NGM 2012
COPENHAGEN

NGM 2012

Proceedings of the 16th Nordic Geotechnical Meeting
Copenhagen, 9-12 May 2012

Vol. 1/2

dgf-Bulletin
May 2012

27

DANISH GEOTECHNICAL SOCIETY
DANSK GEOTEKNISK FORENING

NGM 2012 Proceedings
Proceedings of the 16th Nordic Geotechnical Meeting, Copenhagen, 9-12 May 2012, Vol. 1-2

dgf-Bulletin 27

ISBN 978-87-89833-27-9

Printed at: InPrint, Latvia, 2012

The Danish Geotechnical Society encompasses members interested in geotechnical engineering, engineering geology and rock mechanics. The members of the Society are simultaneously members of one or more of the international societies:

- International Society for Soil Mechanics and Geotechnical Engineering
- International Association of Engineering Geology and the environment
- International Society for Rock Mechanics

Postal address: Dansk Geoteknisk Forening / Danish Geotechnical Society
Maglebjergvej 1
DK-2800 Kgs. Lyngby
Denmark

Phone: +45 4588 4444
Fax: +45 4588 1240
E-mail: dgf@geo.dk
Web site: www.danskgeotekniskforening.dk, www.danishgeotechnicalsociety.dk

Preface

On behalf of the Danish Geotechnical Society, it is a pleasure to welcome both Nordic geotechnical engineers and other participants to the 16th Nordic Geotechnical Meeting at the Tivoli Congress Center in the centre of Copenhagen.

The aim of the conference is to strengthen relationships between practicing engineers, researchers and scientists in the Nordic region within the fields of geotechnics and engineering geology. You are cordially invited to share your experience and knowledge with your Nordic colleagues.

Almost 100 papers have been received, covering 9 topics, and approximately half of these will be presented during the meeting. We have also invited two keynote speakers, Dr. Brian Simpson and Professor Paul Mayne, to give presentations. All presentations are included in this publication and are available in digital format on a USB stick. We are very grateful to the authors of the papers and to the reviewers for their work.

The organising committee would like to thank all who have contributed to the meeting: authors, reviewers, presenters, chairmen and the members of the Danish Geotechnical Society who have helped arrange the social events.

Last, but not least, we would like to thank all participants for coming to Copenhagen. We hope that the meeting will be a positive experience for all.

Copenhagen April 2012

Morten Anker Jørgensen
Chairman of NGM 2012

Anders T. S. Andersen
Chairman of Danish Geotechnical Society

Organizing Committee:
Morten Anker Jørgensen
Carsten Bonde
Caspar Thrane Leth
Pia Hald Sørensen
Helle Trankjær

Secretariat:
DIS Congress Service

Nordic Advisory Committee:

Sweden:	Stefan Aronsson
	Sara-Maria Blomberg
Finland:	Jouko Viitala
	Tim Länsivaara
Norway:	Jan Holme
	Kristian Aunaas
Iceland:	Haraldur Sigursteinsson
Denmark:	Jørgen S. Steenfelt
	Anders T. S. Andersen

Gold Sponsors:

bq byggros RAMBØLL COWI

AARSLEFF GEO WWW.GEO.DK

Silver Sponsors:

Grontmij NIRAS

Table of contents

Volume I:

Volume II:

Keynotes

Geotechnical site exploration in the year 2012

P. W. Mayne
Georgia Institute of Technology, Atlanta, GA USA, paul.mayne@gatech.edu

ABSTRACT
The best available program for geotechnical site exploration involves a blend of rotary drilling and sampling operations, laboratory testing, in-situ field tests, and geophysical measurements, all taken within the context of engineering geology. Yet, this is only viable when sufficient allocations of time and funds are available, i.e., large or critical projects. Thus, for the routine site investigations of soils, it is recommended that use of hybrid geotechnical-geophysical methods be adopted, including the seismic piezocone test (SCPTù) and seismic dilatometer (SDMTà), in order to provide multiple types of in-situ data for analysis and design. Both tests provide up to five independent readings with depth, thereby optimizing information gathered on the subsurface materials in an expeditious and economical manner.

Keywords: field testing, geophysics, geotechnical engineering, in-situ testing, site investigation

1 INTRODUCTION

Each and every geotechnical project requires a site-specific investigation to collect data regarding the subsurface conditions. This is because the ground conditions beneath a particular project location are unique, having been established under the hand of Mother Nature. As such, soil explorations must be made to determine the presence and identification of underlying strata, groundwater conditions, types of geomaterials, their depths and thicknesses, and the associated engineering parameters required for geotechnical design (Simons, et al. 2002).

1.1 Exploratory methods and geology

Of course, engineering geology plays an important part in governing which tests are applicable for site investigations. The conventional approach to site exploration has been accomplished using well-developed rotary drilling methods to create boreholes in order to obtain small split-spoon drive samples. Borings are created using solid or hollow augers, rotary wash methods, and/or wireline drilling. Detailed information can be gained by use of geophysical techniques and/or deployment of downhole in-situ probes to measure specific soil parameters. If needed, rotary drilling can be extended into rock using diamond coring, carbide tungsten bits, and/or alternative percussive methods.

Within North America, the standard tools and procedures for performing subsurface investigations are documented by Mayne et al. (2002). Here, each field and lab test approximately adheres to the guidelines and test methods specified by the American Society for Testing & Materials (ASTM).

For the Nordic countries of Denmark, Sweden, Finland, and Norway, general practices and illustrative examples of site investigations are given in Table 1. Löfroth et al. (2010) provide a concise and general overview of the geology in the Nordic region, including discussions on the predominance of bedrock and hard glacial tills that may be overlain by soft clays, organic soils, sands, and sensitive-to-quick fine-grained deposits, some of which may be explored using cone penetration tests (CPT). The recent development of windmill farms in the North Sea, Norwegian Sea, and Danish Sea has relied heavily on site investigation methods.

Table 1. Selected references concerning site investigations in Nordic countries.

Country	General	Specific
Denmark	Bonde (2009); Denver (1995); Luke (1996)	glacial till (Steenfelt & Hansen 1995)
		silts and clays (Thorsen & Mortensen 1995)
Finland	Halkola & Törnqvist (1995); Gardemeister & Tammirinne (1974)	soft clays (Ilander et al. 1999)
		soft clays (Karstunen et al. 2005)
Norway	Lunne & Sandven (1995); Senneset (1974)	soft sensitive clays (Lunne et al. 2003a)
		loose sand (Lunne et al. 2003b)
Sweden	Löfroth et al. (2010); Möller et al. (1995); Bergdahl et al. (1985) Dahlberg (1974)	soft organic clays and gyttja (Larsson and Åhnberg 2005)
		silts (Larsson 1997)
		glacial clay till (Larsson 2001)

1.2 Traditional site investigation program

For a comprehensive site exploration, Figure 1 shows a program of soil borings that involve the dynamic technique known as standard penetration testing (SPT) which includes a drive sampling approach to procure small 38-mm diameter disturbed soil samples. The SPT is more-or-less suited for use in loose to dense granular and sandy soils, with extended applications to stiff to hard fine-grained geomaterials (Stroud 1988).

When soft to firm clay or silty strata are encountered, the borings can switch over to vane shear testing (VST) in which the undrained shear strength (s_u) and sensitivity (S_t) can be assessed (Larsson and Åhnberg 2005). Alternative or supplemental in-situ data can be collected using pressuremeter tests (PMT) for modulus determination (E' or E_u), as well as strength (either ϕ' in sands or s_u in clays), initial horizontal stress state ($P_0 = \sigma_{ho}$), and limit pressure (P_L), as detailed by Briaud (1992), Clarke (1995), and Gambin et al. (2005). Time rate of consolidation can be evaluated using PMT holding tests to assess c_{vh} = coefficient of consolidation. In addition, pumping tests (PMP) can be implemented for measuring the coefficient of permeability (k).

Geophysical crosshole tests (CHT) may be conducted in parallel cased boreholes to evaluate the compression wave (V_p) and shear wave (V_s) velocities (Ebelhar et al. 1994; Wightman et al. 2003). The shear wave profile allows the direct assessment of the small-strain shear modulus ($G_{dyn} = G_{max} = G_0 = \rho_t \cdot V_s^2$; where ρ_t = total mass density). Therefore, it is not only valuable for seismic site amplification evaluations and dynamic analyses, but serves fundamentally as the initial monotonic stiffness of soils, thus the beginning of all shear stress vs. shear strain curves (Burland 1989; Leroueil and Hight 2003; Clayton 2011).

