U.S. National Report on CPT

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SYNOPSIS: Over the two decades since its introduction into the United States, the CPT has now established its position as a routine, reliable, and expedient means for site characterization, stratigraphic profiling, evaluation of soil engineering parameters, and geotechnical design. Piezocones provide measurements of penetration pore water pressures either midface (type 1) or at the shoulder (type 2). The latter is necessary for the proper correction of tip resistance in soft soils, while the former provides better resolution and detailing in stiff fissured materials.

Most areas of the U.S. are now serviced by specialty firms with cone trucks for optimizing production, penetration depths, and areal coverage. Portable cone systems are available for small projects and remote locations. Research on CPT testing and analysis continues to have high priority within many organizations.

The incorporation of additional sensors has increased cone versatility, thus favoring use of seismic-geophones, resistivity- or conductivity-, natural gamma-, and chemical-cones. This is attractive on geoenvironmental projects for expedient contaminant mapping while minimizing site damage and wastes generated from testing.

1. GEOLOGICAL REGIONS

The vast expanse of the United States of America includes many complex, mixed, and varied geomorphological formations throughout the 50 states. An overview of the surficial geologies of the U.S. is given by Hunt (1986).

While CPT is not possible in the very rocky and mountainous regions of the country, the test is very applicable to the coastal regions, inland sedimentary deposits, residual soil types, as well as reclaimed lands formed from hydraulic fills, dredgings, and mine tailings. The cone has become particularly popular for use in the marine sediments of the Atlantic and Pacific Coastal Plain Provinces, the deltaic and marine sediments of the Gulf states, glacial lacustrine deposits around the Great Lakes to New England, and floodplain alluvium from the Great Plains and following the Mississippi River. Throughout these regions, a number of specialized testing firms with cone trucks or trailers to provide CPT services.

2. TYPES OF PENETRATION TESTING

Penetration tests common to U.S. practice include the standard penetration test (SPT) and cone penetration test (CPT). In some regions, the flat blade dilatometer test (DMT) is used. Testing procedures for these three tests are essentially standardized, for the most part, excepting local practices that accommodate a the specific geology or needs of the region.

Other kinds of penetration tests are employed throughout the U.S., but are unique and localized to certain parts of the country. For example, a variety of dynamic cones and driven penetrometers (Texas Highway-type, Sowers drive cone, Michigan-state, Dinastar), and large split-barrel type samplers (D&M,

Converse, Acker, California-type) is used that are similar in concept to the SPT. However, the cone/spoon diameters, hammer sizes, and driving forces of these devices are not standardized, except perhaps within a given locality.

For gravelly soils, the Becker penetration test (BPT) has been developed and primarily utilized in western North America. Initially developed for use in assessing pile driveability and design of pile lengths in very coarse deposits, the BPT has also proved useful in evaluating liquefaction potential (e.g., Sy & Campanella 1994).

3. CPT EQUIPMENT

Most serious CPT work in the U.S. is now performed using standard electronic cones having a 60° apex pushed continuously at 20 mm/s, essentially making the mechanical versions obsolete. Initial designs that required the amplification of electric cone outputs, have now been replaced with superior electronics within the cone using signal conditioning to provide better resolution, increased reliability, and minimal noise.

Data acquisition systems typically include a portable computer, analog-digital converter, storage media (hard drive, floppy drives), and strip chart recorder or printer.

3.1 Penetrometers and rigs

Penetrometers having diameters of either 35.7 mm (10 cm^2 projected area) and 43.7 mm (15 cm^2) are used routinely. Because of the superior stratigraphic detailing, much CPT is accomplished with piezocones (designated PCPT or CPTU). As shown in Fig. 1, two basic types of piezocones are used for routine site investigations: (1) one with midface element for pore water pressure measurements (designated u_1 or u_t), and (2) with shoulder or behind the tip position (u_2 or u_{bt}). Earlier versions of the type 1 design placed the element at the cone apex. However, later designs put the element midface because it is less vulnerable to damage and excessive wear.

There are advantages and disadvantages associated with either type 1 or 2 cones. Porewater pressure readings from type 2 cones are

Fig. 1. Various Penetrometers (bottom to top): Miniature 4 cm^2 Electric Cone; 10 cm^2 Type 2 Piezocone (shoulder element); Type 1 (midface) piezocones; Type 2 Seismic, Hogentogler Dual Type 1 & 2 Seismic; 15 cm^2 Fugro Triple-Element Cone.

necessary for the proper correction of measured cone tip resistances ($q_c \rightarrow q_T$), as per Campanella & Robertson (1988) and DeBeer et al. (1988). This correction is very important in soft to medium stiff intact clays, but not significant in medium to dense clean sands or overconsolidated fissured clays where small positive, zero, or even negative Δu_2 readings are obtained (Mayne et al. 1990).

In general, type 2 cones may be more appropriate to the northern regions of the U.S. because of the preponderance of near surface recent geologic deposits comprised of soft to firm lightly overconsolidated soils, including marine deposits of the Atlantic coastal plain (e.g, Boston Blue clay; Calvert clay), glacial lacustrine sediments of the Great Lakes, and alluvial deposits. Maximum detailing is accom-plished using type 1 cones, however, and if stratigraphic profiling is paramount, u_1 measurements may be preferred.

