

SOIL MECHANICS II
CIVL 311
COURSE NOTES
2012

PART 2
FOUNDATIONS & EARTH RETAINING
STRUCTURES



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*Analytical, Numerical and Observational Methods for
Foundation Design*

*The Geotechnical Model - Site Characterization for Site
Stratigraphy and Engineering Parameters*

*Uncertainties in Foundation Design, Introduction to Limit
States and Working Stress Design*



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Module 6

Site Characterization and Introduction to Geotechnical Design

Background Reading

- Analytical, Numerical and Observational Methods for Foundation Design (Book 2 pp. 73-79, 83-86, 89-90, 93-96)

The Story So Far - 1

- Identification and classification of soils
- Flow of water through soils
- Total and effective stresses
- Engineering mechanics of soil elements
 - Stresses and strains
 - Shear strength
 - total and effective stress approaches
 - Deformation
 - 1-D compression – amount and rate of settlement

The Story So Far - 2

- Applications
 - Compaction
 - Consolidation settlement
 - Analysis of shear failure
 - Slope stability
 - Bearing capacity
 - Active and passive pressures
- **DESIGN**

Geotechnical Engineering

- Deals with analysis and design of foundations, slopes and structures made from soils and rocks
- Basic theories of mechanics (equilibrium and compatibility) and of material behaviour (stiffness and strength) apply.
- Soil properties not known very well - **engineering judgment important**

Design Process

- Iterative process requiring integration of:
 - The needs of the client
 - Analyses
 - Experience and judgment
 - Economics
 - Constructability
 - Safety
 - Environmental concerns

Components of Design

- Set required performance
- Attempt to develop a complete solution
- Evaluate whether proposed solution will fully meet requirements
- Revise and refine design to optimize the solution, e.g. minimum cost

The Geotechnical Evaluation

- Conceptual Design
 - Establish design criteria (Design Basis Memorandum)
- Preliminary Design
 - one or more promising concepts are subjected to more rigorous analysis and evaluation in order to define and validate the design that best meets the requirements.
- Detailed Design

Geotechnical evaluation and selection of foundation

- Establish as fully as possible the nature of the soils stratigraphy at the site
 - Variability with depth
 - Variability laterally
 - Groundwater regime
- Establish loads to be supported and their distribution
- Make preliminary estimates of foundation type, size and location e.g. bearing stratum?

Foundation Selection (continued)

- Establish performance requirements
- Carry out calculations for bearing capacity and settlement
- Check resistance is greater than demand
- Check serviceability criteria
- If foundation O.K., refine design
- If not, look at alternatives

**Ground
Profile**

geology, hydrogeology
in situ tests, geophysics
drilling, sampling

***Empiricism
Experience***

**Soil
Behaviour**

testing, field
measurements
physical models

**Applied
Mechanics**

idealization,
numerical modeling
analysis

J.B. Burland 1987

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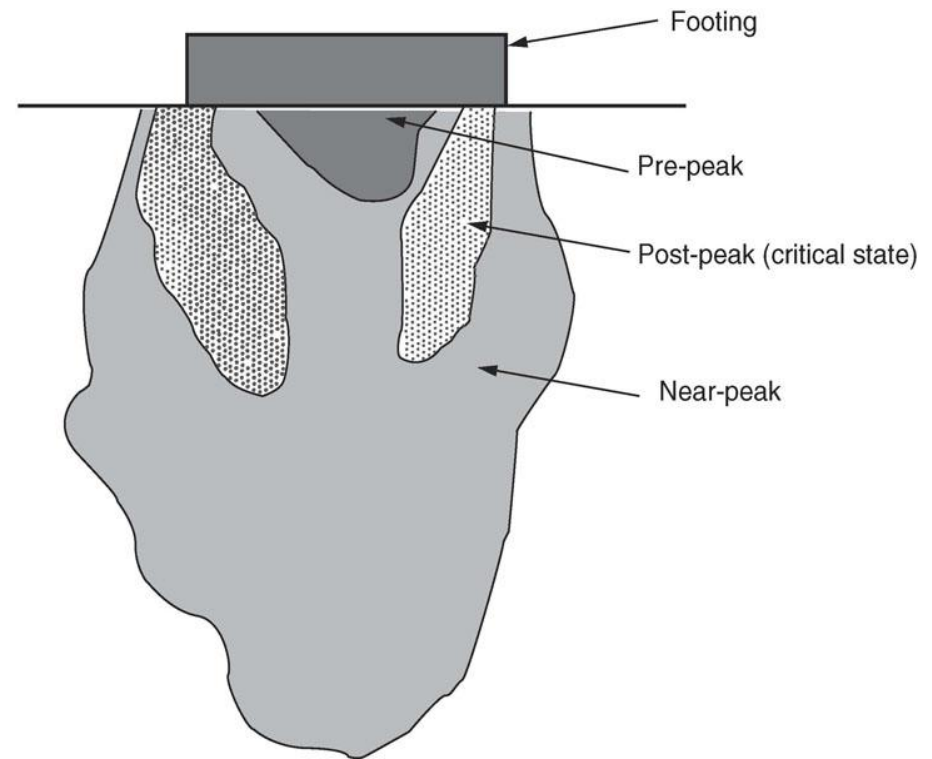
*Analytical, Numerical and Observational Methods for
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Element behaviour to foundation element behaviour

- Soil strength and stiffness varies with stress level
- Soil elements below foundation are at different points on the stress - strain curve
- Some soil elements may have failed while others are in the small strain zone – no mechanism has formed.
- Attempt to model
 - Closed-form solutions
 - Limit analysis
 - Limit equilibrium
 - Numerical analysis



Muni Budhu “Foundations and Earth Retaining Structures”, John Wiley & Sons, NY, 2007

Stress Strain Response

Load \leftrightarrow Deformation Response

Actual material – Complex Response

Ideal Materials



Idealized

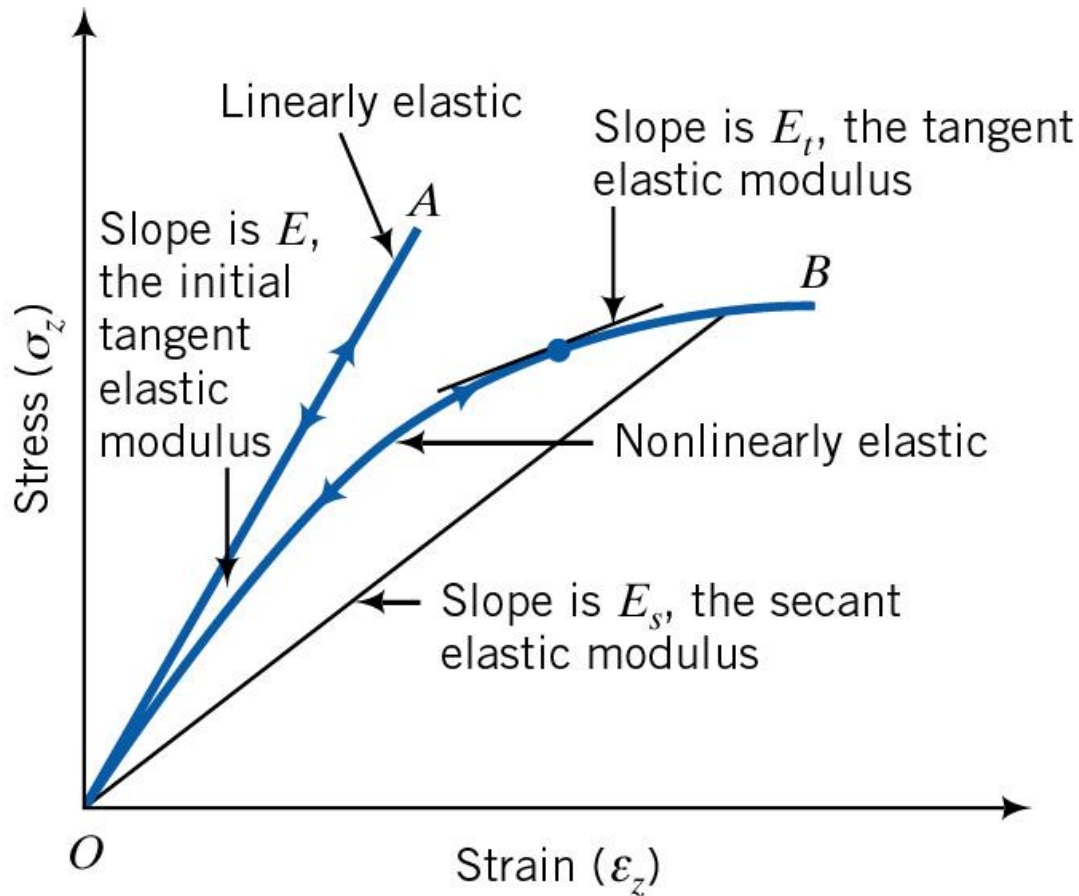
Stress-strain responses

Which idealized response would best represent the actual response?

Answer to this question is not straightforward for soils.

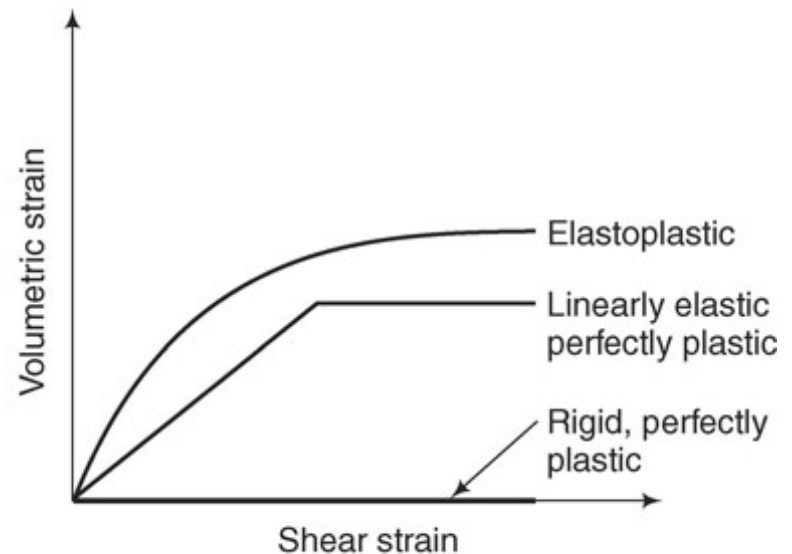
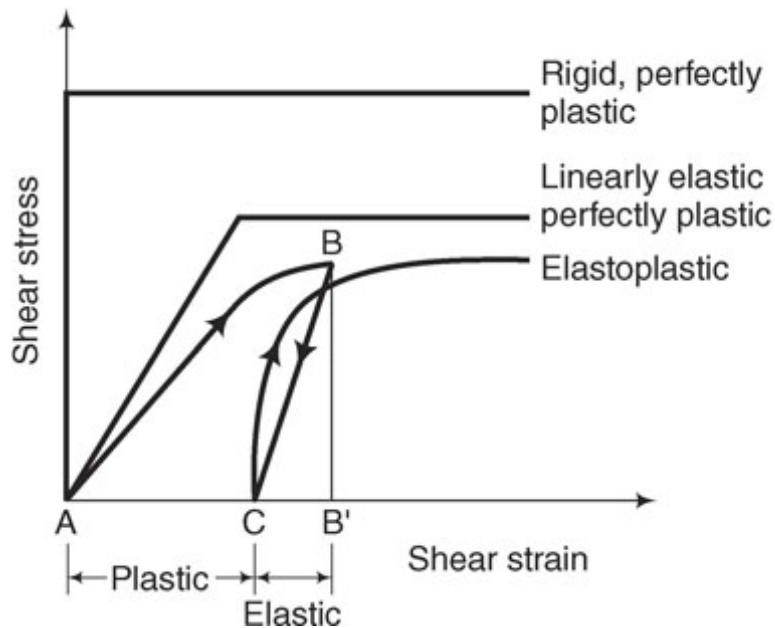
HOW DO WE IDEALIZE SOIL?

ELASTIC MATERIAL



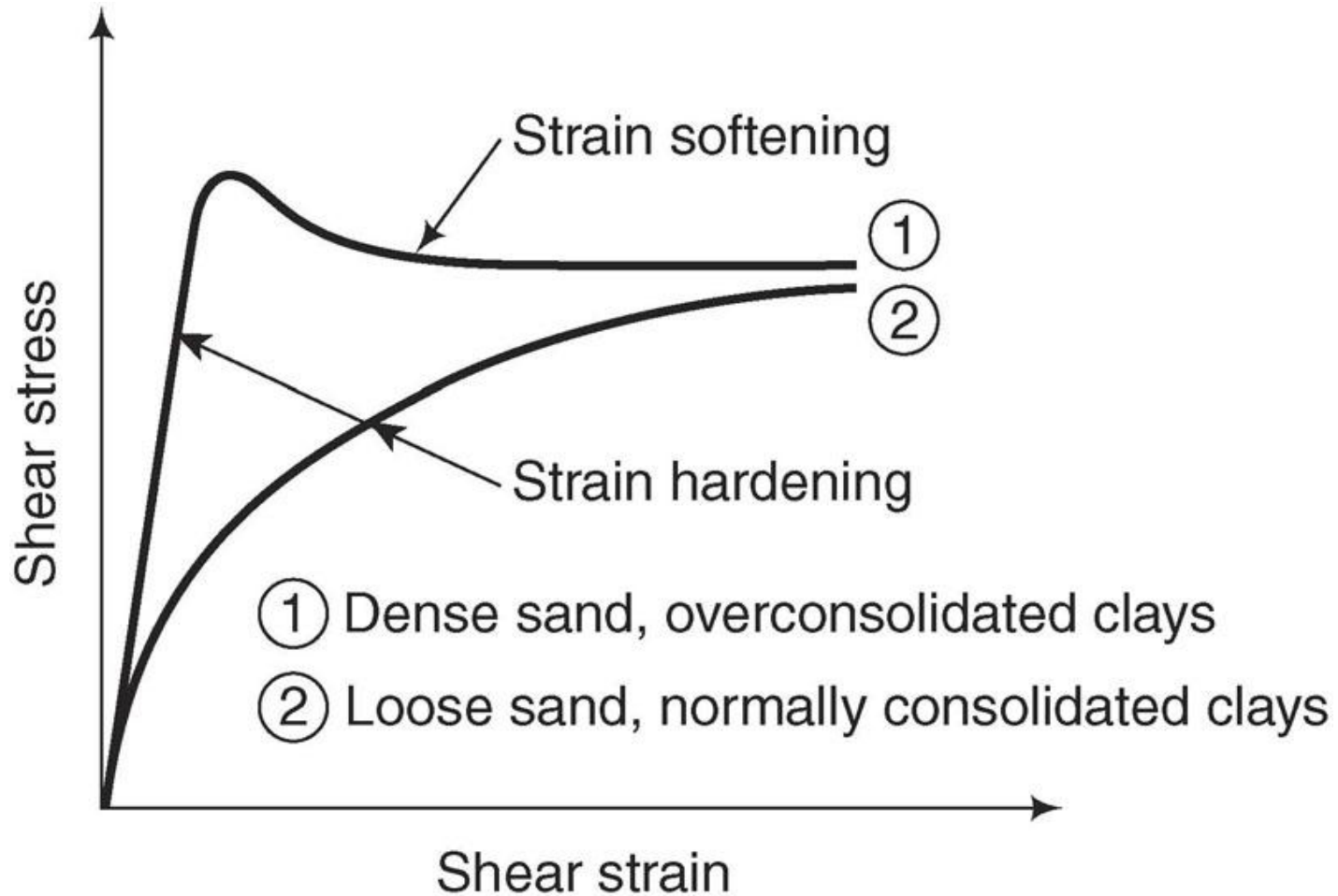
STRESS STRAIN RESPONSE OF IDEAL MATERIALS

Plastic and elastoplastic materials

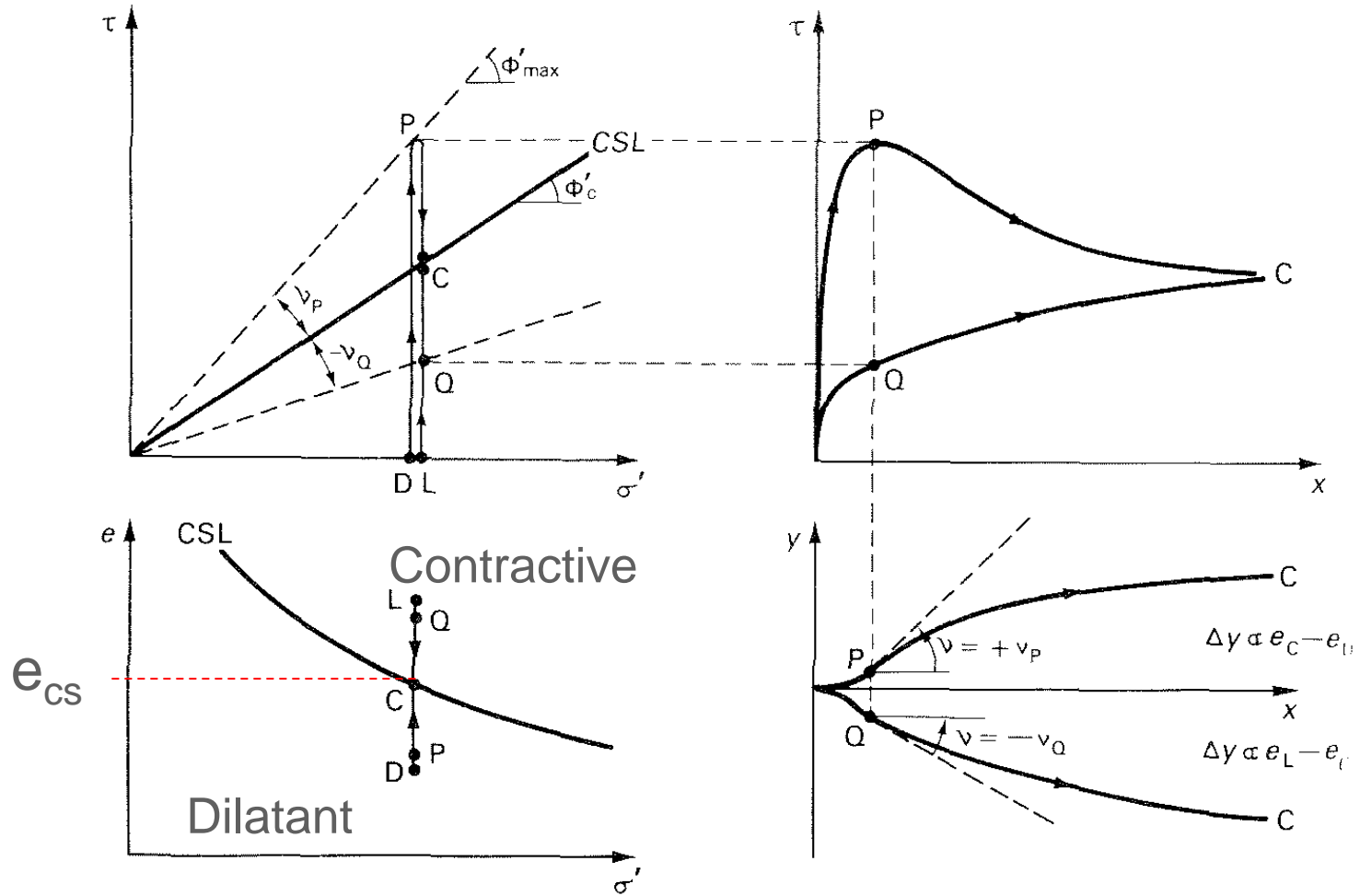


Muni Budhu "Foundations and Earth Retaining Structures", John Wiley & Sons, NY, 2007

STRAIN HARDENING- STRAIN SOFTENING



Stress-strain curves in sand

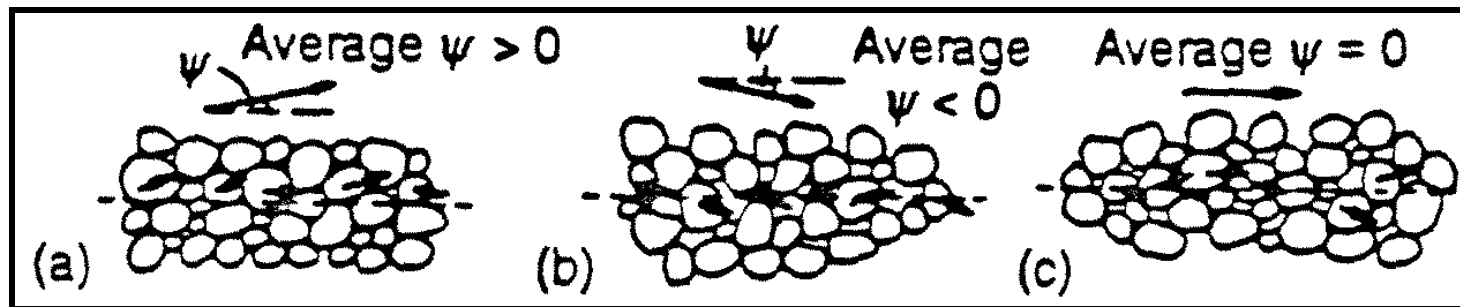


Stress-deformation curves for loose and dense soil samples slowly sheared at the same constant normal stress (Bolton 1979).