1.3 Sampling and Laboratory Testing

In addition to small drive samples, the borings also produce "undisturbed" thin-walled tube samples that are transported to the geotechnical laboratory. These samples usually have nominal diameters (75 mm < d < 150 mm) and lengths of about 1 m and obtained for laboratory testing of the intact soil materials under carefully controlled conditions using various devices, including: consolidometer, triaxial shear, fixed and flexible walled permeameter, direct shear, simple shear, bender elements, and resonant column apparatuses. Lab testing on soil specimens can take days or weeks or even months in order to obtain numerical results and needed information about the inplace geomaterial stress state, compressibility characteristics, soil strength, stiffness, and hydraulic conductivity.

Of additional difficulty is the realization that laboratory soil samples are often fraught with issues of sample disturbance which is unavoidable (Tanaka 2000; Lunne et al. 2006). In soft soils, improved results can be obtained by using special samplers (e.g., Laval, Sherbrooke, JPN), however at great cost and extra field effort. Moreover, the local drilling operations and field procedures can affect the overall quality of results of lab testing, as documented, for example, for projects situated in the well-known very soft

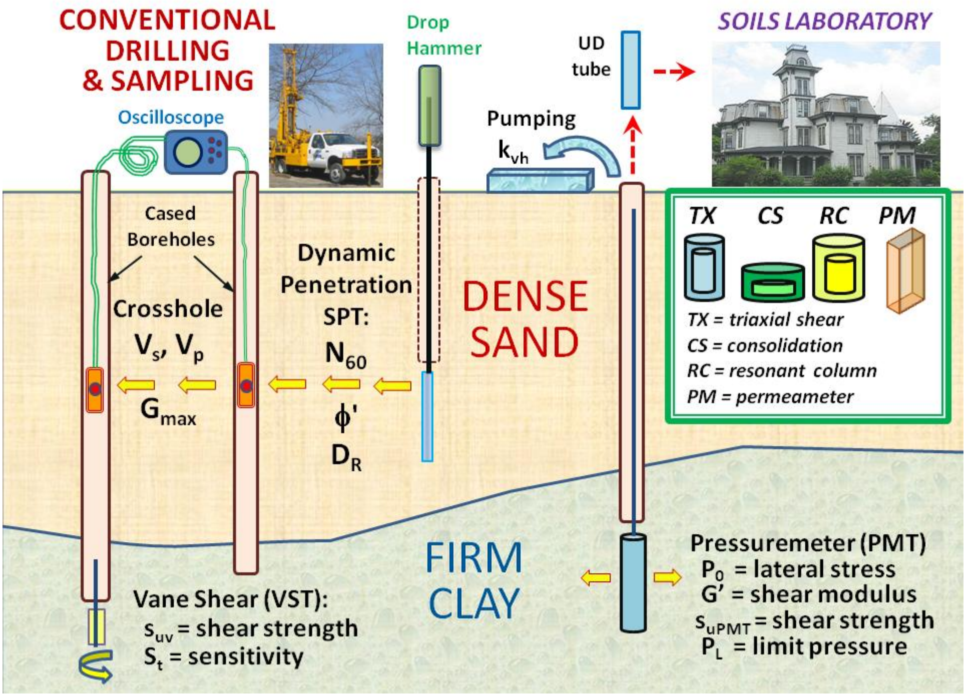


Figure 1 Traditional site investigation practices and testing for large projects or critical structures

Busan clay (e.g., Steenfelt et al. 2008). Undisturbed sampling of granular soils is now also possible by innovative freezing technology (Hoeg, et al. 2000), yet also at great cost [*anecdote: a fellow geotech from Exxon-Mobil indicated he paid $30k per frozen sand sample in 2003*].

While this kind of elaborate program can produce the necessary information regarding geostratification and relevant soil engineering properties, it does so at great time and cost (Clayton 2011). In fact, the full suite of field testing, geophysics, and laboratory testing is so expensive and of such long duration, a program of this level can only be afforded on relatively large scale projects with substantial budgets and lengthy schedules.

On small- to medium-size geotechnical projects, the economies of time and money restrict the amount of exploration and testing that can be performed, even though the engineering analyses also demand a thorough knowledge regarding the site-specific geomaterials lying beneath the property of study. In those instances, many budgets for investigations are too limited, such that insufficient information is obtained. In the USA, for example, a common occurrence is the utilization of a single measurement (alias, SPT-N value) as the only input number. The consequence is that undue conservatism is adopted to offset the poor quality and low reliability, thereby producing foundation solutions that are unnecessarily expensive for the construction of new facilities.

1.4 Risks of inadequate site investigation

A poorly-conducted and inadequate subsurface exploration program can have important and significant outcomes on the final constructed facilities, including possible overconservative designs as well as unsafe and unconservative solutions. Some of the potential consequences may include:

a. Excessively high construction costs and expenses due to unnecessary use of piled foundations or structural mats, whereas spread footings may have actually worked just fine.

b. Extra preparation time and payments for ground modification techniques, when in fact, none were needed.

c. Unexpected poor performance of foundations, embankments, retaining walls, and excavations, possibly including additional costs due to damage and/or retrofit and underpinning.

d. Failure or instability during or after construction operations due to inadequate characterization of the geomaterials or failure to detect soft zone anomalies, buried features, and/or weak layers and inclusions.

e. Legal involvements, litigation, loss of professional reputation and/or license.

Regardless of budget and time, the geotechnical site investigation must still proceed and provide a reasonable amount of high-quality and varied subsurface data for analysis so that the design produces an efficient, safe, and economical solution.

2 FIELD TEST METHODS

The major tools of the trade and methods for subsurface exploration and testing for geocharacterization have primarily developed over the past century. A concise historical summary of the various field devices and test procedures is given by Broms & Flodin (1988).

As new technologies were introduced, the geotechnical profession placed a variable reliance and acceptance on these different methodologies, as depicted conceptually by Figure 2 (Lacasse 1988). Starting circa 1902 with the SPT, limited borings and auger cuttings with index testing provided the bulk of investigative data, coupled with a strong background in geology and engineering "judgment". Over the next century, the advent of innovative in-situ tests, laboratory devices, geophysical techniques, analytical modeling, finite element and finite difference software, and probabilistic risk and reliability analyses have combined to assist the geotechnical engineer in an evaluation of the subsurface conditions. While judgment is still important, more reliance can be placed directly on numbers and measurements.

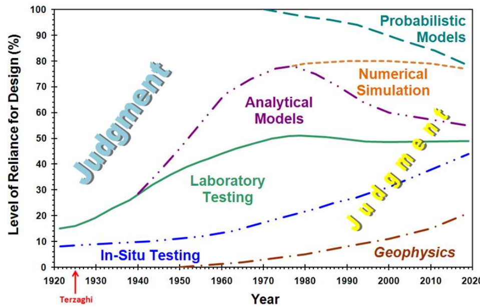


Figure 2 Evolution of methods for geotechnical site characterization (after Lacasse 1985)

2.1 Geotechnical Tests

Today, more than 150 different field devices, in-situ probes, and instruments are available for geotechnical site investigation (Robertson 1986; Lunne et al. 1994; Mayne 2010). Figure 3 illustrates a selected number of these field devices which include blades, probes, vanes, penetrometers, tubes, bars, plates, and/or rigid cells. These are advanced in a variety of approaches, either statically-pushed, dynamically-driven, drilled, torqued, twisted, inflated, vibrated, and/or sonically-installed. Mechanisms for insertion include rotary motion, drop hammers, hydraulics, pneumatics, electromechanics, and/or a combination of the aforementioned. Popular devices include the cone penetration test (CPT), flat plate dilatometer test (DMT), vane shear (VST), and pressuremeter (PMT). Specialty tests include the Iowa stepped blade (ISB), cone pressuremeter (CPMT), push-in spade cells or total stress cells (TSC), and borehole shear test (BST).