In contrast, the hot temperate climate of the southern U.S. has formed overconsolidated and stiff materials by desiccation (e.g., Florida, Lousiana Southern California). If the materials are fissured, little detail is observed with type 2 readings and u_2 measurements can be small or even negative. Thus, a type 1 cone may be of better value in profiling. On the other hand, some difficulties have been noted in smearing and clogging of type 1 face porous elements during penetration of fat plastic clays, e.g. the Beaumont clays of Texas. In this case, less smearing occurs with a type 2 cone. Of course, exceptions to the above geographic generalities occur, and hard OC Cretaceous clays can also be found in the northern U.S. (e.g., Washington, DC), as well as the presence of very soft deltaic sediments in the south (e.g., offshore Gulf of Mexico). Thus, an ideal scenario for general use would be a dual-element cone for site characterization (Juran & Tumay 1989).

In order to maximize production and efficiency, most regions of the U.S. are now serviced by commercial testing firms and research institutions with specialized cone trucks (e.g., see Fig. 2). Compared with a conventional 10-tonne drill rig, a standard cone truck weighs about 20-tonnes, although special 30- and 40-tonne models have been built that use stronger rods in order to successfully penetrate dense sands or facilitate the completion of soundings with penetration depths of up to 60 m or more.

Fig. 2. Cone Truck operated by Fugro Geosciences Conducting CPTUs at Georgia Tech Civil & Environmental Engrg. Building.

During CPT, depth increments are measured above ground using either potentiometers, depth wheels, or ultrasonic beams. Successive increments are summed to give the total depth. Although cableless systems are available (Larsson & Mulabdić 1991), almost all U.S. systems employ a cable through the rods to connect the cone to the data acquisition unit at the ground surface.

3.2 Testing & calibration procedures.

Electronic penetrometers require a minimum of two calibration procedures: (1) load cell cali-bration in a compression apparatus to obtain output voltage for q_c and f_s; and (2) hydrostatic calibration in a triaxial cell for determination of output voltage for u_1 or u_2, as well as the net area ratios for correction of tip (q_T) and sleeve (f_T) resistances. Details on these calibrations have been given elsewhere (e.g., Jamiolkowski et al. 1985; DeBeer et al. 1988). If the cone will be used in very cold or very hot climates, a calibration check for temperature variations is also recommended (Lunne et al. 1986).

Calibrations of ancillary devices such as potentiometers for depth measurements and oscilloscopes for seismic velocity arrival times are handled separately.

Porous elements are often made of flexible polypropylene and are disposed of after each sounding. In stiff or dense soils, stainless steel or rigid ceramic elements are better for type 1 cones because of high abrasion and the compressibility of the filter affects the pore pressure readings (Campanella & Robertson 1988).

Proper saturation of the porous element is important for quality results (Lunne et al. 1986). A 50/50 mixture of glycerine and water provides excellent results, although some testing firms use either silicon oil or distilled water. A prophylactic is placed over the saturated cone with a rubber band to maintain saturation until penetration.

3.3 Corrections & data presentation

Type 1 cones have a non-standard position of the pore pressure element, as shown in Fig. 3, thus giving different recorded u_1 for each particular cone (Brown 1993). For stratigraphic profiling, this is unimportant since only relative variations with depth are compared. For the assessment of soil properties, however, these differences in u_1 affect the numerical outcome and interpretation and therefore should be taken into account.

Measured data from cone soundings are usually presented graphically (and/or digitally)

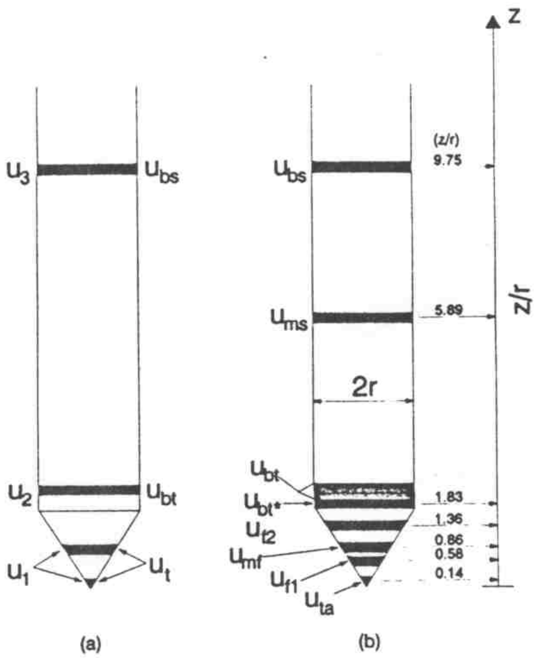

Fig. 3. Porous element positions: (a) general; and (b) specific or "rainbow" cone (Brown 1993).

in terms of the individual readings versus depth, including: cone tip resistance (q_c or q_T), sleeve friction (f_s or f_T), and penetration pore pressure (u_1 or u_2 or excess Δu). Sometimes, an additional profile of dynamic pore pressure, u/q_c, or the normalized piezocone parameter, $B_q = \Delta u/(q_T\text{-}\sigma_{vo})$, is presented (Wroth 1984).

