be established by the Contractor,

subject to the Engineer's approval, to ensure proper warning to all personnel in the area of an impending detonation.

Special

The Contractor shall be cognizant of the possible need to schedule blasting during periods when delicate operations are not being performed (i.e. surgery in nearby hospitals). In the event that operation staff states that blasting cannot be performed at certain times because of negative effects, the Contractor shall reschedule his blasting at no additional charge. Those times shall be determined by the Contractor, and included in the blasting plan (section 1.5).

Radio Transmitters

Radio transmitters shall not be permitted in the immediate area of blasting operations, unless properly locked and sealed. The Contractor shall be responsible for the effect due to any stray currents and the radio communication system within the area of the site, in the case when construction occurs in an area of industrial activities. The Contractor will be furnished with the necessary data pertaining to radio systems and any other available data upon receipt of a written request. Mutually agreeable administrative procedures must be developed between the Contractor, the Engineer, and the supervision of the industrial activities to control the use of any equipment (including mobile transmitters and radios), that emits electromagnetic radiation, within the construction area during blasting operations.

> In some cases where there is particular concern about extraneous electricity, the employment of electric blasting, including use of electric detonators, delays, electric blasting caps, and electric firing of any type may be expressly forbidden. The above requirement is appropriately illustrated by a bumper sticker saying "HAM RADIO ZONE, NO BLASTING ALLOWED"! This sticker refers to the usual sign, which says "Blasting Zone, No Radios Allowed".

Public Awareness (Section 1.7) (2, 4)

The Contractor is required to have both letter and personal contact with residents, institutional operators, and business establishments that are within the construction area, or near enough to it for ground vibrations from blasting operations to be objectionable. This contact shall be made prior to the beginning of any blasting, or other vibration-related activity. The Contractor is required to furnish the Engineer a list of those contacted prior to the blasting operations, and include on that list all pertinent information as approved by the Engineer.

The area concerned in this paragraph is generally defined by a distance of 400 ft (120m) of the nearest blasting activity, in an urban area (WJE, 1987). The action described in this section can also be coordinated with the performing of the condition survey.

Production Blasting (Section 1.8) (1, 2, 4, 5)

Blasting Technique

Production blasting, as covered herein, refers to the main fragmentation blasting, resulting from appropriately spaced production holes, drilled throughout the main excavation area, adjacent to any backslopes shaped by controlled blasting.

For production blasting, the Contractor shall space drill holes and schedule the delays of caps such that shots break to an open face, except as approved by the Engineer. Unless otherwise approved by the Engineer, the depth of blast holes and the amount of explosive per hole shall be progressively reduced as the excavation approaches the final grade, and / or design lines to preserve the rock immediately beneath and adjacent to the foundation for structures in the best possible condition.

The object of this section is to give guidelines for production blasting technique, while leaving enough room for the Contractor to come up with his own method. The open face makes it easier to remove the blasted material from the area.

Muck Removal

The Contractor shall take all necessary measures to ensure that all muck created by production blasting activities is removed from in front of the face in a timely fashion. This operation shall take place immediately after each shot, in order to allow the Engineer to observe the face, and determine if the control is met.

This section is necessary to ensure that the Contractor will not leave large quantities of muck accumulate in front of the final face. Such a process would prevent the Engineer from assessing the quality of the rock face.

Size of Excavated Material

The excavated rock produced by production blasting activities shall be restricted in its size (i.e. volume and / or dimensions), as determined by the Engineer. All excavated material that will not meet these requirements shall be crushed to the limited size, at the Contractor's expense.

Noise / Overpressure (Section 1.9)

This section will be treated in chapter 3.

CONTROLS (Section 2)

Permanent Displacement (Section 2.1) (2, 4, 7)

Line and Grade Survey of Remaining Rock

The line (location) and grade (elevation) survey will be performed by a surveyor licensed by the State in which the construction occurs. It will establish control and grade-lines to detect movements along the exterior faces of buildings. This survey will be conducted on all buildings within a 75-feet (22m) radius of the construction site, and all historic buildings or structures. Reports shall be delivered monthly to both the Engineer and Contractor.

All control lines and grades shall be referenced to existing bench marks, which shall be established far enough from the construction site to be preserved for all surveys. Tilting of the nearest walls of structures will be established by measurement with a portable tilt meter, made by a specialist.

> Buildings included in this survey are those which could experience permanent deformation because of their proximity to the excavation. The amount of expected deformation therefore needs to be quantified.
>
> Reference points are generally taken at a distance greater than 750 ft (225 m) from the site, so that they are well beyond the reach of blasting vibrations. The precision required can vary, but in general surveys should be accurate to 0.06 in. (1.5 mm) (WJE, 1987).

Existing Building Cracks

Permanent deformation of buildings will be monitored with crack monitoring gages. Their sensitivity shall be to the nearest (specify here). **The type of gages shall be determined by the type of potential distress (plaster cracks, movement,...).**

(specify number here) **crack monitoring gages will placed on strategic structures, within a radius of 75 ft (22 m) from the nearest blasting activities, and on buildings or structures of particular concern, such as historical monuments, within a radius of 400 ft (120 m) from the blasting activities.**

Reporting

Surveys and gage readings are generally obtained monthly. A report must be issued to the Contractor and Engineer monthly which summarizes the survey and crack opening data.

Condition Survey (Section 2.2) (2, 4, 7)

A condition survey shall be taken for all buildings within 400 ft (120 m) of the construction activity, and all historic buildings or structures, with the exception that engineered buildings will not be surveyed. This survey shall document the existing exterior and interior conditions of these buildings.

This survey shall include a documentation of interior sub-grade and above-grade accessible walls, ceilings, floors, roof, and visible exterior as viewed from the grade level. It will detail, by video tape or photographs, the existing structural, cosmetic, plumbing, and electrical condition, and shall include all walls, and not be limited to areas in buildings showing existing damage. Notes and sketches may be made, to highlight or enhance the photographic documentation.

The condition report shall present engineering notes and photographs or video records. The report shall also summarize the condition of each building and define areas of concern. Reports of the condition surveys shall be made available to the Contractor for his review prior to the start of any construction or demolition activity.

> A pre-blasting (condition) survey, to be of real value, has to be conducted with care, ensuring that no observable defects are omitted. A poor inspection in which defects are omitted will be of little value to an operator. In many cases, home owners are unaware of all the defects present in their homes, but they will inspect their homes more closely upon being startled, and will notice pre-existing defects for the first time. Such cases lead to complaints, litigation, and sometimes to court orders to halt construction operations. The presence of this survey in the contract considerably reduces the chances of such complaints, and, if they do occur, provides information vital for the assessment of the cracking and settlement of post construction claims. A blank Field Inspection Report can be found in appendix B (Dowding, 1985).

Particle Velocity Controls (Section 2.3) (1, 2, 4, 5, 6 , 7)

Definitions

The peak particle velocity is the maximum rate of change with respect to time of the particle displacement, measured on the ground. The velocity amplitudes are given in units of inches per second (ips), or millimeters per second (mm/s) zero to peak amplitude.

The frequency of vibration is the number of oscillations which occur in one second. The frequency units given are in Hertz, where 1 Hz equals 1 cycle per second.

The <u>dominant frequency</u> is usually defined as the frequency at the maximum particle velocity, which will be calculated from the seismograph strip chart for the half cycle which has as its center point the maximum velocity.

The <u>scaled distance</u> is equal to the distance from the blast, measured in a horizontal plane, divided by the square, or cube, root of the maximum charge weight per delay. Common units are respectively ft (m) and lbs (kg).

> The potential for cosmetic cracking has been found to correlate most closely with the maximum, or peak, particle velocity of a particle in the ground, as opposed to its displacement or acceleration (Dowding, 1985). Particle velocity should not be confused with propagation velocity. The two velocities are best distinguished by considering the motion of a bobbing cork during a passing wave. The particle velocity is the speed with which the cork moves up and down, while the propagation velocity is the speed with which the wave passes the cork.
>
> Scaling of distance is necessary to predict peak particle velocity when both the energy of the blast (proportional to the charge weight per delay), and the distance from the blast vary. The two most popular approaches are square and cube root scaling. Square root scaling is traditionally accepted, but the choice of scaling is left open in this specification.
>
> Frequency considerations are important, because low and high frequency excitations do not have the same effect on structures. The acceptable amount of velocity can vary with frequency, as explained in the following.

<u>Controls</u>

Blasting shall be controlled by limiting ground particle velocity. Peak particle velocity shall be the measure of the level of vibration, and it should be measured with the instrumentation and methods described in section 3.2 of this specification. Peak particle velocity shall satisfy one of the following controls:

- maximum peak particle velocity independant of frequency (option 1),
- maximum peak particle velocity that varies with frequency (option 2).

The choice of the control method to be used is the responsibility of the Engineer. The first criterion is distance related, with no consideration of frequency, and requires that each shot be monitored, with a recording seismograph. The second one requires the monitoring, recording, and analysis techniques that provide complete frequency information, since the limitations imposed are frequency related.

Maximum Peak Particle Velocity Independant of Frequency (option 1)

The peak particle velocity shall be less than a given limit, at the nearest structure. The type of structure and distance between this structure and the nearest hole will condition the allowable value, as described in the table below (fill in table). **Particle velocity shall be recorded in three mutually perpendicular axes. The maximum allowable peak particle velocity shall be that of any of the three axes.**

Numerous variations of this control exist, each specifying different levels of acceptability. The definition of these levels is the responsibility of the Engineer. To reach acceptable levels of limitation, each structure should be examined as a particular case. The main advantage of this option is its simplicity, as it does not require that frequency be determined. However, expected dominant frequency should be estimated or determined before the control limit is chosen. The simplest approach is to adopt one control limit for the entire site with specific exceptions or restrictions.

Maximum Peak Particle Velocity Varying with Frequency (option 2)

Frequency based limits for the peak particle velocity shall be imposed as defined in the table below for distances less than 25 m (85 ft). At all other

distances, the maximum particle velocity shall be 25 mm/s (1 ips) (or some other control limit as appropriate).

For this option, a seismographic record, including both particle velocity time-history and dominant vibration frequency, shall be provided by the Contractor for each blast. The method for the analysis of the predominant frequency contained in the vibrator time histories shall be approved by the Engineer during the submittal of the blast plan.

Numerous frequency based limiting curves of peak particle velocity exist, and are presented in appendix C. They have been derived by organizations, such as the United States Bureau of Mines, National code writing bodies, such as the German DIN, as well as private engineering firms. The choice of the approach is the responsibility of the Engineer.

Rather than employing curves, it has been found that tables of limiting particle velocity by frequency increments are easier for communication. This example was employed by the Minnesota Department of Transportation (MNDOT) for blasting in downtown Duluth (WJE, 1987).

Variation of the particle velocity versus frequency is usually presented with four-axis tripartite paper. The maximum allowable peak particle velocity varies along specified displacement and velocity bounds. In other words, the maximum transient displacement of the ground during blasting is limited. The graph of the particle velocity follows the oblique axis on which the displacement is constant, equal to this limit (Dowding, 1985). In the following example, the maximum displacement allowed during blasting is 0.005 in. (0.13 mm) for frequencies greater than 40 Hz.

The equation used to compute the velocities in the following table is:

$$V = 2\pi\, f\, \delta$$

where:

V is the peak particle velocity,
f is the frequency,
δ is the displacement.

For example, at a frequency of 40 Hz, with an allowable displacement of 0.005 in. (0.13 mm), the maximum allowable particle velocity is 1.25 ips, taken equal to 1.2 ips (31 mm/s) in the following.

Table 1.1 Frequency Based Peak Particle Velocity Control (WJE, 1987)

Dominant Frequency (Hz)	Maximum Particle Velocity (ips)	Maximum Particle Velocity (mm/s)
5	1.0	25
10	1.0	25
20	1.0	25
40	1.2	31
60	1.8	45
80	2.4	61
100	3.0	76

Limitation of the frequency applicability to the closest structures limits the number of structures that need to be intensely investigated during the preconstruction and condition surveys. It also limits the number of structures that are affected by the higher control limits and thus decreases the number of disagreements about the origin of cosmetic cracks.

Optional Additional Clause (2, 4)

The Engineer reserves the right to adjust the values designated in the above paragraphs, if, in their opinion, the blasting procedures being used are damaging the adjacent rock, concrete, or structures.

This paragraph is to make clear that no one but the Engineer has the authority to modify the limit values, and therefore the maximum charge weight per delay.

Curing Concrete (Section 2.5)

Some specifications contain a section specific to blasting within 24 hours after pouring concrete on the site. This section will be treated in the chapter concerning close-in blasting. A cross check should be made with the structural specifications to ensure that the control limits are consistant.