A clear advantage of field testing is that the results are obtained immediately, whereas considerable time is required for the results of laboratory tests to be forthcoming. Another benefit is that near continuous or at least frequent measurements are taken with depth, whereas lab results correspond to only

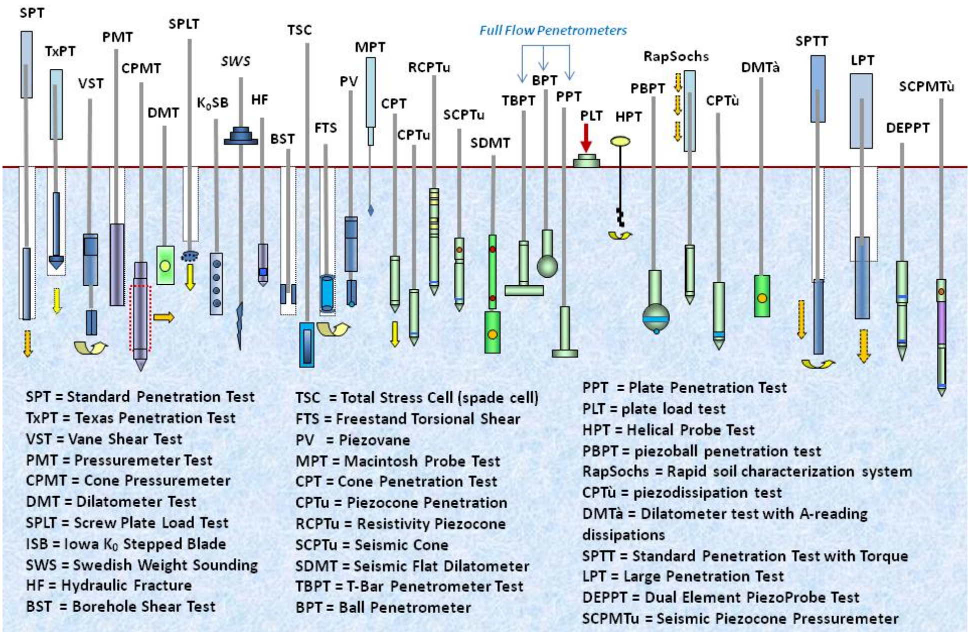


Figure 3 Selection of various in-situ test devices and field probes for geotechnical exploration

specific discrete positions where undisturbed samples are procured.

The notion that in-situ tests avert "disturbance" is incorrectly perceived, in that many of the penetrating probes (SPT, CPT, DMT, CPMT) are in fact actually recording measurements that correspond to maximum disturbance of soil during insertion of the devices. The exceptions would include the pressuremeter, specifically the self-boring type (SBPMT) and self-boring load cell (SBLC), as well as those devices that require a waiting period or dissipation phase following their installation (e.g., TSC, push-in piezometers).

2.2 Geophysical Tests

In addition to geotechnical tests, our friends in geology have also developed a suite of geophysical technologies, all of which are nondestructive and include both invasive (borehole) and noninvasive methods (surface arrays). Two main categories are deployed: (a) mechanical wave methods; and (b) electromagnetic wave measurements (Santamarina et al. 2001; Wightman et al. 2003; Sirles 2006).

2.3 Mechanical wave geophysics

The mechanical wave groupings include measurements of four basic wave types: compression (P-wave), shear (S-wave), Rayleigh (R-wave or Surface wave), and Love waves. Figure 4 presents a summary graphic illustrating the primary methods: refraction, reflection, crosshole, downhole, rotary crosshole, and suspension logging, used for developing profiles of P-and S-wave velocities with depth (Campanella 1994). Seismic tomography can also be implemented in crosshole arrays for site exploration purposes (Larsson and Mattsson 2004).

In addition, a number of surface wave techniques have arisen that are noninvasive: spectral analysis of surface waves (SASW), multi-channel analysis of surface waves (MASW), continuous surface waves (CSW), and passive surface wave readings, such as

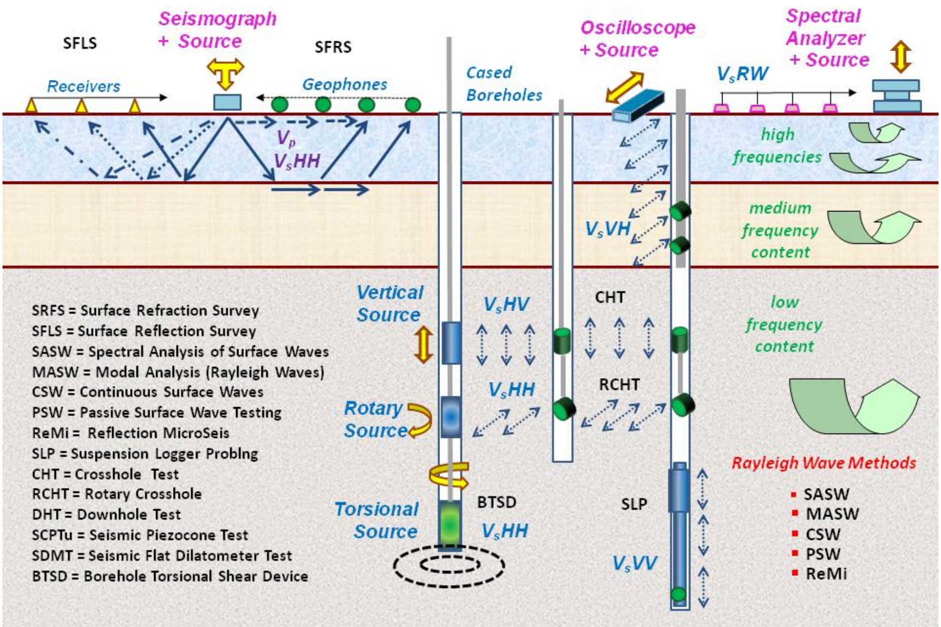


Figure 4 Various geophysical techniques that can be used in geotechnical exploration

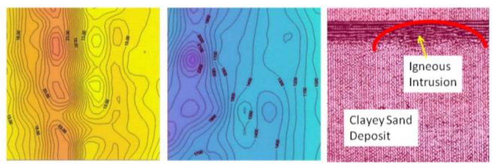
ReMi (Tran and Hiltunen, 2011). The geophysical techniques measure Rayleigh or surface waves and can be deployed to ascertain shear wave velocity profiles and the small-strain elastic properties of the ground, as well as very shallow, intermediate, and/or deep stratigraphic features, layering, and inclusions.

2.4 Electromagnetical geophysics

The electromagnetic wave approaches use electrical measurements of resistivity, dielectric, conductivity, and/or permittivity, as well as magnetometer data. Popular methods include: electrical resistivity surveys (ERS), electromagnetic conductivity (EMC), and ground penetrating radar (GPR). These are normally done quickly to map the area of site and show relative differences in electrical readings across the property. Thus, can be very useful to identify anomalous zones, hard features, soft zones or voids, or just basic differences in soil types related to site variability and heterogeneity.

Figure 5 presents a sampling of these 3 electromagnetic methods conducted at a site in Aiken, South Carolina. The survey results from the EMC and ERS are mapped over an areal viewpoint (10 m by 10 m), while the GPR is performed along a linear array to show variants with depth (10 m long extending 10 m deep).

The electrical readings can also be interpreted to provide data on in-situ moisture content and/or density, such as used in time domain reflectometry.



(a) (b) (c)

Figure 5 Results of electromagnetic geophysical methods conducted near Aiken, South Carolina: (a) conductivity, (b) resistivity, (c) radar. Note: all square sides are 10 m in length or depth.

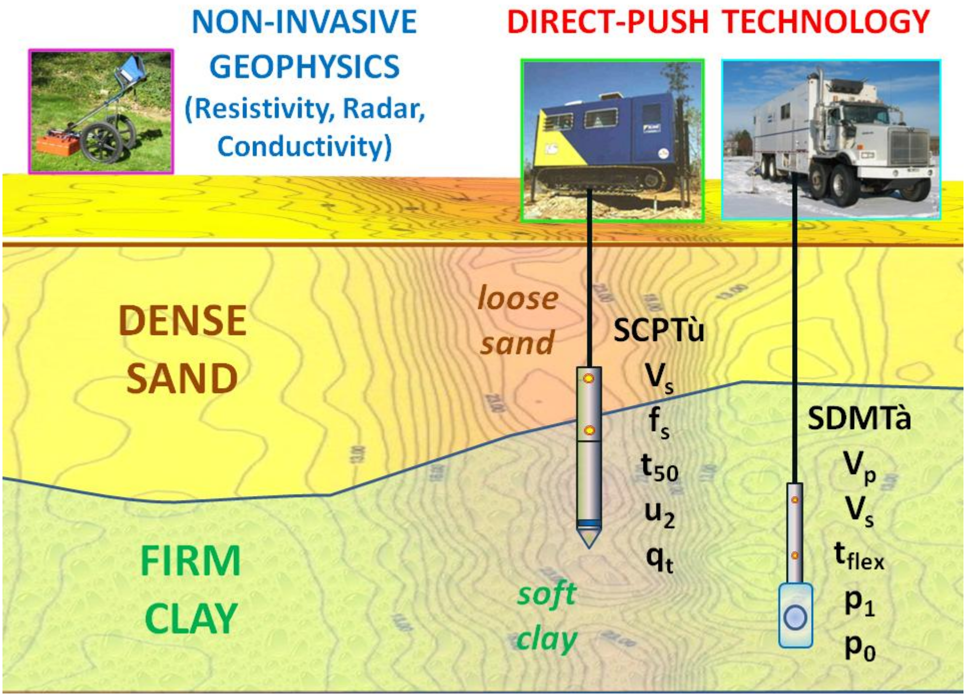


Figure 6. Modern strategy for geotechnical site investigation on routine projects for optimal coverage and collection of multiple data types

3 MODERN SITE EXPLORATION

A modern approach to site investigation can be recommended that includes: (a) initial areal mapping via noninvasive techniques; (b) physical vertical probings by hybrid geotechnical-geophysical soundings (Figure 6). These together offer benefits in terms of improved coverage, insurance, reliability, productivity, and economics, compared with conventional methods.

