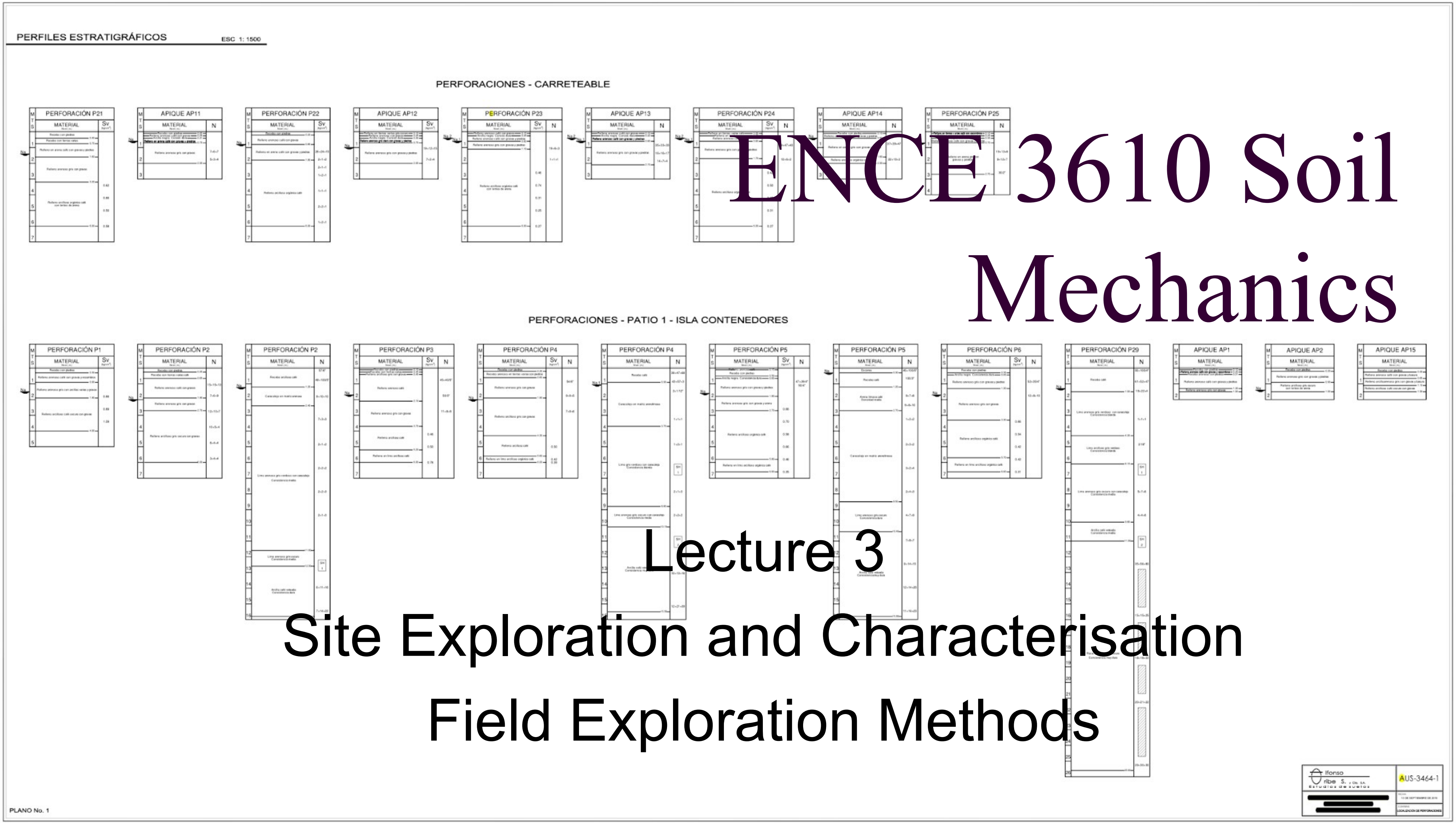


ENCE 3610 Soil Mechanics

Lecture 3

Site Exploration and Characterisation

Field Exploration Methods

Reference Standards for Exploration Techniques

Table 3-3
Reference publications on in-situ testing (FHWA, 2002b)

Test Method	AASHTO/ ASTM Designation	Reference
SPT	AASHTO T206 ASTM D 1586	FHWA (2002b). *Subsurface Investigations (Geotechnical Site Characterization)*. Report No. FHWA NHI-01-031, Authors: Mayne, P. W., Christopher, B. R., and DeJong, J., Federal Highway Administration, U.S. Department of Transportation.
CPT, CPTu, SCPTu	ASTM D 3341, D5778	FHWA (1992a). *The Cone Penetrometer Test*. Report No. FHWA NHI-91-043, Authors: Riaund J-L and Miran J., Federal Highway Administration, U.S. Department of Transportation. Lunne, T., Robertson, P.K., and Powell, J.J.M. (1997) *Cone Penetration Testing in Geotechnical Practice*, E & F Spon.
DMT	Suggested ASTM Method	FHWA (1992b). *The Flat Dilatometer Test*. Report No. FHWA NHI-91-044, Authors: Riaund J-L and Miran J., Federal Highway Administration, U.S. Department of Transportation.
PMT	ASTM D 4719	FHWA (1989a). *The Pressuremeter Test for Highway Applications*. Report No. FHWA IP-89-008, Authors: Briaud J-L, Federal Highway Administration, U.S. Department of Transportation. Clarke, B.G. (1995) *Pressuremeters in Geotechnical Design*, Blackie Academic & Professional.
VST	ASTM D 2573	ASTM (1988). *Vane Shear Strength Testing in Soils: Field and Laboratory Studies*, American Society for Testing and Materials, Committee D-18 on Soil and Rock for Engineering Purposes, Philadelphia, PA.

SPT Test Procedure and Types

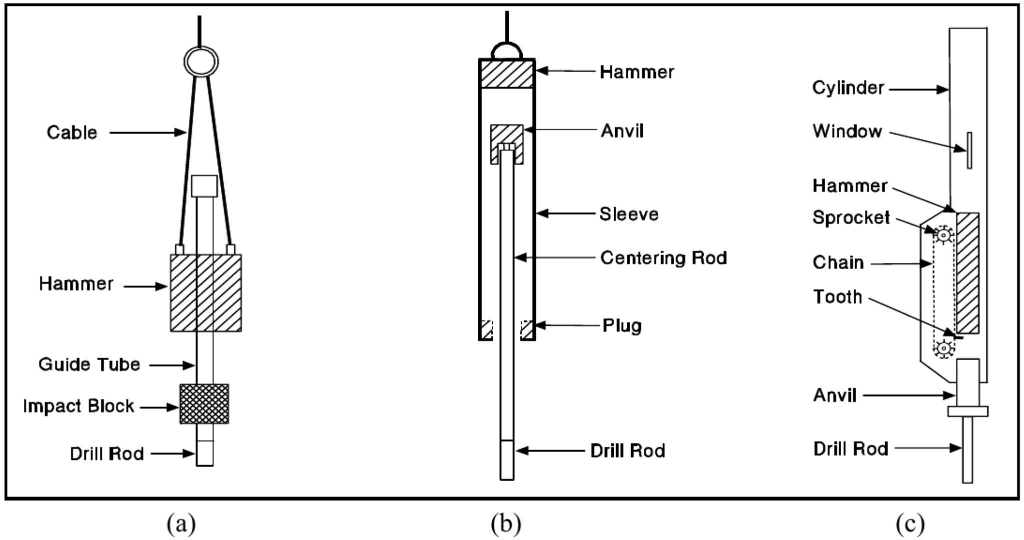


Figure 3-22. SPT hammer types, (a) Donut, (b) Safety, and (c) Automatic (FHWA, 2006a).

The SPT was originally developed in the 1900s and proceeds by driving a thick-walled, split-barrel (a.k.a., “split spoon”) sampler into the ground using incremental blows from a drop hammer. The sampler is driven a total of 18 inches into the ground. The number of blows required to drive the sampler the 12-inch vertical interval between 6 and 18 inches is referred to as an N value or the blow count. The procedure is presented in ASTM D1586, and a schematic of the SPT is shown in the following slide.

The SPT provides a disturbed sample of the tested material and generates useful data that can be used to correlate to many engineering properties. Many factors can affect the SPT results, and there are several vastly superior in situ testing methods. Nevertheless, the test is still almost universally referenced and often required in the United States. One reason for this is the large amount of historical (i.e., legacy) data available. Numerous correlations have been published (see Chapter 8) and their use along with SPT represents the Standard of Practice in many parts of the country. (UFC 3-220-10)

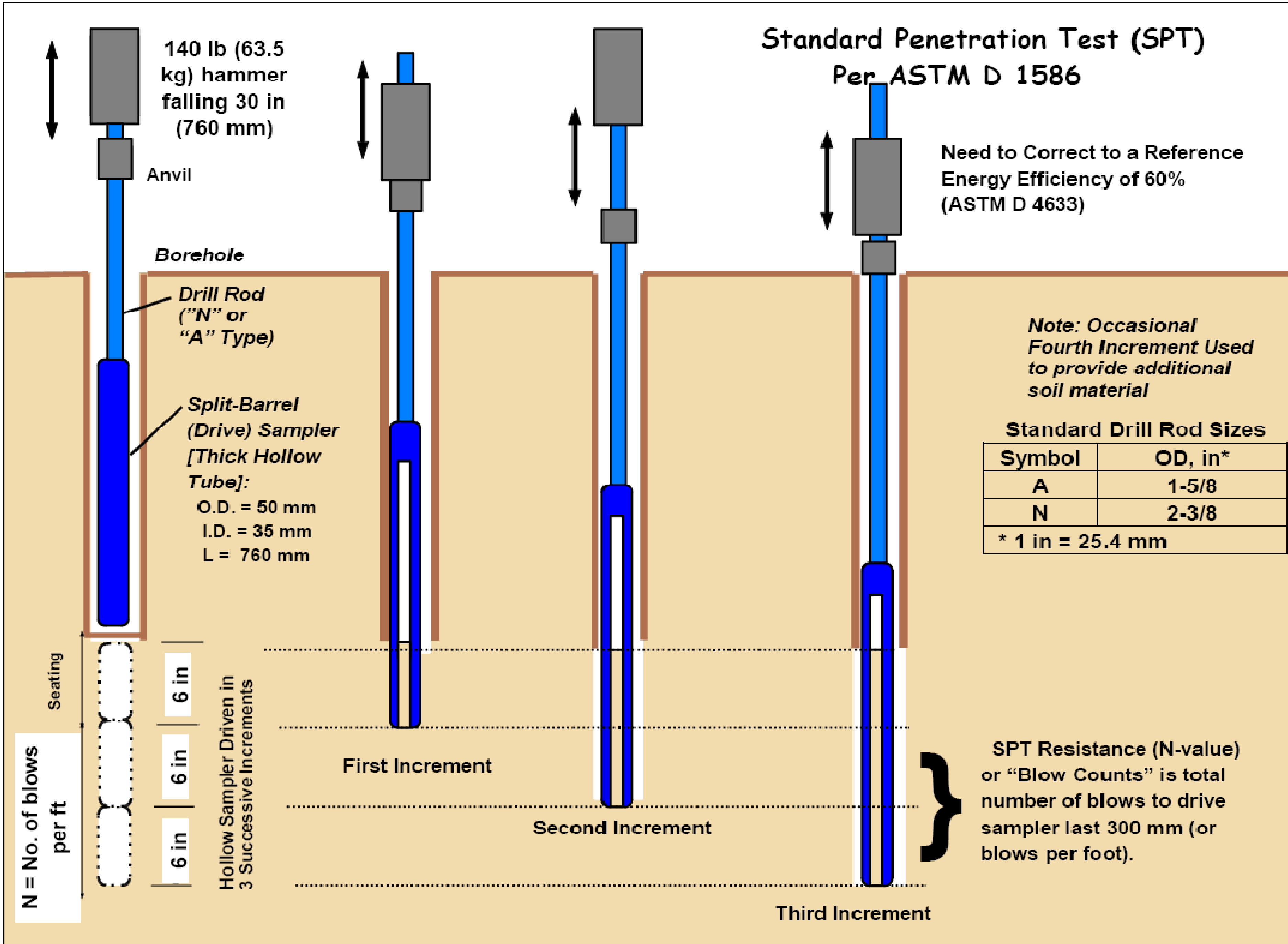


Figure 3-20. Sequence of driving split-barrel sampler during the Standard Penetration Test (modified after FHWA, 2002b).

