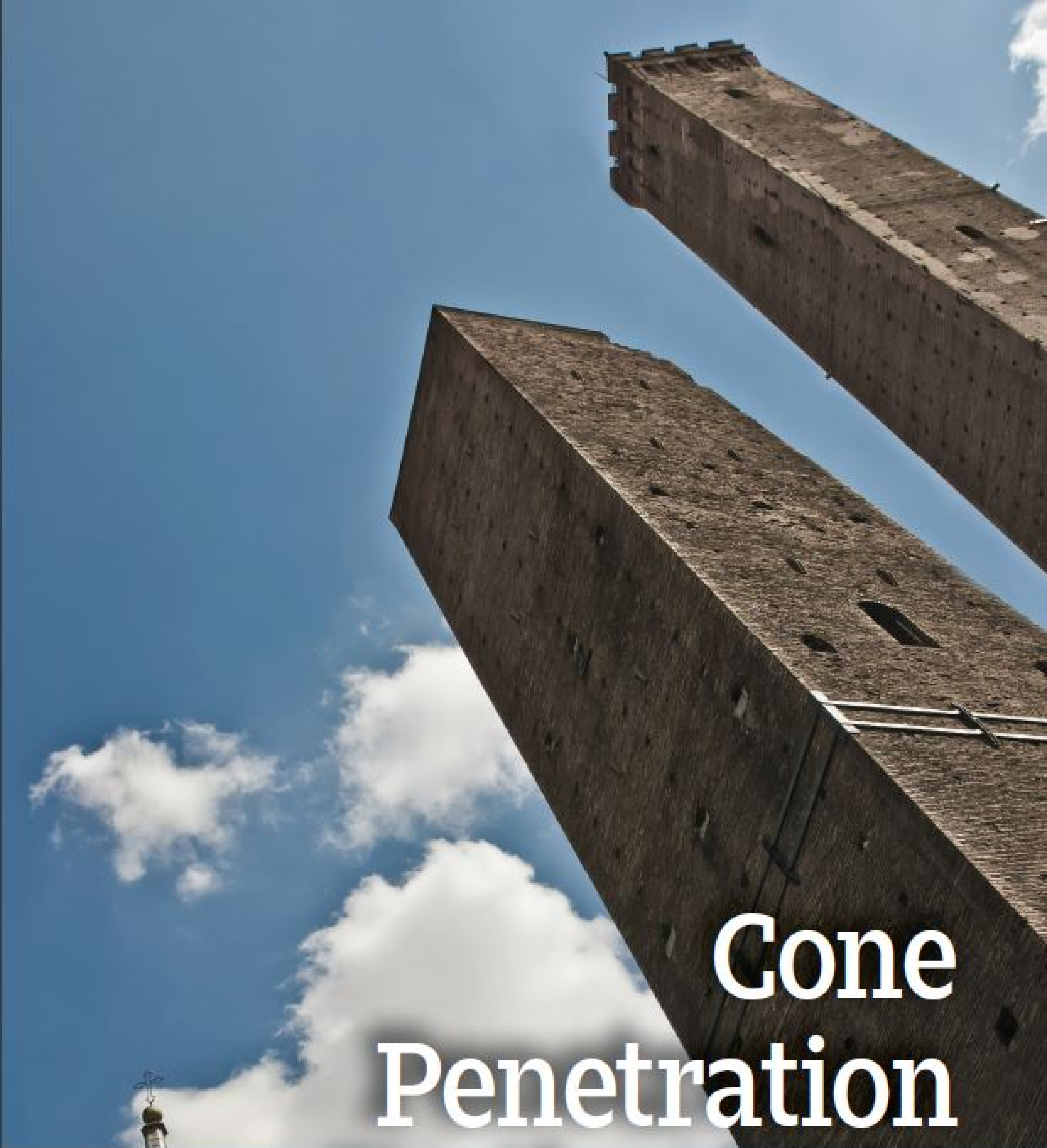

Cone Penetration Testing 2022

CRC Press
Taylor & Francis Group

Editors
Guido Gottardi & Laura Tonni

Undrained shear strength of clays from piezocone tests: a database approach

P.W. Mayne
Georgia Institute of Technology, Atlanta, GA USA

J. Peuchen
Fugro, Nootdorp, The Netherlands

Mayne, P.W. and Peuchen, J. (2022). Undrained shear strength of clays from piezocone tests: a database approach. *Proceedings, 5th Intl. Symposium on Cone Penetration Testing* (CPT'22, Bologna), Paper ID 1107: 546-551.