For instance, in a traditional site investigation, borings or soundings are typically positioned on an established grid pattern over the project building site, say 30 m on center, in an attempt to hopefully capture any lateral variants in geostratigraphy across the site. Of course, this is merely a trial-and-error attempt since the gridded area may or may not coincide with *Mother Nature's* original coordinate system. For instance, it would be completely plausible that a buried ravine, or old natural stream, or other unknown anomaly might easily lie between the chosen grid points for the borings. If such features were discovered during construction, the contractor could demand a redesign of the geotechnical solution (e.g., piles vs. shallow footings), otherwise file for claim charges due to differing site conditions. Of further concern, another unfortunate outcome may include legal action by the owner, architect, structural engineer, and/or contractor against the geotechnical firm.

3.1 Noninvasive geophysical mapping

In 2012, a rational solution to the above situations is the utilization of electromagnetic wave surveys (ERS, GPR, and/or EMC) for mapping the site area for relative changes. Not only are these geophysical surveys quick

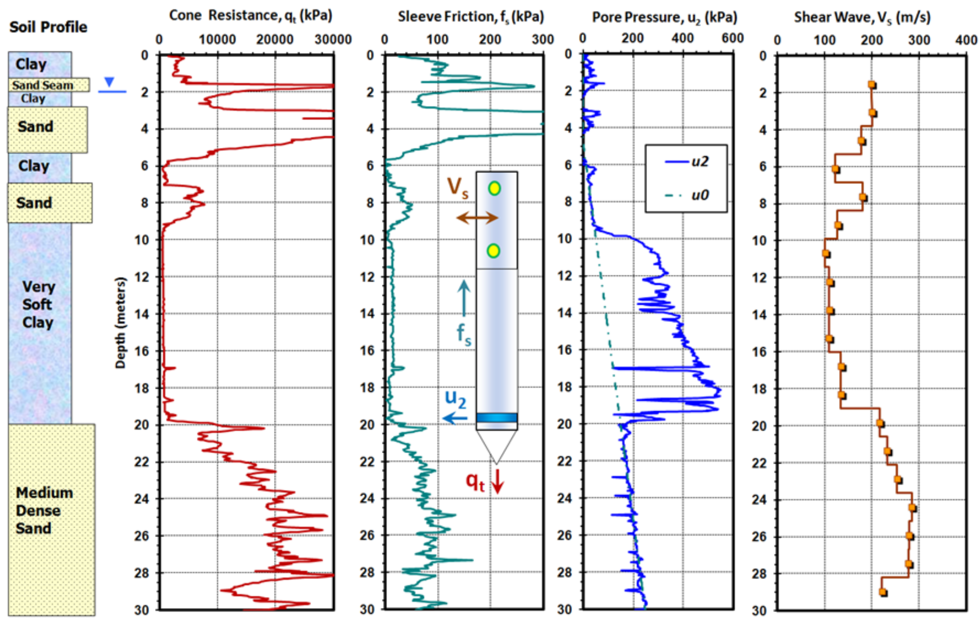


Figure 7 Representative seismic piezocone test (SCPTu) from New Orleans levees, Louisiana

and economical to perform, they offer a chance to rationally direct the probes and soundings of the site investigations towards any variants on the property, thus focusing on the mapping of relative differences in electrical ground properties (electromagnetic conductivity, resistivity, and/or dielectric) across the project area. It is also possible to utilize the aforementioned surface wave methods (SASW, MASW, CSW) for such purposes, albeit at higher cost and degree of implementation.

3.2 Invasive hybrid probes

Hybrid exploratory devices that combine direct-push electromechanical probes with downhole geophysics offer an optimized means to collect data, as information at opposite ends of the stress-strain-strength curve are obtained at one time in a single sounding. Coupled with dissipatory phases, these include the seismic piezocone test (SCPTù) and seismic flat dilatometer test (SDMTà). Taken together with the non-invasive mapping methods above, Figure 6 presents a logical approach to modern site exploration practices.

3.3 Seismic piezocone tests

The seismic cone (SCPT) and seismic dilatometer (SDMT) are not new methods, but were developed some three decades ago (Campanella et al. 1986; Hepton 1988). They offer continuous profiling of strata and soil parameters with multiple readings taken at each depth in a quick and reliable manner. By adding dissipatory phases, the improved SCPTù offers up to 5 separate readings with depth, including: cone tip resistance (q_t), sleeve friction (f_s), porewater pressure (u_2), time rate of dissipation (t_{50}), and shear wave velocity (V_s), as detailed by Mayne and Campanella (2005). Moreover, the data are recorded continuously, digitally, and directly into a computer data acquisition unit for immediate post-processing, so that if necessary, on-site decisions can be made immediately by the geotechnical engineer,

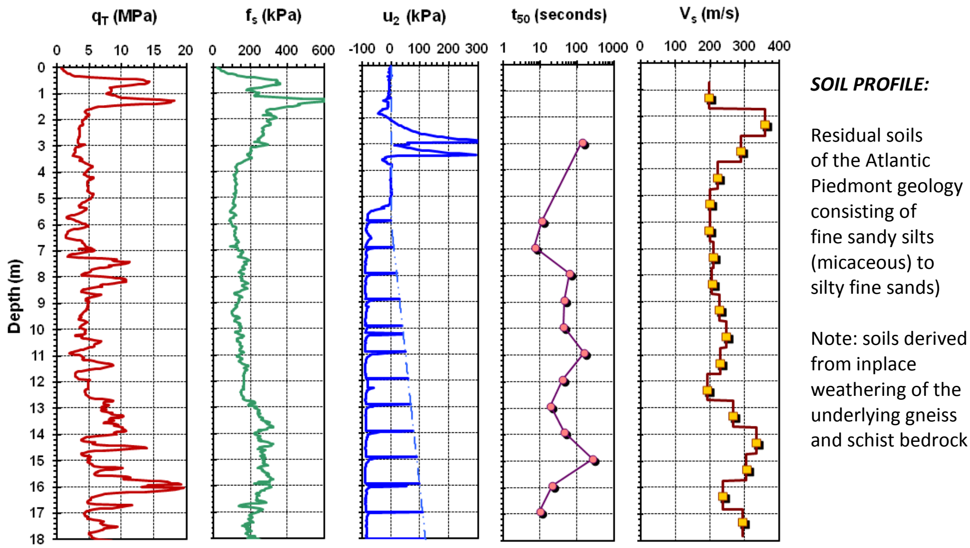


Figure 8. Seismic piezocone with dissipatory phases (SCPTù) in Atlanta, Georgia

else sent by wireless transmission to the chief engineer at the office for review. If desired, additional modules can be added to provide downhole readings on resistivity, dielectric, and electrical conductivity.

One representative standard SCPTu sounding from New Orleans, Louisiana is presented in Figure 7 showing four separate measurements with depth. The sounding was completed as part of the levee restoration project of the area east of the city. The readings clearly show alternating layers of clay/sand strata in the upper 9 m followed by a thick 11-m soft clay layer to 20 m depth, underlain by a 10-m thick sand stratum extending beyond the termination depth at 30 m. As a general guideline, clean sands are distinguished by resistances where $q_t > 50$ atm (5 MPa), whereas clays exhibit $q_t < 50$ atm. Also, porewater pressures in sand layers are nearly hydrostatic ($u_2 \approx u_0$) while in clays that are intact: $u_2 > u_0$. The latter are quite evident in the depth region from 10 to 20 m in Figure 7. In fissured soils, $u_2 < u_0$ and may even be negative values.

In the SCPTù, the aforementioned readings are supplemented with dissipations of porewater pressures at selected test depths so that five recordings with depth are obtained from a single sounding: q_t, f_s, u_2, t_{50}, and V_s. Figure 8 presents results from a SCPTù taken at the Atlanta Hartsfield International Airport. The soil profile is comprised of residual fine sandy silts to silty fine sands with mica derived from the inplace weathering of the underlying bedrock, mostly consisting of gneiss, schist, and granite. The rate of consolidation in these geomaterials is rather quick and therefore possible to perform complete porewater pressure dissipations in only 1 to 4 minutes at each depth. Another interesting characteristic here is that the penetration porewater pressures at the shoulder position (u_2) go negative when the groundwater table is encountered. This is confirmed by the projection of the equilibrium hydrostatic pore pressures (u_0) following full decay to 100% dissipations.

