Calibration of hybrid SCE-CSSM analytical model for piezocone penetration in clays

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ABSTRACT

Piezocone penetration test (CPTu) readings of total tip resistance (q_t), corrected sleeve friction (f_{st}), and shoulder porewater pressure (u_2) in fine-grained soils can be modeled using spherical cavity expansion (SCE) theory and critical state soil mechanics (CSSM) concepts. The predicted profiles can be fitted to the measured CPTu response using input of soil parameters: preconsolidation stress (σ_p'), total unit weight (γ_t), effective friction angle (ϕ'), rigidity index (I_R), and compressibility parameters (C_c and C_s). This paper presents application of such a formulation for CPTu representation obtainable using a hybrid SCE-CSSM model to a variety of clays sites which have been field tested by CPTu. These deposits have known profiles of γ_t, ϕ', σ_p' and compressibility parameters determined from laboratory tests, and shear stiffness (G_{max}) obtained from field measurement of shear wave velocity (V_s). Undrained shear strength (s_u) evaluated via critical-state concepts are used together with G_{max} to evaluate I_R over a range of applicable strains.

RÉSUMÉ

Les lectures de la résistance à la pointe, de la friction sur les parois du manchon de friction et de la pression d'eau interstitielle d'un essai au piézocône, peuvent être modélisées à l'aide de la théorie de l'expansion de cavité sphérique (SCE) et des concepts de mécanique des sols aux états critiques (CCSM). Les profils modélisés peuvent être comparés aux lectures prisent par le piézocône en utilisant les propriétés du sol telles que la contrainte de préconsolidation, le poids du sol en place, l'angle de friction, l'indice de rigidité, et les paramètres de compression. Cet article présente cette application avec la modélisation d'essais au piézocône obtenue en utilisant le modèle SCE-CSSM pour une grande variété d'argiles testées sur le terrain avec le piézocône. Ces dépôts ont déterminés par des essais de laboratoire. Les valeurs de rigidité ont été obtenues aussi sur le terrain par des essais au piézocône sismique. Les résistances au cisaillement en condition non drainée ont été évaluées par la théorie des états critiques et la valeur du module pour évaluer le paramètre de rigidité I_r pour une vaste étendue de niveau de déformation.

1 INTRODUCTION

Ever since the use of cone penetrometer test (CPT) in geotechnical investigations, attempts have been made to interpret different soil engineering parameters from its readings. The evolution of CPT from single parameter measuring device to the hybrid seismic piezocone tests (SCPTu), which can measure up to four different readings (q_t, f_s, u_2 and V_s), has resulted in simultaneous increases in formulation of well-established relationships based on multiple regression analyses on extensive database. A need is constantly felt for improvement of the existing correlations based on the 'ground truth' obtained through comparisons of laboratory test data with CPT readings from the continually increasing number of geotechnical test sites. An alternate approach for such improvements is a framework that utilizes fundamental soil properties to model CPTu readings. The SCE solution by Vesic (1977) together the Cambridge CSSM concepts provides for such a framework to be possibly established.

2 HYBRID SCE-CSSM CPTU MODEL

Using a SCE solution together with a CSSM representation of undrained loading for triaxial compression mode, Mayne (1991, 1993, 2007) showed that the CPTu readings of q_t, f_{st}, and u_2 could be modeled in clays. Here, the penetrometer readings can be expressed in closed-form solutions:

$$q_t = \sigma_{vo} + [(4/3)(\ln I_R + 1) + \pi/2 + 1] \cdot (M/2)(OCR/2)^\Lambda \cdot \sigma_{vo}' \quad [1]$$

$$u_2 = u_o + (4/3) \cdot (\ln I_R) \cdot (M/2) \cdot (OCR/2)^\Lambda \cdot \sigma_{vo}' + [1 - (OCR/2)^\Lambda] \cdot \sigma_{vo}' \quad [2]$$

$$f_{st} = [K_o - \{1 - (OCR/2)^\Lambda\}] \cdot \sigma_{vo}' \cdot \tan\delta' \quad [3]$$

where q_t is the total tip stress = $q_c + (1-a_n) \cdot u_2$; a_n is the net area ratio of the cone; f_{st} is the corrected sleeve friction = $f_s - b_n \cdot u_2$; b_n is the friction correction factor; I_R is the operational rigidity index = G/s_u; G is the operational shear modulus; s_u is the undrained shear strength; OCR is the overconsolidation ratio = σ_p'/σ_{vo}'; σ_p' is the preconsolidation stress; Λ is the plastic volumetric strain potential = $1 - C_s/C_c$; C_s is the swelling index; C_c is the virgin compression index; M is the frictional parameter of Cambridge q–p' space = $6\sin\phi'/(3-\sin\phi')$; ϕ' is the effective friction angle; σ_{vo}' is the effective vertical stress = $\sigma_{vo} - u_o$; σ_{vo} is the total overburden stress = $\Sigma\gamma_{ti} \cdot z_i$; u_o is the

hydrostatic porewater pressure = $\gamma_w \cdot h_w$; γ_{ti} and z_i are the total unit weight and depth of ith soil layer, respectively; h_w is the height of water; γ_w is the unit weight of water = 9.8 kN/m^3; tanδ is the interface friction $\approx 0.4 \cdot tan\phi'$ and K_o is the lateral stress coefficient = $\sigma_{ho}'/\sigma_{vo}'$.