Application of the Particle Velocity Control (Section 2.6) (2)

If the Contractor exceeds 80 % of the ground vibration control limit for any single axis of any blast, he shall cease all blasting activities and submit an additional written report to the Engineer. This report shall give the blast parameter data, and include any necessary proposed corrective action for the next shot to ensure that the specified limit will not exceeded. The next shot shall not be loaded until the Engineer acknowledges, in writing, that a design change is being attempted.

If the Contractor exceeds 100 % of the ground vibration control limit for any single axis of any blast, he shall cease all blasting-related activities, including drilling operations, and submit an additional written report to the Engineer. This report shall give the blast parameter data, and include any necessary proposed corrective action for the next shot to ensure that the specified limit will not be exceeded. Drilling activities shall not resume until the Engineer acknowledges, in writing, that a design change is being attempted.

These controls ensure that the Engineer can regulate blasting activity. Imposition of a control limit, without some activities to accompany its exceedance may lead both parties to assume an outcome, which may not be agreeable to the other. In no case should the Engineer approve the design change, but rather acknowledge that the Contractor is modifying the blast design. It is always the Contractor's responsibility to meet the specified control limits.

MONITORING OF PROGRESS (SECTION 3)

Recorded Data (Section 3.1) (1, 2, 3, 4, 5, 7)

Peak Particle Velocity

All three components (longitudinal, transverse, vertical) of particle velocity will be measured on the ground at the location of the nearest and other strategic structures identified below, at the location of fresh concrete (if necessary), **and / or at any other location as the Engineer deems necessary for any particular blast.** (include list of structures) **This measurement shall be made on the ground adjacent to these structures as blasting progresses.**

The three components of particle velocity are normally defined as follows: (OSMRE, 1987)

- longitudinal (sometimes called radial): measured in a direct line horizontally towards the blast from the point of interest or measurement,
- transverse: measured horizontally at 90 degrees to the longitudinal plane,
- vertical: measured vertically at 90 degrees of both preceding planes.

Shot Record Report

The Contractor shall maintain a blast log and, when blasting is in progress, shall submit daily reports to the Engineer regarding blasting. These shot record reports shall follow the form accepted in the blasting plan (section 1.5).

Instrumentation (Section 3.2)   (2, 4, 7)

The Contractor shall provide the instrumentation agreed to in the blasting plan to monitor the blast vibrations and permanent deformation of the strategic structures. On-site measurements will be made by the Engineer. The Engineer will provide any other additional instrumentation not defined herein.

Despite this language, three different options may be considered:

- Contractor provides the instrumentation and makes the measurements,
- Contractor provides the instrumentation and Engineer makes the measurements (as written),
- Engineer provides the instrumentation and make the measurements.

The option selected here corresponds to that applied most generally in highway construction in the United States. If the Contractor is required to provide the instrumentation, its cost will appear in the commercial bid, and therefore, the Federal Government will pay the majority of the amount. If not, the Engineer (or the State, in the case of highway construction) will have to pay for the totality.

Different Types and Characteristics

Blast Monitors

Particle Velocity shall be monitored by Type I and Type II blast monitors. These types are defined as below:

- Type I is the waveform recorder. It provides a particle velocity waveform or time-history of the recorded event, sometimes in conjunction with peak event information. This type of recorder must be used in option 2,

- Type II is known as a continuous peak particle velocity recorder. It provides no waveform, and therefore no frequency information. Both Type I and II can be employed for monitoring in option 1.

Acceptable monitors include (precise manufacturer and model number). **Characteristics of these recorders are** (frequency range for ground motion and air overpressure, digitalization rate, method of calculating dominant frequency, telecommunication capability).

Transducer Attachment

When the measurement surface consists of rock, asphalt, or concrete, the transducers shall be bolted to the measurement surface, or bounded with either double-side tape, epoxy, quick setting cement. For significant accelerations (greater than 1.0g), only cement or bolts shall be used. All transducers mounted on vertical surfaces shall be bolted in place.

For accelerations above 1 g when the measurement surface consists of soil the transducer shall be buried and held in place with compacted soil. For repeated monitoring at the same location, a permanent soil bolt anchor system shall be constructed. An acceptable design consists of a thin (50 to 75 mm) concrete pedestal, buried 300 mm, and welded into the surounding soil mass by compacting soil around and above. A small diameter hole for the transducer should then be excavated to reach the bolt seat.

Usually, the horizontal radial and transverse directions are aligned with the principal axes of the structures of concern (Linehan and Dowding, 1986). The advantage of this option is that potential blast effects on the structure can be more directly related to the measured motions.

Number and Location

Blast Monitors

The number of instruments required by the project is (specify here). **However, there shall be, as a minimum, 2 monitors of Type I, and 1 monitor of Type II. Only one monitor of Type I will be used on site, while the other one will be kept as a backup, or used off-site for specific demands, such as important complaints.**

Archiving (Section 3.3)   (2, 4, 5, 7)

The Contractor will provide the Engineer with all data necessary for record keeping purposes. These data shall be kept by both parties, for at least three years, and shall include, as a minimum, the following information:

- **all monthly surveys conducted for vibration control purposes, including the pre-construction survey,**
- **the original blasting plan, as well as any adjustments made to it during the course of the construction activities,**
- **all monitored data, relative to each and every shot. Those shot record reports shall contain all information, as required and approved in the blasting plan, including all information concerning the type and characteristics of the monitoring instruments used on the site, their location and orientation,**
- **all shot loading data for each and every shot, correlated with the monitored data,**
- **all weather conditions, occurring during the blasting activities, including those which may cause possible adverse blasting effects,**
- **all details concerning the blasting mats, or any other protection used.**

Those archiving requirements are necessary in case of litigation. In this event, these data are certain to be called into evidence, and as evidence they should be absolutely unassailable.

CRACKING DEFORMATION (Section 4)

Types of Cracking (Section 4.1)   (2)

The Engineer will distinguish different types of cracking in structures. The two categories considered will be:

- cosmetic cracking,

- structural cracking.

These categories are usually defined as follows (Edwards and Northwood, 1960, Northwood et al., 1963, and Dowding, 1985):

Cosmetic cracking includes:

- threshold damage: opening of old cracks, and formation of new plaster cracks; dislodging of loose objects (e.g. loose bricks in chimneys),
- architectural or minor damage: superficial, not affecting the strength of the structures (e.g. broken windows, loosened or fallen plaster), hairline cracks in masonry.

Structural cracking, also referred to as major cracking, results in serious weakening of the building (e.g. large cracks or shifting of foundations or bearing walls, major settlement resulting in distortion or weakening of the structure, walls out of plumb).

Control Limits (Section 4.2)   (2, 4, 5, 7)

The Engineer will select the most appropriate cracking criterion for the site, to control blasting operations. This criterion will be used, in conjunction with the expected peak particle velocities from blast vibrations, to develop safe vibration control limits, as described in section 2.3.

Different types of cracking appear at different peak particle velocities. Thus, different cracking controls have been developed to control vibrations, in order to prevent certain types of cracking. Appendix C contains several frequency based criteria.

CHAPTER 2

PILE DRIVING AND VIBRATIONS

PRECONSTRUCTION SURVEY

A preconstruction survey shall be undertaken prior to the start of any activity on the site, including the test pile program. This survey shall be completed according to the requirements presented in the "Blasting and Vibrations" part of these specifications, and should address susceptibility ratings of structures, microvibrations and sensitive equipment / operations, and surrounding soil densification.

GENERAL PROVISIONS (Section 1)

Except as otherwise specified in the following , the Contractor shall comply with all sections of the "Blasting and Vibrations" part of these specifications.

Pile Driving Equipment (Section 1.1)

Two types of pile drivers can be used: impact or vibratory hammers. The Contractor shall be aware of the fact that ground vibrations induced by these machines are of different nature, and therefore he shall take the utmost care in the selection of his equipment and driving method.

> In the case of an impact hammer, the pile is driven by separate blows from a hammer, which is raised by a rope, compressed gas or air, and falls back by gravity (single-acting) or is accelerated downwards (double-acting). The driving energy is transmitted to the pile through a

hammer cushion, and, at every blow, the inertia of the pile and the resistance of the soil must be overcome. Ground vibrations caused by an impact hammer are essentially of transient nature, and attenuation with increasing distance occurs generally within a few cycles.

A vibratory hammer consists of a static mass, which is connected to an oscillating mass by steel or plastic springs. The oscillating part is rigidly attached to the head of the pile, and the pulsating force, which acts along the entire pile, causes it to continuously move upwards and downwards. Ground vibrations caused by vibratory hammers are essentially of steady-state nature, and can propagate relatively far from the source, and even amplify when resonance is reached, *i.e.* the frequency of the vibration of the machine equals the natural frequency of the soil layer in which the pile is driven. Resonance effects usually occurs while starting up and switching off the vibrator (Massarch, 1992).

Driving plan (Section 1.2)

No less than three weeks prior to commencing the test pile program, or at the preconstruction conference (whichever is earliest), or at any time the Contractor proposes to change the driving method, the Contractor shall submit a driving plan to the Engineer for review. The driving plan shall contain (1) all information required under the general piling specifications, and (2) all information relative to vibrations and vibration controls, as described in the following.

The driving plan is for quality control and record keeping purposes. Review of the driving plan by the Engineer does not relieve the Contractor from his responsibility for the accuracy and adequacy of the plan when implemented in the field.

Test Pile Program (Section 1.3)

Definition / Responsible Party

The Contractor shall provide any necessary cooperation with the Engineer for conducting a test pile program. While the Engineer will take the lead role in this program, the Contractor shall concur in the intent, design and process of the testing. This program shall be performed prior to the start of any piling activities. It shall be performed to show how the vibrations decrease with increasing distances from the pile, and vary with the type of pile used. This program is intended to verify prior design assumptions, and not to define any envelope or relationship to be used as a control.

Velocity control limits will not be raised on the basis of data obtained from the test pile program. If, during the test pile program or during the course of construction, it becomes evident that the limits established are too high for safe piling activities, more restrictive limits may be established.

The Contractor will be held responsible for any consequences resulting from this program in terms of damage to structures and / or to persons, on the same basis as for any other piling activity conducted on the site.

This testing is most economically accomplished if conducted with other pile test programs, such as the load-deflection testing. The program should be designed to include a range in the pile parameters. The Contractor should try different pile configurations (if possible) as well as hammer / pile combinations, to determine the best way to minimize construction vibrations.

Monitoring

The number, type, and location of the seismographs used to monitor the test pile program shall be determined by the Engineer.

Monitoring of the test pile program can be done using the provisions described in section 1.5 of the "Blasting and Vibrations" part of these specifications for the test blast program, with the necessary modifications to piling activities.

Analyses

Statistical analyses of the test data will be performed by the Engineer. The results of these analyses will be transmitted to the Contractor within three weeks after the completion of the test pile program. The three analyses to be performed are:

- **a seismic analysis,**
- **a frequency analysis,**
- **a response spectrum analysis.**

The seismic analysis establishes the rate at which the vibration intensity decreases from the source. The vibration intensity can then be predicted for any other distances within the bounds of the testing parameters. Propagation laws can take the following form: (WJE, 1984)

$$V = I_j (D)^{-n_j}$$

where:

V = vibration particle velocity, in mm/s,

D = distance from the pile driving activity, in m,

I = intercept, vibration particle velocity when D = 1m,

n = propagation slope,

j = seismic component.

The propagation slope, n, quantifies the rate at which the seismic vibration intensity decreases with increasing distances. The intercept, I, is a function of the type of pile, the type of hammer, and the geology of the site. This attenuation relationship should be established so that 95% of the measurements fall below its bound.

The frequency analysis is performed to determine the ranges of frequency associated with each pile, and / or hammer.

The response spectrum analysis is conducted based on time history records of ground motions, and assuming the motion was applied to the base of a structure having a variety of natural frequencies. The spectra are usually shown in tripartite coordinates.

Air Overpressure (Section 1.4)

This section will be treated separately in the "Air Overpressure" chapter of these specifications.

CONTROLS (Section 2)

Cracking (Section 2.1)

Crack monitoring gages shall be placed (fill in number and location), **and a condition survey shall be taken. These dispositions shall follow the requirements exposed respectively in sections 2.1 and 2.2 of the "Blasting and Vibrations" part of these specifications. The purpose is to report the cracking situation in the buildings surrounding the site, both prior to and during piling operations.**

Permanent Deformation of Soil (Section 2.2)

Line and Grade Survey

A line and grade survey, establishing control and grade lines to detect movements along the exterior faces of nearby buildings, will be performed, in accordance with the requirements exposed in section 2.2 of the "Blasting and Vibrations" part of these specifications.

Lateral Deformation of Retaining Structure

In addition to the above requirements, control lines and benchmarks shall be established for any eventual temporary lateral support system, in order to monitor the deformation of this system during the progress of piling activities. Surveys shall be obtained monthly.