3.4 Seismic dilatometer tests

In the SDMTà, as many as five or six independent readings can be obtained with depth, usually at 0.02m intervals, including:

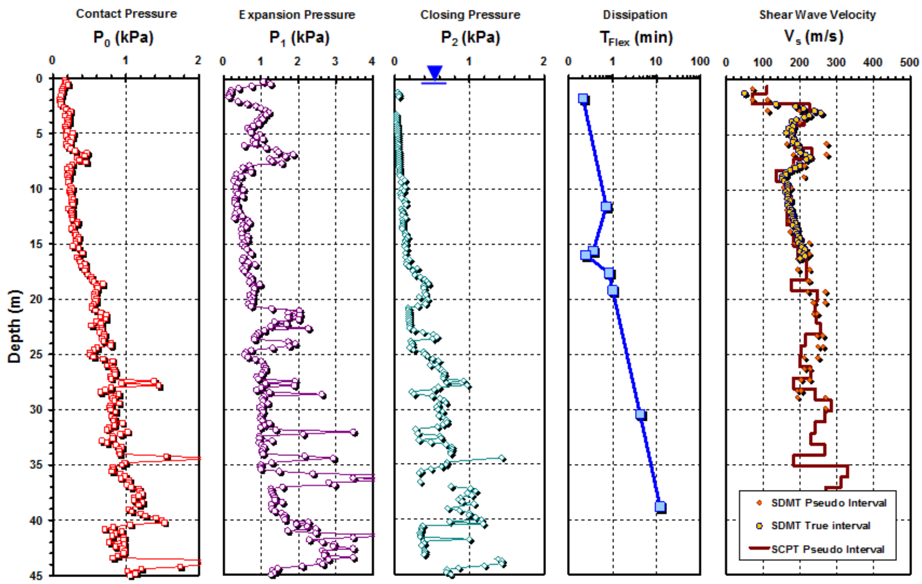


Figure 9 Seismic flat dilatometer test with dissipations (SDMTà) at Treporti test embankment

contact pressure (p_0), expansion pressure (p_1), deflation pressure (p_2), time rate decay (t_{flex}), compression wave velocity (V_p), and shear wave velocity (V_s), per details by Marchetti et al. (2008). It is also possible to measure blade thrust resistance (q_D) between success-ive push depths. An illustrative example of a SDMTà sounding performed in highly-stratified alluvial-marine sediments at the Treporti test embankment site near Venice, Italy is shown in Figure 9. Details on the complementary laboratory and field tests in these sediments are given by Simonini et al. (2007).

4 GEOTECHNICAL PARAMETERS

The interpretation of in-situ tests to ascertain soil engineering parameters is a most challenging task. One reason for this is the wide diversity in geomaterials that have a multitude of particle constituents, grain size distributions, geologic origins, stress and strain histories, environments, and long ages on the planet. Another aspect is due to the fact that soils are complex entities that exhibit variability, initial geostatic stress state anisotropy, nonlinearity in their stress-strain-strength response, strain rate effects, prestressing, and drainage related behavior due to their inherent permeability and hydro-mechanical conductivity characteristics (Mayne et al. 2009). Therefore, interpret-ations must be generalized, at least until substantial calibrations and validations are documented. This has recently become possible through established geotechnical test sites.

4.1 Geotechnical experimentation sites

Recent symposia have documented information and data from 66 international geotechnical experimentation sites (IGES) on the theme entitled: Characterization and Engineering Properties of Natural Soils (Tan et al. 2003; Phoon et al. 2007). In these proceedings, technical papers summarize the efforts of various prominent research groups, institutions, universities, and commercial testing firms in the detailed field and laboratory testing programs.

The IGES include a diverse selection of geomaterials, each within a particular geology, topographic setting, and geodetic

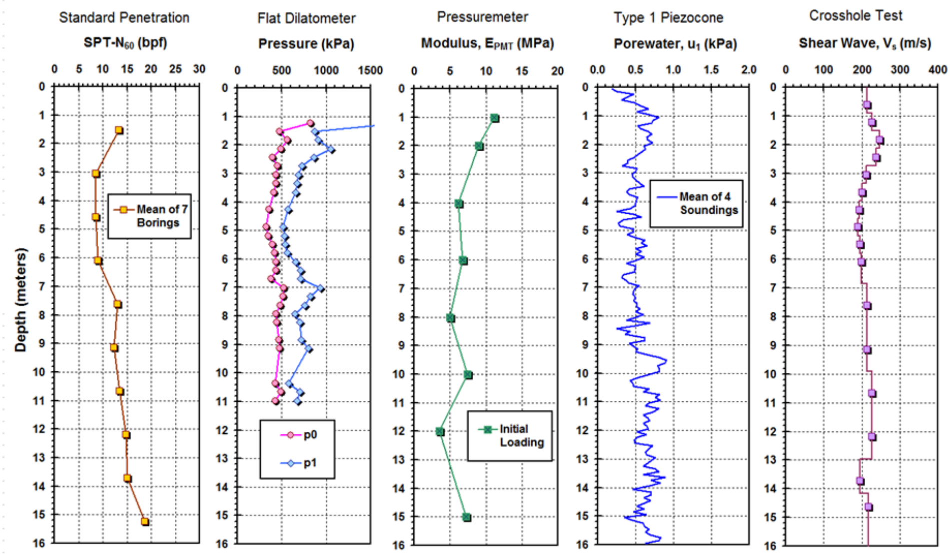


Figure 10 Summary of selected in-situ test results at Opelika national experimentation site, Alabama

environment. In all cases, the IGES research programs have been underway for many years, if not decades. Still, a comprehensive understanding of these geomaterials is not available.

One excellent IGES example is the loose sand site at Holmen, Norway established and studied by the Norwegian Geotechnical Institute for over 5 decades (Lunne et al. 2003b). At Holmen, extensive types of geotechnical lab sets, in-situ testing, pile foundation research, building foundation settlements, and geophysical measurements have been collected in these sandy sediments, all of which can be cross-referenced. Another example includes the very soft sensitive clay at Onsøy (Lunne et al. 2003a).

In nearby Sweden, 9 test sites situated over soft clays have been subjected to extensive laboratory, geotechnical, and geophysical studies, as well as full-scale embankment loadings (Larsson and Mulabdić 1991).

In some cases, a large civil engineering project can serve as an IGES, such as the Storebælt bridge/tunnel link connecting Denmark to Sweden, because of the large volume and varied types of geotechnical information that were collected for this effort (Steenfelt and Hansen 1995). Here, a sizable total 2227 soil borings and 2465 CPT soundings were completed. A similar case can be made for the smaller yet instrumented Murro embankment in Finland where the site conditions were investigated using 4 in-situ test methods and laboratory testing program (Karstunen et al. 2005).

Within the continental USA, six national geotechnical experimentation sites (NGES) have been established to provide a full set of documents from laboratory, geotechnical, geophysical, and full-scale performance testing of structures such as footings, piling foundations, retaining walls, and ground modification (Benoît and Lutenegger, 2000).

For illustration, a summary of selected in-situ test profiles measured in Piedmont residual soils at the Opelika NGES in eastern Alabama is presented in Figure 10. More details on this site are presented in Mayne and Brown (2003). In addition to a full array of SPT, CPT, CPTù, SCPT, SDMT, PMT, CHT, SASW, DHT, and BST, the site soils have been fully tested in the laboratory (e.g., PM, TX, RCT, CS, DSB) and full scale load tests have included axial driven piles, drilled shaft foundations, lateral pile load tests, and displacement type piles.

The geotechnical experimentation sites are of great importance because many different types of measurements are taken on the same geomaterials in the same vicinity. This permits a benchmark for ground truthing, where the laboratory tests can be compared with in-situ results, as well as the full-scale performance of prototype foundations, walls, excavations, and slopes. Geotechnical parameters acquired from analytical methods and/or numerical simulations, as well as various constitutive soil models, can be calibrated and cross-validated.

4.2 In-situ test interpretation

General approaches to the evaluation of soil parameters from in-situ test data are given in Jamiolkowski et al. (1985), Kulhawy & Mayne (1990), Lunne et al. (1994), Mayne (2007), and Schnaid (2009). For the Nordic countries, methods for field test interpretation are documented in the literature (e.g., Larsson & Mulabdić 1991; Luke 1996; Lunne et al. 1997; Larsson & Åhnberg 2005; Löfroth et al. 2010).