In order to study the reliability of this model, an attempt has been made to apply it to a variety of clays sites which have been field tested by CPTu or SCPTu. These deposits have known profiles of γ_t, ϕ', σ_p' and compressibility parameters (C_s, C_c, Λ) determined from laboratory tests, and the fundamental shear stiffness (G_{max}) obtained from field measurement of shear wave velocity (V_s). The s_u evaluated via critical-state concepts is used together with G_{max} to estimate appropriate values of I_R over a range of applicable strains.

3 CASE STUDY APPLICATIONS

Data on the fundamental soil parameters from a variety of worldwide prominent sites (predominantly clay and silty clay) are used to generate full profiles of CPTu: q_t, f_{st}, and u_2. Table 1 summarizes the necessary input parameters that drive the complete SCE-CSSM analysis for each case study. These sites represent a wide variety of geomaterials: soft to stiff clay, silty clay/clayey silt, alternating clay and silty/sandy clay beds, clay with silt and sand seams, and glacial clay till. In terms of stress history, these deposits range from normally consolidated (NC) to heavily overconsolidated (OC) (OCR > 10). Accordingly, the overconsolidation difference (OCD = $\Delta\sigma_p'$ = $\sigma_p' - \sigma_{vo}'$) ranges from 25 to 900 kPa. The maximum depths of CPT soundings taken at these sites vary from 6 to 94 m. The depth to groundwater table (z_w) ranges from 0 to 6 m. The friction characteristics of soils (ϕ') vary from 23° to 40°. The characteristic value of I_R for each site was selected from the information on G_{max} and s_u. Further descriptions, reference sources, and the resulting CPTu calibrations are separately given in this paper. The remaining parameters, required for these analyses, summarized in Table 1, have been selected from the information directly given in the relevant references cited in this paper. The index properties of the geomaterials at each site are also summarized in Table 2.

3.1 Cowden, North Humberside, UK

The site at Cowden, located on the Holderness coast in UK was first established in 1976 for research and to determine parameters to be used as standard against which to evaluate a wide range of laboratory and in-situ tests. Since then, this site has been extensively used for geotechnical investigations and widely reported in multiple publications (e.g., Powell & Butcher 1991, 2003, Lunne et al. 1986, Powell et al. 1988, Atkinson et al. 1989). The site is characterized by the presence of a 25 m deep sequence of predominantly clayey glacial deposit, underlain by dissected plateau of Cretaceous chalk. The clay at this site is heavily OC in the upper layer with the degree of overconsolidation decreasing with depth. This site has been investigated by extensive cone penetrometer testing: CPT, CPTu, and SCPTu. Figure 1 shows the forward fitting of the SCE-CSSM model for typical CPTu profiles at this site, by using representative values of the required parameters summarized in Table 1.

3.2 Foothills Medical Center, Calgary, Alberta, Canada

The construction of a new Foothills Medical Center (FMC) in Calgary, AB, Canada warranted the use of drilled shaft foundations for support of building loads (Mayne and Woeller 2008). The site is underlain by thin shallow fill and sandy silt layers overlying a thick deposit of very stiff to very hard silty clay till. The site investigations program included soil borings/sampling with standard penetration testing (SPT), CPTu, and SCPTu. The SPT N-values between 25 and 65 blows/0.3 m indicate a very hard nature of the clay till bearing stratum (Kort 2005, Elbanna et al. 2007). The OCD was estimated from the SPT-N based correlation for σ_p' (after Mayne et al. 2007). The forward fitting of CPTu readings from the SCE-CSSM algorithms are presented in Figure 2.

3.3 Golden Ears Bridge, British Columbia, Canada

The Golden Ears Bridge (GEB) is a 970-m long newly constructed cable-stayed bridge over the Fraser River connecting Maple Ridge and Pitt Meadows to Langley and Surrey in BC, Canada. Extensive geotechnical testing was conducted for site characterizations on both the bridge approaches (Amini et al. 2008, Naesgaard et al. 2008). Specific details of investigation results on the north and south approaches of the GEB are given below.

3.3.1 North approach

Field investigations at this site include borings/sampling and SCPTu. The subsoils at this site consist of 12 m of soft NC silty clay/clayey silt, overlying lightly OC to OC silty clay. The G_{max} profile interpreted from V_s readings of SCPTu and γ_t represent Gibson type soil. Using representative values of the required parameters listed in Table 1, SCE-CSSM solutions yield reasonable match with the measured CPTu parameters (see Figure 3).

