

# Session Report 3: CPT Applications

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**ABSTRACT:** Since the early applications of CPT results to estimate bearing capacity, current practice covers a large range of problems such as: site characterization, prediction of soil properties, design of shallow and deep foundations, assessment of ground improvement and soil liquefaction, as well as a variety of geo-environmental applications. Fifty one (51) papers submitted to this Conference addressing these major topics are discussed herein, key issues are identified and areas of uncertainty acknowledged.

## 1 INTRODUCTION

The purpose of this report is to conduct a brief summary of CPT applications based on the topics covered by the presented papers. Papers have been organised in five main themes that allow a broad view of CPT applications:

- a) site characterization
- b) prediction of soil properties
- c) foundations bearing capacity and settlements
- d) soil liquefaction
- e) geo-environmental investigation

Although some overlapping inevitably exists, an attempt is made to summarise the main issues related to each topic by emphasising current practice and need for further research.

## 2. SITE CHARACTERIZATION

Continuous profiles from CPTU equipment has gained acceptance as an accurate, reliable and cost-effective means for site characterization. This capability is explored by papers dealing from site characterization of natural deposits to evaluation of soil improvement after ground treatment. Example of a refined subsurface characteriza-

tion for a subway project is reported by *Yang et al*, comprising seismic measurements for liquefaction assessment. Difficulties involved in the CPT characterization process are reported to be associated with the spatial variability of deposits requiring sufficient and detailed site investigation to be carried out. Although the amount and extent of CPT logs are generally selected by engineering experience, there have been attempts to use probabilistic analysis to optimize site characterization using the CPT. An example brought by *Ng & Zhou* describes an uncertainty-based optimization model derived for site characterization using CPT data, in which a probabilistic model of the soil profile is introduced for determining the vertical and horizontal distances required for a given project. *Moss, Hollenback & Ng* examined heterogeneity as a function of the lateral distance between CPT logs. From the representation of the relative variogram concept introduced by *Issaks & Srivastava (1989)* the authors define minimum stretches of a levee that can be used as guidance to assess the probability of failure of embankments resting on peat organic foundation soil. Generally, the limiting factor of probabilistic approaches is the lack of data both in quantity and at reasonably spatial intervals to perform robust statistical analysis.

Reported experience on site characterization of natural deposits has been extended to evaluate the effectiveness of ground improvement techniques, such as static and dynamic compaction (*Ku & Juang, Agrawal et al, Ozer et al, Skutnik et al*), dynamic replacement (*Bates & Merfield*) and soil mixtures (*Sinha et al*). Some innovative procedures are introduced for assessing the degree of compaction of both coarse- and fine-grained soils. *Agrawal et al* presented a method to estimate compaction of large areal fill on the bases of a relative compaction ( $RC = \gamma_d / \gamma_{max}$ ), where  $\gamma_d$  is the in situ dry density and  $\gamma_{max}$  is the maximum soil dry density. An example illustrating the estimation of RC is presented in Figure 1, in which data gathered from CPTU is shown to depict the RC values computed from density data obtained from both field and laboratory tests. Alternatively, *Squeglia & Lo Presti* presented a procedure based on mini-CPT results performed on a laboratory calibration chamber using compacted samples. The method is latter used to evaluate at a river embankment constructed using compacted fine-grained soils.

The growing interest for using penetration techniques for ground improvement projects is examined in four papers submitted to the conference (*Skutnik; Bates & Merfield; Ku & Juang; Ozer et al*). The procedure consists of evaluating the conditions of a site prior and after dynamic compaction techniques. A typical example from *Talga Ozer at al* is shown in Figure 2, allowing the change in properties by the compaction process to be estimated and the possible impacts on liquefaction to be assessed.

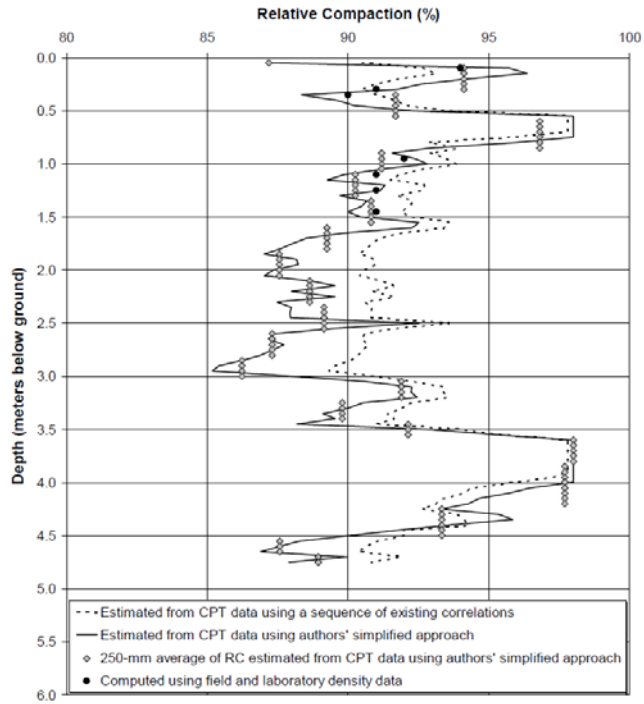


Figure 1. Relative compaction estimated from CPT data (Agrawal, Pekin & Chandra)