Figure 4 illustrates an example profile summary of q_T, f_s, and u from single-, dual-, and triple-element soundings in overconsol-idated desiccated clay in Baton Rouge, Louisiana. Note the u_3 position is located behind the friction sleeve. Excellent repeata-bility of results is evident for the first three channels, while differences are observed for the two trailing pore pressure locations, thus inferring difficulties in maintaining saturation.

If piezocone dissipation tests at specific test depths are made, the results are presented with either penetration pore pressure (u) or excess Δu versus time or logarithm of time (e.g., Levadoux & Baligh 1986).

For seismic cone soundings, a downhole assessment of the time arrivals of the compression (P) and shear (S) waves can be obtained, thus producing profiles of the interpreted P- and S-wave velocities vs. depth (Campanella 1994). Usually, these data are presented at discrete increments corresponding to rod changes (approx. each meter). Alter-natively, the complete wave trace record with time (forward and/or reverse) can be shown for each event.

If a conductivity cone is used (Campanella & Weemes 1990), a continuous profile of electrical resistivity is presented and used to infer the presence of subsurface contaminants.

3.4 National standards

Standard procedures for CPT have been established by ASTM D-3441 since 1975 that addressed mechanical and electrical friction cones. For the piezocone test, a revised ASTM D-3441 procedure has been proposed in which a type 2 porous element position is recom-mended (Farrar 1995).

4. INTERPRETATION

The results of CPT and PCPT are used for delineating soil strata and for evaluating the geotechnical engineering parameters of the subsurface layers. In recent environmental applications, cone data are used to infer or detect the presence of anomalies such as contaminants in the pore fluid.

4.1 Soil classification and stratigraphy

Piezocone results are unsurpassed in the detail-ing of soil stratigraphy. Exceptional resolution makes the detection of thin seams and lenses possible, particularly via the pore pressure channel. This facet is very important from a geoenvironmental viewpoint and for slope stability evaluations.

Soil classification using CPT and PCPT data is indirect and relies entirely on empirical charts for interpretation of strata (see Table 1).

4.2. Engineering parameters

Considerable effort has been made to derive soil engineering properties from the results of cone and piezocone data. Methodologies have

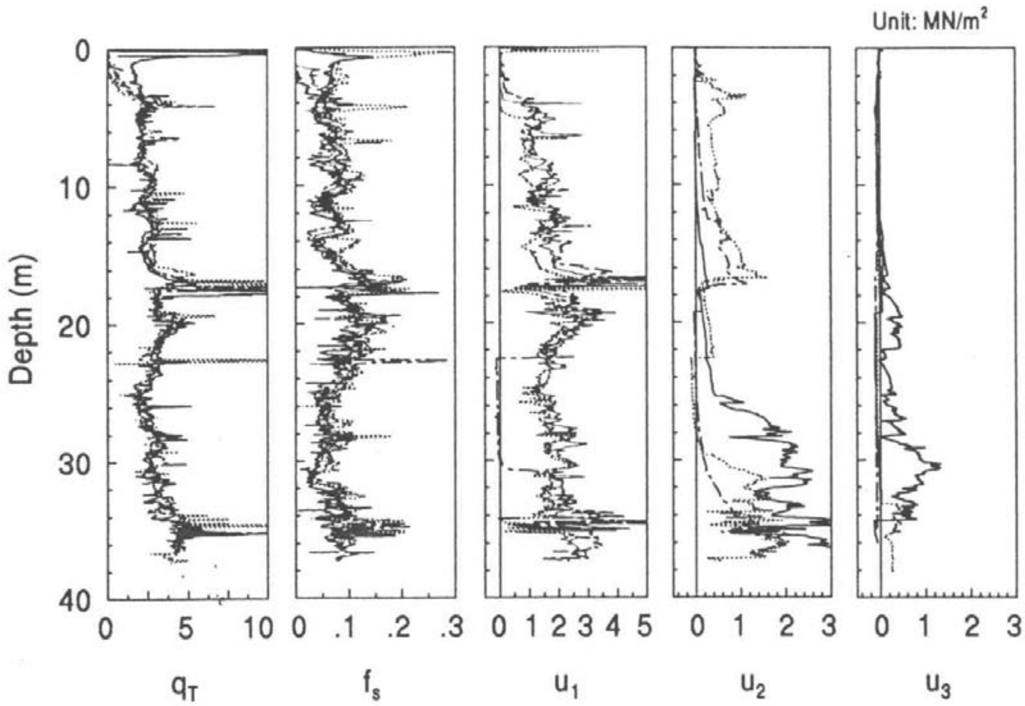

Fig. 4. Summary profiles of single-, dual-, and triple-element piezocone soundings in desiccated overconsolidated clay at I-10 and Route 42 in Baton Rouge, LA (Chen 1994).

been developed using empirical and statistical methods, backcalculation, analytical studies, and numerical simulation.

In organizing Table 1, various interpretation methods have been grouped into one of three basic categories: those specifically addressing (a) clays and cohesive materials, (b) sands and cohesionless materials, and (c) applicable to both soil types. Abbreviated references are given in the table to conserve space.