3.3.2 South approach

Two sets of site investigations were conducted on the south approach adjacent to the two pile load test locations, about 1600 m apart.

The soils at the head-down load test location consist of 2.5 m of gravelly sand fill over 3 m of sandy gravel, overlying lightly to OC stiff clay to the maximum depth of exploration of 50 m (Amini et al. 2008). Two SCPTu and one CPTu were conducted in the vicinity of the test pile to depths greater than 45 m. Information on s_u was obtained from the data of the standard, Nilcon and Geonor field vane tests at the site (Amini et al. 2008, and Sully 1991). Average s_u/σ_{vo}' ratio of 0.4 are found to be reasonable estimates for this site. The G_{max} profile at the site was interpreted from V_s reading of SCPTu. Using representative values of ϕ', I_R, Λ, and OCD (see Table 1). CPTu representations of SCE-CSSM expressions are shown in Figure 4.

The soil profile at the Osterberg cell load test location consists of 40 m of loose to dense sand and silty sand

over stiff NC to lightly OC clay with intermittent thin silty sandy layers to depth beyond 100 m. One SCPTu and one CPTu were conducted in the vicinity of the test pile to depths greater than 90 m. s_u/σ_{vo}' ratio of 0.23 is estimated for this site (Amini et al. 2008). Figure 5 shows comparable results of SCE-CSSM representation and measured readings of the CPTu parameters.

Table 1. Summary of the selected clay sites along with respective SCE-CSSM input parameters.

Site Name	Location	Sounding depth (m)	Predominant soil type	z_w (m)	$\Delta\sigma_p'$ (kPa)	OCR	ϕ' (deg.)	Λ	I_R
Cowden	N. Humberside, UK	26	Glacial clay till	1.0	800	3–15	27	0.9	850
FMC	Calgary, AB, Canada	30	Sandy silt layers overlying a thick deposit of very stiff to very hard silty clay till	6.0	850	3–15	32–40	0.9	100
GEB: North	Maple Ridge, BC, Canada	77	silty clay/clayey silt	2.1	60	1–4	29	0.7	600
GEB: South– I	Langley, BC, Canada	47	Stiff clay	2.1	115	1–3	28	0.80	450
GEB:South– II	Langley, BC, Canada	94	Sitly sand over clay	3.0	100	1–3	30	0.85	350
Grimsby	Waltham, UK		Glacial clay till	1.5	700	3–15	28	0.9	900
High Prairie	N. AB, Canada		Soft to stiff clay with silty sand/sand lenses	4.5	95	1–2	30	0.7	40
Sarapui clay	Rio de Janeiro, Brazil	6	Soft clay over hard silty clay	0.0	25	2-7	26	0.8	30
Amherst NGES	Univ. of Massachusetts, USA	15	Alternating layers of silt and clay	1.5	25–300	1–8	25	0.9	300
Northwestern NGES	Evanston, IL, USA	27	Sand fill over soft to medium clay over stiff clay	4.0	25–80	< 2	29–35	0.8	65
Treporti Test Site	Venice, Italy	40	Predominant silty clay, combined with sand	0.5	30	1–2	36	0.85	250
US-95 Sandcreek Byway Project	Sandpoint, ID, USA	60	Sandy/silty soil over clay with seams of sand/silt	4.0	80	1–3	27	0.8	70

Table 2. Summary of index properties at the clay sites.

Site Name	w_n (%)	PL (%)	LL (%)	PI (%)	CF (%)	Average γ_t (kN/m³)
Cowden	13 – 22	11 – 23	28 – 55	14 – 40	18 – 45	21.6
FMC	13 – 17	27	37	10	5 – 22	19.0
GEB: North	35 – 85	20 – 49	37 – 90	17 – 36	Not available	17.5
GEB: South– I	35 – 75	20 – 35	50 – 90	32 – 55	Not available	17.0
GEB: South– II	18 – 52	15 – 38	22 – 96	10 – 60	Not available	16.8
Grimsby	14 – 24	12 – 18	20 – 36	7 – 20	20 – 38	22.0
High Prairie	15 – 45	18 – 32	31 – 76	14 – 50	Not available	18.5
Sarapui clay	184	53	158	105	77	15.0
Amherst NGES	29 – 70	17 – 33	36 – 56	10 – 28	Not available	16.7
Northwestern NGES	19 – 24	14 – 21	30 – 43	10 – 24	Not available	18.5
Treporti Test Site	22 – 41	19 – 36	26 – 57	7 – 23	Not available	18.7
US-95 Sandcreek Byway Project	28 – 57	12 – 30	37 – 49	22 – 24	Not available	17.5