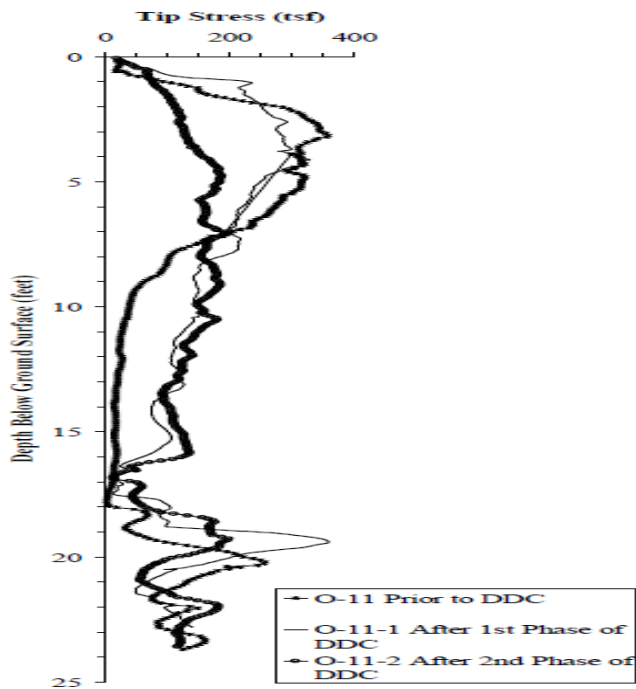


Figure 2. Comparison of cone resistance prior and after dynamic compaction (Talga Ozer at al)

### 3. PREDICTION OF SOIL PROPERTIES

Soil parameter evaluation from CPT is now a routine and established practice that may allow assessment to a large number of state parameters such as void ratio ( $e_0$ ), unit weight ( $\gamma$ ), relative density ( $D_R$ ), stress history ( $\sigma'_p$ , OCR), strength ( $c$ ,  $\phi$ ,  $S_u$ ), stiffness ( $E$ ,  $G$ ), compressibility ( $C_c$ ), consolidation coefficient ( $c_h$ ), permeability ( $k$ ), subgrade reaction coefficient ( $k_s$ ), among others. The 10 papers submitted to this conference give room to two different considerations: (a) best practice should be based on both established and locally developed correlations and (b) there are clear benefits in combining results from different testing techniques.

The majority of the papers are related to the prediction of properties on soft clay deposits. There is comprehensive literature providing the necessary background in this field from where all established correlations can be obtained (e.g. Lunne et al, 1997; Mayne et al, 2009; Schnaid, 2009; Yu, 2004). This existing background has been extensively used by the authors to predict the overconsolidation pressure, coefficient of consolidation and undrained shear strength of cohesive soils.

*Torum et al* present a comparison from CPTU and laboratory tests, emphasizing that results generally require good sample quality. Figure 3 shows the undrained shear strength interpreted from CPTU profiles and compared to laboratory anisotropically consolidated triaxial compression tests (CAU). Although some discrepancies are observed, CPTU methods provide reliable soil parameters, particularly when local correlations are developed.

Similar efforts are reported by *Farrar; Steiner; Camp et al; Sunitsakul et al* when comparing CPTU data to laboratory tests and in situ vane and dilatometer tests. In addition, *Sotil et al* report a site investigation program carried out to predict the properties of low strength, saturated, organic materials that are later adopted as input parameters in stockpile performance evaluation.

Estimation of parameters made from regression equations set against laboratory tests or other in situ tests is presented by *Ozer et al*. Table 1 summarizes the data variables and linear regression equations for normalized preconsolidation pressure. In this particular reported case, Model E prediction (Table 1) is shown to reproduce laboratory CRS measured values. *Liao et al* extend these views when comparing predicted values of  $\sigma'_p$  with those calculated from overburden pressure before a deep excavation at Lake Michigan, USA. Scatter in this site is attributed to the fissured nature of the clay where standard expressions based on  $q_t$ ,  $u_2$  and  $G_0$  may not be applicable.

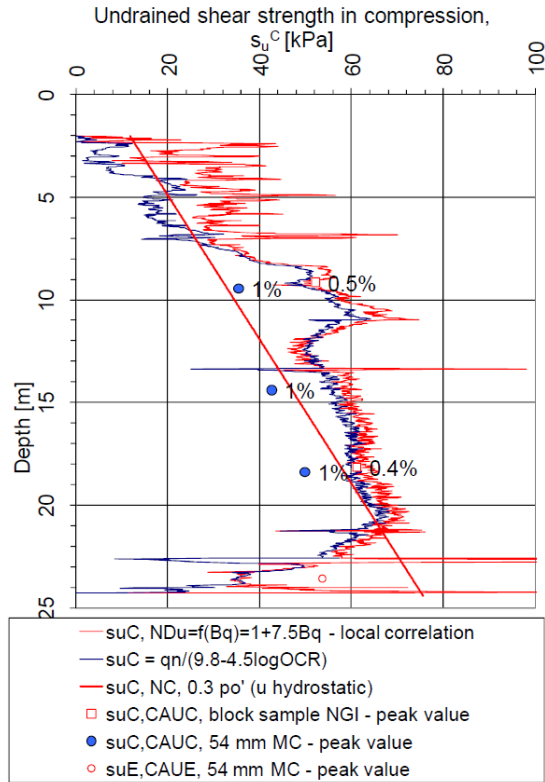


Figure 3. Interpretation of undrained shear strength in quick clay (*Torum et al*)

