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ENHANCED GEOTECHNICAL SITE CHARACTERIZATION

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ABSTRACT:

Geotechnical engineers are confronted with the need to interpret engineering properties of natural soils and treated ground from laboratory and field test data for use in analysis of stability, deformation, and flow problems. Laboratory testing provides the necessary reference background with which the various soil properties are defined, yet the majority of data utilized by practicing geo-engineers come from field testing. The standard penetration test (SPT) is well-known, but overused in trying to extrapolate the wide diversity of soil engineering parameters from a single N-value. Emphasis is therefore given towards the utilization and interpretation of in-situ cone penetration tests (CPT) for site characterization, since multiple readings are taken in a single sounding. The basic test provides two readings: cone tip stress (q_c) and sleeve friction (f_s), yet it is important that porewater pressures (u) also be measured (piezocone test = CPTu or PCPT) because a necessary correction of tip stress (q_t) becomes paramount when testing in clays and silts. The test has a rigorous basis in theory and thus amenable to interpretation for a selection of soil parameters, including relative density (D_R), effective friction angle (ϕ'), and liquefaction potential of sands, and preconsolidation stress (σ_{vmax}'), undrained shear strength (s_u), and the coefficient of consolidation (c_h) in clays. Additional sensors can be incorporated in the CPT to provide measurements of resistivity, shear wave velocity, dielectric (permittivity), and pressuremeter-type parameters. Of particular interest, the seismic piezocone with dissipation phases (SCPTu) provides five independent readings with depth and the seismic flat dilatometer (SDMT) provides four readings, thus optimizing the types & amounts of information collected in assessing the complex behavior & nuances of geomaterials. The downhole shear wave velocity provides a measure of fundamental stiffness at small-strains that applies to static & dynamic, as well as undrained & drained loading conditions.

IN-SITU	LABORATORY
ADVANTAGES	
• Test soil in natural environment	• Well-controlled boundary conditions
• Generally fast and economical	• Controlled drainage conditions
• Immediate results for evaluation	• Engineering parameters well-defined
• Frequent/Continuous profiles	• Can measure σ-ϵ-τ_{max}-time effects
DISADVANTAGES	
• Unknown drainage conditions	• Time-consuming and expensive
• Issue of variability	• Only test small specimens
• Boundary effects not known	• Need high-quality samples
• Severe disturbance for most tests	• Discrete testing

TABLE OF CONTENTS

UNITS CONVERSION

Parameter	Measure	Conversions
length	foot (ft) inch (in)	0.3048 meters (m) 25.4 millimeters (mm)
mass	pound (lb)	0.4526 kilograms (kg)
force	ton (t)	2000 pounds (lb) 2 kips (k) 8.896 kiloNewtons (kN)
	pound (lb)	4.45 Newtons (N)
	kip (k)	4.45 kiloNewtons (kN)
stress	atmosphere (atm)	1.058 tons/square foot (tsf) 2.116 kips/square foot (ksf) 1.033 kilograms/square centimeter 101.3 kiloNewtons/square meter (kN/m^2) 101.3 kiloPascals (kPa) 0.1013 MegaNewtons/square meter (MN/m^2) 14.70 pounds/square inch (psi) 1.013 bars
	kiloPascal (kPa)	1.000 kiloNewtons/square meter (kN/m^2) 20.9 psf 0.145 psi
unit weight	pound/cubic foot (pcf) (actually pound-force)	0.157 kiloNewtons/cubic meter (kN/m^3)
density	pound/cubic foot (pcf) (actually pound-mass)	16.02 kilograms/cubic meter (kg/m^3)

Notes: 1 atm (p_a) ~ 1 tsf ~ 2 ksf ~ 1 ksc ~ 100 kN/m^2 ~ 100 kPa ~ 0.1 MN/m^2 ~ 14.7 psi ~ 1 bar
unit weight of fresh water (γ_w) = 62.4 pcf = 9.80 kN/m^3
unit weight of salt water (γ_{ws}) = 64.0 pcf = 10.0 kN/m^3

In-Situ Testing and Site Characterization

Abbreviations for References in Geotechnical Publications

Societies:

ASCE - American Society of Civil Engineers, New York.
ASTM - American Society for Testing and Materials, Philadelphia.
BRE - Building Research Establishment, U.K.
EPRI - Electric Power Research Institute, Palo Alto, CA.
FHWA - Federal Highway Administration, Wash. D.C.
ICE - Institution of Civil Engineers, London.
ISMES - Geotechnical Testing Laboratory, Bergamo, Italy.
ISSMFE - International Society of Soil Mechanics and Foundation Engrg.
JSSMFE - Japanese Society of Soil Mechanics and Foundation Engrg (now the Japanese Geotechnical Society).
NGI - Norwegian Geotechnical Institute, Oslo.
NTH - Norwegian Institute of Technology, Trondheim University, Norway.
NRCC - National Research Council of Canada, Ottawa.
SGI - Swedish Geotechnical Institute, Linkoping.
TRB - Transportation Research Board, Wash. D.C.
WES - Waterways Experiment Station, US Army Corps of Engrs., MS

Types of Publications:

CGJ - Canadian Geotechnical Journal, NRCC.
Geot. - Geotechnique, Journal by ICE.
GSP - Geotechnical Special Publication (ASCE).
GT - Geotechnical Division of ASCE = Journal of Geotechnical Engineering.
GTJ - Geotechnical Testing Journal, ASTM.
ECSMFE - European Conference on Soil Mechanics and Foundation Engineering.
ICSMFE - International Conference on Soil Mechanics and Foundation Engineering.
JGE - Journal of Geotechnical Engineering, ASCE.
JSMFD - Journal of Soil Mechanics and Foundations Division, ASCE ("old JGE").
OTC - Offshore Technology Conference, Houston.
STP - Special Technical Publication (ASTM).
S&F - Soils and Foundations, Japanese Geotechnical Society, Tokyo.
TRR - Transportation Research Record (TRB), Washington, DC.

Special Publications:

ESOPT-1 - European Symposium on Penetration Testing, Stockholm, (Balkema) 1974.
ESOPT-2 - European Symposium on Penetration Testing, Amsterdam, (Balkema) 1982.
In-Situ '86 - Use of In-Situ Tests in Geot. Engrg. (ASCE GSP 6), Blacksburg, VA 1986.
ISOPT - International Symposium on Penetration Testing, Orlando, (Balkema) 1988.
ISOCCT - International Symposium on Calibration Chamber Testing, Clarkson (Elsevier) 1991.
PTUK - Penetration Testing in the U.K., ICE, Birmingham, UK, (Thomas Telford) 1988.
CPT'95 - Proceedings, Intl. Symposium on Cone Penetration Testing, Linköping, Sweden, 1995.

CEE 6423 - Websites on In-Situ Testing & Site Characterization

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USUCGER Links: http://www.usucger.org/insitulinks.html
(U.S. Universities Council on Geotechnical Engineering Research)

Electronic Journal of Geotechnical Engineering:

http://geotech.civen.okstate.edu/magazine/soiltest.htm

Videos and CDs:

http://www.liquefaction.com/insitutests/cpt/mayneCPTlinks.htm

WEBSITES of REFERENCE

Soil Sampling, Drilling Rigs, & Augering Equipment details at:

http://www.christensenproducts.com/html/products.htm

http://www.ams-samplers.com/amss1.html

http://www.paddockdrilling.com/html/ct250.html

Direct-push soil sampling:

http://www.ams-samplers.com/amsc1.html

http://www.geoprobesystems.com/66dtdesc.htm

Websites on Vane Shear Test (VST) or field vane (FV) are shown at:

http://www.pagani-geotechnical.com/

http://www.geonor.com/Soiltst.html

http://www.envi.se/products.htm

http://www.geotech.se/Vanes/evt-2000.html

http://www.liquefaction.com/insitutests/vane/index.htm

Geophysical testing & equipment:

http://www.matrixmm.com/geophysics_cd-rom.htm

http://www.pagani-geotechnical.com/english/geophi.htm

http://www.geometrics.com/products.html

http://www.geonics.com/products.html

http://www.gdsinst.com/barcpap.html

Pressuremeter Testing (PMT):

http://www.pagani-geotechnical.com/english/pressure.htm

Coneheads will be interested in penetrometer equipment and cone rigs at the following sites related to Cone Penetration Testing (CPT):

[The CPT site]: http://www.liquefaction.com

http://www.fugro.com/cpt.html

http://www.ara.com/division/arane/cpt/CPTList.htm

http://www.conetec.com/

http://www.apvdberg.nl/

http://www.pagani-geotechnical.com/english/geotec2.htm

http://www.geomil.nl

Sites on Flat Plate Dilatometer Test (DMT):

http://www.pagani-geotechnical.com/english/dmt.htm

http://webdisat.ing.univaq.it/labs/labgeo.html

http://www.gpe.org/products/dmt.htm

http://webdisat.ing.univaq.it/labs/dmt/geodmt.html

In-Situ Testing & Site Characterization

FORMAT FOR EXAMS and HOMEWORK ASSIGNMENTS

Please use the following format:

1. Document your work with your name and date on each page.

2. Cite the references of each graph, equation, correlation, chart, & table used in your solution [for your own future documentation].

3. Please use **SPREADSHEETS** (or Mathcad) for homeworks, especially where graphs and figures can assist in presentation of results. QPRO, Excel, Lotus 1-2-3, Symphony all will be adequate for these purposes. Be sure to use x-y graphs to plot results of data synthesis and equations [e.g, not use the line graph option]. If need be, use a software package just for the graphics (e.g., CoPlot, Grapher, Surfer,.....).

4. When graphing, use scaled axes (preferably by computer). Use evenly numbered scales (i.e. 10, 20, 30 etc. and not uneven enumeration (e.g., not 7, 14, 21, 28, etc). Please label all axes legends (with appropriate units). Put in realistic ranges for the graph axes. In many cases, it is not necessary to include every single point (in other cases, yes it is). There should be some judgment. Don't Let Bill Gates draw YOUR graphs. You do it. Try to optimize the graphs features. Make an art form out of your graphs so that you can Present them in Corel, Freelance, or Powerpoint. Also, save paper: Put 2 or 4 graphs on each page, if possible

5. Be careful of **UNITS** conversions and *LABEL* all answers, graph axes, and tables with the correct units. Numbers without proper units are meaningless in today's world of engineering.

6. Do your own work. **Do not** hand in the same spreadsheet as someone else that has the same legends, same fonts, same graphs, same layout, same nine-place decimals .

7. Be neat and prepare your work properly in an organized format for the grader and faculty to examine.

8. Use no more than 4 or 5 single sheets of paper (i.e., use both sides of paper). Think ***Sustainable Environment.*** Do not produce endless pages of numbers from computer dumps. **Put 2 or 4 graphs on each page, if possible.**

9. If you have questions, please feel free to email (or call. or even stop by) and obtain clarification on those items that need additional details.

10. Please abide by the GT Honor Code.

Geologic Origins

Soil and rock materials on the surface of the planet Earth have resulted from varied and different geological and environmental origins. The exploration of the subsurface media therefore requires a variety of tools to penetrate the ground and provide samples. The types of drilling and testing methods will depend upon the mineralogy, consistency, and age of the formation, as well as the geologic history. Common rock origins include: sedimentary, igneous, and metamorphic. Soil origins include: marine (sedimentary from seas and oceans), glacial, lacustrine (lakes), alluvial and fluvial (river deposits), deltaic (mouth of river), diluvial (flooding), colluvial (mass wasting from slope), eolian (wind-blown materials), and residual (weathered inplace from rock decomposition), as well as combinations of these.

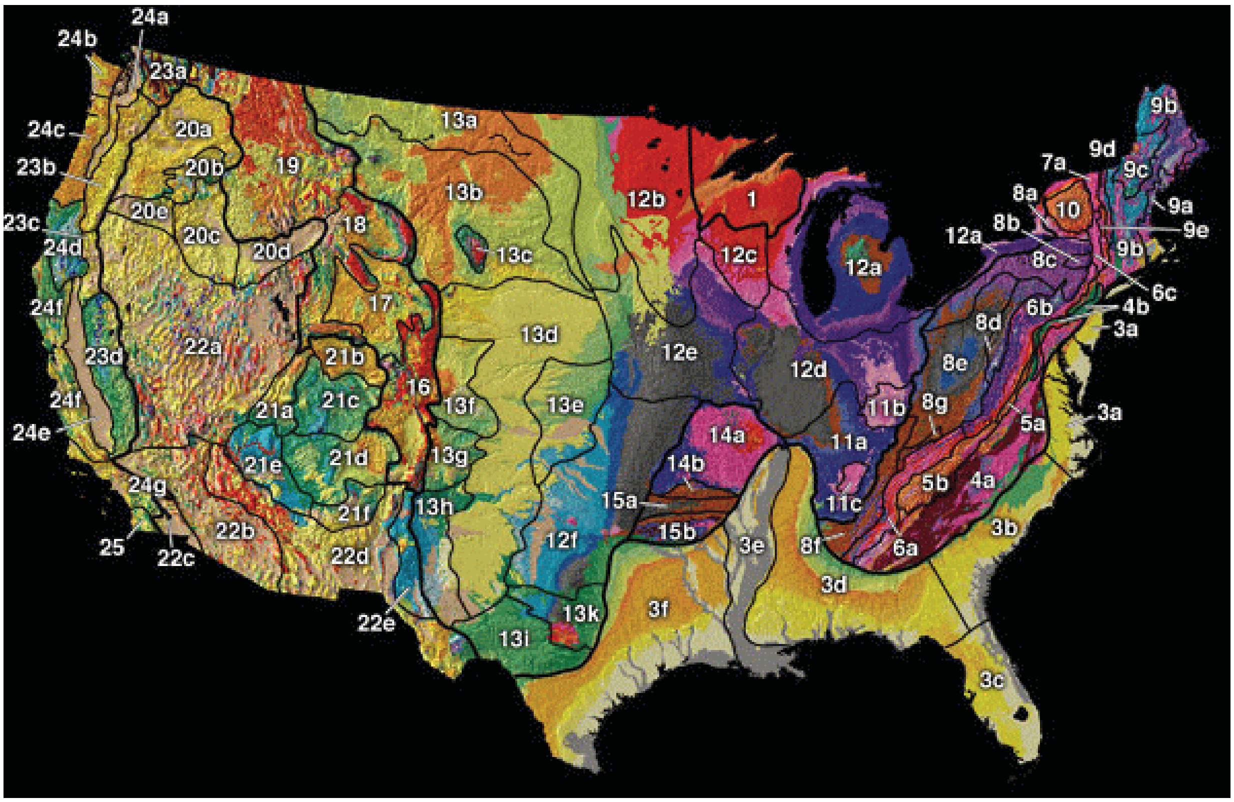


Figure GO-1. Landform map of the U.S. showing surficial soil deposits (www.usgs.gov).