> The presence of lateral support systems between the piling area and the surrounding structures allows for a direct control of the soil deformations, produced by the excavation and / or vibrations of loose sands and silts. A maximum allowable displacement can be introduced here. Cracking criteria for adjacent structures are based upon a fixed and stable subsurface.

Condition of Soil After Piling

Monitoring of permanent displacement of the soil is required during the dismantling of the temporary support system.

During dismantling operations, release of stresses in the ground will induce permanent deformation of the soil. This displacement is directly related to the one that the surrounding buildings will endure, and is therefore important to control.

Particle Velocity Controls (Section 2.3)

Particle velocity controls shall comply with the requirements exposed in section 2.3 of the "Blasting and Vibrations" part of these specifications.

Controls limits used in this section, for both impact and vibratory pile hammers, are typically the ones used for blasting activities. However, blast vibrations, which typically have larger energies, longer attenuation distances, and fewer repetition, are not necessarily representative of pile driving vibrations. But, since no special limits have ever been raised for pile driving, it is necessary to make reference to blasting specifications.

MONITORING (Section 3)

The requirements under this section are the same as those exposed in section 3 of the "Blasting and Vibrations" part of these specifications, with the following modifications:

- **"piling" shall replace "blasting" in the wording,**

- **"vibration monitors" shall be used instead of "blast monitors",**

These machines are the same, and can be rented or leased from the company who perform blast vibration monitoring.

- monitoring schemes and specific record keeping requirements concerning ground motions shall be performed according to the following.

Threshold Values of Particle Velocities for Monitoring Purposes (Section 3.1)

Two threshold values of peak particle velocity shall be considered for monitoring purposes:

- the control value, specified in section 2.3 above,

- the "significant event" value, equal to half the control value, below which no record of either peak or wave form is retained.

Monitoring Schemes and Record Keeping (Section 3.2)

Time histories of all pile driving events producing peak particle velocities greater than the control value, measured at the location of adjacent structures, shall be obtained.

Peak values of all pile driving events producing peak particle velocities greater than the "significant event" value, but less than the control value, measured at the location of adjacent structures, shall be obtained.

The five largest motions of pile driving events producing peak particle velocities less than the "significant event" value, measured at the location of adjacent structures, shall be recorded, regardless of their intensity. These records shall be kept for any period between two significant events.

As opposed to blasting, pile driving involves a great number of events. However, only a small portion of the activity will produce significant particle velocities. But, since all events should be accounted for in some fashion, the formulation of two threshold values of peak particle velocities is meant to allow for the necessary selection between "insignificant" and "significant" events. The monitoring schemes described above can be achieved easily by programming self-triggering vibration (or blast) monitors.

Time histories for pile driving activities exceeding the control value are required to allow for the determination of dominant frequencies. For particle velocities less than the control value, only peaks are of interest, to show that the control is not exceeded. While it is useless to keep record of insignificant events, it is still necessary to be able to show that the recording equipment was functioning. Therefore, the five highest motions under the second (*i.e.* the lowest) threshold value should be kept to demonstrate functionality.

CHAPTER 3

AIR OVERPRESSURE

PRELIMINARY CONCERNS AND DEFINITIONS (Section 1)

Air overpressure, as covered herein, is defined as airborne pressure waves, resulting from detonation of explosives (also called air blast) and to a lesser extent concussion mechanisms, such as impact pile driving. Noise is the high frequency audible portion of the air overpressure.

The Contractor shall be fully aware of the two different kinds of air pressure waves, and of their possible adverse effects:

- **low frequency waves, such as those generated by air blasts. They are virtually inaudible, but have a cracking potential because they induce vibration in structures,**
- **high frequency waves, referred to as noise. They generate noise pollution, which produces community annoyance.**

This specification does not establish acceptable noise levels and does not relieve the Contractor from obeying all OSHA and community noise standards.

NOISE LEVEL CRITERIA FOR IMPACT EVALUATION (Section 2)

The Engineer should use a noise level criterion for impact evaluation. This criterion should give an appreciation of the noise level, as a function of the percentage of time that this given level is exceeded.

This criterion allows for considerations of duration. Indeed, the effect of a continuous event, repeated, say, more than 100 times a day, such as the impact of a pile driver, will not be the same than the one of a punctual event, occurring less than 5 times a day, such as a blast.

For instance, the US Department of Housing and Urban Development (HUD) provides the criteria presented in Figure 3.1, based upon the definition of the 'noise pollution level', or NPL, given below:

$$L_{NP} = L_{eq} + 2.56\,\sigma$$

where:

L_{NP} is the noise pollution level (NPL),
L_{eq} is the mean intensity of the noise over a specific time period,
σ is the standard deviation of the instantaneous level considered as a statistical time series over the specified time period.

Integration of the noise level over time is accomplished assuming that the event is continuous (pile driving). However, there is little experimental evidence to support this procedure.

Four different levels of acceptability of noise emission can be defined as shown in Figure 3.1:

- clearly acceptable: indoors and outdoors pleasant,
- normally acceptable: outdoors reasonably pleasant, and indoors acceptable even for sleeping,
- normally unacceptable: costly construction required to make indoors acceptable, and barriers required to make outdoors acceptable,
- clearly unacceptable: prohibitive costs to make indoors and outdoors acceptable.

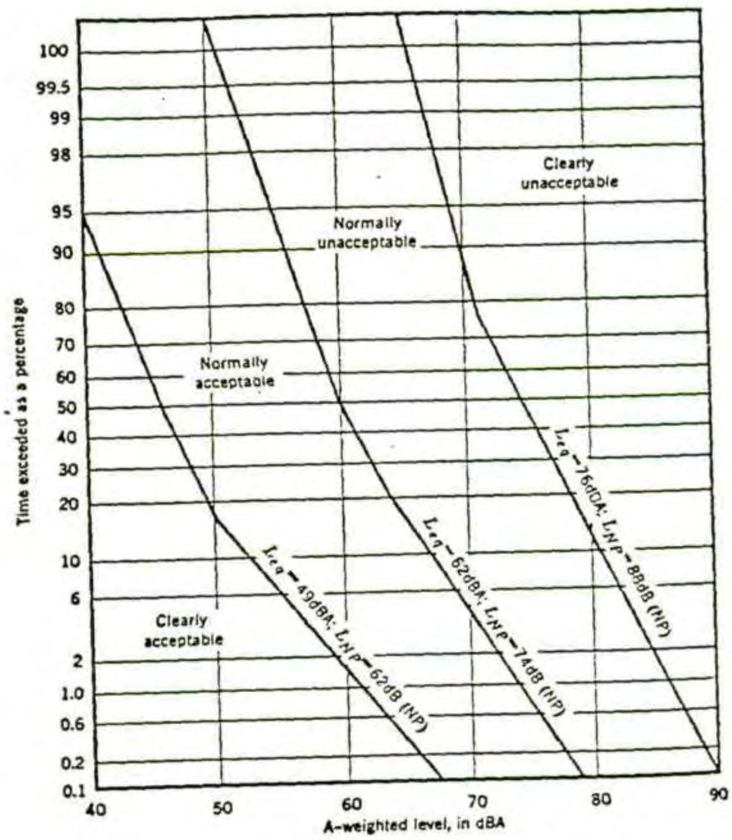

Figure 3.1 Provisional Criteria Relating NPL to Community Noise Acceptability (from Hersh, 1974)

GENERAL PROVISIONS FOR NOISE CONTROL (Section 3)

The Contractor shall take the necessary time and effort to understand and conform to the existing noise ordinances adopted in the community where the construction site is located.

The Contractor shall be informed of the noise radiation characteristics of his equipment (such as impact pile drivers). This shall imply periodic measurements, despite the equipment manufacturer's noise specifications.

Equipment noise often increases with use, especially if improperly maintained. Furthermore, the resulting sound levels may rise in confined spaces, or where the air waves (creating the sound) are channeled by structures.

The Contractor shall include noise as a factor in planning his operations. If the predicted noise emission is to be excessive for a particular period, the Contractor shall discuss this problem with the local residents and officials, to reach some type of agreement, <u>before the commencement of the work</u>.

> With careful planning, it is possible to maintain a highly efficient work output with a minimal noise output. It is necessary to identify, in chronological order, the various tasks with their associated equipment. This information, along with accurate sound level measurements of the equipment, allow a prediction of the noise which will be emanated from the construction site at any specific time, and this prediction can be checked against local noise regulations.

The Contractor shall use all of the above information to work with local officials and equipment manufacturers, in order to formulate rational noise reductions which can be implemented within a reasonable time frame.

<u>AIR BLASTS CONTROLS (Section 4)</u>

<u>General (Section 4.1)</u>

The Contractor shall design his blast rounds in order to minimize air blast overpressures. A well designed blasting round that breaks and moves rock efficiently seldom produces excessive air blast overpressures. If detonating cord is used, it shall be covered with sand to minimize air blasts. Postponement of blasting operations shall be considered when a heavy low-level cloud cover exists. Blasting operations shall take into account wind direction and possibility of focusing.

The five primary causes of air blast overpressures, that are under the control of the blaster, are: (Rosenthal and Morlock, OSMRE, 1987)

- the Air Pressure Pulse, caused directly by the rock displacement at the free surface or mounding at the borehole collar,
- the Rock Pressure Pulse, caused by vibrating ground,
- the Gas Release Pulse, caused by gas escaping from the detonation through fissures in the fractured rock,
- the Stemming Release Pulse, caused by gas escaping from blown-out stemming,
- presence of uncovered detonating cord.

In addition, some other factors, normally outside the control of the blaster, such as nature and shape of the terrain and / or weather conditions, can increase adverse air blast effects. It is the responsibility of the Contractor to use his best knowledge of blasting effects in order to prevent, or inhibit the propagation of excessive air overpressures.

Air Overpressure Control Limits (Section 4.2)

Air blast overpressures shall not exceed the limits listed in the table below, measured at the location of any public building, residence, school, church, or community or institutional building. If necessary to prevent damage, the Engineer will specify lower maximum allowable air blasts levels than those given in this section for use in the vicinity of specific structures.

The following values of maximum air blast overpressures are proposed by the USBM, in the Report RI 8485 (1980).

Table 3.1 Maximum Allowable Air Blast Overpressures (from Siskind, Stachura, Stagg, and Kopp, USBM, 1980)

Lower Frequency Limit of Measuring System, in Hz	Maximum Air Blast Overpressure, in dB (± 3 dB)
0.1 Hz, high pass system	134
2 Hz, high pass system	133
5 or 6 Hz, high pass system	129
C-weighted (events less than 2 s duration)	105

These levels are 'based on a minimal probability of the most superficial type of cracking (threshold cracking) in residential-type structures'. It is also important to consider the effect of weighting scales on the level of overpressure measured. This aspect will be discussed in section 5.1.

Blasting Noise (Section 4.3)

The Contractor shall comply with all existing noise ordinances adopted in the community where the construction site is located. In order to minimize adverse effects, the Contractor shall be aware of that.

Noise created by blasting is merely an impulse, and has the same causes as those exposed in section 4.1 above. The punctual character of blasting noise, if not accompanied by low frequency vibrations more likely to produce a rattle in structures, makes it improbable that this component of the blast will lead to serious complaints.

PILE DRIVING CONTROLS (Section 5)

General / Air Overpressure Control Limits (Sections 5.1 & 5.2)

Pile driving operations shall be subjected to the same general provisions and air overpressure control limits as the one established for blasting, and described above.

However, it is not expected that pile driving will produce the low frequency air overpressures associated with blasting.

Pile Driving Noise (Section 5.2)

The Contractor shall comply with all existing noise ordinances adopted in the community where the construction site is located. The Contractor shall be fully aware of the necessity to take noise-reduction measures, including modifications of the pile driver (such as enclosure of the hammer, modification of the muffler, ...) in the event that the Engineer and / or municipal officials determine noise levels to exceed OSHA and / or local community standards..

Pile driving is considered to be a continuous event. The impact of the hammer on the pile is reproduced thousands of times a day; thereby inducing high annoyance even at relatively low noise levels. Noise control measures can be applied to pile driving in a cost-effective manner, to reduce the objectionable off-site noise by about 10 dB (Kessler, 1985).

MONITORING OF CONSTRUCTION SITE AIR OVERPRESSURES (Section 6)

Instrument Scaling and Range (Section 6.1)

Linear scaling of instruments shall be used as default. In cases where no low-frequency overpressure (likely to crack structures) is expected, and only noise community annoyance is of concern, A or C weighted instruments can be used, if approved by the Engineer.

The instruments' scale employed for control shall be (specify here).

The A weighted scale is known to represent the manner in which the ear interprets the loudness of a given event throughout the frequency range of human sensitivity. It has therefore been used to interpret the effects of human annoyance.