Table 1. Linear regression for normalized preconsolidation pressure (*Ozer et al*)

Data Set	Independent Variables	$R^2$ (%)	Equation (From the model given in Equation 1, and regression output by using Microsoft EXCEL, the linear regression can be back transformed to):
A	$(\sigma_{vo}/P_a)$	87.5	$\frac{\sigma'_p}{P_a} = 0.932 \left( \frac{\sigma_{vo}}{P_a} \right)^{0.892}$
B	$(q_t/P_a)$	88.1	$\frac{\sigma'_p}{P_a} = 0.290 \left( \frac{q_t}{P_a} \right)^{0.863}$
C	$((q_t - \sigma_{vo})/P_a)$	82.9	$\frac{\sigma'_p}{P_a} = 0.429 \left( \frac{q_t - \sigma_{vo}}{P_a} \right)^{0.798}$
D	$(\sigma_{vo}/P_a), (q_t/P_a)$	90.8	$\frac{\sigma'_p}{P_a} = 0.478 \left( \frac{\sigma_{vo}}{P_a} \right)^{0.438} \left( \frac{q_t}{P_a} \right)^{0.469}$
E	$(\sigma_{vo}/P_a), ((q_t - \sigma_{vo})/P_a)$	90.9	$\frac{\sigma'_p}{P_a} = 0.632 \left( \frac{\sigma_{vo}}{P_a} \right)^{0.565} \left( \frac{q_t - \sigma_{vo}}{P_a} \right)^{0.342}$
F	$(q_t/P_a), ((q_t - \sigma_{vo})/P_a)$	90.4	$\frac{\sigma'_p}{P_a} = 0.192 \left( \frac{q_t}{P_a} \right)^{1.953} \left( \frac{q_t - \sigma_{vo}}{P_a} \right)^{-1.046}$
G	$(\sigma_{vo}/P_a), (q_t/P_a), \text{ and } ((q_t - \sigma_{vo})/P_a)$	90.7	$\frac{\sigma'_p}{P_a} = 0.960 \left( \frac{\sigma_{vo}}{P_a} \right)^{0.756} \left( \frac{q_t}{P_a} \right)^{-0.693} \left( \frac{q_t - \sigma_{vo}}{P_a} \right)^{0.842}$

*Gadeikis et al* discuss the comparison between static  $q_c$  and dynamic  $q_d$  cone penetration resistance. This type of comparison should be viewed with great caution, because the values of  $q_c$  and  $q_d$  are not a function of the same variables. In granular materials the static cone penetration is mainly a function of relative density, vertical stress and horizontal stresses, whereas the dynamic cone penetration is a function of three groups of parameters: (1) soil properties, (2) hammer mass and height of fall and (3) rod geometry (length and cross-sectional area).

The characterisation of French Loess is studied by *Karan et al*. A method developed for evaluating instability mechanisms induced by high speed trains requires fines and carbonate percentage, initial water content, dry density and CPT measurements. The major criticism is the attempt of deriving the shear wave velocity profile empirically as a function of  $q_c$  and  $f_s$ .

#### 4. FOUNDATION BEARING CAPACITY AND SETTLEMENT

Twelve papers address the theme of pile bearing capacity and settlements, comprising CPT-based bearing capacity methods, estimation of the entire load-settlement curve and prediction the driving force of piles. Finally four papers describe methods designed to predict the response of shallow foundations.

##### *Pile analysis*

Four papers describe conventional axial pile load testing and the corresponding predictions from well established CPT-based bearing capacity methods. *Pardoski* presents two CFA pile load tests carried out in silty clay soils in Canada. Pile capacity was estimated using two direct CPT methods (LCPC and Eslami-Fellenius, 1997) and two indirect methods based on CPT derived soil parameters (Coleman and Arcement, 2002; O'Neill and Reese. 1999). Overall the agreement between the predicted and measured pile capacity was good with predictions being within 20% of measured values. Similarly, *Togliani* discuss the results of a tapered precast concrete pile test in a soft lacustrine deposit overlaying a dense alluvial layer. The author approaches the problem by using a number of different methods, including his own, to conclude that CPT data can be useful in deriving realistic pile capacity predictions provided that the “right”  $q_c$  and  $f_s$  values are selected.

The two other case studies refer to the unusual conditions of residual soils where predictions have to be extrapolated to environments outside of the database to which methods were calibrated. Bored pile load tests carried out in unsaturated and collapsible porous clay are discussed by *Cunha & Stewart*. The LCPC method is shown to produce reasonable predictions of bearing capacity. *Prakoso & Hadiwardoyo* back-analyze two axial pile load tests performed in predominantly silt-clay residual soil us-

ing an axisymmetric finite element model. In the back-analysis, CPT data guided the design process with soil strength and stiffness being adjusted to match the actual pile response. Specific recommendations are given to guide future applications.