ABSTRACT: Deriving undrained shear strength of clays from piezocone tests (CPTU) suits the use of a database approach, particularly because good correlations are expected on the basis of theoretical correspondence. Benefits of a database approach include a minimal environmental footprint and field schedule shortening, primarily because of reduced borehole sampling and laboratory testing focused on verification rather than development of comprehensive site-specific data sets. This paper expands on the classic expression $s_u = q_{net}/N_{kt}$ where s_u is a reference undrained shear strength obtained by laboratory testing, q_{net} is the net cone resistance and N_{kt} is a cone bearing factor that is noted to decrease with increasing values of CPTU pore pressure ratio B_q. The database includes CPTU results and high-quality laboratory triaxial compression tests from 70 different clay deposits, of which 8 represent new case studies. The clays are allocated to 5 main categories: (a) soft-firm offshore; (b) soft-firm onshore; (c) soft sensitive; (d) stiff overconsolidated intact; and (e) stiff fissured clays. Organic clays and cemented clays are excluded.

1 INTRODUCTION

When a geotechnical exploration discovers that clay forms all or a portion of the subsurface environment, the magnitude of the undrained shear strength (s_u) parameter is generally sought for input into calculation models involving ground stability, particularly related to shallow foundations, pilings, and slopes. Undrained shear strength can also be important for transitional soils and sands, where combinations of geometry and loading rate can lead to undrained soil response.

Undrained shear strength is not a unique property of clays but affected by many variables, including mode of shearing, rate of loading, shear direction, initial stress state, failure criterion and other factors (Mayne 2008). This paper expands on the most common expression $s_u = q_{net}/N_{kt}$ where s_u is a reference undrained shear strength, q_{net} is net cone resistance and N_{kt} is a cone bearing factor according to classical bearing capacity theory. Values of N_{kt} can be obtained from analytical, theoretical, or numerical solutions, such as those based on limit plasticity, cavity expansion, finite elements, and strain path method. Well over 50 solutions are available for N_{kt} (e.g., Lunne, et al. 1997; Yu & Mitchell 1998; Colreavy 2016; Agaiby 2018).

Here, an empirical database approach is considered for N_{kt}. The database approach uses data from high quality piezocone penetration test (CPTU) results matched at the same elevations as high quality samples subjected to laboratory testing.

2 DATABASE PARAMETERS

2.1 *Triaxial compression tests*

The reference undrained shear strength was defined as a triaxial compression mode, designated s_{uc}:

- Derived value (Eurocode 7) of s_{uc} from laboratory tests on Class 1 samples (ISO 22475-1:2006);
- Anisotropically-consolidated undrained triaxial compression tests (CAUC or CK_0UC) according to ISO 17892-9:2018 or equivalent; Note for fissured clays, often only CIUC tests were available;
- Recompression to the estimated in-situ stress conditions, using conventional back pressures for specimen re-saturation;
- $s_{uc} = ½(\sigma_1-\sigma_3)_{max}$ defined as failure criterion or $(\sigma_1'/\sigma_3')_{max}$ as failure criterion when $(\sigma_1-\sigma_3)$ provides no distinct maximum (Ladd & DeGroot 2003; Lade 2016), where σ_1' and σ_3' are the effective principal stresses.

2.2 *Piezocone penetration tests*

For the CPTU (ISO 22476-1:2012), three separate measurements are obtained: (a) corrected cone resistance, q_t; (b) sleeve friction, f_s; and (c) pore pressure, u_2. These measurements are acquired at depth intervals of between 10 mm and 50 mm during a constant vertical push rate of 20 mm/s.

For each elevation, values of q_{net} and pore pressure ratio B_q were derived:

- $q_{net} = q_t - \sigma_{vo}$, where σ_{vo} = total vertical overburden stress;
- $B_q = \Delta u_2/q_{net}$, where $\Delta u_2 = u_2 - u_0$ and u_0 = hydrostatic pressure.

Of further note, f_s can be used to provide an evaluation of the soil unit weight (γ) needed in the calculation of σ_{vo} (Mayne et al. 2010a, 2010b; Mayne & Peuchen 2012). Consequently, all three readings (q_t, f_s, u_2) are utilized in the assessment of s_{uc} of clays.

3 TRIAXIAL - PIEZOCONE DATABASE

A total of 62 natural clays that were subjected to CAUC lab testing (n = 407) provided the initial basis for this study (Mayne 2014). The majority of clays were deposited in a marine environment, although a few were lacustrine or alluvial or deltaic in origin. A few sensitive clays were originally formed as sediments in salt-water and later exposed to leaching by freshwater.