4.3 Environmental data

Many recent developments in CPT (or direct-push technology) have centered around its use for geoenvironmental concerns. The incorporation of additional sensors within the penetrometer to instantaneously and continuously monitor phenomena offers significant potential for evaluating subsurface chemical and biological conditions.

Some success has been obtained with sensors that quantify bulk resistivity of the pore fluid (Campanella & Weemees 1990) or electrical conductivity (Woeller et al. 1991a, 1991b), temperature (MacFarlane et al. 1983), pH and redox (Olie et al. 1992), light hydrocarbons (Malone et al. 1992), neutron moisture (Shibata et al. 1992), and petroleum vapors (Horsnell 1988). Most of these methods involve contaminant mapping by inference, however, and no direct chemical assessment is made. A review of some additional sensors and technologies under development is given by Bowders & Daniel (1994).

In addition to modifications and add-on modules to the standard cone penetrometer, direct-push technology has led to other specialized probes for sampling & testing groundwater & soil during environmental site characterization, including: push-in soil samplers, push-in water samplers, push-in piezometers, and soil-gas extraction-type samplers. One example of a specialized device is the "hydro-trap", a commercially-made groundwater sampler used to obtain volatile

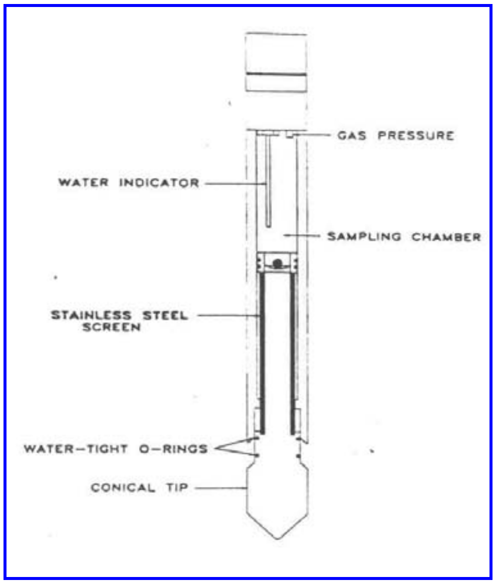

Fig. 5. Push-in hydro trap for obtaining groundwater samples (Yilmaz 1995).

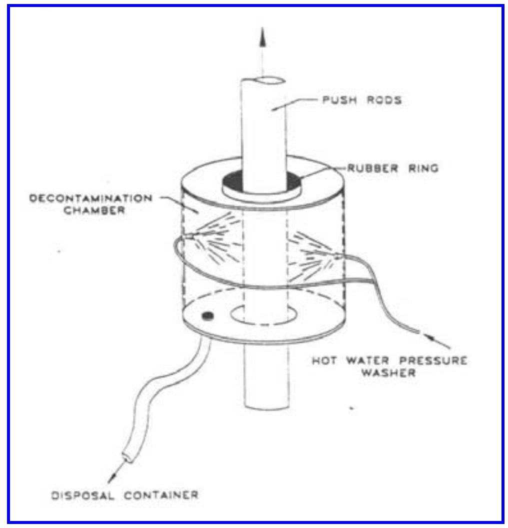

Fig. 6. Environmental CPT rod washing system (Yilmaz 1995).

organic compounds under controlled confining pressures, as shown in Figure 5.

For geoenvironmental CPT explorations, additional measures must be undertaken to decontaminate the push rods during extraction from the ground. This is necessary for the safety and health of the crew and to reduce potential contamination of the subsequent test location. Fig. 6 illustrates one commercial concept used for rod washing.

Of equal concern is the potential for cross-contamination of aquifers and groundwater reserves by penetration. Many states (e.g., LA, NJ, CA) require that exploratory holes be grouted upon completion. Thus, self-grouting systems or companion grouting units for hole closure have been developed (Yilmaz 1995).

5. CPT IN FOUNDATION DESIGN

Routinely, CPT data are used for the analysis and design of foundations, including bearing capacity and settlement of spread footings, driven piles, and drilled shafts (bored piles). Both direct and indirect methods of CPT assessment are used, as discussed in the following sections.

In a recent ASCE/FHWA-sponsored prediction symposium involving large footings on sand (Briaud & Gibbens 1994), the CPT proved to be the most preferred test (used by 30% of predictors) for assessing the foundation performance, as compared with 25% for SPT, 16% for PMT, 14% for DMT, and 10% for triaxial tests.

The CPT is also useful in assessing compaction control during placement of structural fills and in the evaluation of effectiveness of ground modification techniques (e.g., vibroflotation, dynamic compaction) and site improvement works (Mitchell 1986).

5.1 Direct methods

In these approaches, the measured CPT data are directly input into empirical formulas to provide estimates of foundation capacity and settlement (e.g., Schmertmann 1978). For example, regarding the prediction of axial capacity of deep foundations, there are at least 6 methods for driven piles (Robertson et al. 1988) and 5 for drilled shafts or bored pile systems (Alsammam 1995). Poulos (1989) provides a review for both types.

