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SOA: Geotechnical Site Characterization in the Year 2012 and Beyond

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ABSTRACT: Due to the inherent complexities of natural soil materials, a thorough geotechnical site investigation program requires an integrated testing program of geophysics, rotary drilled borings with sampling, in-situ measurements, and various laboratory test series in order to provide ample information for design and analysis. This is only possible on large projects or situations where critical structures receive sufficient funding. For routine site exploration, realistic limitations in cost and time would dictate that the seismic piezocone test (SCPTù) and seismic flat dilatometer test (SDMTà) with dissipation phases be adopted in practice since as many as five separate measurements are obtained in an economical, continuous, and expedient manner from a single sounding. The collection of multiple readings is necessary to provide adequate information on geomaterials for rational engineering evaluations.

INTRODUCTION

In the past precedence of geotechnical site exploration programs on small- to medium size projects, it could have been considered adequate to drill a few soil borings on the property with standard penetration testing (SPT) and split-spoon sampling taken at regularly-spaced 1.5-m (5-ft) depth intervals, which were later supplemented by a few laboratory tests on recovered thin-walled tube specimens. Yet, the majority of information collected for analysis and design in this traditional approach rests mostly on N-values. A quick glance at a wide variety and diverse selection of geomaterials is shown in Figure 1. It is quite evident that these soils and rocks exhibit a vast and variable range in grain components, constituencies, and mineralogies with particle sizes varying from microns to millimeters to meters and larger. The corresponding array of geotechnical parameters applicable to each of these geomaterials can be expected to show tremendous ranges in strength, stiffness, stress state, and flow properties. Consequently, while valuable as an index, the SPT-N value is undisputedly a single number (an integer, at that), and as such, insufficient in and by itself to provide enough data for the full and proper evaluation of soil materials.

In the year 2012, the geotechnical engineer has many options towards preparing an advisory report to the client that offers solutions to the successful construction works

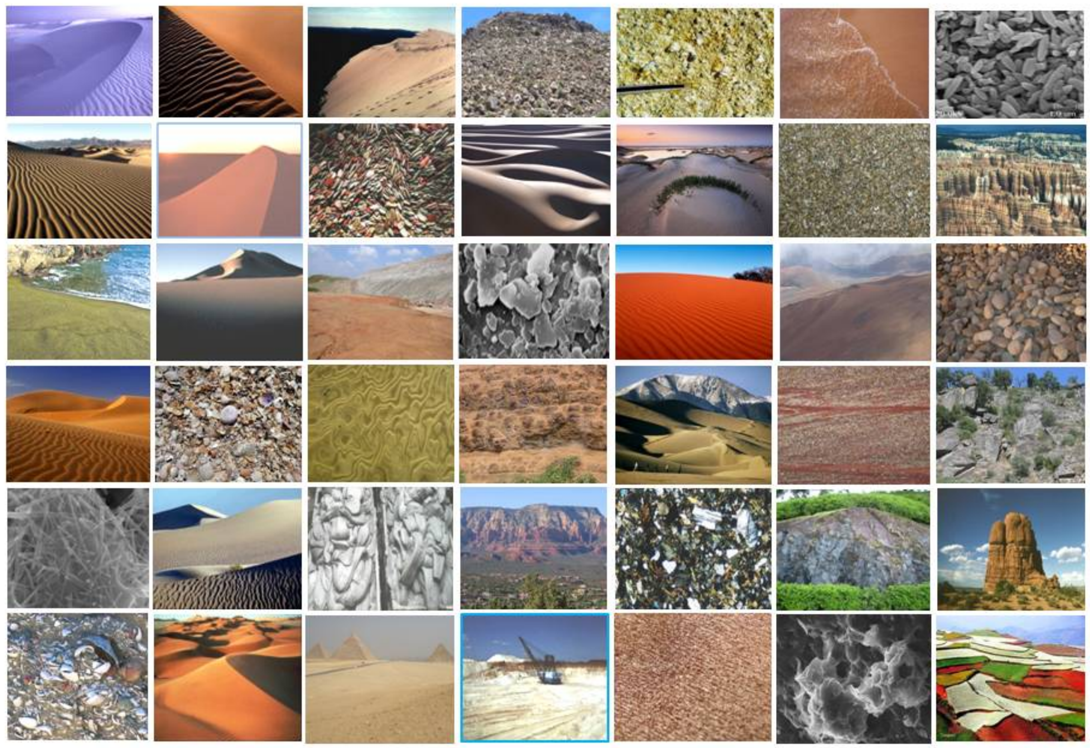


FIG. 1. Assorted geomaterials showing ranges of diversity and uniqueness

that involve foundation support, temporary & permanent excavations, short- & long-term stability, ground deformations, and seismic hazard concerns. For most civil engineering projects, a wide range of geotechnical solutions may be possible. For instance, the evaluation, comparison, and final choice of a suitable foundation system for an office building may include shallow footings, reinforced mat, driven pilings, bored piles, and geopiers, as well as over 40 different types of ground modification and site improvement. Certainly, the single N-value will not provide an adequate amount of information and input data for the engineering assessment of all of these possible solutions, even if the geoengineer has considerable experience, knowledge, and judgment in making her/his decisions.

Finding the solution(s) that offer the best value, least risk, most efficient, fastest construction time, and lowest cost should be a goal of the geotechnical engineer. As many methods are comparable in cost and performance, it will fall upon the designer to have as much understanding of the underlying ground conditions as possible, in order that the optimum solution is selected. Thus sets the stage for the necessary first step in geotechnics that always requires a site-specific subsurface exploration. In this mini-state-of-the-art (SOA) on geotechnical site exploration, a brief review is given on the various in-situ tests available for use (particularly the SCPTù and SDMTà), as well as, several upcoming new devices and procedures of merit.

CONSEQUENCES OF SUBSTANDARD SITE INVESTIGATION

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

- Excessively high construction costs and expenses due to unnecessary use of piled foundations or structural mats. In the case of truly-needed deep foundation systems, a substandard investigation may result in overdesigns with larger pile groups, diameters, and lengths than are warranted.
- Extra time and payments for implementation and conduct of unnecessary ground modification techniques.
- Unexpected poor performance of embankments, walls, excavations, and foundations, possibly including additional costs due to damage and/or retrofit and underpinning.
- Failure or instability during or after construction operations due to inadequate characterization of the geomaterials and/or missed anomalies, buried features, and/or weak layers and inclusions.
- Legal involvements, litigation, loss of professional reputation and/or license, and weakened credibility.

The upfront budgets for geotechnical site investigations should be sufficient to allow a reasonable amount of subsurface data to be procured and analyzed so that the design produces an efficient, safe, and economical solution.

TRADITIONAL SITE EXPLORATION

The tools of the trade and methods for subsurface investigation for geotechnical site characterization 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). Moreover, as new technologies became available and accepted, the geotechnical profession placed a higher or lower reliance and dependency on each methodology, 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", thus serving towards design of a geotechnical solution. Over the next ten decades, the advent of a variety of in-situ tests, laboratory devices, geophysical methods, analytical modeling, numerical simulation, and probabilistic risk assessments have all emerged to play an important role in assisting the geoengineer towards an improved understanding on the material characteristics of the ground. Thus, while judgment is still warranted, more emphasis can now be placed on the utilization of direct-push probings with digital outputs, geophysical surveys with computer-enhanced imagery, trial searches for critical stability surfaces, numerical finite element simulations, and risk analysis with fuzzy logic.

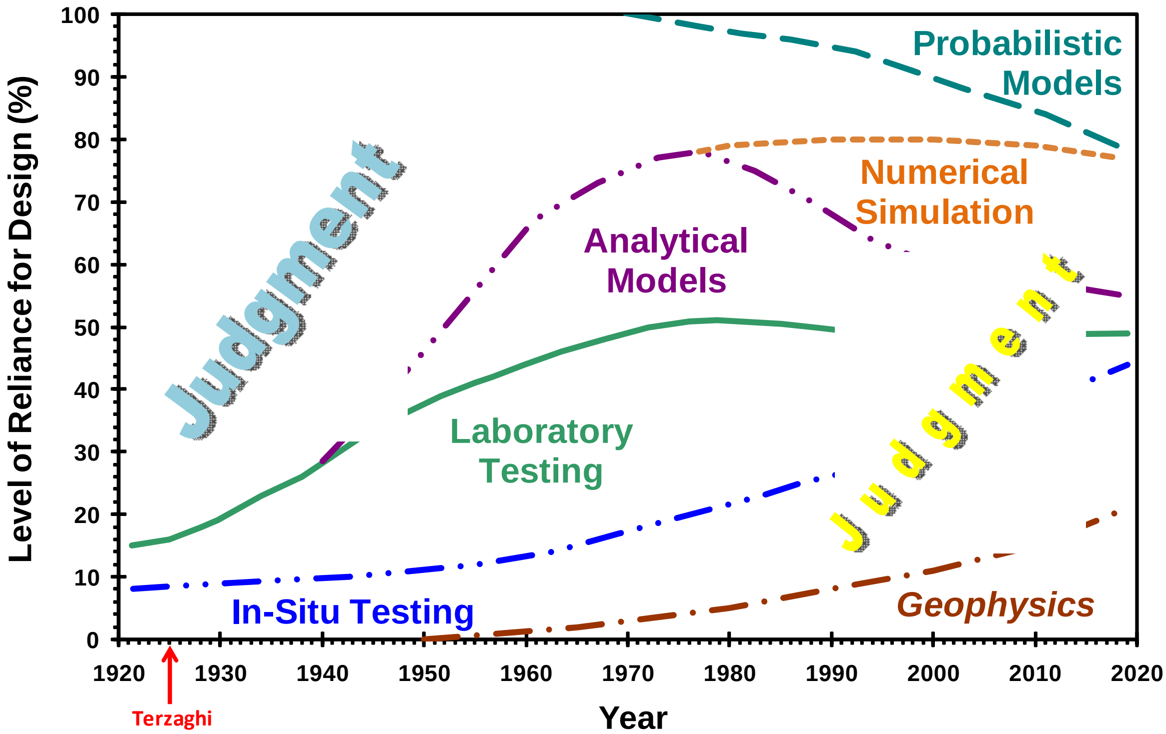


FIG. 2. Evolution of design-based processes for geotechnics (after Lacasse 1988)