The clay sites were classified into 5 separate groups (Mayne & Peuchen 2018), including: (a) 17 offshore clays that were normally-consolidated (NC) to lightly-overconsolidated (LOC); (b) 29 onshore clays that were also NC - LOC, (c) 6 soft sensitive clays; (d) 5 intact overconsolidated clays (OC); and (e) 5 fissured OC clays.

From the database approach, the general trend of the relationship for evaluating N_{kt} is presented in Figure 1 and Equation 1 (Mayne & Peuchen 2018), for when $B_q > -0.1$:

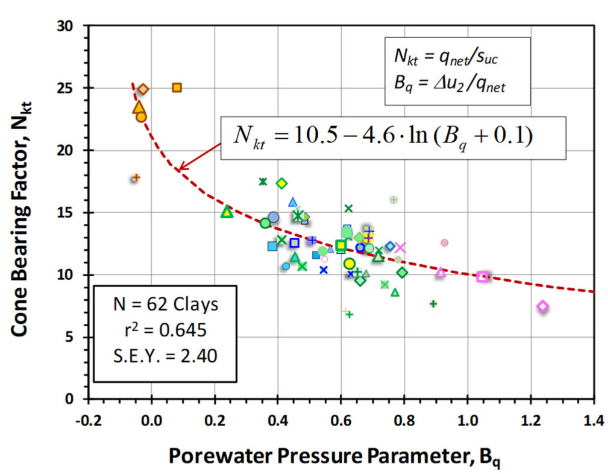

Figure 1. Trend of N_{kt} with B_q (Mayne & Peuchen 2018)

$$N_{kt} = 10.5 - 4.6 \cdot \ln_e (B_q + 0.1) \quad (1)$$

Comments are as follows:

- An advantage of this approach over many other solutions for N_{kt} is that the CPTU provides all the necessary input;
- The methodology covers a wide range of clays showing $B_q > -0.1$, including soft to firm to stiff clays which vary from sensitive to insensitive, and intact to fissured;
- The approach does not apply to organic or cemented clays.

Since the initial database findings, a number of new case studies have become available that permit a validation of Equation 1. Herein, triaxial and CPTU data from 8 clays from Europe, Asia, and North America are presented. Three sites are from offshore locations and five clays are onshore deposits.

4 NEW CASE STUDIES

4.1 *Luva, Norwegian Sea*

Luva is an offshore gas reserve located in 1300 water depth of the Norwegian sea. The site consists of very soft plastic clays having sensitivities in the range of 2 to 5. Index testing indicates a natural water content $w_n \approx 65$ % to 75 %, liquid limit $w_L \approx 70$ %, plastic limit $w_P \approx 29$ %, and plasticity index $I_p \approx 41$ % (Lunne et al. 2014). Series of consolidation tests indicate that the site has not been mechanically overconsolidated, showing yield stress ratios (YSR = σ_p'/σ_{vo}') in the general range of 1.2 to 1.7, primarily due to ageing.

Figure 2 shows q_t and u_2 with depth below the seafloor, pore pressure ratio B_q, and derived profile of s_{uc} from the N_{kt} relationship. In the last graph, the CPTU results are shown in comparison with 42 CAUC triaxial tests with good agreement.

4.2 *Sipoo, Finland*

Sipoo is located about 30 km north of Helsinki. The site consists of a homogeneous soft clay deposit between 2 and 9 m depth and water table near the surface (DiBuò et al. 2019). Index tests on the clay include: $w_n = 101 \pm 12$ %, $w_L = 79 \pm 10$ %, $w_P = 30 \pm 1$ %, $I_p = 50 \pm 9$ %, and clay fraction CF = 79 ± 11 %. Laboratory CRS consolidation tests give a mean YSR = 1.76 and sensitivity by laboratory fall cone ranges from 15 to 44 with a mean $S_t = 25 \pm 8$.

Results from a representative CPTU at Sipoo are shown in Figure 3. The CPTU-evaluated profiles of s_{uc} compare well with the four laboratory CAUC test values on high-quality samples taken from the site.