Dilation and Contraction during shear:



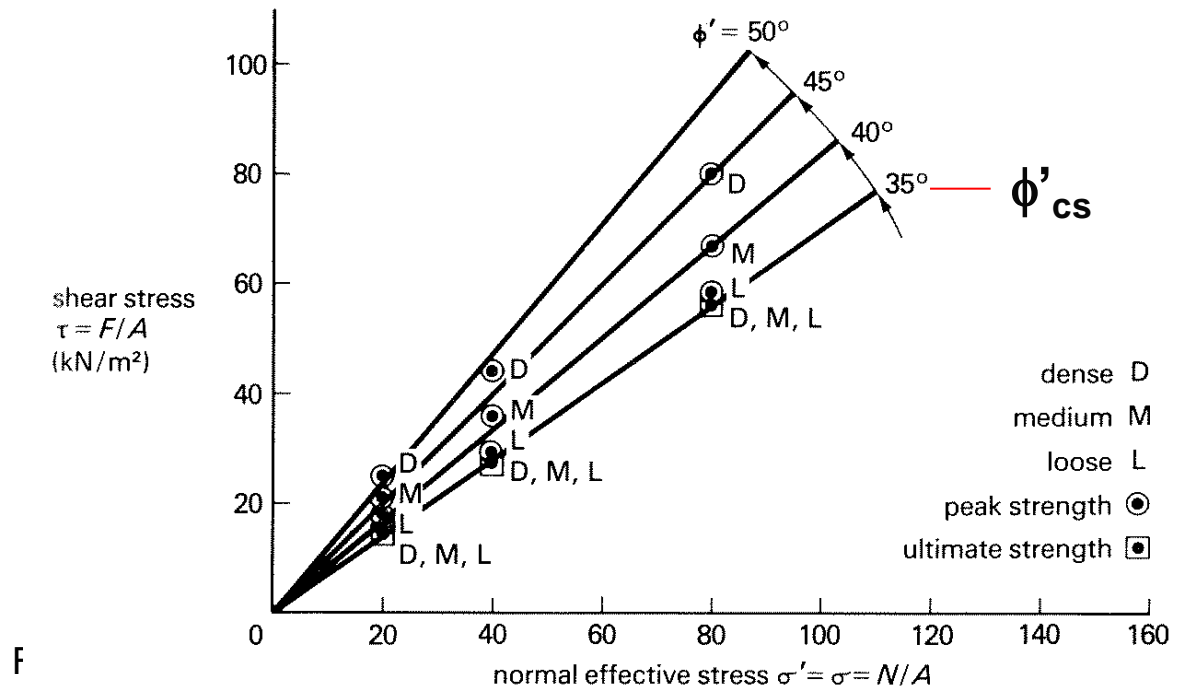
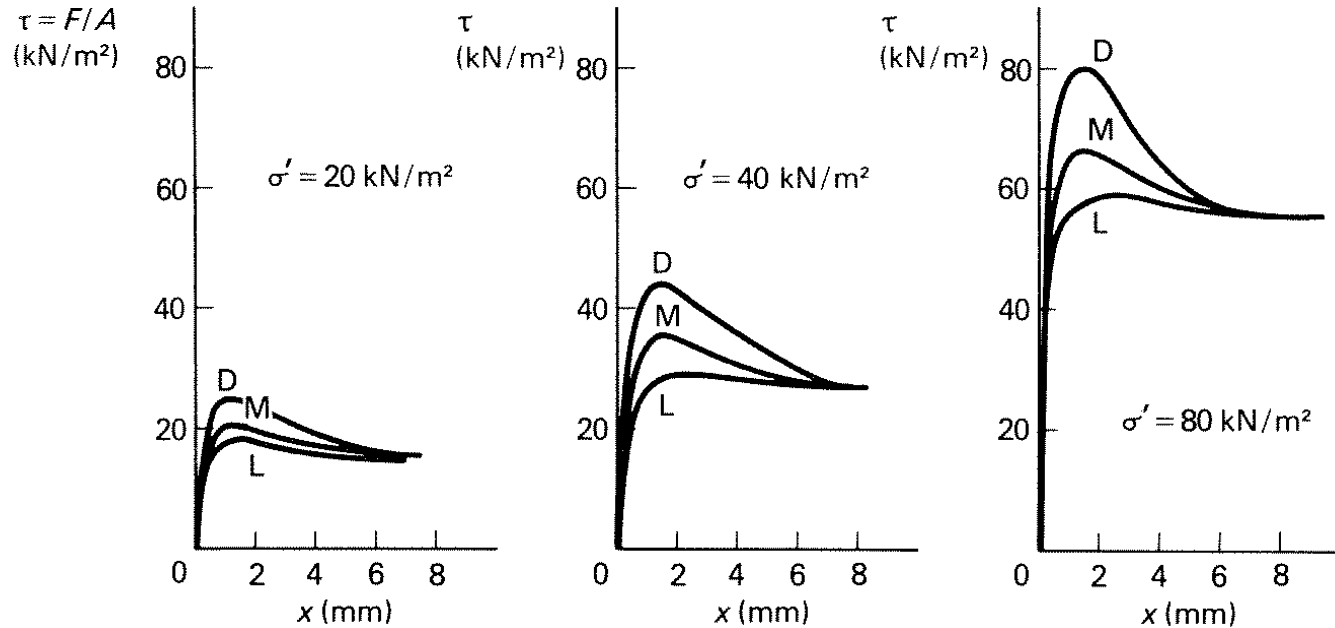
Conceptual model for (a) compression and (b) dilation during shear.



Visualization of rearrangement of soil particles during shear. (Bolton, 1991.)

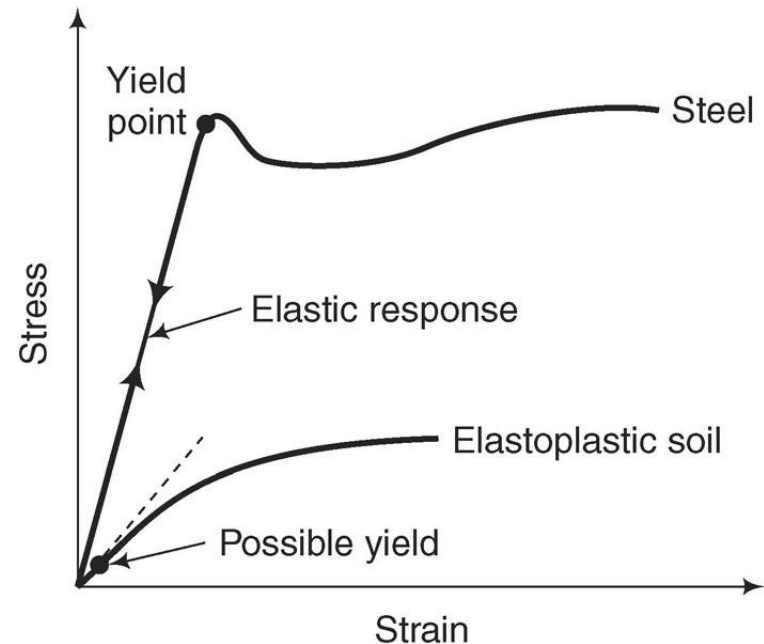
Drained shear tests results in sand

Typical averaged drained shear test results for a sand (Bolton 1979).

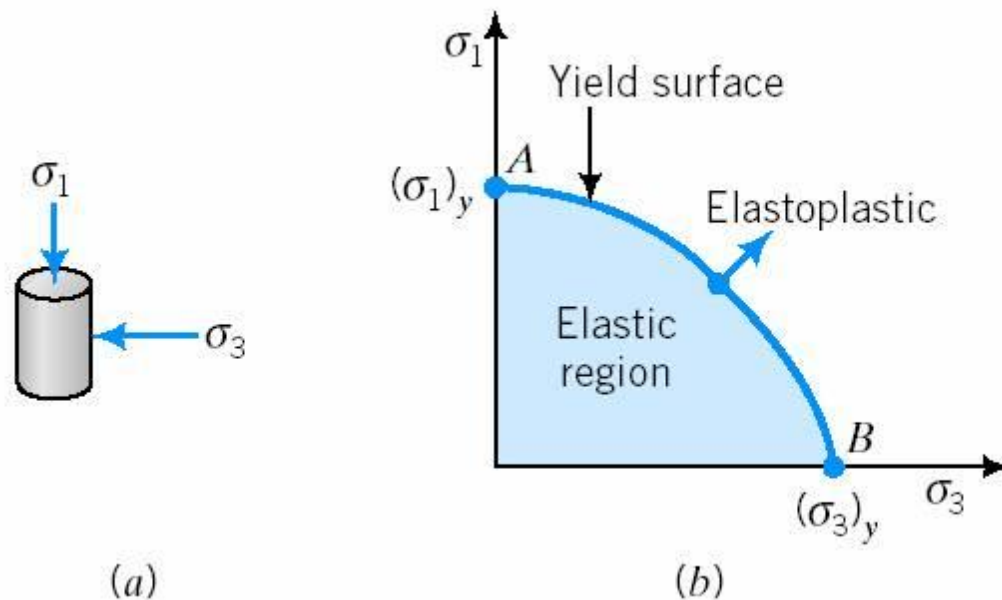


YIELDING OF SOILS - 1

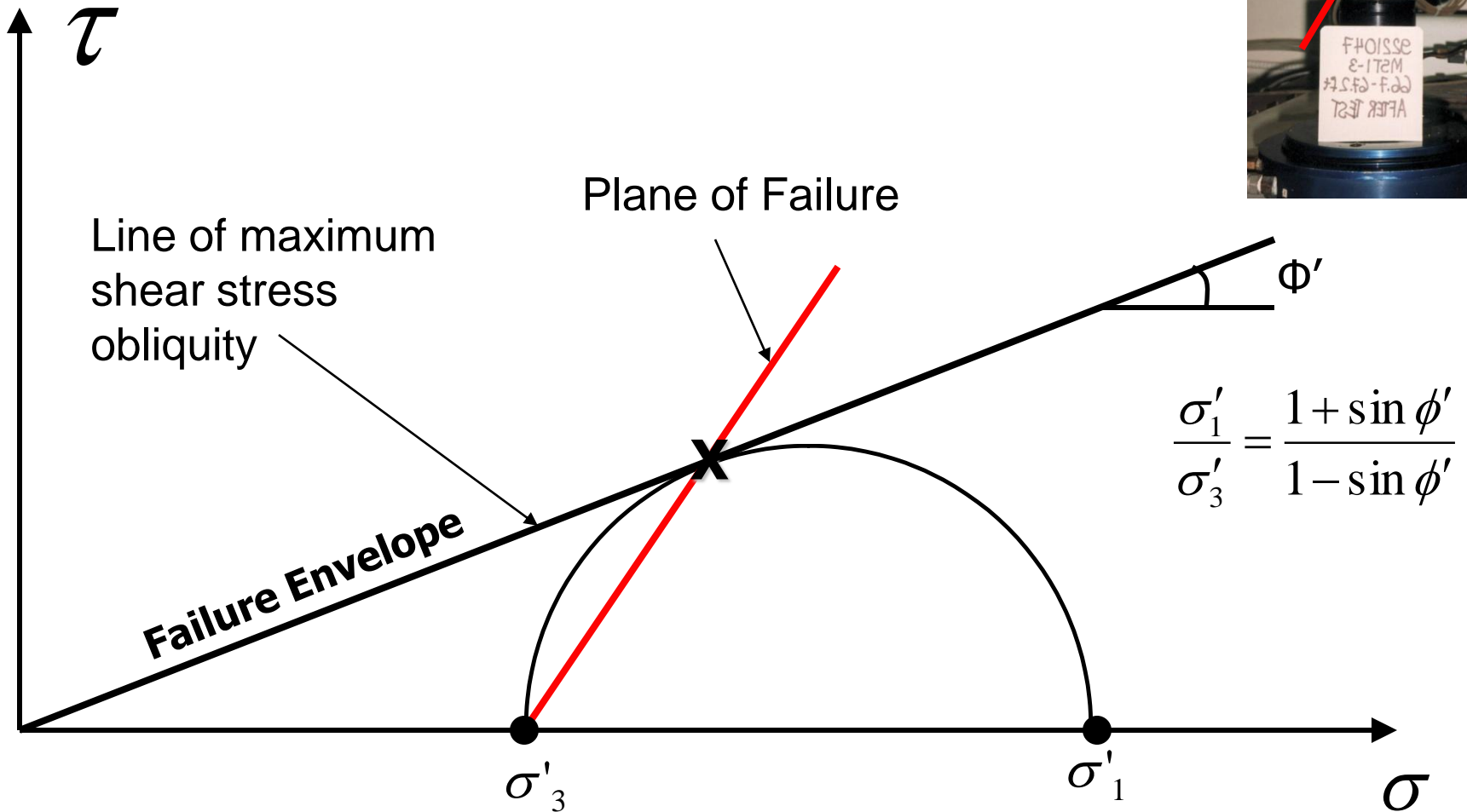
- Yielding occurs when elastic limit has been exceeded
- Yielding for soils occurs at very small strains – i.e., strains $< 0.001\%$
- Yield criterion: Set of rules that defines the combination of stresses that causes material to yield
- Tresca and Huber - von Mises Criteria developed for metals are also used in defining yielding for soils.



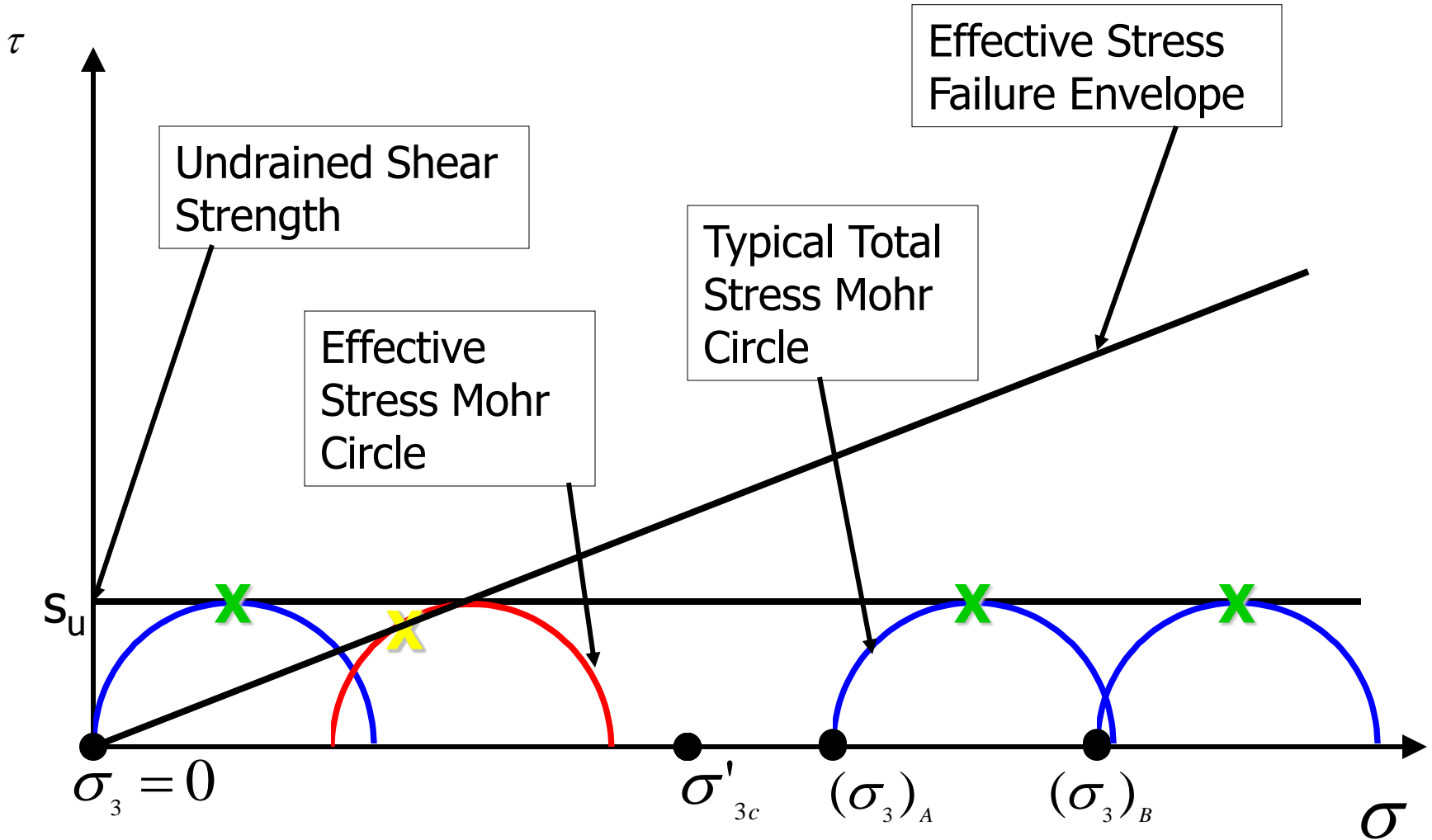
YIELDING OF SOILS - 2



Failure Criteria – Mohr-Coulomb



Failure Criteria – Tresca

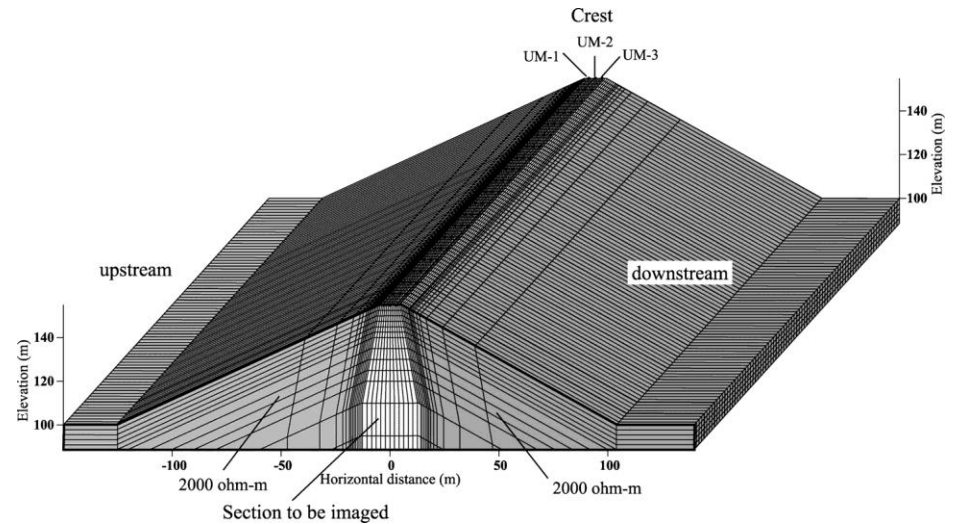


Limit Equilibrium Analysis

- Speculate on possible failure mechanisms;
- Consider free body diagrams, use limit equilibrium equations;
- Not all equations are necessarily satisfied;
- Soil failure is usually assumed to be rigid-plastic;
- Provides ultimate load for a particular assumed mechanism but no consideration of strains and displacements;
- This is the most popular method of analysis (due to simplicity)

Numerical Analysis Methods

- Need to satisfy:
 - Equilibrium
 - Compatibility
 - Soil Stress Strain Relations
 - Boundary conditions



<http://jeeg.geoscienceworld.org/>

Observational Method

- Soil behaviour is complex – hence, observational method has a major role to play;

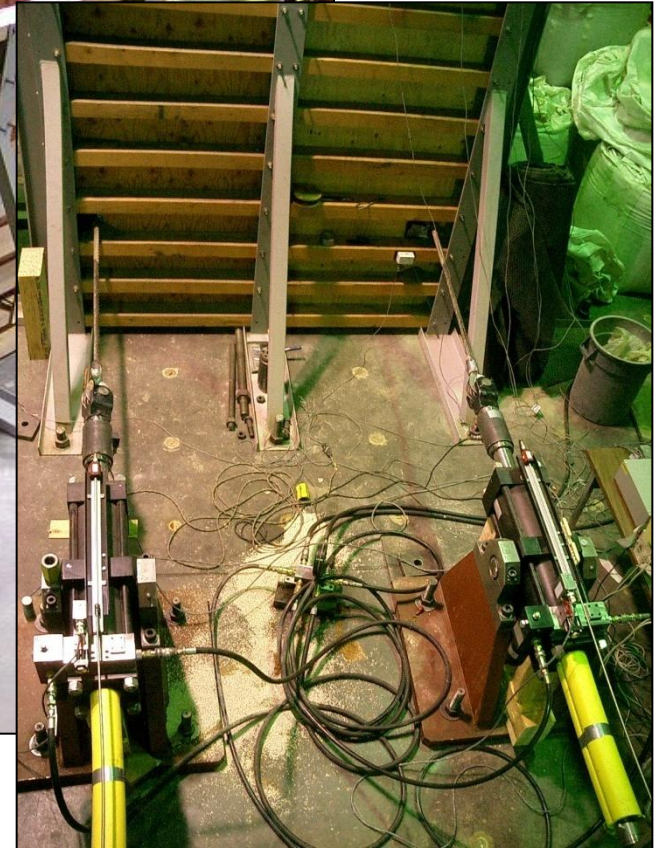
Observational method:

- Conduct field reviews during construction as necessary to confirm that the field conditions agree with design assumptions;
- If not, adjust the design as required;
- A key part in reduction of risk in geotechnical engineering.

Observational Method

- Physical modeling (to develop/validate numerical approaches):
 - Full-scale models;
 - Reduced scale (1g) models;
 - Reduced scale (Ng) models (centrifuge);

Full Scale Physical Modeling UBC Soil-pipe Interaction Chamber



Reduced Scale N*g Physical Modeling C-CORE Centrifuge



<http://www.c-core.ca/expertise/geotechnical.php>

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The Geotechnical Model - Site Characterization for Site Stratigraphy and Engineering Parameters



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Module 6

Site Characterization and Introduction to Geotechnical Design

Background Reading

- The Geotechnical Model - Site Characterization for Site Stratigraphy and Engineering Parameters (Book 2 pp. 139-173, 126-136)

Learning objectives of this section

Students will:

- Understand the purpose of a geotechnical evaluation;
- Be aware of the procedures followed to plan and implement a geotechnical evaluation;
- Be able to identify common techniques of field exploration;
- Understand the difference between classification testing of soils and laboratory and field testing to derive specific engineering parameters;
- Recognize the typical contents of a Geotechnical Evaluation Report

Geotechnical site characterization

Geotechnical site characterization requires the determination of:

1. Soil Stratigraphy
2. Geotechnical design parameters
3. Hydrogeologic Parameters
4. Geomechanical and biological characteristics of soil and pore fluid.

Typically all four are required for a geoenvironmental site characterization but only the first three are required for most projects.