Today, there are well over 150 different types of in-situ probes, field methods, and innovative gadgets available for purposes of geotechnical site investigation (Robertson 1986; Lunne et al. 1994). Figure 3 illustrates a number of the more well-known devices, many of these being rather narrowly focused on the quantification of a particular soil parameter or geomaterial property. The insertion type methods include an assortment of blades, probes, vanes, penetrometers, tubes, bars, plates, and/or cells that are either statically-pushed, dynamically-driven, drilled, torqued, twisted, inflated, vibrated, and/or sonically-advanced using hydraulics, pneumatics, rotation motion, electromechanics, or a combination thereof to collect data about the subsurface media. Some such devices include the cone penetration test (CPT), flat plate dilatometer test (DMT), borehole shear test (BST), and total stress cells (TSC). In addition, a number of nondestructive geophysical technologies, both invasive and noninvasive, have matured using either mechanical waves (compression, shear, Rayleigh, Love) and/or electromagnetic waves (resistivity, dielectric, electrical conductivity, permittivity) that can be deployed to ascertain very shallow, intermediate, and/or deep stratigraphic features, layering, and inclusions, as well as the small-strain elastic properties of the ground.

For a thorough investigation, a full suite of different field and laboratory tests must be conducted to ascertain the geostratigraphy, soil classification, site heterogeneity, and geotechnical engineering parameters. As an illustrative guide, Figure 4 shows one of the best available procedures for conduct of a detailed site exploration that include a series of soil borings to detail the stratigraphy, with in-situ strength testing by SPTs in

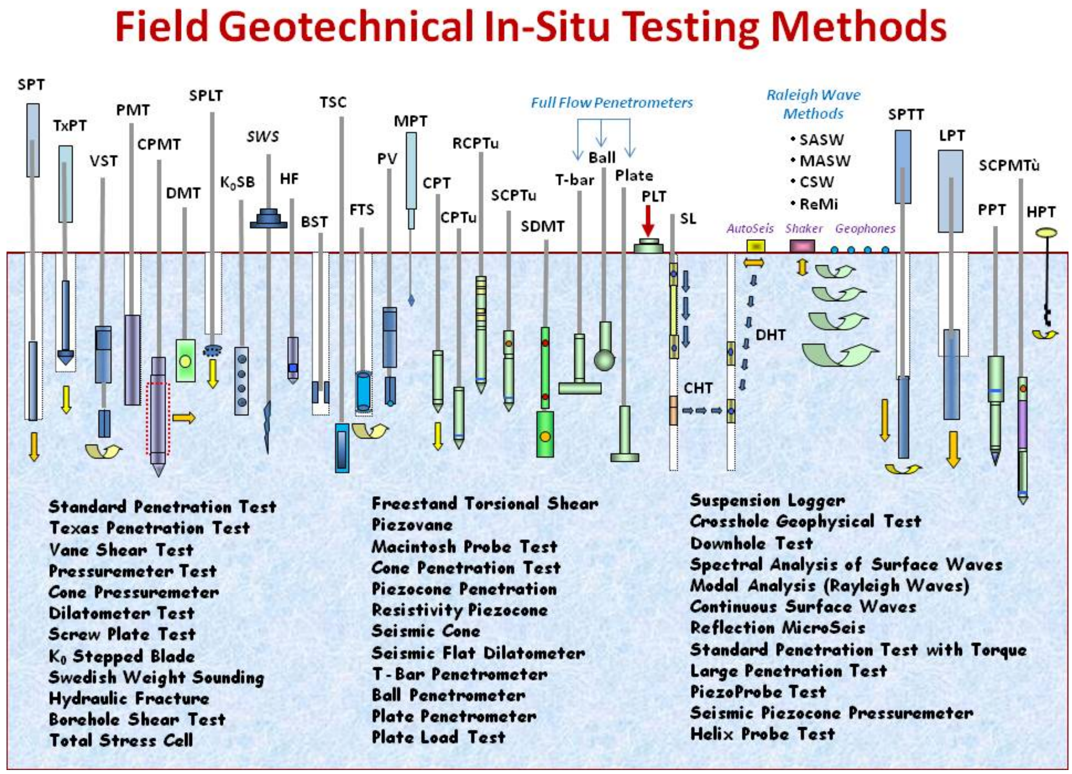


FIG. 3. Selection of in-situ devices and methods for ground investigations

sandy layers and field vane shear testing (VST) in clayey layers. The initial K_0 stress state and deformation modulus (E) can be evaluated using a series of pressuremeter tests (PMT), which also provide additional evaluations on the limit pressure (P_L) as well as the undrained shear strength (s_u) of clays and silts or effective friction angle (ϕ') in sands. The coefficient of permeability (k) of the ground can be assessed via field pumping tests, slug testing, or packer testing.

For small-strain measurements, crosshole tests (CHT) and/or downhole tests (DHT) provide means to map the profiles of compression wave (V_p) and shear wave (V_s) velocity with depth, although these may now be substituted with several noninvasive geophysical techniques that are readily available, including: spectral analysis of surface waves (SASW), refraction surveys (RfS), modal analysis of surface waves (MASW), continuous surface waves (CSW), and/or reflection microtremor (ReMi), the latter of which is a type of passive surface wave measurement.

In addition, with the collection of undisturbed thin-walled tube samples, a complementary laboratory program of index, grain size, hydrometer, triaxial (TX) shear, one-dimensional consolidation (CS), direct shear box (DSB) or direct simple shear (DSS), permeameter (PM), and resonant column (RC) or bender element (BE) testing can provide information about small specimens of the on-site materials and various soils strata. Undeniably, such an extensive site exploration program can only be afforded on large civil engineering projects such as interstate highway bridges and metropolitan water reservoirs or critical facilities including electrical power plants and

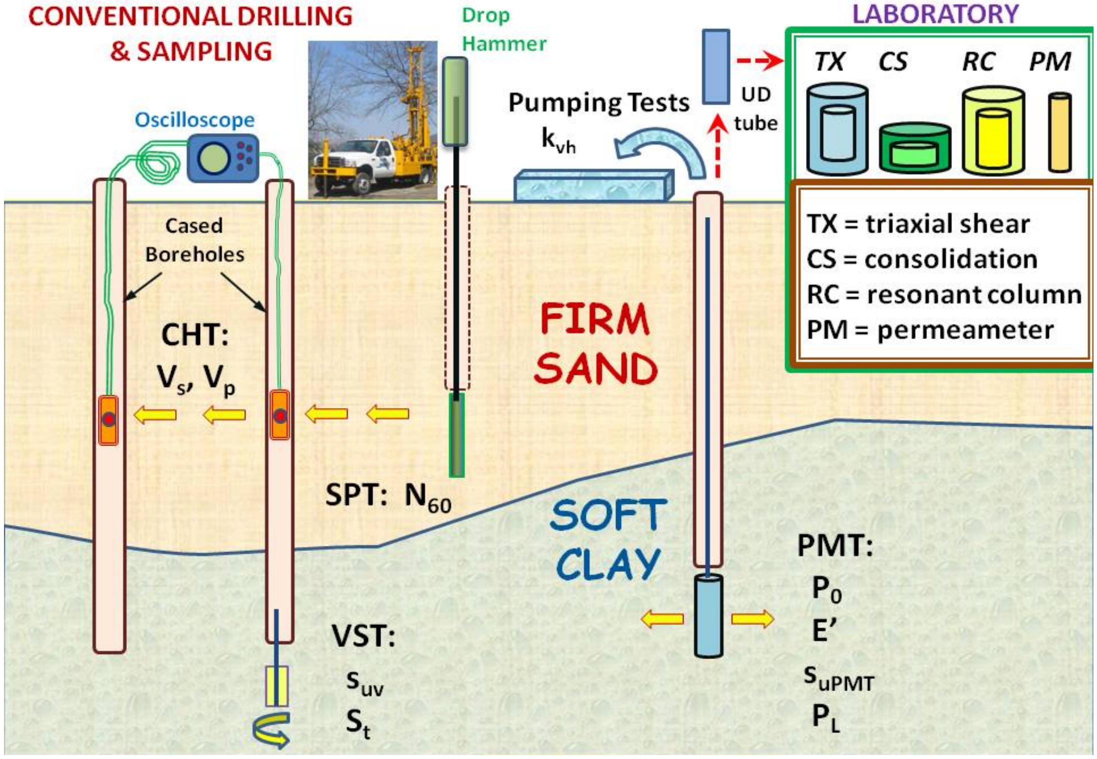


FIG 4. Current best practices for detailed geotechnical site exploration

nuclear facilities, due to high budgetary costs and lengthy durations for field deployment operations and laboratory test turnaround times. For routine projects of small- to medium-size concerns, a faster and less expensive alternative is needed, yet still able to provide adequate amounts and types of essential data for the analysis and design phase, as well as helping to avert legal issues which can arise because of reliance on too little or insufficient information.