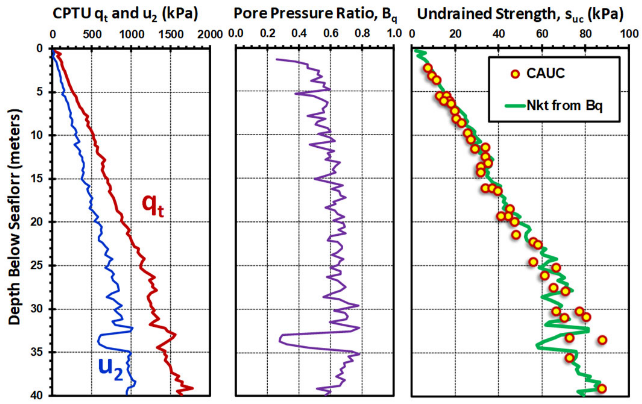

Figure 2. Profiles in clay at offshore Luva site, Norwegian Sea (data from Lunne et al. 2014)

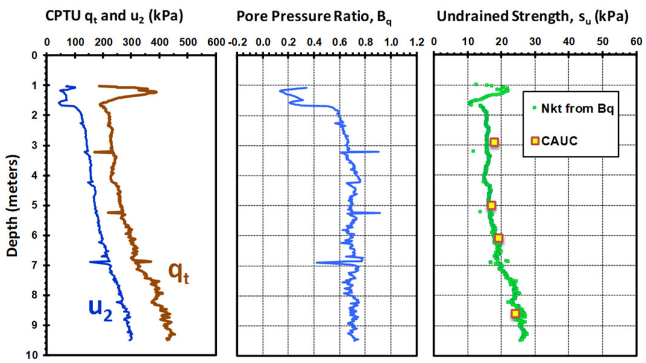

Figure 3. Profiles at Sipoo soft clay test site, Finland (data from DiBuò et al. 2019)

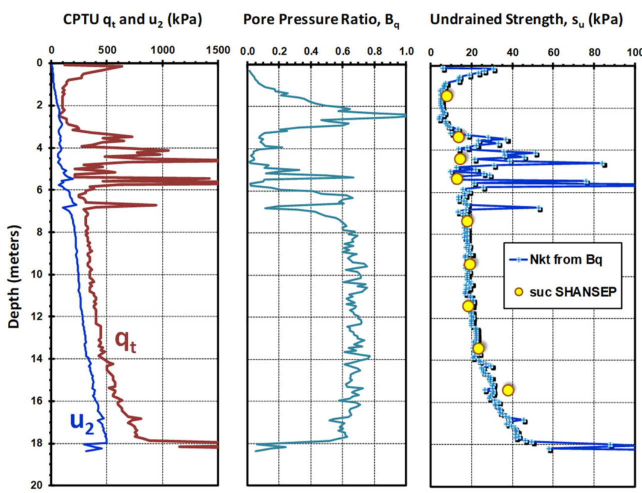

Figure 4. Profiles in soft clay at Saga, Japan (data from Hossain & Chai 2014)

4.3 Saga, Japan

The Saga TB site is located at the south of Japan next to the Ariake Sea. The upper 4 to 5 m is comprised of sandy silty clay while the underlying 12 m is a silty clay. Groundwater is encountered at a depth of 0.6 m.

Figure 4 shows profiles from a representative CPTU at the site (Hossain & Chai 2014). Nine consolidation tests on this clay indicated a mean YSR = 1.83. Mean values of laboratory index parameters include: $w_n = 107 \pm 20$ %, $w_L = 88 \pm 20$ %, $w_P = 38 \pm 4$ %, and $I_p = 54 \pm 13$ %.

Using the aforementioned consolidation data and normalized undrained strength ratios from triaxial compression tests on Saga clay reported by Samang and Miura (2005), a profile of undrained shear strength was developed using the SHANSEP method (Ladd & DeGroot 2003). Figure 4 shows the comparison of the laboratory reference profile of s_{uc} in very good agreement with the CPTU derived values.

4.4 Tiller-Flotten, Norway

Tiller-Flotten near Trondheim, Norway serves as the experimental grounds involving quick clay research (L'Heureux et al. 2019). Groundwater is subjected to drawdown so that the hydrostatic pressure is considerably lower than normal.

Figure 5 shows a representative piezocone sounding (Mayne et al. 2019). The uppermost 2.5 m of soil is interpreted as a dry/desiccated layer of stiff overconsolidated sandy clay. Beneath this crust, throughout the sounding depths up to 30 m lies a soft fine-grained soil. The clay is extremely sensitive to quick from approximately 7.5 m below the surface (sensitivity > 100). In the quick clay zone below 7 m depth, typical index parameters are $w_n = 45$ %, $w_L = 35$ %, $w_P = 20$ %, and $I_p = 15$ %, with CF ≈ 45 %.