The author's basic methods for parameter evaluation of stress state in soils for three in-situ test methods (SPT, CPT, DMT) are given in Table 2. Stress state includes the apparent preconsolidation stress, or yield stress ($\sigma_{p'}$) and current effective vertical overburden stress (σ_{vo}') where $\sigma_{vo}' = \sigma_{vo} - u_o$. The total overburden stress is obtained from the accumulation of unit weights with depth:

$$\sigma_{vo} = \int_0^z \gamma_t \cdot dz \quad (1)$$

where γ_t = total soil unit weight. The hydrostatic porewater pressure is calculated from the groundwater table or obtained from piezometer measurements. The yield stress ratio (YSR) is a more precise representation of the apparent overconsolidation ratio (OCR $= P_c'/\sigma_{vo}'$) and is determined from:

$$YSR = \sigma_p'/\sigma_{vo}' \quad (2)$$

An alternate means to express the stress history is via the yield stress difference (YSD), analogous to the overconsolidation difference (OCD $= P_c' - \sigma_{vo}'$):

$$YSD = \sigma_p' - \sigma_{vo}' \quad (3)$$

which appears advantageous for soil deposits that have been mechanically loaded-unloaded (Mayne 2007).

An interesting aspect of the relationships in Table 2 is that they apply to a wide range of varied soil types, including intact clays, silts, mixed geomaterials, and quartz/silica sands, primarily Holocene to Pleistocene. They do not apply, however, to structured and problematic soils, such as carbonate or calcareous sands, quick clays, diatomaceous geomaterials, or highly organic peats.

Of special note, the generalized approach to evaluating the effective stress friction angle (ϕ') of (all) soils by CPTu devised at NTNH (Senneset et al. 1989) seems a particularly attractive goal, as this serves as a fundamental property in the behavior of sands, silts, and clays, as well as a key parameter in critical state soil mechanics (Mayne, et al. 2009).

5 FUTURE DIRECTIONS

In the past decade, a number of new field tests and testing procedures have become available for site exploration.

5.1 New devices

Some of the new equipment include full-flow devices, such as T-bar and ball penetrometers (Randolph 2004; DeJong et al. 2010), free-fall harpoon piezocones (Stegmann et al. 2006; Moser et al. 2007), electromechanical vanes (Randolph et al. 2005), multi-channel dynamic piezo-cone penetrometers (Kianirad et al. 2011), auto-seis sources for DHT and SCPT (McGillivray 2008), and in-situ scour probes (Caruso & Gabr 2011). In lieu of rotary drilling, new methods of direct push sampling have emerged which provide continuous collection of soil samples (Geoprobe, PowerProbe) to depths of 30 to 45 m by a single operator. Sonic drilling (Boart-Longyear) facilitates the collection of

Table 2 Parameter interpretation for unit weight and stress state evaluations in soils

Soil Engineering Parameter	In-Situ Test Method	Interpretative Relationship
Unit Weight, γ_t (kN/m^3)	DHT	$\gamma_t = 8.32 \log(V_s) - 1.61 \log z$ where V_s = shear wave velocity (m/s) z = depth (m)
	SPT	a. Estimate $V_s = 97\ (N_{60})^{0.337}$ (see Note 1) b. Use above expression for DHT where N_{60} (bpf) = energy-corrected SPT resistance
	CPT	$\gamma_t = 1.95\ \gamma_w\ (f_s/\sigma_{atm}+0.01)^{0.06}\ (\sigma_{vo}'/\sigma_{atm}+0.01)^{06}$ (see Fig. 11) where γ_w = unit weight water σ_{atm} = atmospheric pressure (= 1 bar = 100 kPa) f_s = sleeve resistance σ_{vo}' = effective vertical overburden stress
	DMT	$\gamma_t = 1.12\ \gamma_w\ (E_D/\sigma_{atm})^{0.1}\ (I_D)^{-0.05}$ where γ_w = unit weight of water E_D = dilatometer modulus I_D = material index
Yield Stress, σ_p' (kPa)	DHT	$\sigma_p' = 0.101\ G_{max}^{0.478}\ \sigma_{vo}'^{0.420}\ \sigma_{atm}^{0.102}$ where $G_{max} = (\gamma_t/g_a)(V_s)^2$ = small-strain shear modulus γ_t = soil total unit weight g_a = gravitation acceleration constant (= 9.8 m/s^2)
	SPT	$\sigma_p' = 0.47\ (N_{60})^{n^*}\ \sigma_{atm}$ where n^* = empirical soil-dependent exponent: intact clays (n^*=1); silts (n^*=0.8); sands (n^* = 0.6)
	CPT	$\sigma_p' = 0.33\ (q_t - \sigma_{vo})^m\ (\sigma_{atm}/100)^{1-m}$ (see Figure 12) where q_t = total cone resistance σ_{vo} = total overburden stress and m = empirical soil-dependent exponent: intact clays (m=1); sensitive clays (m=0.9); silts (m = 0.85); silty sands (m=0.8); clean quartz/silica sands (m = 0.72)
	DMT	$\sigma_p' \approx 0.51\ (p_0 - u_0)$ where p_0 = contact pressure (corrected A-reading) u_0 = hydrostatic porewater pressure

Note 1. after Imai and Tonouchi (1982)

both soil and rock samples continuously and much faster than traditional rotary drilling or augering.

5.2 New testing procedures

Using existing devices, several new approaches to assess inplace soil parameters include: (a) twitch testing to evaluate strain rate and drainage conditions (Chung et al. 2006; Yafrate & DeJong 2007); (b) frequent-interval shear wave measurements and continuous SCPT (Mayne & McGillivray 2008); (c) evaluation of in-situ modulus reduction curves (Stokoe et al. 2008); and cone load tests for axial pile response (Ali et al. 2010).

6 CONCLUSIONS

The complexities of natural soil behavior are now evident from decades-long studies involving complementary suites of laboratory studies, in-situ testing, geophysics, and full-scale load test measurements at international geotechnical test sites (IGES). The IGES are situated in various geomaterials including clays, silts, sands, and mixed soils. As such,

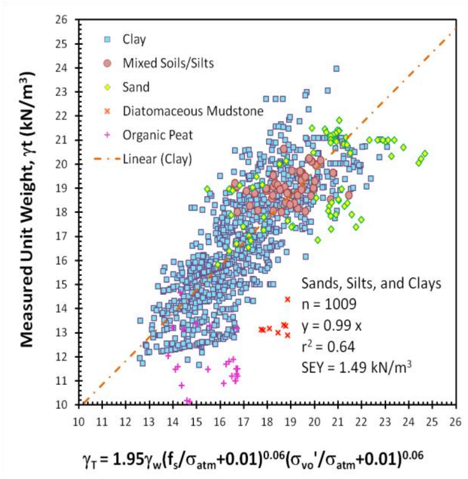


Figure 11 Unit weight relationship with CPT sleeve friction in soils

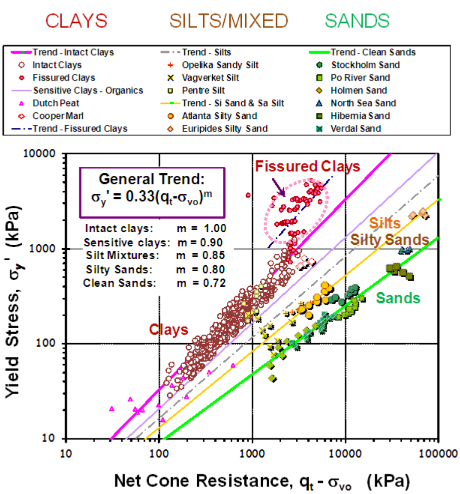


Figure 12 Yield stress relationship with CPT cone resistance in soils (after Mayne et al. 2009)

geotechnical site characterization is best-handled by deployment of many different types of in-situ probes, penetrometers, and sounding, coupled with geophysical surveys, sampling, and laboratory testing. This is only feasible on large or critical projects because of funding and time issues. Therefore, for routine explorations, the geoengineering profession should adopt a two-fold phased investigation involving: (a) areal geophysical mapping by EMC or ERS followed by: (b) either seismic piezocone test (SCPTù) and/or seismic dilatometer test (SDMTà). Both tests provide up to 5 independent readings with depth in a single sounding. In this way, no compromise is made in acquiring the necessary and varied types of important data and subsurface information about the ground conditions.

7 ACKNOWLEDGMENTS

The author appreciates the generosity and assistance of ConeTec Investigations, US Dept. of Energy at the Savannah River Site, and Fugro Engineers BV in their support of in-situ research activities at Georgia Tech.

8 REFERENCES

Ali, H., Reiffsteck, P., Baguelin, F., van de Graaf, H., Bacconnet, C. and Gourvés, R. (2010). Settlement of pile using cone loading test. Proc. CPT'10 (Huntington Beach/CA), Omnipress: www.cpt10.com

Benoît, J. and Lutenegger, A.J., ed. (2000). National Geotechnical Experimentation Sites. GSP 93, ASCE, Reston,Virginia: 398 p.