Site characterization – key concepts

- Obtain enough information about foundation materials to predict soil response to proposed imposed loading
- Determine soil/rock conditions at the site
- Select soil model and representative parameters for input to analysis

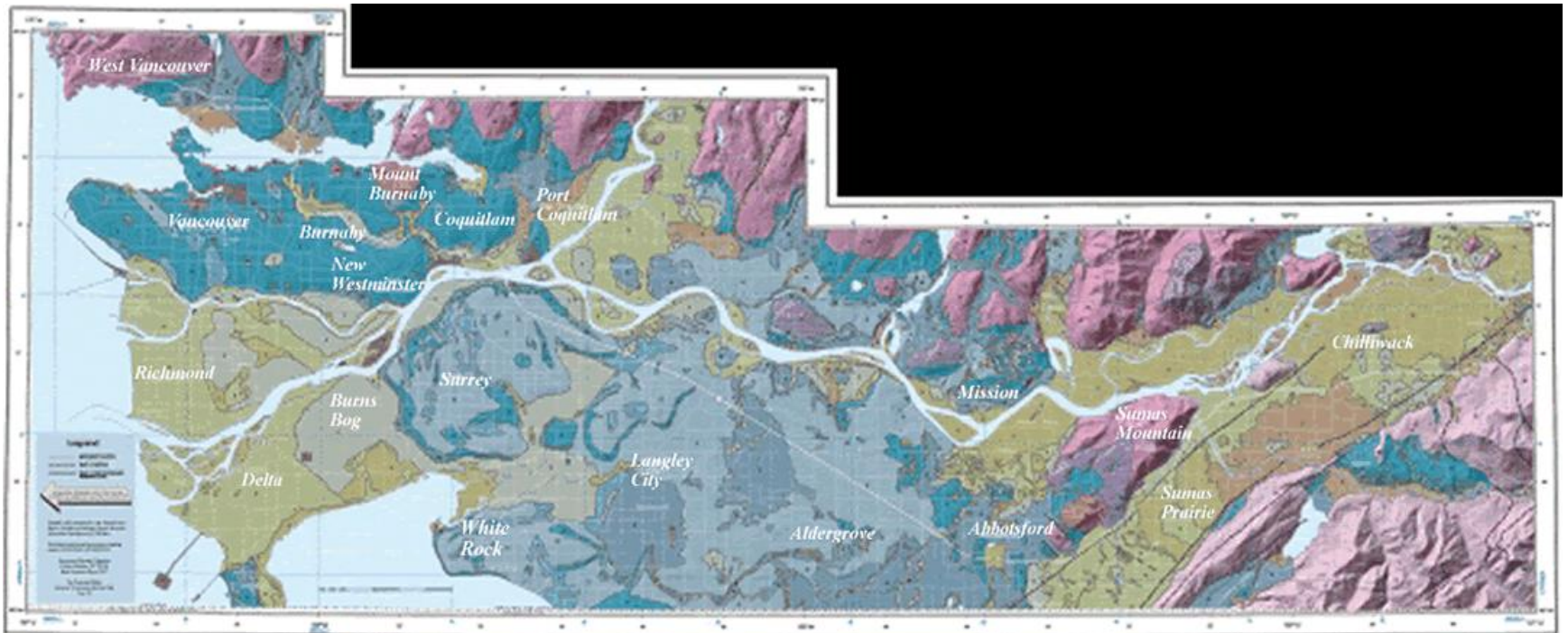
Phases of Site Characterization

1. Collection of available data
2. Preliminary site reconnaissance;
Formulation of geological model and identification of design issues;
3. Detailed site exploration;
4. Laboratory testing (if necessary);
Confirm geological model and estimate material properties from field observation, in situ and laboratory testing
5. Reporting - Baseline Geotechnical Report.

Collection of available data

- Geological maps and reports
- Soil survey reports
- Topographic maps
- Hydrographic charts
- Aerial photos
- Hydrology
- Climate
- Seismicity

GeoMap Vancouver



http://gsc.nrcan.gc.ca/urbgeo/geomapvan/index_e.php

First step

- Develop preliminary geological model based on
 - Desk study – collection of available information
 - Field reconnaissance
- Determine type and extent of field investigation required
- Plan field work

Field Reconnaissance

- Visit the site
- Take Photos
- Observe visible geotechnical conditions
- Utilities
- Fences, site access constraints
- Adjoining sites

Geotechnical Evaluation Report

- INTRODUCTION
- SITE DESCRIPTION
- FIELD INVESTIGATION AND LABORATORY TESTING
- SOIL AND GROUNDWATER CONDITIONS
- DESIGN CONSIDERATIONS
 - Seismic considerations
 - Site Preparation
 - Foundation alternatives
 - Construction considerations
- CONCLUSION AND RECOMMENDATIONS
 - Recommended foundation scheme and construction sequence.
 - Any other considerations, disclaimers, etc.
- APPENDICES

What Do We Need to Know To Predict the Material Behaviour?

- Soil type
- Soil consistency
- Total stress
- Determination of pore pressure distribution
- Stress history

Field exploration

- Main objectives
 - Confirm geological model
 - Soil layer sequence, thickness and lateral extent
 - Determine current groundwater conditions and likely fluctuations
 - Estimate stress history
 - Estimate engineering properties
 - In-situ testing and sampling

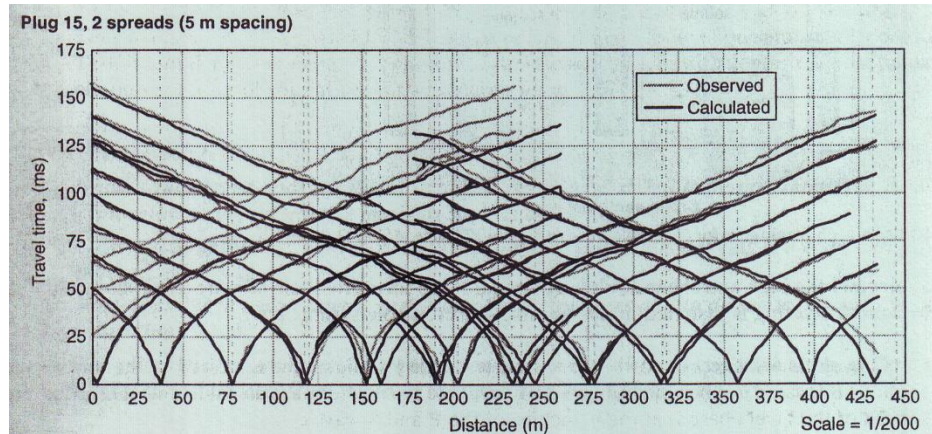
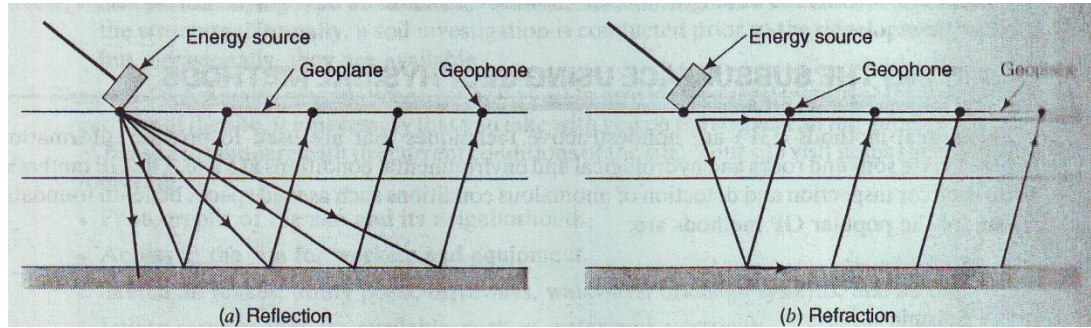
Field exploration

- Determine stratigraphy and groundwater conditions
 - Geological maps
 - Geophysics
 - Penetration testing
 - Drilling and sampling
 - Instrumentation e.g. piezometers
- Measure or estimate soil properties
 - Correlations to in situ test parameters
 - In situ measurements, e.g. vane shear test
 - Laboratory tests

Field Reconnaissance

- Site condition, topography, vegetation
- Site drainage, flooding, streams
- Outcrops
- Existing cut slopes, trenches or ditches
- Existing structures and foundation conditions
- Access for equipment, cut trails
- Existing services: power, gas, telecommunications
- Neighbours or local authorities

Geophysical Methods - Seismic Surveys



Non-intrusive

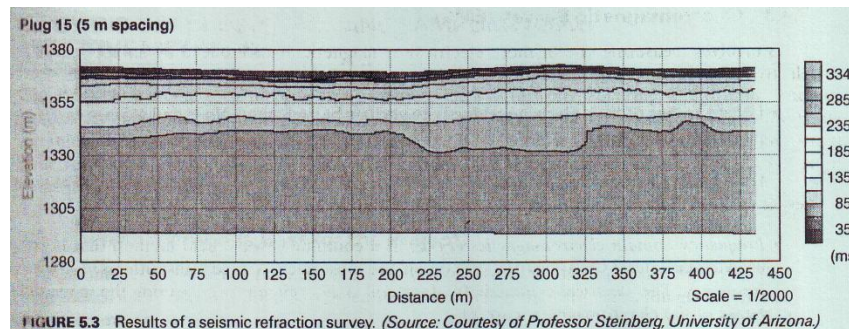
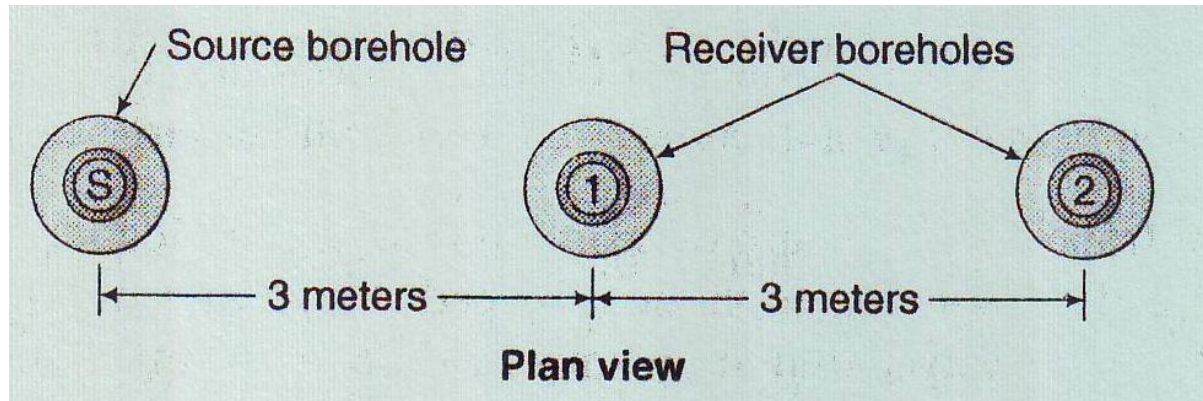
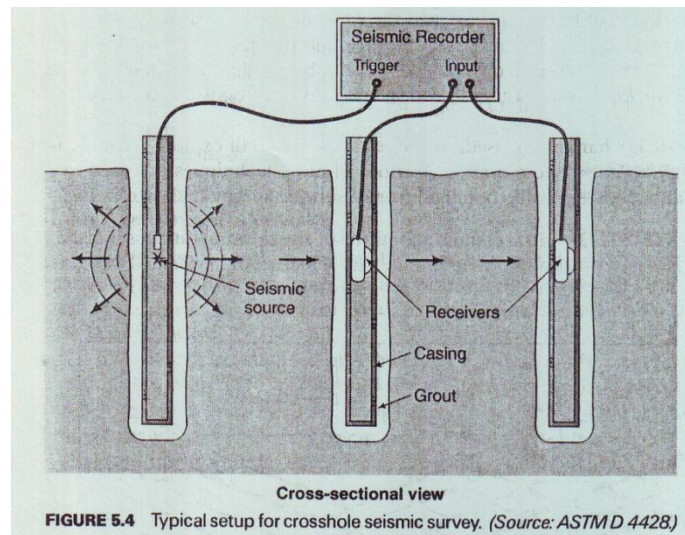


FIGURE 5.3 Results of a seismic refraction survey. (Source: Courtesy of Professor Steinberg, University of Arizona.)

Geophysical Methods - Seismic Surveys



Intrusive – can sample in boreholes



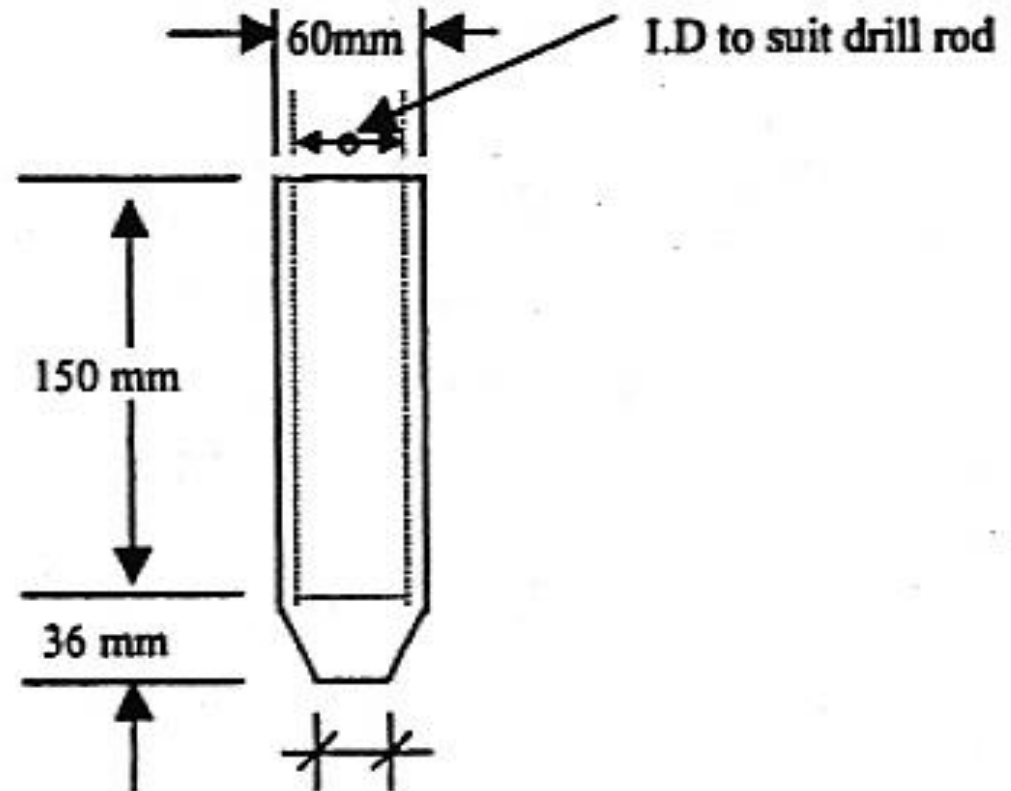
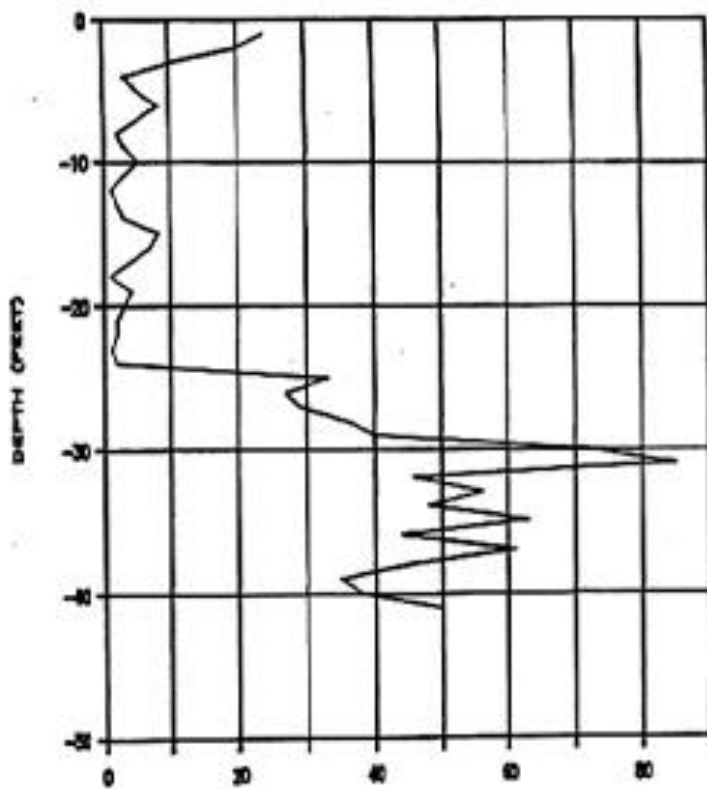
In-Situ Testing

- Piezometer Cone Penetration Test (CPTU)
- Dynamic Cone Penetration Test (DCPT)
- Becker Penetration Test (BPT)
- Dilatometer Test (DMT)
- Standard Penetration Test (SPT)
 - At intervals in borehole
- Vane Shear Test (VST) – at intervals
- Shear Wave Velocity Testing
 - Downhole or crosshole
- Other specific tests

Uses of in situ tests

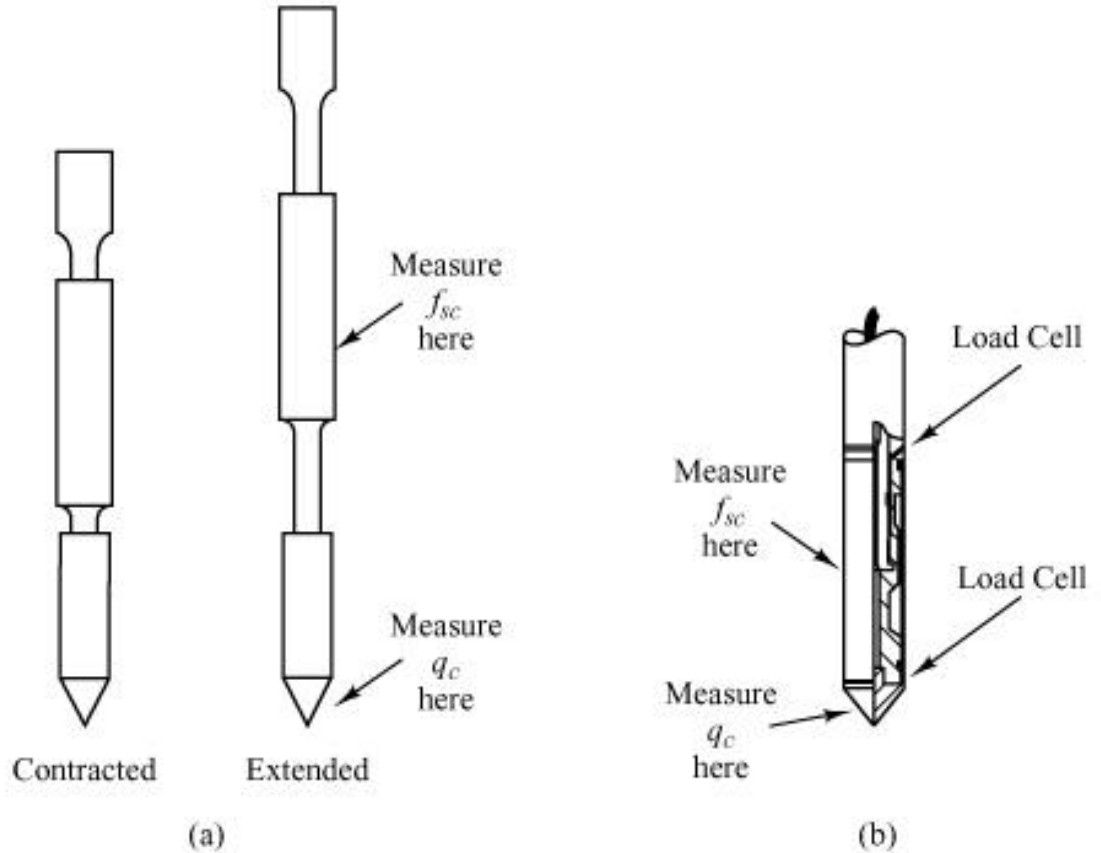
- Determination of stratigraphy
 - CPTU, DMT
- Estimates of engineering properties of soil using correlations, e.g. to q_t or N
Note: q_t is q_c corrected for pore pressure effects on tip

Dynamic Cone Penetration Test (DCPT)



Cone Penetration Test (CPT)

Figure 4.12 Types of cones:
(a) A mechanical cone (also known as a Begemann Cone);
and (b) An electric cone (also known as a Fugro Cone).