*Schneider et al* proposed a new method based on a set of correlations between axial pile resistance in compression and CPT measurements. A physical mechanism is described for end bearing and shaft resistance within the framework of bearing capacity theory and account is taken for factors such as scale effects, degree of mobilization of plug end bearing and stress distribution. A statistical analysis supports the proposed correlations, but additional research is needed to quantify the effects on the  $q_t$ -shaft friction relationship.

*Niazi et al* developed a method based on the seismic piezocone readings ( $V_s$ ,  $q_t$ ,  $f_s$ ,  $u$ ), considering that this set of measurements represent the two ends of the stress-strain-strength curve and can be used as input parameters in an approach that combines bearing capacity theory with analytical close-form elastic continuum pile solution (e.g. Randolph, 2003). Calculated pile capacities for a pile test carried out at the Grimsby research site, UK are shown in Table 2 for various methods of analysis. The proposed formulae are shown to match the load-settlement response (Figure 4).

Table 2. Calculated pile capacities from direct and indirect CPT methods (*Niazi et al*)

Method	Tip capacity, $Q_b$ (kN)	Shaft capacity, $Q_s$ (kN)	Mean unit skin friction (kPa)				
			$f_{p1}$ (0 - 0.74 m)	$f_{p2}$ (0.74 - 1.96 m)	$f_{p3}$ (1.96 - 2.96 m)	$f_{p4}$ (2.96 - 4 m)	$f_{p5}$ (4 - 12.1 m)
LCPC	264.63	711.76	12.43	13.04	35.00	35.00	34.79
Unicone	307.08	1077.6	29.27	26.40	85.9	59.58	45.79
KTRI		4875.1	11.29	13.55	448.2	473.94	199.56
Limit plasticity	299.26						
Beta		1378.33	7.30	13.53	73.3	72.68	69.36
Alpha		903.36	19.71	34.37	41.3	40.51	41.99

There are case studies that refer to the use of finite element analysis. For example, *Tolooian & Gavin* describe a procedure involved in performing FEA to model measured tip cone resistance  $q_c$  in cohesionless soils. Estimated  $q_c$  values are latter compared to end bearing resistance mobilized by model bored piles to investigate the value of the empirical reduction factor  $\alpha$ . Mohr-Coulomb and Harding Soil Models have been used in the analysis.

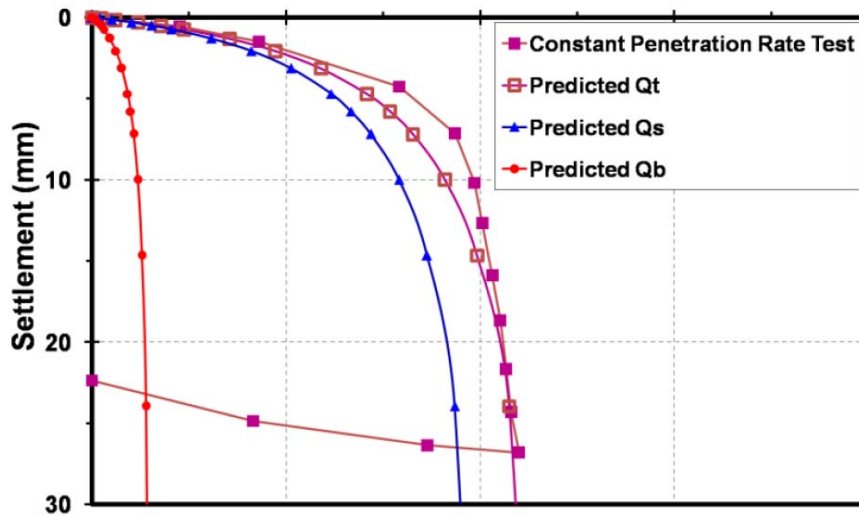


Figure 4. Comparisons between predicted and measured pile (*Niazi et al*)

Pile installation has been analyzed in two papers. Pile jacking force mobilized during installation is predicted by *Marchi et al.* Data from a well documented field study in Italy are reported, in which the short-term base resistance recorded from jacked piles installed in predominantly clayey and silty soils with local sandy layers is evaluated. Comparisons between various methods of analysis indicate that strong dependence of the  $q_b/q_t$  ratio on the grain size in each layer. *Ryzhkov & Isaev* describe a method to assess pile drivability that is supported by CPT profiles performed to reveal soil stratification. Application to marine and moraine deposits with large boulders described by the authors relies on the depths of cone refusal.

All above described methods have to take into account natural soil variability, which has to be considered on the bases of experience or from statics type of approach. *Doherty & Gavin* examine measured CPT values in a Monte Carlo simulation to determine the in situ soil variability at a dense sand site that is later used to predict the likely scatter in pile capacity. An example is given to select a suitable site for conducting pile research by demonstrating that for the case of long tension piles the expected capacities will be unaffected by soil variability.

#### *Shallow foundations*

A method conceived to predict footing response directly from CPT cone resistance in sand is introduced by *Mayne & Illingworth*. A database of 30 shallow foundations has been normalized in a plot that correlates the characteristic stress vs. square root of normalized displacement,  $(s/B)$ . When the applied stress is normalized by the cone tip resistance all footings follow a unified response, as illustrated in Figure 5. This simple approach appears to be very useful to estimate the response of isolated footings resting on homogeneous soil profiles.