In complex scenarios, the stratification may have alternating formations of differing origin, as when fresh-water deltaic deposits form next to salt-water sediments at seaside coasts. In other circumstances, soils originally placed in a salt-water environment may be subject to leaching whereby the salt is washed from the pores due to isostatic uplift, changes in the groundwater environment, or post-glacial activities. In these case, the leaching has often resulted in voids left in the soil fabric, as is common with sensitive clays which extend along the U.S. eastern seaboard, from Virginia to Massachusetts to Quebec.

A program of geophysical surveys can be useful in delineating the overall geostratigraphy of soil and/or rock layers at a given site. These may include seismic refraction, resistivity, ground penetrating radar, and other techniques. For geotechnical evaluations, a phase of drilling, sampling, and in-situ field testing will be required to further assess the actual depths & thicknesses of the layers, the consistency of the materials (e.g., soft or loose, hard or dense), and the soil engineering parameters (geostatic stress state, degree of preconsolidation, strength, stiffness, permeability).

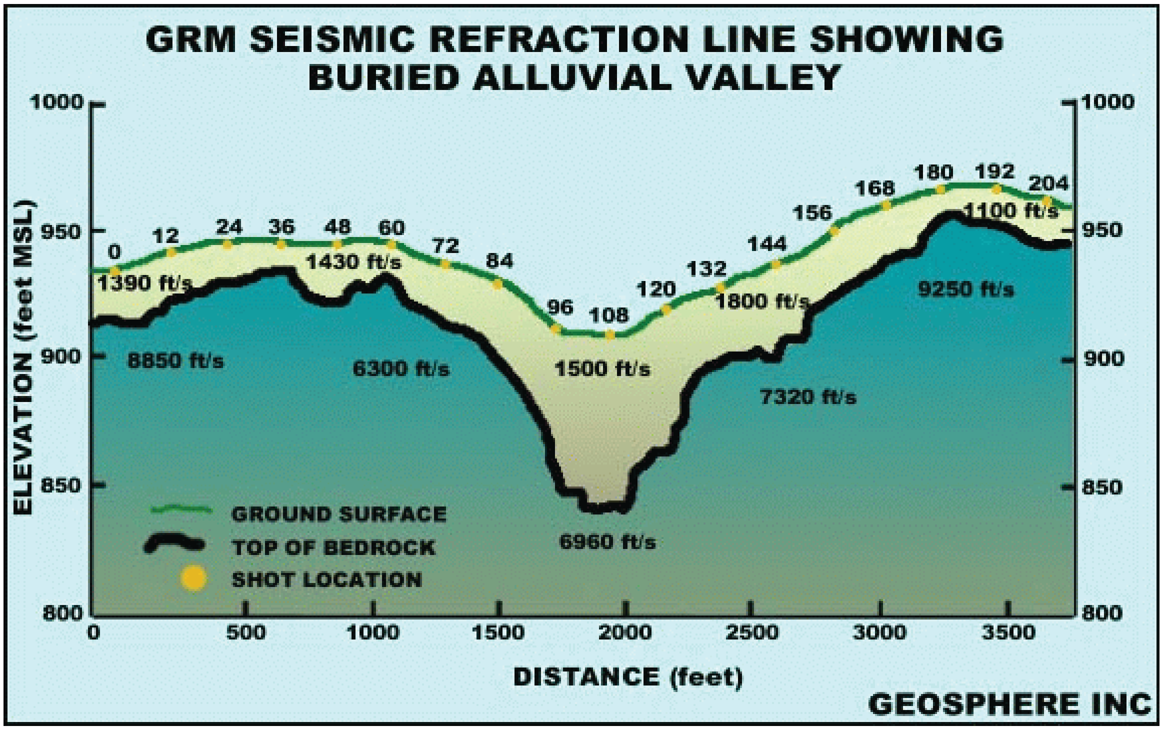


Figure GO-2. Results of Geophysical Seismic Refraction Survey showing the implicated depth to bedrock and respective compression wave velocities of soil overburden and underlying rock. (www.geosphere.com).

It is important to obtain an understanding of the geologic background of the subject site prior to field investigation and sampling. As 75 percent of today's Earth is covered by large oceans, yesterday's Earth was similar such that a good portion of the crust is underlain by sediment of marine origin. Under increasing overburden stresses, "unconsolidated" sediment (in the geologic sense of the word) becomes compressed and formed into sedimentary bedrock, as in clay to shales and mudstones, clay & shells transformed to limestone, silt to siltsone, and sand to sandstone (see map by Pough, 1988). With age and in-place chemical and mechanical weathering, however, the reverse process may take place, such that the rocks deterioriate and decompose into soils. These residual soils and saprolitic materials behave quite differently than sediment.

If the sedimentary rocks are subjected to increasing overburden stresses, the materials are converted into metamorphic rocks. Examples include the transformation of limestone into marble and sand into quartzite. In increasing degrees of metamorphism, the sedimentary shale bedrock is converted into slate, then to phyllite to schist to gneiss. At deeper depths, the crustal boundaries of interplate tectonics result in magma as adjacent plates collide and the volcanic activities produce lavas that cool to form igneous rock types including extrusive basalts, obsidians, and tuffs and the intrusive granites, gabbros, diabase, and diorites.

With age and in-place chemical and mechanical weathering, however, the reverse processes may take place, such that the rocks deterioriate and decompose into soils. These are residual soils and saprolities that behave quite differently than sediment. Examples include the famous residual clays of Brazil weathered from gneiss and clayey sands of Hong Kong weathered from granites, both highly susceptible to slope instability and landsliding problems. In Hawaii, the volcanic rocks weather to form porous plastic clays. In the eastern U.S., the Piedmont consists of residuum (silts and sands) weathered inplace from schist and granitic gneiss.

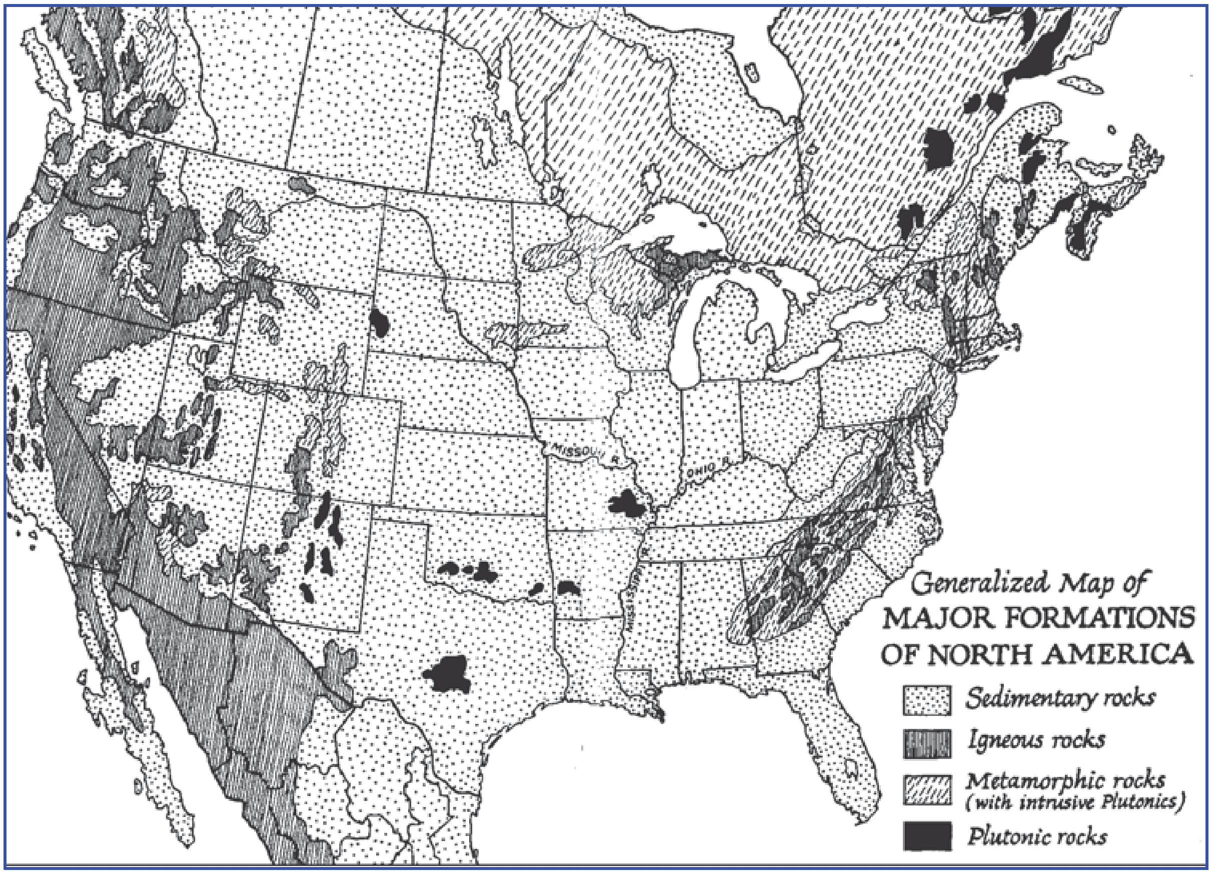


Figure GO-3. Generalized Map of Major Rock Formations of North America.
(Pough, F.H., 1988, *A Field Guide to Rocks & Minerals*, Peterson's Guidebook Series, Houghton-Mifflin, Boston, 317 p.).

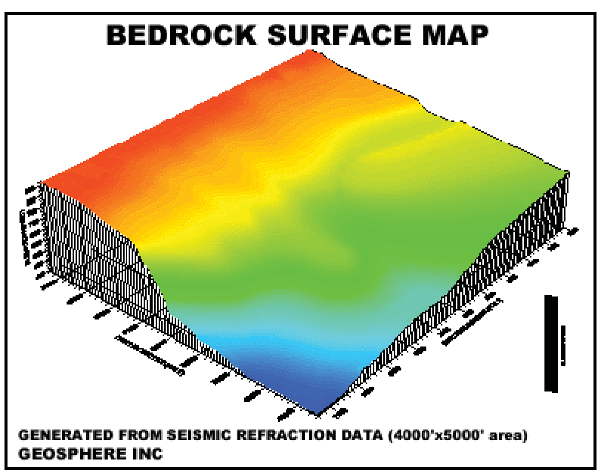


Figure G0-4. Bedrock Surface Map from Geophysical Survey Interpretation
(Reference: www.geosphere.com).

The Atlanta area is contained within the Piedmont Geologic Province, consisting of ancient metamorphic and igneous rocks (gneiss, schist, granite). These Paleozoic mountainous regions have long been eroded from the topography and only a few remnants are evident (e.g., Stone Mountain, Kennesaw Mountain., Black Jack Mountain, Lost Mountain). The weathering profile is highly erratic and variable over the region, with the result that at some locations, bedrock outcrops occur extending above the ground surface (e.g., just west of Hemphill & Ferst intersection on GT campus), whereas in other locations, the residual soil profile is thick and the depth to the bedrock surface is 30 meters or more. The relict structure of the residuum is variable due to differential weathering, as is the variation of soil properties.

In residual soil/rock profiles, one must anticipate the need for soil testing at shallow depth and perhaps the need to continue drilling using rock coring techniques, particularly if several sub-basement levels are planned for a building or if deep cut excavations must be made during site grading operations. In certain cases, the use of geophysical methods may be used to evaluate bedrock rippability. Since the cost of rock excavation is quite high (≈ $50/m^3$) compared with soil excavation (≈ $4/m^3$), it is important to characterize the soil-rock interface. In many cases, several gradations or categorizations of soil/weathered rock/partially-weathered/intact rock classifications are appropriate, depending upon the ease of extraction.

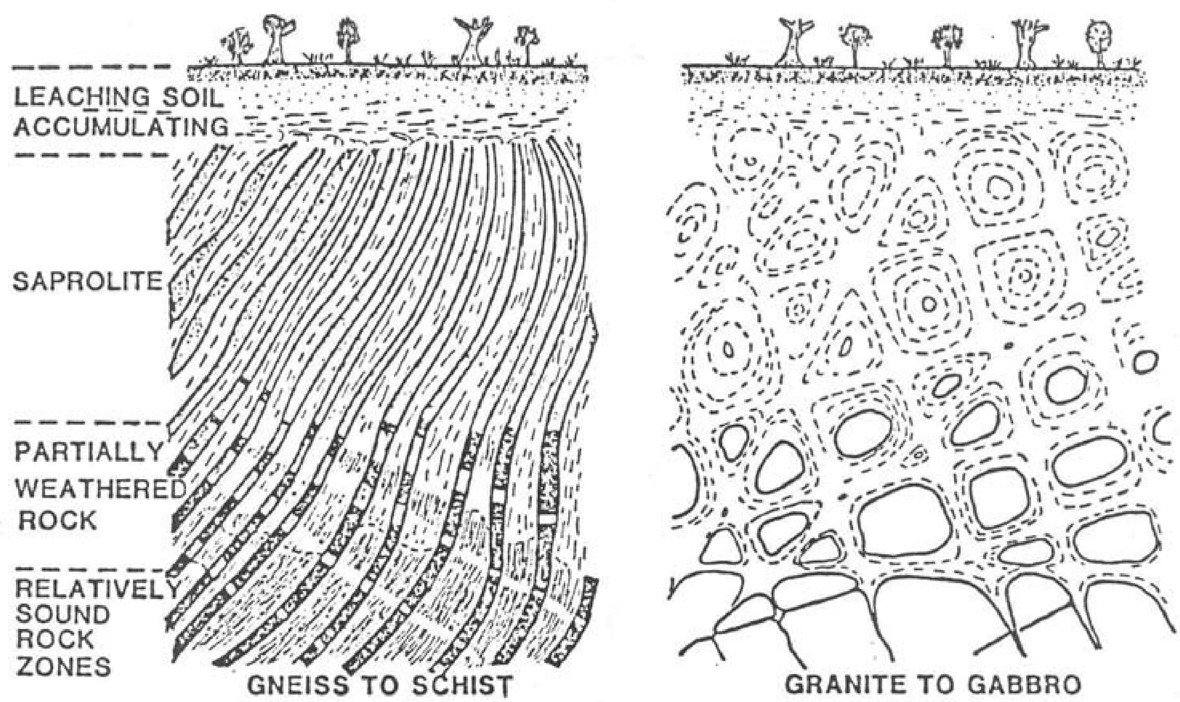


Figure GO-4. Residual Soils and Saprolites Profiles in Weathered Rock of the Piedmont Geology.