Figure 5 shows very good agreement from the CPTU-derived s_{uc} values with those obtained from 7 benchmark CAUC series on high-quality block samples.

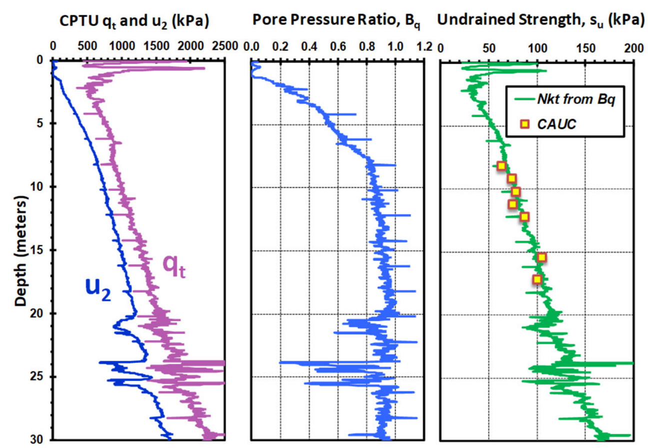

Figure 5. Profiles in highly sensitive clay at Tiller-Flotten research site, Norway (data from L'Heureux et al. 2019)

4.5 Sainte-Monique, Canada

Locat et al. (2015) detail the results of ground investigations for a major landslide involving firm to stiff sensitive nearly normally-consolidated plastic grey silty clay. The site is located some 130 km northeast of Montreal near the Nicolette River. Index tests show $56 \leq w_n \leq 77$%, $53 \leq w_L \leq 65$ %, $28 \leq I_P \leq 40$%, 72

< CF < 85%, and liquidity index $1.1 \leq LI \leq 1.4$. Sensitivities derived from fall cone indicate $39 \leq S_t \leq 55$. Laboratory consolidation tests gave YSR between 0.9 and 1.2.

Figure 6 shows the piezocone profile in an undisturbed area outside of the limits of the landslide. The high value of B_q gives a low value of N_{kt} which in turn compares well with two CAUC and three CIUC triaxial tests performed on undisturbed samples.

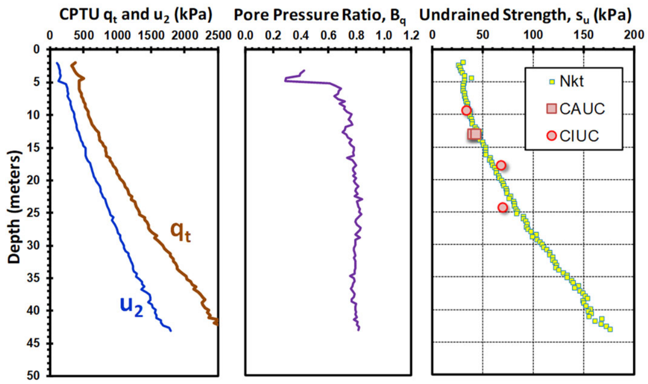

Figure 6. Profiles in sensitive clay at Sainte Monique, Quebec (data from Locat et al. 2015)

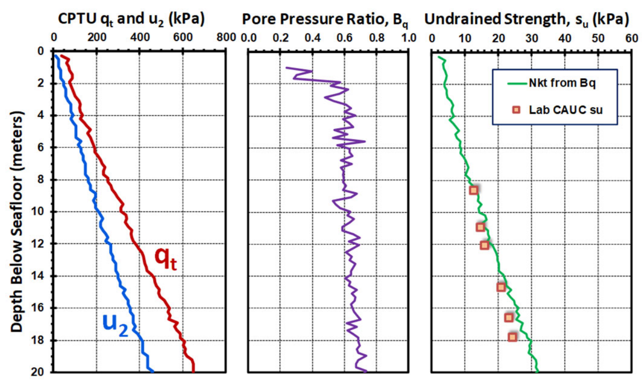

Figure 7. Profiles in soft plastic clay at Liwan offshore site, South China Sea (data from Palix et al. 2013)

4.6 *Liwan, South China Sea*

A deepwater geotechnical investigation was performed at the Liwan 3-1 offshore site in the Pearl River Mouth Basin of the South China Sea involving geophysics, sampling, piezocones, T-bars, vane, dissipation tests, and advanced laboratory testing (Palix et al. 2013). The site is underlain by soft highly-plastic clays. Liquid limits decrease from 130 % at seafloor to 80 % at 10 m below seafloor, with corresponding I_p going from 85 % to 50 % over the same depth interval. Clay fractions range between 25 to 50 %. Natural water contents vary from over 200 % at seafloor to about 90 % at 20 m depth. Measurements of calcium carbonate content range from 6 % to 25 %.