Note: w_n: natural water content; PL: plastic limit; LL: liquid limit; PI: plasticity index; CF: clay fraction (< 0.002 mm); γ_t: total unit weight.
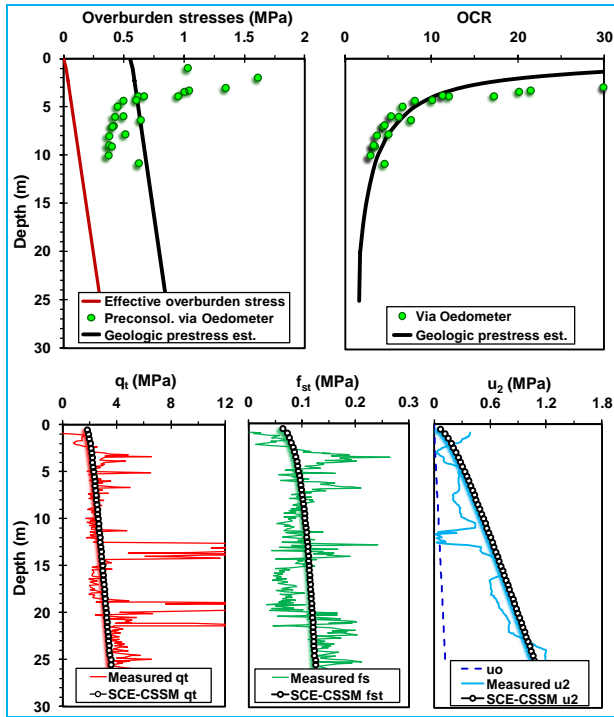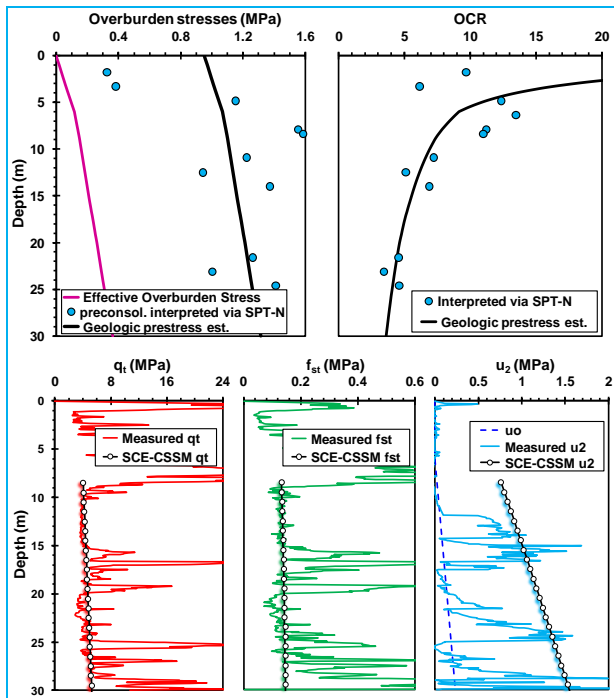
Figure 1. Fitted OCR and CPTu profiles at Cowden.

Figure 2. Fitted OCR and CPTu profiles at FMC.

3.4 Grimsby Research Site, Waltham, UK

The Grimsby research site is located near Waltham, Grimsby, UK, 900 m north of the nearest watercourse and 7.5 km southwest of the nearest coastline (Brown 2004).
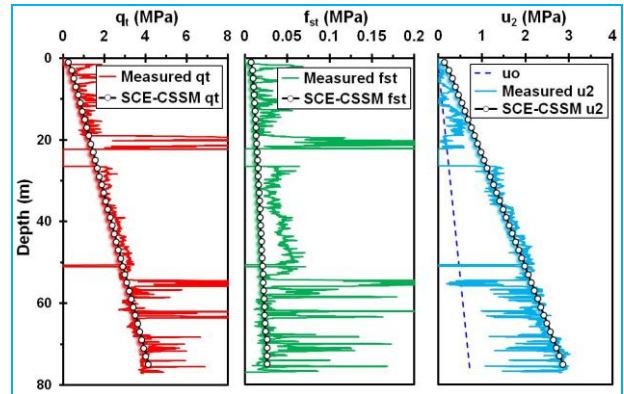