(Sowers & Richardson, *Transportation Research Record* No. 919, 1983).

In-Situ Drilling, Sampling, and Testing for Site Characterization

The traditional approach to characterizing a particular site for stratigraphy and the evaluation of soil engineering parameters has been to drill borings (auger or rotary methods) and collect samples at regular intervals. The borings can be advanced into soil using solid flight augers ($z < 10$ m), hollow stem augers ($z < 30$ m), or wash boring techniques using rotary drilling techniques ($z > 30$ m). If the borings must continue into bedrock material, usually wash boring methods with diamond bit coring techniques are used to obtain intact rock core samples. If no rock samples are needed, a tri-cone bit can be used to obliterate a hole. If deep borings are needed ($z > 60$ m), wire-line drilling is used whereby special cable systems are used to transport the core samples to the surface.

In soils, the samples are obtained using a variety of hollow tube-type devices: split-barrel (or spoon), thin-walled (shelby) tube, piston, denison, and pitcher samplers. Drive-type samplers (split-barrel or split-spoon) correspond to the standard penetration test (SPT), as detailed in ASTM Standard D-1586. The shelby tube and piston samplers are hydraulically pushed into the ground. The denison and pitcher samplers utilize jacking and coring to obtain soil samples (see ASTM D-4700 for overview). The samples are transported (carefully) back to the laboratory for extrusion, trimming, and testing. Several specimens are usually obtained from each tube sample. Index tests (plasticity, water content, grain size) are conducted for classification purposes. Geotechnical engineering parameters (stiffness, strength, rate and flow response) are obtained by subjecting the specimens to consolidation, triaxial, direct shear, and permeability testing.

The latest trend in characterizing soil materials is via in-situ tests and probes whereby the soils are tested in their natural environment. These include the cone penetration test (CPT), piezocone (PCPT), pressuremeter (PMT), flat dilatometer (DMT), vane shear test (VST), and various in-situ geophysical techniques, such as crosshole test (CHT), downhole (DHT), and spectral analysis of surface waves (SASW). The simple geophysical survey using the seismic refraction of P-waves is useful for detecting the depth to shallow rock. The downhole test is a quick and economical means of profiling S-waves for determining the static and dynamic stiffness of soils..

Figure SC-1: Computerized Cone Truck for In-Situ Testing of Subsurface Media.

Types of In-Situ Tests and General Applicability

There are a great number of different tools and devices used for the in-situ measurement and evaluation of soil parameters or soil properties. Wroth (1984, Geotechnique) and Robertson (1986, CGJ) provide a general listing and description of the various types of tests and their applicability for certain soil types and geologies. Many of the devices are limited to sands, silts, and clays, with only a few appropriate in very coarse materials such as gravels and cobbles. Specialized devices are available for measurement in rock masses.

Certain tools have been developed for a specific need, while others have been expanded to provide interpretations of multiple soil parameters. For example, the push-in spade cell (total stress cell) provides a single measurement corresponding to the in-situ total horizontal stress (σ_{ho}) in soft to stiff clays. In contrast, utilization of the flat dilatometer in soils has been expanded and empirically correlated with many soil properties (ϕ', D = 1/m_v, c_v) and soil parameters (K_o, OCR, s_u, D_r, γ_T).

TABLE: General Applicability of Various In-Situ Tests
Ref: Robertson, P.K., 1986, Canadian Geotechnical Journal 23 (4), 573-584

	Geotechnical information													Ground conditions						
Test method	Soil type	Profile	Piezometric pressure (u)	Angle of friction (ϕ)	Undrained shear strength (S_u)	Density (D_r)	Compressibility (m_v, C_c)	Rate of consolidation (C_v, C_h)	Permeability (k)	Modulus: shear and Young's (G, E)	*In situ* stress (K_0)	Stress history (OCR)	Stress–strain curve	Hard rock	Soft rock—till, etc.	Gravel	Sand	Silt	Clay	Peat—organics
Dynamic cone (DCPT)	C	B	—	C	C	B	—	—	—	C	—	—	C	—	C	B	A	B	B	B
Static cone:																				
Mechanical	B	A	—	B	C	B	C	—	—	C	C	C	—	—	C	—	A	A	A	A
Electronic friction (CPT)	B	A	—	B	C	B	C	—	—	B	C	C	—	—	C	—	A	A	A	A
Electronic piezo	B	A	A	B	B	B	C	A	B	B	C	B	B	—	C	—	A	A	A	A
Electronic piezo/friction (CPTU)	A	A	A	B	B	B	C	A	B	B	C	B	B	—	C	—	A	A	A	A
Electronic seismic/piezo/friction (SCPTU)	A	A	A	B	B	B	C	A	B	A	B	B	B	—	C	—	A	A	A	A
Acoustic probe	B	B	—	C	C	C	C	—	—	C	—	C	—	—	C	—	A	A	A	A
Flat plate dilatometer (DMT)	B	A	C	B	B	C	B	—	—	B	B	B	B	—	C	—	A	A	A	A
Field vane shear (VST)	C	C	—	—	A	—	—	—	—	—	C	B	—	—	—	—	—	B	A	B
Standard penetration test (SPT)	A	B	—	B	C	B	—	—	—	B	—	C	—	—	C	B	A	B	C	C
Resistivity probe	B	B	—	B	C	A	C	—	—	C	—	—	—	—	C	—	A	A	A	A
Electronic conductivity probe	A	B	—	C	C	A	B	—	—	B	C	C	C	—	—	—	A	A	A	B
Total stress cell	—	—	—	—	—	—	—	—	—	—	B	B	—	—	—	—	—	C	A	A
K_0 stepped blade	—	—	—	—	—	—	—	—	—	—	B	B	—	—	—	—	B	A	A	B
Screw plate	C	C	—	C	B	B	B	C	C	A	C	B	B	—	—	—	A	A	A	A
Borehole permeability	C	—	A	—	—	—	—	B	A	—	—	—	—	A	A	A	A	A	A	B
Hydraulic fracture	—	—	A	—	—	—	—	C	C	—	B	B	—	B	B	C	C	B	A	C
Borehole shear	C	C	—	B	C	—	—	—	—	C	—	C	—	B	B	C	B	B	C	C
Prebored pressuremeter (PMT)	B	B	—	C	B	C	C	C	—	A	C	C	C	A	A	B	B	B	A	B
Push-in pressuremeter (PPMT)	A	B	B	C	B	C	C	A	B	A	C	C	C	—	—	—	B	A	A	B
Full-displacement pressuremeter (FDPMT)	C	B	B	C	B	C	C	A	B	A	C	C	C	—	—	—	A	A	A	A
Self-boring pressuremeter (SBPMT)	B	B	A	A	B	B	B	A	B	A	A	A	A	—	C	—	B	A	A	A
Self-boring devices:																				
K_0 meter	B	B	—	—	—	—	—	—	—	—	A	A	—	—	—	—	B	A	A	A
Lateral penetrometer	B	B	—	B	B	B	—	—	—	B	C	C	C	—	—	—	B	A	A	A
Shear vane	B	B	—	—	A	—	—	—	—	—	C	B	—	—	—	—	B	A	A	A
Plate test	B	B	—	C	B	B	B	C	C	A	B	A	C	—	—	—	B	A	A	B
Seismic cross/downhole/surface	C	C	—	—	—	—	—	—	—	A	—	—	—	A	A	A	A	A	A	A
Nuclear probes	—	—	—	B	—	A	—	—	—	—	C	—	C	—	—	—	A	A	B	A
Plate load tests	C	C	—	C	B	B	B	C	C	A	C	B	B	B	A	B	B	A	A	A

NOTE: A = high applicability. B = moderate applicability. C = limited applicability. — = not applicable.

In addition to the consideration of the applicability of different test methods, there is a degree of reliability and accuracy associated with each test. Some tests are more difficult to perform than others and may require a considerable level of expertise in order to properly conduct in the field. Always remember the governing rule of in-situ testing: *MURPHY'S LAW* ("if something can and will go wrong, it will go wrong at the worst most possible time and place"). This oftens happens in field testing: You are out in the middle of nowhere with a laptop computer, power supplies, electronic cables and pneumatic tubing, and a thunderstorm appears; or the battery goes dead, or the air pressure dies out, or you snag the electrical cord; etc.

Of additional consideration is relative costs. Certain devices, such as the self-boring pressuremeter, will likely be used only on high-visibility projects and critical structures because they require high level of expertise and high costs (e.g., US $800/test). On the other hand, some very simple hand-operated field tests provide a rather low cost (e.g., dynamic cone), yet at a much lower degree of certainty in results.

Table: Degree of Reliability and Relative Costs of Major In-Situ Tests

Ref: Lunne, Lacasse, & Rad, 1992, General Report, *Proceedings*, 12th Interational Conference on Soil Mechanics & Foundation Engineering, Vol. 4, Rio, 2239-2403.

TEST EQUIPMENT (Section 3)	Soil Type	INTERPRETATION (Section 4): Initial State Parameters (4.1)					Strength Parameters (4.2)			Deformation Charact. (4.3)			Flow Charact. (4.4)		Direct Application (4.5)							Relative cost of performing test
Section ↓	Section →	γ, D_r (4.1.1)	ϕ (4.1.2)	K_o (4.1.3)	OCR (4.1.4)	S_t (4.1.5)	s_u (4.2.1)	ϕ'_δ (4.2.2)	$\phi'_{c'}$ (4.2.3)	E, G (4.3.1)	M (4.3.2)	G_{max} (4.3.3)	k (4.4.1)	c_v (4.4.2)	A_{PC} (4.5.1)	L_{PC} (4.5.2)	L_P (4.5.3)	C_P (4.5.4)	S_{PR} (4.5.5)	C_C (4.5.6)	S_F (4.5.7)	
Cone Penetrometer[a] (3.1)	Clay			4-5	3	2-3	2-3		3-4	5	5	5	2-4	2-3	1-2	P		2-3	1-2	2		I-II
	Sand	2-3	2	4-5				2		2-4	2-4	2-3			1-2	P	2-3	3	1-2	1	2-3	
Dilatometer (3.2)	Clay	3		2	3		3		P	2-4	2-4	4	2-4	2-4	3	2				2		I
	Sand	2-3	3	3	4			3		2-3	2-3	3					3			1	2-3	
Field Vane (3.3)	Clay			2	2-3	1	1-2		4	5												II
	Sand																					
Pressuremeter (3.4)	Clay			1-3[b]			4		3	1-2[c]		P	2-4	2-4	4	2		3		3	3-4	III-V
	Sand			2-3[b]				1-3		1-2[c]		P			4	2-4	P	3		3	3-4	
Seismic Cone[a] (3.5)	Clay			4-5	3		2-3		3-4	5	5	1	2-4	2-3	1-2	P		2-3	1-2	2		III
	Sand	2-3		4-5				2		2-4	2-4	1			1-2	P	2-3	3	1-2	1	2-3	
Density Probes (3.6)	Clay	1-2																		1		III-IV
	Sand	1-2																		1		
Total Stress Cells (3.7)	Clay			2									P	P								III
	Sand			P																		
Piezometers and BAT Probe (3.8)	Clay			2									1-2	1-3								III
	Sand												1-2	2-3								

RATING

1 - High reliability
2 - High to moderate reliability
3 - Moderate reliability
4 - Moderate to low reliability
5 - Low reliability

LEGEND

a) Including piezocone
b) Self-boring pressuremeter only
c) Unload-reload modulus (elastic response)

P Device has potential

ABBREVATIONS

APC - Axial Pile Capacity
LPC - Lateral Pile Capacity
LC - Liquefaction Potential
CP - Creep Parameters in frozen soils
SPR - Skirt Penetration Resistance
CC - Compaction Control
SF - Shallow Foundation

RELATIVE COST

I - Low

V - High

7

Results from in-situ tests may be evaluated by a number of different approaches including:

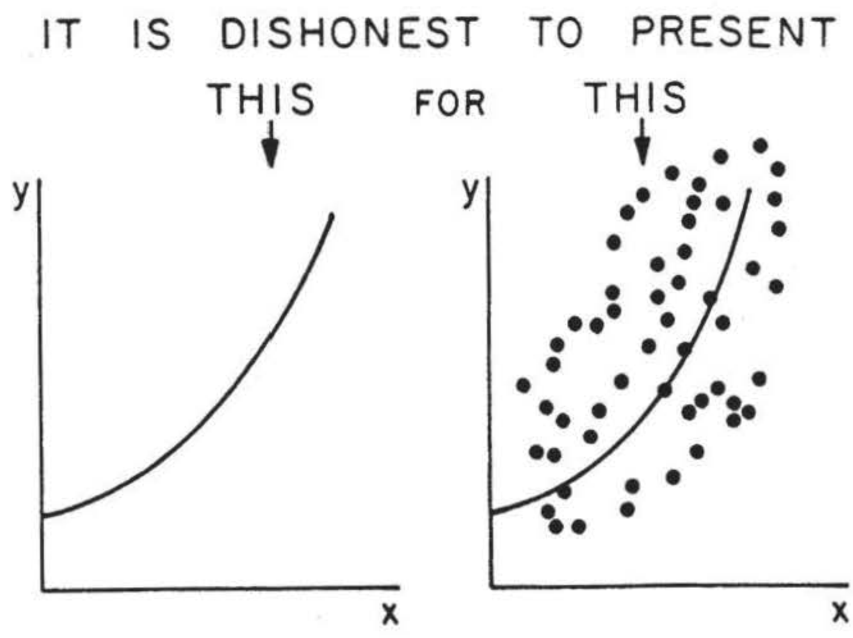
1. Theoretical (limit plasticity, limit equilibrium, cavity expansion).
2. Numerical (finite elements, discrete elements, boundary elements, strain path).
3. Correlative statistics (empirical).