Cone Penetrometers

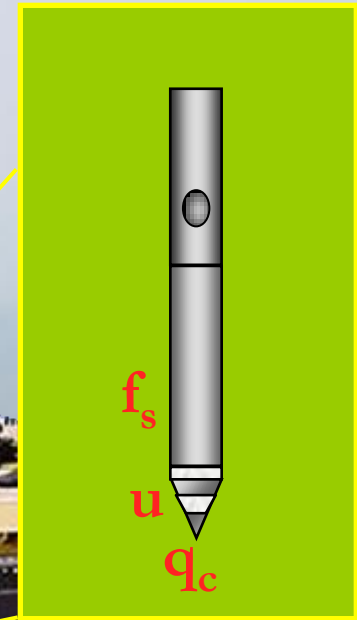
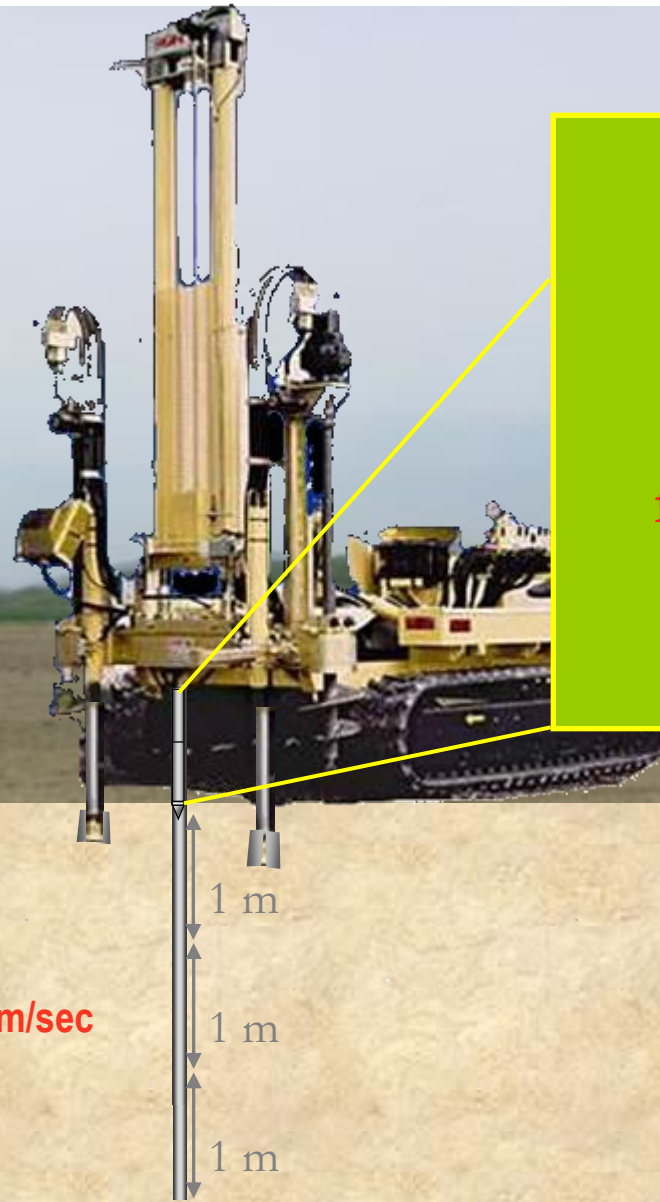


Standard Piezocone (CPTU) - recorded parameters

- q_C = tip force /10 cm²
- f_S = friction sleeve force/150 cm²
- u_2 = pore pressure at filter behind tip at shoulder
- Record pore pressure dissipation (PPD) when pushing stops
- Inclination: if $> 12^\circ$ or $> 4^\circ/1\text{m}$ stop penetration
- Temperature

Piezocone

Test



(CPTu)

CPT Profile

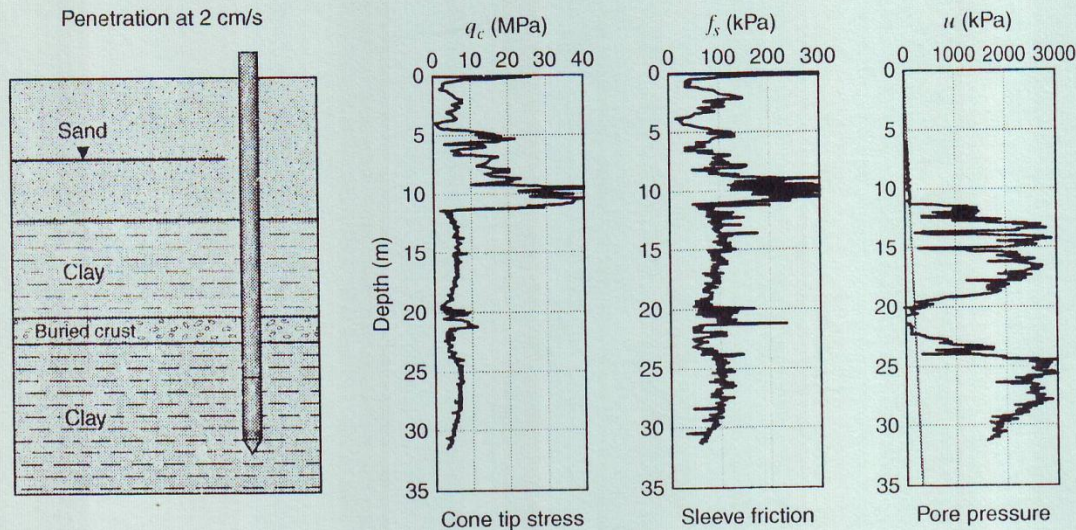
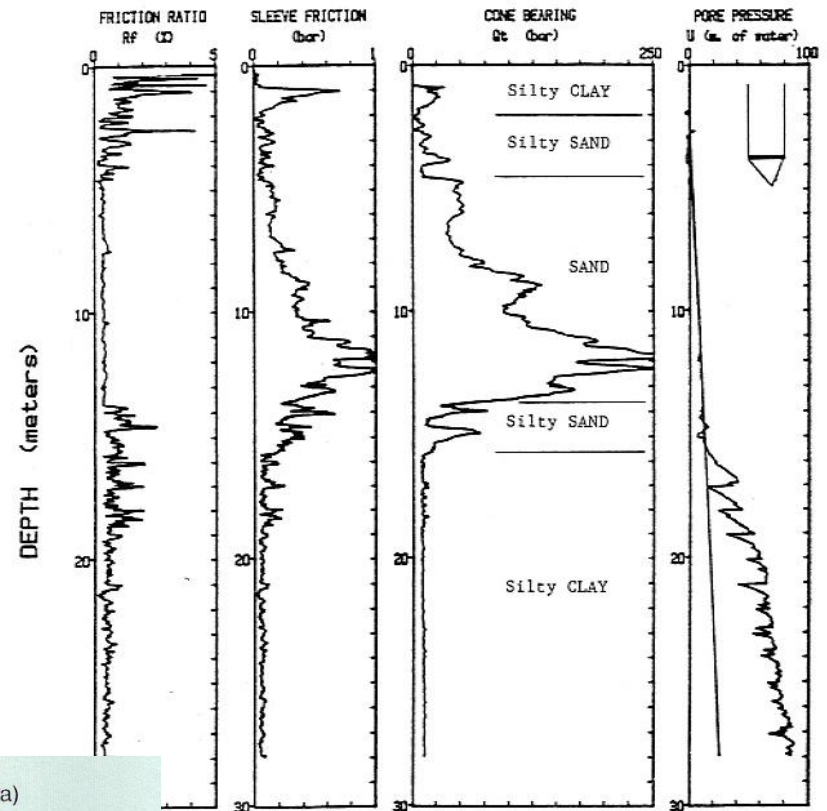
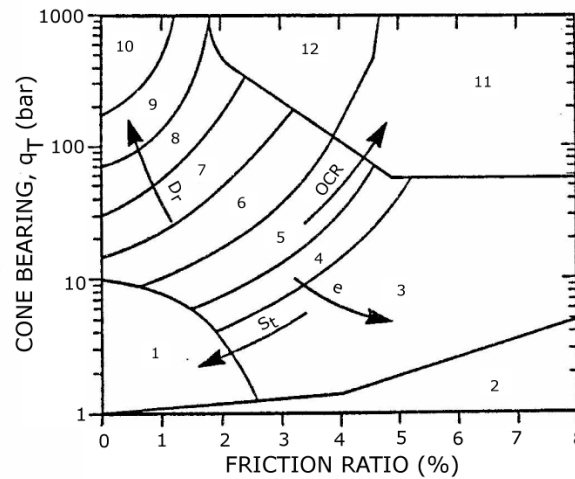


FIGURE 5.15 Piezocone results. (Source: Professor Paul Mayne, Georgia Tech.)

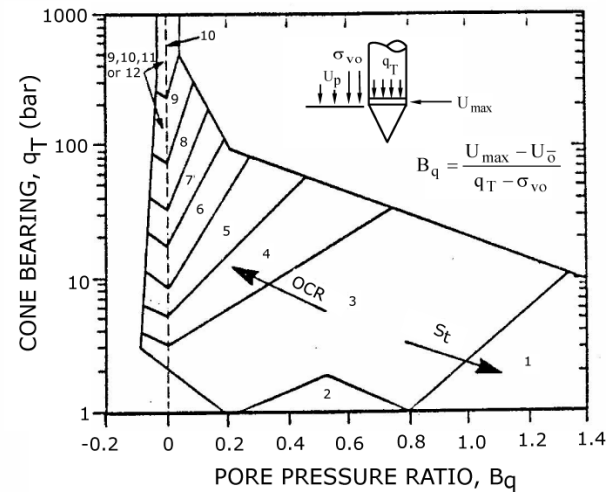
Traditional (Computerized) Soil Behaviour Type Interpretation Chart

(Adapted from
Robertson and
Campanella, 1983a)



Notes:

1. Expect some overlap in zones.
2. Local correlations preferable.
3. Based mainly on data obtained from depth < 30 m.
4. Review available dissipations of u to guide overlap in charts.



Zone	Soil Behaviour Type	q_T/N	t_{50} (minutes)
1)	sensitive fine grained	2	10-500
2)	organic material	1	2-20
3)	clay	1	10-100
4)	silty clay to clay	1.5	5-10
5)	clayey silt to silty clay	2	2-5
6)	sandy silt to clayey silt	2.5	1-2
7)	silty sand to sandy silt	3	.5-1
8)	sand to silty sand	4	0-5
9)	sand	5	drained
10)	gravelly sand to sand	6	drained
11)	very stiff fine grained (*)	1	unknown
12)	sand to clayey sand (*)	2	unknown

(*) overconsolidated or cemented

Drilling and Excavation Methods

e.g. Budhu, Table 5.1

- **Test pits**
 - backhoe; for all soils above water table
- **Hand augers**
 - limited depth; soft soils
- **Mechanical augers**
 - solid stem or hollow stem augers; all soils
- **Rotary drilling**
 - most versatile; mud or casing; all soils and rocks
- **Becker hammer drill**
 - open-ended double-walled casing; sand and gravel
- **Sonic drill**
 - high frequency vibration; continuous core; all soils and soft rock

Augers

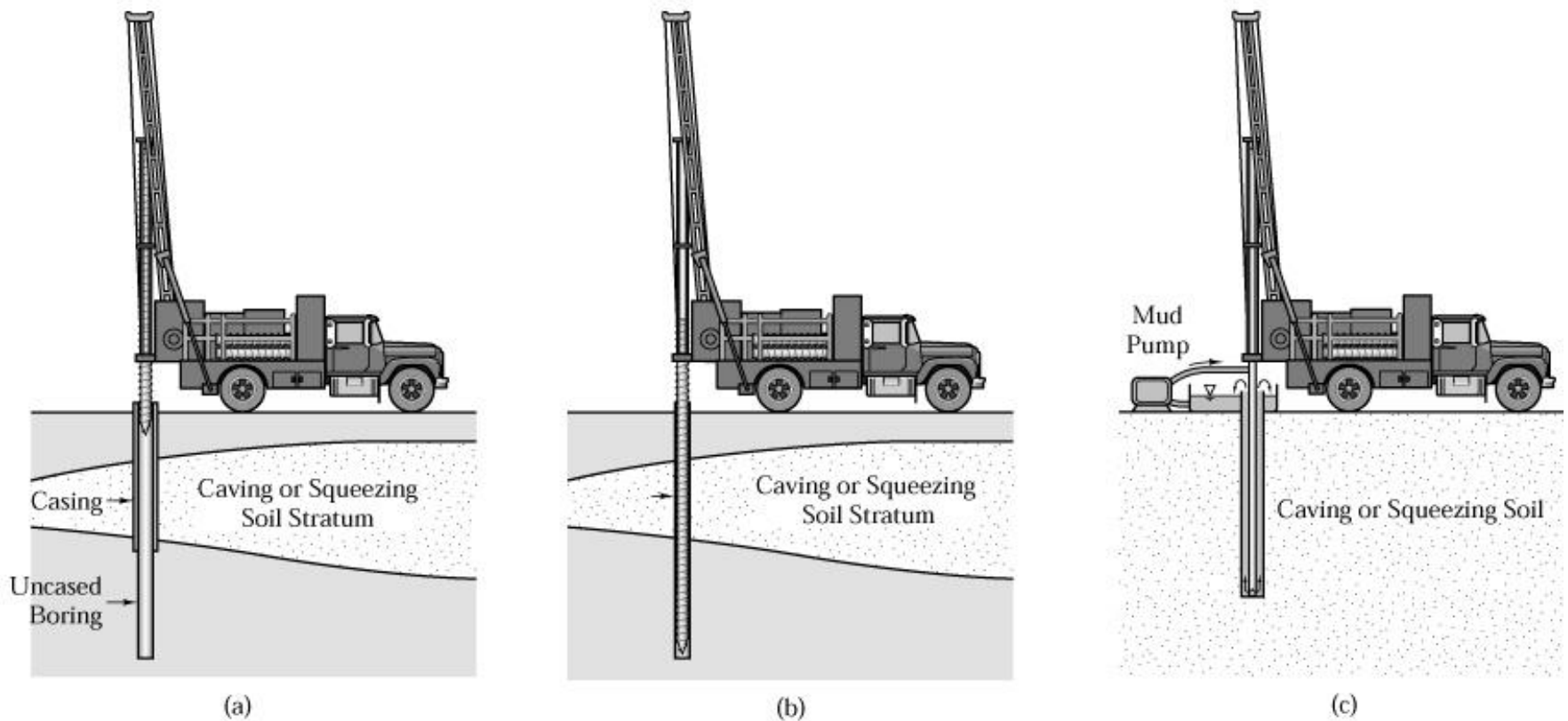


(a) Solid stem auger

(b) Hollow stem auger

Drill Rigs

Figure 4.3 Methods of dealing with caving or squeezing soils: (a) casing; (b) hollow-stem auger; and (c) rotary wash boring.



Wash Boring & Rotary Drilling

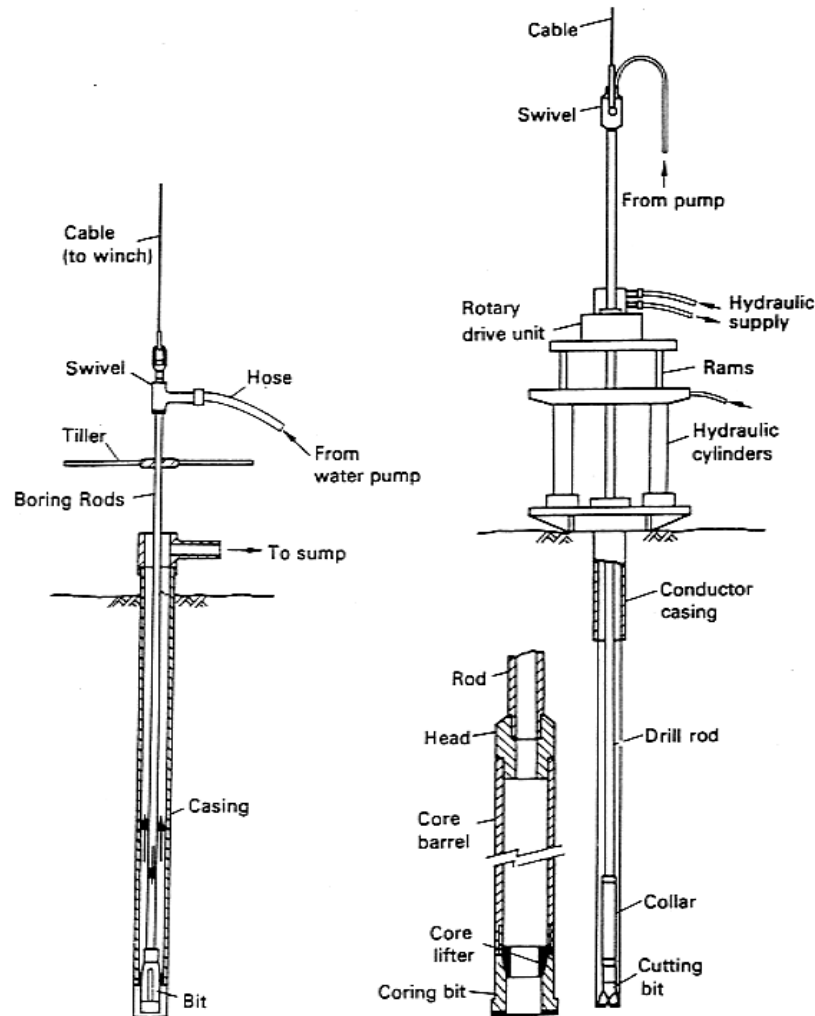
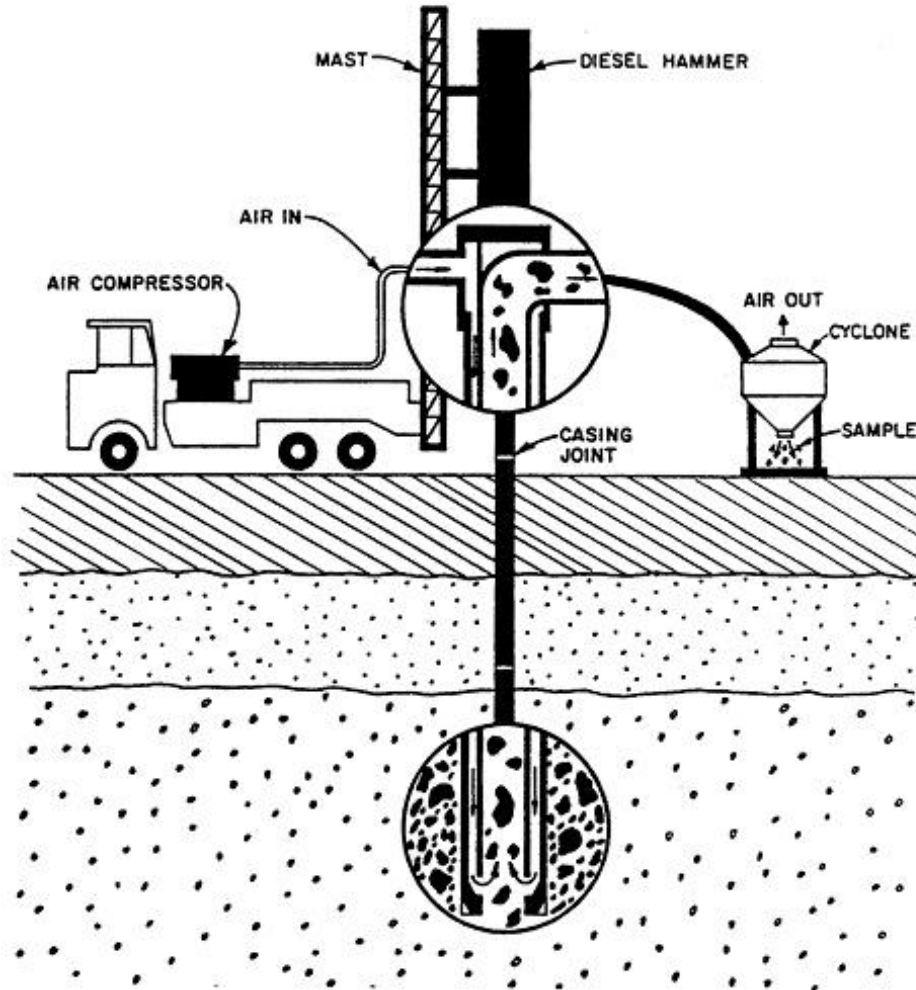


Figure 10.3
Wash boring

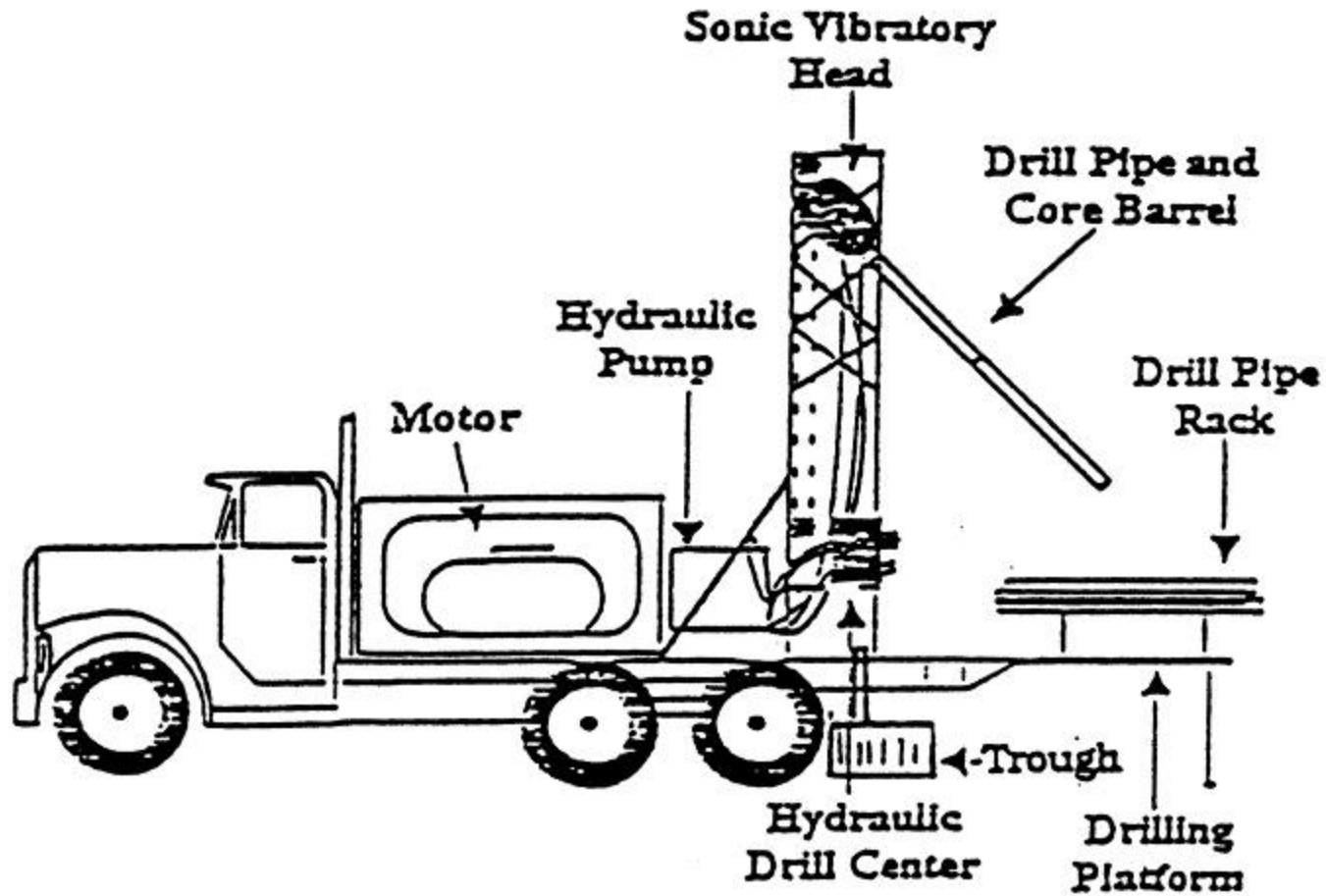
Figure 10.4
Rotary drilling

(Craig, 1997)