INTERPRETATION OF IN-SITU TESTS

The results of in-situ tests are utilized to evaluate certain geotechnical parameters for input into analysis and design methodologies. The interpretations can be based on empirical or statistical relationships, analytical closed-form solutions, numerical simulations, and/or physical models, otherwise a combination of these approaches. The in-situ tests can be employed in a multi-stepped procedure, whereby the data are used to interpret soil engineering properties that are input into an engineering scheme or theoretical framework, or alternatively, used in a direct scaling to ascertain the necessary parameters. For instance, the use of CPT data can be applied to the evaluation of vertically-loaded pile foundations in a wide range of approaches, as depicted in Figure 5. Here, direct and/or indirect methods may be relied upon to calculate the side resistance, end-bearing, and total axial capacity in compression and tension, as well as the soil stiffness along the pile sides, beneath the pile tip, and top-

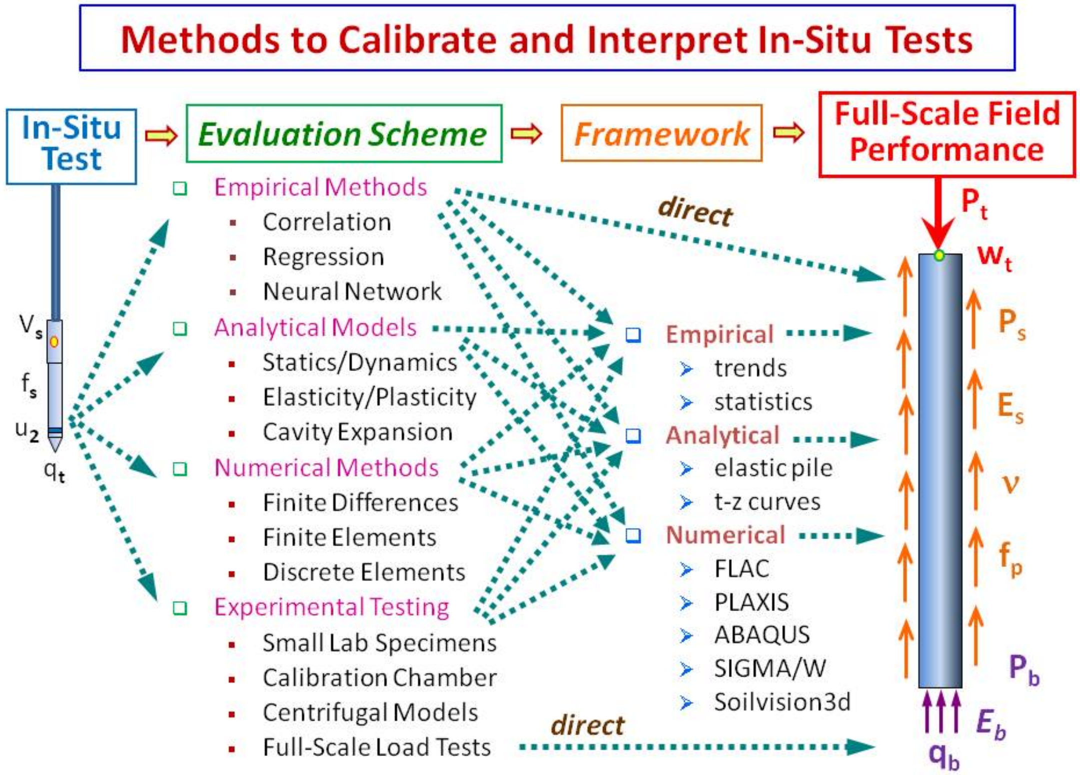


FIG. 5. Means of relating in-situ test results to full-scale performance

down load-displacement response and percentage of axial load transfer along the length of the pile.

From a practical standpoint, many in-situ tests have been calibrated against reference parametric values obtained from laboratory tests, primarily performed on specimens of natural clays cut from undisturbed tube samples or from reconstituted sand specimens. However, the issues of "sample disturbance" and "representative sample" must be raised for calibrations made in clay soils because of the wide assortment and quality of different tube samples (e.g., Shelby, piston, Laval, Sherbrook, Gus, JPN, ELE, etc.) as detailed by Tanaka (2000) and Lunne et al. (2006). This is furthermore complicated by the fact that certain parameters have multiple modes and thus non-unique benchmark values.

For clays, the notorious case is that concerning the evaluation of undrained shear strength ($s_u = c_u$), as this parameter exhibits a wide range (both theoretically and experimentally) depending upon which laboratory device is employed for the measurement (e.g., unconfined compression, triaxial shear, simple shear, fall cone, compression, extension, etc). Moreover, the undrained shear strength and stiffness are well-known to be influenced by strain rate effects, thus the faster the testing, the stiffer and stronger the clay appears (Randolph 2004; Peuchen & Mayne 2007). This too adds differences to the s_u values obtained from various modes of testing because of standardized testing rates (e.g., 1%/hour for DSS; 0.1°/sec for VST; 20 mm/s for CPT, etc.) which are not necessarily compatible. As a consequence, much confusion and uncertainty has arisen in the in-situ test evaluation of s_u profiles because of mixing of varied and inconsistent strength modes in their comparisons. As a solution to this dilemma, the author recommends calibrating the in-situ tests with the yield stress (σ_p'), or the effective vertical preconsolidation stress ($\sigma_p' \approx P_c' = \sigma_{vmax}'$), obtained from one-dimensional consolidation tests, because this parameter is uniquely defined (at least in concept). Then, the yield stress ratio (YSR = σ_p'/σ_{vo}'), or the more well-known overconsolidation ratio (OCR = P_c/σ_{vo}'), can be used to obtain the undrained shear strength via its relationship with normalized strength ratio (s_u/σ_{vo}'), as discussed elsewhere (e.g., Ladd & DeGroot 2003).

Reconstituted sand samples have been used in laboratory test programs to investigate the stress-strain-strength behavior of clean sands at different relative densities (D_R), effective confining stresses, drainage conditions (dry, saturated, undrained, drained, partially saturated), loading paths (e.g., triaxial compression, extension, plane strain, simple shear, direct shear), as well as other facets (e.g., Lade & Bopp, 2005). However, in the case of reconstituted sands, the dilemma and choice of which sample preparation method must be considered, since each of the various techniques (i.e., compaction, sedimentation, slurry, moist-tamping, vibration, static compression) can all result in significantly differing stress-strain-strength and stiffness behavior during shear and associated flow-permeability characteristics (Hoeg, et al. 2000; Vaid & Sivathayalan, 2000). Consequently, a number of incompatible and contradictory assessments have been made on the basis of mixed types of laboratory testing modes on sands, sample preparation techniques, stress paths, and other factors (e.g., large scale chamber boundary effects). These variables have considerable influence on calibrating in-situ test results, primarily in evaluating relative density, friction angle, and shear rigidity (Mayne et al. 2009).

GEOTECHNICAL EXPERIMENTATION SITES

Within the continental USA, six national geotechnical experimentation sites (NGES) have been established to provide a full range database that includes laboratory, geophysical, geotechnical, and full-scale prototype performance results for cross-referencing, comparative studies, and benchmark calibrations (Benoît and Lutenegger, 2000). Of particular value towards understanding soil behavior and the interpretation of test data, the NGES include test sites that are situated for research in sands (Texas A&M Site 1, TX; Treasure Island, CA), soft clay (Univ. Mass-Amherst, MA; Northwestern Univ., IL), sandy silts (Opelika, AL), and stiff clays (Univ. Houston, TX; Texas A&M Site 2; TX). For illustration, data from 5 different field tests obtained in the sandy soil layers at the Texas A&M site 1 are presented in side-by-side plots in Figure 6. Additional information and details concerning the characteristics and response of the sand can be found in Briaud (2007).

Recent symposia held in Singapore produced four full volumes on summary 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 summarized the efforts of various prominent geotechnical research institutions, universities, and commercial testing firms in the detailed field and laboratory testing of a wide variety and array of differ-

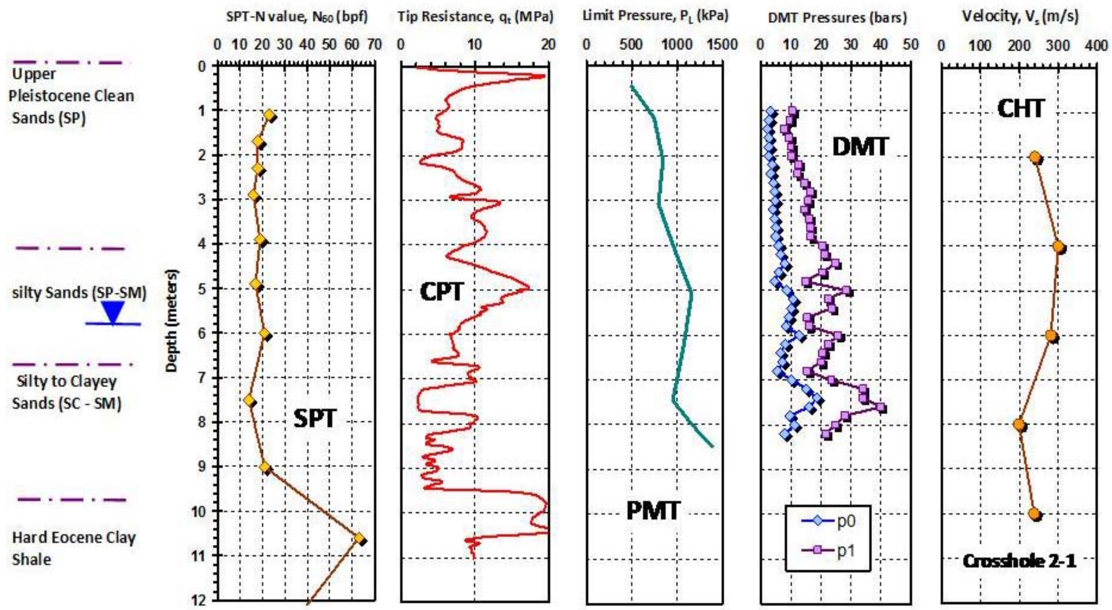


FIG. 6. Sand profile and results from SPT, CPT, PMT, DMT, and CHT at the Texas A&M national geotechnical experimentation site (data from Briaud 2007).

ing geomaterials, each within a particular geologic origin, setting, and location of a country or continent. In all cases, the IGES research programs have been underway for many years, in fact, often many decades, with most having not yet fully answered all of the behavioral subtleties within that particular soil formation. One excellent example is the Holmen sand site near Drammen, Norway, established and researched by the Norwegian Geotechnical Institute since 1956 (Lunne et al. 2003). At Holmen, extensive types of geotechnical lab sets, in-situ testing, pile foundation performance, building foundation settlements, and geophysical measurements have been collected in these sandy sediments, all of which can be cross-referenced.