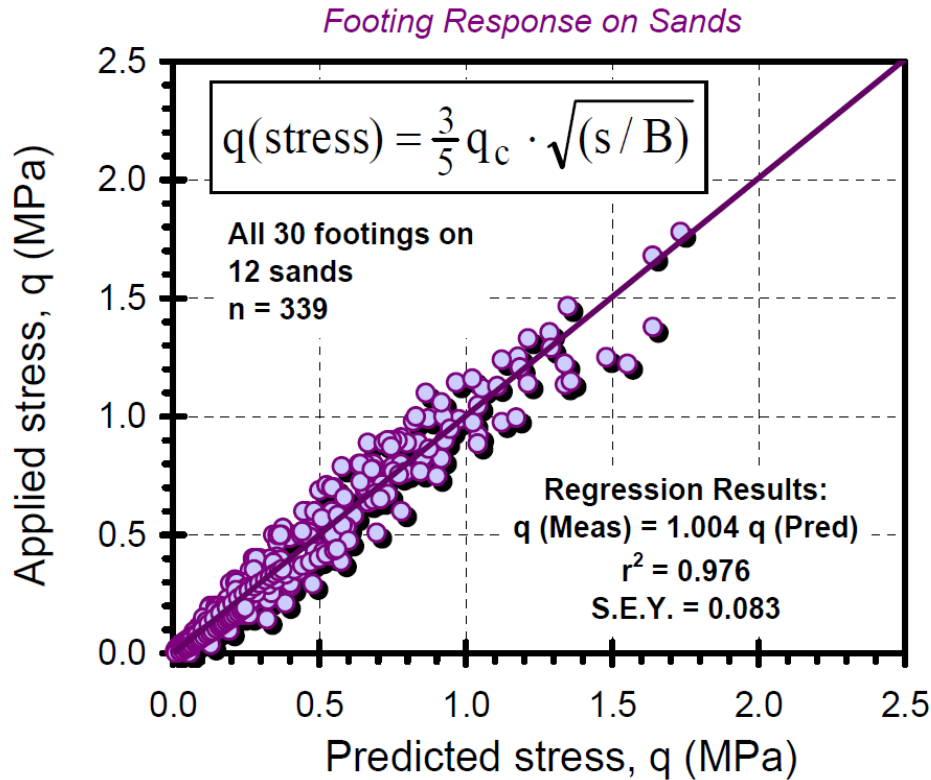


Figure 5. Applied vs. predicted stresses using a direct CPT-based approach (*Mayne & Illingworth*)

*Lee et al* examine the settlement estimation of multiples footings in sand by accounting for the interaction between adjacent foundations. 3D non-linear finite element analysis performed to obtain the load-settlement response and strain distributions in the foundation soils has been evaluated for various multiple configurations. The method is based on Schmertmann's framework where the elastic modulus of each individual layer is obtained from representative cone resistance. From the results of the numerical work the depth of the strain influence zone is shown to be a dominant parameter in settlement calculations.

Examples of the design of shallow bridge foundations are described by *Bentler et al*. Strength and stress history estimated from piezocone test are adopted in bearing capacity and settlement calculations to demonstrate feasibility of the solution.

Finally, *Reiffsteck et al* describe a new testing method - called Cone Loading Test (CLT) – conceived to estimate settlements. After a dissipation test performed with the rod unclamped, the cone is loaded in a minimum of ten successive steps lasting 60 s each, or at constant very slow speed until the full cone resistance of the soil is reached. The stress settlement curve links the pressure applied on the cone to the displacement of the top of the pushing rods. Discrepancies observed between the measured CLT and model footing test response is attributed to scale and form effects.

## 5. SOIL LIQUEFACTION

Nine papers contribute to the development of CPT-based simplified models for liquefaction evaluation. Attempts are made to extend existing experience by discussing and extending the approaches published by Wang (1979), Robertson and Wride (1998), Juang et al (2003), Moss et al (2006), Robertson (2009), among others.

*Juang et al* introduce an approach that adjusts the cyclic stress ratio (CSR) calculated by Idriss & Boulanger (2006) and determines the cyclic resistance ratio (CRR) as a function of both cone tip resistance and soil behaviour type index  $I_c$ . Values of  $I_c$  are determined on the bases of  $Q_t$  and  $B_q$  whereas the CRR model is a function of  $q_{tIN}$  and  $I_c$ . The authors state that the method is applicable to a wide range of soils including those considered “too clay-rich to liquefy” and justify the accuracy of the proposed method from an extensive database of ground failure sites (Figure 6).