Ideally, interrelationships between the various in-situ tests and the associated engineering parameters should (Wroth, ISOPT-1, 1988):

(a) Have a physical basis;
(b) Be set against a theoretical framework;
(c) Expressed in dimensionless form to allow scaling via continuum mechanics.

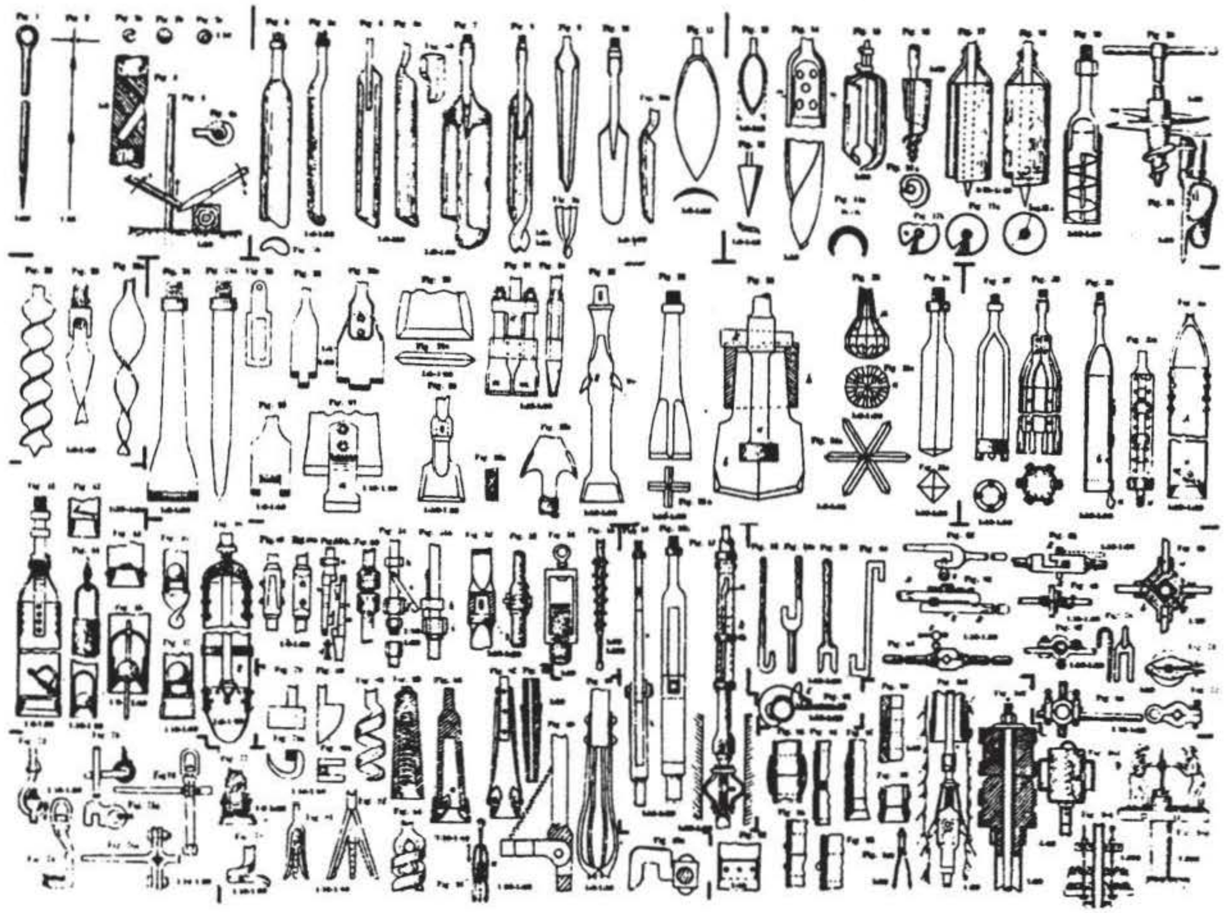
Unfortunately, this is not always possible because of the complexities of the tests, unknown drainage conditions, uncertainties in the reference values used for calibration and vertification, and difficulties in adequately representing the highly nonlinear and anisotropic behavior of soils in their stress-strain-strength-time response to loading. Consequently, out of necessity and a means-to-an-end, a number of empirical relationships often prevail in the interpretation and evaluation of in-situ test data. This is perhaps a point of frustration for students of engineering mechanics and theory-prone individuals, yet is a necessary facet of a discipline that addresses the characterization of natural geomaterials.

When it is necessary to invoke empiricism in a particular relationship, the complete dataset should be shown and appreciated by the using party. That is: Always know the origin, sources, and limitations of the database when using empirical trends.



Reference: Moroney, M.J. (1956), Facts From Figures, Third Edition, Penguin Books, Baltimore, 472 p.

(8)



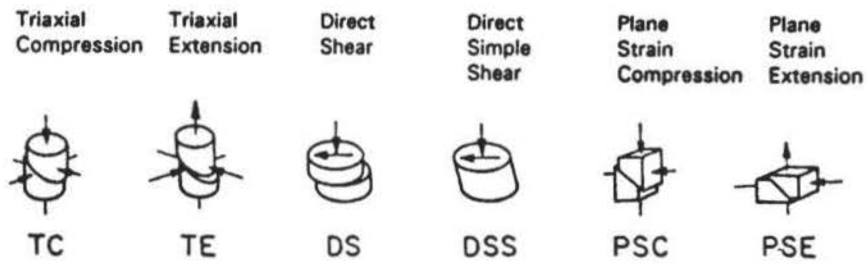
Collection of boring equipment used during the 19th century (Strukel, 1895)

From: Broms, B.B. and Flodin, N. (1988). History of soil penetration testing. *Penetration Testing 1988*, Vol. 1, (Proceedings, ISOPT-1, Orlando), Balkema, Rotterdam, 157-220.

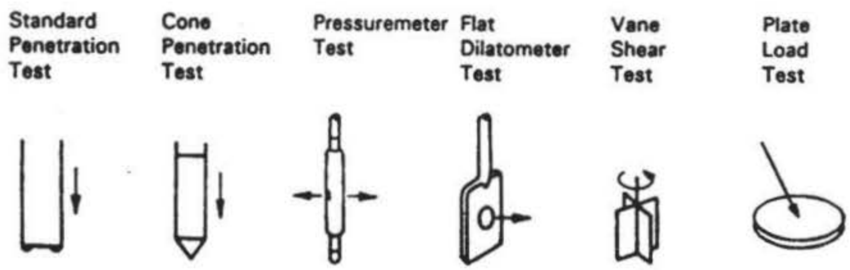
(9)

Laboratory Devices and In-Situ Test Methods

LABORATORY STRENGTH TESTS



IN-SITU STRENGTH TESTS

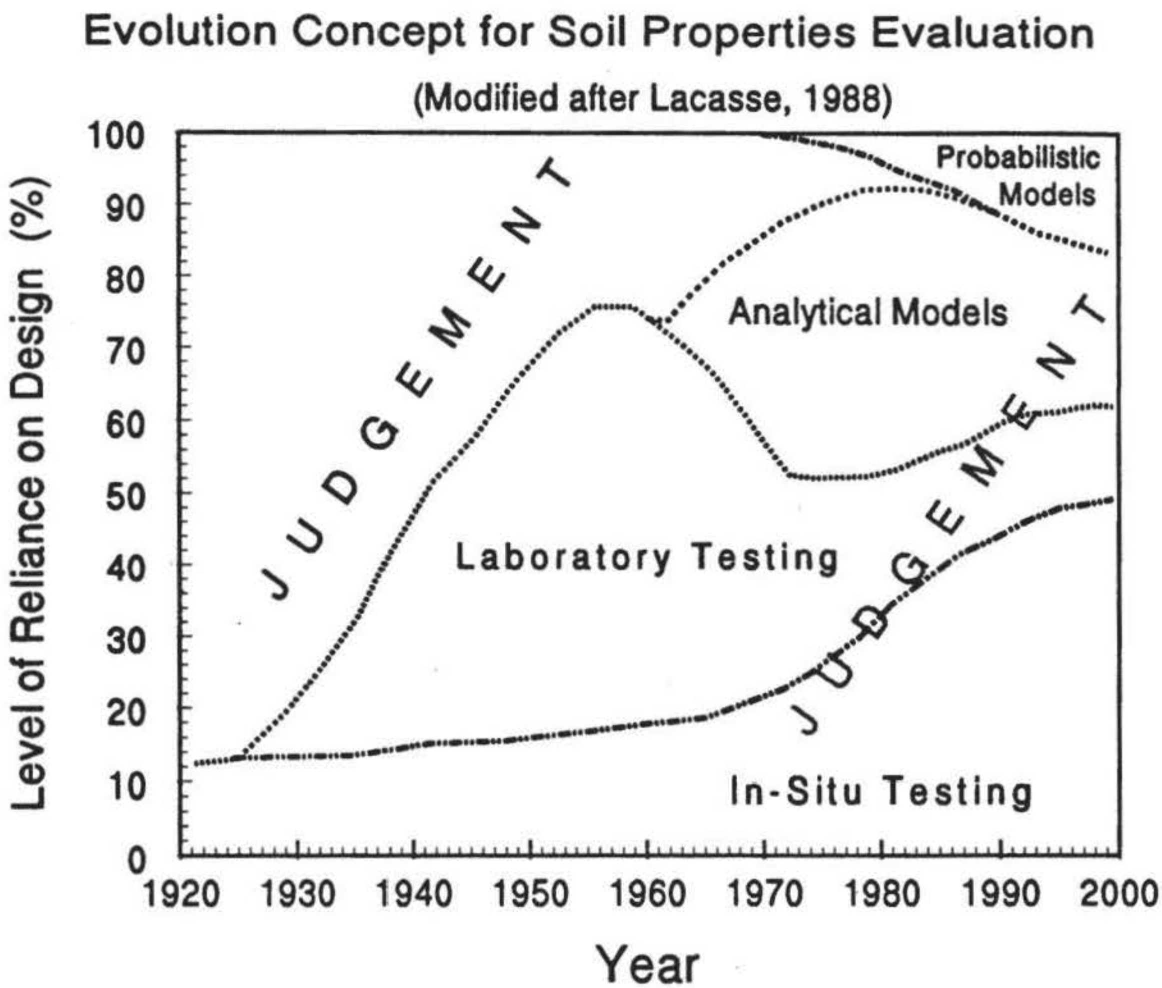


Laboratory

UC = unconfined compression
TC = triaxial compression
TE = triaxial extension
DS = direct shear (box)
DSS = direct simple shear
PSC = plane strain compression
PSE = plane strain extension
RC = resonant column
Oed = oedometer or consolidometer
UU´ = unconsolidated undrained
TTX = true triaxial (cubical)
HC = hollow cylinder
TSC = torsional shear cell
DSC = directional shear cell
TXV = triaxial vane
RSD = ring shear device
BE = bender elements
FCP = fall cone penetrometer

Field

SPT = standard penetration test
CPT = cone penetration test
PMT = pressuremeter test
SBP = self-boring pressuremeter
DMT = dilatometer test
VST = vane shear test
PLT = plate load test
PCPT or CPTU = piezocone
CHT = crosshole seismic test
SR = seismic refraction
BHST = borehole shear test
K_oSB = stepped-blade
TSC = total stress cell (spade)
HF = hydraulic fracturing
SPLT = screw plate load test
SCPT = seismic cone
CPMT = cone pressuremeter
LSCPT = lateral stress cone
DHT = downhole seismic test
SASW = spectral analysis surface waves



Evolution Curve for Source of Design Parameters in Geot. Engrg. Practice.

(Lacasse, 1988, "Design parameters of clays from in-situ and lab tests", Symposium on New Concepts in Geot. Engrg., Rio de Janeiro, Brazil, NGI Rept. No. 52155-50).