5.2 Indirect methods

In these methods, the CPT data are used to estimate soil properties that are input into a theoretical model for predicting capacity or deformation response. General procedures for interpreting engineering parameters for foundation analysis from in-situ data are given by Kulhawy & Mayne (1990). Berardi et al. (1991) outline settlement analysis procedures for spread footings on sand from CPT data. CPT-based methods for calculating axial capacity and settlement of driven piles are discussed by Robertson et al. (1988) and Poulos (1994), respectively. Van Impe (1994) extensively covers drilled and bored pile analysis from CPT.

6. COMPARISONS & CORRELATIONS OF CPT WITH OTHER METHODS

Comparisons of cone measurements can be made within the test (intra-correlative) or between other in-situ tests that are conducted in the field adjacent to the CPT location (inter-correlative).

6.1 Intra-correlative studies

Internal relationships among paired sets of q_c and f_s readings with physically-retrieved soil samples form the original basis for empirical soil classification charts. In sands, intra-correlative trends for f_s vs. q_c are discussed by Parkin (1988). For clays, Mayne et al. (1990) present u vs. q_T trends for face- and shoulder-type PCPTs. More specifically, one set of intra-correlations for uncemented intact clays is shown in Fig. 7. However, the relationships also depend on OCR and degree of fissuring (Powell et al. 1988).

Initially, q_c vs. f_s plots were used to infer soil type (e.g., Schmertmann 1978). Later, Senneset et al. (1989) developed a soil classification scheme based on q_T vs. B_q, while Robertson (1990) suggested a system that utilizes all three readings of the PCPT. However, the normalization scheme for q_T and f_T (and u) should actually depend upon soil type (Olsen 1994). That is, $Q = (q_T-\sigma_{vo})/\sigma_{vo}'$ is appropriate for clays, while for clean sands,

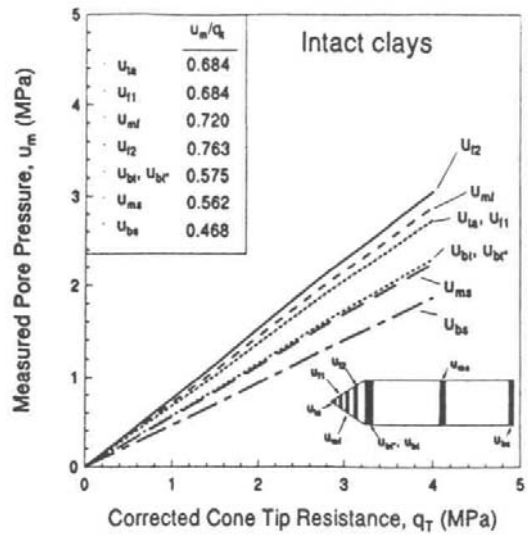

Fig. 7. Summary interrelationships between penetration pore pressures and tip resistance for unstructured intact clays (after Brown, 1993).

the parameter $Q^* = (q_T-\sigma_{vo})/(\sigma_{vo}')^{0.5}$ may be more appropriate.

6.2 Extra-correlative studies

Relationships between the SPT-N value and CPT-q_c have been studied for a variety of soil types (Schmertmann 1978; Robertson et al. 1983; Mullen, 1991). The ratio of q_c/N generally increases with mean grain size and averages (Kulhawy & Mayne 1990):

$$q_c/N_{60} \approx 544\ (D_{50})^{0.26} \qquad (1)$$

where q_c is in kPa, N_{60} = energy corrected SPT resistance, and D_{50} is in mm. However, there is considerable variation around this average. The ratio q_c/N_{60} also depends on the percent fines (particles < 75μ), as well as other factors.

Correlations between CPT and DMT have also been investigated. For clays (intact and fissured), the DMT contact pressures (p_o) are comparable to type 1 PCPT penetration pore pressures (Mayne & Bachus 1989), such that:

Clays: $u_1 \approx p_o$ (2)

In clean sands, measurement of the DMT blade thrust provides a wedge resistance (q_D) that is comparable in magnitude to q_c. For

McDonald Farm sand, Campanella & Robertson (1991) found that:

Sands: $q_D/q_c \approx 1.1$ (3)

which was later confirmed appropriate for Toyoura sand in calibration chamber studies (Bellotti et al. 1994).

6.3 National Test Sites (NGES)

Since 1988, a combined effort by the Federal Highway Administration (FHWA) and National Science Foundation (NSF) resulted in the cataloging and establishment of several National Geotechnical Experimentation Sites (NGES) throughout the U.S. (Woods, 1994).

Currently, 40 designated sites have been cited throughout the 48 contiguous states and Alaska, with the majority classified as Level 3 (unfunded) sites, as shown by Fig. 8. Two high-priority (Level 1) and three medium-priority (Level 2) sites receive annual funding for databasing, management, and site improvements. The NGES permit the opportunity to compare cone and piezocone data with results derived from other in-situ tests and/or laboratory devices.