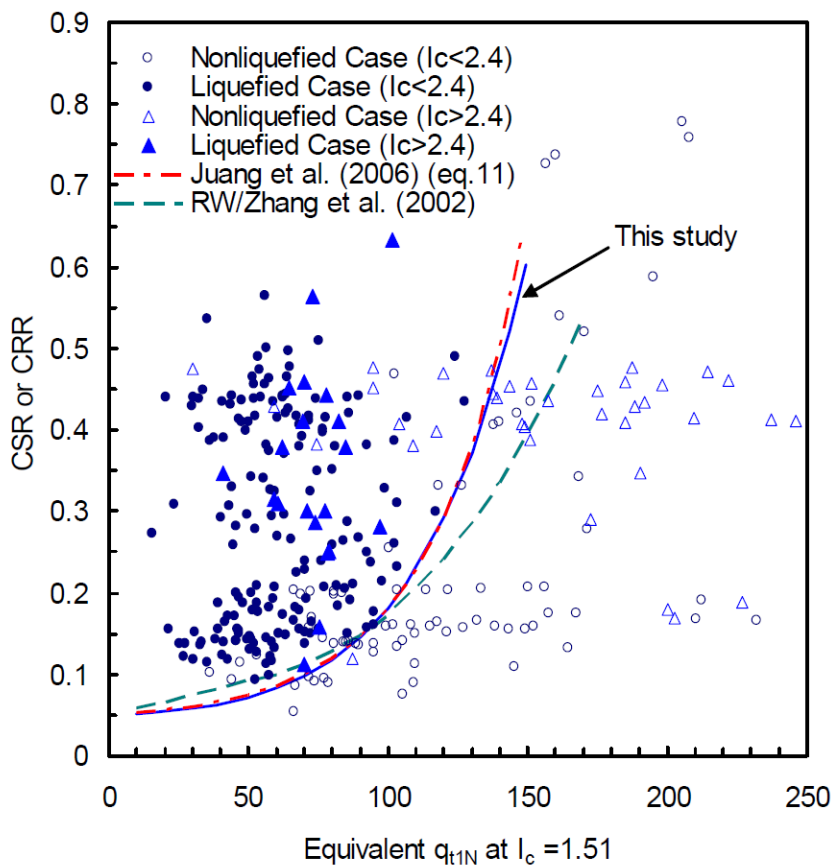


Figure 6. Boundary curve for assessment of liquefaction potential (*Juang et al*)

Another (new) relationship is presented by *Baxter et al* for non-plastic silts with fine contents greater than 95%, and is compared to CPT-based liquefaction approaches proposed by Robertson and Wride (1998) and Moss et al (2006). The work is developed on the bases of ten mini-cone calibration chamber tests conducted to deter-

mine the relationship between relative density and cone resistance. There is reasonable agreement between the new method and published correlations.

Several other authors state the need for local correlations. *Pease* discusses the uncertainty associated with CPT-based liquefaction correlations, indicating that site specific correlation is critical in cases where either CPT measurements or soil response vary. *Ozocak & Sert* alter the Iwasaki et al (1978) liquefaction potential index LPI concept by assuming a soil depth of 10m for liquefaction analysis, claiming that the corresponding increase in LPI better reproduce the hazardous effects caused by the 1999 earthquakes in Turkey.

*Pehlivan et al* discuss the need for a new framework to interpret ground failure case histories between 1994 and 1999 given the fact that low-plasticity silt-clay mixtures generated significant cyclic pore pressures and exhibited strain-softening responses. The authors proposed a pore water pressure generated model that provides liquefaction susceptibility boundary curves as a function of soil index parameters (PI, LL, w/LL) and a correlation between pore water pressure ratio and shear strains, which support an empirical correlation to cone resistance and friction ratio. Relying on pore pressure measurements, *Bol et al* identify liquefaction potential from dissipation test in fine grained soils, taking the time corresponding for 90% dissipation as reference. The authors established  $U_{90}$  of 300 seconds as a frontier between liquefiable and non-liquefiable ML silts.

Uncertainties in assessing liquefaction potential prompted the various approaches described above. These uncertainties are highlighted by *Marchetti* in a stimulating discussion that compares the sensitivity of CPT and DMT to stress history and aging in sand. *Marchetti* recalls that sand liquefaction depends on factors such as relative density, in situ  $K_0$ , stress and strains history, aging and soil structure. From a number of case studies, the author compares profiles of shear velocity  $V_s$ , dilatometer  $M_{DMT}$  and  $K_D$  and cone penetration  $q_t$  during construction stages of a Venetian embankment fill (Figure 7). From pre-construction and post-removal profiles, it can be noted that overconsolidation has a negligible effect on  $V_s$ , moderate effect on  $q_t$  and maximum effect on  $M_{DMT}$ . Since ignoring the effects of stress history and aging is equivalent to omitting important parameters controlling CRR, CPT-base correlations are disperse and local correlations might be necessary in every application.

*Unutmaz et al* address the liquefaction induced settlements beneath mat foundations from simplified procedures adopted to calculate cyclic shear stresses, and strains. The authors convert available cone profiles into SPT blow counts to compute settlements, an approach that is likely to introduce errors for reasons discussed earlier in section 2. Finally, *Yi* also attempts to evaluate seismic settlements. Attention is paid to estimation of fine contents and conversion of CPT data to SPT  $(N_1)_{60}$  due to the absence of a method to directly calculate seismic settlements from the CPT. A relationship is derived between volumetric strain, cyclic shear strain and normalized tip

resistance. Since the method is validated against SPT predictions and no measured data is available, future validation is necessary.