Furthermore, note that a number of other well-documented sites are also available but were not included in these sets of proceedings yet would certainly qualify for IGES status, including the Canadian national test site at South Gloucester, Ontario. This site is underlain by the well-known Champlain sensitive marine clays and has served as the subject of geotechnical research for over 60 years (McRostie & Crawford 2001). At that site, the results of full-scale embankment performance and foundation settlements have been documented along with laboratory tests (e.g., index, triaxial, consolidation, time rate behavior, etc.) as well as soil borings, vane shear tests, pressuremeter, and piezocones. Of recent vintage, Yafrate & DeJong (2006) performed SCPTu, T-bar, and ball-penetration tests at the South Gloucester site. Also missing from the 2003 and 2007 IGES series is the infamous Boston Blue Clay, such as the site at Saugus, Massachusetts which has been used for studies involving embankment behavior, self-boring pressuremeter calibrations, piezoprobe tests, and series of laboratory tests (Whittle et al. 2001).

The geotechnical experimentation sites are of great value because many different types of measurements are taken in the same geomaterials in the same vicinity and location, hopefully validating issues related to test repeatability and minimizing issues of site or test variability. Furthermore, it is possible here to obtain a form of "ground truthing" in terms of interpretation, whereby the laboratory test data can be compared with field test results as well as the full-scale prototype structures. Geotechnical parameters acquired from analytical methods and/or numerical models can be calibrated properly with the recorded performance of full-scale geostructures, such as walls, pilings, footings, and excavations. Also, statistical or empirical correlations can be developed amongst different test methods. Having alternative methods of interpretation can in fact be helpful in geotechnical site characterization because there are not yet consensus procedures for assessing parameters for all types of geomaterials, thus multiple methods can be adopted in parallel towards their evaluation or range of values.

Although these research sites have been thoroughly studied using many series of field and laboratory tests, a number of unexpected facets in soil behavior have come to awareness following subsequent monitoring and construction. For instance, short- and long-term footing load tests on the IGES soft clays at Bothkennar in the UK indicated: (a) appreciable drainage, (b) lower excess porewater pressures less than expected for "undrained conditions", (c) deviations from traditional linear elastic behavior, and (d) significant long-term creep settlements comparable to those of primary consolidation (Lehane & Jardine 2003). In another full-scale instrumented case study, a large 40-m diameter circular fill over soft ground showed essentially drained behavior and significant long-term settlements due to secondary compression (Simonini et al. 2007). In yet another situation, the results of a symposium exercise involving 22 separate predictors using the same lab and field data gave a 6-fold range in bearing capacity evaluations for a large 2-m square footing pad load test on soft clay (Lehane 2003). Of final note, the unexpected large 14-m settlements of the reclaimed island of Kansai I in Osaka Bay may be attributed in part to inadequate characterization of the underlying clays (Puzrin et al. 2010). As a consequence, the findings and documented results from full-scale measurements at the IGES offer invaluable means for verifying our geotechnical engineering practice in terms of material testing, parameter assessment, constitutive modeling, and theoretical understanding on the complex nature of geomaterials.

NONINVASIVE GEOPHYSICAL MAPPINGS

In a traditional site investigation, borings or soundings are located on an established grid pattern, say 30-m on center, in order to systematically and hopefully capture any lateral variants in geostratigraphy and/or soil consistency across the site. Of course, in reality, this is merely a trial-and-error attempt since the gridded area may or may not coincide with Mother Nature's original coordinates. In fact, it would be plausible that a buried natural stream or area of old uncontrolled dumped fill could easily lie within the chosen grid points for the borings. If such buried anomalies and features were discovered during the construction operations, the contractor could demand a redesign of the geotechnical solution, otherwise alternatively claim "changed conditions". Of

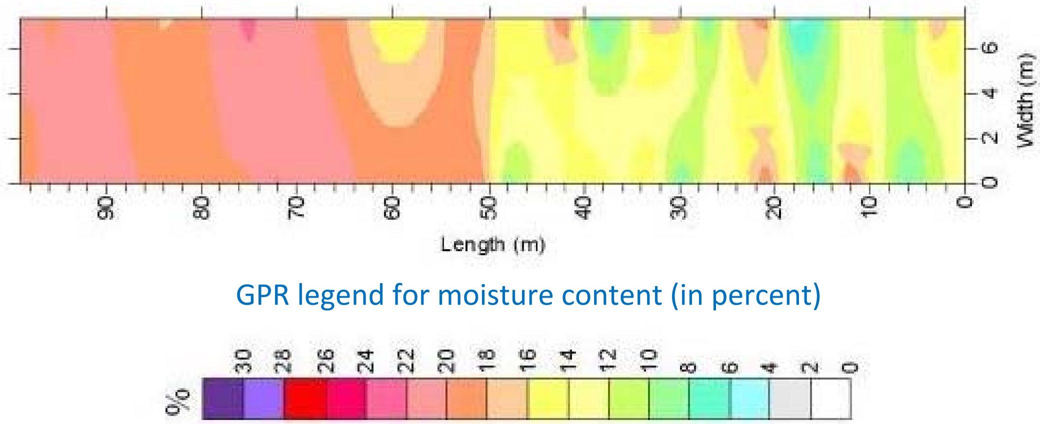


FIG. 7. Illustrative use of ground radar-mapped moisture contents for pavement studies in Waycross, GA (Larrahondo et al. 2008).

further concern, another unfortunate outcome may also include legal action by the owner, architect, structural engineer, and/or contractor against the geotechnical firm.

In 2012, a rational solution to these above situations is the utilization of surface geophysics via electromagnetic wave surveys. These well-established techniques include: ground penetrating radar (GPR), electrical resistivity surveys (ERS), and electromagnetic conductivity (EMC). Not only are these geophysical surveys quick and economical to perform, they offer a chance to rationally direct the site investigations towards the 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.

An example of the use of interpreted water contents from GPR measurements in the pavement subgrade for a GDOT pavement are presented in Figure 7 (Larrahondo et al. 2008). It can be seen that higher moisture contents ($16 < w_n < 24\%$) are notable across the western half of the site than for the eastern portion ($8\% < w_n < 16\%$). Similar mapping by EMC and SRS can be used for confirming site homogeneity and/or identifying anomalous zones and variability in the subsurface environment. The relative mapping of electrical conductivity or resistivity across a given site thus presents a rational opportunity to direct the next phase of site investigation using exploratory soundings and/or drilling and sampling methods.

HYBRID TECHNOLOGIES

The seismic piezocone test (SCPTù) and seismic flat dilatometer test (SDMTà) are hybrid in-situ exploratory methods that combine direct-push mechanical probings with downhole geophysics and therefore afford a modern means to site characterization for routine studies (Figure 8). These are not new methods, but were developed some three decades ago (Campanella et al. 1986; Hepton 1988). They offer continuous profiling