(11)

CHECKLIST FOR SITE RECONNAISSANCE

- ☐ Date____________________
- ☐ Prepared by:________________
- ☐ Organization________________

☐ **ACCESSIBILITY**
- ☐ Easy
- ☐ By Vehicle only
- ☐ Difficult by car - Walk only.
- ☐ Requires 4-wheeled drive
- ☐ Dozer and Grading Required
- ☐ Inaccessible
- ☐ Details____________________

____

☐ **VISIT TO SITE.**
- ☐ Date
- ☐ Time of Day
- ☐ Visitors
- ☐ Weather Conditions
  - ☐ Sunny
  - ☐ Cloudy
  - ☐ Rain
  - ☐ Snow
  - ☐ Icy
  - ☐ Freezing
  - ☐ Humid
  - ☐ Other________________

  ____

☐ **GROUND COVER**
- ☐ Asphalt
- ☐ Grass
- ☐ Flowers
- ☐ Bushes
- ☐ Trees
- ☐ Forest
- ☐ Soil
- ☐ Gravel
- ☐ Concrete
- ☐ Rock Outcroppings
- ☐ Evidence of fill/debris
- ☐ Prior Construction
- ☐ Exisiting Buildings
- ☐ Roadways
- ☐ Other____________________

____

☐ **EXISTING TERRAIN**
- ☐ Level Ground
- ☐ Sloping Conditions
  - ☐ Gentle Dip
  - ☐ Steep
  - ☐ Hummocky
  - ☐ Rolling Hills
  - ☐ Mountainous
- ☐ Other remarks__________

____

☐ **SITE HYDROLOGY**
- ☐ Dry - Barren
- ☐ Desert
- ☐ Surface Water Conditions
  - ☐ None
  - ☐ Swampy
  - ☐ Pond
  - ☐ Lake
  - ☐ Ocean
  - ☐ Stream
  - ☐ River
- ☐ Subsurface Water
  - ☐ None
  - ☐ Not Obvious
  - ☐ Major Aquifer
  - ☐ Water Wells
  - ☐ Pumping from deep wells
  - ☐ Other Details___________

  ____

  ____

☐ **SITE DRAINAGE**
- ☐ Runoff Features
  - ☐ Erosion
  - ☐ Ponding
  - ☐ Waterfalls
  - ☐ Piping
  - ☐ Swale
  - ☐ Other
- ☐ Natural
  - ☐ Excellent
  - ☐ Good
  - ☐ Fair
  - ☐ Poor
- ☐ Artificial Drains
  - ☐ Stormwater System
  - ☐ Retention Pond
  - ☐ Vertical wick drains
  - ☐ Pumping Stations
  - ☐ Other________________

  ____

☐ **SOIL AND ROCK CONDITIONS**
- ☐ Surface Soils
  - ☐ Topsoil
  - ☐ Presence of Fills
  - ☐ Evidence of Debris
  - ☐ Pollutants/Contaminants
  - ☐ Agrarian types/farming
  - ☐ Evidence of slope stability

  Problems:
    - ☐ Landslides/slips

(12)

SOIL & ROCK (Continued)

- ☐ Creep
  - ☐ Cracking
  - ☐ Scour
  - ☐ Heave
  - ☐ Subsidence
- ☐ Cut/Quarry Operations
- ☐ Fill/Borrow
- ☐ Other______________

____

☐ **Subsurface Soils**

- ☐ USCS soil types:
  - ☐ GM, GC, GP, GW
  - ☐ SM, SC, SP, SW
  - ☐ CL, CH, ML, MH
  - ☐ Pt, OL, OH
  - ☐ Other__________
- ☐ AASHTO Classification Types:__________
- ☐ FAA Types: __________
- ☐ Surface Rocks
  - ☐ Loose cobbles
  - ☐ Boulders
  - ☐ Rock outcroppings
- ☐ Type of rocks
  - ☐ Igneous
  - ☐ Sedimentary
  - ☐ Metamorphic
  - ☐ Details________

    ____
- ☐ Rock Features
  - ☐ Jointing Patterns
  - ☐ Faults
  - ☐ Discontinuities
  - ☐ Weathering
  - ☐ Planes of weakness
  - ☐ Evidence of talus
  - ☐ karst/sinkholes
  - ☐ caves
  - ☐ Other__________

☐ **INVESTIGATIVE OPERATIONS**

- ☐ Existing test pits
- ☐ Existing boreholes
- ☐ Cased holes
- ☐ Blasting operations
  - ☐ Dynamite
  - ☐ ANFO
  - ☐ Rippers
  - ☐ Percussive Drills
- ☐ Erratics/ boulders
- ☐ Coreholes
  - ☐ Diamond drilling
  - ☐ Wireline drilling
- ☐ Exploratory Adits
  - ☐ Vertical shafts
  - ☐ Tunnels
  - ☐ Pilot Holes

Other info:____________________

____

☐ **PRIOR INFORMATION**

- ☐ Tax map records
  - ☐ Federal Documents
  - ☐ State records
  - ☐ County tax maps
  - ☐ City records files
  - ☐ Personal files
  - ☐ Interviews with neighbors and nearby businesses: ________

    ____

☐ **TOPOGRAPHIC DATA**

- ☐ USGS Quadrangle Maps
- ☐ State Survey
- ☐ County Surveys
- ☐ Site Survey
  - ☐ Transit/Level
  - ☐ Aerial Photos
  - ☐ GPS data
- ☐ Details____________

  ____

  ____

☐ **GEOLOGIC INFORMATION**

- ☐ USGS Geologic Maps
- ☐ State Geologic Surveys
- ☐ Field Mapping by geologists
- ☐ Specimens for lab analysis
- ☐ Details on geologic setting:

____

☐ **UTILITIES**

- ☐ Existing overhead lines
- ☐ Marked gas lines
- ☐ Easements
- ☐ Manholes
- ☐ Sewer outfalls
- ☐ Power substations
- ☐ Electromagnetic readings
  - ☐ ground penetrating radar,
  - ☐ EM surveys
  - ☐ magnatometer
  - ☐ resistivity measurements
- ☐ Other________________

☐ NOTES & REMARKS

____

____

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(13)

In-Situ Testing and Site Characterization

For each and every geotechnical study, the project site must be explored using field testing and sampling methods to determine what subsurface materials exist and evaluate their engineering properties. The geologic setting and past environmental conditions have already pre-decided whether the property is underlain by clay, silt, sand, gravel, or rock. The materials may be residual (weathered in place), glacial, or sedimentary in marine, alluvial, fluvial, lacustrine, or diluvial in origin. The rocks may be igneous, metamorphic, or sedimentary type. The level of the groundwater is also needed for analysis. Testing may therefore require a variety of tests, including soil test borings, cone soundings, piezocones, flat dilatometer, pressuremeter, and/or geophysical methods.

Soil Test Borings

Auger and rotary drilling techniques are normally used to advance a borehole, approximately 100 to 200 mm in diameter, to typical depths of 10 to 50 meters. If rock is encountered, diamond core drilling techniques (or new synthetic carbide bits) are used to sample the rock material. Within the soil borings at regular intervals (generally 1.5 m), small 50-mm diameter drive samples are taken using a drop hammer system system and split-barrel sampler (steel hollow tube). The repetitive blows required to drive the sampler 300 mm are recorded and thus designated the standard penetration test (SPT) N-value. Because of variations in systems, the N-resistance should be corrected to 60% energy efficiency before used in any analysis.

Undisturbed soil samples may be obtained using a larger 75 mm diameter thin-walled tube sample (Shelby) to provide quality specimeris for laboratory triaxial and consolidation tests.

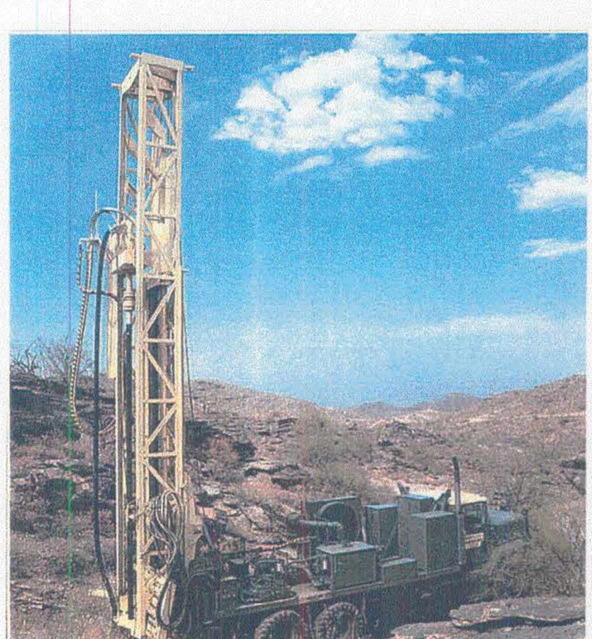
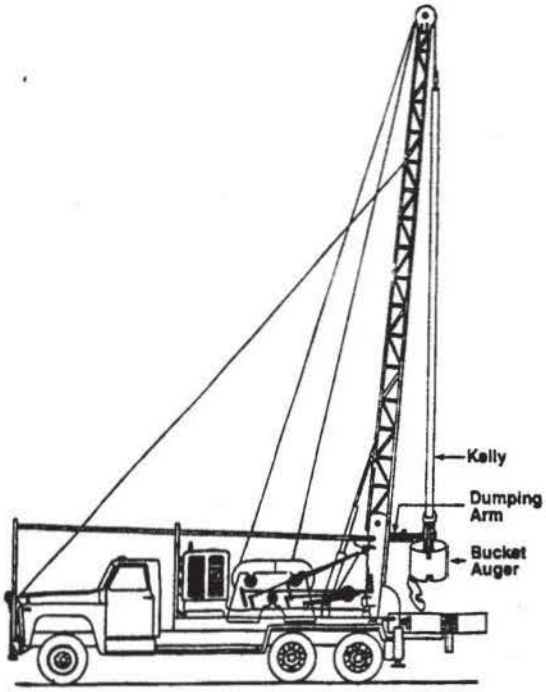
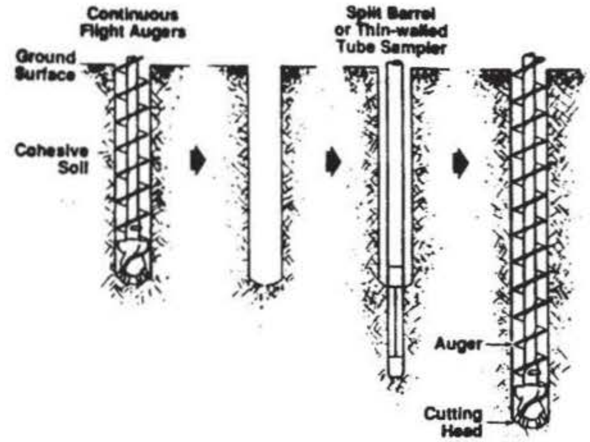


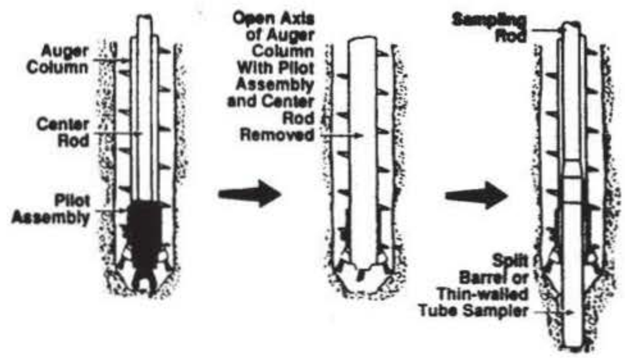
Photo :
Truck-mounted drill rigs for conducting soil test borings, augering, soil sampling, and rock coring.



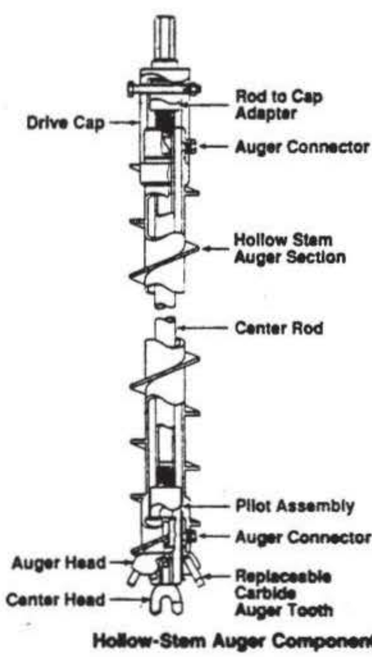
Bucket Auger and Drilling Rig



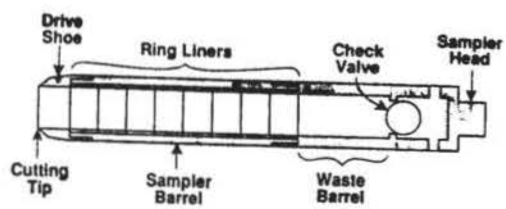
Solid Stem Auger Sampling



Hollow-Stem Auger Sampling



Hollow-Stem Auger Components



Ring-Lined Barrel Sampler

(15)

Sampling of Soils

McGuffey, V.C., Modeer, V.A., and Turner, A.K. (1996). Subsurface exploration (Chapter 10), *Landslides: Investigations & Mitigation*, Special Report 247, Transportation Research Board, National Academy Press, Washington, D.C., 231-277.