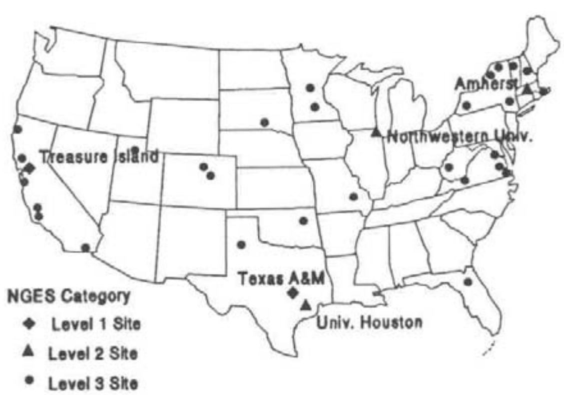

Figure 8. Locations of the initial National Geotechnical Experimentation Sites (NGES) in the U.S.A.

[June 2002: Note: addition of the Opelika, Spring Villa NGES in Alabama]

7. MAJOR RESEARCH ACTIVITIES

Academic research on CPT has been mainly directed at improved means of interpretation, including analytical studies based on limit plasticity (Masood 1990) or cavity expansion (Chen 1994 for clays; Salgado 1993 for sands). In addition, numerical simulation of the penetration problem has been attempted using dislocation-based models (Elsworth 1991), strain paths (Whittle & Aubeny, 1993), and discrete elements (Huang & Ma, 1994).

Empirical and theoretical methods for interpreting CPT data have been derived from analyses of available field data (Birgisson 1991; Brown 1993; Olsen 1994) or from controlled laboratory calibration chamber testing (Kulhawy & Mayne, 1990). Recent programs providing additional reference data include field studies by Mullen (1991) and Murray (1995) and chamber tests for sands (Puppala et al. 1991; Rix & Stokoe 1991; Salgado 1993), silty sands (Brandon & Clough, 1991), and clays (Kurup et al. 1994).

Research by cone manufacturers and commercial testing firms has focussed on improvements in equipment performance and reliability (also see future trends). The effects of temperature variations, electromagnetic noise, and zero drift have essentially been eliminated with the use of internal signal conditioning and microelectronics.

Many innovative ideas have resulted in the increased applicability of the cone to difficult soil conditions and to geoenvironmental problems (Mitchell 1988). Bratton et al. (1995) and Auxt & Gilkerson (1995) provide recent reviews of the various types of geoenviron-mental penetrometers, their capabilities, and shortcomings.

8. FUTURE TRENDS

Innovative new developments and the incorpor-ation of additional capabilities to the CPT are currently underway (Bowders & Daniel 1994). A few interesting ongoing projects are dis-cussed briefly in the following paragraphs.

The USAE Waterways Experiment Station has developed an elaborate design (SCAPS =

site characterization and analysis penetrometer system) that includes a fiber-optics guide from a sapphire window located near the cone tip to measure the laser-induced fluorescence (LIF) of petroleum chemicals which may be present (Schroeder et al. 1991; Stark, 1991). A similar system using a fiber optic chemical sensor (FOCS) and photo-ionization detector was developed (Leonard & Tillman 1993), but has been discontinued because the sensor is not reversible. An LIF probe utilizing a tuneable laser fluorescence system (ROST system) is now in use for the identification of aromatic hydrocarbons (Yilmaz 1995).

A miniature cone unit for expedient CPTs has been designed with a caterpillar thrust system and self-coiling rods that mount at the front of a 4-wheel drive diesel pickup truck (Tumay 1994).

A new subsurface vision probe has been proposed for direct optical soil classification by CPT. The development will use a sapphire viewing window, high-resolution video camera, and image processing center to determine grain size distributions in real time (Hryciw & Raschke 1996).

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Table 1. List of soil parameters interpreted from cone and piezocone data.

ALL SOIL TYPES *(Clays, Silts, and Sands)*

- **Soil Classification**
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  Robertson, et al. (1986). ASCE GSP 6, 1263-1280.
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  Robertson (1990), CGJ 27 (1), 151-158 and CGJ 28 (1), 173-178.
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- **Unit Weight (γ_T)**
  Lunne, Robertson, & Powell (1997), Cone Penetration Testing in Geot. Practice, Routledge, New York

- **Effective Friction Angle (ϕ')**
  Senneset & Janbu (1985), STP 883, ASTM, Philadelphia, 41-54.
  Senneset, Sandven, & Janbu (1989). TRR 1235, 24-37.
  Sandven (1990), PhD Thesis, Norwegian Institute of Technology (NTH 1990.3), Trondheim.
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- **Effective Cohesion Intercept (c')**
  Senneset et al. (1989), Transporation Research Record 1235, 24-37.

- **Hydraulic Conductivity (k)**
  Schmertmann (1978), Report TS-78-209, FHWA, Washington, DC, 145 p.
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- **Constrained Modulus ($M = 1/m_v$)**
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  Senneset, et al. (1982), ESOPT (2), Amsterdam, 863-870.
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- **Shear Wave Velocity (V_s)**
  Hegazy & Mayne (1995), Paper A87, CPT'95, Linköping.