Advantages and Disadvantages of SPT Test

Advantages	Disadvantages
• Obtain both a sample and an N-value	• Disturbed sample (index tests only)
• Simple and rugged	• N-value is a crude number for analysis
• Suitable in many soil types	• Not applicable in soft clays & loose silts
• Can be performed in weak rocks	• High variability and uncertainty
• Readily available throughout the U.S.	• Unreliable in gravelly soils

- SPT Tests are generally corrected in two stages:
  - Mechanical aspects of hammer and boring (borehole size, efficiency of hammer, etc.)
  - Overburden (effective or intergranular) stress

Correction of SPT Results

The measured N-value is the number of blows required to drive the split spoon sampler a distance of 300 mm. The efficiency of the system can be obtained by comparing the kinetic energy, KE, (i.e., $KE=\frac{1}{2}mv^2$), with the potential energy, PE, of the system, (i.e., PE=mgh). The energy ratio (ER) is defined as KE/PE. For routine engineering practice in the United States, correlations for engineering properties are based on SPT N values measured based on a system which is 60 percent efficient, i.e., ER=60 percent. The N values corresponding to 60 percent efficiency are termed N_{60}. Numerous correction factors to the measured N-value are necessary because of energy inefficiencies and procedural variation in practice. When all factors are applied to the field recorded N-value (N_{meas}), the corrected value is calculated as:

$$N_{60} = N_{meas} C_E C_B C_S C_R \qquad \text{(Equation 3)}$$

where correction factors are presented in table 9 and include the effects of energy (C_E), borehole diameter (C_B), sampling method (C_S), and rod length (C_R). As can be noted from table 9, values of the correction term for energy, i.e., C_E, vary over a relatively wide range. For this reason, accurate estimates of C_E are more important than estimates of the other correction factors. More accurate estimates of C_E should be evaluated by directly measuring the energy ratio (ER) of a particular SPT setup according to procedures in ASTM D 4633. Commercially available equipment can be used to perform this calibration. Hammer systems used for standard penetration testing should be periodically calibrated using the procedures outlined in ASTM D 4633.

SPT Efficiency Correction Factors (without overburden correction)

Table 9. Corrections to the SPT (after Skempton, 1986).

Factor	Equipment Variable	Term	Correction
Energy Ratio	Donut Hammer Safety Hammer Automatic Hammer	$C_E = ER/60$	0.5 to 1.0[(1)] 0.7 to 1.2[(1)] 0.8 to 1.5[(1)]
Borehole Diameter	65 to 115 mm 150 mm 200 mm	C_B	1.0 1.05 1.15
Sampling method	Standard sampler Non-standard sampler	C_S	1.0 1.1 to 1.3
Rod Length	3 to 4 m 4 to 6 m 6 to 10 m 10 to >30 m	C_R	0.75 0.85 0.95 1.0

[1] Values presented are for guidance only. Actual ER values should be measured per ASTM D 4633

SPT Correction Example (without overburden)

- Given
  - SPT reading 20m below ground surface
  - Readings: 10 – 15 – 12
  - Using Automatic Hammer, 80% efficiency
  - Borehole diameter = 100 mm
  - Standard Sampler
  - Rod length at least distance below ground surface
- Find
  - Corrected N_{60} SPT reading

- Solution
  - N-value = sum of last two 6” blow counts = 15 + 12 = 27
  - Correction Factors
    - E_f = 80, for automatic hammer (efficiency of the hammer=80%), so C_E=80/60=1.333
  - All other correction factors C_R=C_S=C_B=1
  - N_{60} = (27)(1.333)(1)(1)(1) = 36 blows/ft (or blows/300 mm)

Correction for Overburden

Since N-values of similar materials increase with increasing effective overburden stress, the corrected blowcount (N_{60}) is often normalized to 1-atmosphere (or about 100 kPa) effective overburden stress using overburden normalization schemes. The normalized corrected blowcount is referred to as $(N_1)_{60}$, and is equal to:

$$(N_1)_{60} = C_N N_{60} \qquad \text{(Equation 4)}$$

where C_N is the stress normalization parameter calculated as:

$$C_N = (P_a/\sigma_{vo}')^n \qquad \text{(Equation 5)}$$

where P_a is atmospheric pressure in the same units as σ_{vo}', and n is a stress exponent typically equal to 1 in clays (e.g., Olsen, 1997; Mayne & Kemper, 1988) and 0.5 to 0.6 in sands (e.g., Seed et al., 1983; Liao & Whitman, 1986; Olsen, 1997). Figure 11 illustrates a correlation for C_N that is used for sands. There exist several soil specific correlations for C_N, as reported in the literature. C_N may vary slightly from the general values identified previously, depending upon the specific correlation.

SPT Correction for Overburden

- Applied after the other correction factors
- Only applied to an N_{60} SPT result
- Example
  - $N_{60} = 20$
  - $\sigma'_z = 2.5$ ksf

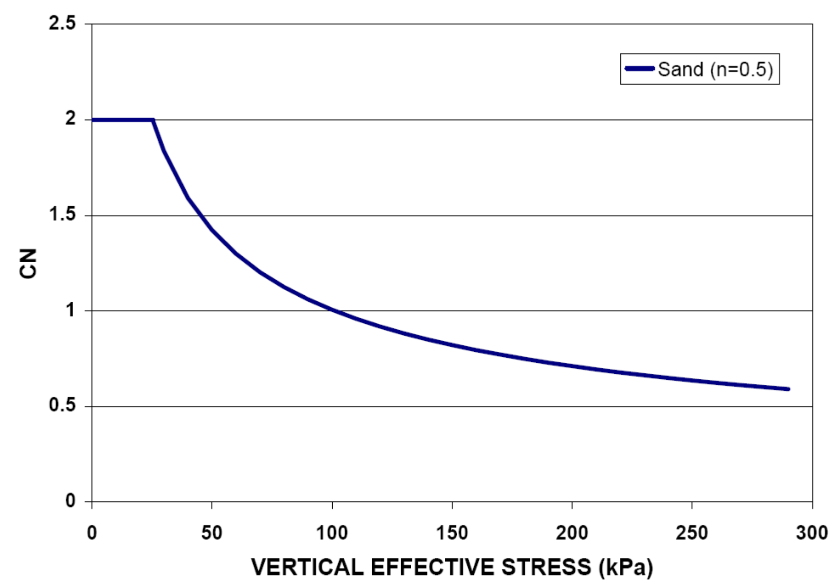


Figure 11. Stress normalization parameter, C_N, for sands.

$$(N_1)_{60} = N_{cor} = C_N N_{60}$$

$$C_N = \sqrt{\frac{2}{\sigma'_z}} \leq 2 \;(U.S.Units,\, ksf)$$

$$C_N = \sqrt{\frac{100}{\sigma'_z}} \leq 2 \;(SI\,Units,\, kPa)$$

$$C_N = \sqrt{\frac{2}{\sigma'_z}} = \sqrt{\frac{2}{2.5}} = 0.89 \leq 2 \;(U.S.Units,\, ksf)$$

$$(N_1)_{60} = C_N N_{60} = (0.89)(20) = 17.9\, {}^{blows}/_{ft} \Rightarrow 18\, {}^{blows}/_{ft}$$

SPT Correlations for Soil Properties

Table 3-9
Soil properties correlated with Standard Penetration Test values (after Peck, *et al.*, 1974)

Sands (Reliable)		**Silts and Clays (Unreliable)**	
N_{60}	**Relative Density**	**N_{60}**	**Consistency**
0-4	Very loose	Below 2	Very soft
5-10	Loose	2-4	Soft
11-30	Medium Dense	5-8	Medium
31-50	Dense	9-15	Stiff
Over 50	Very dense	16-30	Very stiff
		Over 30	Hard

Other Field Tests

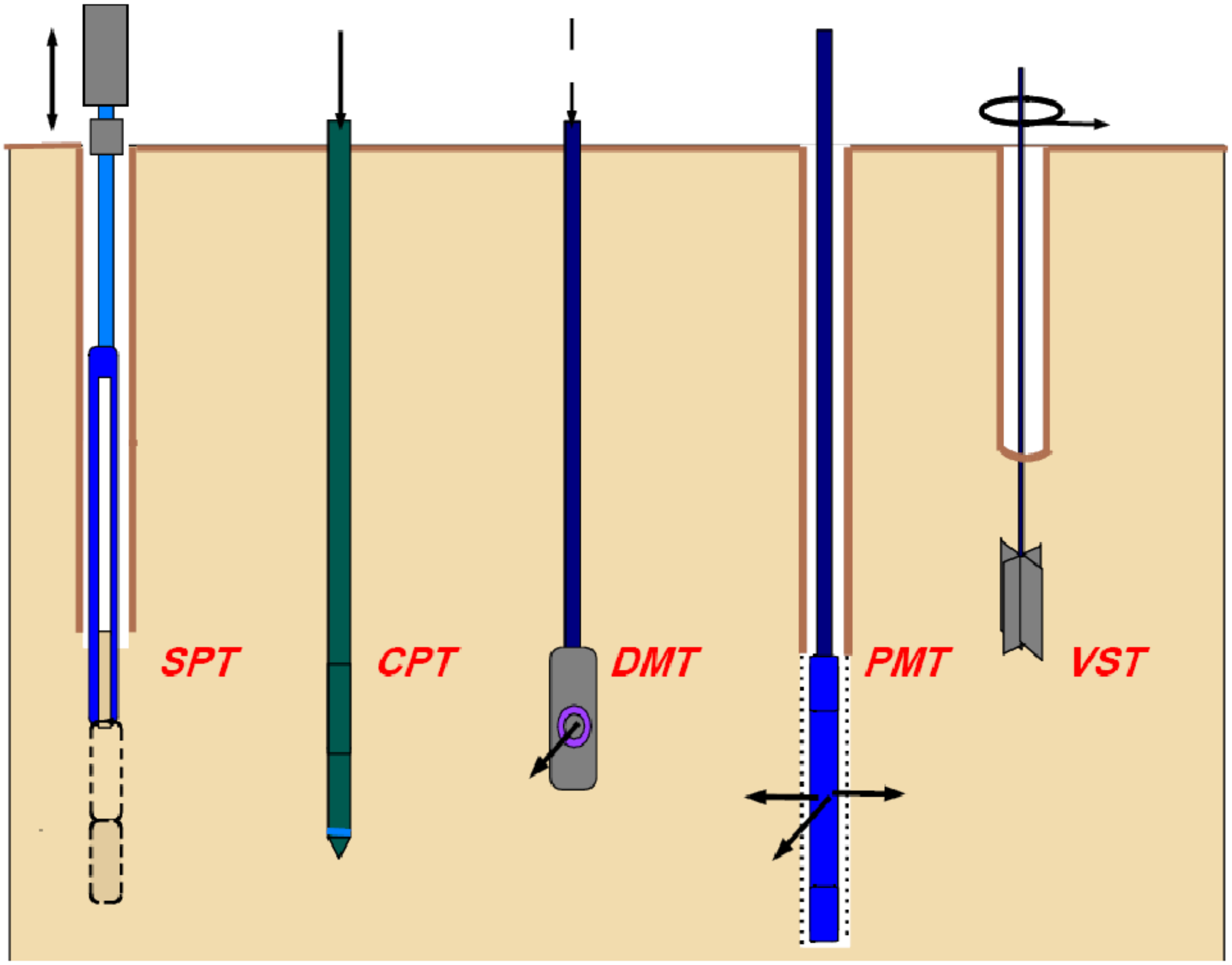


Figure 3-4. Common in-situ tests for geotechnical site characterization of soils (FHWA, 2002b).