The C weighted scale is also adequate for studying hearing response, but, as the A weighted scale, it will not record the information necessary for correlation with structural response.

The linear scale records accurately the air overpressures in both the structurally critical range, usually between 5 to 20 Hz, and the range critical for human hearing. This system is therefore the most reliable in critical monitoring situations. (Hersh, 1974, and Dowding, 1985)

Figure 3.2 represents the difference between the actual loudness of a given event and its weighted value, as a function of the frequency.

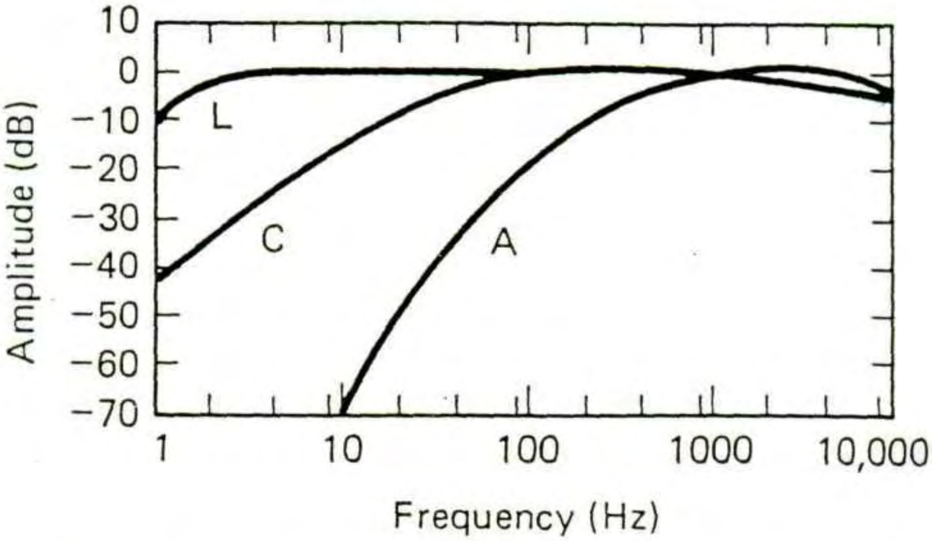

Figure 3.2 Effect of Weighting Scales (from Dowding, 1985)

Analysis of Data (Section 6.2)

Air overpressures shall be recorded as time histories. For certain events that do not require extreme attention, the Engineer may allow the Contractor, as an exceptional measure, to use peak recording instruments only.

CHAPTER 4

CONTROLLED BLASTING

SOURCES

The following list comports the existing specifications used in the writing of the specification part of this text. The complete details of these references, as well as the literature used for the comments, are featured in appendix A.

(1) Federal Highway Administration (FHWA), Controlled Blasting Specification, 1985,

(2) Wiss, Janney, Elstner, Associates Inc.(WJE), Blast Vibration Protection Guidelines for various projects, 1987 to 1991,

(3) Hendron and Oriard, Specifications for Controlled Blasting in Civil Engineering Projects, 1972,

(4) Stone and Webster Engineering Corporation, Technical Specifications for different projects, 1974, 1975,

(5) US Army Corps of Engineers, Typical CE Blasting Specifications, 1972

GENERAL PROVISIONS (Section 1) (1, 2)

All controlled blasting techniques described below shall be performed in accordance with the requirements specified in the 'Blasting and Vibrations' part of these specifications.

Unless otherwise permitted by the Engineer, the Contractor shall completely remove all overburden soil, and loose or decomposed rock, along the top of the excavation, for a specified distance, to be determined by the Engineer, of the production hole drilling limits, or to the end of the cut, before drilling the controlled blasting holes. Potentially dangerous material located beyond the excavation limits shall also be removed.

DESCRIPTION (Section 2)   (1, 2)

Controlled blasting refers to the controlled use of explosives and blasting accessories in carefully spaced and aligned drill holes, to produce a free surface, or shear plane, in the rock along the specified backslope. Controlled blasting techniques covered by this specification include line drilling, cushion (or trim), presplitting, and smooth-wall blasting techniques.

Blast damage to the final rock face may cause (1) backbreak and over excavation, as well as (2) instability and rockfall hazards. For these reasons, among others, controlled blasting is an indispensable routine in excavation for structures and elsewhere. Controlled blasting techniques minimize overbreakage, and permit steeper slope design, because of increased mechanical stability and resistance to weathering. They also reduce deeper fracturing and weakening of the finished excavation. The techniques described can be used to excavate rock to accurate lines around vertical and horizontal corners, even when contiguous to adjacent structures.

Sometimes, slope dimension criteria is specified to establish when controlled blasting should be used, such as "**when blasting to excavation slopes 1/2:1 or steeper, and more than 10 ft high**". Inclusion of specific slope and/or depth criteria in the specification, if desired, is left open.

DIFFERENT METHODS (Section 3)   (3)

The remaining face is a function of:

- **the diameter, depth, and spacing of the perimeter holes,**
- **an approximate range of the charge per foot of hole,**
- **the type of stemming material,**
- **the tolerances in the alignment of the perimeter holes,**

- **rock type,**
- **joint type and orientation.**

Formation of a fracture plane in the rock is influenced by borehole spacing, with the closer spacing forming a more prominent fracture. Because of the high cost of drilling, the optimum spacing is the largest at which radial cracks will join, and form a continuous undamaged surface. This distance is a function of (1) the rock type and joint patterns, as well as (2) the hole loading and shot initiation characteristics.

Because of this complex interation, the Contractor should choose the method using the 'test face' approach, described below, in section 4. The characteristics given for each method should not be chosen by the Engineer, but are included as guides for the blaster's plan.

<u>Line Drilling (Section 3.1)</u> (1, 3, 4, 5)

Line drilling is a method that, under proper geologic conditions, can be used to produce a cosmetically appealing final wall. It consists of drilling a single row of very closely spaced holes along the perimeter of the excavation, not loading the holes, having a suitable burden / spacing ratio, a reduced explosive charge in the lines of holes nearest to the line-drilled holes, and a limit on the distance between the line-drilled holes and the nearest line of primary blast holes. The drilled holes form a surface of weakness to which the primary blast can break. They also reflect some of the shock waves, protecting the rock mass behind the final grade.

The spacing of the holes is generally two to four times the hole diameter, while the primary blasting is usually conducted to within two to three rows of the line-drilled row to decrease the burden (Hendron and Oriard, 1972). A typical arrangement is shown in figure 4.1.

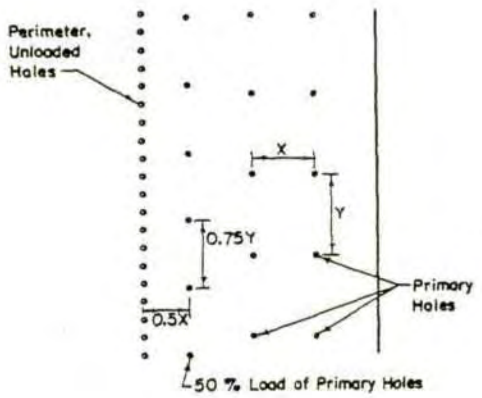

Figure 4.1. Typical Hole Pattern for Line Drilling (after DuPont Blasters Handbook, 1966).

One of the most important factors affecting the results of a job where the line drilling technique is used is the drill hole alignment. Hole tolerances given in most blasting specifications typically vary from 6 to 12 inches, depending on the depth of drilling.

Cushion Blasting (Section 3.2) (1, 2, 3, 4, 5)

Cushion, or trim, blasting is a control technique which is used to trim a final wall, after production blasting has taken place. It consists of drilling a single row of closely spaced holes along the perimeter of the excavation, with a suitable burden / spacing ratio, loading the holes lightly and continuously, stemming the entire length of each hole, and then firing them simultaneously to detach the berm left in place from the previous primary blast.

The sole purpose of a trim blast is to create a cosmetically appealing, stable perimeter. It offers no protection to the wall from the production blast.

It is important to remember that cushion blasting is similar to presplitting, except that the detonation along the cut face occurs <u>after</u> all production holes have been detonated. After a primary cut is removed, a minimum burden should be left in front of the excavation line, as shown in figure 4.2. The burden will vary with the hole diameter being used, as displayed in table 4.1.

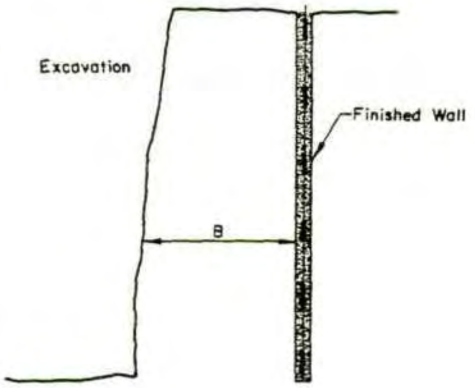

Figure 4.2 Typical Layout for Cushion Blasting (after DuPont Blasters Handbook, 1966).

Table 4.1. Guidelines for Drill Holes Spacing and Loading for Various Drill Holes Diameters (from Hendron and Oriard, 1972).

Hole Diameter in.	Spacing ft	Burden ft	Hole Loading lb/ft	Hole Loading kg/m
2 - 2.5	3	4	0.08 - 0.25	0.12 - 0.37
3 - 3.5	4	5	0.13 - 0.50	0.19 - 0.74
4 - 4.5	5	6	0.25 - 0.75	0.37 - 1.11

Presplitting (Section 3.3)   (1, 2, 3, 4, 5)

Presplitting consists of drilling a single row of holes along the perimeter of the excavation, loading the holes lightly and continuously, stemming the entire length of each hole, and then firing groups of holes simultaneously, before any production hole is detonated. The purpose of this method is to form a fracture plane, which inhibits the propagation of radial cracks from the production blast.

This method is similar to cushion blasting, except that, in this case, controlled blastholes are fired before the production blast. Presplitting should be thought as a protective measure, to keep the final wall from being damaged by the production blasting. Ideally, a single fracture connects adjacent blastholes, and half of the hole (cast) remains at each presplit hole, as shown in figure 4.3.

Figure 4.3. Presplit Blasting in Limestone.

A typical pattern of presplit holes is shown in figure 4.4. Usual loads and spacing are displayed in table 4.2.

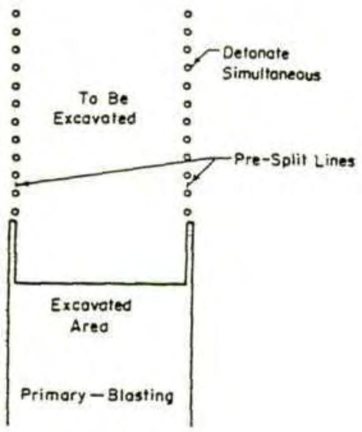

Figure 4.4 Typical Layout for Presplit Holes (after DuPont Blasters Handbook, 1966)

Table 4.2 Typical Loads and Spacing for Presplitting (from Hendron & Oriard, 1972)

Hole Diameter in.	Spacing ft	Explosive Charge lb/ft	Explosive Charge kg/m
2 - 2.5	1.5 - 2	0.08 - 0.25	0.12 - 0.37
3 - 3.5	1.5 - 3	0.13 - 0.50	0.19 - 0.74
4	2 - 4	0.25 - 0.75	0.37 - 1.11

Smooth Wall Blasting (Section 3.4)   (1, 3, 4, 5)

Smooth wall blasting consists of drilling a single row of closely spaced holes along the perimeter of the excavation, with a suitable burden / spacing ratio, loading the holes lightly and continuously with a small-diameter low-strength explosive, stemming all holes, and then firing them simultaneously as the last delay period in the round.

> Smooth blasting is very similar to cushion blasting, the only difference being the diameter and charge of the holes and/or the type of explosives. It is often used in tunnels to obtain a smooth perimeter.
>
> For smooth wall blasting, the spacing of the perimeter holes should be about 15 times the hole diameter, and loaded with light, distributed charges, ranging from 1/8 to 1/4 lb per foot of hole. The burden on the perimeter holes at the time of firing should always be greater than the spacing of the perimeter holes. A burden of 1.5 times the spacing of the perimeter holes is commonly used, but may have to be altered slightly for various rock conditions (Hendron and Oriard, 1972).

TEST FACE PROGRAM (Section 4)   (1, 2, 4, 5)

Prior to commencing full-scale controlled blasting operations, the Contractor shall demonstrate the adequacy of the proposed blast plan by drilling, blasting, and excavating short test sections, up to 100 ft in length, to determine which combination of method, hole spacing, and charge works best.