Becker Hammer Drill Rig



Sonic Drill Rig



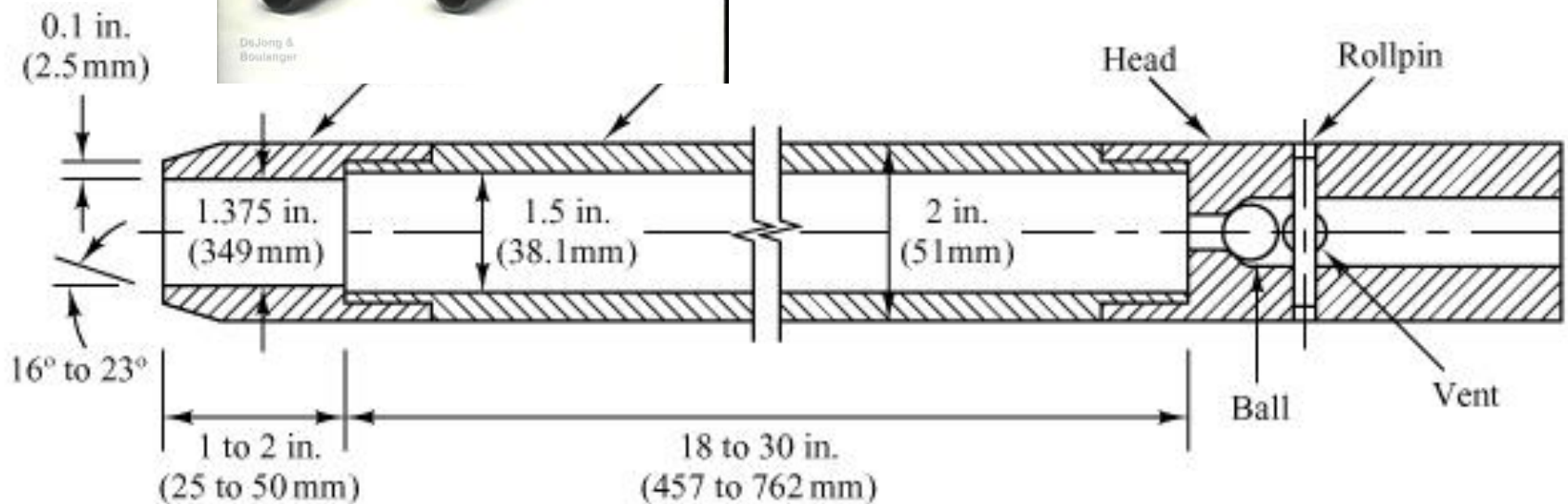
Sampling

- **Disturbed** – grab samples; thick-walled tube samples
 - for soil identification and classification testing such as grain size determinations and Atterberg limits
 - compaction tests
- **Undisturbed** - block samples, thin-walled tube samples
 - For determination of mechanical properties including shear strength and consolidation testing

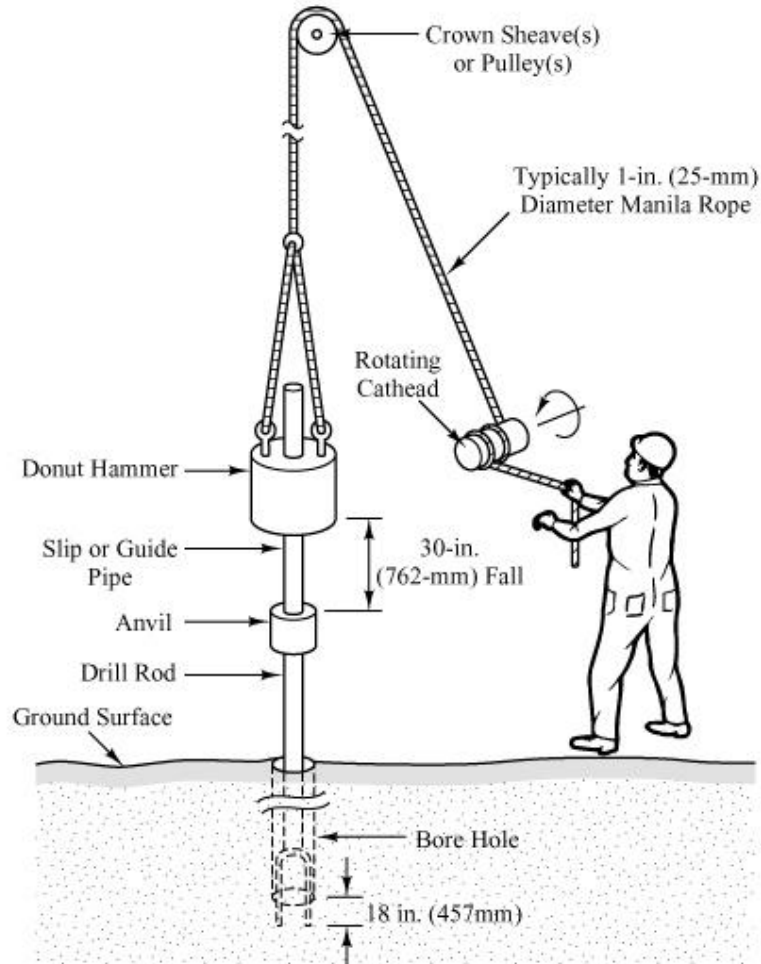
SPT Split-Spoon Sampler



Figure 4.8 The SPT sampler.
(Adapted from ASTM D1586).



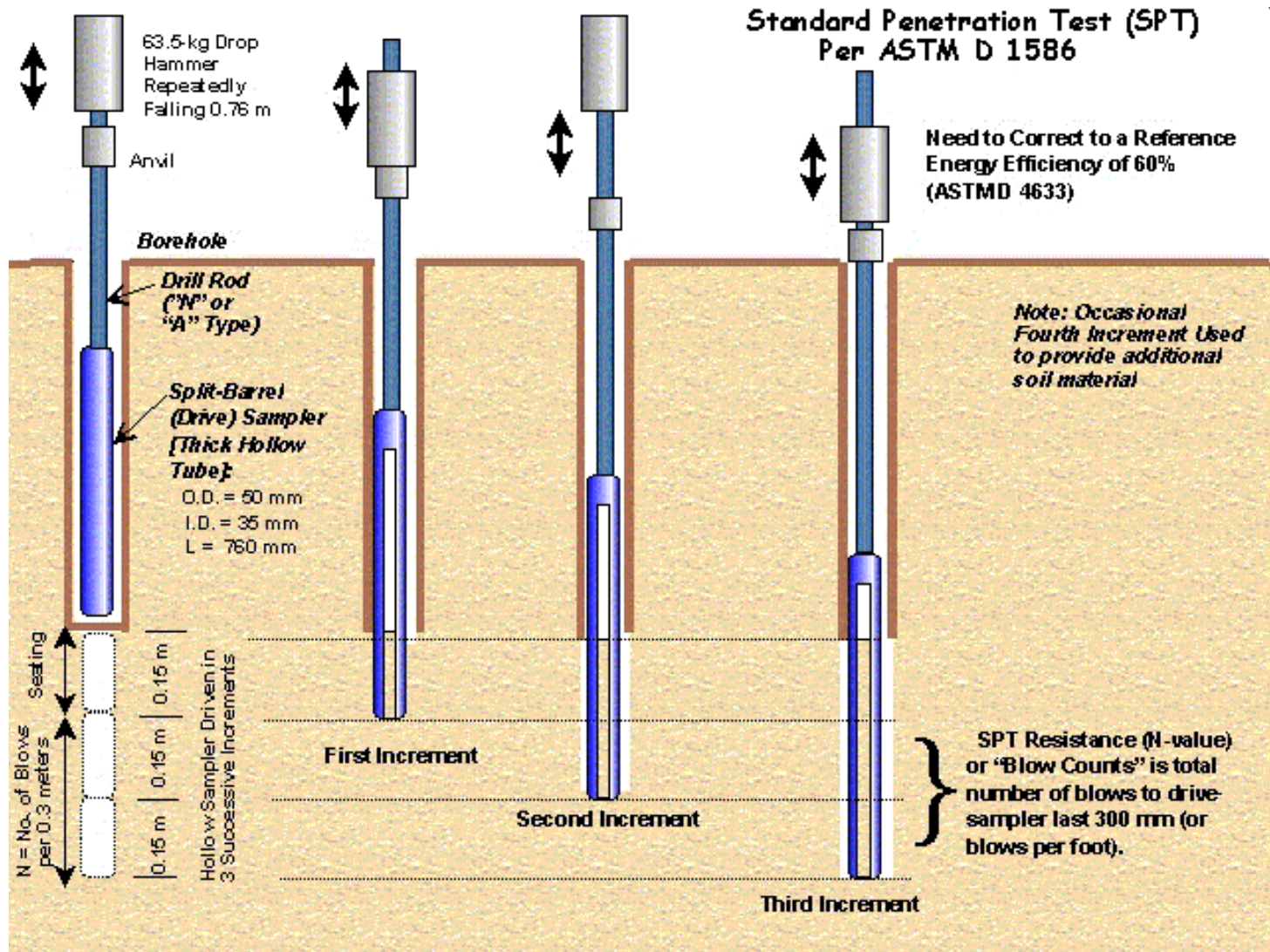
Standard Penetration Test (SPT)



SPTs are carried out at intervals (typically 1.5 m) within a borehole.

Figure 4.9 The SPT sampler in place in the boring with hammer, rope, and cathead. (Adapted from Kovacs, et al., 1981).

SPT



Tube Samplers

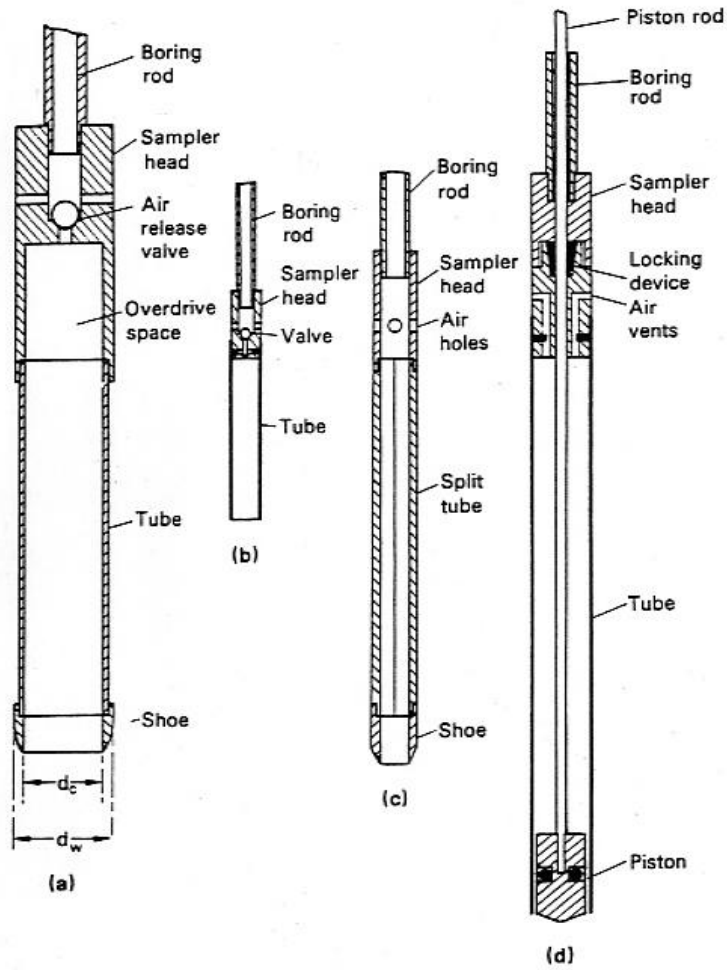
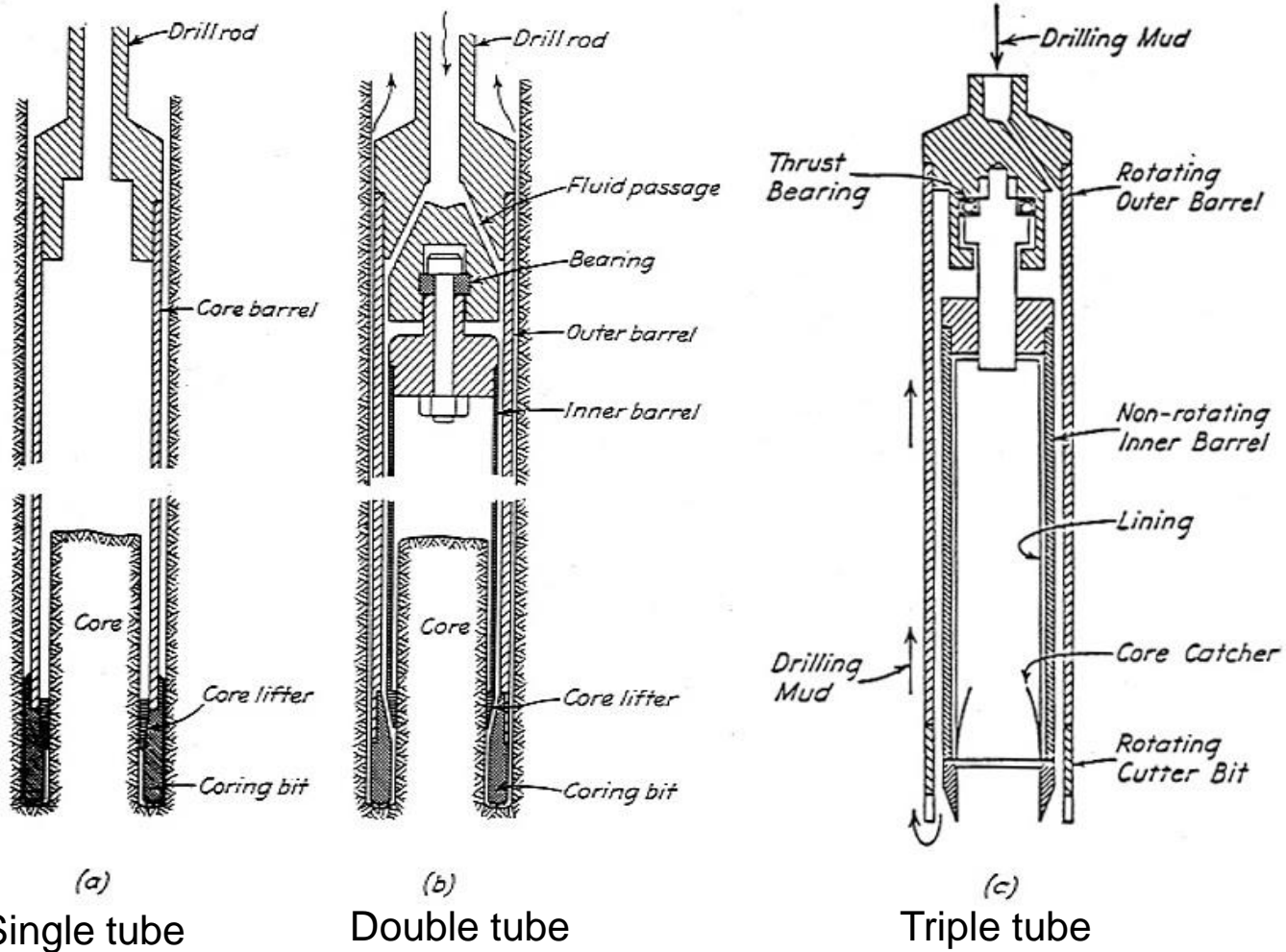


Figure 10.5 (Craig, 1997)

- (a) open drive sampler
- (b) thin-walled sampler
- (c) split-barrel sampler
- (d) stationary piston sampler

Rock Core Barrels



Field exploration

- Estimation of soil properties
 - Correlations to penetration test results
 - SPT, CPT, DMT
 - Correlations to classification tests
 - In situ testing
 - Field vane (FV), Downhole Seismic (V_s), Pressuremeter, Pumping tests, etc.
 - Laboratory testing
 - Triaxial (UU, CU, CD), Direct Shear, Compaction testing, etc.

Extent and Depth of Investigation

- Depends on size and type of project, and ground conditions
- Borings to extend into a suitable bearing stratum, or to where increase in soil stress due to foundation load is small
- Some guidelines in Budhu Table 5.2 - only a guideline (geological model helps).
 - Geological model and building layout should determine location of borings

Foundation Stress Influence

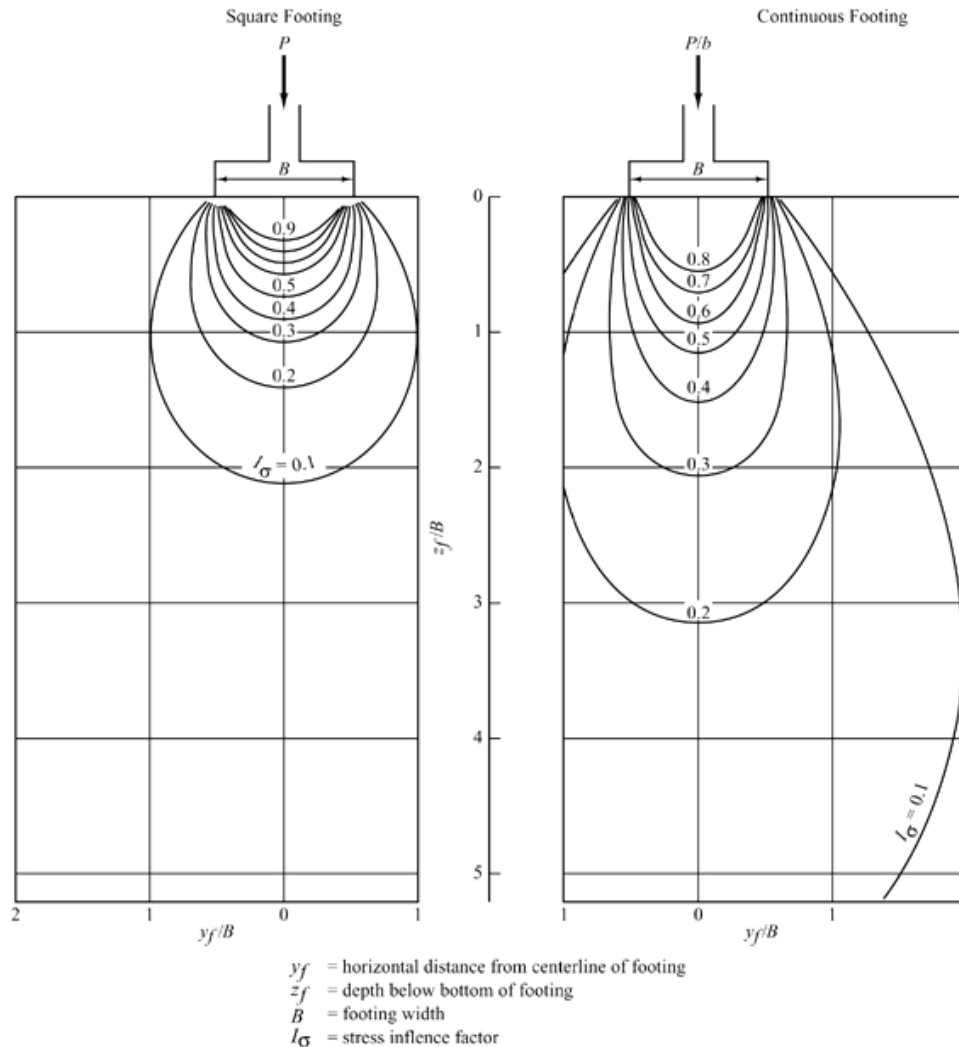


Figure 7.2
Stress bulbs based on Newmark's solution of Boussinesq's equation for square and continuous footings.

How do we identify and
classify soil and rock?

How do we estimate properties?

Field identification

Classification by Grain Size

	Soil Description	Proportion by mass
Noun	gravel, sand, silt, clay	>50%
"and"	and gravel, and silt, etc.	>35%
Adjective	gravelly, sandy, silty, clayey, etc.	>20-35%
"some"	some sand, some silt, etc.	>10-20%
"trace"	trace sand, trace silt, etc.	>1-10%

Field classification of shear strength/consistency of fine-grained soils.

Table 3.2 and 3.3. (CFEM, 1992)
Approximate Consistency of cohesive soils

Consistency	Field identification	Undrained Shear Strength (kPa)
Very soft	Easily penetrated several centimetres by the fist	<12
Soft	Easily penetrated several centimetres by the thumb	12 – 25
Firm	Can be penetrated several centimetres by the thumb with moderate effort	25 – 50
Stiff	Readily indented by the thumb, but penetrated only with great effort	50 – 100
Very stiff	-Readily indented by the thumb nail	100 – 200
Hard	Indented with difficulty by the thumbnail	> 200

Field classification of rock

Table 11.2: Field estimates of uniaxial compressive strength.

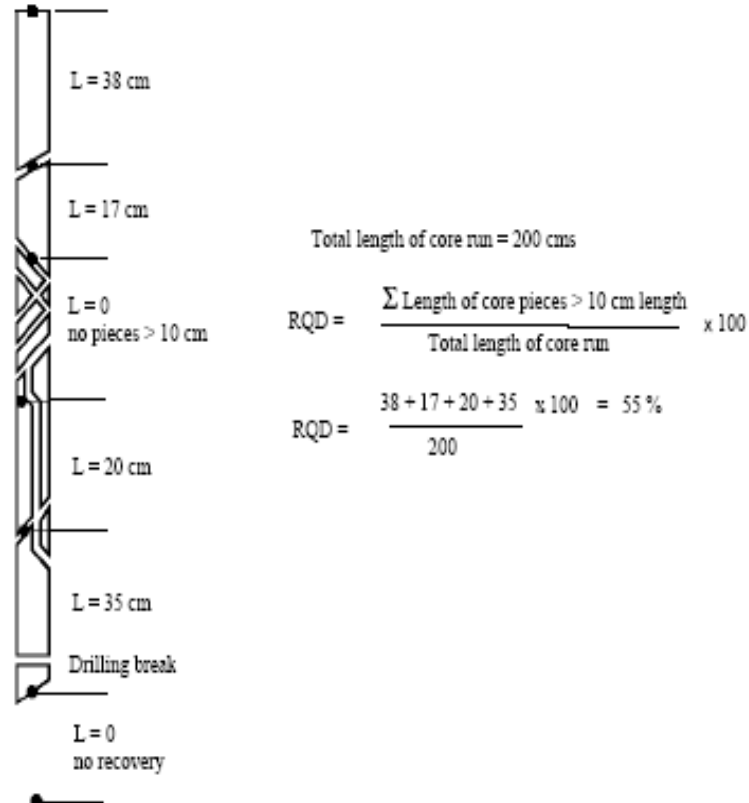
Grade*	Term	Uniaxial Comp. Strength (MPa)	Point Load Index (MPa)	Field estimate of strength	Examples
R6	Extremely Strong	> 250	>10	Specimen can only be chipped with a geological hammer	Fresh basalt, chert, diabase, gneiss, granite, quartzite
R5	Very strong	100 - 250	4 - 10	Specimen requires many blows of a geological hammer to fracture it	Amphibolite, sandstone, basalt, gabbro, gneiss, granodiorite, limestone, marble, rhyolite, tuff
R4	Strong	50 - 100	2 - 4	Specimen requires more than one blow of a geological hammer to fracture it	Limestone, marble, phyllite, sandstone, schist, shale
R3	Medium strong	25 - 50	1 - 2	Cannot be scraped or peeled with a pocket knife, specimen can be fractured with a single blow from a geological hammer	Claystone, coal, concrete, schist, shale, siltstone
R2	Weak	5 - 25	**	Can be peeled with a pocket knife with difficulty, shallow indentation made by firm blow with point of a geological hammer	Chalk, rocksalt, potash
R1	Very weak	1 - 5	**	Crumbles under firm blows with point of a geological hammer, can be peeled by a pocket knife	Highly weathered or altered rock
R0	Extremely weak	0.25 - 1	**	Indented by thumbnail	Stiff fault gouge

* Grade according to Brown (1981).