Cone Penetrometer Test (CPT)

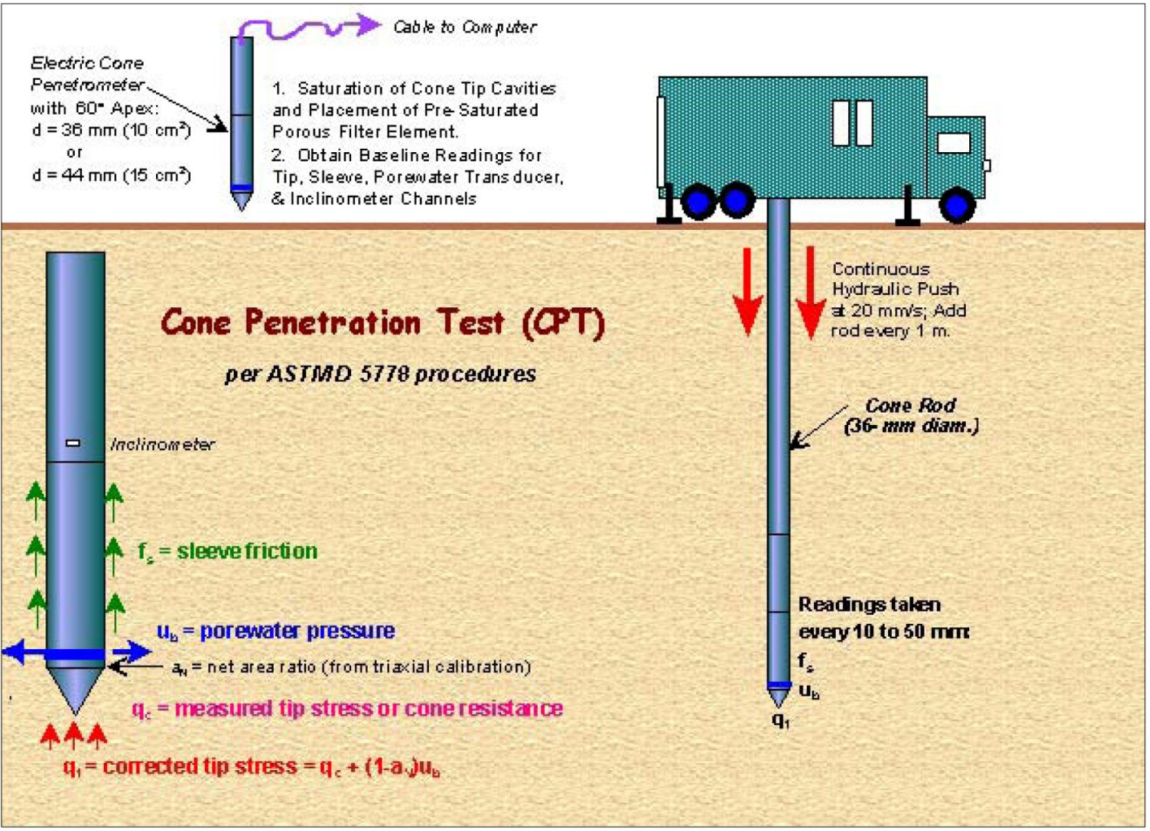


Figure 3-26. Procedures and components of the Cone Penetration Test (FHWA, 2002b).

- Direct reading of soil resistance – both lateral and direct – is possible with 280 mm long cone penetrometer
- Allows considerable data to be obtained in a short time
- Does not allow for sample recovery
- Friction Ratio:

$$R_f = f_c/q_c$$

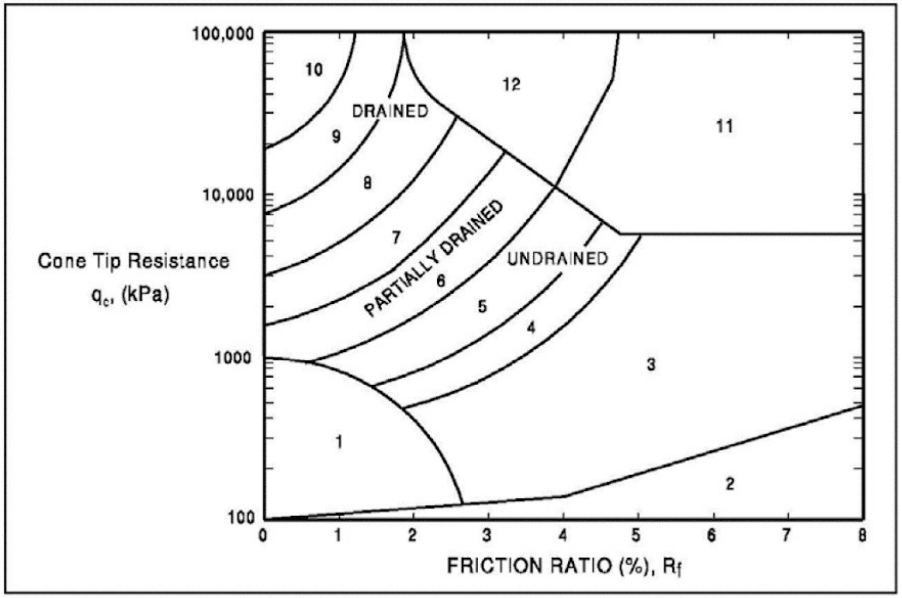
Types of CPT Devices and Correlations

- Types
  - Dutch (Delft) mechanical cone penetrometer
  - Fugro Penetrometer
    - Electrical Cone Penetrometer
    - Piezocone Penetrometer
  - Dynamic cone penetrometer

- Correlations
  - Modulus of elasticity (sands and clays)
  - Undrained Shear Strength (sleeve and cone resistance)
  - SPT
  - Soil Classification (since no sample recovery, should be used with another technique which allows visual inspection of soil samples
  - D_{50}

Soil Classification Using CPT

It is important for the reader to understand that CPT procedures do not allow retrieval of physical samples that can be tested in the laboratory to characterize various phenomena such as consolidation and shear strength. Thus, it is most beneficial to use the CPT with another method, such as the boring technique used in the SPT, that allows the retrieval of physical samples for laboratory testing. Performing the CPT before sampling in borings will permit identification of the specific depths where disturbed and undisturbed physical samples should be obtained for laboratory tests.

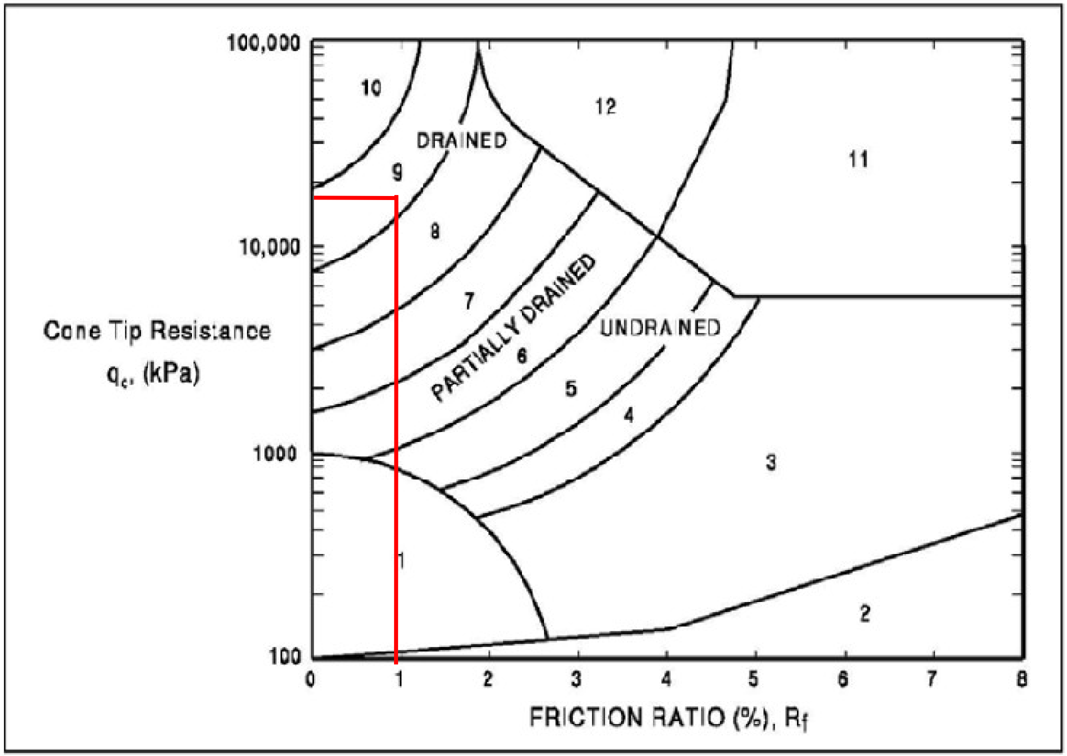


Zone	q_c/N	Soil Behavior Type
1)	2	sensitive fine grained
2)	1	organic material
3)	1	clay
4)	1.5	silty clay to clay
5)	2	clayey silt to silty clay
6)	2.5	sandy silt to clayey silt
7)	3	silty sand to sandy silt
8)	4	sand to silty sand
9)	5	sand
10)	6	gravelly sand to sand
11)	1	very stiff fine grained
12)	2	sand to clayey sand

Figure 3-31. A commonly used simplified soil classification chart for standard electronic friction cone (after Robertson, *et al.*, 1986).

CPT Soil Classification Example

- Given
  - CPT Result
  - q_c = 19.1 MPa
  - R_f = 1 %
- Find
  - Soil classification solely based on CPT Results
- Solution
  - First: 19.1 MPa = 19,100 kPa



Zone	q_c/N	Soil Behavior Type
1)	2	sensitive fine grained
2)	1	organic material
3)	1	clay
4)	1.5	silty clay to clay
5)	2	clayey silt to silty clay
6)	2.5	sandy silt to clayey silt
7)	3	silty sand to sandy silt
8)	4	sand to silty sand
9)	5	sand
10)	6	gravelly sand to sand
11)	1	very stiff fine grained
12)	2	sand to clayey sand

Figure 3-31. A commonly used simplified soil classification chart for standard electronic friction cone (after Robertson, *et al.*, 1986).

Menard Pressuremeter

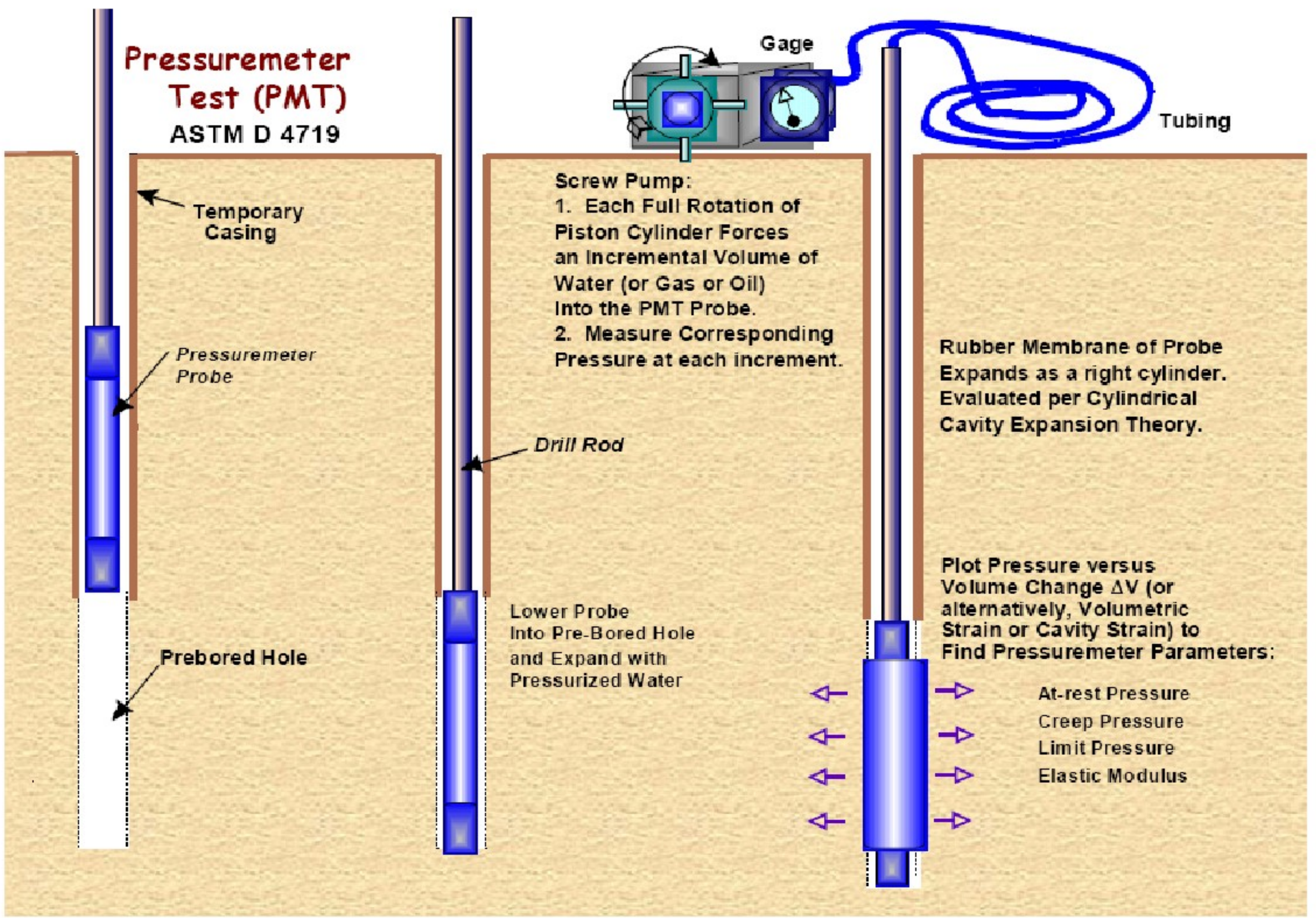


Figure 3-33. Pressuremeter test schematic (FHWA, 2002b).