When field conditions warrant, as determined by the Engineer, the Contractor may be ordered / permitted to use test section lengths other than specified above. Such test sections may be incorporated as part of the planned excavation along the designed backslope. The term test section shall

mean drilling, loading, shooting, and exposure of the complete face to viewing.

The contractor shall begin the tests with the controlled blastholes spaced at a given distance, usually 30 ft apart, as determined by the Engineer, then adjust, if needed, until the Engineer approves the spacing to be used for full-scaled blasting operations. The requirements for blasting operations, covered elsewhere in this specification, shall also apply to the blasting carried out in conjunction with the test shots.

The Contractor will not be allowed to drill ahead of the test shot area, until the test section has been excavated and the results examined by the Engineer. An ideal presplit face will have a relatively smooth fracture connecting adjacent drill holes, the half cast of each hole will be clearly evident, and specification for face tolerances will be met. If the results of the test shots, in the opinion of the Engineer, are unsatisfactory, then, notwithstanding the Engineer' prior review of such methods, the Contractor shall adopt such revised methods as are necessary to achieve the required results. Unsatisfactory results include an excessive amount of fragmentation or overbreak beyond the perimeter line, absence of satisfactory evidences of casts, out-of-tolerance face, excessive fly-rock, or violation of other requirements within these specifications.

If, at any time during the progress of the work, the methods of drilling and blasting do not produce a uniform slope and shear face, within the tolerance specified, the Contractor will be required to drill, blast, and excavate in short sections, not exceeding 100 ft in length, until a technique is arrived at, that will produce the required results. Extra cost resulting from this requirement shall be borne by the Contractor.

> The test face program is particularly important in areas where no recent experience with blasting and rock response is known. The importance of proper wall control, and the effects of blasting, both with and without controlled techniques, are shown in figure 4.5. It is also an important control mechanism, when the Contactor does not adequately control his

blasting subcontractor, and ,as a result, faces are not exposed in a timely fashion.

Portions of the slope where uncontrolled blasting was used have extensive fracturing of the rock due to blast damage, and the cut face is extremely ragged with overhangs. This will result in a significant amount of long-term rock fall, high maintenance cost, and safety hazards, versus the presplit portions of the slope.

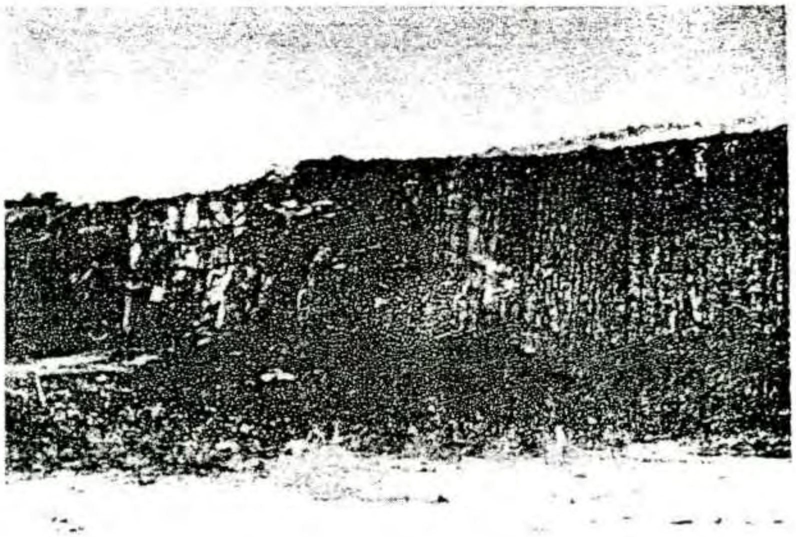

Figure 4.5. Test Blast both with and without Presplitting

CONTROL (Section 5) (1, 2, 3, 4, 5)

The Contractor shall control his drilling operations, by the use of proper equipment and technique, to ensure that no hole shall deviate from the plane of the planned backslope of any lift interval by more than a certain distance (usually 6 in.), **either parallel or normal to the slope.**

No rock shall protrude more than a given distancefrom the final face, as determined by the Engineer (commonly one foot), **from the plane of the designated backslope.**

The Engineer may use the "half cast factor" as an indication of acceptable work. The half cast factor is the percentage of the total half casts visible after the rock has been excavated. If only 40% of the drill holes remain visible on the final wall as half casts, then the half cast factor would be 40%.

> The half cast factor method of assessing acceptable work is more efficient when blasting in solid, homogeneous massive material. A half cast is the approximately 1/2 of the blast hole that remains after the blast, <u>if the rock shears along the plane of the last line of holes</u>. However, half casts may totally disappear in geologically complicated rock. Therefore, half cast factors only have validity if the rock type, in which the half casts are being counted, is considered in the evaluation.

<u>APPLICATION OF CONTROL (Section 6)</u> (1, 2, 4, 5)

If more than 5% of the half casts are misaligned, the Contractor shall reduce the depth of drilling, until the alignment tolerance is met.

If the half cast factor requirement, as determined by the Engineer, is not met by the Contractor for any shot, all controlled blasting activities shall stop. The Contractor shall submit a written report to the Engineer, proposing any corrective action plan for future controlled blasting activity to take place on the site.

<u>Protrusions</u>

The Engineer may require the removal of any rock protruding beyond the permissible tolerance or, at their discretion, relax the backslope tolerance, for an occasional protruding rock that is not a safety hazard. For the slopes to be covered by retaining structures, the face tolerance requirement may also be waived by the Engineer, but these discretionary

actions do not relieve the Contractor from his responsibility for removing any protrusions that might, in any way, interfere with adjacent structures, the forming for such structures, or the intention of the design.

Backbreak

The presplit slope face shall not deviate more than one foot from a plane passing through adjacent drill holes, along the expected perimeter, except where the character of the rock is such that, as determined by the Engineer, irregularities are unavoidable. The one foot tolerance shall be measured perpendicular to the plane of the slope.

Material ouside the excavation limits which are disturbed, due to the fault or negligence of the Contractor, or due to his failure to exercise construction practices, shall be either replaced by him with suitable material, and / or bolted, as directed by the Engineer, and at his own expense.

There are many causes of backbreak. It can be a result of excessive burden on the holes, thereby causing the explosive to break and crack radially further behind the last row of holes (as shown in figure 4.6), or it may result from locally heavily jointed rock mass, or a combination of the two.

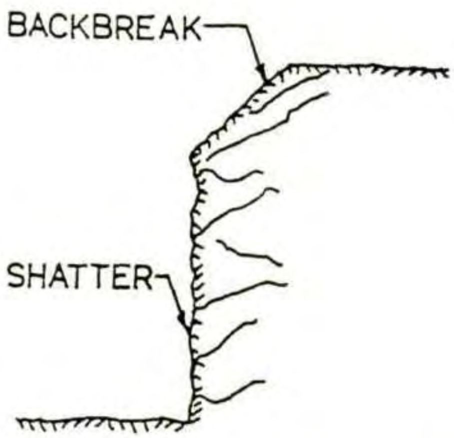

Figure 4.6 Backbreak Due to Excessive Burden (from Konya and Walter, FHWA, 1985)

Benches which are excessively stiff cause more uplift and backbreak near the collar of the hole (as shown in figure 4.7).

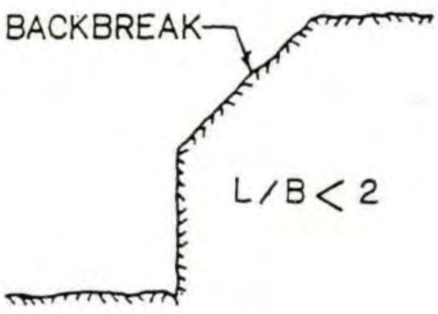

Figure 4.7 Backbreak Due to Excessive Stiffness (from Konya and Walter, FHWA, 1985)

MUCK REMOVAL (Section 7)

The Contractor shall take all necessary measures to ensure that all muck created by controlled blasting activities is removed from in front of the face. This operation shall take place immediately after each shot, in order to allow the Engineer to observe the face, and determine if the control is met. If this necessary condition is not met, the Engineer will order that all controlled blasting operations, including drilling, shall be stopped, until all excessive muck is removed, and face controls can be exerted.

This section is necessary to ensure that the Contractor will not allow large quantities of muck accumulate in front of the final face. Such a process would prevent both the Engineer and the Contractor from using their best judgment to assess the quality of the rock face, and modify controlled blasting techniques if necessary.

SIZE OF EXCAVATED MATERIAL (Section 8)

The excavated rock produced by controlled blasting activities shall be restricted in its size (i.e. volume and / or dimensions), as determined by the Engineer. All excavated material that will not meet these requirements shall be crushed to the limited size, at the Contractor's expense.

If there is a need for size restrictions (either large or small) for final disposal or use, this issue must be explicitely established in this specification.

CHAPTER 5

CLOSE-IN BLASTING

GENERAL PROVISIONS (Section 1)

Except as otherwise specified herein, all close-in blasting activities shall be performed in accordance with the requirements specified in the "Blasting and Vibrations" and "Controlled Blasting" parts of these specifications.

DESCRIPTION (Section 2)

Close-in blasting refers to drilling and rock excavation activities within a distance to existing structures that is equal to the final excavation depth. Close-in blasting activities involve the use of controlled blasting techniques, as described in the "Controlled Blasting" addendum of these specifications.

> If not carefully controlled, the release of delayed gas pressures and high particle velocities can have undesirable side effects. Blasting activities falling into this category are generally those carried out at less than 20 m from existing facilities.

BLASTING TECHNIQUE (Section 3)

When blasting near adjacent structures, production blasting shall start as far as possible from the existing facilities so that blast vibrations and bedrock geology can be evaluated as blasting approaches the structures.

Controlled perimeter blasting techniques, as described in the "Controlled Blasting" addendum of these specifications, shall be utilized along the excavation perimeter, to assist in obtaining a stable, undisturbed rock face. Smaller blast rounds may be desirable, as blasting approaches the adjacent structures, to minimize explosive charge weights and mitigate impacts in the event normally sized charges do not produce expected results.

> An important side effect of close-in blasting is potential permanent ground deformations, resulting from cratering and backbreak near the blast source, and from block movement caused by delayed gas pressure that may be transmitted through open joints and seams in the rock. In addition, there is still concern for the relatively large elastic ground motions (McKown, 1991).

<u>CONTROLS (Section 4)</u>

<u>Surveys (Section 4.1)</u>

A line and grade and a condition survey shall be performed on the adjacent structures. These surveys shall comply with all requirements exposed in Section 2.1 of the "Blasting and Vibrations" part of these specifications.

> Close-in blasting is the most likely type to be associated with permanent displacement. The line and grade surveys are needed to distinguish excavation induced displacements from suspected vibration induced movements. It should be remembered that vibration controls were established with the assumption that there would be no permanent displacement of the structure.

Ground Motions (Section 4.2)

All frequency based provisions concerning control of ground motions, as presented in the "Blasting and Vibrations" part of these specifications, shall apply here. Blasting within 30 m of the following structures shall be controlled by the respective following limits, provided no other structure is closer. (include list of "sensitive" structures here)

> Greater peak particle velocities may be allowable, in this case, since this type of blasting most often results in very high vibration frequencies, and little to no amplification by the adjacent structure (McKown and McClure, 1988). The control structure may not be a house with plaster walls, but may be a reinforced concrete or steel frame commercial building, or another engineered structure, that is much more resistant to damage than a residential structure. Application of usual criteria may be too conservative, thereby increasing the costs and resulting in longer construction times.

Ground Deformations (Section 4.3)

General

The Contractor shall take all necessary measures to prevent, or to limit, as far as possible, the permanent deformation of the rock immediately adjacent and beneath the structures, along the perimeter of the excavation.

> Permanent ground deformations are promoted by the following factors that should be of particular concern for the Contractor: (McKown, 1991)

- high blast confinement, resulting of a too large burden, low angles of breakage, absence of a free face, or other situations that tend to restrict the fragmentation of the blasted rock,
- lack of rock mass confinement, for exterior corners in particular,
- open joints and seams, which provide unusual avenues for the escape of explosive gasses,
- concentrated loading, resulting in overbreak and rock block movement outside the limits of excavation,
- low powder factor (weight of explosive per unit volume), which results in inadequate fracture and rock movement, and ultimately leads to greater energy released through ground vibrations.

Sometimes, a limit to ground heave or settlement is imposed (generally 1 inch, measured at the ground surface immediately adjacent to structures).

Special Rock Joint Requirements

Drillers shall keep detailed, written records of penetration rates, loss of fluids, etc. , that identify the depths of the seams and fracture zones that are encountered.

This provision is optional and should normally be part of the Contractor's method of producing a quality result. If specified, then the definition and collection methods must be included.

To allow for the study of the exposed vertical rock face after each round, so that open joints that could cause gas venting can be identified, as well as to reduce confinement, all excavated rock shall be removed from the blast area after each round (as specified in Section 7 of the "Controlled Blasting" addendum of these specifications).