Common Samplers To Collect Disturbed Soil Samples

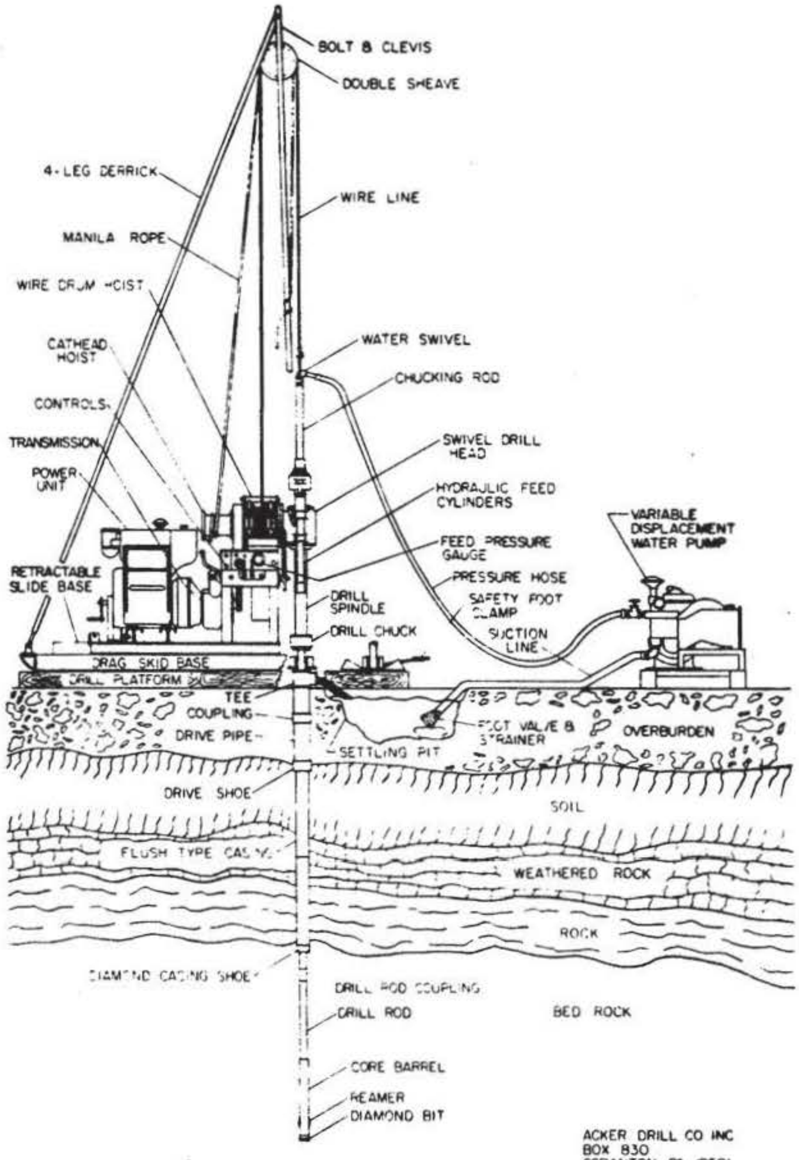
Sampler	Typical Dimensions	Soils That Give Best Results	Method of Penetration	Cause of Disturbance or Low Recovery	Remarks
Split barrel	Standard is 50 mm outside diameter (OD) and 35 mm inside diameter (ID); penetrometer available up to 100 mm OD and 89 mm ID	All fine-grained soils that allow sampler to be driven; gravels invalidate drive data	Hammer driven	Vibration	SPT is made using standard penetrometer and hammer (see text); undisturbed samples obtained by using liners, but some sample disturbance is likely
Retractable plug	Tubes 150 mm long and 25 mm OD; maximum of six tubes can be filled during a single penetration	Silts, clays, fine and loose sands	Hammer driven	Improper soil types for sampler; vibration	Lightweight, highly portable units can be hand carried; some sample disturbance is likely
Continuous-helical-flight auger	Diameters range 76 to 406 mm; penetrations to depths exceeding 15 m	Most soils above water table; will not penetrate hard soils or those containing cobbles or boulders	Rotation	Hard soils, cobbles, boulders	Rapid method of determining soil profile; bag samples can be obtained; log and sample depths must account for lag time between penetration of bit and arrival of sample at surface
Hollow-stem auger	Generally 150 to 200 mm OD with 75 to 100 mm ID hollow stem	Same as flight auger	Rotation	Same as flight auger	Special type of flight auger with hollow center through which undisturbed samples or SPT can be taken
Disc auger	Up to 1070 mm diameter; usually has maximum penetration depth of 8 m	Same as flight auger	Rotation	Same as flight auger	Rapid method of determining soil profile; bag samples can be obtained
Bucket auger	Up to 1220 mm diameter common; larger sizes available; with extensions, depths over 24 m are possible	Most soils above water table; can dig harder soils than above types and can penetrate soils with cobbles and boulders if equipped with a rock bucket	Rotation	Soil too hard to dig	Several bucket types available, including those with ripper teeth and chopping tools; progress is slow when extensions are used

Common Samplers To Collect Undisturbed Soil Samples

Sampler	Typical Dimensions	Soils That Give Best Results	Method of Penetration	Cause of Disturbance or Low Recovery	Remarks
Shelby tube	76 mm OD and 73 mm ID most common; available from 50 to 127 mm OD; 760-mm sampler length standard	Cohesive fine-grained or soft soils; gravelly soils will crimp tube	Pressing with fast, smooth stroke; can be carefully hammer driven	Erratic pressure applied during sampling, hammering, gravel particles, crimping of tube edge, improper soil types for sampler	Simplest device for undisturbed samples; boring should be clean before sampler is lowered; little waste area in sampler; not suitable for hard, dense, or gravelly soils
Stationary piston	76 mm OD most common; available from 50 to 127 mm OD; 760-mm sampler length standard	Soft to medium clays and fine silts; not for sandy soils	Pressing with continuous, steady stroke	Erratic pressure during sampling, allowing piston rod to move during press, improper soil types for sampler	Piston at end of sampler prevents entry of fluid and contaminating material; requires heavy drill rig with hydraulic drill head; samples generally less disturbed compared with Shelby tube; not suitable for hard, dense, or gravelly soil; no positive control over specific recovery ratio
Hydraulic piston (Osterberg)	76 mm OD is most common; available from 50 to 101 mm OD; 910-mm sampler length standard	Silts and clays, some sandy soils	Hydraulic or compressed air pressure	Inadequate clamping of drill rods, erratic pressure	Needs only standard drill rods; requires adequate hydraulic or air capacity to activate sampler; samples generally less disturbed compared with Shelby tube; not suitable for hard, dense, or gravelly soil; not possible to limit length of push or amounts of sample penetration
Denison	89 to 177 mm OD, producing samples 60 to 160 mm; 610-mm sampler length standard	Stiff to hard clay, silt, and sands with some cementation, soft rock	Rotation and hydraulic pressure	Improper operation of sampler; poor drilling procedures	Inner tube face projects beyond outer tube, which rotates; amount of projection can be adjusted; generally takes good samples; not suitable for loose sands and soft clays
Pitcher sampler	105 mm OD; uses 76-mm diameter Shelby tubes; sample length 610 mm	Same as Denison	Same as Denison	Same as Denison	Differs from Denison in that inner tube projection is spring controlled; often ineffective in cohesionless soils

16

Acker, W.L. III (1974).
Basic Procedures for Soil Sampling and Core Drilling.
Acker Drill Co., Inc.
Scranton, PA. 246 p.



TYPICAL DIAMOND DRILLING RIG · FOR EXPLORATION

ASTM (1995). Standard practice for diamond core drilling for site investigation (D-2213). *Annual Book of ASTM Standards*, Vol. 04.08, Section 4/Construction.

TABLE 1 Core Bit Sizes

Size Designation	Outside Diameter		Inside Diameter	
	in.	mm	in.	mm
RWT	1.16	29.5	0.375	18.7
EWT	1.47	37.3	0.905	22.9
EWG, EWM	1.47	37.3	0.845	21.4
AWT	1.88	47.6	1.281	32.5
AWG, AWM	1.88	47.6	1.185	30.0
BWT	2.35	59.5	1.750	44.5
BWG, BWM	2.35	59.5	1.655	42.0
NWT	2.97	75.3	2.313	58.7
NWG, NWM	2.97	75.3	2.155	54.7
2¾ × 3⅞	3.84	97.5	2.69	68.3
HWT	3.89	98.8	3.187	80.9
HWG, . . .	3.89	98.8	3.000	76.2
4 × 5½	5.44	138.0	3.97	100.8
6 × 7¾	7.66	194.4	5.97	151.6

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Standard diamond core bit

Bottom discharge "M" design diamond core bit

Acker, W.L. III (1974).
Basic Procedures for Soil Sampling and Core Drilling.
Acker Drill Co., Inc.
Scranton, PA. 246 p.

Pilot type non-coring diamond bit

Taper type non-coring diamond bit

Typical tricone roller rock bit

Diamond casing shoe bit

Standard carbide insert core bit

Pyramid type carbide coring bit

(18)

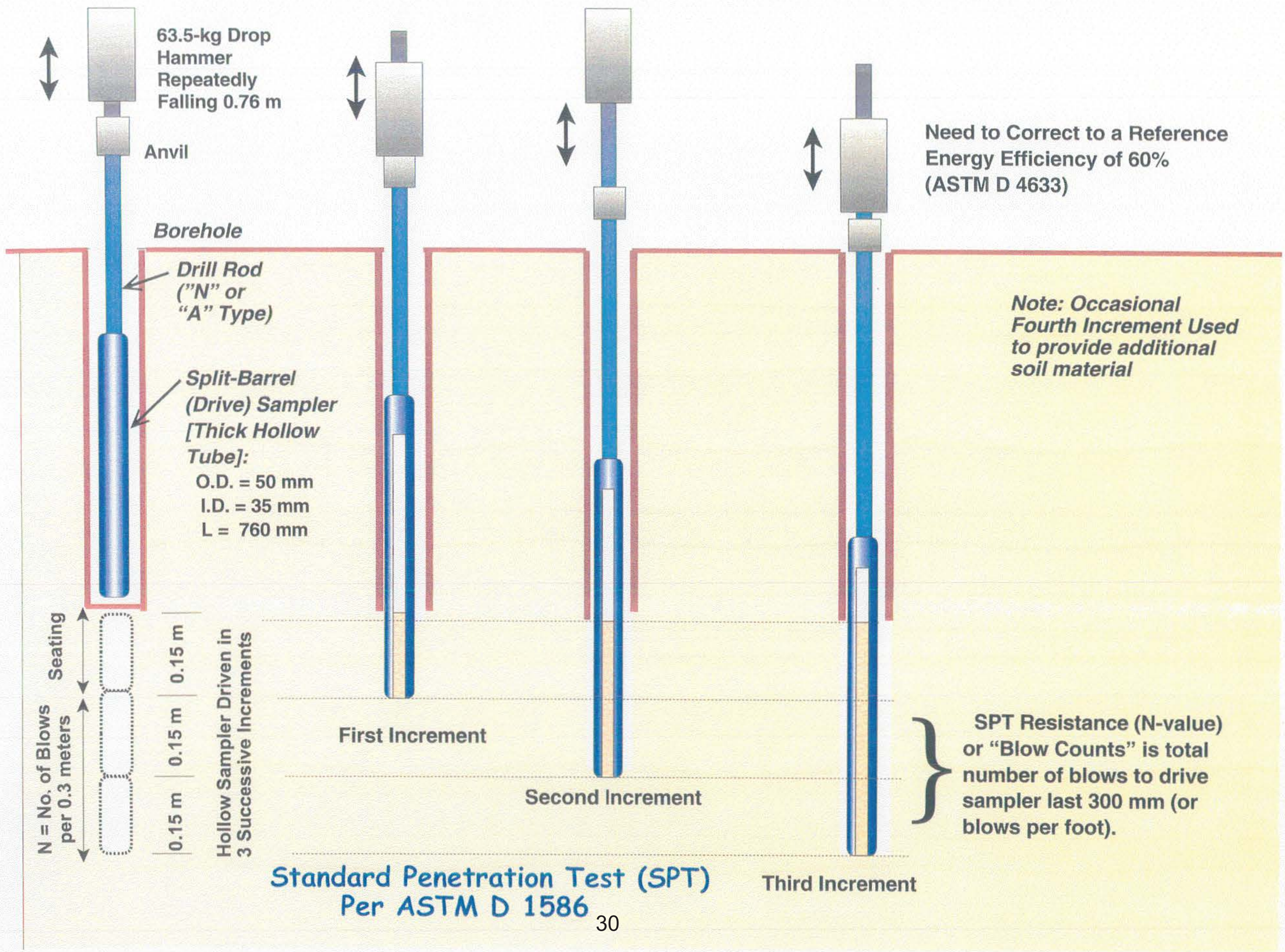
Borehole Logging Techniques

McGuffey, V.C., Modeer, V.A., and Turner, A.K. (1996). Subsurface exploration (Chapter 10), *Landslides: Investigations & Mitigation*, TRB Special Report 247, National Academy Press, Washington, D.C., 231-277.

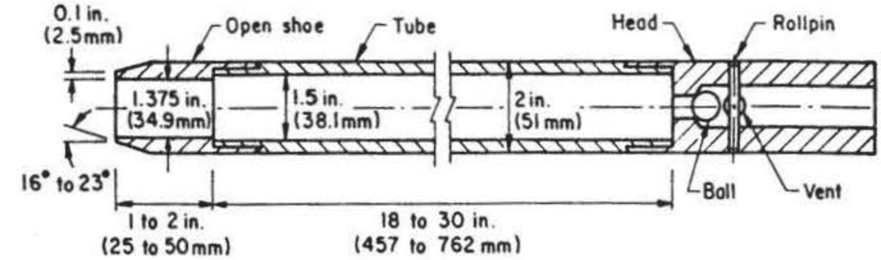
Table 10-5
Borehole Logging Methods

Category	Parameter Measured	Casing			Saturated	Unsaturated	Radius of Investigation	Effect of Borehole Diameter and Mud	Applications	Limitations
Caliper logging	Borehole diameter	Yes	No	No	Yes	Yes	At immediate borehole wall	NA	Used to continuously measure and record borehole diameter	Requires an uncased hole
Electric logging										
Induction	Electrical conductivity	Yes	Yes	No	Yes	Yes	75 cm	Negligible	Provides continuous measure of conductivity for materials surrounding borehole	Information has lower resolution than resistivity log but can evaluate unsaturated zone and PVC-cased boreholes
Resistivity	Electrical resistivity	Yes	No	No	Yes	No	30 to 150 cm	Significant to minimal, depending on probe	Provides continuous measure of resistivity from which material types can be deduced when compared with borehole material logs	Generally information provided is only semi-quantitative; requires borehole log and is restricted to saturated zone and uncased borehole
Spontaneous-potential	Electrical potentials from mineral reactions and groundwater flow	Yes	No	No	Yes	No	Immediately adjacent to borehole wall	Significant	Identifies lithology, oxidation-reduction reaction zones, and subsurface flows	Provides ambiguous data that require considerable interpretation; can only valuate saturated zone in uncased borehole
Nuclear logging										
Natural-gamma	Natural-gamma radiation	Yes	Yes	Yes	Yes	Yes	15 to 30 cm	Moderate	Determines presence and integrity of clay and shale formations	May be affected by presence of mud coatings on borehole walls
Gamma-gamma	Material density	Yes	Yes	Yes	Yes	Yes	15 cm	Significant	Provides continuous measurement of material density	Provides only material density measurements; health and safety regulations may influence operational costs
Neutron-neutron	Moisture content (above water table); porosity (below water table)	Yes	Yes	Yes	Yes	Yes	15 to 30 cm	Moderate	Provides continuous measurement of natural moisture content; locates rupture zones when used in combination with gamma logging	Provides only in situ moisture values; health and safety regulations may influence operational costs
Remote sensing										
Borehole cameras	Visual images of fractures and structures in borehole walls	Yes	No	No	Yes	Yes	At immediate borehole wall	Significant	Special videocamera obtains continuous image of borehole walls; software can be used to interpret dips of fractures	Requires uncased hole; images are affected by water quality in hole
Ultrasonic acoustic	Contiguous images of borehole wall showing fractures	Yes	No	No	Yes	Yes	At immediate borehole wall	Significant to moderate	Provides continuous image of borehole wall showing fractures and other discontinuities	Requires uncased hole; images are much less clear than those obtained by borehole cameras
Thermal profiling	Temperature	Yes	No	No	Yes	No	Within borehole	NA	Determines zone of water inflow into borehole	Requires uncased hole
Seismic methods										
Uphole survey	Material dynamic properties	Yes	No	No	Yes	Yes	NA	NA	Determines dynamic properties and rock-mass quality of materials surrounding borehole	Requires uncased and mud-filled hole
Downhole survey	Material dynamic properties	Yes	No	No	Yes	Yes	NA	NA	Determines dynamic properties and rock-mass quality of materials surrounding borehole	Requires uncased and mud-filled hole
Crosshole survey	Material dynamic properties	Yes	No	No	Yes	Yes	NA	NA	Determines dynamic properties and rock-mass quality of selected stratum	Requires array of uncased holes

NOTE: NA = not applicable.