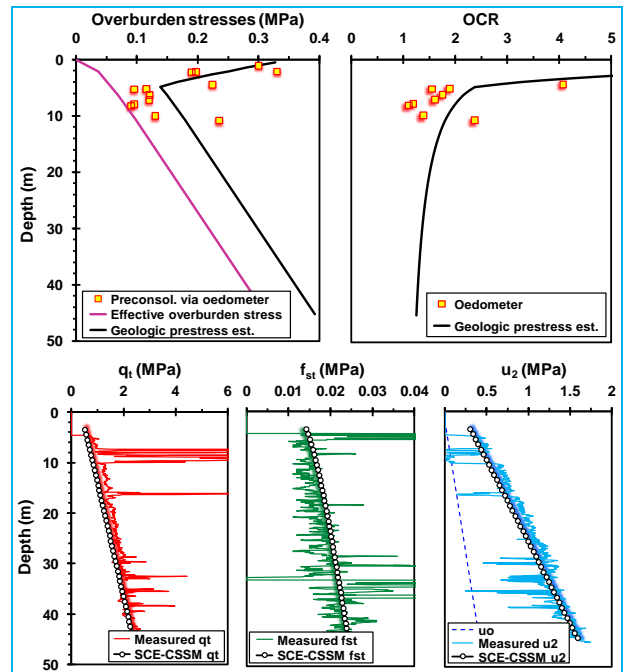Figure 3. Fitted CPTu profiles at GEB North side.
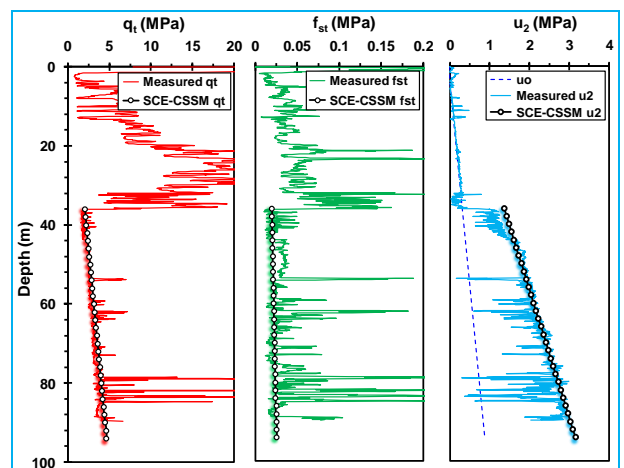

Figure 4. Fitted OCR and CPTu profiles at GEB South-I.

Figure 5. Fitted CPTu profiles at GEB South-II.

Brown et al. (2006) report the ground conditions at the site as matrix-dominant glacial clay till underlain by cretaceous chalk bedrock; till being cohesive, OC stiff to firm, grayish to dark brown, predominantly silty clay with cobbles, boulders and pebbles. In addition to the index properties presented in Table 2, specific gravity (G_s) value of 2.69 was reported for this site. Based on the information given in Brown et al. (2006) and Brown (2004), representative values of the required parameters summarized in Table 1 were adopted for SCE-CSSM representation of the CPTu readings, shown in Figure 6.

3.5 High Prairie, Alberta, Canada

At High Prairie, Alberta – a soft to firm silty clay site was used for testing two continuous flight auger (CFA) test piles (Cruz et al. 2008, Padros & Papanicolas 2008). The site is located near east end of the town High Prairie in northern Alberta above a 170 m deep buried bedrock valley. Site investigation (two SCPTu and one DMT) revealed soft to stiff, medium to high plastic clay interbedded with very loose to compact silty sand/sand lenses, extending to about 16 m and overlying a fairly homogeneous deposit of stiffer and high plastic clay to silty clay extending to the maximum depth of investigation (i.e., 25 m). Higher plasticity values have been reported for depths > 17 m. From the CSSM concepts, s_u/σ_{vo}' ratio was taken as 0.21 for top 17 m and 0.32 for the remaining depth of investigation (this matched fairly well with DMT and SCPTu interpretations). The soil at the site is OC near the crust. Between the crust and a depth of 17 m, the soil is NC. Below 17 m depth, the degree of overconsolidation increases remaining within the lightly OC range. Representative values of the required parameters (see Table 1) were adopted for SCE-CSSM representation of CPTu readings shown in Figure 7.

3.6 Sarapui clay, Rio de Janeiro, Brazil

The Sarapui clay site is located adjacent to Guanabara Bay, near Sarapui River, northeast of Rio de Janeiro in Brazil. This site was used for static and dynamic load testing of a small driven pile. As reported by Alves et al. (2009), the soil in this region consists of a gray, very soft clay deposit, overlying hard silty clay. The soft clay layer is about 5.5 – 6 m thick at the test site. This layer presents an OC crust, formed by fluctuation of the water table. The soil mass below is slightly OC (OCR between 2 and 3). The average s_u for this site has been reported as 8 kPa. The site investigations reported by Alves et al. (2009) include one CPTu, vane shear tests at multiple depths and borings/sampling. Based on the information in Alves et al. (2009), adopted values of I_R, OCD, ϕ' and Λ from Table 1 for the uppers soft clay layer yielded fairly good representation of the SCE-CSSM CPTu model at this site (see Figure 8).