If open, continuous joints are found at locations and orientations that could result in rock block movement adjacent to or below the structures, grouted rock dowels shall be installed, to reinforce the rock between the blast area and the structures. In addition, the Contractor shall take precautions to avoid placing explosives in areas where gas venting could occur.

> To prevent explosive gasses from opening joints, damaging rock, and moving rock blocks outside the excavation limits, the Contractor can use steel bars grouted into nearly vertical drill holes, located just outside the excavation limits, to reinforce the rock while, at the same time, filling with grout any open joints.

Application of Control (Section 4.4)

If specified vibration limits at the existing adjacent structures are exceeded, and / or if the half cast factor requirement is not met, and if the Engineer feels that continued blasting would threaten the integrity of adjacent structures, the Contractor shall be required to stop his blasting activities in the area of concern. The Contractor shall then be required to use non explosive techniques of rock fragmentation, near the existing structures, at no additional cost to the Owner.

> Examples of non explosive fragmentation methods would be a hoe ram (hydraulic impact hammer), expansive cement, or ripping with a bulldozer or a large backhoe.

CURING MASS AND IN-SITU CONCRETE (Section 5)

When necessary to blast in areas where concrete is curing, special limits of allowable peak particle velocities, as determined by the Engineer, shall be applied. If the Contractor wishes to utilize higher vibration limits, and can show, by independent testing or consultant data, that higher limits

can be used without damaging the concrete, the Engineer will consider such information when evaluating the request. The limits for concrete do not relieve the Contractor in any way from complying with the other limits set forth elsewhere in these specifications. If cracking of concrete, or deterioration of support rock below footings occurs, lower vibration levels will be established.

While numerous vibration controls for curing concrete exist, most of them are too conservative and / or are based on little experimental evidence. The following control is based upon experiments with a factor of safety of 2 applied during the first 20 hours.

Table 5.1 Peak Particle Velocity Control Limits for Curing Concrete (Esteves, 1978)

Concrete Age (hours)	Maximum Peak Particle Velocity (mm/s)
0 - 3	No limit
3 - 10	75
10 - 20	50
20 - 48	75
48+	100

CHAPTER 6

BLAST DENSIFICATION OF SANDS

GENERAL PROVISIONS (Section 1)

Except as otherwise specified in the following, the Contractor shall comply with all sections of the "Blasting and Vibrations" part of these specifications.

Specialists (Section 1.1)

Blasting Specialist

Same as in the general provisions, except that in addition the blasting specialist shall have previous experience in detonating explosives below the water table.

> Detonating explosives below the water table can produce adverse effects if not conducted properly. The shock waves generated in the water by the explosion of the first delay(s) can sympathetically detonate remaining delayed charges if the proper explosives and techniques are not employed.

Geotechnical Engineer

The Contractor shall engage a geotechnical engineer for advise on the soil conditions, as well as on the resulting densification and ground vibrations. His qualifications shall be approved as part of the review of the

blasting plan. The geotechnical engineer shall work in full cooperation with the blasting specialist to assist him in the design of the densification process.

The presence of a geotechnical engineer on site is necessary to ensure that the soil properties are correctly accounted for in the blast design.

Blasting Plan (Section 1.2)

General

No less than three weeks prior to commencing the test blast program, or at the preconstruction conference (whichever is earliest), or at any time the Contractor proposes to change the drilling and blasting methods, the Contractor shall submit a blasting plan to the Engineer for review. The blasting plan shall contain the full details of the drilling and blasting patterns and controls the Contractor proposes to use for densification blasting. The blasting plan shall contain the following minimum information:

- **station of proposed shots,**
- **number of coverages for a given number of charges per unit area** (e.g. single coverage at a tight spacing, or multiple overlapping coverages at a wider spacing)
- **plan and section view of proposed hole pattern, including spacing, diameter, and depth,**
- **loading diagrams for each hole, showing type and amount of explosives, type of casing, primers, initiators, and location, depth and type of stemming between separately delayed charges,**
- **initiation sequence of blast holes, including delay times and delay system,**
- **form for reporting vibration results for each blast,**
- **identification of explosive suppliers, blasting specialist, and geotechnical engineer,**

- manufacturers data sheets for all explosives, primers and initiators,
- procedures to inform the public and protect adjacent properties,
-plan for de-initiation in case of misfire.

The blasting plan submittal is for quality control and record keeping purposes. Review of the blast plan by the Engineer does not relieve the Contractor from his responsibility for the accuracy and adequacy of the plan when implemented in the field.

Test Blast Program (Section 1.3)

In addition to the general requirements, this program is intended to:

- determine the optimum blasting parameters,
- obtain ground vibration data,
- verify the increased soil density,
- correlate density improvement with ground surface and deep settlements.

The test blast program is also useful to reassure the project owner and developer that this unconventional method (compared to more common alternatives) will indeed achieve the intended purpose without undue environmental effects. The sheer number of variables, combined with the scarcity of experience with this particular method, make it prudent to perform a test program to achieve a design that will minimize the possible adverse effects.

Public Awareness (Section 1.4)

Because blast densification of sands produces low frequency vibrations, effects can be felt far away from the source; it is necessary to take extra measures to develop public awareness.

CONTROLS (Section 2)

Pre-Blasting Conditions of Soil (Section 2.1)

Prior to the commencement of any activity on the site, the Contractor shall conduct in-situ tests in order to determine the initial soil conditions. The results of these tests shall show the penetration resistance and / or density of the soil.

These tests shall consist of (specify here:

- type,
- method,
- location,
- frequency)

Such in-situ tests can be Cone Penetration Test (CPT), Standard Penetration Test (SPT), or any other method that the Engineer will deem necessary for the particular site. The type of density characteristic varies with the test method. For the CPT, it is the tip pressure, usually in psi; for the SPT, it is the blowcount (La Fosse and Gelormino, 1991, and Hryciw and Dowding, 1986).

Air Overpressures and Ground Motions (Section 2.2)

In addition to the preceding requirements, air overpressures and ground motions will be recorded on the form of time histories during blasts.

Post-Blasting Conditions (Section 2.3)

Settlements

Ground settlements shall be determined by surveying settlement platforms placed just below the ground surface, and deeper settlement points. The depths and locations of those measurements are (specify here).

Settlement control points shall be placed so that they extend out to a distance where less than 1 mm of settlement is expected. The exact spacing and location of the control points are (specify here).

> During the densification process, settlements are inevitable as they are the objective of the process. In addition, the amount of ground settlement must be controlled because it is of importance not only in the design of the facilities to be constructed on the site, but also to the existing and adjacent structures.
>
> Shallow platforms are generally placed at approximately two feet below the surface, while the position of the deeper points is a direct function of the soil conditions, as well as the amount of densification required.

Densification

The degree of densification achieved by blasting shall be measured by the Contractor with the same method of in-situ testing, and at the same

locations, as during the pre-blasting survey. The length of time between the two measurements shall be determined to account for the increase in penetration that ultimately is produced by blasting. The success of the densification operations shall be measured by comparison between the pre-blasting and post-blasting tests results.

Although this specification is intended for the control of vibrations, the degree of densification sought can be added explicitly in the text, as well as a control criterion for the result, such as a given minimum percentage of increase in penetration resistance.

GROUND MOTIONS MONITORING (Section 3)

Optional Monitoring of Dynamic Pore Pressures (Section 3.1)

The Engineer will record time histories of dynamic pore pressures created by deep blasting. The characteristics of this monitoring (depth, location, instrumentation, ...) will be determined by the Engineer, and the instrumentation shall be furnished by the Contractor.

Deep blasting induces significant dynamic pore pressures. Some projects, where this parameter is of particular concern, may require the monitoring of these pore pressures.

CHAPTER 7

DEMOLITION BLASTING

GENERAL PROVISIONS (Section 1)

Explosives (Section 1.1)

Transportation, handling, storage, and use of explosives shall be subject to the requirements stated in Section 1.1 of the "Blasting and Vibrations" part of these specifications.

Specialists (Section 1.2)

Demolition Blasting Specialist

The Contractor shall engage a blasting specialist as required to establish satisfactory demolition. The specialist shall have considerable experience in the use of explosives in general, and in demolition blasting in particular. His qualifications shall be subject to the approval of all parties involved in the demolition process. He shall be responsible for the design of all blasting operations, and his services shall be continued as long as the Engineer deems them to be necessary. When more than one person is involved in the conception of the blasting, the qualifications of all members of the blasting team shall be equally submitted to the above requirements.

> The skill in demolition is, even today, very largely based on practical experience and empiricism. Therefore, these requirements are necessary

to ensure that an appropriately trained person (or group of persons) designs and supervises the work.

Structural Engineer

The Contractor shall engage a structural engineer to advise on the stability of the building (or structure) to be demolished and of neighboring buildings (or structures). His qualifications shall be subject to the approval of all parties involved in the demolition process. The structural engineer shall work in full cooperation with the demolition blasting specialist, to assist him in the design of the demolition sequence.

The cooperation of a structural engineer is necessary to determine which parts of the building can be severed to bring the factor of safety down to 1.00001 before the final blast. His experience will also be of great use in assisting the demolition blasting specialist to select the location of the charges.

Demolition Plan (Section 1.3)

No less than three weeks prior to commencing any operations on the site, the Contractor shall submit a demolition plan to the parties involved for review. The demolition plan shall contain the full details of the demolition sequence, and the following minimum information:

- **description of the members to be pre-cut, and in which order to severe them, so that the unloaded factor of safety is reduced to 1.00001,**
- **location of proposed charges,**
- **plan view and section view of proposed drill patterns, including blast hole spacing, blast hole diameter, blast hole angles,**

- loading diagrams for each hole, showing type and amount of explosives, primers, initiators,
- initiation sequence of blast holes, including delay time and delay system,
- specific plan to control air blast, dust, and debris thrown from the impact,
- specific plan for evacuation of adjacent structures before final blast, if necessary,
- identification of explosive suppliers, demolition blasting specialist(s) and structural engineer(s),
- manufacturers data sheets for all explosives, primers, initiators, and delay system to be used,
- forms for reporting the vibration results and air blast overpressure,
- all safety codes and procedures to inform and protect the workers, public and adjacent property,
- plan for de-initiation in case of misfire.

The demolition plan submittal is for quality control and record keeping purposes. Review of the demolition plan does not relieve the Contractor from his responsibility for the accuracy and adequacy of the plan when implemented in the field.

<u>DEMOLITION BLASTING TECHNIQUE (Section 2)</u>

The best modern practice of demolition blasting shall be employed. Acceptable demolition techniques are the ones that limit ground motions induced by blasting and collapse of the structure, air blast overpressure, as well as expulsion of debris and dust from the site.

The Contractor and his consultants shall design the loads and the initiation sequence to control:

- the direction of collapse,
- the disintegration of mass concrete,

- **the emission of projectiles and dust,**
- **the ground motions and air blast overpressure,**
- **the impact of the falling structure on the ground.**

Determination of a general method of demolition blasting is simply impossible, since each building or structure has its own characteristics to be taken into account. Therefore, this specification is intended as a performance specification. It is the responsibility of the Contractor to meet the requirements of this text, by using the method that he will deem necessary.

Proximity of adjacent structures usually requires the building to collapse in a given direction. Such directionality can be ensured by a correct explosive sequence. Explosive demolition usually produces four environmental effects: (1) ground motions, (2) air blast, (3) projectiles, and (4) dust. It is therefore important to control these four elements. Air blast can be significant, unless specifically controlled. Moreover, ground motions are produced by two separate sources: ground coupling of the explosion, and impact of the falling structure. Previous work (Dowding, 1993) has shown that the second is the more important in terms of induced vibrations. Designing the demolition so that the building will tilt on one side, and then "progressively" fall, is therefore recommended.

PREBLAST PROCEDURES (Section 3)

Projectiles (Section 3.1)

Before the demolition blasting of the building, the Contractor shall erect barriers, to prevent expulsion of any but dust sized particles. The Contractor will be held liable for the damage caused to any property, and / or person, by projectiles that were permitted to escape the barriers.

In addition to the erection of barriers, the Contractor shall take all necessary measures to protect, on the buildings immediately adjacent to the structure to be demolished, the windows facing the location of blasting. This protection can take the form of screens or mats designed to prevent breakage of these windows.

> As observed, parking of trailor trucks around structures has been employed as barrier protection at some demolition sites. It is the responsibility of the Contractor to develop efficient means to limit ejection of projectiles. Since he is liable for any damage, he will very likely pay attention to this aspect.
>
> Building demolition is a punctual event. Therefore, no corrective measure can be taken <u>after</u> the blast, and all necessary prevention must be carefully thought out and planned <u>before</u> the blast. Another aspect of this punctuality is that the assessment of damage is possible <u>immediately after</u> the explosion and the collapse of the building.