Marchetti Dilatometer

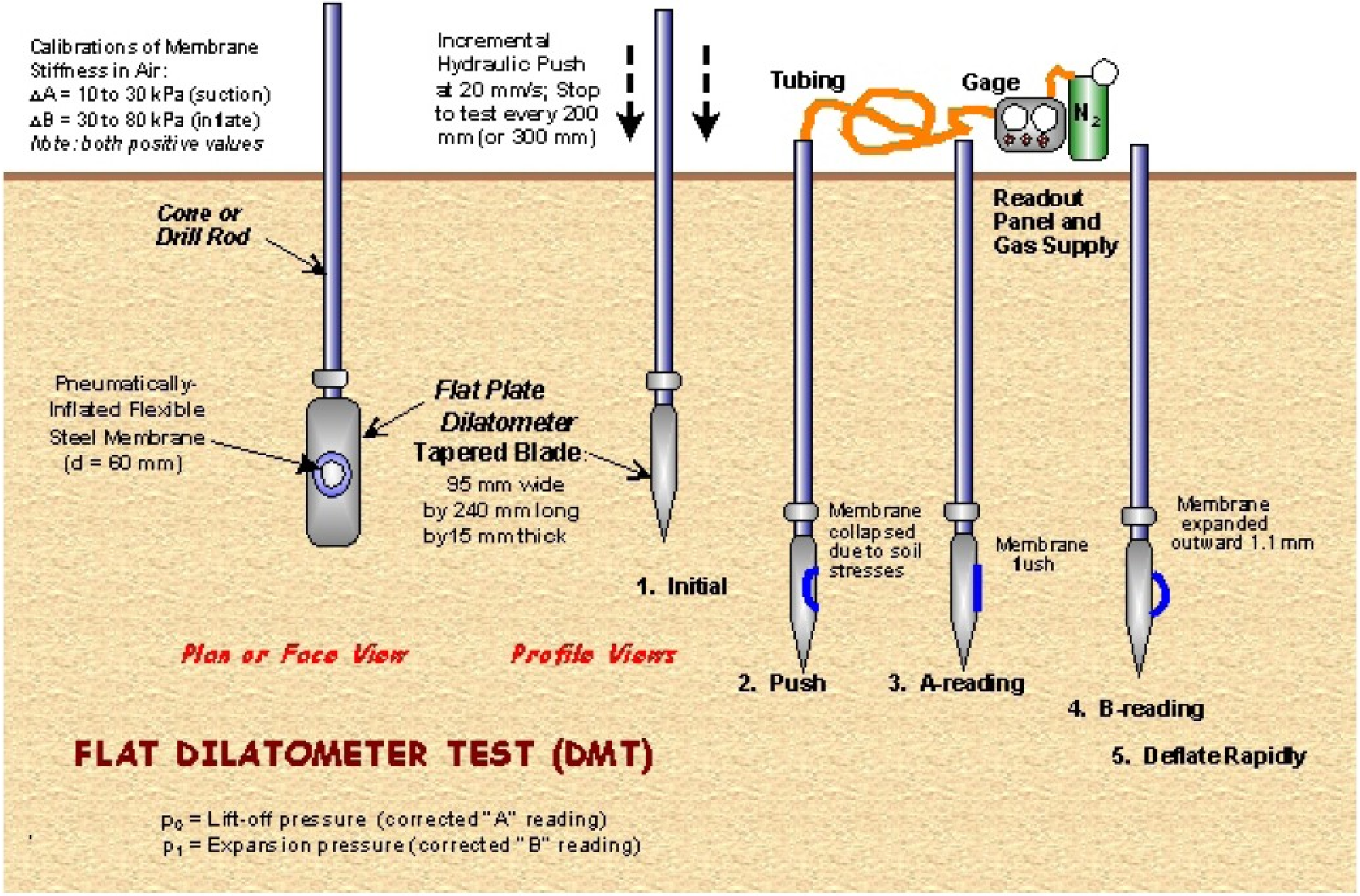


Figure 3-32. Dilatometer test equipment and procedure (FHWA 2002b).

Vane Shear Test

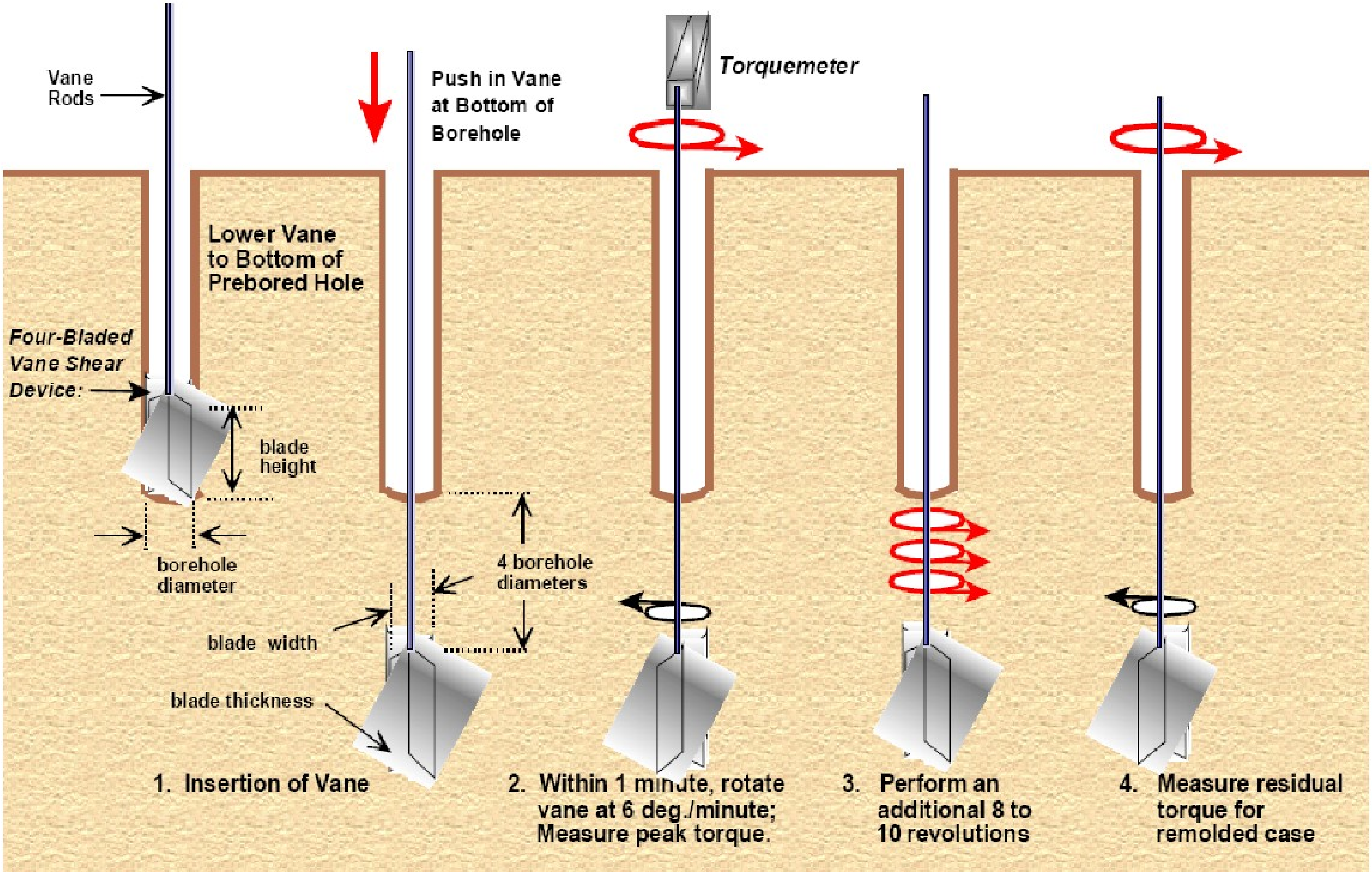


Figure 3-34. Vane shear test equipment and procedure (after FHWA, 2002b).

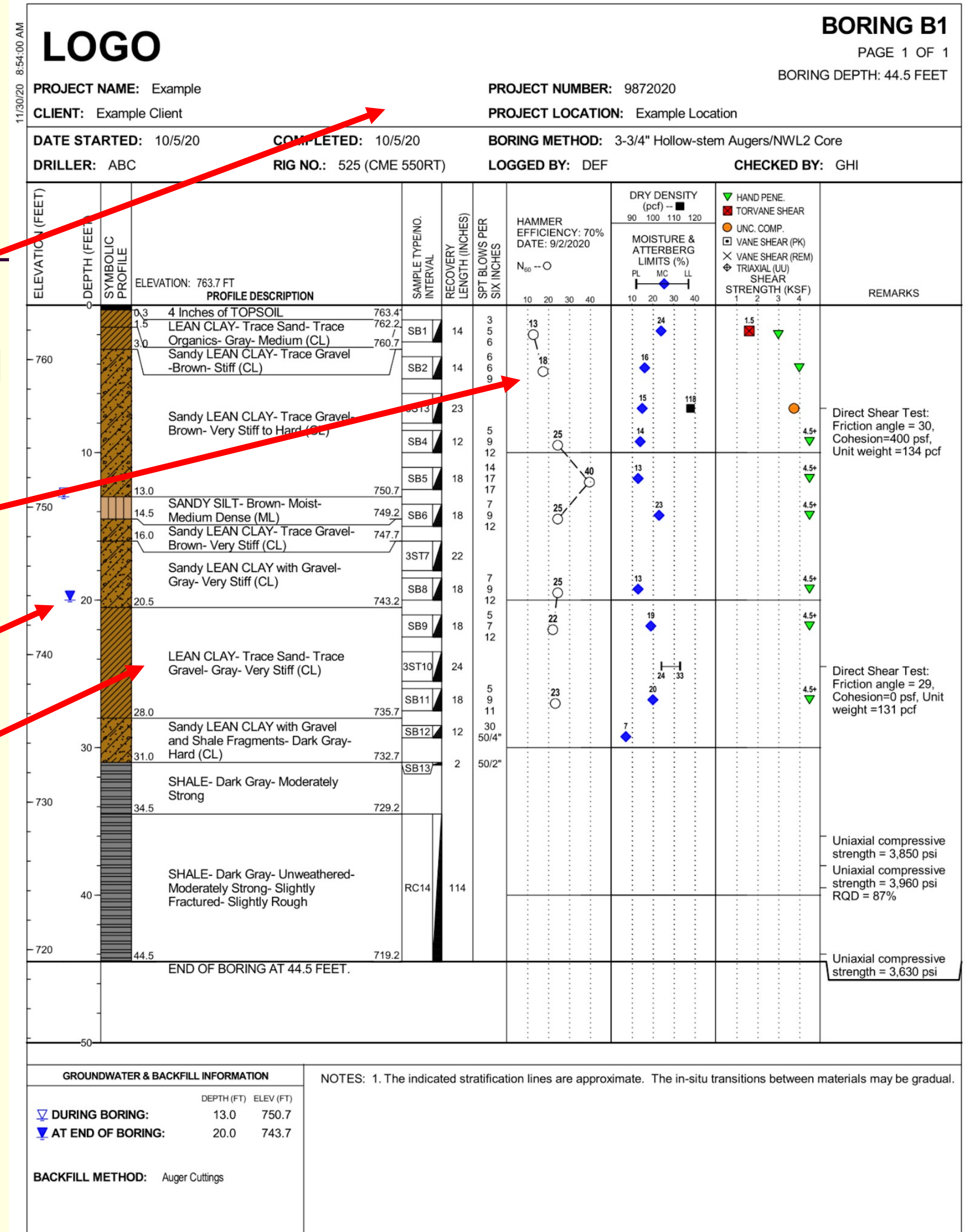
Soil Boring Logs

- Probably the most common – and thus the most important – method of communicating the results of soil borings used
- Lack of adequate soil borings is the most common reason problems arise in construction of foundations
- Gives a profile of the soil and rock types and qualities as a function of depth