CLAYS

- **Undrained Strength (s_u)**
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  Robertson & Campanella (1983), CGJ 20 (4), 734-745.
  Lunne et al. (1985), 11th ICSMFE (2), San Francisco, 907-912.
  Keaveny & Mitchell (1986), ASCE GSP 6, Blacksburg, 668-685.
  Aas et al. (1986), ASCE GSP 6, Blacksburg, 1-30.
  Konrad & Law (1987), CGJ 24 (3), 392-405.
  Marsland & Powell (1988), PTUK, Birmingham, 209-214.
  Jamiolkowski et al. (1988), ISOPT-1 (1), Orlando, 263-296.

Rad & Lunne (1988), ISOPT-1 (2), Orlando, 911-917.
Stark & Juhrend (1989), 12th ICSFME (2), Rio, 327-330.
Houlsby & Wroth (1989), 12th ICSFME (1), Rio, 227-232.
Stark & Delashaw (1990), Transportation Research Record 1278, 96-102.
Chen & Mayne (1993), ICCHGE (II), St. Louis, 1305-1312.

- **Stress History (σ_p' or OCR)**

Tavenas & Leroueil (1979), 7th ECSMFE (1), Brighton, 281-291.
Tumay et al. (1982, ESOPT (2), Amsterdam, 915-921.
Wroth (1984), Geotechnique 34 (4), 449-489.
Jamiolkowski et al. (1985), 11th ISCMFE (1), San Francisco, 57-154.
Battaglio et al. (1986), 4th SE Asian Geotechnical Seminar, Singapore, 129-143.
Konrad & Law (1987), Geotechnique 37 (2), 177-190.
Mayne & Bachus (1988), ISOPT (2), Orlando, 857-864.
Sills et al. (1988), PTUK, Birmingham, 247-250.
Sully et al. (1988), ASCE JGE 114 (2), 209-215.
Sandven (1990), PhD Thesis, Norwegian Inst. of Tech (NTH 1990.3), Trondheim.
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Jamiolkowski (1995). CPT'95, Vol. 3, Swedish Geot. Society, 7-15.
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Senneset & Janbu (1985), ASTM STP 883, Philadelphia, 41-54.
Lunne et al. (1985), 11th ICSMFE (2), San Francisco, 907-912.
Keaveny & Mitchell (1986), ASCE GSP 6, Blacksburg, 668-685.
Sandven et al. (1988), ISOPT-1 (2), Orlando, 939-953.
Senneset et al. (1989), Transportation Research Record 1235, 24-37.

- **In-Situ Stress State (K_o)**

Mayne & Kulhawy (1990), Transportation Research Record 1278, 141-149.
Sully & Campanella (1991), ASCE JGE 117 (7), 1082-1088.
Masood & Mitchell (1993), ASCE JGE 119 (10), 1624-1639.

- **Coefficient of Consolidation (c_h)**; from dissipation tests:

Hansbo et al. (1981), Geotechnique 31 (1), 45-66.
Battaglio et al. (1981), Cone Testing & Experience, ASCE, New York, 264-302.
Tumay & Acar (1985), ASTM STP 883, Philadelphia, 72-82.
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Robertson et al. (1988), CGJ 25 (1), 56-61.
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- **Hydraulic Conductivity (k)**

Tavenas et al. (1982), ESOPT (2), Amsterdam, 889-894.
Robertson et al. (1992), CGJ 29 (4), 539-550.
Elsworth (1993), ASCE JGE 119 (10), 1601-1623.
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  Robertson & Campanella (1983), CGJ 20 (4), 734-745.
  Sandven et al. (1988), ISOPT-1 (2), Orlando, 939-953.
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- **Shear Wave Velocity (V_s)**
  Mayne & Rix (1995), Soils & Foundations 35 (2).

- **Low-Strain Shear Modulus (G_{max})**
  Bouckovalas et al. (1989), 12th ICSMFE (1), Rio, 191-194.
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  Tanaka, et al. (1994). PreFailure Deformation of Geomaterials, Sapporo, 235-240.

- **Sensitivity (S_t)**
  Robertson & Campanella (1983), CGJ 20 (4), 734-745.

- **Unit Weight (γ_T)**
  Larsson & Mulabdic (1993), Rept 42, Swedish Geotechnical Institute, Linköping, 240 p.
  Denver (1995). Proc. CPT'95, Vol. 3, Swedish Geot. Society, 105-118.

- **Rigidity Index (I_r)**
  Chen and Mayne (1994), Report CEEGEO-94-1, Georgia Tech, Atlanta, 280 p.
  Mayne (2001). In-Situ 2001, Intl. Conf. on In-Situ Meas. of Soil Properties, Bali, 27-48.

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- **Effective Friction Angle (ϕ')**
  Trofimenkov (1974), ESOPT-1 (1), Stockholm, 147-154.
  Mitchell & Lunne (1978), ASCE JGE 104 (7), 995-1012.
  Robertson & Campanella (1983), CGJ 20 (4), 734-745.
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  Lunne, et al. (1992). ICSMFE, Vol. 4, Rio de Janeiro, 2339-2366.
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  Schmertmann (1978), Report TS-78-209, FHWA, Washington, DC, 145 p.
  Lunne & Christophersen (1983), 15th Offshore Technol. Conf. (1), Houston, 181-192.
  Jamiolkowski et al. (1985), 11th ISCMFE (4), San Francisco, 1891-1896.
  Kulhawy & Mayne (1991), Calibration Chamber Testing, Elsevier, 197-211.