63.5-kg Drop Hammer Repeatedly Falling 0.76 m
Anvil
Borehole
Drill Rod ("N" or "A" Type)
Split-Barrel (Drive) Sampler [Thick Hollow Tube]:
O.D. = 50 mm
I.D. = 35 mm
L = 760 mm
Need to Correct to a Reference Energy Efficiency of 60% (ASTM D 4633)
Note: Occasional Fourth Increment Used to provide additional soil material
Seating
N = No. of Blows per 0.3 meters
0.15 m
0.15 m
0.15 m
Hollow Sampler Driven in 3 Successive Increments
First Increment
Second Increment
Third Increment
SPT Resistance (N-value) or "Blow Counts" is total number of blows to drive sampler last 300 mm (or blows per foot).
Standard Penetration Test (SPT)
Per ASTM D 1586

- Test normally taken at approximate 5-foot (1.5-m) depth intervals, so discrete values.
- Initially started in 1902 by Colonel Charles Gow of Raymond Pile Company.
- Seating correction recommended by Karl Terzaghi in 1947.
- Different procedures in 11 countries (see Decourt et al. 1988).



Longitudinal Section View of the Split-Spoon (Barrel) Sampler.

ADVANTAGES	DISADVANTAGES
• Obtain both a sample & a number	• Obtain both a sample & a number
• Simple & Rugged	• Disturbed sample (index tests only)
• Suitable in many soil types	• Crude number for analysis

The SPT is highly-dependent upon the equipment used and operator performing the test. Most important factor is the energy efficiency of the system. The theoretical energy of a free-fall system is 4200 in-lb (140 lb falling 30 inches), but is almost always much less due to frictional losses and eccentric loading. Cathead and rope systems common in use and efficiency depends on: number of turns of rope around cathead, sheaves, age of rope, actual drop height, type of hammer (pinweight, donut, safety), vertical plumbness, and other factors. Calibration of energy efficiency recommended by ASTM D-4633 with strain gages and accelerometer measurements (usually not done by commercial firms). Standard of practice varies from about 35% to 85% with cathead system, but averages about 60%. Newer automatic trip-hammers (trip monkey in Japan) available that may deliver 80 to 100% efficiency, but depends on the system. If efficiency is measured (E_r), then corrected N-value is designated N_{60} and given by:

$$N_{60} = (E_r/60)\, N_{meas}$$

Approximate magnitude of corrections for energy efficiency, sampler, rod lengths, and borehole diameter are given by Skempton (1986), but only for general guide. Best to measure E_r to get proper correction to N_{60}.

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PROCEDURES

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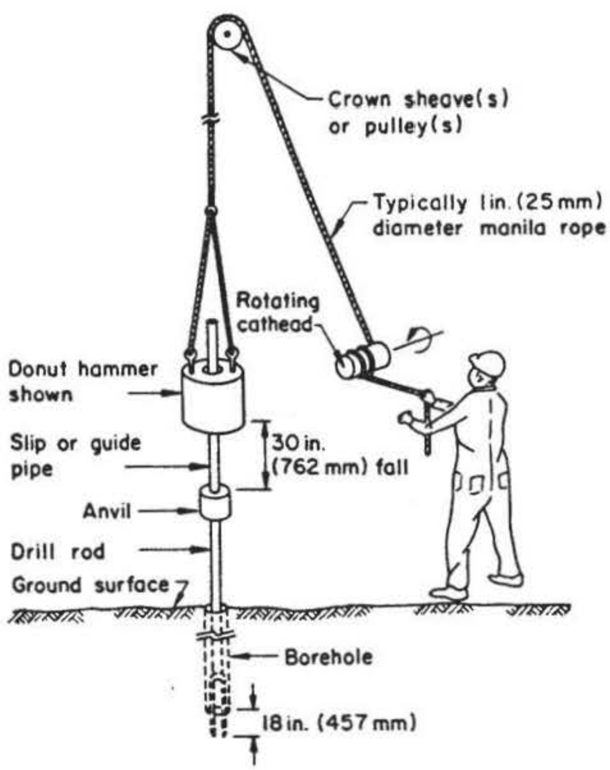
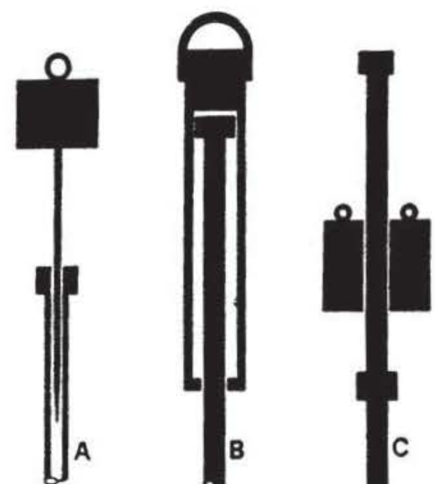
Standard Penetration Testing (SPT) and Split-Barrel Sampling Method

- **First, need to advance a boring to test depth:**
    1. Solid flight augers (must remove each time before conducting SPT).
    2. Hollow stem augers (popular because augers also act as temporary casing and allow sampling and testing devices to be lowered to borehole bottom without removal).
    3. Continuous boring (new technique allowing complete logging of strata).
    4. Rotary methods
        - wash boring techniques (water or drilling mud);
        - drilling bits with temporary steel casing;
    5. Other methods (percussive drilling for blasting; wireline drilling for mining).

STANDARD PENETRATION TEST

- Most common in-situ test worldwide; drive a hollow thick-walled tube into the ground and measure number of blows to advance 1 foot.
- Split-barrel (spoon) is 2.0 inches O.D. (50 mm) and 1.375 inches I.D. (35 mm). Minimum length is 18 inches (457 mm), although many are 24 inches (610 mm) or more. Shoe at front end; tube is split longitudinally to allow sample to be removed.
- ASTM D-1586 procedures: Use 140-lb hammer (63.5 kg) falling 30 inches (0.76 m). Repeatedly drop hammer onto anvil/rod system and drive split-spoon (split-barrel sampler) three successive increments of 6-inches each (150-mm each). First increment = seating is disregarded (may reflect fall in from sides of borehole. Blows to advance second and third increments are summed to give blows per foot (bpf), referred to as N-value ("blow count") or **SPT-resistance.**





A. Pinweight hammer
B. Safety hammer
C. Donut hammer

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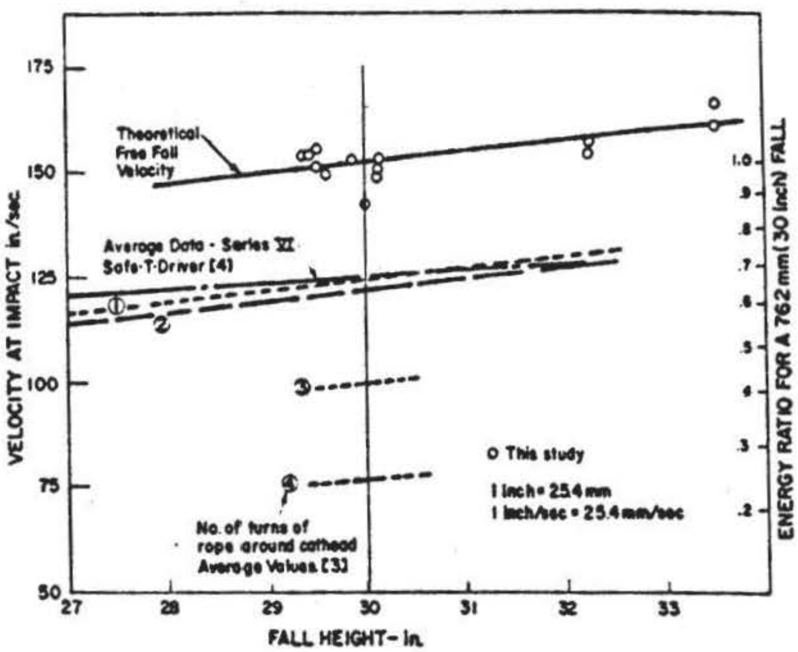
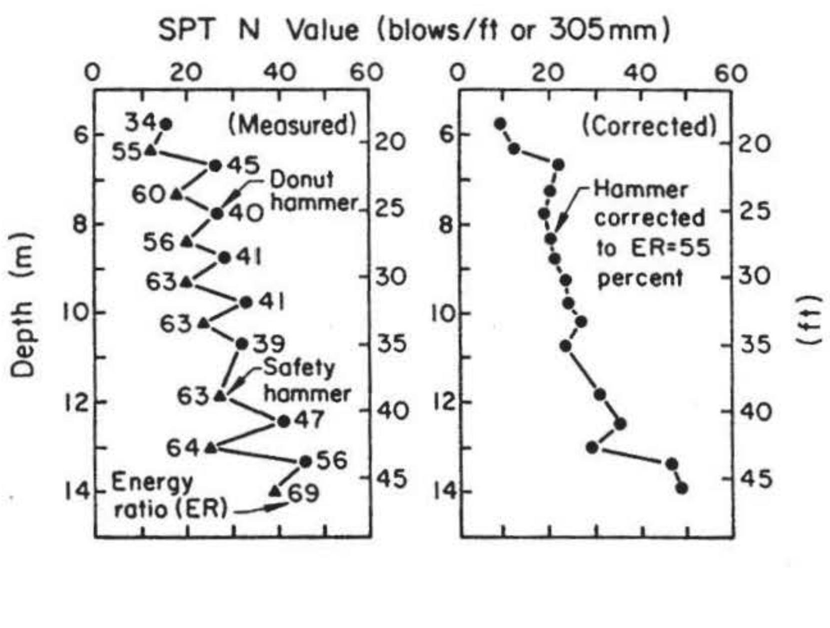
The efficiency may be obtained by comparing the kinetic energy, $KE = \frac{1}{2}mv^2$, with the potential energy of the system, $PE = mgh$; or by calculating the work done. The energy ratio (ER) is defined as the ratio of $ER = KE/PE$. Again, routine engineering practice and SPT correlations have been developed on the basis of an average $ER \approx 60$ percent.





AUTOMATIC SPT HAMMER SYSTEMS

There exist a number of automatic hammer systems today for conducting SPT, usually based on combined hydro-mechanics to lift and drop the 140-lb weight the required 30-inches. Separate systems have been developed, however, by Central Mine Equipment (CME), Failing, Acker, Mobile, and Dietrich. With automatic hammers and true free-fall mechanisms, one could get the 100% efficiency of 4200 in-lbs. However, the standard-of-practice and all of the empirical correlations and experience gained from the SPT for the past 50 years has been based on an inefficient system, averaging about 60%. Thus, the recommendations are to correct the measured N-values to an efficiency level of 60% (or N_{60}). This now presents a problem with the advent of commerical auto-hammers, as some of these have been directed at maximizing efficiency, while others have "tuned" their system to deliver the 60-percent efficiency directly (thru damping). Unfortunately, too geotechnical engineers have become somewhat sloppy in the record-keeping, and many times do not detail what hammer or system is used on the boring log. As a result, the old donut hammers gave around 30 to 50 percent efficiency and the conventional safety hammers between 50 to 80 percent, with an average of 60% efficiency (Skempton, 1986). Now, with adding the auto hammers, we can get anywhere from 30 to 100% efficiency [but the logs not tell which system!].