- Soil Borings Should Include:
  - Site Location Map
  - Location of Borings w/respect to proposed structure
  - Boring Logs
  - Laboratory Test Results
  - Other Special presentations

Sample Log

- Description of location of boring and site, and sometimes conditions during test
- SPT or other sampling results
- Phreatic Surface (water table)
- Types of soils, usually with classification



REGION 3 | SUBSURFACE EXPLORATION LOG | HOLE BAF-2
COUNTY Orange | LINE Baseline
PROJECT Interstate 0 | STA. 92+00
DATE START 5/4/92 | HAMMER FALL-CASING 18" | OFFSET 50' Lt
DATE FINISH 5/6/92 | HAMMER FALL-SAMPLER 30" | SURF. ELEV. 996.2
CASING O.D. 2½" I.D. 2¼" | WEIGHT OF HAMMER-CASING 300 LBS.
SAMPLER O.D. 2" I.D. 1-3/8" | WEIGHT OF HAMMER-SAMPLER 140 LBS.
RIG TYPE Acker B-40
CORE BARREL Double Tube

	TIME	4:00 pm	8:00 am	
	DATE	5/4/92	5/6/92	
	DEPTH TO WATER	10'	10'	

DEPTH BELOW SURFACE	BLOWS ON CASING	SAMPLE NO.	BLOWS ON SAMPLER 0/0.5	0.5/1.0	1.0/1.5	1.5/2.0	RECOVER (in)	DESCRIPTION OF SOIL AND ROCK	MOIST CONT %
0	6	J1	1	2	2		5		
	19								
	27	J2	1	3	3		10		
	35								
	21	J3	2	5	6		17		
	30	J4	7	9	12		15		
	22								
	25	J5	8	7	15		18	GR. FINE TO COARSE SAND MOIST NON PLASTIC	
	24								
10	28	J6	14	20	20		16		
	27	J7	15	18	19				
	36								
	34	J8	13	16	17		17		
	37								
	39	J8	15	10	3		18	15'	
	31								
	40								
	46								
	46								
20	45								
	41	J10	2	4	4		15		
	42								
	56								
	52								
	58							GR. SILTY CLAY	
	50	J11	2	3	3		14	MOIST - PLASTIC	
	56								
	52								
	49								
30	58								
	52	J12	1	2	3		18		
	56								
	61								
	63								
	65								

THE SUBSURFACE INFORMATION SHOWN HERE WAS OBTAINED FOR STATE DESIGN AND ESTIMATE PURPOSES. IT IS MADE AVAILABLE TO AUTHORIZED USERS ONLY THAT THEY MAY HAVE ACCESS TO THE SAME INFORMATION AVAILABLE TO THE STATE. IT IS PRESENTED IN GOOD FAITH, BUT IS NOT INTENDED AS A SUBSTITUTE FOR INVESTIGATION, INTERPRETATION OR JUDGMENT OF SUCH AUTHORIZED USERS.

CONTRACTOR ACME Drilling, Inc. SM ________

DRILL RIG OPERATOR Klinedinst
SOIL & ROCK DESCRIP. Chassie
REGIONAL SOILS ENGR. Cheney
SHEET 1 OF 2
STRUCTURE NAME/NO. Apple Freeway #2

HOLE BAF-2

Figure 3-25a. Example subsurface exploration log (0 – 35 ft depth).

REGION 3 | SUBSURFACE EXPLORATION LOG | HOLE BAF-2
COUNTY Orange | LINE Baseline
PROJECT Interstate 0 | STA. 92+00
DATE START 5/4/92 | HAMMER FALL-CASING 18" | OFFSET 50' Lt
DATE FINISH 5/6/92 | HAMMER FALL-SAMPLER 30" | SURF. ELEV. 996.2
CASING O.D. 2½" I.D. 2¼" | WEIGHT OF HAMMER-CASING 300 LBS.
SAMPLER O.D. 2" I.D. 1-3/8" | WEIGHT OF HAMMER-SAMPLER 140 LBS.
RIG TYPE Acker B-40
CORE BARREL Double Tube

	TIME	4:00 pm	8:00 am	
	DATE	5/4/92	5/6/92	
	DEPTH TO WATER	10'	10'	

DEPTH BELOW SURFACE	BLOWS ON CASING	SAMPLE NO.	BLOWS ON SAMPLER 0/0.5	0.5/1.0	1.0/1.5	1.5/2.0	RECOVER (in)	DESCRIPTION OF SOIL AND ROCK	MOIST CONT %
	62	J13	1	2	4		16	GR. SILTY CLAY	
	63							MOIST - PLASTIC	
	72								
	71							39'	
40	89								
	75		30	20	35				
	81								
	104								
	120							GR SANDY GRAVEL	
	140							MOIST - NON PLASTIC	
	110							(Cored Boulder 42.5' to 45' recovered 12"-7 pieces: used boulder buster)	
	136								
	166								
	191								
50	482							TOP OF ROCK 50'	
								HARD UNWEATHERED BASALT	
								Run 1 50 - 55'	
								RQD = 80%	
								55'	
								HARD UNWEATHERED BASALT	
								Run 2 55 - 60'	
								RQD = 75%	
60								60'	
								END OF BORING 60'	
70									

THE SUBSURFACE INFORMATION SHOWN HERE WAS OBTAINED FOR STATE DESIGN AND ESTIMATE PURPOSES. IT IS MADE AVAILABLE TO AUTHORIZED USERS ONLY THAT THEY MAY HAVE ACCESS TO THE SAME INFORMATION AVAILABLE TO THE STATE. IT IS PRESENTED IN GOOD FAITH, BUT IS NOT INTENDED AS A SUBSTITUTE FOR INVESTIGATION, INTERPRETATION OR JUDGMENT OF SUCH AUTHORIZED USERS.

CONTRACTOR ACME Drilling, Inc. SM ________

DRILL RIG OPERATOR Klinedinst
SOIL & ROCK DESCRIP. Chassie
REGIONAL SOILS ENGR. Cheney
SHEET 2 OF 2
STRUCTURE NAME/NO. Apple Freeway #2

HOLE BAF-2

Figure 3-25b. Example subsurface exploration log (35 - 60 ft depth).

CPT Boring Results

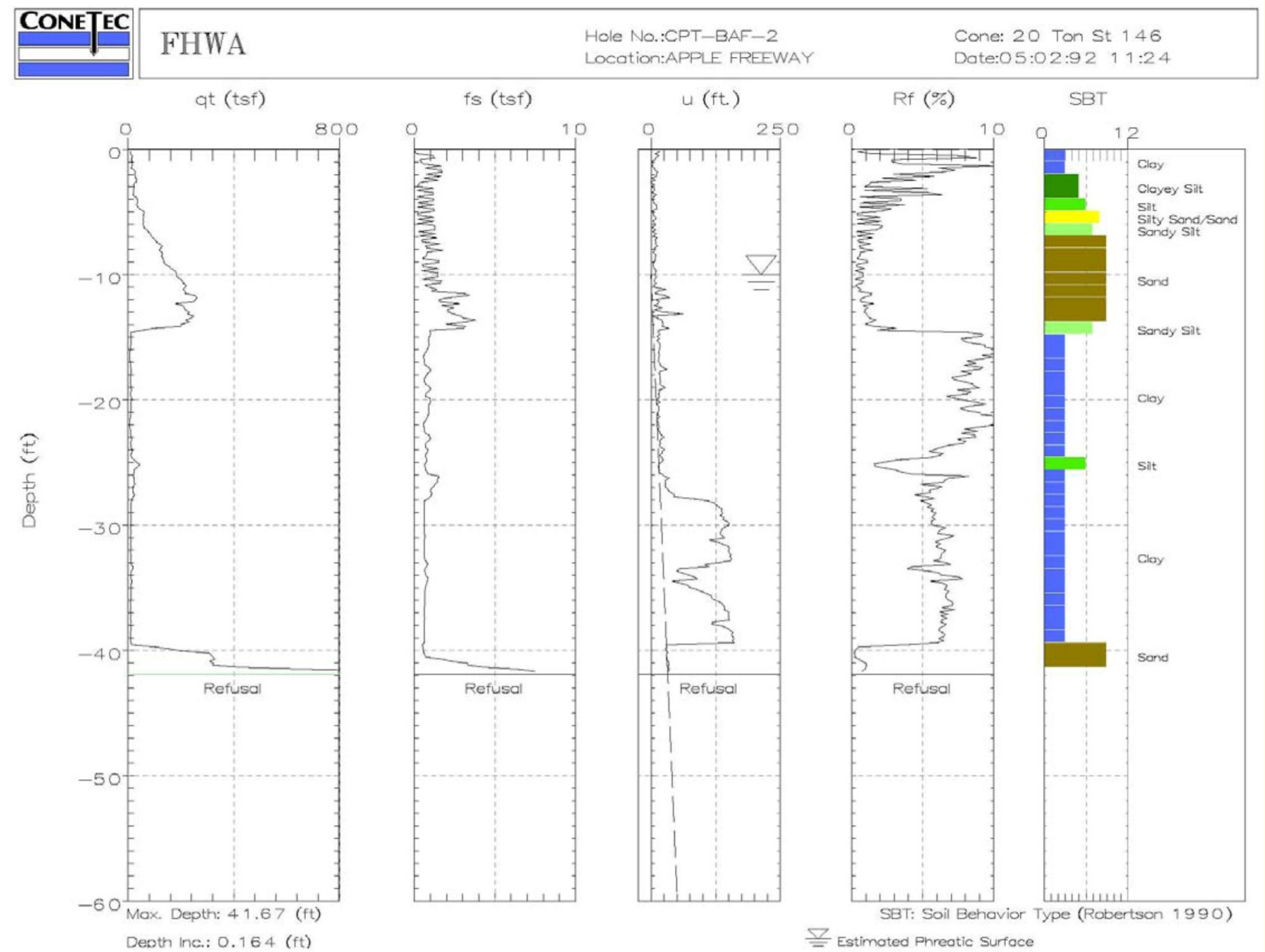


Figure 3-30. Piezo-cone results for Apple Freeway Bridge.