Bergdahl, U., Hult G., and Ottosson E., 1985. Calculation of settlements of footings in sands. Proceedings of the 11th International Conference on Soil Mechanics and Foundation Engineering, Vol. 4, San Francisco: 2167-2170.

Bonde, C. (2009). Status report: national anneks EC7 Del 2. Feltkomitéen, Danish Geotechnical Society: 11 p. www.danskgeotekniskforening.dk

Briaud, J-L. (1992). The Pressuremeter. Swets & Zeitlinger, Lisse, The Netherlands: 340 p.

Broms, B.B. & Flodin, N. (1988). History of soil penetration testing, Penetration Testing 1988, (Proc. ISOPT, Orlando), Balkema: 157-220.

Burland, J.B. (1989). Small is beautiful: The stiffness of soils at small strain. Canadian Geotechnical J. 26 (4): 499-516.

Campanella, R.G., Robertson, P.K. and Gillespie, D. (1986). Seismic cone penetration test. Use of In-Situ Tests in Geot. Engrg. (GSP 6), ASCE, Reston, VA: 116-130.

Campanella, R.G. (1994). Field methods for dynamic geotechnical testing. Dynamic Geotechnical Testing II (STP 1213), ASTM, Pennsylvania: 3-23.

Caruso, G. and Gabr, M. (2011). In-situ assessment of scour potential with depth using jetting approach. GeoFrontiers 2011: Advances in Geotechnical Engineering (Dallas), ASCE, Reston, Virginia: 1483-1492.

Clayton, C.R.I. (2011). Stiffness at small strain: research and practice. Geotechnique 62 (1): 5-37.

Chung, S.F., Randolph, M.F., and Schneider, J.A. (2006). Effect of penetration rate on penetrometer resistance in clay. Journal of Geotechnical & Geoenvironmental Engrg. 132 (9): 1188-1196.

Clarke, B.G. (1995). Pressuremeters in Geotechnical Design, Blackie Academic/ Chapman & Hall, London: 367 p.

Dahlberg, R. (1974). Penetration testing in Sweden. Proc. ESOPT, Vol. 1, National Swedish Building Research, Stockholm: 115-131.

DeJong, J.T., Yafrate, N., DeGroot, D., Low, H.E. and Randolph, M.F. (2010). Recommended practice for full-flow penetrometer testing and analysis. ASTM Geotechnical Testing J. 33 (2): 1-13.

Denver, H. (1995). CPT in Denmark: national report. Proc. CPT'95, Vol. 1, Swedish Geotechnical Society, Linköping: 55-61.

Ebelhar, R.J., Drnevich, V.P. and Kutter, B.L. (1994). Dynamic Geotechnical Testing II, ASTM, West Conshohocken, PA: 426 p.

Gambin, M., Magnan, J-P., and Mestat, Ph., ed. (2005). Intl. Symposium: 50 Years of Pressuremeters (Proc. ISP5- Pressio 2005), Vols 1 & 2, Laboratoire Central des Ponts et Chaussée, Paris: 1484 p.

Gardemeister, R. and Tammirinne, M. (1974). Penetration testing in Finland. Proc. ESOPT, Vol. 1, National Swedish Building Research, Stockholm: 35-46.

Halkola, H. and Törnqvist, J. (1995). National report on CPT - Finland. national report. Proc. CPT'95, Vol. 1, Swedish Geotechnical Society, Linköping: 63-66.

Hepton, P. (1988). Shear wave velocity measurements during penetration testing. Penetration Testing in the UK, Thomas Telford, London: 275-278.

Hoeg, K, Dyvik, R., and Sandbækken, G. (2000). Strength of undisturbed versus reconstituted silt and silty sand specimens. Journal of Geotechnical & Geoenvironmental Engineering 126 (7): 606-617.

Ilander, A., Forsman, J. and Lahtinen. P. (1999). Combined mass- and column stabilization in Kivikko test embankment. Dry Mix Methods by Deep Soil Stabilization, Balkema, Rotterdam: 185-192.

Imai, T. and Tonouchi, K. (1982). Correlation of N-value with S-wave velocity. Proc. 2nd European Symp. on Penetration Testing, Amsterdam: 67–72.

Jamiolkowski, M., Ladd, C.C., Germaine, J.T. and Lancellotta, R. (1985). New developments in field and lab testing of soils. Proc., 11th International Conference on Soil Mechanics and Foundation Engineering, Vol. 1, San Francisco: 57-154.

Karstunen, M., Krenn, H., Wheeler, S.J., Koskinen, M. and Zentar, R. (2005). Effect of anisotropy and destructuration on the behavior of Murro test embankment. Intl. J. Geomechanics 5 (2): 87-97.

Kianirad, E., Gamache, R.W., Brady, D. and Alshawabkeh, A.N. (2011). Equivalent quasi-static estimation of dynamic penetration force for near surface soil characterization. GeoFrontiers 2011: Advances in Geotechnical Engineering (GSP 211, Dallas), ASCE, Reston, Virginia: 2325-2334.

Kulhawy, F.H. and Mayne, P.W. (1990). Manual on estimating soil properties for foundation design. Report EL-6800, Electric Power Research Institute, Palo Alto, 306 p. Website: www.epri.com

Lacasse, S. (1988). Design parameters of clays from in-situ and lab tests. Proc. Symposium on New Concepts in Geotechnical Engineering, Rio de Janeiro; also Norwegian Geotechnical Inst. Report No. 52155-50, Oslo.

Larsson, R. (1997). Investigations and Load Tests in Silty Soils. SGI Report R-54, Swedish Geotechnical Institute, Linköping: 260 p.

Larsson, R. and Åhnberg, H. (2005). On the evaluation of undrained shear strength and preconsolidation pressure from common field tests in clay. Canadian Geotech-nical J. 42 (4): 1221-1231.

Larsson, R. and Mattsson, H. (2004). Estimation of shear strength increase beneath embankments by seismic crosshole tomography. Geotechnical & Geophysical Site Characterization, Vol. 1 (Proc. ISC-2, Porto), Millpress/Rotterdam: 971-978.

Larsson, R. and Mulabdić, M. (1991). Piezocone tests in clay. SGI Report 42, Swedish Geotechnical Institute, Linköping: 240 p.

Larsson, R. (2001). Investigations and load tests in clay till. SGI Report 59, Swedish Geotechnical Institute, Linköping: 169 p.

Leroueil, S. and Jamiolkowski, M. (1991). Exploration of soft soil and determination of design parameters. Proc. Geo-Coast'91, Vol. 2, Yokohama: 969-998.

Leroueil, S. and Hight, D.W. (2003). Behaviour and properties of natural soils and soft rocks. Characterization and Engineering Properties of Natural Soils, Vol. 1, Swets and Zeitlinger, Lisse: 29-254.

Löfroth, H., Sandven, R., Bonde, C. and Halkola, H. (2010). Regional report for the Nordic countries. Intl. Symp. on Cone Penetration Testing, Vol. 1 (Proc. CPT'10, Huntington Beach, California), Omnipress. www.cpt10.com

Luke, K. (1996). Cone factors from field vane and triaxial tests in Danish soils. Proc. XII Nordic Geotechnical Conf., Vol. 1, Reykjavík, Icelandic Geotechnical Society: 203-208.

Lunne, T. and Sandven, R. (1995). CPT-national report for Norway. national report. Proc. CPT'95, Vol. 1, Swedish Geotechnical Society, Linköping: 163-173.

Lunne, T., Lacasse, S. and Rad, N.S. (1994). General report: CPT, PMT, and recent developments on in-situ testing of soils. Proc. 12th Intl. Conf. on Soil Mechanics and Foundation Engineering (4), Rio de Janeiro: 2339-2403.

Lunne, T., Berre, T., Andersen, K.H., Strandvik, S. and Sjursen, M. (2006). Effects of sample disturbance and consolidation procedures. Canadian Geotechnical Journal 43 (7): 726-750.

Lunne, T., Long, M. and Forsberg, C. (2003a). Characterization and engineering properties of Onsøy clay. Characterization and Engineering Properties of Natural Soils (1) Swets & Zeitlinger, Lisse: 395-428.

Lunne, T., Long, M. and Forsberg, C. (2003b). Characterization & engineering properties of Holmen sand. Characterization and Engineering Properties of Natural Soils (2) Swets & Zeitlinger, Lisse: 1121-1148.

Lunne, T., Robertson, P.K. & Powell, J.J.M. (1997). Cone Penetration Testing in Geotechnical Practice, Blackie Academic, London: 312 p.