<u>Dust (Section 3.2)</u>

The collapse of a structure is accompanied with the emission of fine grained soil sized particles and dust, that no barrier or mat can prevent from being emitted. The Contractor shall remove all dust, created and emitted by his demolition blasting activities, in a radius of (specify here) **from the structure. Dust shall be removed from any place where it can cause annoyance, whether it is in the adjacent streets, public places, or private properties, within a period of <u>two weeks</u> after the demolition has occurred.**

<u>Surveys (Section 3.3)</u>

Condition and line and grade surveys shall be performed in compliance with the requirements exposed in sections 2.1 and 2.2 of the "Blasting and Vibrations" part of these specifications.

> It might be necessary to correct the requirements concerning the radius within which all buildings will be surveyed. In an urban area, 400 ft, as specified before, include a significant number of structures, and all of them cannot be surveyed.

Blast Warning Procedures (Section 3.4)

The Contractor shall comply with all the requirements exposed in section 1.6 of the "Blasting and Vibrations" part of these specifications concerning erection of warning signs, radio transmitters, and public awareness.

In addition, a system of reliable, audible warnings shall be established by the Contractor, subject to approval, to ensure proper warning to all personnel in the area of detonation. It is important that visitors are made aware of this warning procedures. The code shall contain three signals:

1) a warning signal before blasting. A suitable time for the warning signal is that it is sufficient for people to reach a place of safety before the blast is fired,
2) a firing signal,
3) an all-clear signal.

The Contractor is responsible for developing a system to ensure that no personnel remain inside the building during the blast initiation process.

Evacuation Plan (Section 3.5)

The Contractor shall have both letter and personal contacts with residents, institutional operators, and business establishments that are adjacent to the demolition site, in order to establish an evacuation plan of the concerned buildings.

MONITORING AND CONTROL OF EVENT (Section 4)

The ground vibrations and air blast overpressures shall be subject to the same provisions concerning control methods, monitoring processes, and instrumentation, as those exposed in the "Blasting and Vibrations" and "Noise and Overpressure" parts of these specifications, respectively.

POSTBLAST PROCEDURES (Section 5)

The Contractor shall establish a construction bond, to cover the risks of unpredicted damages to adjacent buildings or structures.

Postblast surveys of the buildings and / or structures surrounding the demolition site will be made in the event that owners or residents make a specific blast-related damage claim. These surveys will be conducted by an independent specialist consultant, whose qualifications shall be submitted to approval of the involved parties. The postblast survey, then, will be based on the particular damage claim, and will serve simply to confirm or deny the validity of the damage claim. The complaint damage itself shall be inspected, documented, and photographed if necessary, in order to make comparison reference to the original preblast survey. A report shall be issued, stating if the claim is confirmed or denied, and transmitted to the Contractor.

CONCLUSIONS
AND
RECOMMENDATIONS

In this thesis, technical specifications, focused on the control of ground vibrations induced by blasting and pile driving, and of air overpressures, have been developed to incorporate frequency based approaches. In addition, special chapters have been developed for situations such as controlled blasting, close-in blasting, demolition blasting, and blast densification of sands. After the review of existing texts, collection of numerous articles, and synthesis of these specifications, the following conclusions can be advanced, concerning respectively the geotechnical, the procedural, and the management aspects of vibration control specifications.

Too many ground vibration controls are over conservative. Respecting these unnecessarily stringent limits requires time, money and energy, that could be employed more profitably. Use of realistic controls for the particular site should be one of the principal objectives of both the Contractor and the Engineer.

Frequency considerations are important, because both structural and human responses are a function of the excitation frequency. This aspect is also critical in the choice of the instrumentation for monitoring purposes.

A clear distinction should be made between air overpressures in general, and noise, which is the high frequency audible portion of the air overpressure. Noise is harmless to structures, but produces community annoyance and should therefore be controlled.

Control of permanent displacement of the soil and / or rock is more critical for some operations, such as pile driving and close-in blasting, than limiting ground motions. Special design and control measures should be taken in critical cases.

Specifications should be written to measure outcomes rather than methods. This performance approach leaves room for the Contractor to meet the requirements with his own method(s) and creativity.

Vibration considerations should be taken into account early in the design of the project. Making a preconstruction survey, to identify critical structures and processes is an example of an appropriate measure to be taken prior to the writing of the specifications.

It is necessary for the Contractor to work in collaboration with specialists of the operations carried out on the site. These persons, whether they are geotechnical, structural, or blasting specialists, must be qualified to assist the design and / or to be consulted on specific problems.

Test programs should always be carried out before starting full-scale operations. This measure allows for any eventual correction in the methods used, in the event that the tests do not produce the expected effects.

The choice of the type of instrumentation to be used for the monitoring of the ground motions is a function of the expected velocities, and / or the conditions of the site. Nevertheless, monitors providing time histories of the event should be preferred.

Two threshold values of peak particle velocity should be introduced for monitoring purposes during piling activities. It is then possible to carry out an exhaustive, but not data intensive, monitoring program.

The above specifications are intended to be customized to fit the characteristics of each project. The text will not be appropriate if this necessary tailoring operation is not carried out.

The role of the Engineer should not be limited to the control authority. He should be available for advise on specific problems, but the final results should remain the responsibility of the Contractor.

APPENDICES

APPENDIX A

APPENDIX A

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APPENDIX B

APPENDIX B

FIELD INSPECTION REPORT (from Dowding, 1985)

IV. DESCRIPTION OF LOT

Level ________ , sloping to front ________ ,

to rear ________ , or to side ________

Graded ________ , or filled ________ area

Is area properly drained? ________

Provisions for handling water from roof? ________

Is subsoil drainage carried away from wall? ________

Are there large trees nearby? ________

Depth of water table ________

Any settlement of nearby structures? ________

COMMENTS: ________

V. DESCRIPTION OF ROOM NUMBER ____ (reference drawing on sheet one)

Ceiling, plaster ________ , wood lath ________ , metal lath ________ ,

gypsum board ________

Walls, plaster ________ , plaster and lath ________ , or gypsum board ________

paper ________ , paint ________

Ceiling: cracks? (Yes) (No)

Location and size; state whether horizontal (H), vertical (V), slanting (S)

____

Estimate age of cracks ________

Walls: cracks? (Yes) ________ (No) ________

Location and size: state whether horizontal (H), vertical (V), slanting (S); where partition wall joins exterior wall ________

North South East West

____

Corners of windows ________

Corners of doors ________

Others, i.e., windows ________

Estimate age of cracks ________

FIELD INSPECTION REPORT

BY ________
(Type in name)

____
House Number and Street

Present During Inspection

(yes) ________ (no) ________

____
Name of Occupant

____
Full name

I. DESCRIPTION OF HOUSE

Floors, one ________ or two ________

Basement, full ________ or partial ________

Number of rooms, up ________ , down ________

Type of construction, frame ________ , brick ________ ,

brick veneer ________ , concrete block ________ ,

stone veneer ________ , shingle ________ , stucco ________ .

If brick, type of lintels, ________

Roof, wood shingle ________ , composition ________ , or

clay title ________

Chimney construction and type, ________

Age of house, ________ , condition ________ , paint ________

Any addition to house? ________ If so, is it same as original construction?

____

II. SKETCH OF FLOOR PLANS WITH IDENTIFYING ROOM NUMBERS

III. DESCRIPTION OF FOUNDATION AND BASEMENT

Excavated depth ________ or above ground ________

Footings, concrete ________ , block ________ , brick ________

Width of footings ________ , proportional to loads ________

Walls, concrete ________ , concrete blocks ________ , or ________

brick ________ , thickness ________

Are the four corners level? Measure ________

Is the first brick coarse level? ________

Floor Joists

Are both ends on masonry ________ or wood ________ ? Size ________

Length ________ Distance between floor joists ________ Size ________

Are there double joists under unsupported partitions? ________

Span and type of midspan support for joists ________

SHOT RECORD REPORT (from Berger, 1983)

CLIENT ____________ OPERATION ____________

BLAST DATA

Shot No. ______	Specific Blast Location ______
Date ______	Bench No. ______ ______
Time ______	Material Being Blasted ______
No. Holes ______	Blaster's Name (Printed) ______
Diameter ______ in.	Blaster's Signature ______
Depth ______ ft.	Blaster's License No. ______ State ______
Subdrilling ______ ft.	Distance To Nearest Building* ______ ft.
Spacing ______ ft.	Direction To Nearest Building* ______
Burden ______ ft.	Weather ______ Wind Dir'n: ______ Velocity: ______ mph

* = Dwelling, School, Church, Hospital, [illegible] or Commercial Building

Explosives - Kind	Weight	Firing Information
______	______ lbs.	ES Caps (Brand) ______
______	______ lbs.	Delay Nos. ______
______	______ lbs.	Blasting Machine (Check One)
______	______ lbs.	______ Conventional
______	______ lbs.	Identification ______
______	______ lbs.	Type of Circuit ______
Total Weight	______ lbs.	No. Circuits ______
Average Load Per Hole	______ lbs.	______ Sequential Timer
Loading Factor	______ lbs./c.y.	Identification ______
Top Stemming		No. Series ______ Interval ______ ms.
Depth	______ ft.	Cord ______ Type ______ gr.
Material ______		Delay Connectors ______ ms.

Maximum Weight Of Explosives Detonated Within Any 8 Millisecond Period ______ lbs.

Maximum Number Of Holes Detonated Within Any 8 Millisecond Period ______

Scaled Distance ______ Were Mats Or Other Protection Used? YES ______ NO ______

BLAST DIAGRAM

CLIENT ______	OPERATION ______
ADDRESS ______	PERMIT NO. ______
______	SUPERINTENDENT ______

SEISMOGRAPH RECORDING DATA

	Shot No. ______ Date ______
Property Owner ______	Exact Location Of Seismograph ______
Address ______	______
______	______
Seismograph Type ______	Serial No. ______ Gain ______
Distance From Blast ______ ft.	Direction From Blast ______
Distance Measured By ______	Operator ______
Scaled Distance (Seis. Location) ______	Witnesses ______
Was Recording Location Closest Occupied	______
Building To Blast? YES ______ NO ______	______

VIBRATION MEASUREMENTS Analyst ______

Component	Monitor	Maximum Particle Velocity	Maximum Displacement
Transverse	______	______ in./sec.	______ in.
Vertical	______	______ in./sec.	______ in.
Longitudinal	______	______ in./sec.	______ in.
Percentage Of ______		______ in./sec.	______ %
Air Blast	______	______ psi	______ dB(L)
Percentage Of ______		______ psi	______ %

Remarks ______

APPENDIX C

APPENDIX C

REVIEW OF EXISTING CONTROLS FOR BLASTING VIBRATIONS

Peak Particle Velocity Constant with Frequency

The Office of Surface Mining Reclamation and Enforcement (OSMRE) of the United States Department of the Interior requires that, at a structure:

- from 0 to 300 ft distance, $V_{max} = 1.25$ ips,
- from 301 to 5000 ft distance, $V_{max} = 1.00$ ips,
- from 5001 ft to beyond, $V_{max} = 0.75$ ips.

The American Association of State and Highway Transportation Officials (AASHTO) specifies different allowable limits for different types of buildings, as displayed in Table C.1.

Table C.1 Maximum Vibration Levels for Preventing Damage: Intermittent Excitation on Transportation Construction or Maintenance (from AASHTO, 1979)

Type of Situation	Limiting Velocity (ips)
Engineered Structures, without plaster	0.1
Residential buildings in good repair, with gypsum board walls	0.2 to 0.3
Residential Building, plaster walls	0.4 to 0.5
Historical sites, other critical locations	1 to 1.5

Stone and Webster Engineering Corporation uses the following: (nuclear plant construction site, V_{max} measured at a structure)

- from 0 to 120 ft distance, $V_{max} = 5$ ips,
- at 120 ft distance, $V_{max} = 2$ ips.

Peak Particle Velocity Varying with Frequency

The OSMRE regulations specify the following ground vibration limits.