Boring Location Plan and Interpreted Subsurface Profile

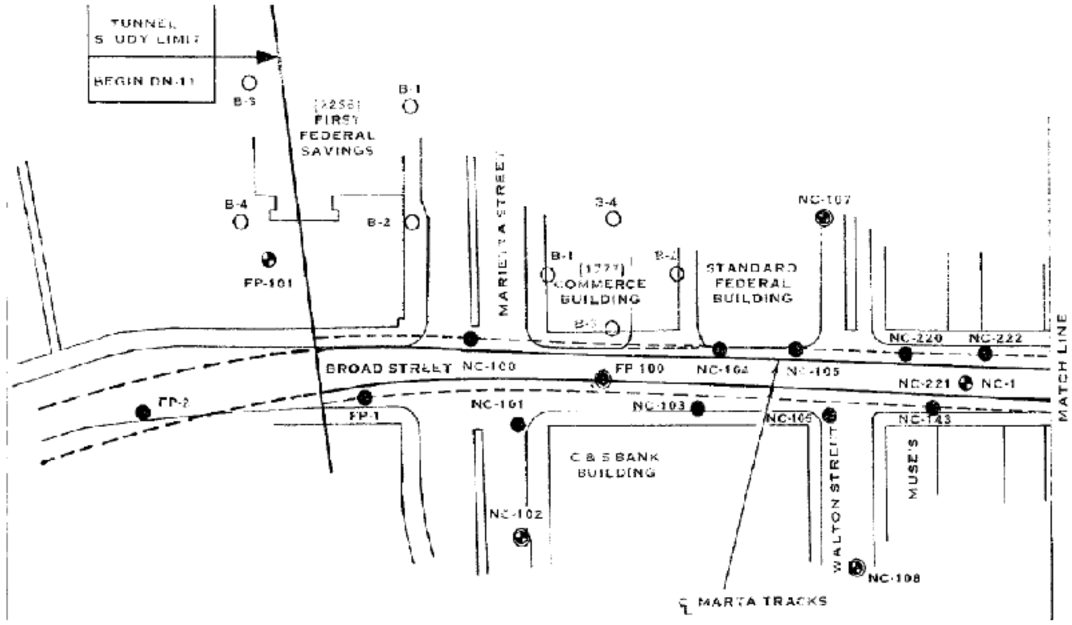


Figure 45. Boring location plan

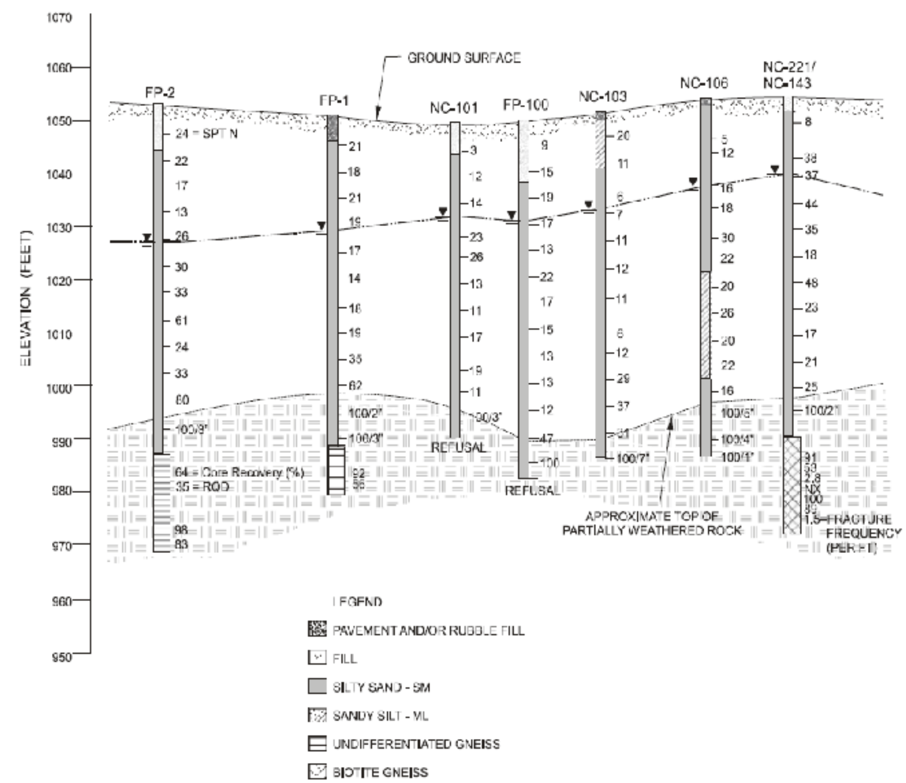
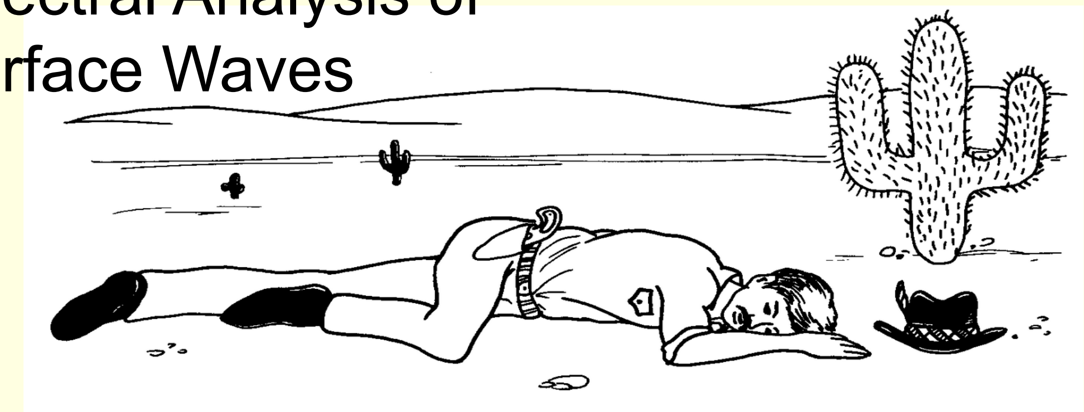


Figure 46. Interpreted subsurface profile.

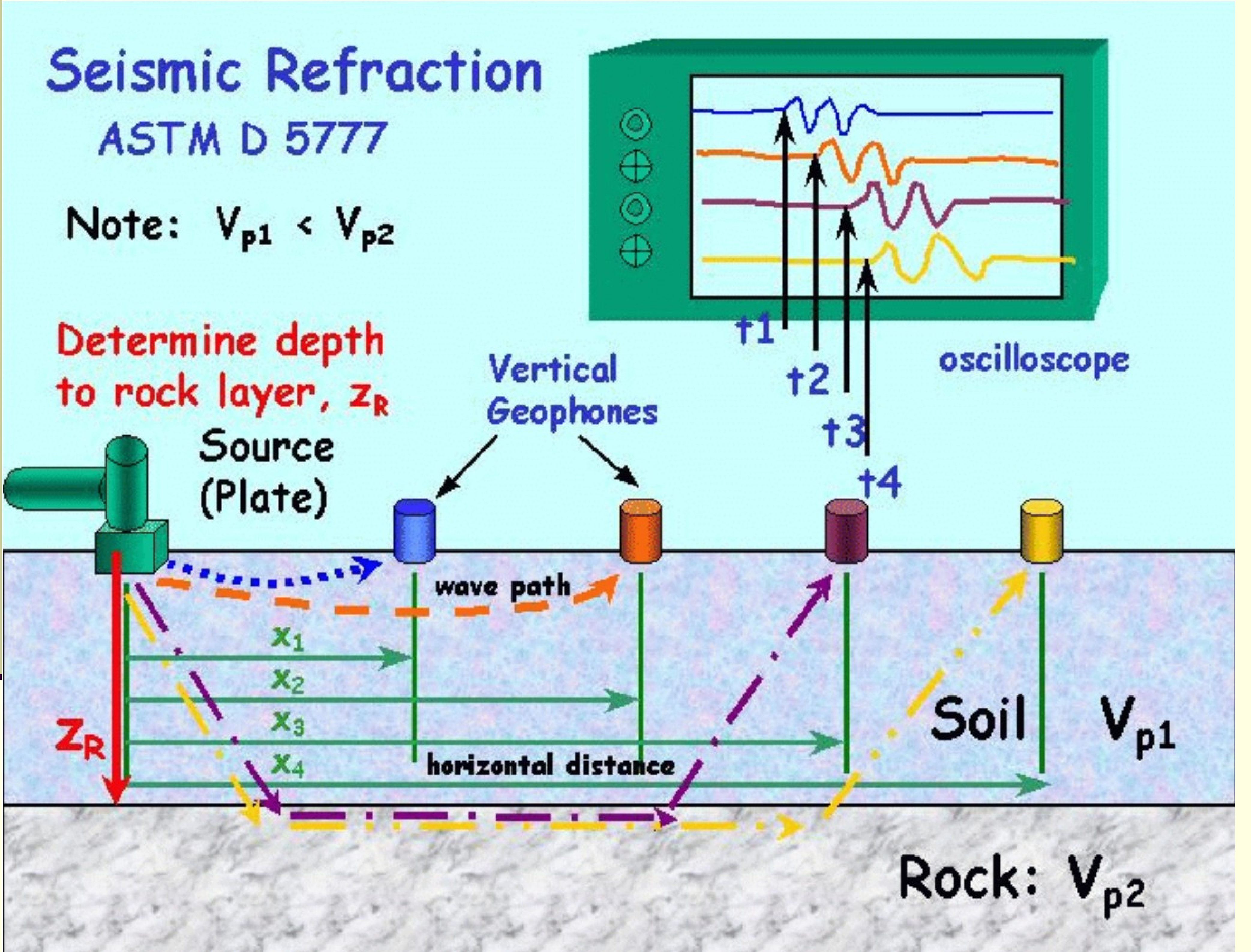
Geophysical Methods

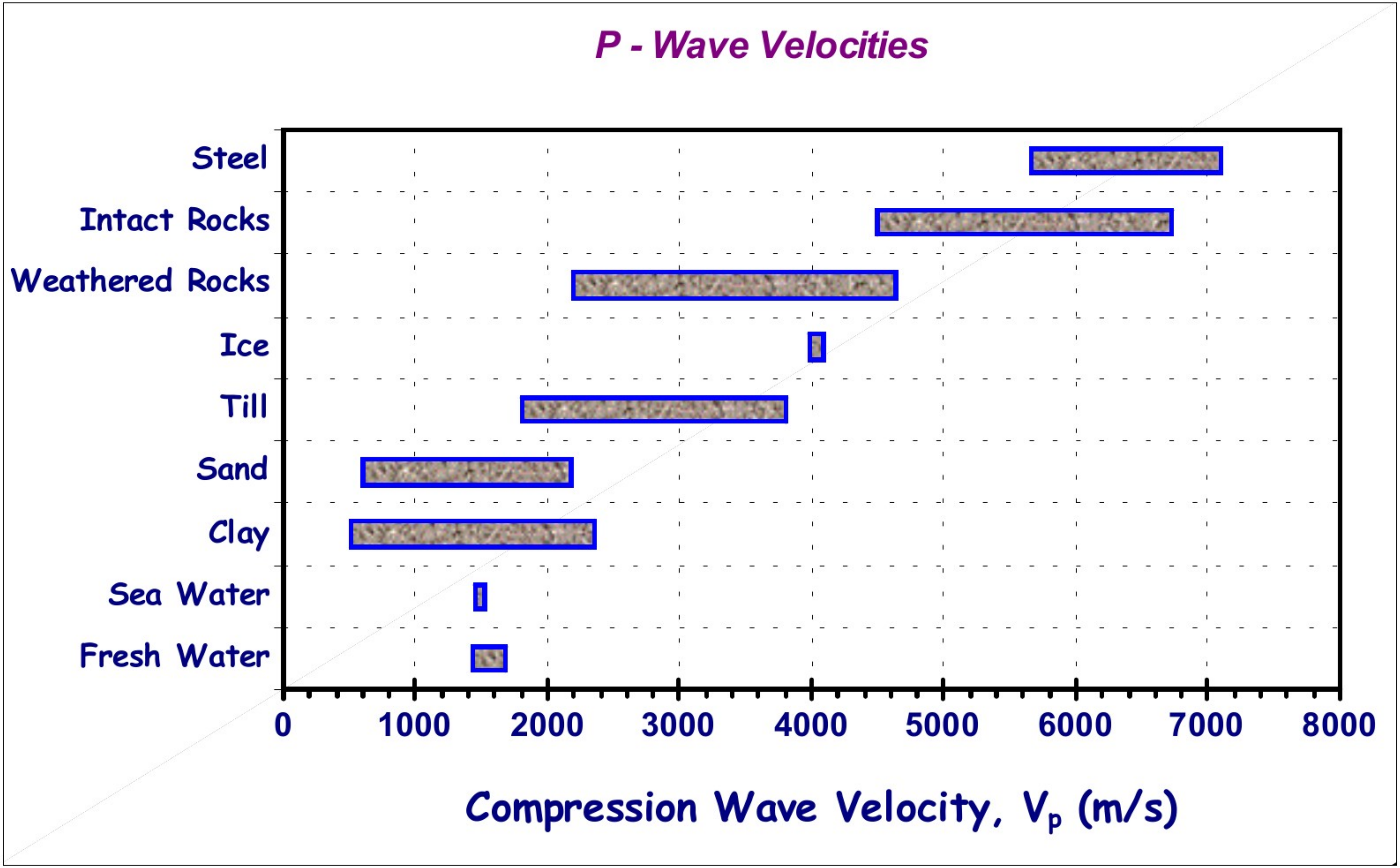
- Based on methods used for geologic research, especially in the oil and gas industry
- Acoustic Methods
  - Seismic Refraction
  - Crosshole Tests
  - Downhole Tests
  - Spectral Analysis of Surface Waves
- Electromagnetic Wave Methods
  - Electric Resistivity
  - Ground Penetrating Radar
  - Magnetic or Electromagnetic Surveys