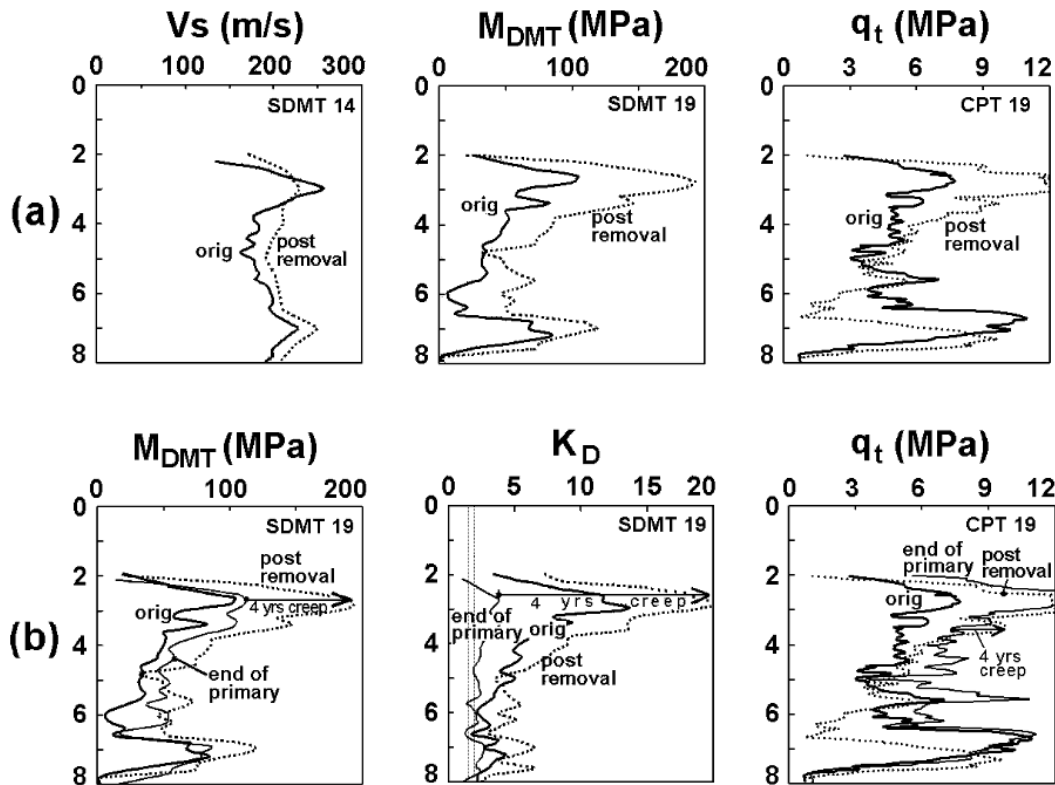


Figure 7. Profiles of shear wave velocity, dilatometer  $M_{DMT}$  and  $K_D$  and cone penetration  $q_t$  (Marchetti)

## 5. GEO-ENVIRONMENTAL INVESTIGATION

Ten papers support a wide range of geo-environmental applications, comprising the profiling capability of the piezocone in contaminated areas, applications of geo-environmental cone penetrometers and investigation of the behaviour of mineral tailings.

The profiling capability of CPTU is explored in four papers. *Jones & Taylor* inspect the in situ wall-backfill of a deep soil-bentonite barrier using CPTU. *Osborne* presents a case study combining CPT and HP (HydraulicPunch) technology for characterization of ground plume trichloroethylene (TCE). *Quinnan et al* examine the hydrostratigraphic and permeability profiling from CPT, direct push injection logging (DPIL), direct push permeameter (DPP) and electrical conductivity (EC) methods. Basic concepts are introduced through case studies such as the one illustrated in Figure 8, showing a typical profile where DPIL mirrors the pore pressure response of CPTUs. DPIL and DPP are shown to produce consistent and accurate differentiation

of low-K from high-K profiles. Finally, *Kram et al* describe the use of a recently developed high-resolution piezocone (HRP) capable of generating highly resolved hydraulic head values to measure hydraulic conductivity, while collecting critical soil type information.