- **State Parameter (ψ)**
  Been et al. (1986), Geotechnique 36 (2), 239-249.
  Been et al. (1987), Geotechnique 37 (3), 285-299.
  Jamiolkowski & Robertson (1988), PTUK, Birmingham, 321-342.
  Robertson & Fear (1995). CPT'95, Vol. 3, Swedish Geot. Society, 57-79.

- **Stress State (K_o)**
  Manassero (1991), ISOCCT-1, Clarkson University, 239-248.
  Mayne (1991), ISOCCT-1, Clarkson University, 249-256.
  Masood & Mitchell (1993), ASCE JGE 119 (10), 1624-1639.
  Schnaid & Houlsby (1994). Geotechnique 44 (3), 529-532.
  Mayne (1995). Proc. CPT'95, Vol. 2, Swedish Geot. Society, 215-220.
  Lunne, Robertson, & Powell (1997). Cone Penetration Testing in Geotech Practice, Routledge.
  Mayne (2001). In-Situ 2001, Intl. Conf. on In-Situ Meas. of Soil Properties, Bali, 27-48.

- **Constrained Modulus ($M = 1/m_v$)**

  Robertson & Campanella (1983), CGJ 20 (4), 734-745.
  Jamiolkowski et al. (1988), ISOPT-1 (1), Orlando, 263-296.
  Kulhawy and Mayne (1990), Report EL-6800, EPRI, Palo Alto, 306 p.

- **Low-Strain Shear Modulus (G_{max})**

  Baldi, et al. (1988). Penetration Testing, Vol. 2, Orlando, 643-650.
  Baldi, et al. (1989). Proc. 12 ICSMFE, Vol. 1, Rio de Janeiro, 165-170.
  Rix & Stokoe (1991), ISOCCT-1, Clarkson University, 351-362.
  Lunne et al. (1994), Proc. 12th ICSMFE (4), Rio, 2339-2403.
  DeAlba et al. (1994), Proc. 13th ICSMFE (1), New Delhi, 173-176.
  Olsen (1994), Rept. TR-GL-9429, USAE Waterways Experiment Station, Vicksburg, 322 p.
  Jamiolkowski (1995). Proc. CPT'95, Vol. 3, Swedish Geot. Society, 7-15.

- **Shear Wave Velocity (V_s)**

  Baldi et al. (1989), 12th ICSMFE (1), Rio, 165-170.

- **Overconsolidation Ratio (OCR)**

  Mayne (1991), Calibration Chamber Testing, Elsevier, (ISOCCT-1, Clarkson University), 249-256.
  Lunne, Robertson, & Powell (1997). Cone Penetration Testing in Geotech Practice, Routledge.
  Mayne (2001). In-Situ 2001, Intl. Conf. on In-Situ Meas. of Soil Properties, Bali, 27-48.

- **Liquefaction Potential**

  Jamiolkowski et al. (1985), 11th ICSMFE (4), San Francisco, 1891-1896.
  Robertson & Campanella (1985), ASCE JGE 111 (3), 394-403.
  Seed & DeAlba (1986), ASCE GSP 6, Blacksburg, 281-302.
  Shibata & Teparaksa (1988), Soils & Foundations 28 (2), 49-60.
  Sugawara (1989), 12th ICSMFE (1), Rio, 233-238.
  Stark & Olson (1995), ASCE JGE 121 (12).
  Suzuki, et al. (1995). Proc. CPT'95, Vol. 2, Swedish Geot. Society, 583-588.
  Robertson & Wride (1998). Canadian Geotechnical Journal 35 (3), 442-459.
  Youd, Idriss, et al. (2001). ASCE Journal of Geotechnical Engineering 127 (10), 817-833.

NOTES:

ASCE	= American Society of Civil Engineers, New York.
ASTM	= American Society for Testing and Materials, Philadelphia.
CGJ	= Canadian Geotechnical Journal, National Research Council/Canada, Ottawa.
ECSMFE	= European Conference on Soil Mechanics & Foundation Engineering.
EPRI	= Electric Power Research Institute, Palo Alto, CA.
ESOPT	= European Symposium on Penetration Testing.
FHWA	= Federal Highway Administration (US DOT), Washington, DC.
GSP	= Geotechnical Special Publication (ASCE).
GTJ	= Geotechnical Testing Journal, ASTM, Philadelphia.
ICCHGE	= International Conference on Case Histories in Geotech. Engineering.
ICSMFE	= International Conference on Soil Mechanics & Foundation Engineering.
ISOPT	= International Symposium on Penetration Testing, Orlando, FL.
ISOCCT	= International Symposium on Calibration Chamber Testing, Potsdam, NY.
JGE	= Journal of Geotechnical Engineering, ASCE, New York.
JGGE	= Journal of Geotechnical & Geoenvironmental Engineering, ASCE, Reston/Virginia.
PTUK	= Penetration Testing in the UK, Thomas Telford, London.
STP	= Special Technical Publication (ASTM).
TRR	= Transportation Research Record (TRR), National Academy Press.

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