** Point load tests on rocks with a uniaxial compressive strength below 25 MPa are likely to yield highly ambiguous results.

Rock Quality Designation

RQD



RQD CLASSIFICATION	RQD-VALUE (%)
Very poor quality	< 25
Poor quality	25 - 50
Fair quality	50 - 75
Good quality	75 - 90
Excellent quality	90 - 100

Figure 4.1: Procedure for measurement and calculation of RQD (After Deere, 1989).

Types of SPT Hammers

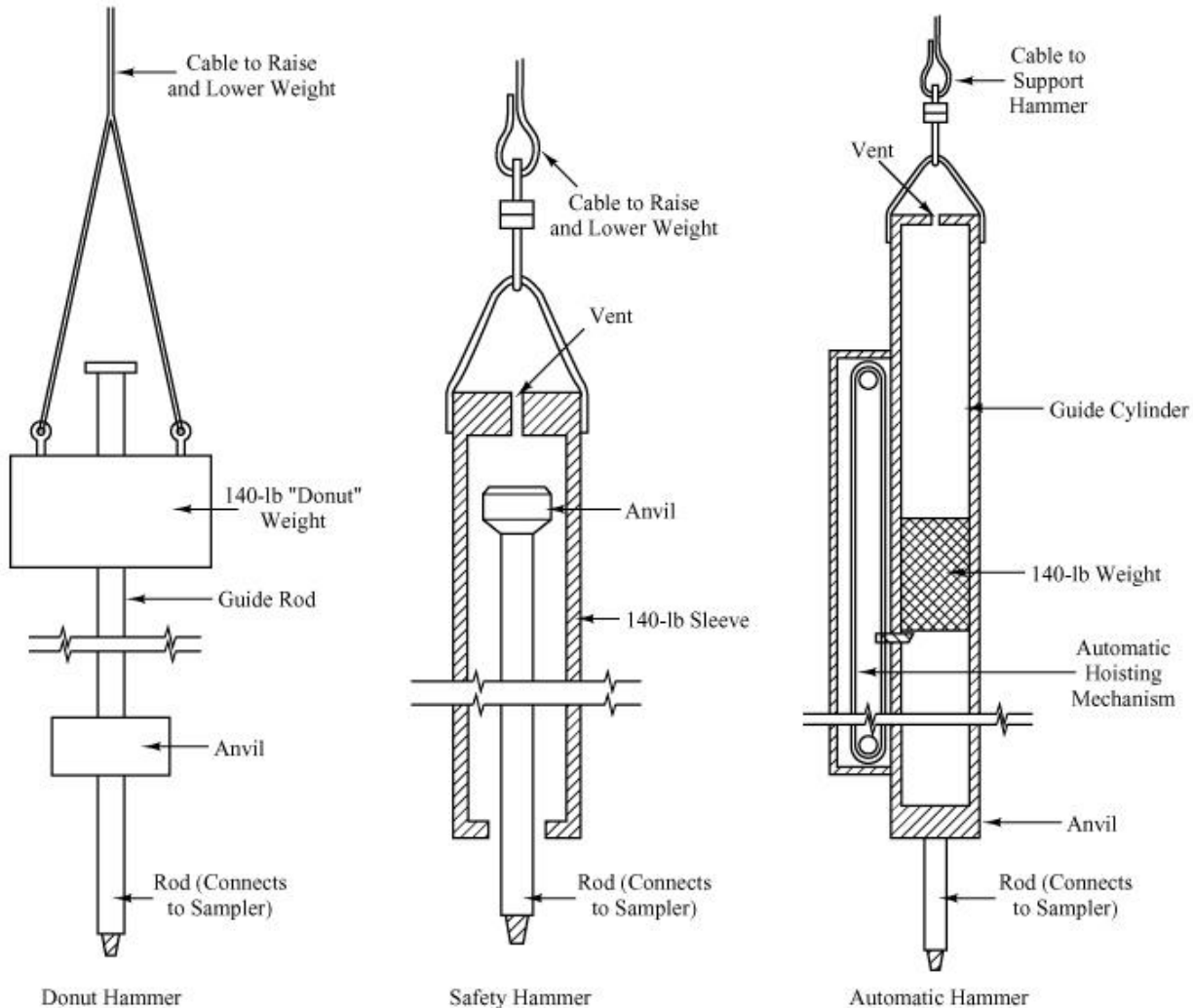


Figure 4.10 Types of SPT hammers.

SPT Hammer Energy Correction

TABLE 4.3 SPT HAMMER EFFICIENCIES (Adapted from Clayton, 1990).

Country	Hammer Type (per Figure 4.10)	Hammer Release Mechanism	Hammer Efficiency E_{re}
Argentina	Donut	Cathead	0.45
Brazil	Pin weight	Hand dropped	0.72
China	Automatic	Trip	0.60
	Donut	Hand dropped	0.55
	Donut	Cathead	0.50
Colombia	Donut	Cathead	0.50
Japan	Donut	Tombi trigger	0.78–0.85
	Donut	Cathead 2 turns + special release	0.65–0.67
UK	Automatic	Trip	0.73
US	Safety	2 turns on cathead	0.55–0.60
	Donut	2 turns on cathead	0.45
Venezuela	Donut	Cathead	0.43

Corrections to SPT

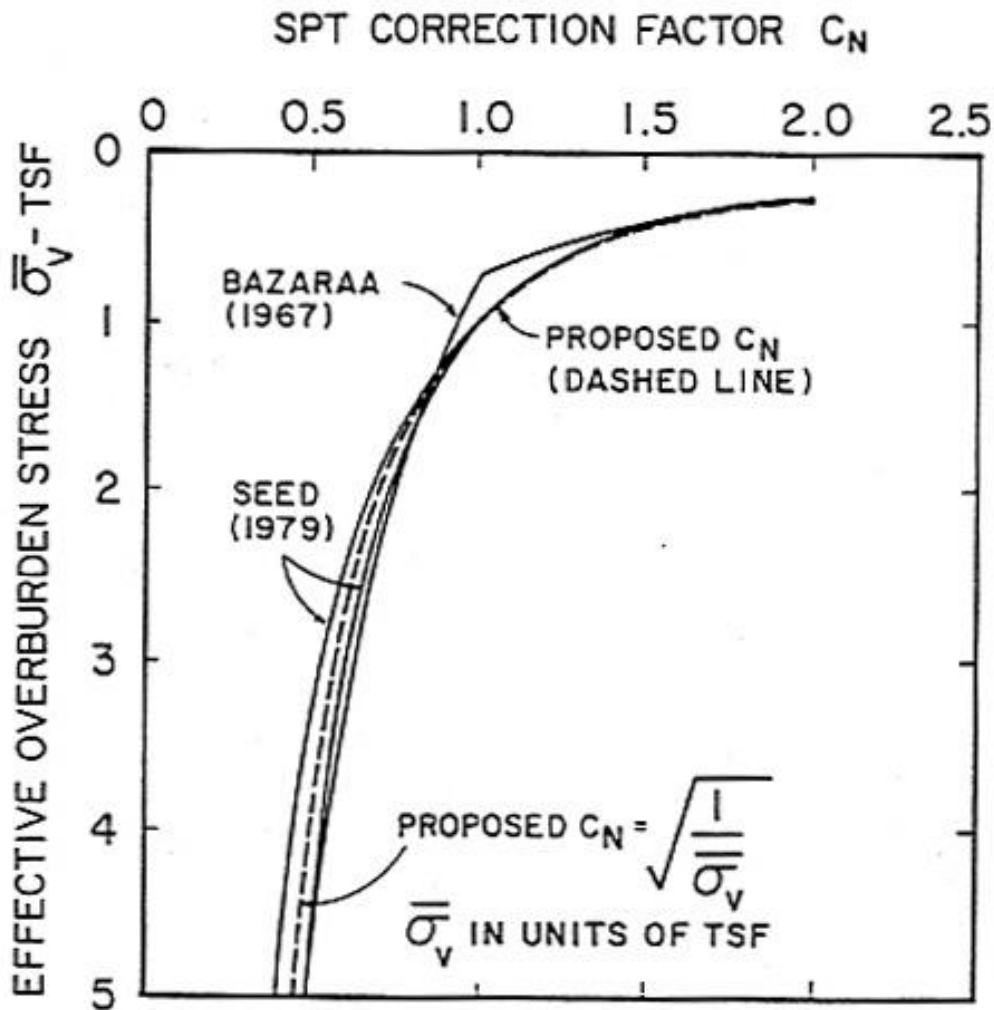
- Correct to energy of 60% of maximum PE

$$N_{60} = N_{measured} \frac{E_m(\%)}{60}$$

- Correct to overburden stress of 100 kPa

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

SPT Overburden Correction



Coduto

$$C_N = \sqrt{\frac{100 \text{ kPa}}{\sigma'_z}}$$

CPT – SPT Correlation

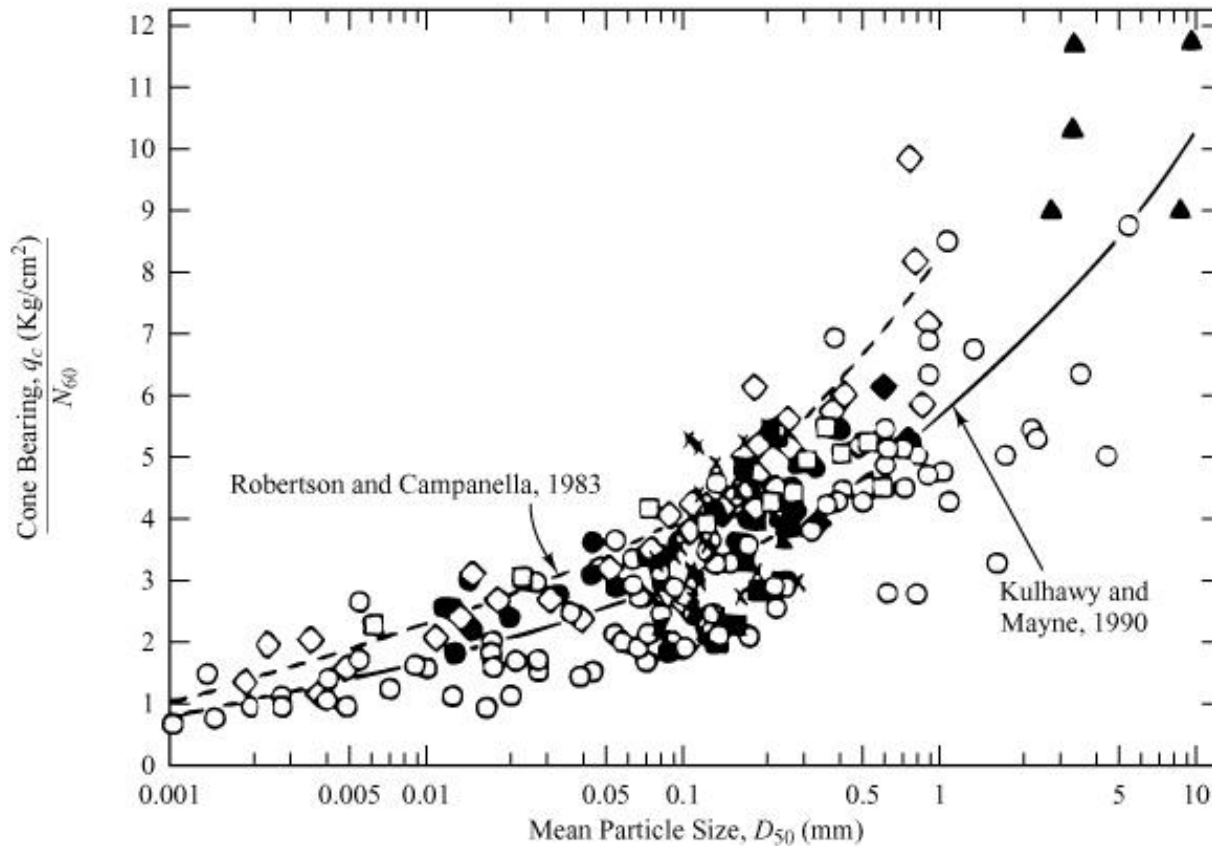
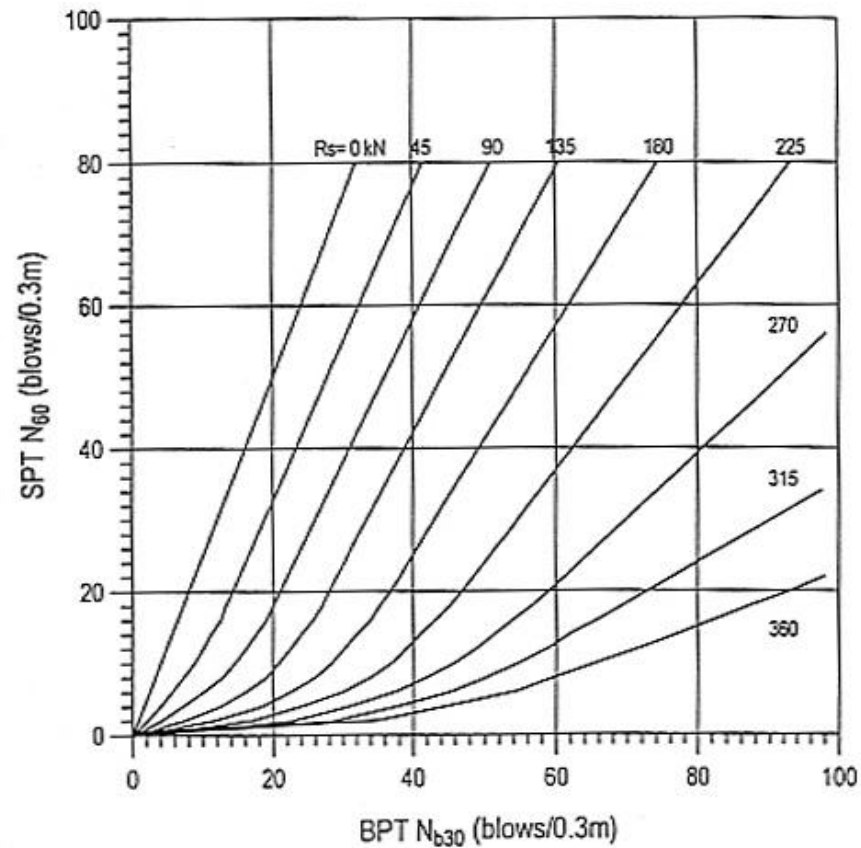


Figure 4.17 Correlation between q_c/N_{60} and the mean grain size, D_{50} . (Adapted from Kulhawy and Mayne, 1990.)

Becker Penetration Test (BPT)

$$N_{b30} = N_b \cdot \frac{ENTHRU(\%)}{30}$$



Consistency from N_{60}

Table 8.3 Relative Density of Sands

(1) N value	(2) Classification	(3) D_r (%)	(4) $(N_1)_{60}$
0–4	Very loose	0–15	0–3
4–10	Loose	15–35	3–8
10–30	Medium dense	35–65	8–25
30–50	Dense	65–85	25–42
>50	Very dense	85–100	42–58

Consistency from CPTU

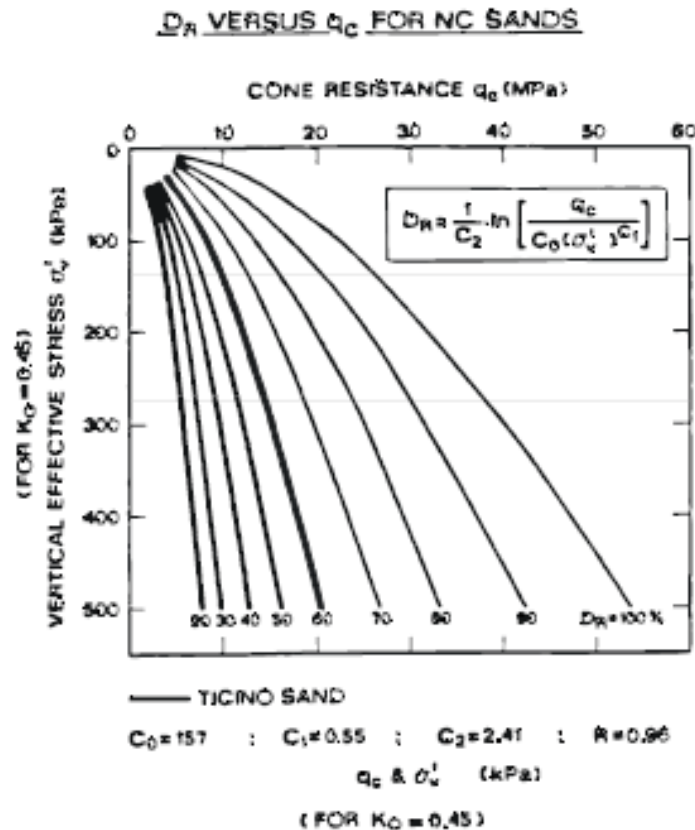
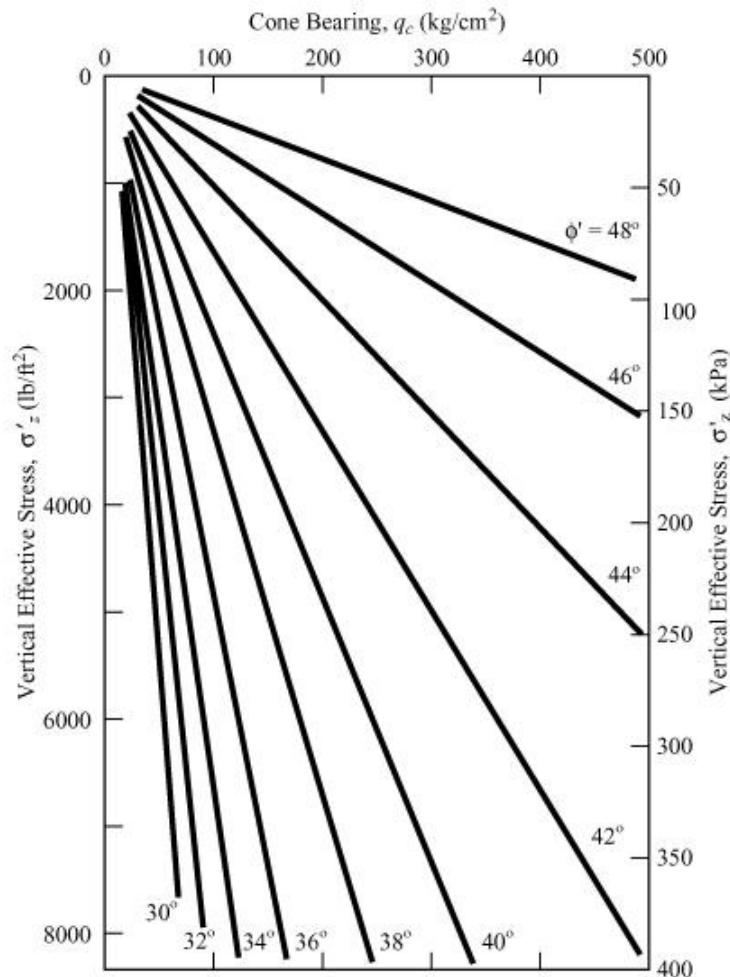


Figure 4.8 Relative Density Relationship for N.C., Moderately Compressible, Uncemented, Unaged Quartz Sands (After Baldt et al, 1987)

Shear Strength from CPT - Sands



NB: This chart gives an estimate of the friction angle that would be obtained from triaxial compression testing

Note - $q_c \sim q_t$ in sands

Figure 4.16 Relationship between CPT results, overburden stress and effective friction angle for uncemented, normally consolidated quartz sands (Adapted from Robertson and Campanella, 1983).