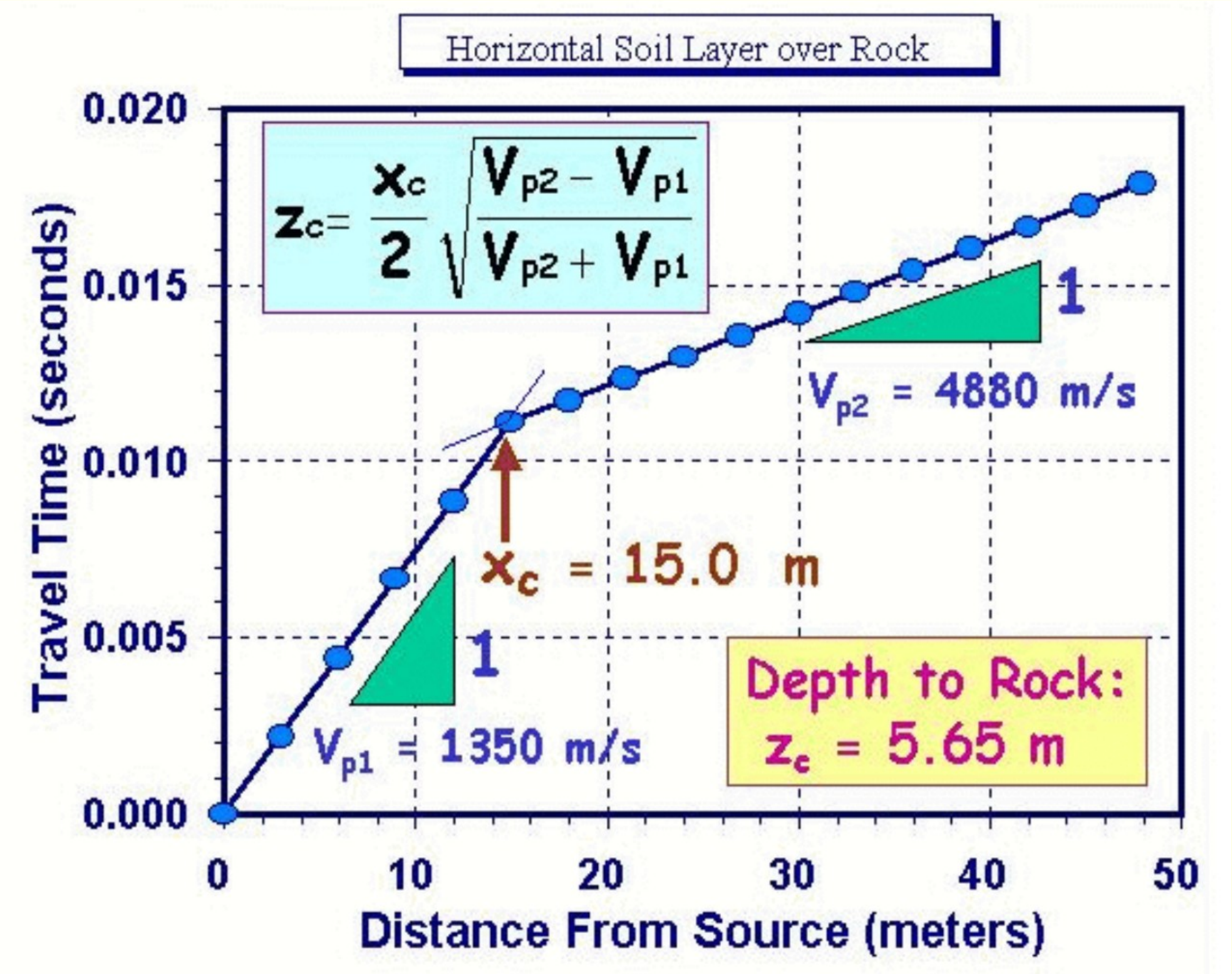
Seismic Refraction

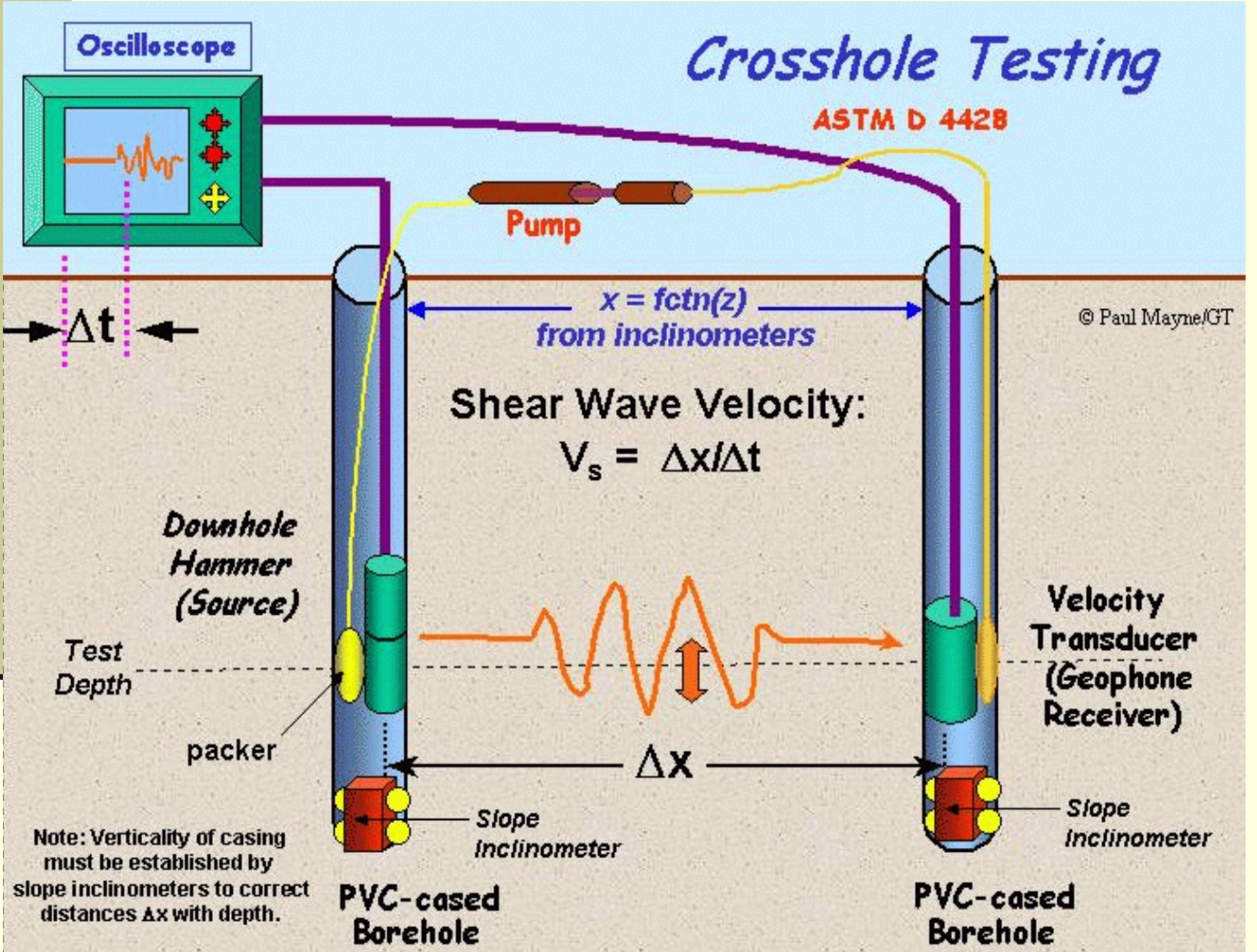
- Shock is made at one point, usually using a special hammer
- Sound waves (specifically “p” compression waves) travelling through the soil are picked up at various distances from the hammer blow point by geophones
- Analysing the reflections can indicate the depth and nature of the soil layers
- Should not be used where a hard layer overlays a softer layer; will indicate two layers being one
- Should not be used in an area covered with asphalt or concrete
- Should not be used when a frozen layer is at the surface

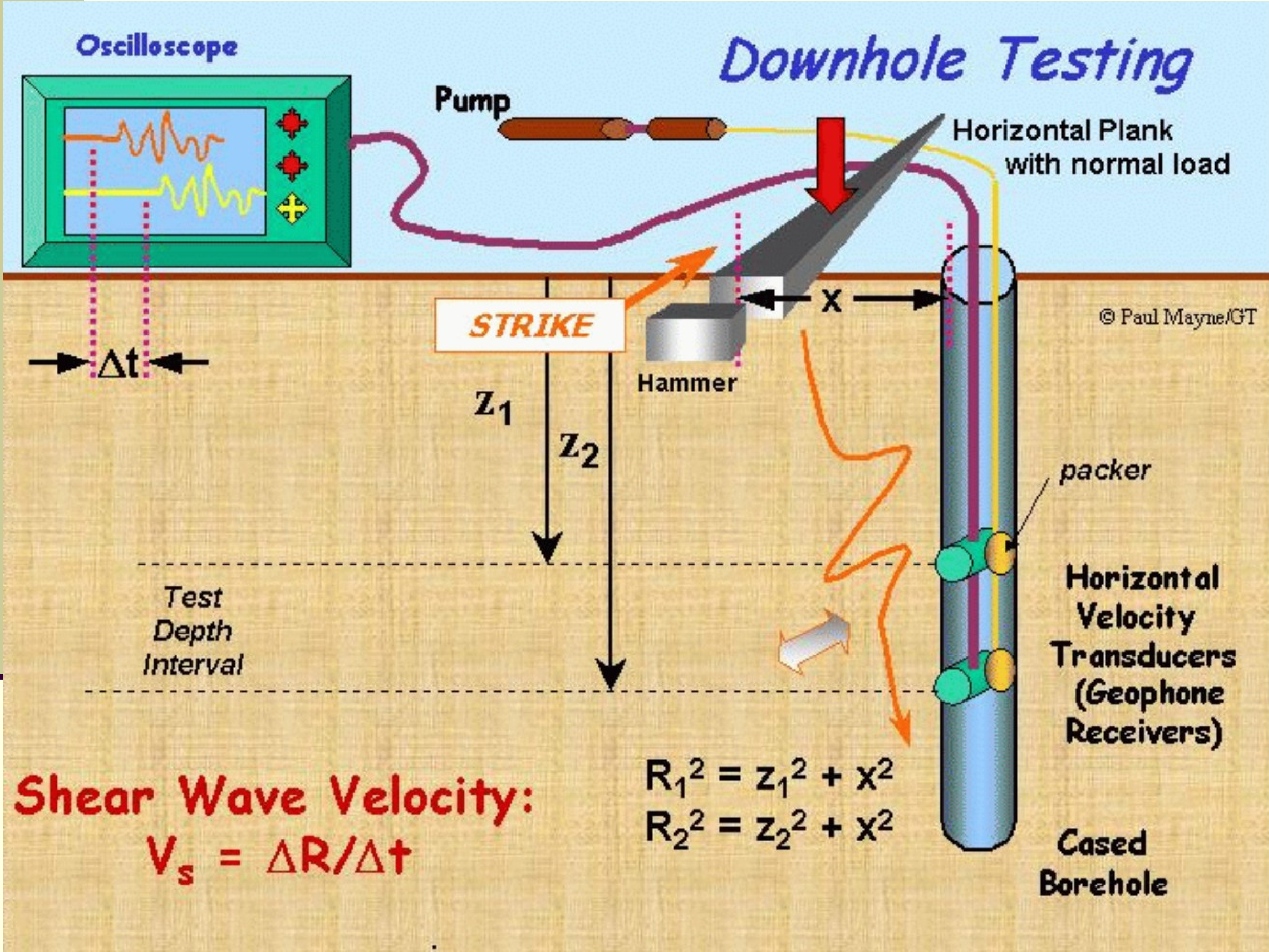

Seismic Refraction
ASTM D 5777
Note: V_p1 < V_p2
Determine depth to rock layer, z_R
Source (Plate)
Vertical Geophones
oscilloscope
t1
t2
t3
t4
wave path
x1
x2
x3
x4
horizontal distance
z_R
Soil V_p1
Rock: V_p2


P - Wave Velocities
Steel
Intact Rocks
Weathered Rocks
Ice
Till
Sand
Clay
Sea Water
Fresh Water
0
1000
2000
3000
4000
5000
6000
7000
8000
Compression Wave Velocity, V_p (m/s)