3.7 National Geotechnical Experimentation Site (NGES) at University of Massachusetts, Amherst, USA

The NGES at University of Massachusetts at Amherst is located on the main university campus. It lies in the Connecticut River valley of Western Massachusetts, within the boundary of glacial Lake Hitchcock. This site has been extensively used for geotechnical investigations and the results reported (e.g. Iskander 2003, Benoit 2000, Lutenegger 2000, and Lutenegger & Miller 1993). The deposit of lacustrine origin consists of alternating layers of silt and clay. Below a 1.5 m natural surface layer of loosely compacted fill is mottled clay which extends to about 4 m. Beneath this layer lies the varved clay deposit that extends down to a depth of about 25 m, which in turn rests on granular glacial clay till. As a result of different geological mechanisms, an OC crust has developed at the test site which extends to a depth of about 5 to 6 m. The crust grades into a soft near NC clay with increasing depth (Benoit 2000 and Lutenegger 2000).

This site has been characterized by extensive CPT, CPTu, SCPTu, and 2 cm^2 mini cone penetrometer test (MCPT) (Tumay 1998). A decreasing trend of the γ_t from top to bottom has been reported at this site. Using representative values of the required parameters, SCE-CSSM forward modeling provides reasonable match with the measured CPTu parameters (see Figure 9).
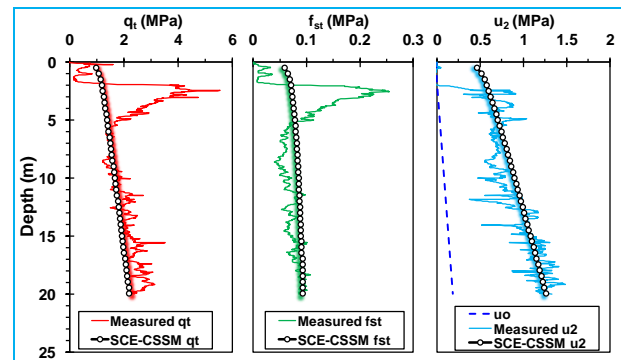

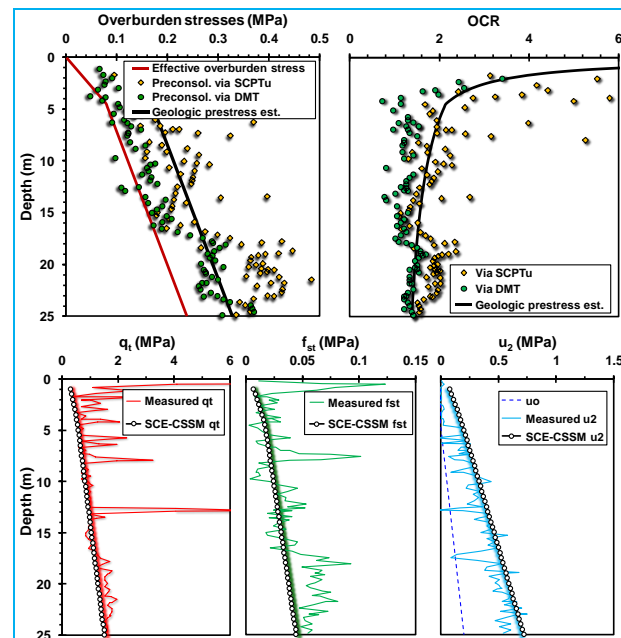Figure 6. Fitted CPTu profiles at Grimsby, UK.

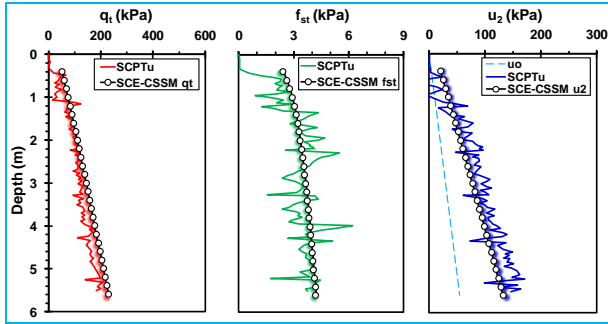Figure 7. Fitted OCR and CPTu profiles at High Prairie.
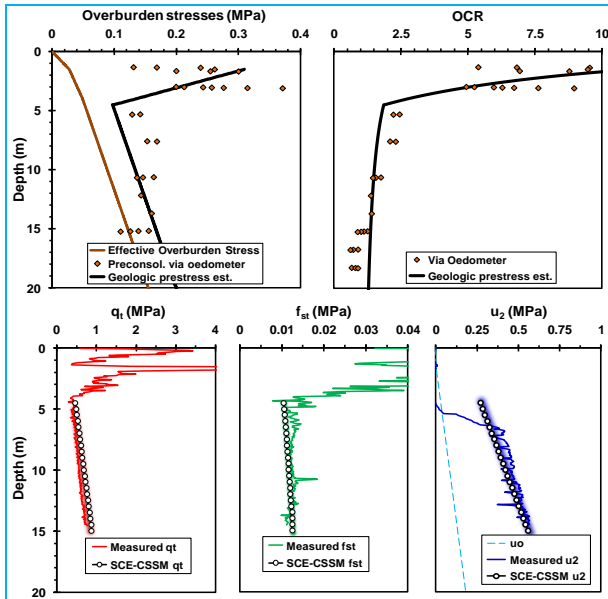
Figure 8. Fitted CPTu profiles at Sarapui clay site.