Figure 7 shows a piezocone profile and the corresponding and reasonable profiles of s_{uc} from the representative CPTU sounding and 6 CAUC triaxial tests.

4.7 *Martin's Point Bridge, United States*

A field case study with CPTU soundings in natural overconsolidated intact clays of the Presumpscot Formation is presented using data from Martin's Point Bridge, near Portland, Maine (Hardison & Landon 2015). The general stratification of the site (Figure 8) consists of a shallow organic silt layer underlain by stiff OC Presumpscot clay that extends from depths to 2 to 14 m and overlies glacial outwash sand and bedrock.

Shelby tube samples of the clay were collected at the site from different elevations and tested for index properties, consolidation parameters, and triaxial strength characteristics. The results of laboratory index testing on the clay gave an average unit weight $\gamma = 16.5$ kN/m^3, natural water contents $w_n \approx 30$ to 40 %, liquid limits in the range of $20 \leq w_L \leq 45$ %, and plasticity indices (I_p) between 10 and 20 %. Sensitivities derived from field vane and fall cone were generally in the range of 2 to 9.

The groundwater table is located at a depth of 2 m. The stress history profile was determined by a series of 13 constant-rate-of-strain (CRS) consolidation tests that showed YSRs decreasing from 11 at 2 m depth to YSR = 3 at 14 m depth.

A total of 15 CAUC triaxial tests were performed, including both recompression and SHANSEP type methods (Ladd & DeGroot 2003). The derived profile of s_{uc} from the CPTU is presented in Figure 8 with values increasing from about 35 to 100 kPa in the deposit and shown to be in reasonably good agreement with the triaxial series.

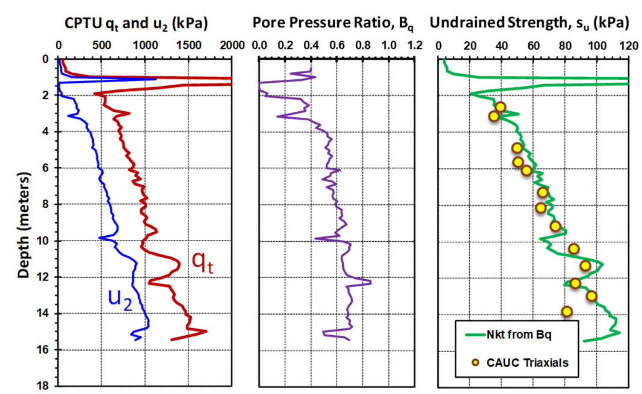

Figure 8. Profiles in firm OC clay at Martin's Point Bridge, Maine (data from Hardison & Landon 2015)

4.8 *Offshore Denmark*

This case study considers the Danish sector of the North Sea. The site has a water depth of about 45 m and includes about 3 m of Holocene sands which are underlain by hard Pleistocene age clays of the Doggerbank formation. Laboratory index tests on the clay indicate mean values: $w_n = 34$ %, $w_L = 49$ %, $I_p = 27$ % and $\gamma = 19.4$ kN/m^3. Calcium carbonate contents average 19 % for the clay. Consolidation tests indicate the clay to be overconsolidated with YSR decreasing from about 9 to 4 in the depth interval from 3 to 15 m below the seafloor.

Figure 9 shows low B_q values averaging 0.08, the N_{kt}-B_q algorithm gave a high mean value of $N_{kt} = 21$ for the clay and the corresponding profile of s_{uc} compares reasonably with the values from only two CAUC tests on undisturbed samples from the site.

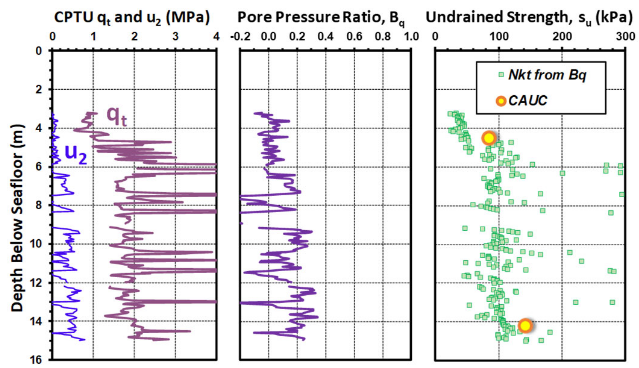

Figure 9. Profiles in stiff fissured OC Doggerbank clay at Danish offshore site.