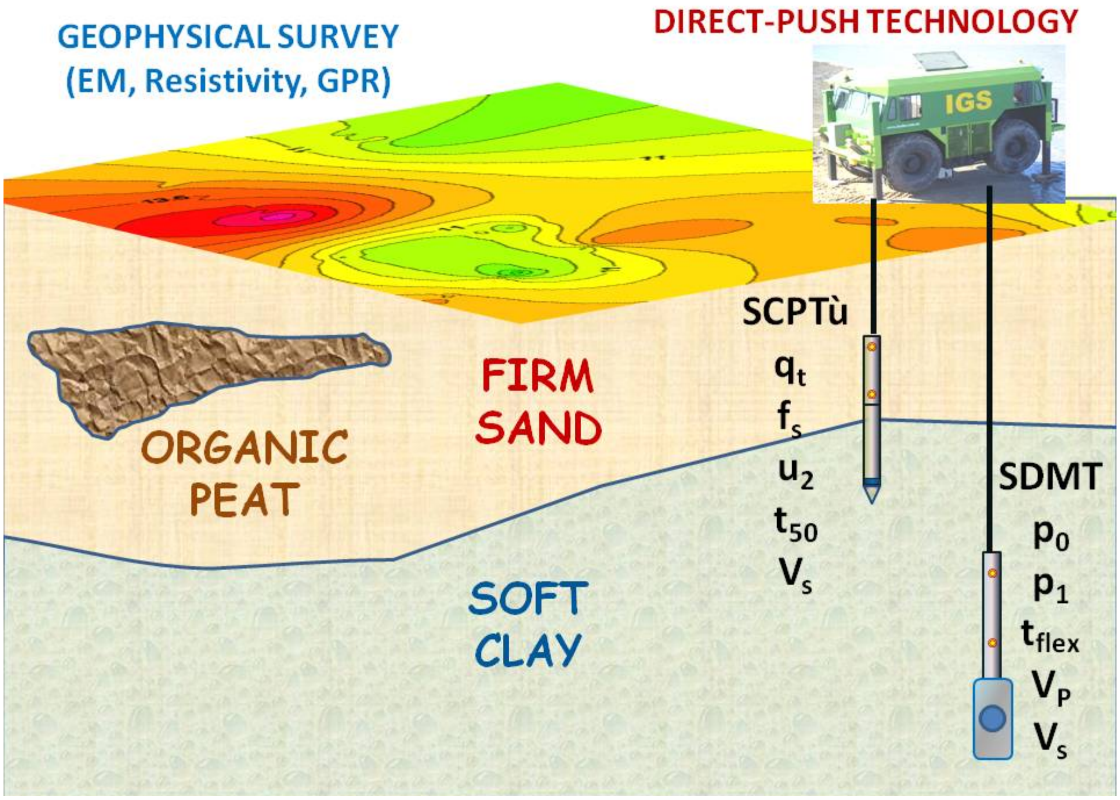


FIG. 8. Recommended routine site exploration: (a) quick areal mapping by electromagnetic geophysics; followed by: (b) direct-push soundings by either seismic piezocone or seismic dilatometer.

of strata and soil parameters with multiple readings taken at each depth in a quick and reliable manner. The SCPTù offers up to 5 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).

Two representative SCPTù soundings from Charleston, SC are presented in Figure 9 showing five separate measurements with depth. The soundings were performed for the recently completed Arthur Ravenel cable-stayed concrete segmental bridge over the Cooper River. The upper 20 m of soils consist of recent variable deposits of alluvial/marine origin that are underlain by the older Cooper Marl that is comprised of a stiff sandy calcareous clay (Camp et al. 2002). The marl is evident by the high penetration porewater pressures and rather high shear wave velocities.

In the SDMTà, the corresponding five readings can include: contact pressure (p_0), expansion pressure (p_1), deflation pressure (p_2), time rate of consolidation (t_{flex}), and either compression wave velocity (V_p), and/or shear wave velocity (V_s), or both. It is also possible to add additional readings such as blade thrust resistance (q_D) between successive push depths at 20-cm intervals (Marchetti et al. 2006), or resistivity, dielectric, and electrical conductivity. An illustrative example of five separate measurements taken during a SDMTà sounding performed in highly-stratified alluvial-

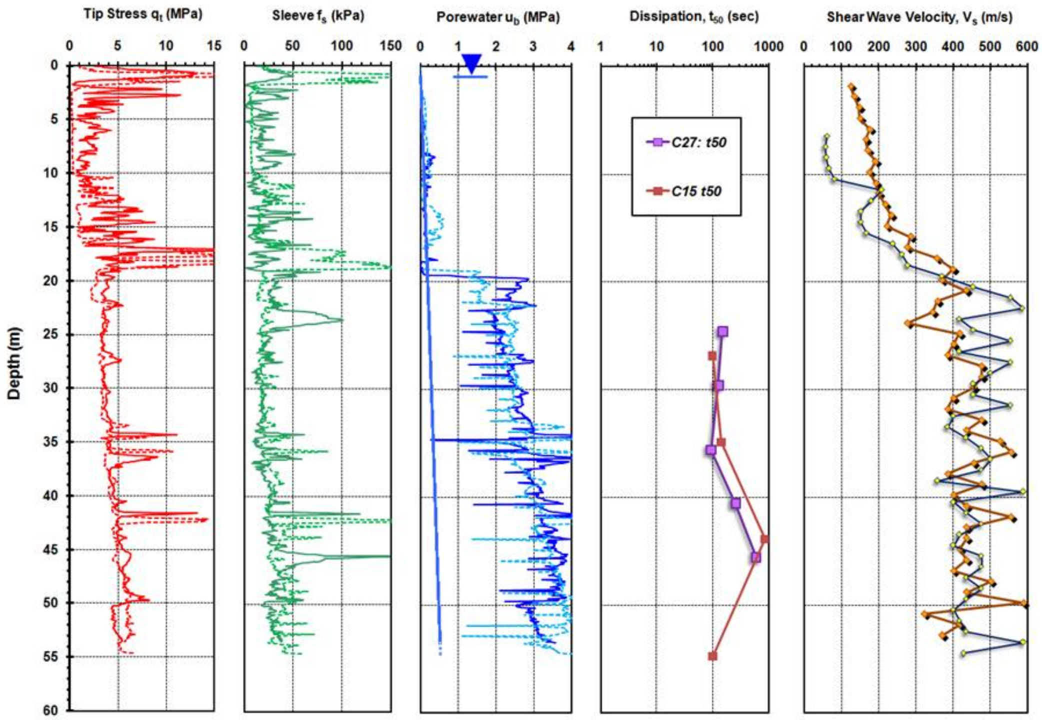


FIG. 9. Two seismic piezocone soundings at Charleston, SC

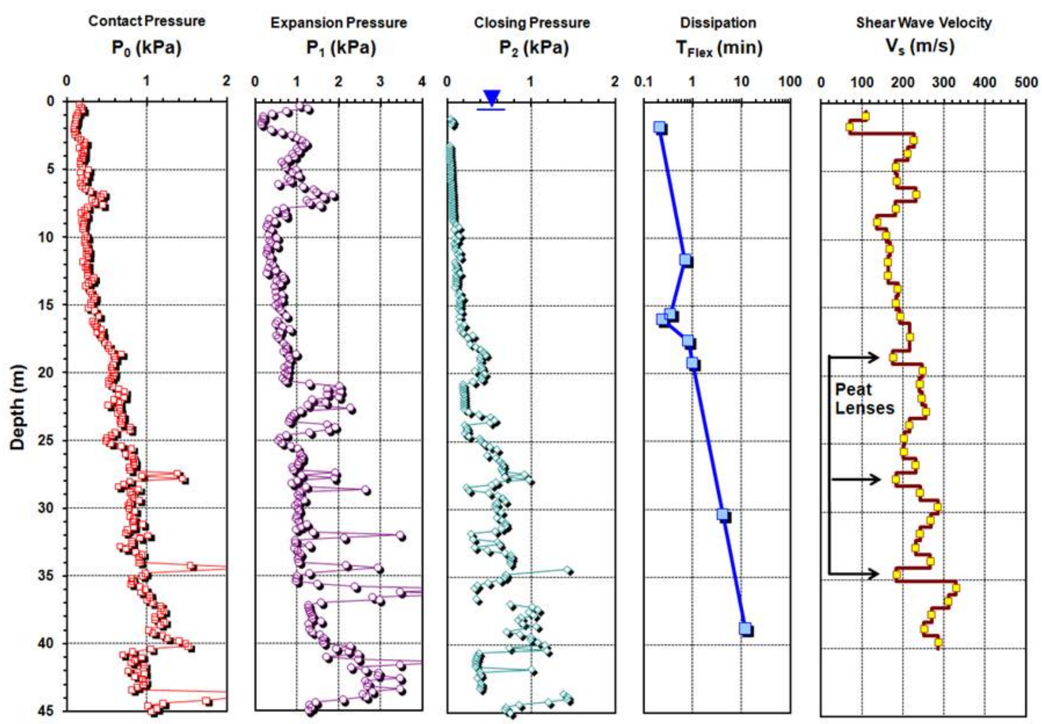


FIG 10. Seismic flat dilatometer sounding at Treporti site, Italy

marine sediments at the Treporti test embankment site near Venice, Italy is shown in Figure 10. Details on the extensive lab and field testing of these interwoven deposits are given by Simonini et al. (2007).

NEW DEVELOPMENTS

Advances in equipment, procedure, and interpretation of in-situ testing have occurred that can be used to the betterment of professional practice.

New Equipment

Over the past decade, several new in-situ devices have been introduced for site characterization, as well as a number of improvements in field testing equipment, as discussed subsequently.

While rotary drilling and augering methods are still widely used, sonic drilling and direct push methods have now become available for advancing boreholes and obtaining geomaterial samples (see Figure 11). Sonic drilling uses mechanic vibrations and resonance (50 to 150 Hz) to achieve penetration to depths of up to 300 m, thereby does not rely on air, water, or mud circulation. Spoils and excess cutting wastes are reduced to only 10 to 20 percent compared with traditional rotary drilling. Sonic drilling offers very fast penetration rates and the ability to collect continuous soil and/or rock samples with core diameters of between 100 mm 250 mm. In contrast, direct push sampling uses hydraulic or pneumatic systems to procure continuous soil samples by inserting and removing steel mandrels lined with plastic tubing.

For direct-push in-situ testing, large heavy-weight trucks and hydraulic track rigs continue to be employed to advance probes and penetrometers. Recent advances in

(a) (b) (c)

FIG. 11. Drilling equipment: (a) conventional rotary type truck rig by CME; (b) sonic rig by Boart Longyear; (c) rotosonic rig by Geoprobe Systems.

this arena include the development of light-weight rigs that have better accessibility and are easier to manuever and mobilize, particularly in areas of limited access. For capacity, either temporary anchors are installed or adjustable weights used in order to provide reaction (Figure 12). Essentially, the smallest versions of these rigs are also single-operator vehicles and therefore quite economical to deploy on small projects.