Figure 9. Fitted OCR and CPTu profiles: NGES Amherst.

3.8 NGES at Northwestern University, Illinois, USA

The lakefill site at Northwestern University in Evanston, Illinois, was the location of the pile prediction symposium held in conjunction with the 1989 Foundation Engineering Congress. It is located on the northeast corner of the campus adjacent to Lake Michigan. Results of comprehensive laboratory and field testing have been widely reported, characterizing the geotechnical properties of the soil strata at this site (e.g., Finno 1989, Finno et al. 2000, and Benoit 2000). The idealized profile at the site shows 7 m fine dense sand fill followed by 10.5 m of soft to medium clay and 6.5 m of stiff to hard gravelly clay and silt. Beneath this hard stratum, dolomite bedrock is encountered. Field investigations at this site include: soil borings with SPT, field vane, CPT, CPTu, SCPTu, Menard pressuremeter tests (PMT), dilatometer tests (DMT), and cross-hole seismic testing. Figure 10 shows the good fitting obtained for the SCE-CSSM expressions for piezocone readings by adopting the relevant values of parameters shown in Table 1.

3.9 Treporti Test Site, Venice, Italy

To protect the city of Venice and the surrounding lagoon against recurrent flooding, a huge project was undertaken, involving the design and construction of movable gates at the lagoon inlets. Comprehensive geotechnical studies were carried out to characterize the Venetian soil and achieve a suitable design of the movable gates foundations. The details of these and earlier investigations at this site have been extensively reported (e.g., Jamiolkowski et al. 2009, Cola & Simonini 2002, and Simonini 2004). One of the two main test sites, namely Treporti test site (TTS) was designed to directly measure in-situ stress-strain-time properties of the heterogeneous Venetian soils, using a vertically-walled circular embankment, loaded up to 107 kPa. The ground beneath the embankment was heavily instrumented. Boreholes with undistorted sampling, DMT, CPTu, SCPTu and SDMT were carried out to characterize the subsoil profile and estimate the soil properties. The soil profile to the depth of 55m can be summarized as heterogeneous interbedding of clay, silt, sand and mixed soil type with dominance of silty clay beneath 22 m depth. Based on the soil grading and the index properties, the geomaterials contributing to the soil profile include: sands and slightly silty sands (SM + SP) 22%, silts (ML) 32%, inorganic silty clays (CL) 37% and organic clays + peat (CH+Pt) 9%. Using representative values of the required parameters (see Table 1), SCE-CSSM expressions generated CPTu profiles shown in Figure 11.
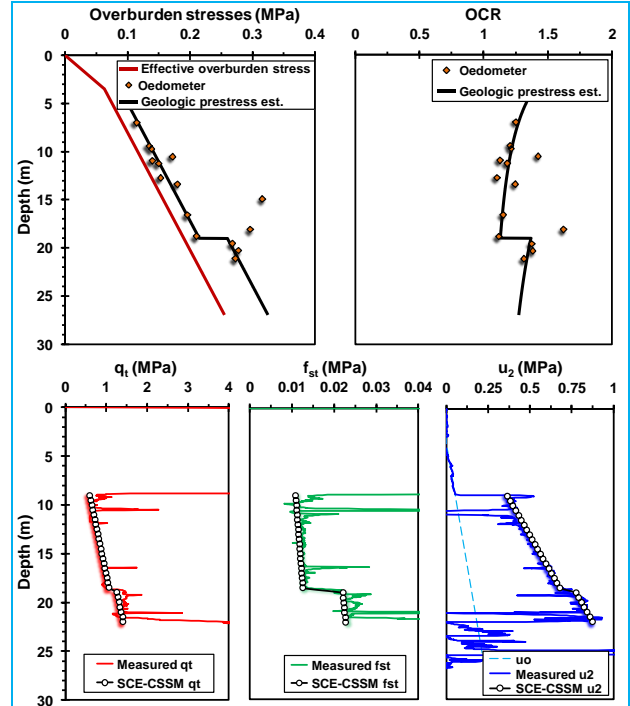