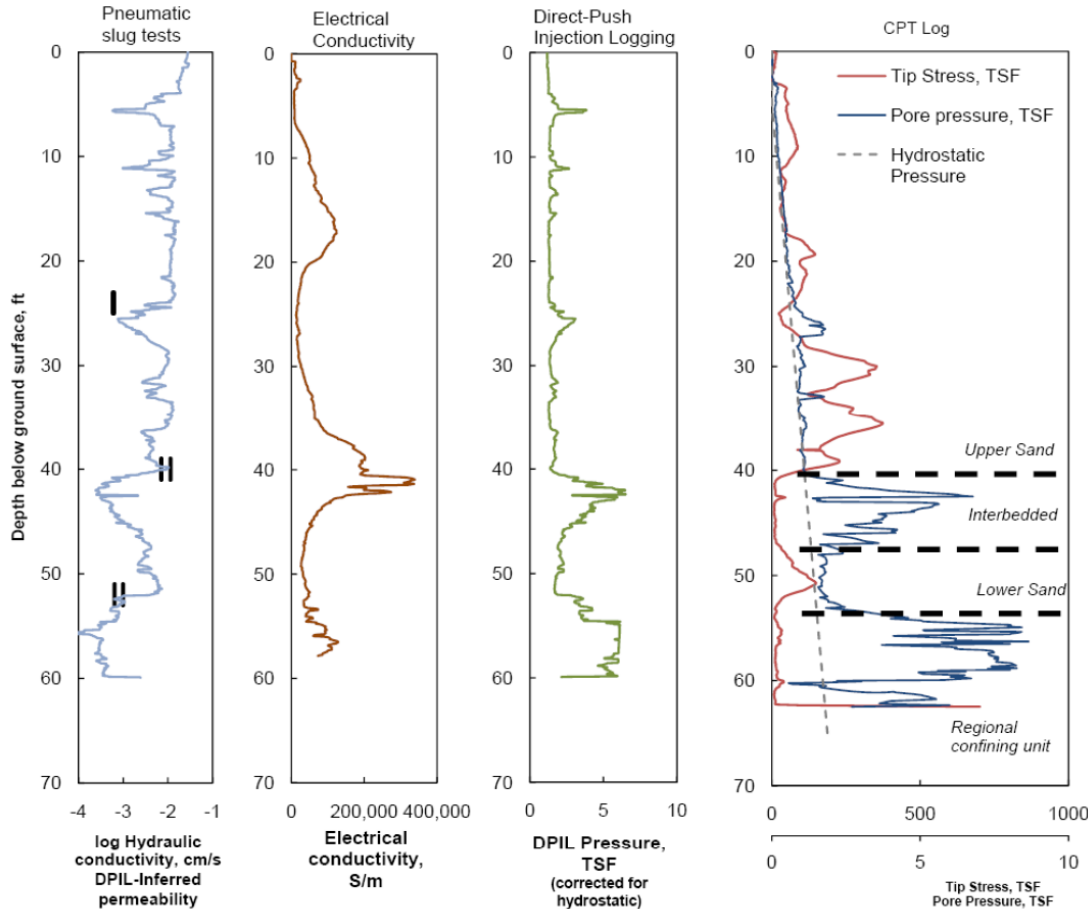


Figure 8. Case study combining slug tests, ECT, DPIL and CPT data (*Quinnan et al*)

Three papers describe environmental applications with laser induced fluorescence (LIF). *Laber* describes the use of ultra-violet optical screening technology (CPT-UVOST) to characterize multiple contaminant sources and determine the lateral extent of environmental impacts. *Patton et al* discuss the use of multiple induced fluorescence tools at a pipeline site to characterize residual LNAPL. Experience with ultraviolet induced fluorescence (UVIF) and ultraviolet optical screening tool (UVOST) is reported and 3-D representation of LNAPL body distribution is produced. *Smith & Gleason* attempt to characterize LNAPL saturation from ROST-CPT investigation. Similar to other methods, ROST measures the fluorescence emitted from hydrocarbons that have been excited by an ultraviolet light produced by a laser. It is important to notice that LIF techniques are not designed to detect or measure dissolved concentrations, but to measure re-emitted light from concentrations. Accord-

ing to the above papers, LIF enhances the logging capability of penetrometers for detecting hydrocarbon contamination because, due to poly-aromatic constituents, hydrocarbon produces fluorescence when irradiated with various forms of light.

Three other papers describe the characterization of tailing deposits. Characterization of a copper ore post-flotation deposit is discussed by *Tschuschke* in two successive papers. Analysis is essentially based on drainage and consolidation conditions that are used to estimate stress history and strength parameters. *Schnaid et al* evaluate the same problem by examining the effects of drainage that takes place during cone penetration. A series of tests under different penetration rates is presented allowing drained characteristic curves to be determined to identify the transition of drained to partial drained to undrained response. Study of tailing geo-materials is an area where further research is needed.

## 6. FINAL CONSIDERATIONS

A large number of publications provide a wide view of established recommendations, procedures and methods conceived to guide CPT applications on site characterization, prediction of soil properties, design of shallow and deep foundations, assessment of ground improvement, soil liquefaction and geo-environmental investigation. Papers submitted to this Conference cover most of these themes and allow the following considerations to be drawn:

- a) Current research efforts are placing emphasis on correlations with mechanical properties that are based on the combination of results from different sensors in a single test device, preferably combining the robustness of the cone with stiffness measurements (seismic-cone and cone-pressuremeter). Surprisingly most reported applications are concentrated on the standard cone (CPT and CPTU), with few references to the seismic-cone and no reference to the cone-pressuremeter.
- b) Best practice for assessing soil parameters comes from a combination of established and locally developed correlations. Established correlations set the ground for the order of magnitude of a given parameter whereas local correlations can fine tune this estimation to a more accurate value.
- c) In addition to empirical correlations relating CPT data to foundation performance, there are interesting approaches that (i) attempt to normalize foundation response in rational ways to take advantage of scale effects and (b) investigate pile-soil interaction mechanism using a theoretical framework that combines different methods of analysis, such as bearing capacity and cavity expansion theory.
- d) The ongoing debate related to CPT-based correlations developed for assessment of soil liquefaction is still animated. There is no consensus on how to

take full account of the combined effects of relative density, stress and strain history, aging and soil structure. New methods are reported on this subject to adjust predictions in non-plastic silt soils with large fines content.

- e) Devices and methods for geo-environmental investigation are still under improvement but the field has matured in recent years with the cone penetrometer being recognized as an useful, cost-effective technique.

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