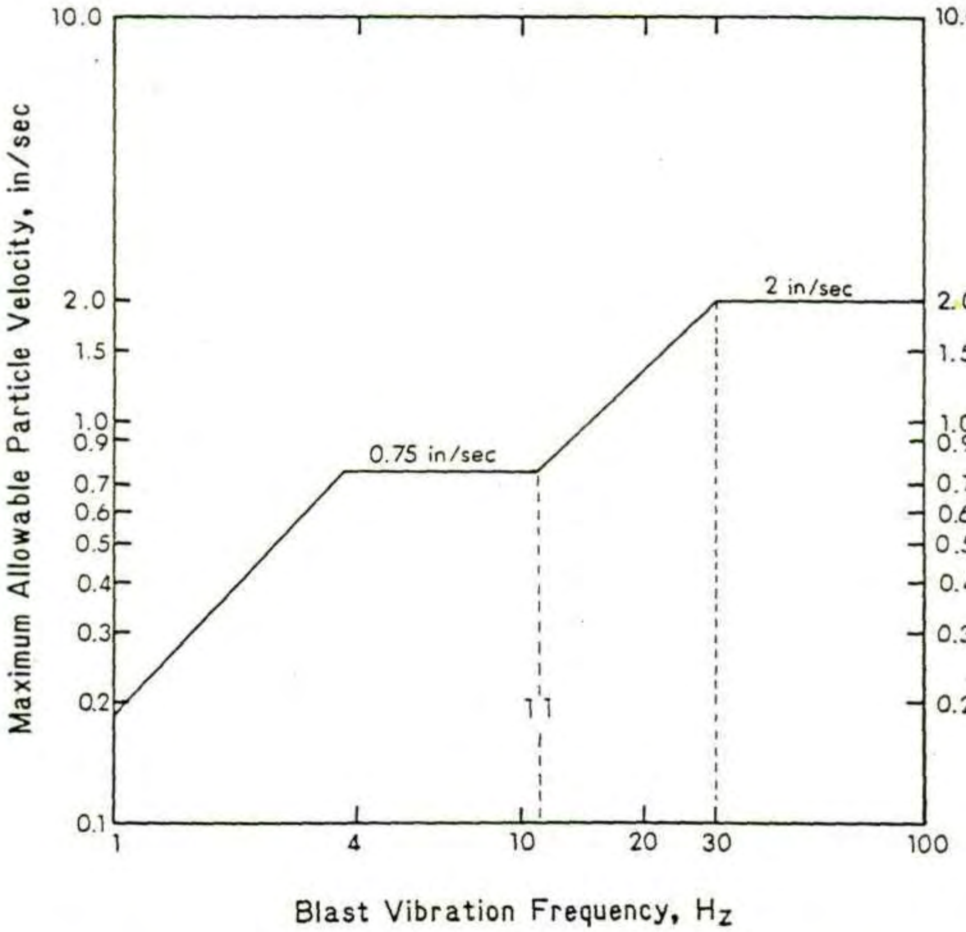

Figure C.1 Blasting Level Chart (from Rosenthal and Morlock, 1987)

The United States Bureau of Mines advises the following curves:

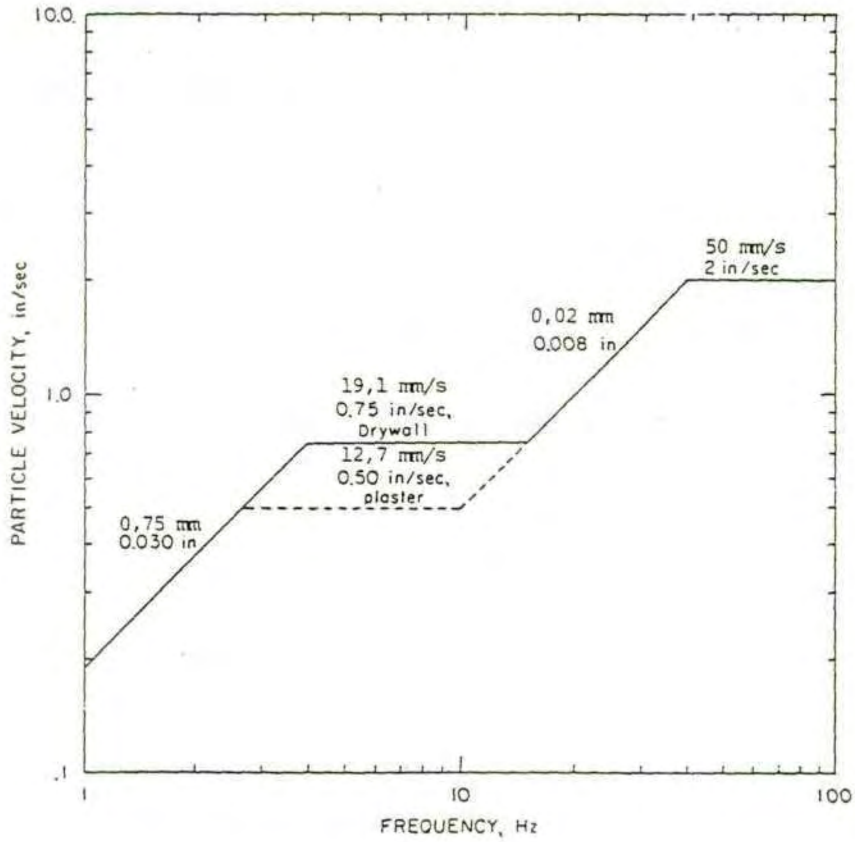

Figure C.2 Safe Levels of Blasting Vibration for Houses using a Combination of Velocity and Frequency (from Siskind et al, RI 8507, 1980)

The German Norm DIN 4150 gives different curves, as a function of the type of building. Table C.2 describes the different criteria, while Figure C.3 displays the corresponding curves.

Table C.2 References Values for the Peak Particle Velocity for the Assessment of the Effect of Vibrations (from DIN 4150, 1982).

Building Type	Frequencies		
	< 10 Hz	10 to 50 Hz	50 to 100 Hz
	Peak Particle Velocity (mm/s)		
I) Commercial and industrial buildings	20	20 to 40	40 to 50
II) Residential buildings, buildings with plaster work	5	5 to 15	15 to 20
III) Buildings with special sensitivity to vibrations	3	3 to 8	8 to 10

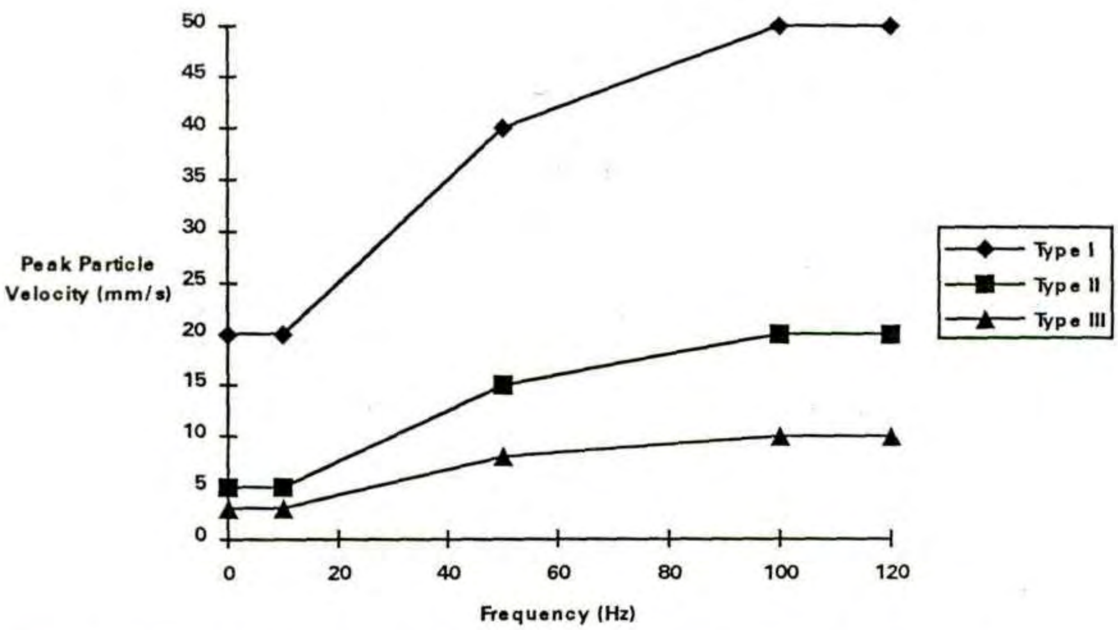

Figure C.3 Graphic Representation of the Values in Table C.2 (from DIN 4150, 1982)

Wiss, Janney, Elstner, Associates, Inc. developed its own limiting chart, for the Minnesota Department of Transportation, on sites in St. Paul, Duluth, and Minneapolis, Mn.. Figure C.4 shows the curve:

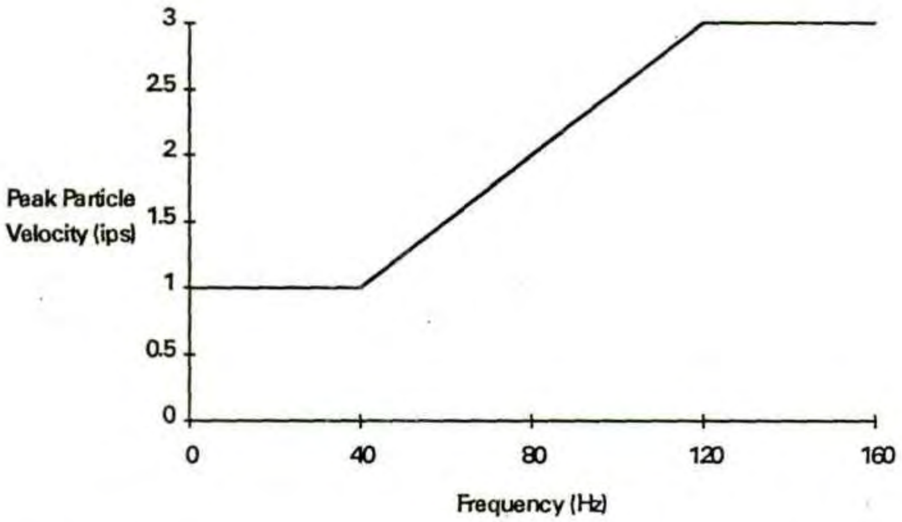

Figure C.4 Limiting Values of Peak Particle Velocity vs. Frequency (from WJE, 1990)

The Swiss Standard considers different types of buildings, as shown in Table C.3, and advises the values shown in Figure C.5.

Table C.3 Structural Types for Swiss Standard (from Studer and Suesstrunk, 1978)

Type	Description
I	Reinforced concrete and steel construction (without plaster) such as industrial buildings, retaining walls, bridges, towers, above-ground pipelines. Underground structures like caverns, tunnels, galleries with or without concrete lining.
II	Buildings with foundation walls and floors in concrete with walls in masonry (brickwork, stonework) or concrete. Retaining walls of ashlar construction. Underground structures like caverns, tunnels and galleries with masonry lining. Pipelines buried in soft ground (soil)

III	Buildings with foundations and basement floors of concrete construction, with wooden beam construction in upper floors, brickwork walls
IV	Buildings which are especially sensitive or worthy of protection

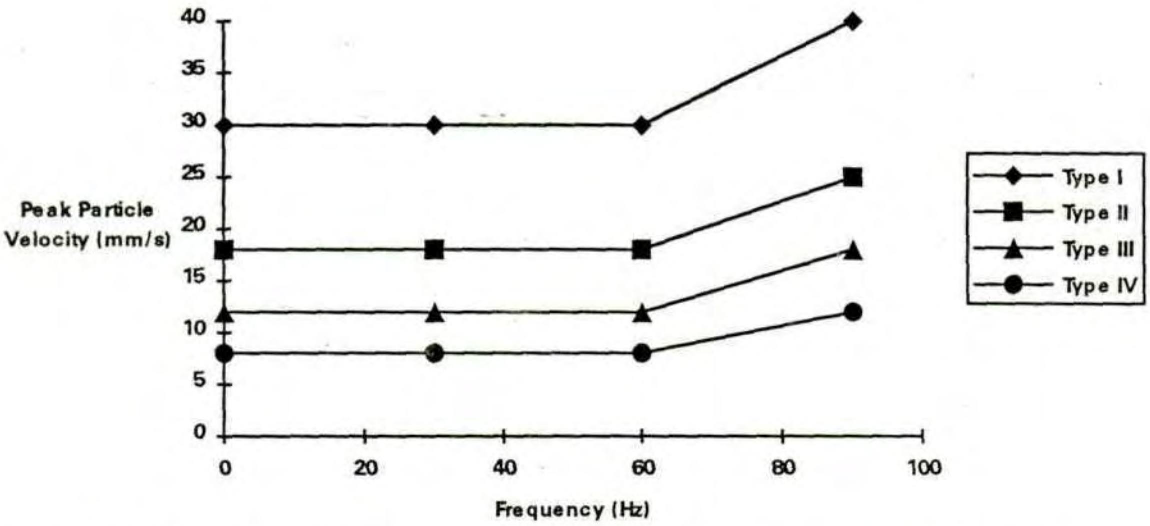

Figure C.5 Limiting Curves of Particle Velocity vs. Frequency (after Studer and Suesstrunk, 1978)