Vane Shear Test (VST)

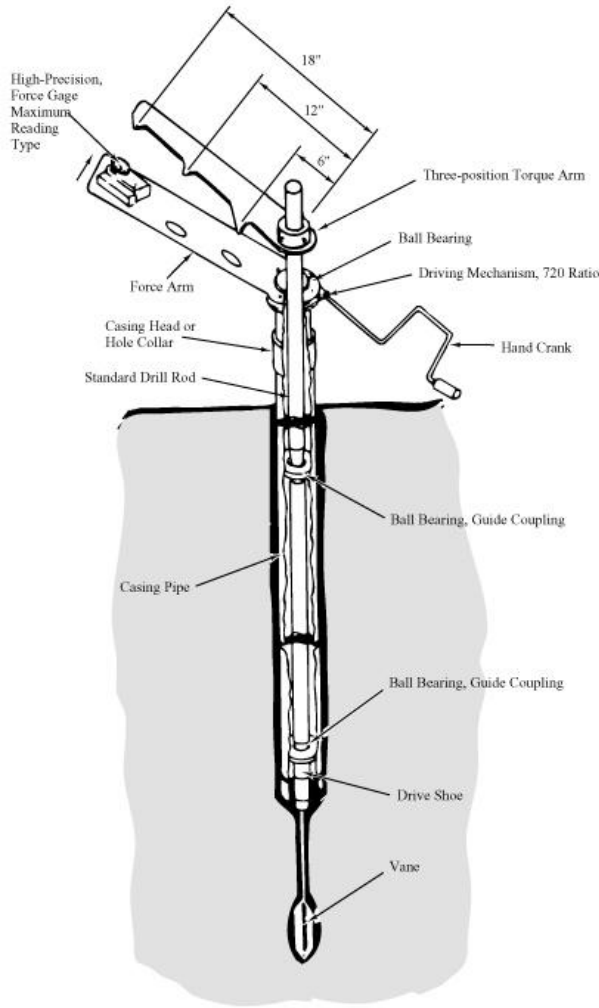
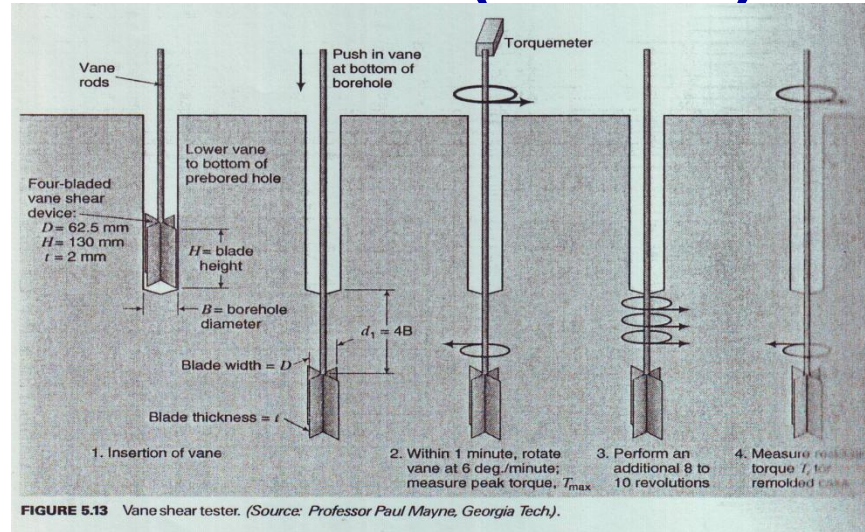


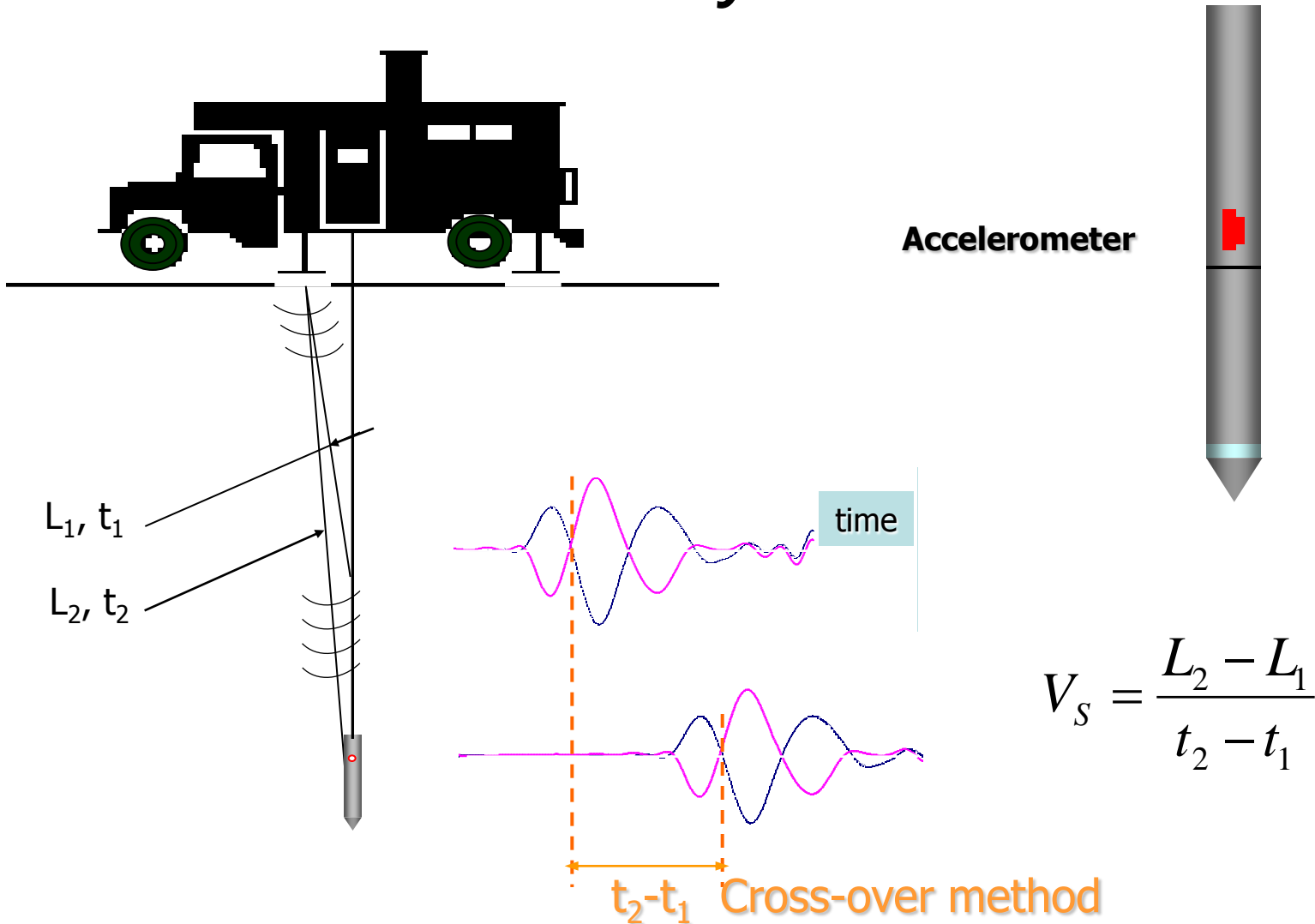
Figure 4.18 The vane shear test (U.S. Navy, 1982a).



Measure
torque to fail
soil

Gives $(s_u)_{FV}$

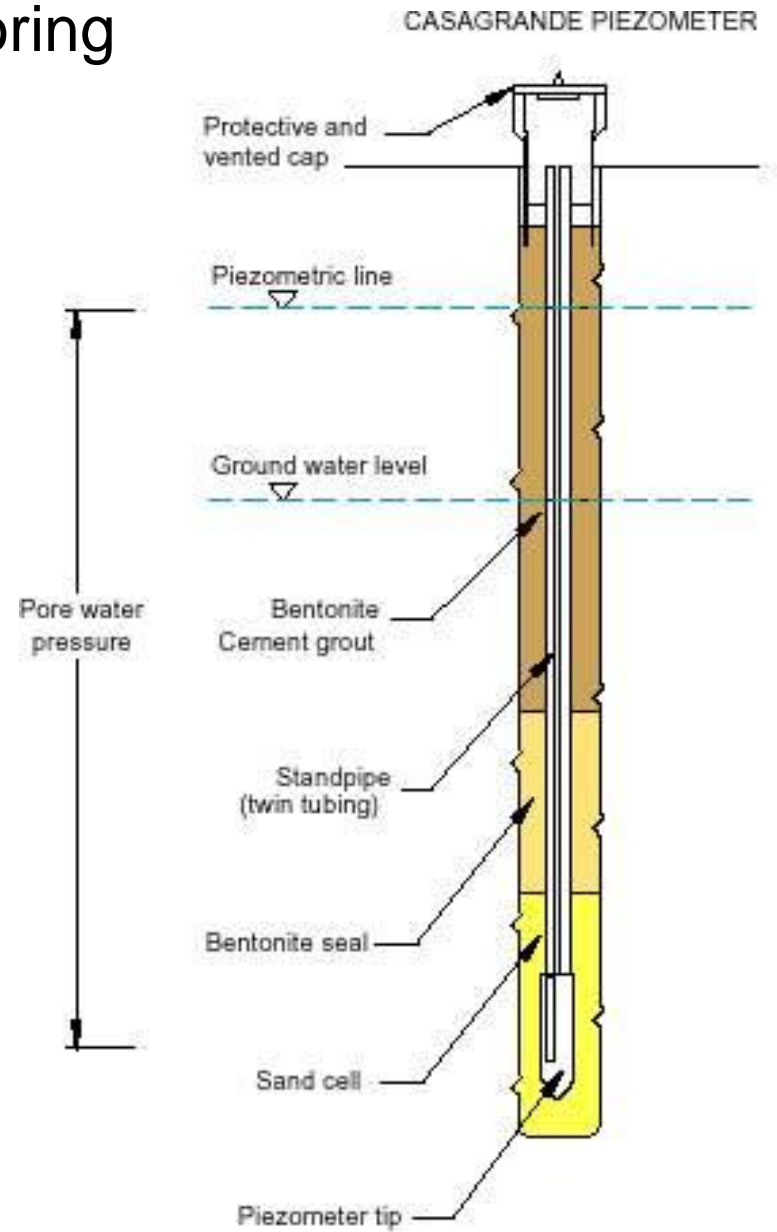
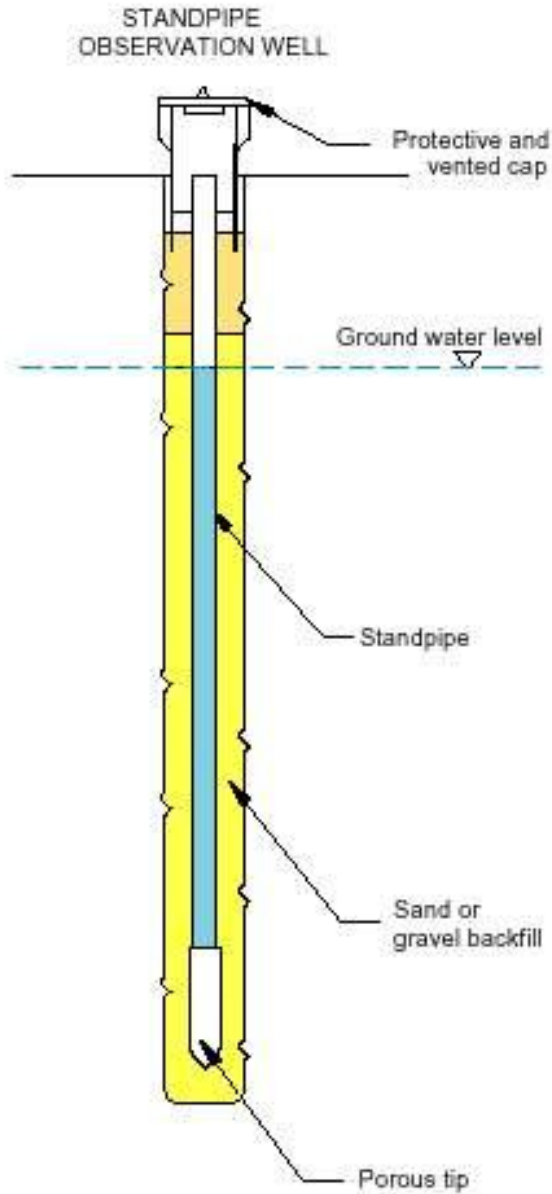
Shear wave velocity from seismic cone



Instrumentation

- Groundwater monitoring
 - Observation wells or standpipes – no seals
 - Piezometers
- Inclinometers
 - Measure lateral displacements
- Settlement gauges
 - Measure vertical displacements
 - Can be on surface or at depth

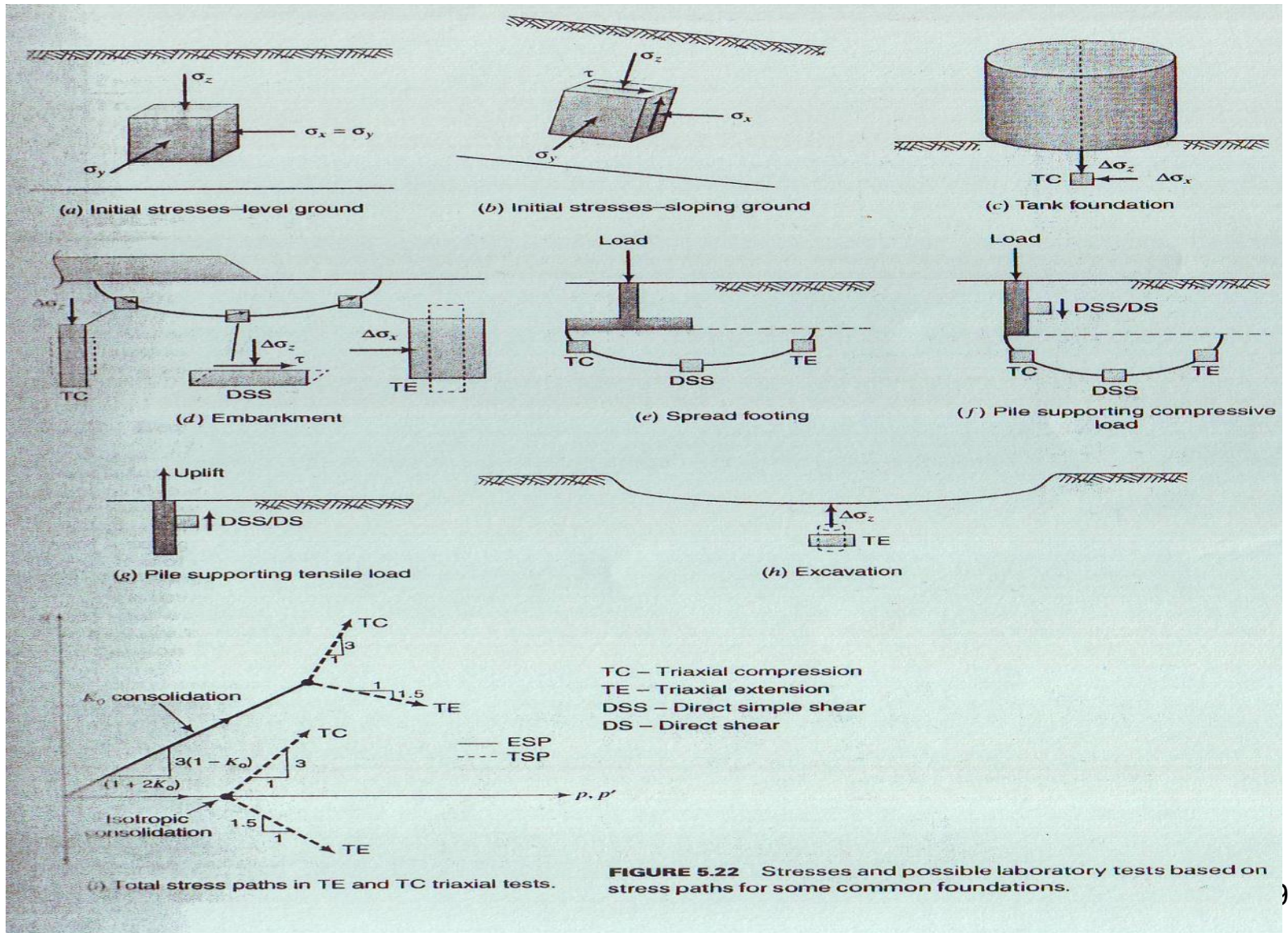
Groundwater monitoring



Laboratory Testing

- Soil classification – Class I
 - Moisture Content (ASTM D2216)
 - Grain Size (ASTM D422)
 - mechanical sieve analysis for sand and gravel
 - hydrometer analysis for silt and clay
 - Atterberg Limits (ASTM D4318)
 - Compaction
 - standard Proctor (ASTM D698)
 - modified Proctor (ASTM D1557)
- Mechanical properties – Class II
 - Direct Shear (ASTM D3080)
 - Triaxial Compression (ASTM D4767)
 - One Dimensional Consolidation (ASTM D2435)
 - Direct Simple Shear

Laboratory Testing



Typical Borehole Log

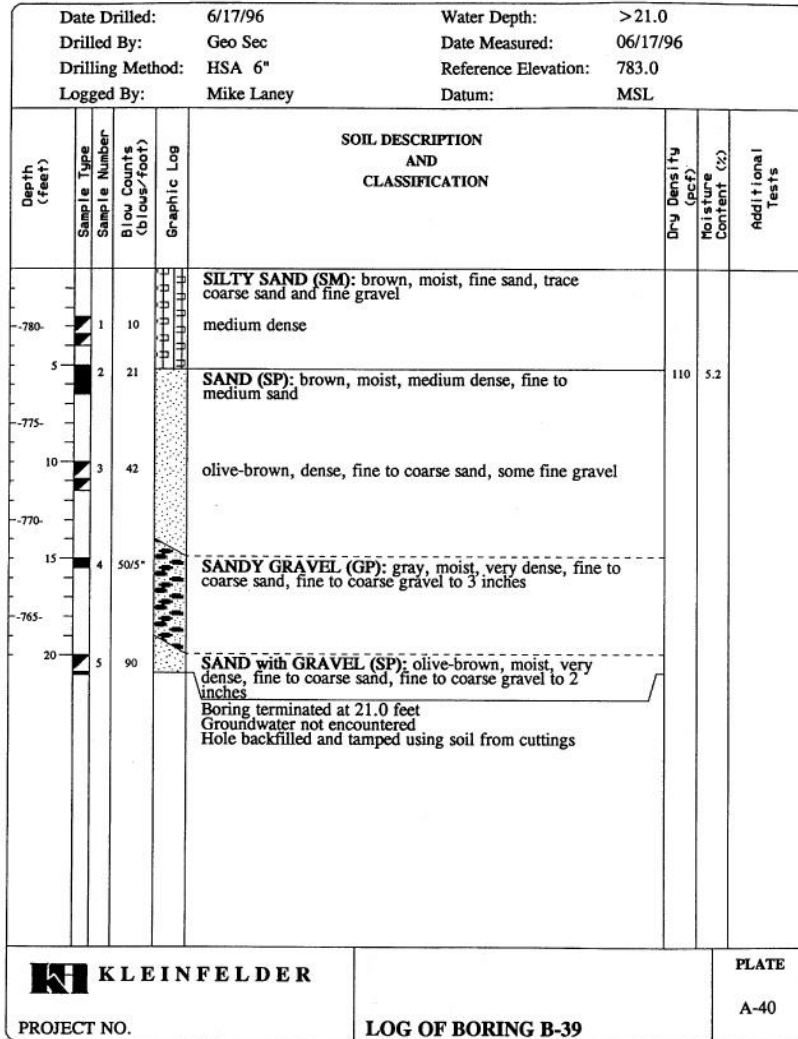
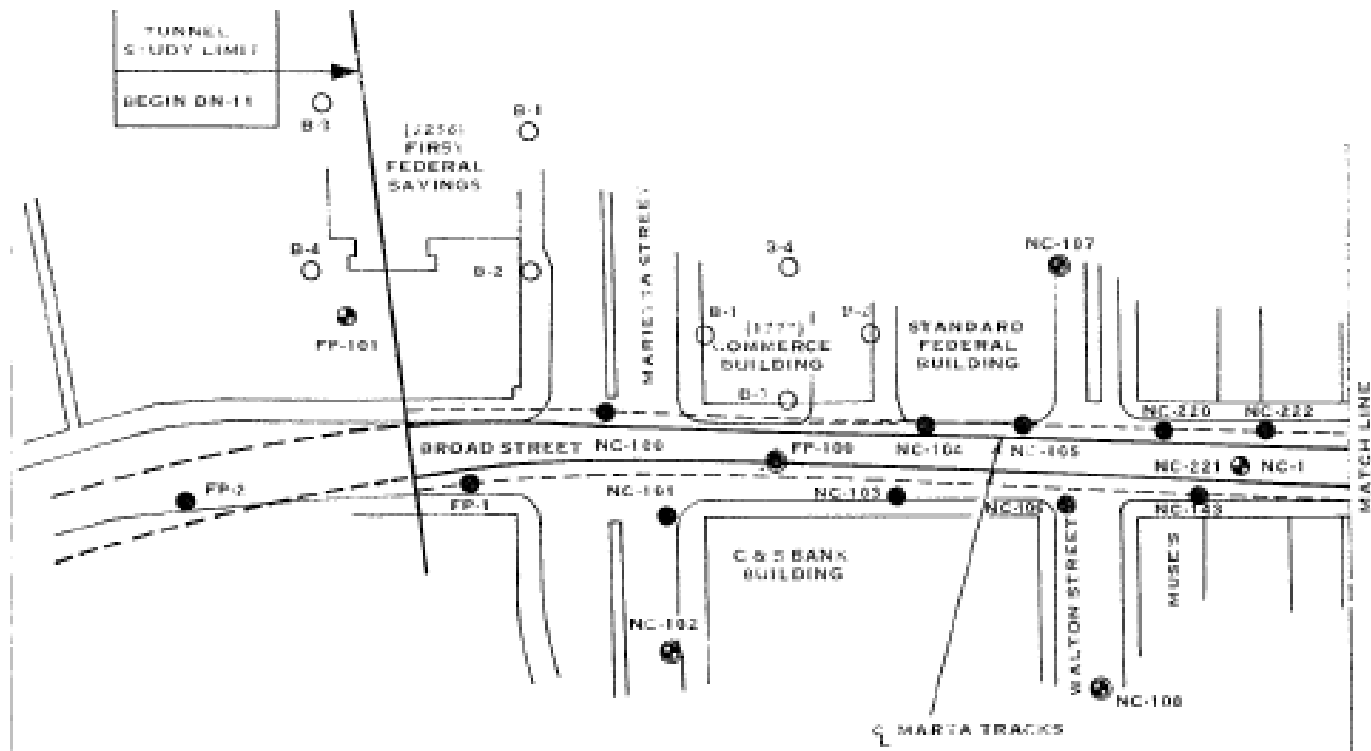
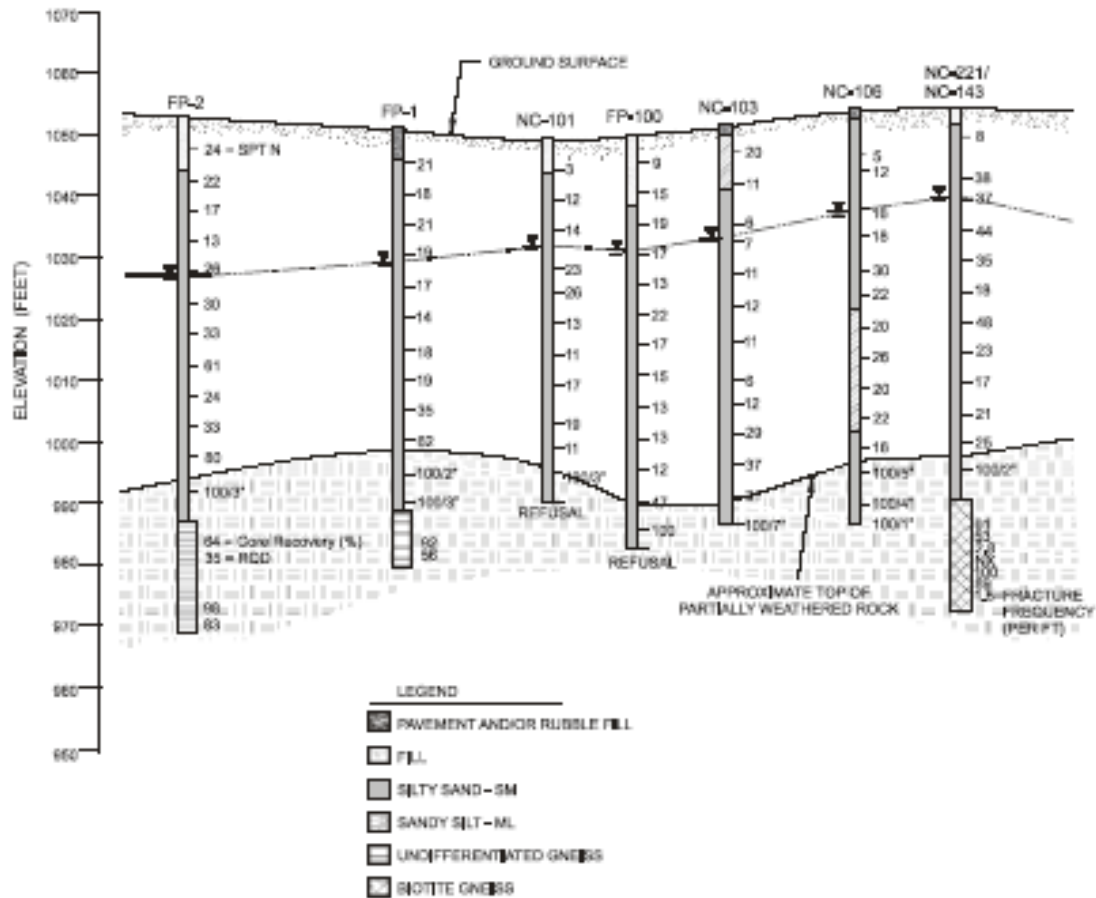


Figure 4.4 A boring log. Samples 2 and 4 were obtained using a heavy-wall sampler, and the corresponding blow counts are the number of hammer blows required to drive the sampler. Samples 1, 3, and 5 are standard penetration tests, and the corresponding blow counts are the N_{60} values.