(a) (b) (c)

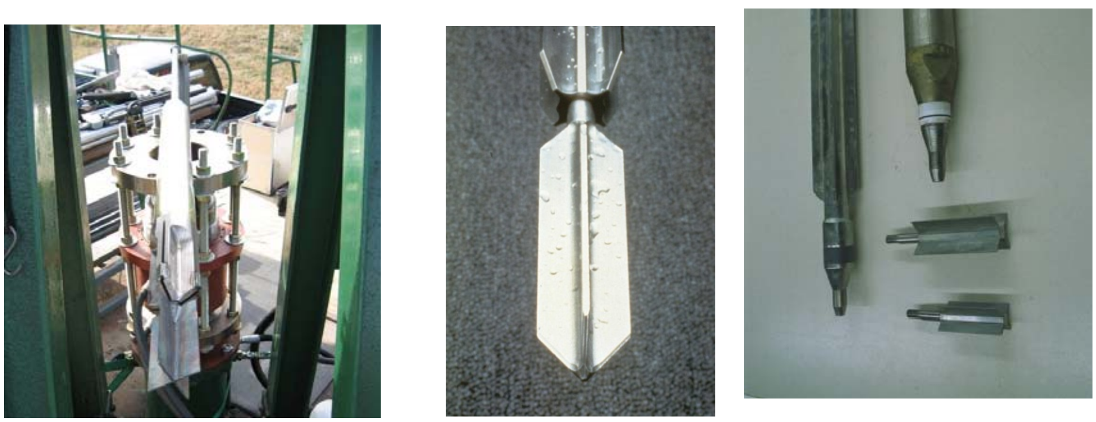
FIG. 12. Direct push vehicles: (a) 30-tonne track rig by ConeTec; (b) anchored rig by Pagani; (c) adjustable-weight Esme rig by IGS-Brisbane.

For cone penetration testing, the standard penetrometer sizes remain the 10-cm^2 and 15-cm^2 probes for production testing on routine geotechnical explorations (see Fig. 13). For special conditions involving soft soils and/or large coarse gravels, large 33-cm^2 (Fugro) and 40-cm^2 (ConeTec) penetrometers have been developed (Mayne 2010). Even larger cones have been developed for fast profiling seabeds by free-fall dropping off ships, thus requiring no pushing system whatsoever (Thompson et al. 2002; Stegmann et al. 2006). These free-fall penetrometers, or harpoon CPTs, have sizes of 60-cm^2 to 200 cm^2 and are reliant only on gravity impact to achieve penetration depths of up to 12 m (e.g, Aubeny and Shi 2006; Moser et al. 2007).

For increased resolution and profiling of shallow depths, smaller mini-cones have been built that have sizes of 1-cm^2 to 5-cm^2. These mini-CPTs are used for offshore seabed and pipeline studies (Peuchen et al. 2005), mapping of varved layers (DeJong et al. 2003), and pavement subgrades (Titi et al. 2000), as well as the obvious advantages associated with shortened dissipation times for porewater measurements (Kim 2004). Even smaller penetrometers have been devised for checking uniformity and density in centrifuge chamber deposits including 0.28-cm^2 (Wilson et al. 2004) and 0.38-cm^2 (O'Loughlin and Lehane 2010) size cones. Finally, a set of micro-cones (0.008-cm^2) have been developed using fiber bragg grating sensors with the results that diameters of 1-, 3-, 5-, and 7-mm have been built to look at soil-pile smearing, wick drains, and highly-stratified soil layering (Kim, et al. 2010). At this level, it may be possible to measure forces at the particle-penetrometer scale, thus perhaps useful in developing direct measurements for use in discrete element modeling (DEM).

(a) (b) (c)

FIG. 13. Cone penetrometer sizes: (a) standard 10- and 15-cm^2; (b) harpoon free-fall type (Moser et al. 2007); (c) micro-FBG type (Kim et al. 2010).



(a) (b) (c)

FIG. 14. Downhole electromechanical vanes: (a) Geotech AB onshore type; (b) McClelland offshore tapered vane; (c) Fugro offshore rectangular vane.

Electro-mechanical vanes now offer superior measurements and quality over the old long-standing mechanical vanes (Randolph et al. 2005). The vane shear test (VST) has been available for the in-situ determination of undrained shear strength (s_{uv}) and sensitivity (S_t) of clays for over 6 decades, but has long been plagued by issues of equipment maintenance problems because of rod coupling slippage, rusting, bent rods, soil-rod friction that all affect the measured torque. Moreover, the torquemeter resided at the surface and readings were either taken by hand or pen-plotted with ink onto paper. Modern electrovanes (Fig. 14) mitigate the aforementioned problems by deployment of the four-sided blade from a special housing that is located at downhole elevation and thus the measurements of torque and rotation are captured directly and digitally logged onto computer hard drives. The resulting data are quite similar in appearance to stress-strain-strength curves (Peuchen and Mayne 2007).

Some additional test devices of merit are shown in Figure 15 that include the commercial seismic flat dilatometer (Marchetti, et al. 2008) which is a hybrid pressure probe combined with downhole geophysics measurements, a gas or air permeameter

(a) (b) (c)

FIG. 15. Selected in-situ field test devices: (a) seismic flat dilatometer, (b) air permeameter, (c) scour probe.

(a) (b) (c)

FIG. 16. Modern electronic hand-held penetrometers for field use: (a) Spectrum Scout SC900, (b) Rimik CP40, (c) Eijkelkamp Penetrologger (Kees 2005).

for evaluating the hydraulic conductivity or specific permeability of granular surface soils, particularly base course materials (White et al. 2007), and an in-situ scour probe for providing a quick field evaluation of the erosion potential of soils (Caruso and Gabr 2011).

Of additional interest are the small portable electronic penetrometers for manual use by field personnel (Kees 2005). In lieu of having your site technician or field engineering being embarrassed by having to use the old heavy, burdensome and antiquated dynamic drop-weight penetrometer in a hand-bored hole, or the worse

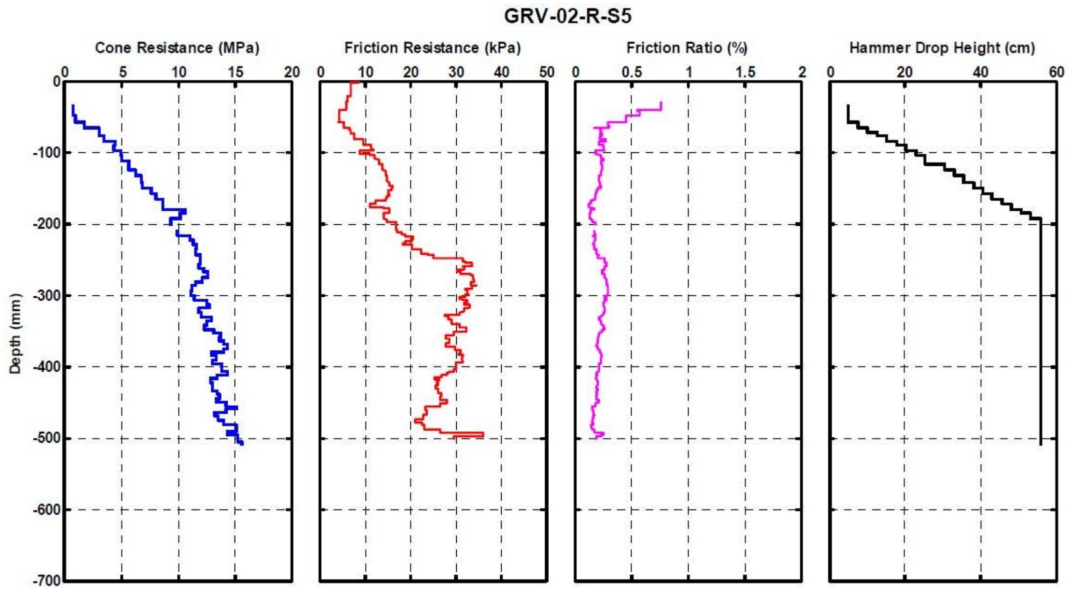


FIG. 17. Example multi-channel sounding results using the portable RapSochs system (Kianirad 2011)

alternative (e.g., a piece of No. 4 rebar), Figure 16 shows three available flashy models which offer means for quick and repeatable electronic profiling of tip resistance with depth. Note that the importance of showing a professional image and establishing a high respect for geotechnical engineering practice should not be underestimated.

Regarding light-weight and portable dynamic penetrometers, recent developments of a portable multi-channel probe termed "RapSochs" (rapid soil characterization system) have been made by Kianirad (2011), as presented in Figure 17. Here, equivalent readings of tip resistance, sleeve friction, and corresponding hammer drop height with depth are presented, using the calibrated algorithms developed by Kianirad et al. (2011). Future versions of the RapSochs device are to include measurements of moisture content and penetration porewater pressures.

New Procedures

Several new and improved testing procedures for soils have been made in the past decade, allowing for the evaluation of additional geotechnical parameters or producing better quality data.