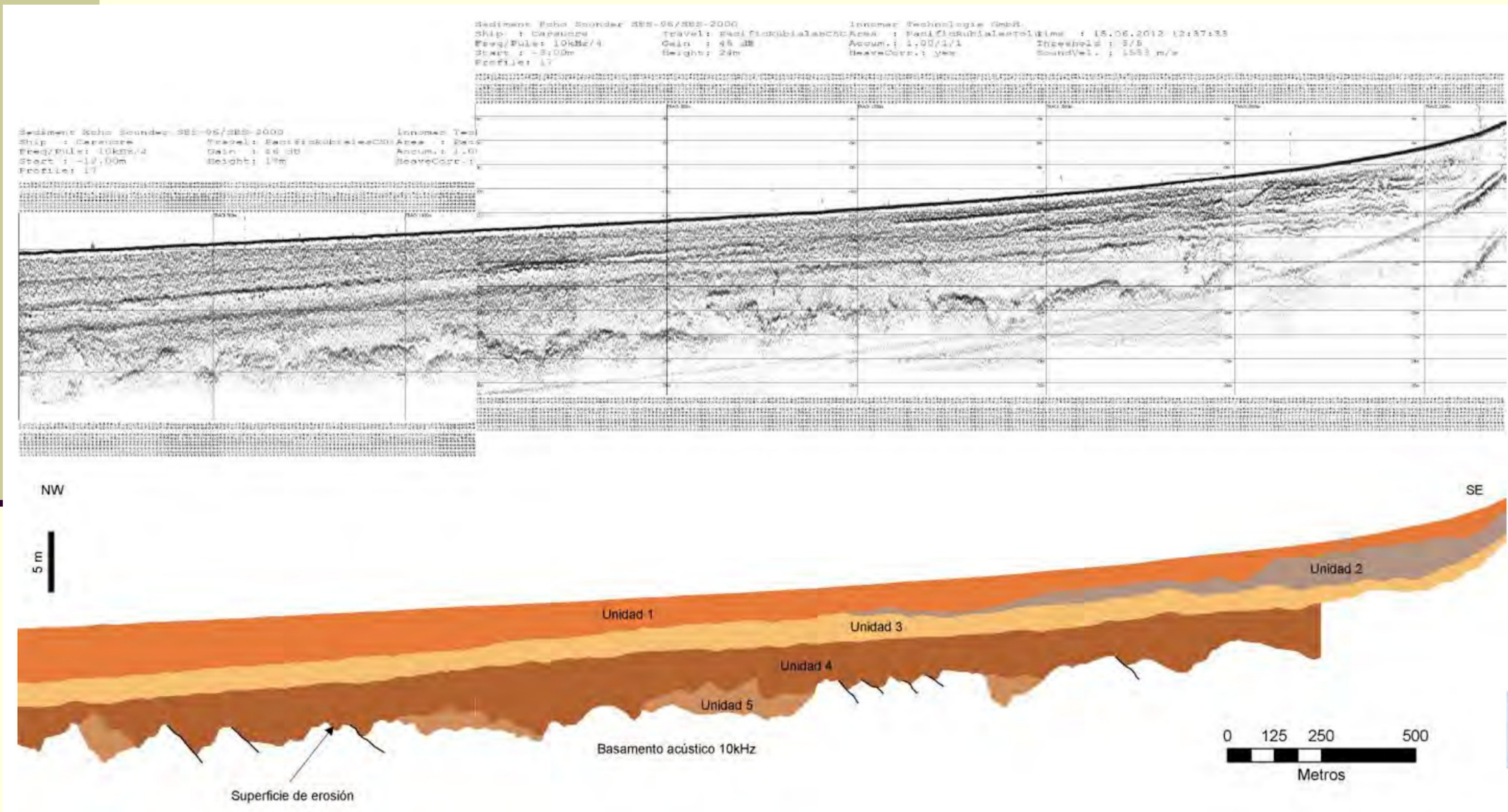
Seismic Refraction Example (Single Layer)




Oscilloscope
Crosshole Testing
ASTM D 4428
Pump
Δt
x = fctn(z)
from inclinometers
© Paul Mayne/GT
Shear Wave Velocity:
$V_s = \Delta x/\Delta t$
Downhole Hammer (Source)
Test Depth
packer
Velocity Transducer (Geophone Receiver)
Δx
Slope Inclinometer
Slope Inclinometer
Note: Verticality of casing must be established by slope inclinometers to correct distances Δx with depth.
PVC-cased Borehole
PVC-cased Borehole

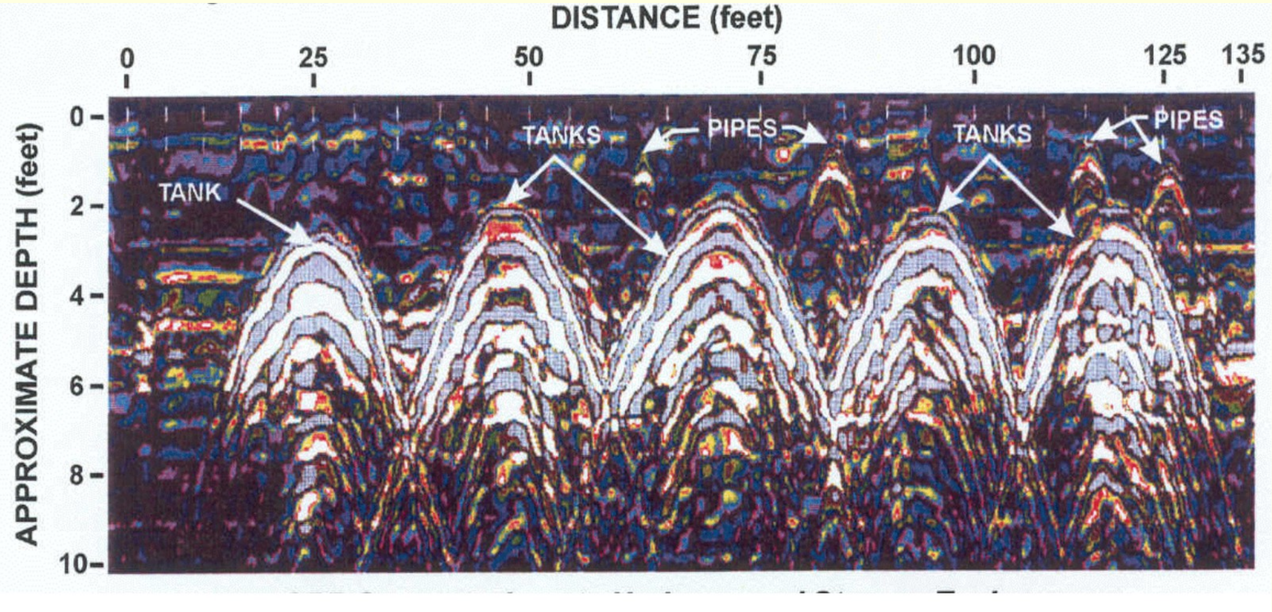

Oscilloscope
Downhole Testing
Pump
Horizontal Plank
with normal load
STRIKE
X
© Paul Mayne/GT
Δt
Hammer
z_1
z_2
packer
Test
Depth
Interval
Horizontal
Velocity
Transducers
(Geophone
Receivers)
$R_1^2 = z_1^2 + x^2$
$R_2^2 = z_2^2 + x^2$
Cased
Borehole
Shear Wave Velocity:
$V_s = \Delta R/\Delta t$

Example of Spectral Analysis of Surface Waves



Ground Penetrating Radar

- Radio waves are transmitted into the earth and their reflection is recorded
- Especially useful in finding rock and other hard formations or objects such as pipes, tanks, etc.
- Limited to a depth of 10 m or less in electrically conductive soils (wet, fine grained soil deposits)

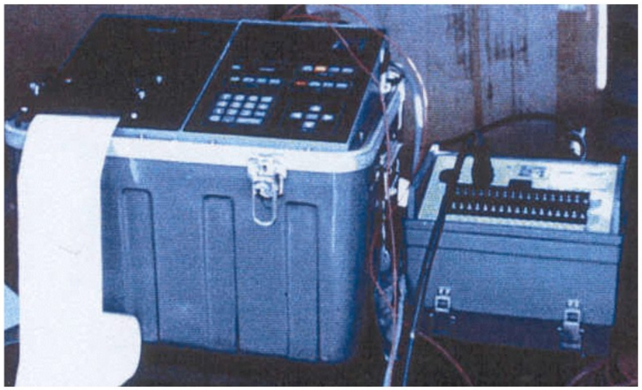


Electric Resistivity

- Uses the variations in resistivity of different materials
- Electrical currents are induced into the ground through electrodes
- Soil or rock resistivity can be determined by measuring the potential difference between known horizontal distances

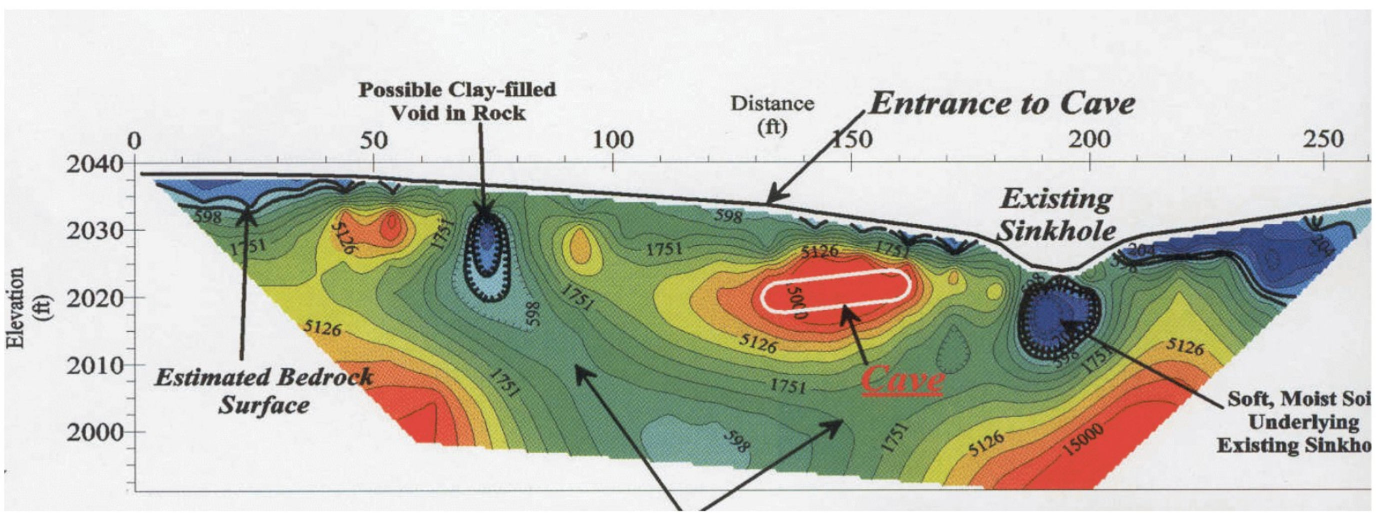
- Methods of conducting the test
  - Electrical Profiling: electrodes are spaced over an area and lines are run across the area. Practical for prospecting for sand and gravel deposits or ore deposits
  - Electrical Sounding: central location for the electrodes is selected and series of reading is taken by increasing the electrode spacing from the centre. Can provide information on variation of subsurface conditions and depth of water table

Electrical Resistivity



(a)

(b)



(c)

Figure 5-35. Electrical Resistivity Equipment and Results: (a) Oyo System; (b) Advanced Geosciences Inc.; (c) Two-Dimensional Cross-Section Resistivity Profile for Detection of Sinkholes and Caves in Limestone (from Schnabel Engineering Associates).

Selecting a Geophysical Method

Table 1-22 Selection of Geophysical Method (after ASTM D6429)

Application or Method	Seismic		Electrical	Electromagnetic				
	Refraction or Reflection	MASW	DC Resistivity	Freq. Domain	Time Domain	Very Low Frequencies	Ground Penetrating Radar	Gravity
Depth to rock	A	A	B	B	B	B	A	B
Voids and sinkholes	B	A	B	B	B		A	A

Notes: “A” means preferred method and “B” alternate method based on the 2020 version of the standard.

From UFC 3-220-10

Questions?