5 CONCLUSIONS

The empirical methodology considers cone bearing factor ($N_{kt} = q_{net}/s_{uc}$) as a function of pore pressure ratio ($B_q = \Delta u_2/q_{net}$). The underlying database includes statistical analyses of 407 CAUC triaxial tests performed on 62 different clay deposits that were also field tested by CPTU.

The general trend shows N_{kt} varying from as high as 30+ for stiff fissured overconsolidated clays to low values of around 6 for soft sensitive and quick clay deposits. Generally, N_{kt} decreases with B_q.

Eight new case studies are presented showing the reasonableness and reliability of the earlier-derived methodology for assessing undrained strength of clays from piezocone penetration tests. Triaxial compression tests (CAUC, CK_0UC, and occasionally CIUC) on high-quality undisturbed samples were used as the benchmark reference tests. The final tally for the database now includes CPTU data from 70 clay sites and a total of 497 triaxial compression tests that provide the benchmark values of s_{uc}.

6 REFERENCES

Agaiby, S.S. (2018). Advancements in the interpretation of seismic piezocone tests in clays and other geomaterials. *PhD dissertation*, Civil & Environmental Engineering, Georgia Institute of Technology, Atlanta, GA: 923 p.

Colreavy, C. (2016). Use of piezoball penetrometers for measuring shear strength and consolidation characteristics of soft soil. *PhD dissertation*, Centre for Offshore Foundation Systems, Univ. of Western Australia, Perth: 304 pages.

DeGroot, D., Lunne, T. and Tjelta, T.I. (2011). Recommended best practice for geotechnical site characterization of cohesive offshore sediments. *Frontiers in Offshore Geotechnics II* (Proc. ISFOG, Perth), Taylor & Francis Group, London: 33-57.

DiBuö, B., D'Ignazio, M., Selãnpaã, J., Länsivaara, T. and Mayne, P.W. (2019). Yield stress evaluation of Finnish clays based on analytical CPTu models. *Canadian Geotech. Jour.* 57 (11): 1623 - 1638; doi.org/10.1139/cgj-2019-0427.

Hardison, M.A. and Landon, M.L. (2015). Correlation of engineering parameters of the Presumpscot formation to SCPTU. *Report No. ME 15-12*, prepared by Univ. of Maine for Maine DOT, Augusta, 394 p.

Hossain, J. and Chai, J. (2014). Estimating coef. of consolidation and hydraulic conductivity from piezocone test results. *Geomechanics and Engineering* 6 (6): 577-592.

Hong, S.J., Lee, M.J., Kim, J.J. and Lee, W.J. (2010). Evaluation of undrained shear strength of Busan clay using CPT. *Proc. 2nd Intl. Symp. on Cone Penetration Testing*, Vol. 2 (Huntington Beach, CA), Omnipress: 313-320.

ISO (International Organization for Standardization) 2012. Geotechnical investigation and testing – Field testing – Part 1: Electrical cone and piezocone penetration tests, International Standard ISO 22476-1:2012. (with technical corrigendum 1, January 2013). Geneva.

Karlsrud, K., Lunne, T. and Brattlien, K. (1996). Improved CPTU interpretations based on block samples. *Proc. Nordic Geotechnical Meeting*, Reykajavik, Paper 3.4: 195-201.

Knappett, J.A. and Craig, R.F. (2012). *Craig's Soil Mechanics, 8th Edition*, Spon Press, Taylor & Francis Group, London: 570 pages.

L'Heureux, J-S., Lindgård, A. and Emdal, A. (2019). The Tiller-Flotten research site: geotechnical characterization of a very sensitive clay deposit. *AIMS Geosciences* Volume 5, Issue 4: 831-867

Ladd, C.C. and DeGroot, D.J. (2003). Recommended practice for soft ground site characterization. *Soil & Rock America 2003*, Vol. 1 (Proc. 12 PCSMGE, MIT), Vertag Glückauf, Essen: 3-57.

Lade, P.V. (2016). *Triaxial Testing of Soils*, John Wiley & Sons, Ltd, Chichester, UK: 402 p.

Locat, A., Leroueil, S., Fortin, A., Demers, D. and Jostad, H.P. (2015). The 1994 landslide at Sainte-Monique, Quebec: geotechnical investigation. *Canadian Geotechnical Journal* 52 (4): 490-504.