Twitch Testing. An adjustable rate procedure termed "twitch testing" offers a means to evaluate viscosity strain rate effects during undrained loading of clays and silts, as well as the demarcation of drainage conditions (i.e., drained vs. partially drained vs. undrained), as described by Randolph (2004). Twitch testing procedures can be applied to vane shear, cone penetration, piezocone, t-bar, ball penetrometer, and piezoball results (Chung et al. 2006; Yafrate & DeJong 2007). It can be particularly useful in the evaluation of mine tailings (Oliveira et al. 2011). The piezocone and piezoball tests are especially valuable in twitch testing as both the tip resistances and porewater readings can be tracked together using a normalized and dimensionless velocity: $V = v \cdot d/c_v$ where v = test velocity, d = probe size, and c_v = coefficient of consolidation. A full range of twitch test rates using CPTu is presented by Kim et al. (2008) for clay-sand mixtures (Figure 18). For the soils tested, these results suggest that undrained conditions prevail for V > 10, while fully drained response occurs for V

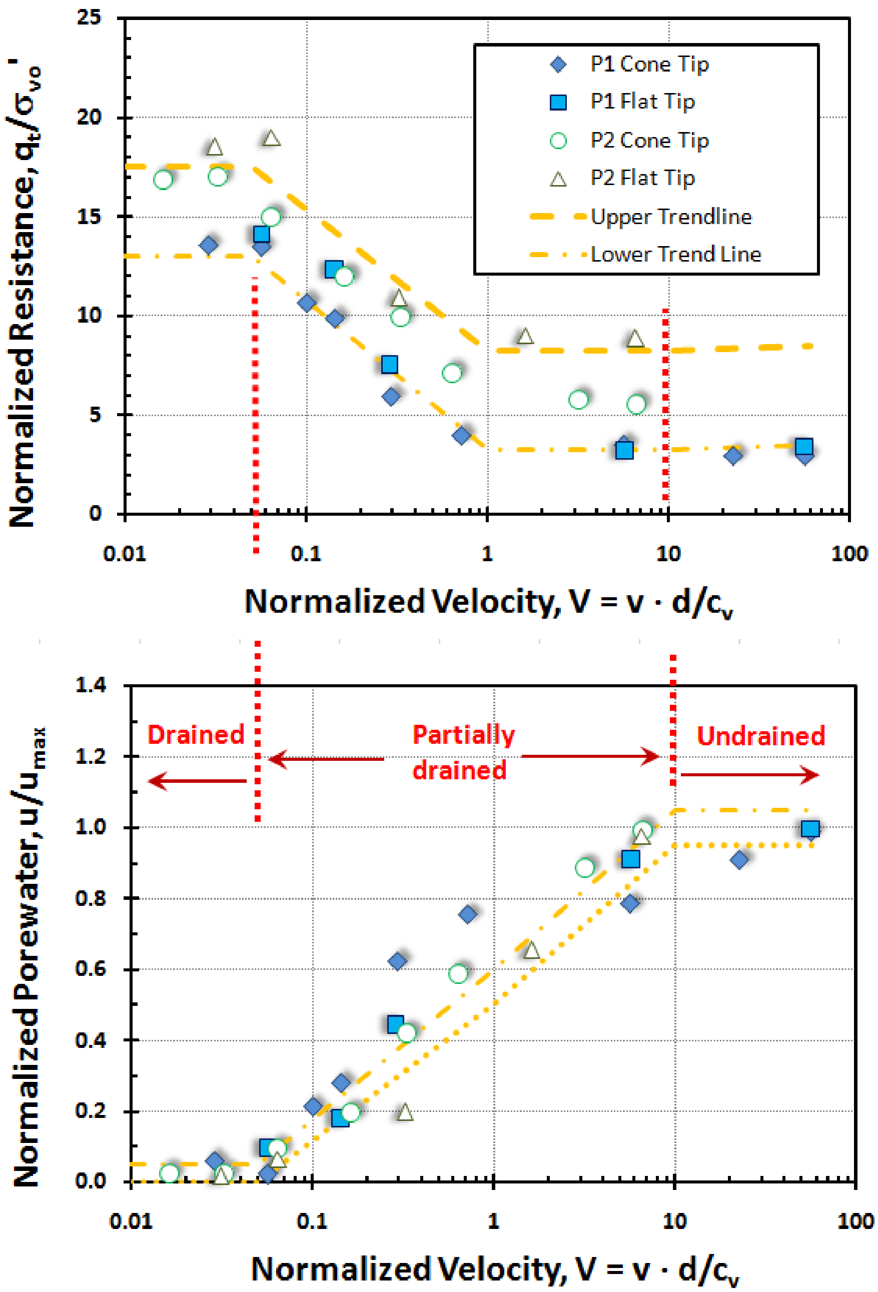


FIG. 18. Twitch testing results from two series of piezocones in clayey soils (data from Kim et al. 2008).

< 0.05, and intermediate V values correspond to partially drained and partly undrained cases. As laboratory testing forces an "undrained" response corresponding to conditions of constant volume, the twitch testing can be useful in confirming the validity of such cases and help to resolve difficulties in matching field and lab determinations of s_u. Twitch testing can also be used to quantify strain rate parameters during undrained shear (Peuchen & Mayne 2007).

Modulus Reduction Curves. For evaluating the in-situ dynamic properties of the ground, Stokoe et al. (2008) have developed a special pattern series of embedded geophones to measure wave arrivals, including arrival times for shear wave velocity and amplitudes for determining shear strain level: $\gamma_s = PPV/V_s$, where PPV = peak particle velocity. Using large portable shakers with "ominous" names (e.g., T-rex, Liquidator, Thumper), the hefty ground sources can be used to profile deep V_s profiles via low frequency waves. Moreover, the procedures can be used to obtain site-specific G/G_{max} reduction curves with logarithm of shear strain and in-situ damping responses on-site using variable frequencies and modes, supplemented with measurements taken at various locations and depths away from the shakers. Results appear comparable to those obtained on lab specimens using resonant column-torsional shear testing on clean to silty sands, as illustrated in Figure 19c.

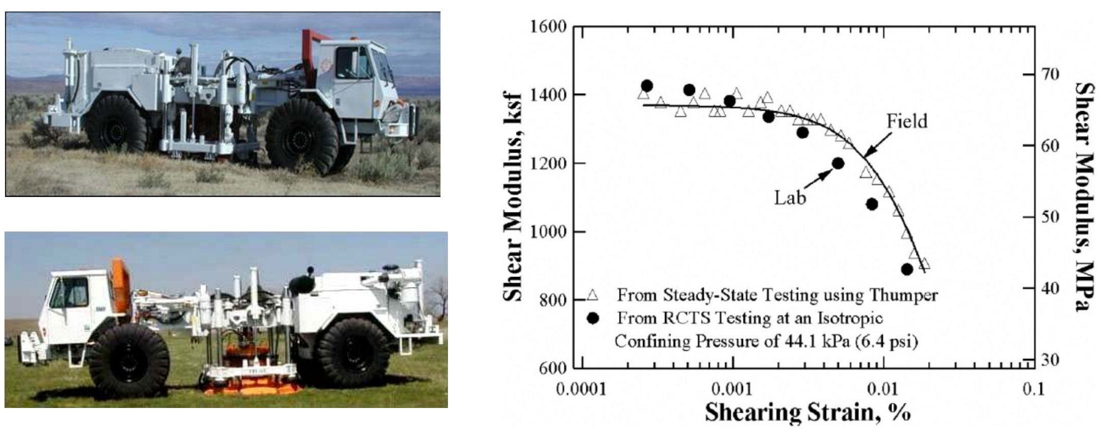


FIG. 19. In-situ dynamic measurements: (a) the Liquidator; (b) T-rex vibrator; (c) comparison of G/G_{max} reduction curves from field and lab testing on sands (Stokoe et al. 2008).

Downhole Shear Wave Testing. The original version of the SCPT used paired sets of left- and right-strikes to provide a crossover point and allow pseudo-interval downhole shear wave velocity profiling at 1-m intervals. As a single data point (arrival time) between consecutive test depths was paramount in the field measurement, a common procedure is to obtain two left strikes (for repeatability confirmation), as well as two right strikes. The result is that many SCPT today spend too much time collecting the DHT part of the SCPT. Two simple improvements to procure higher quality and faster results include: (a) autoseis source; (b) cross-correlation in the post-processing phase. Use of an autoseis (Figure 20a) is advantageous because the generated wave is repeatable (McGillivray and Mayne 2008). Cross-correlation utilizes the main wave arrival to match say 2000 data points (in lieu of the single sole data point in a first crossover). Plus the cross-correlation is automated in standard software (Excel, Matlab, Shearpro), whereas the cross-over point is usually evaluated by visual inspection.

Additional developments include the introduction of two improved field procedures: (1) frequent-interval DHT; (2) continuous SCPT (Mayne and McGillivray 2008). Frequent-interval downhole testing is the slowest approach, but offers the best detailing and delineation of V_s profiling with increased resolution at 20-cm intervals (Fig. 20b). Continuous SCPT is the fastest method available as wavelet data are generated and captured at approximately 1 to 5 second intervals. Such data require special considerations including fast sampling rates and noise filtering, time- and frequency-domain analysis, and post-processing methods.