Marchetti, D., Marchetti, S., Monaco, P. and Totani, G. (2008). Experience with the seismic dilatometer in various soils. Geotechnical & Geophysical Site Characterization, Vol. 2 (Proc. ISC-3, Taipei), Taylor & Francis, London: 1339-1345.

Mayne, P.W. and Brown, D.A. (2003). Site characterization of Piedmont residuum of North America. Characterization & Engineering Properties of Natural Soils (2), Swets & Zeitlinger, Lisse, 1323-1339.

Mayne, P.W., Christopher, B.R. and DeJong, J.T. (2002). Subsurface Investigations: Geotechnical Site Characterization. Publication No. FHWA-NHI-01-031, National Highway Institute, Federal Highway Administration, Washington, DC: 301 p.

Mayne, P.W. and Campanella, R.G. (2005). Versatile site characterization by seismic piezocone tests. Proc. 16th Intl. Conference on Soil Mechanics & Geotechnical Engineering, (ICSMGE, Osaka), Vol. 2, Millpress, Rotterdam: 721-724.

Mayne, P.W. (2007). Invited overview paper: In-situ test calibrations for evaluating soil parameters. Characterization & Engineering Properties of Natural Soils, Vol. 3 (Proc. Singapore 2006), Taylor & Francis Group, London: 1602-1652.

Mayne, P.W. and McGillivray, A.V. (2008). Improved shear wave measurements using autoseis sources. Deformational Characteristics of Geomaterials, Vol. 2, (Proc. 4th IS, Atlanta), Millpress/IOS, Amsterdam: 853-860.

Mayne, P.W., Coop, M.R., Springman, S., Huang, A-B., and Zornberg, J. (2009). State-of-the-Art Paper (SOA-1): Geomaterial Behavior and Testing. Proc. 17th Intl. Conf. Soil Mechanics & Geotechnical Engineering, Vol. 4 (ICSMGE, Alexandria, Egypt), Millpress/IOS Press, Amsterdam: 2777-2872.

Mayne, P.W. (2010). Regional CPT report for North America. Proc., 2nd Intl. Symposium on Cone Penetration Testing, Vol. 1, Omnipress: 275-312.

Mayne, P.W, Peuchen, J., and Bouwmeester, D. (2010). Soil unit weight estimated from CPTu in offshore soils. Frontiers in Offshore Geotechnics II (Proc. ISFOG 2010, Perth), Taylor & Francis Group, London: 371-376.

McGillivray, A.V. and Mayne, P.W. (2008). An automated seismic source for continuous shear wave profiling. Geotechnical & Geophysical Site Characterization, (ISC-3, Taipei), Taylor & Francis Group, London: 1347-1352.

Möller, B., Massarsch, R., Elmgren, K., Torstensson, B-A., Hellgren, N., Tremblay, M., Larsson, R. and Viberg, L. (1995). CPT - national report for Sweden. Proc. CPT'95, Vol. 1, Swedish Geotechnical Society, Linköping: 221-234.

Mosher, D.C., Christian, H., Cunningham, D., MacKillop, K., Furlong, A., & Jarrett, K. (2007). The harpoon free-fall cone penetrometer for rapid offshore geotechnical assessment. Proc. 6th Intl. Offshore Site Investigation & Geot. Conf., Society for Underwater Technology, London: 195-202.

Phoon, K.K., Hight, D.W., Leroueil, S., and Tan, T-S. (2007). Characterization and Engineering Properties of Natural Soils. Vol. 3 and 4, Taylor & Francis Group, London: 2791 p.

Randolph, M.F. (2004). Characterization of soft sediments for offshore applications. Geotechnical and Geophysical Site Characterization, Vol. 1 (Proc. ISC-2, Porto), Millpress, Rotterdam: 209-232.

Randolph, M.F., Cassidy, M., Gourvenec, S. and Erbrich, C. (2005). Challenges of offshore geotechnical engineering. Proc. 16th Intl. Conf. Soil Mechanics & Geotechnical Engrg., Vol. 1 (ICSMGE, Osaka), Millpress, Rotterdam: 123-176.

Robertson, P.K. (1986). In-situ testing and its application to foundation engineering. Canadian Geotechnical Journal 23 (6): 573-594.

Robertson, P.K. (2009). Interpretation of CPT data: a unified approach. Canadian Geotechnical Journal 46 (11): 1337-1355.

Robertson, P.K. and Mayne, P.W., ed. (2010). Proceedings, 2nd Intl. Symposium on Cone Penetration Testing (CPT'10), Huntington Beach, California, Vols 1, 2, and 3. Omnipress, 1371 pages. Website: www.cpt10.com

Santamarina, J.C., Klein, K.A. and Fam, M.A. (2001). Soils and Waves: Particulate Materials Behavior. John Wiley & Sons, Chichester: 488 p.

Schnaid, F. (2005). Geocharacterization and properties of natural soils by in-situ tests. Proc. Intl. Conf. Soil Mechanics & Geotechnical Engineering, Vol. 1 (ICSMGE, Osaka), Millpress, Rotterdam: 3-46.

Schnaid, F. (2009). In-Situ Testing in Geomechanics: The Main Tests. Taylor & Francis Group, London: 329 p.

Senneset, K. (1974). Penetration testing in Norway. Proc. ESOPT, Vol. 1, National Swedish Building Research, Stockholm: 85-95.

Senneset, K., Sandven, R. and Janbu, N. (1989). Evaluation of soil parameters from piezocone tests. Transportation Research Record 1235: 24-37.

Simonini, P., Ricceri, G. and Cola, S. (2007). Geotechnical characterization and properties of Venice lagoon heterogeneous silts. Characterization and Engrg Properties of Natural Soils, Vol. 4, Taylor & Francis Group, London: 2289-2327.

Simons, N., Menzies, B., and Matthews, M. (2002). A Short Course in Geotechnical Site Investigation, Thomas Telford, London: 353 p.

Sirles, P.C. (2006). Use of Geophysics for Transportation Projects. NCHRP Synthesis 357, Transportation Research Board, Washington DC: 117p.

Steenfelt, J.S., Jackson, P.G., Christensen, C.T., Lee, J-S. and Ha, Y-B. (2008). Ground investigations for the Busan-Geoje immersed tunnel. Geotechnical &

Geophysical Site Characterization, Vol. 2 (Proc. ISC-3, Taipei), Taylor & Francis, London: 1431-1436.

Steenfelt, J.S. and Hansen, H.K. (1995). Keynote address: The Storebælt link - a geotechnical view. Proc. 11th ECSMFE, Vol. 10, Danish Geotechnical Society, Bulletin 11, Copenhagen: 10.11-10.40.

Stegmann, S., Mörz, T. and Kopf, A. (2006). Initial results of a new free fall cone for geotechnical in-situ characterization of soft marine sediments. Norwegian Journal of Geology, Vol. 86: 199-208.

Stokoe, K.H., Menq, F-Y., Wood, S.L., Park, K., Rosenblad, B. and Cox. B.R. (2008). Experience with NEES large scale mobile shakers in earthquake engineering. Geotechnical & Geophysical Site Characterization, Vol. 2 (ISC-3, Taipei), Taylor & Francis Group, London: 1365-1371.

Stroud, M.A. (1988). The standard penetration test: its application and interpretation. Penetration Testing in the U.K., Thomas Telford, London: 29-49.

Tan, T.S., Phoon, K.K., Hight, D.W. and Leroueil, S., editors. (2003). Characterization & Engineering Properties of Natural Soils, Vols. 1 & 2, Balkema, Rotterdam: 1531 p.

Tanaka, H. (2000). Sample quality of cohesive soils: Lessons from three sites: Ariake, Bothkennar, and Drammen. Soils and Foundations 40 (4): 54-74.

Thorsen, G. and Mortensen, P.K. (1995). CPT investigations in young sediments in the northern part of Jutland. Proc. CPT'95, Vol. 2, SGF Report 3-95, Linköping: 317-322.

Tran, K.T. and Hiltunen, D.R. (2011). An assessment of surface wave techniques at the Texas A&M national geotechnical experimentation site. Proc. GeoRisk 2011 (GSP 224), ASCE, Reston/VA: 859-866.

Wightman, W.E., Jalinoos, F., Sirles, P. and Hanna, K. (2003). Application of Geophysical Methods to Highway Related Problems. Contract No. DTFH68-02-P-00083, Federal Highway Administration, Washington, DC: 742 p.

Yafrate, N.J. and DeJong, J.T. (2007). Influence of penetration rate on measured resistance with full-flow penetrometers in clay. Proc. GeoDenver, GSP 173: Advances in Measurement and Modeling of Soil Behavior, ASCE, Reston, VA.