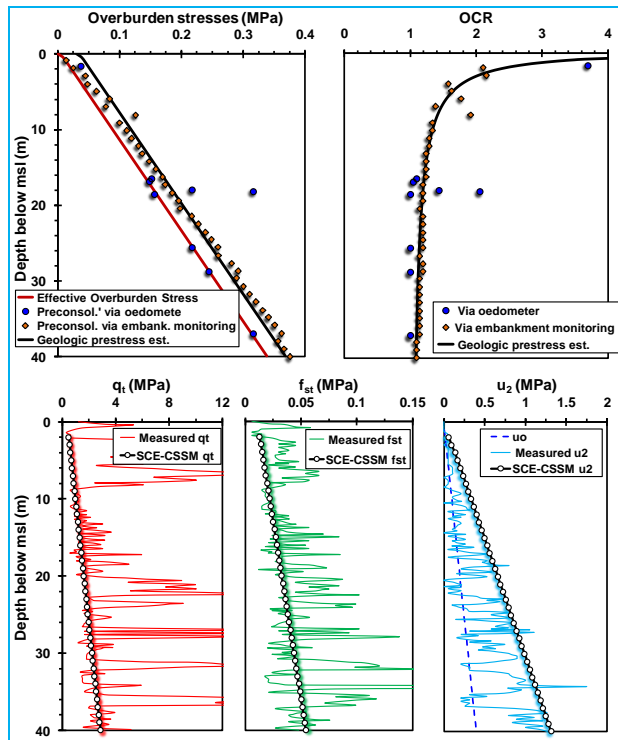Figure 10. Fitted OCR and CPTu profiles: NGES NWU.

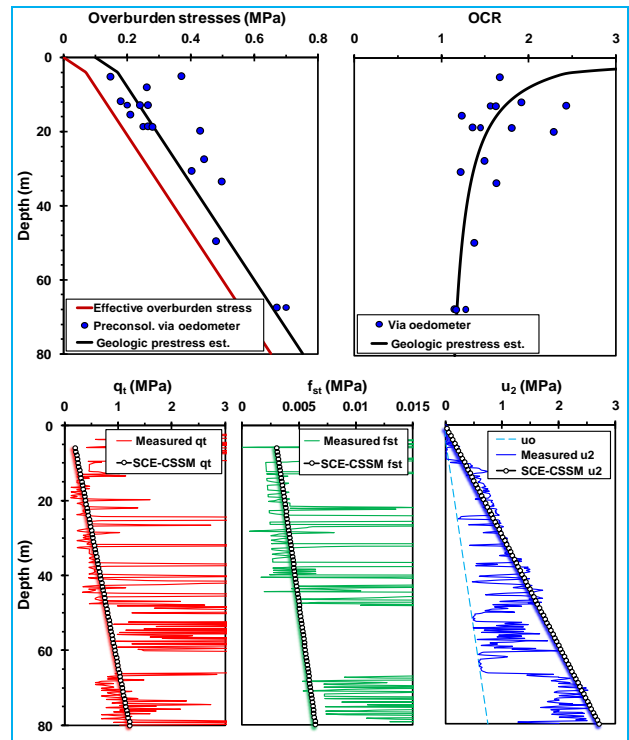Figure 11. Fitted OCR and CPTu profiles: Treporti Test Site, Venice, Italy.

Figure 12. Fitted OCR and CPTu profiles at US95 HW project, Sandpoint, Idaho, USA.

3.10 US-95 Sandcreek Byway Project, Sandpoint, Idaho, USA

To study the pile response to axial loading for a proposed bridge foundation along the realigned US-95 highway, a static loading test was conducted on a steel pipe pile in Sandpoint, Northern Idaho, along the shores of Lake Pend Oreille. Published documents (e.g., Breckenridge & Sprenke 1997, and Fellenius et al. 2004) contain details of the geology and geotechnical properties evaluated at this site. The postglacial alluvial soil consists of 9 m thick sandy/silty layer above a 40 m thick slightly OC clay layer with many sandy silt and silty sand seams. Field explorations at this site include soil borings/sampling and CPTu soundings advanced beyond the clay layer. In addition to the index properties presented in Table 2, the s_u has been reported as increasing with depth within the range of 30–70 kPa. Forecasting of CPTu readings via SCE-CSSM expressions yield fairly good match with the measured profiles in the 40 m thick clay layer (see Figure 12).

4   SUMMARY AND CONCLUSIONS

The hybrid SCE-CSSM model provides a logical framework for forecasting the CPTu profiles in clayey soils corresponding to constant volume. The concept was applied to twelve different sites with clay and silty clay as predominant geomaterials and which have been field tested using cone penetrometers. The overall results of the predictions compared to the measured CPTu response lead to the following conclusions:

4.1   This model in its present form is adequate to capture the general trend of CPTu readings in clayey soils from the well established information on the required parametric input.

4.2   The key parameters that play significant role in fitting models of CPTu readings via SCE-CSSM concept are the stress history (σ_p', OCR, OCD) and I_R (derived from G and s_u). Other parameters: γ_t, ϕ' Λ, K_o and δ' appear to have relatively lesser significance in fitting of the model.

4.3   SCE-CSSM in its current form is inadequate to model CPTu readings for mixed soil types (e.g., silty/sandy clays), where partially drained conditions dominate.

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