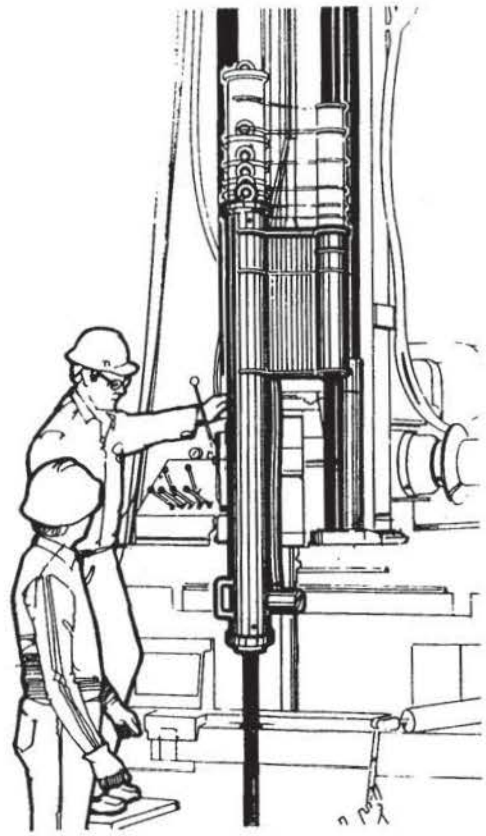


FIG. 6—*The CME 140-lb (63.5-kg) Automatic SPT Hammer during performance of the SPT.*

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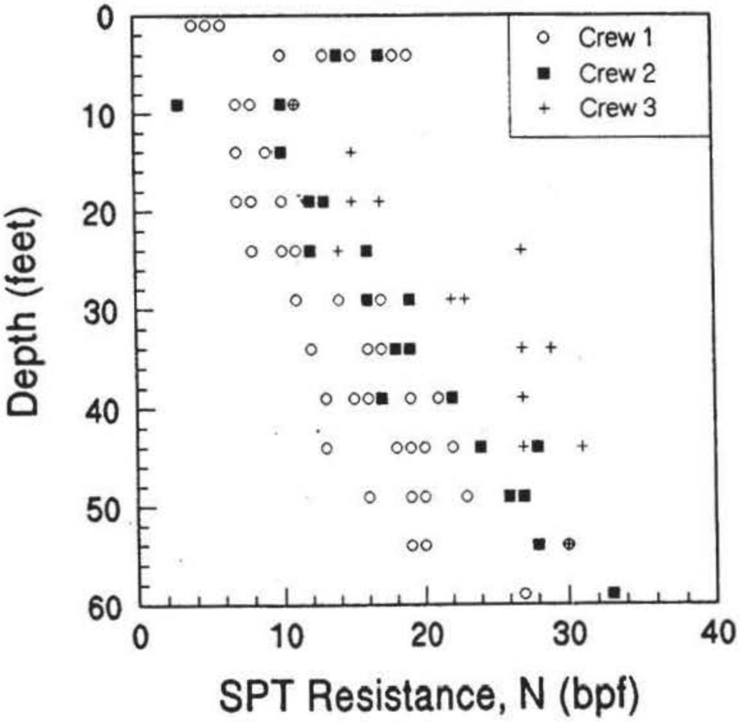
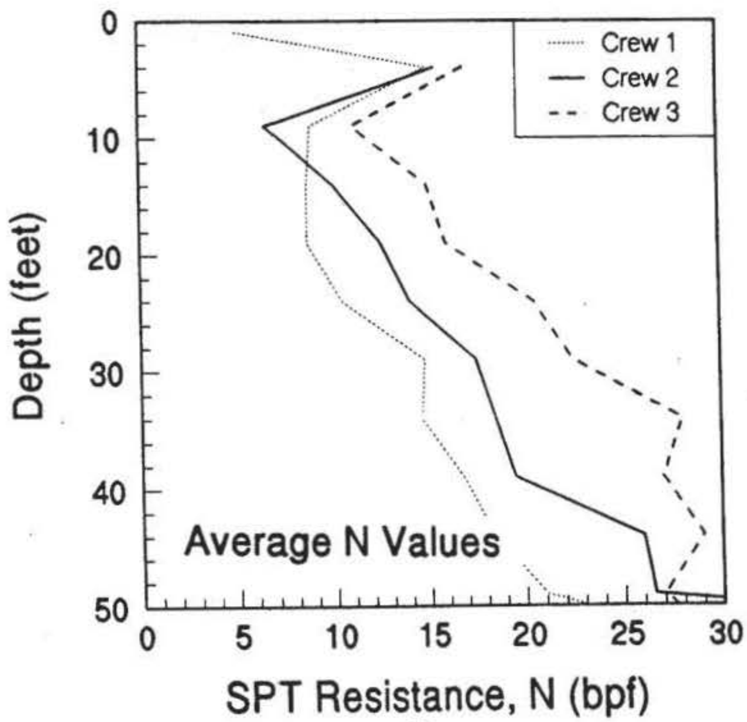
VARIABILITY OF SPTs DUE TO ENERGY EFFICIENCY DIFFERENCES

An example of SPT variability is illustrated from a test site approximately 10-meters square located at the west end of GT campus. Separate drill rigs and crews from 3 different firms conducted SPTs using hollow stem augers and safety hammer with cathead & rope systems, as shown in the below figure. The tests were conducted in Piedmont residual soils consisting of silty fine sands (SM). Below a 3-meter deep fill layer, the N-values are seen to increase gradually with depth. However, it is clear that crew #1 shows consistently lower N-values than crew #2, which in turn are lower than crew #3. Mean trends for the measured raw N-values for each crew are shown in the second figure.

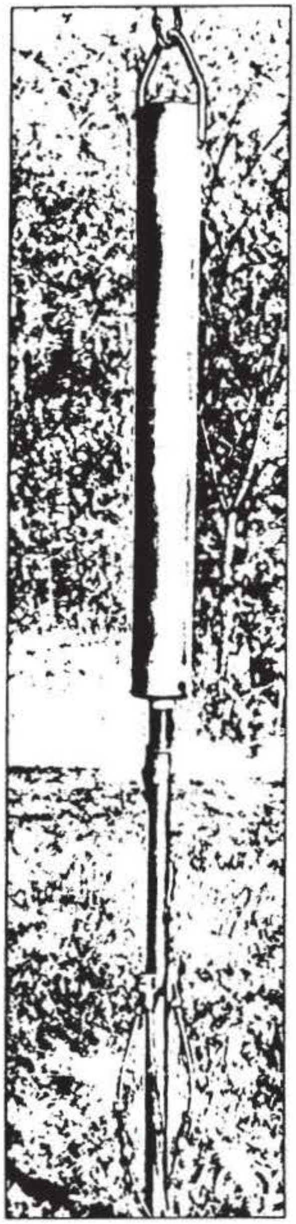




(25)

SPT ANALYZER™

For Improved Reliability of SPT N-values



Measures and Checks SPT Hammer Performance

(Energy Transfer)

- Immediate results for each hammer blow
- Conforms to ASTM D4633 specification for SPT energy measurement
- Measures energy transfer; results used to normalize measured SPT N-value to N_{60}
- Provides definitive answers as to consistency of operation, operator performance, or efficiencies of specific rig or rig type
- Measurements also indicate static strength during test and dynamic soil response for future pile driving predictions or static pile performance

The Standard Penetration Test (SPT) is a widely used soil exploration tool (ASTM D1586) which involves driving a split barrel sampler at the bottom of a drill string to recover disturbed soil samples. The number of blows required to drive the last 300 mm (one foot) is the "N-value" and indicates soil strength. The SPT N-value and retrieved soil sample are used for many geotechnical evaluations. The SPT N-value data influences the engineer's design. With low reliability, the design must be very conservative to reduce risk. Reliable N-values result in lower and more economical safety factors. However, the N-value depends also upon SPT hammer energy input.

ASTM D1586 allows a wide diversity of equipment for sampling and N-value measurement. It has been clearly demonstrated that the type and operational characteristics of the SPT hammer significantly influence the energy transfer and resulting SPT N-value. Donut or safety hammers which are otherwise identical can have different efficiencies due to the skill of the operator using a cathead and rope system. Different automatic trip hammers have different impact velocities due to the differences in the lifting and dropping mechanisms. Because of the known extreme variability of SPT hammers, a separate specification for measuring SPT energy was developed (ASTM D4633). A task group reviewing ASTM D1586 has suggested that the N-value be modified to a standard "N_{60}"

$$N_{60}\, E_{60} = N_{field}\, E_{measured}$$

where N_{field} is the field observed N-value, $E_{measured}$ is the measured energy, and E_{60} is 60 percent of the theoretical potential energy (60 percent represents the historical average that many empirical relations have been based upon). This approach provides a more rational approach to geotechnical design. The SPT Analyzer measures the energy for any manufacturer or type of SPT hammer, allowing the design engineer to compute the rational N_{60} value from the observed field N-value. Optional software can extract static and dynamic soil response for direct determination of "wave equation" parameters for pile driving analysis.

Pile Dynamics, Inc.
4535 Emery Industrial Parkway
Cleveland, Ohio 44128 U.S.A.
Tel: (216) 831-6131
Fax: (216) 831-0916
Email: info@pile.com

PDI designs all its equipment to be rugged and to endure harsh construction conditions. Reliability is proven by hundreds of PDI units in the field and our strong commitment to quality products and support. The SPT Analyzer is designed for the professional engineer or researcher and comes with a full one year warranty for normal use. PDI's solid international reputation is the result of quality products, decades of dedicated engineering research, and commitment to technical support of its clients, including suggestions and advice on unusual applications and data interpretation for dynamic pile testing. Training is available as requested, as are continuing education courses on dynamic testing on a regular basis at various locations around the world.

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KEY TO SOIL SYMBOLS

FILL	GW - Well graded gravels
CL - Low plasticity inorganic clays	OL - Low plasticity organic silts & clays
CH - High plasticity inorganic clays and very fine sands	OH - High plasticity organic silts & clays
ML - Low plasticity inorganic silts and very fine sands	SM - Silty sands
MH - High plasticity inorganic silts	GM - Silty gravels
SP - Poorly graded sands	SC - Clayey sands
SW - Well graded sands	GC - Clayey gravels
GP - Poorly graded gravels	SP-SM - Typical Dual Classification

DECOMPOSED ROCK - A transitional material between soil and rock which retains the relict structure of the parent rock and exhibits penetration resistances between 60 blows per foot and 100 blows per 2 inches of penetration.

CORRELATION OF PENETRATION RESISTANCE WITH RELATIVE DENSITY AND CONSISTENCY

NO. OF BLOWS, N		RELATIVE DENSITY
	0-4	Very Loose
	5-10	Loose
SANDS:	11-30	Firm
	31-50	Dense
	OVER 50	Very dense

		CONSISTENCY
	0-2	Very Soft
	3-4	Soft
SILTS	5-8	Firm
&	9-15	Stiff
CLAYS:	16-30	Very stiff
	31-50	Hard
	OVER 50	Very Hard

PARTICLE SIZE IDENTIFICATION

BOULDERS:	Greater than 12"
COBBLES:	3" to 12"
GRAVEL:	Coarse- 3/4" to 3"
	Fine- 4.76 mm to 3/4"
SAND:	Coarse- 2 mm to 4.76 mm
	Medium- 0.42 mm to 2 mm
	Fine- .074 mm to .42 mm
SILT & CLAY:	Less than 0.074 mm

SOIL TEST BORING RECORD – Georgia Institute of Technology

Boring No. GEOB-1
Location: Brunswick, GA
Ground Elev. = +2 metres msl
Groundwater Depth: 0.83 m
Client: Confidential
Date: Feb. 3, 1994
Driller: Van Halen

NOTES:
1. ss = split spoon or split barrel sample per ASTM D-1586
2. Tube = Shelby thin-walled tube sample per ASTM D-1587 standards

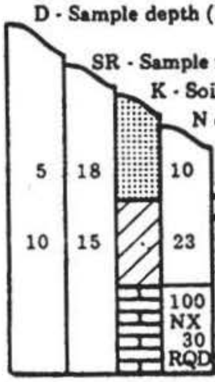
Soil Classification for each sample	Depth (feet)	Sample Details No.	Rec.	Type	SPT Blows Per 6-in.
(6 in. topsoil)					
Desiccated si clay	1.0–2.5	1	15	ss	3–4–5
with sand (CL)					
Brown si Clay (CH)	3.0–4.5	2	18	ss	1–0–1
Gray–tan Clay (CH)	4.5–6.0	2A	18	Tube	N.A.
Brown si Clay (CH)	6.0–7.5	3	18	ss	0–1–1
Gray–Brn Clay (CH)	9.0–10.5	4	18	ss	1–0–2
Brown si Clay (CH)	14.0–15.5	5	18	ss	1–1–1
Brown si Clay (CH)	19.0–20.5	6	18	ss	0–1–2
Gray Sand (SP–SM)	24.0–25.5	7	12	ss	5–5–6
with trace silt					
Gray Fine Sand (SP)	29.0–30.5	8	10	ss	4–6–6
trace silt fines					
Gray–tan slightly	31.0–33.0	9	12	ss	5–5–7
silty Sand (SP–SM)					
Gray Silty Sand (SM)	34.0–35.5	10	18	ss	6–6–7
with trace gravel					
Red–Brn Clay (CL)	39.0–40.5	11	18	ss	6–6–5
Red–Blue Clay (CL)	41.0–43.0	11A	24	Tube	N.A.
Red–Blue Clay (CL)	44.0–45.5	12	18	ss	7–5–8
Red–Brn si Clay (CL)	49.0–50.5	13	18	ss	8–7–8
w/ trace fi sand					
Red–Blue Clay (CL)	51.0–53.0	14	24	ss	7–7–7
Blue si Clay (CL)	54.0–55.5	15	18	ss	3–8–8

Boring Terminated at 55.5 feet

LAW ENGINEERING TEST BORING RECORD

ELEV.	STRATUM DEPTH	VISUAL SOIL DESCRIPTION	D	SR	K	N or CR/RQD	REMARKS
12.0							
	0.3	TOPSOIL, grass and roots					
10		FILL: clayey sand with construction debris including concrete, boulders, asphalt and rebar	3.5	7		29	
			6.0	10		17	
5	7.5						at 7.0' on 10-22-86
		Stiff brown sandy CLAY with trace of organics (CH)	8.5	10		14	
			11.0	0		8	
0							
	15.0						
		Very soft dark brown silty CLAY with trace of fine sand (OL-OH)	16.0	10		2	
-5							
	20.0						
		Firm brown silty fine to medium sand with trace fine gravel (SM)	21.0	8		20	
-10							
			26.0	9		19	
-15							
			31.0	10		20	
-20							
	34.1						
		Very dense brown silty fine to medium sand with trace fine gravel (SM)	36.0	8		100	
-25	35.5						
		Boring terminated at 36.5' on 10-21-86					
-30							NOTES: (1) Method of drilling: wash borings with roller cone 3 3/4" I.D. (2) Drillers: Joe Trout. Jim Williams.
-35							
-40							

D - Sample depth (Ft.)



SYMBOLS:
- Undisturbed Sample
- Water level, time of drilling
- Water level
- C Caved depth of boring
- ◄ Loss of Water

N - Penetration in blows per foot (ASTM D-1586)
CR - % core recovery; NX or BX designates bit size (ASTM D-2113)
RQD - Rock Quality Designation

BORING NUMBER BW-4
DATE DRILLED 10-21-86
JOB NUMBER W6-5523

W.H.C.A. FACILITY
ANACOSTIA NAVAL STATION
WASHINGTON, D.C.

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