Borehole distribution



Interpreted subsurface profile



Geotechnical Evaluation Report

- INTRODUCTION
- SITE DESCRIPTION
- FIELD INVESTIGATION AND LABORATORY TESTING
- SOIL AND GROUNDWATER CONDITIONS
- DESIGN CONSIDERATIONS
 - Seismic considerations
 - Site Preparation
 - Foundation alternatives
 - Construction considerations
- CONCLUSION AND RECOMMENDATIONS
 - Recommended foundation scheme and construction sequence.
 - Any other considerations, disclaimers, etc.
- APPENDICES

Summary

- Obtain enough information about foundation materials to predict soil response to proposed imposed loading
 - Develop geological model
 - Determine soil/rock stratigraphy and groundwater conditions at the site
 - Select soil model and representative parameters for input to analysis

Interpretation of Soil States

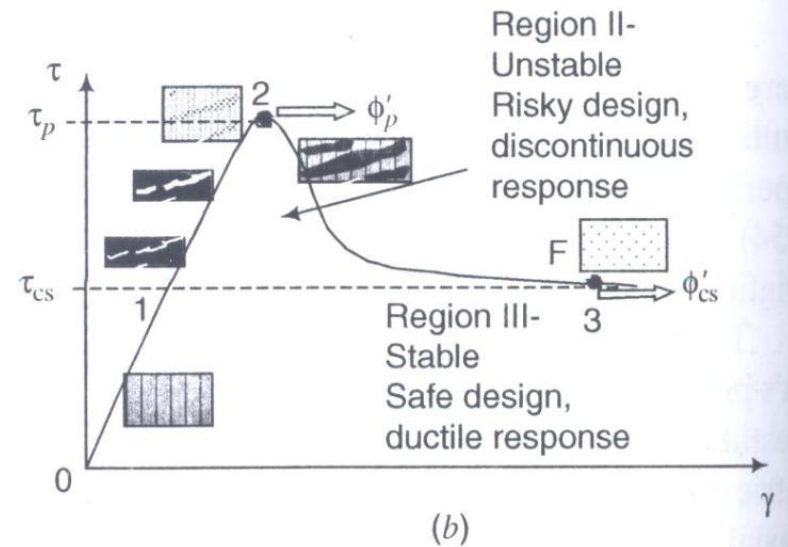
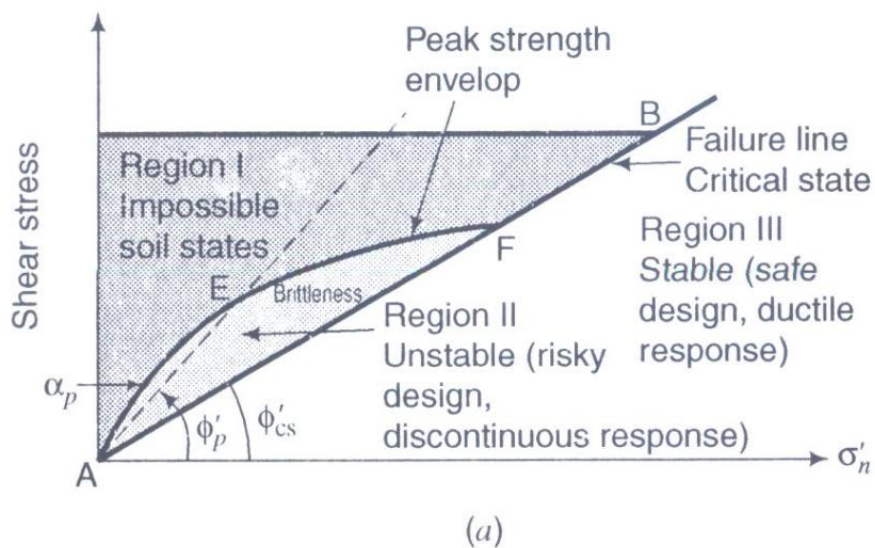


FIGURE 4.20 Interpretation of soil states.

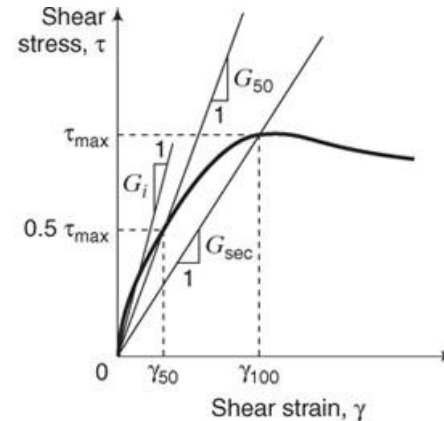
Soil Moduli

$$G = \frac{E}{2(1 + \nu)}$$

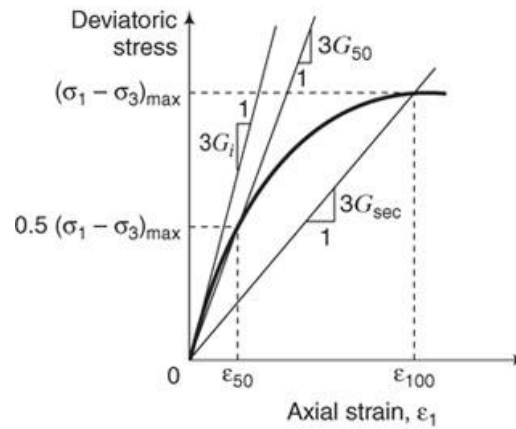
$$K = \frac{E}{3(1 - 2\nu)}$$

$$\gamma = \frac{2(1 + \nu)}{E} \tau = \frac{\tau}{G}$$

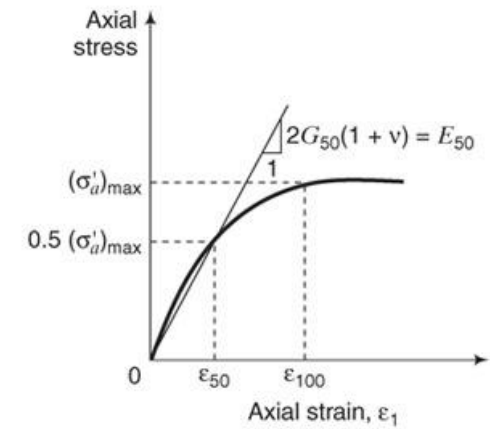
$$\varepsilon_p = \frac{p'}{K}$$



(a) Direct simple shear test

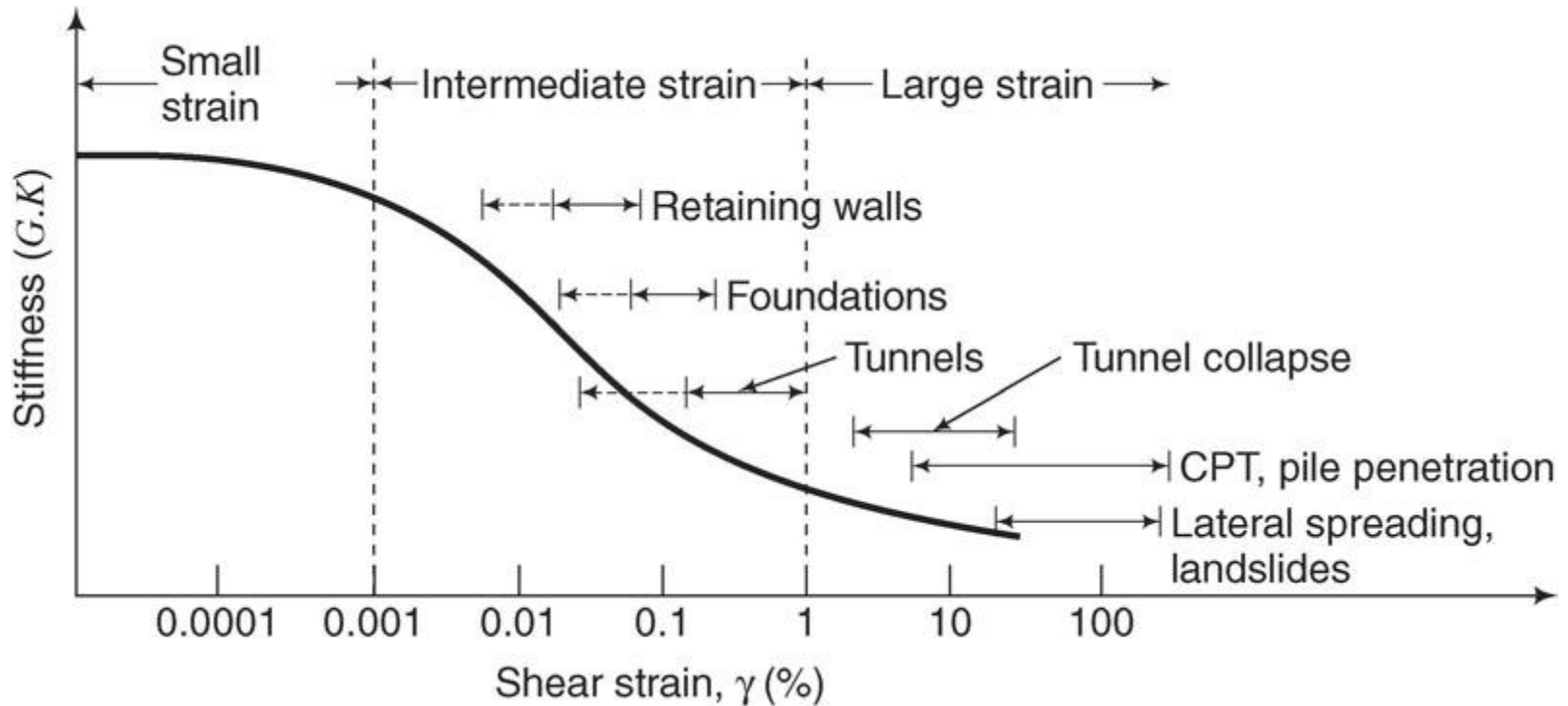


(b) Triaxial



Soil Moduli - 2

- Use appropriate stiffness parameter based on shear strain level



SOIL MECHANICS II
CIVL 311
COURSE NOTES
2012

Uncertainties in Foundation Design, Introduction to Limit States and Working Stress Design



Instructors: Dr. D. Wijewickreme, P. Eng.
Department of Civil Engineering
University of British Columbia

*Uncertainties in Foundation Design,
Introduction to Limit States and Working Stress Design*

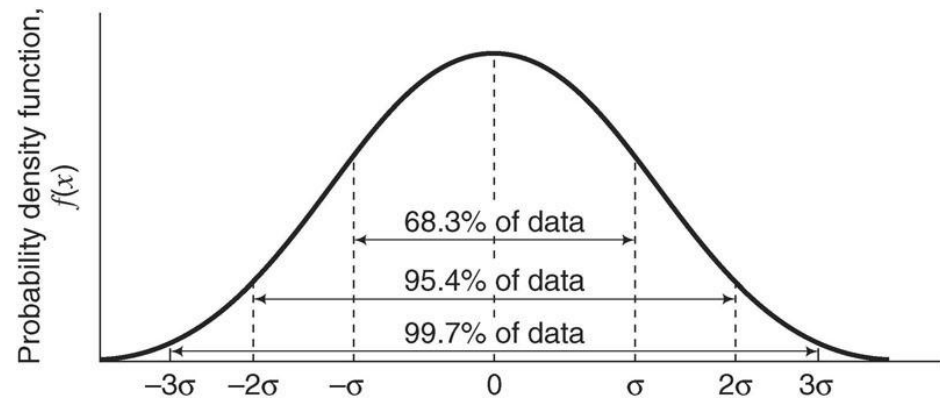
- *Overall Learning Objectives*
 - Understand uncertainties in geotechnical design;
 - Understand geotechnical design process;
 - Design methodologies (allowable stress design (ASD) and load resistance factor design)

Uncertainties in Foundation Engineering

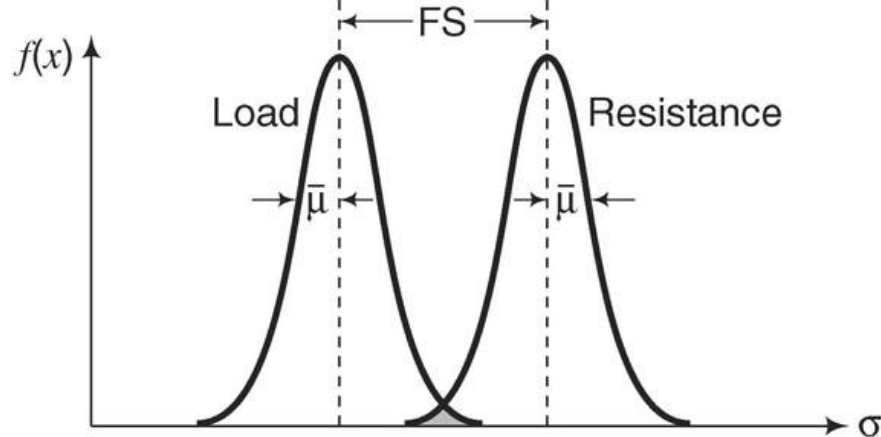
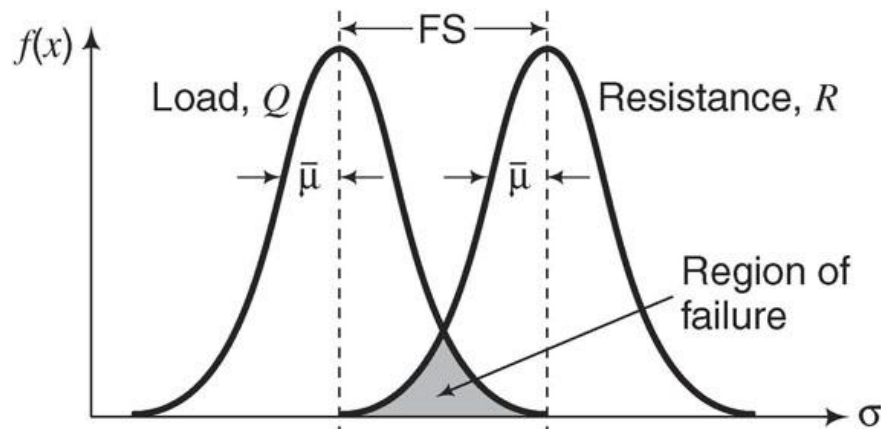
- Areas of uncertainties
 - uncertainty in the magnitude and direction of the loads
 - natural or inherent uncertainty from soil formation
 - epistemic uncertainty (lack of knowledge or incomplete or insufficient information)
 - human errors. Human errors (e.g. incorrect calculations, lack of experience) can be eliminated by quality control and will not be further discussed here.

Measures of uncertainties

- Normal distribution
- Log normal distribution (no negative values)
- Smaller COV \rightarrow lower variation from mean
- Data items tightly bunched together \rightarrow probability distribution curve is steep; the standard deviation is small (low level of uncertainty)
- Data items spread apart \rightarrow probability distribution curve is relatively flat; the standard deviation is large (high level of uncertainty).



Probability distributions for load and resistance



- Same factor of safety
- Different probabilities of failure

Uncertainty

- Despite uncertainty, the public expects engineers to be able to develop reliable and economical designs.
- Have to compromise between cost and reliability or probability of failure.
- Limit States Design provides framework

Approaches to design

- ASD - Allowable Stress Design
 - also known as working stress design or WSD
 - Traditional approach in Geotechnical Engineering
- LSD - Limit States Design
 - also known as Load and Resistance Factor Design or LRFD
 - First widely accepted LRFD Code was ACI code for reinforced concrete
 - Ontario Bridge Code uses LRFD

Allowable Stress Design

Factor of Safety = Resistance/Demand

- In geotechnical engineering, Factors of Safety vary with the type of problem being considered.
- **Factor of Safety** is to account for:
 - Uncertainty in the load
 - Uncertainty in material strength parameters
 - Uncertainty due to variability in ground at site
 - Uncertainty in the analysis method

TABLE 6.2 Typical Values of Factor of Safety

Foundation/earth structures	Factor of safety
Foundations—bearing capacity	2 to 3 (normally 3)
Retaining walls	1.5 to 2
Earthworks	1.3 to 1.5
Seepage—uplift	1.5 to 2
Piping	2 to 3
Slopes	1.25 to 1.75

Key points on uncertainties

- Foundation design consists of many uncertainties that should be reduced for safety and economics.
- Uncertainties due to natural processes such as soil formation cannot be eliminated.
- Epistemic uncertainties can be reduced and in some instances eliminated through sufficient, high quality information and assessment.
- There are several statistical measures that you can use to quantify uncertainties but you should use them in conjunction with engineering experience and physical reality.

LRFD or Limit States Design

Factored Resistance \geq Factored Load

- Factored Load = $\sum \rho_i Q_i = Q_u$
- For example $Q_u = 1.25 Q_{DL} + 1.5 Q_{LL}$
- Factored Resistance = $\Phi_R R_{ult}$
For example $R_f = 0.5 R_{ult}$

$$\Phi_R R_{ult} \geq Q_u$$

where R_f = Characteristic resistance
 Φ_R = Resistance Factor
 ρ_i = Load factor

TABLE 6.3 Load Factors

Loads	IBC		
	(2006)	CFEM	Eurocode 7
Dead (Q_{DL})	1.4	1.25	1.1
	0.9	0.8	0.9
Live (Q_{LL})	1.6	1.5	1.5
	0		
Fluid (Q_{FL})	1.4	1.25	1.0
	0	0.8	1.0
Earthquake (Q_{EL})	1.0		
Wind (Q_{WL})	1.6		
	0.8		
Lateral loads (Q_{HL})	1.6		
	0		

Top values are maximums and lower values are minimums.

Which design method should be used?

- ASD is called conventional design because it has been the method in use over the last 50 years in geotechnical practice.
- LRFD is a popular choice in structural engineering.
- LRFD is growing in popularity in geotechnical design mainly because it is desirable that design methods in structures and geotechnical engineering be consistent, coherent and compatible.
- As LRFD matures, it is quite likely to become the preferable method of design because it attempts to rationally address the many uncertainties of materials, construction and analysis.

ASD vs LRFD

- The resistance factors in LRFD
 - intended to consider the uncertainties in the analysis, soil properties and methods of obtaining them, construction practice, etc,
 - have been obtained by calibration to match the design obtained by ASD using factors of safety consistent with good engineering practice and experience.
- Designs obtained using ASD and LRFD are likely to be similar.

Which design method should be used? 2

- Both ASD and LRFD are strength – based methods, i.e. prevent collapse
- A separate analysis is needed to check that deformations do not exceed the serviceability limit state.
- Serviceability limit state governs the design of many geotechnical systems (for example, shallow foundations and retaining walls).

NB: The load factor for serviceability limit state is 1.0

Design methods – serviceability limit state

Relative rotation δ/L	Type of structure
1/150	Statically determinate structures with flexible cladding and retaining wall
1/250	Open steel and reinforced concrete frames, offshore platforms, steel storage tanks and tilt of high, rigid structures
1/500	Panel walls of frame buildings and tilt of bridge abutments
1/1000	Sagging of un-reinforced load-bearing walls
1/2000	Hogging of un-reinforced load bearing walls

Structural – Geotechnical Interaction

- Problem: In the current state of practice with both Allowable Stress and Limit States design being used, there is often confusion as to what a given load or capacity represents.
- It is important to have a clear understanding of both the Allowable Stress and Limit States Methods and to communicate clearly on which is being used.

Key Points on Design Methods

- The allowable stress design method does not consider the uncertainty in loads and soil parameters. A factor of safety (an arbitrary, subjective value based on experience) is applied to the ultimate resistance to reduce the potential for failure.
- The load and resistance factor design method is based on consideration of the uncertainties of the loads and the soil resistance.
- LRFD is calibrated against ASD using factors of safety consistent with good engineering practice. Therefore, LRFD and ASD with the appropriate factor of safety should produce the same design.