Low, H.E., Lunne, T., Andersen, K.H., Sjursen, M.A., and Randolph, M.F. (2010). Estimation of intact and remoulded undrained shear strengths from penetration tests in soft clays. *Geotechnique* 60 (11): 843-859.

Lunne, T., Christoffersen, H.P. and Tjelta, T.I. (1985). Engineering use of piezocone data in North Sea clays. *Proc. ICSMFE*, Vol. 2, San Francisco, 907-912.

Lunne, T., Robertson, P.K. and Powell, J.J.M. (1997). *Cone Penetration Testing in Geotechnical Practice*, Routledge - Taylor & Francis Group, London: 352 p.

Lunne, T. (2010). The CPT in offshore soil investigations - a historic perspective. *Geomechanics & Geoengineering*, Vol. 7 (2): 75-101.

Lunne, T., Andersen, K.H. and Yang, S.L. (2014). Undrained shear strength for deep water field development in the Norwegian Sea. *Proceedings. 5th International Workshop on CPTU and DMT in soft clays and organic soils*, Polish Committee of Geotechnics, Poznan: 213-228.

Mayne, P.W. (2008). Piezocone profiling of clays for maritime site investigations. *Geotechnics in Maritime Engineering*, Vol. 1 (Proc. 11th Baltic Sea Geotechnical Conference, Gdansk), Polish Committee on Geotechnics: 333-350.

Mayne, P.W, Peuchen, J., and Bouwmeester, D. (2010a). Unit weight evaluation from CPT. *Proceedings, 2nd Intl. Symposium on Cone Penetration Testing* (CPT'10), Vol. 2, Huntington Beach, California: 169-176.

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

Mayne, P.W. and Peuchen, J. (2012). Unit weight trends with cone resistance in soft to firm clays. *Geotechnical and Geophysical Site Characterization 4*, Vol. 1 (Proc. ISC-4, Pernambuco), CRC Press, London: 903-910.

Mayne, P.W. (2014). Development of an automated methodology for evaluation of undrained shear strength of offshore clays from piezocone penetration tests. *Report 122931* by Georgia Tech Research Corp. (Project No. 2006U94) to Fugro, The Netherlands: 192 p.

Mayne, P.W., Peuchen, J. & Baltoukas, D. (2015). Piezocone evaluation of undrained strength in soft to firm offshore clays. *Frontiers in Offshore Geotechnnics III*, Vol. 2 (ISFOG, Oslo), Taylor & Francis, London: 1091-1096.

Mayne, P.W. & Peuchen, J. (2018). Evaluation of CPTU N_{kt} cone factor for undrained strength of clays. *Cone Penetration Testing 2018* (Delft), CRC: 423-429.

Mayne, P.W., Paniagua, P., L'Heureux, J-S., Lindgård, A., and Emdal, A. (2019). Analytical CPTu model for sensitive clay at Tiller-Flotten, Norway. *Proc. XVII ECSMGE*: Paper 0153, Reykjavik, Icelandic Geotechnical Society: www.issmge.org.

Palix, E., Chan, N., Yangrui, Z. and Haijin, W. (2013). Liwan 3-1: How deep water sediments from South China Sea compare with Gulf of Guinea sediments. Proceedings, Offshore Technology Conference, Houston, Texas, OTC Paper 24010, Vol 2, 1101-1108.

Paniagua, P., L'Heureux, J-S., Carroll, R., Kåsin, K. and Sjursen, M. (2017). Evaluation of sample disturbance of three Norwegian clays. Proc. Intl. Conf. on Soil Mechanics and Geotechnical Engineering, Seoul, 481-484. www.issmge.org

Powell, J.J.M. & Quarterman, R.S.T. (1988). The interpretation of cone penetration tests in clays with particular reference to rate effects. Penetration Testing 1988, Vol. 2 (Proc. ISOPT-1, Orlando), Balkema, Rotterdam: 903-909.

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

Samang, L., Miura, N. and Sakai, A. (2005). Geotechnical properties of soft cohesive lowland soils deposited in Saga Airport Highway, Japan. Media Komunikasi Teknik Sipil, Vol. 13 (3): EDISI XXXIII: 19-35

Schnaid, F. (2009). In Situ Testing in Geomechanics: The Main Tests. CRC Press, Taylor & Francis Group, London, 352 pages.

Yu, H.S. and Mitchell, J.K. (1998). Analysis of cone resistance: review of methods. Journal of Geotechnical and Geoenvironmental Engineering 124 (2): 140-149.