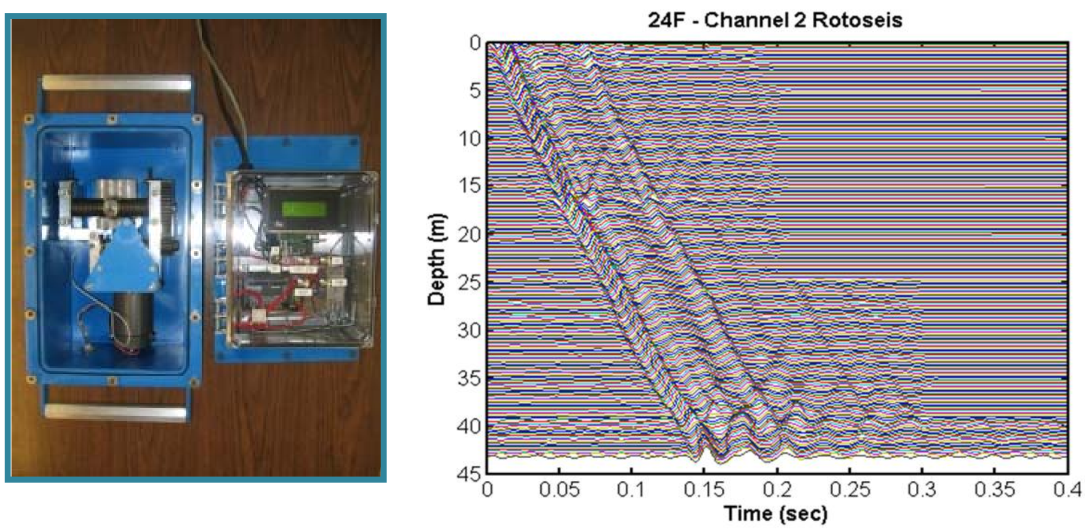


FIG. 20. Enhancements to downhole testing: (a) rotoautoseis source generator, (b) wavelet cascade from frequent-interval shear wave testing in Aiken, SC.

Interpretation Methods

The evaluation of geotechnical parameters from in-situ testing can be based on analytical, theoretical, numerical, and/or empirical-statistical trendline approaches. Table 1 gives a brief summary of selected references that address the interpretation of the primary set of in-situ field tests, yet is surely not comprehensive. Where appropriate, the test procedures per ASTM guidelines are also listed. Currently, no single framework or methodology has been established for interpreting the main tests (CPT, DMT, PMT, SPT, VST) together in a consistent manner. Instead, an assortment of different approaches are employed for each test; e.g. for clays: vane shear testing evaluated via limit equilibrium, cone penetrometer via strain path method, pressuremeter test via cavity expansion, etc. Moreover, the interpretations of in-situ tests are normally tackled assuming one of two extreme conditions: (a) undrained

Table 1. Select References for In-Situ Test Procedures and Interpretation

In-Situ Method	Title	Publisher	Author/Editor
General Overview on Field Tests	In-Situ Tests in Geomechanics (SPT, CPT, DMT, PMT, VST)	Taylor & Francis Group	Schnaid (2009)
	Geotechnical & Geophysical Site Characterization (ISC-3)	Taylor & Francis	Huang (2008)
	Site investigation and mapping in urban areas	14th ECSMGE: Millpress	Młynarek (2007)
	Geotechnical & Geophysical Site Characterization (ISC-2)	Millpress	Viana da Fonseca (2004)
	Geotechnical Site Investigation	Thomas Telford	Simons et al. (2002)
	Subsurface Investigations: Geotechnical Site Characterization	NHI Manual	Mayne et al. (2002)
	Evaluation of Soil & Rock Properties	FHWA Circular 5	Sabatini et al (2002)
	Geotechnical Site Characterization (ISC-1)	Balkema	Robertson (1998)
	Exploration of soft soil and determining design parameters	Port & Harbour Res. Inst. Japan	Leroueil & Jamiolkowski (1991)
	Manual on Estimating Soil Properties for Foundation Design	EPRI	Kulhawy & Mayne (1990)
	Developments in Field and Lab Testing of Soils	ISSMGE	Jamiolkowski et al. (1985)
Cone Penetration Test (CPT): ASTM D5778	Proceedings CPT '10	Omni Press	Robertson (2010)
	In-Situ Soil Testing	Lankelma	Brouwer (2007)
	Synthesis 368 on Cone Penetration Testing	TRB/NCHRP	Mayne (2007)
	CPT in Geotechnical Practice	Blackie Academic	Lunne et al. (1997)
	Proceedings CPT '95	Swedish Geotech-nical Society	Massarsch et al. (1995)
Dilatometer Test (DMT): ASTM D6635	The Flat Dilatometer Test in Soil Investigations	PCU, Indonesia	Marchetti et al. (2001)
	Flat Dilatometer Testing (International Symposium)	In-Situ Soil Testing	Failmezger and Anderson (2006)
Pressuremeter Test (PMT): ASTM D4719	Intl. Symposium: 50 Years of PMT	LCPC Press	Gambin et al. (2005)
	Cavity Expansion Methods in Geomechanics	Kluwer Academic	Yu (2000)
	Pressuremeters in Geotechnical Design	Blackie Academic	Clarke (1995)
	The Pressuremeter and Its New Avenues	Balkema	Ballivy (1995)
	The Pressuremeter	Swets & Zeitlinger	Briaud (1992)
	Pressuremeters	Thomas Telford	Houlsby (1990)

Table 1 (continued)			
In-Situ Method	Title	Publisher	Author/Editor
Standard Penetration Test (SPT): ASTM D1586	Penetration Testing	Institution of Civil Engineers, UK	Stroud (1988)
Vane Shear Test (VST): ASTM D2573	Rate effects in VST	SUT	Peuchen (2007)
	On the evaluation of s_u and P_c' in clays	CGJ	Larsson, R. and Åhnberg, H. (2005)
	Vane Shear Strength Testing in Soils	ASTM	Richards (1988)
Full-Flow Penetrometers (T-bar; Ball)	Geotechnical Testing Journal	ASTM	DeJong et al. (2010)
	JGGE	ASCE	Yafrate et al. (2007)
	Proc. ISC-2, Porto	Millpress	Randolph (2004)
Geophysics: including Crosshole (CHT): ASTM D4428, Downhole (DHT): ASTM D7400; SASW, MASW; GPR; Refraction, Reflection; ReMi, and Resistivity	Synthesis on Geophysics for Transportation Projects	NCHRP/TRB	Sirles, P.C. (2006)
	Application of Geophysics to Highway Problems	FHWA	Wightman et al. (2003)
	Soils and Waves	Wiley & Sons	Santamarina et al. (2001)
	Dynamic Geotechnical Testing II	ASTM	Ebelhar, et al. (1994)
Notes: ASTM = American Society for Testing & Materials; CGJ = Canadian Geotechnical Journal; EPRI = Electric Power Research Institute; FHWA = Federal Highway Administration; ISC = International Site Characterization; ISSMGE = Intl. Society Soil Mechanics & Geotechnical Engrg; NCHRP = National Cooperative Highway Research Program; NHI = National Highway Institute; SUT = Society for Underwater Technology; TRB = Transportation Research Board			

behavior (i.e., loading at constant volume: $\Delta V/V_0 = 0$); or (b) drained response (i.e.,loading with no excess porewater pressure: $\Delta u = 0$). Consequently, many interpretation methods are established for "clays" (i.e., undrained) vs. "sand" (i.e., drained). However, partially-drained behavior is also plausible such that some Δu is generated at the same time that some ΔV changes occur. Partly undrained cases may also occur where some Δu is generated (but not fully developed).

What are needed are global interpretative schemes, able to address many types of soils (clays, silts, sands, mixtures) that exhibit possible responses for various drainage conditions under a range of strain rates of loading. For instance, the evaluation of the effective friction angle (ϕ') from piezocone measurements using an undrained/drained penetration theory has been developed for use in sands, silts, clays, and mixed soils by the Norwegian Institute of Technology (Senneset et al. 1989). The interpretation of DMT data has offered a generalized approach, primarily towards foundation settlements, that is found applicable to many soil types (Marchetti et al. 2001). An analytical-empirical CPTu soil classification system has been put forth by Schneider et al. (2008). Also, a generalized approach to permeability evaluation on-the-fly by piezocone using a moving volumetric dislocation model has been derived (Elsworth & Lee 2007; Lee et al. 2008).

Moreover, a universal approach should be able to assist in the evaluation of several types of in-situ test methods. An initial set of calibrations using a cavity expansion-critical state approach to evaluating PMT, CPTù, and DMT has been applied to data from six clay sites (Mayne 2007b, Mayne & Burns 2008). In that approach, only five input soil parameters are needed: effective friction angle (ϕ'), prestress (σ_p'-σ_{vo}'), rigidity index (I_R), plastic volumetric strain potential ($\Lambda = 1\text{-}C_s/C_c$), and void ratio ($e_o$) to produce full profiles of q_t, u_1, u_2, f_s, p_0, and p_1 with depth. With additional information (i.e., c_{vh}), the analytical model provides u_1 and u_2 dissipations with time.

For future research directions, it will be helpful to employ results from numerical simulations using finite elements, discrete elements, and/or finite difference solutions towards a unified approach to in-situ test evaluation for all test types under all drainage conditions, and can also be used to directly model the full prototype situation (e.g., driven offshore pile, jacked tunnel, supported excavation, etc.). This is the major challenge for the next generation of researchers in geotechnical site characterization.

CONCLUSIONS

The complexities of natural soil behavior are now evident from decades-long studies involving complementary suites of laboratory studies, in-situ testing, and full-scale structural performance results at international geotechnical experimentation test sites located in various geomaterials including sedimentary deposits of clays, silts, sands, mixed soils, and structured cemented geomaterials, as well as residua derived from in-place weathering of rocks. As such, site characterization is best-handled by deploying many types of in-situ geotechnical probings and geophysical surveys together in concert with laboratory testing programs on high-quality undisturbed samples. As this is only feasible on large projects or critical facilities with full funding, the profession would be best positioned to adopt the seismic piezocone and/or seismic dilatometer for routine subsurface explorations because up to 5 independent readings are collected in a single sounding, thus no compromise is made in acquiring the necessary and varied types of information about the ground conditions.

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