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Characterization and undrained shear strength of Nile delta soft deposits using peizocone

Caractérisation et dépôts mous non drainés de la force de dépouillement du delta du Nil en utilisant peizocone

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ABSTRACT
Geotechnical investigation was carried out in three sites of the Nile Delta, Egypt for major projects. The investigations used Piezocone, Field Vane, and continuous "undisturbed" sampling to establish the stratigraphy, soil properties, and natural variability. The Deltaic deposits include silty sand and inter-layered clay, organic silt and sand. The aim of this paper is of two folds. The first one is to calibrate the existing correlations to classify the Deltaic deposits using the results of Peizocone. The second fold is to address the applicability of CPTU-undrained shear strength correlations to Deltaic clay/silt deposits. An existing CPTU-undrained shear strength correlation is updated. The data in this paper, together with published data, is used to propose a new CPTU-undrained shear strength correlation for wide ranges of plasticity index using corrected Field Vane undrained shear strength of the clay.

RÉSUMÉ
L'investigation géotechnique fut exécutée dans 3 sites du Delta du Nil, Égypte pour quatre, grands projets. Les investigations ont utilisé Piezocone une girouette de campagne et des échantillons « non troublés » continus pour établir la stratigraphie, propriétés du sol et la variabilité naturelle. Les dépôts du Delta comprenant du limon de sable et de l'argile dans les couches limon organique et du sable. Le but de ce papier est double. Le premier est pour calibrer les corrélations existantes pour classifier les dépôts du Delta en utilisant les résultats de Piezocone. Le second est pour adresser l'applicabilité de CPTU des corrélations de la force de dépouillement des dépôts d'argile / limon non drainés du Delta. Une existante CPTU corrélation de la force de dépouillement non drainée est à jour. Les données dans ce papier ensembles avec les données publiées sont utilisées pour proposer un nouveau CPTU corrélation de la force de dépouillement non drainée pour de larges étendus d'index de plasticité en utilisant une girouette de campagne corrigée force de dépouille non drainée pour l'argile.

1 INTRODUCTION

Developments of gas industry and the new gas discoveries in the North sides of the Nile Delta, as well as, construction of ports along the existing Suez canal bypass east to Nile Delta motivated the need for geotechnical investigation and characterization of the deposits in the area for the purpose of design and construction of major projects. Three of these investigations (Hight et al. 2000 and Hamza et al. 2002 & 2003) are used in this paper. The investigations used Piezocone, Field Vane, and continuous "undisturbed"/disturbed sampling to establish the stratigraphy, soil properties, and natural variability. Extensive Nile Delta deposits present at the site and extend to depths from 30 to 60 m below ground level. The Deltaic deposits include sand to silty sand, clay, organic silt, and transition layer of inter-bedded thin sub-layers of sand, silt, clay and mixtures.

The present paper compares the results of piezocone penetration test with penetration-induced porewater pressure measurement (CPTU) with the information and results obtained from side by side boreholes. This comparison is focusing on two aspects. The first one is to examine the existing piezocone based soil classification correlations by Robertson (1990). The second aspect is to calculate the cone factor, N_{kt} , based on the undrained shear strength measured using Field Vane test. The cone factors are used to examine and update the existing correlations to estimate undrained shear strength using CPTU records.

2 SITES STUDIED

Site A is located West of the Nile Delta, while sites B and C are located East of the Nile Delta. The three sites are close to the Mediterranean coast. Site B is located west of Port Said and is adjacent to the inland salt Lake Manzala. Site C is located East of Port Said on the Sinai Peninsula east of existing Suez Canal Bypass. The three sites are located within the earliest recognized deltaic system, which is the Nile Delta system, where the Holocene delta sediments began accumulating with the rise in sea level at the end of the last glaciations. Figure 1 shows the stratigraphy at the three sites. The Holocene normally to slightly overconsolidated Deltaic deposits tend to thicken moving from west to east, with a major similarity of a silty sand to sand layer underlain by alternating layers of silt/sand/clay over clay. The alternating layers tend to be clear and relatively thick at the west site. While they tend to be thin at the east sites.

The following sections provide the detailed site stratigraphy of the deltaic deposits only as determined on the basis of the CPTU records and borehole logs. Figures 2 and 3 show the variation of liquid limit w_l, plastic limit w_p, natural water content w_n, and the undrained shear strength using field vane test su(FV) with elevation in the three sites. Figures 4 to 6 show typical CPTU record in the three sites.

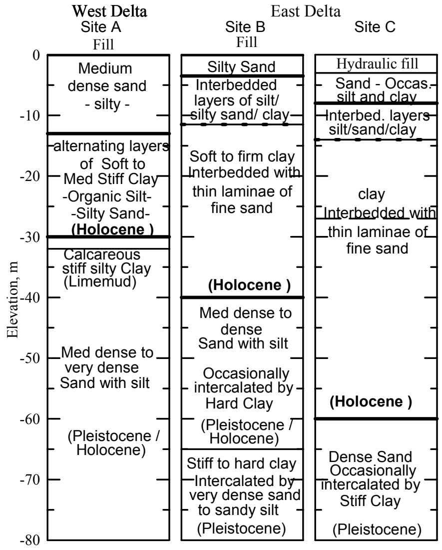


Figure 1. Simplified geotechnical profiles at the three sites

2.1 *Site A*

The sand in the top layer is medium dense poorly graded silty sand (10-14m thick). Few thin laminae of stiff fat clay and soft sandy clay are recorded in the lower part of the layer. Under the sand layer, there is a layer that consists of repeated alternating sequence includes; a) dark gray soft to medium stiff high plasticity clay (3 to 10m), b) high compressibility organic silt layer (0-3m), and c) medium dense to dense poorly graded fine to medium calcareous silty sand layer with clay lumps (1-12m). Shell fragments and traces of mica may be found along the entire deltaic deposit. If it exists, the elevation at which the organic silt may exist varies from one locality to another. Therefore, the results in Fig. 2 are plotted at the elevations where clay or silt layers are encountered.

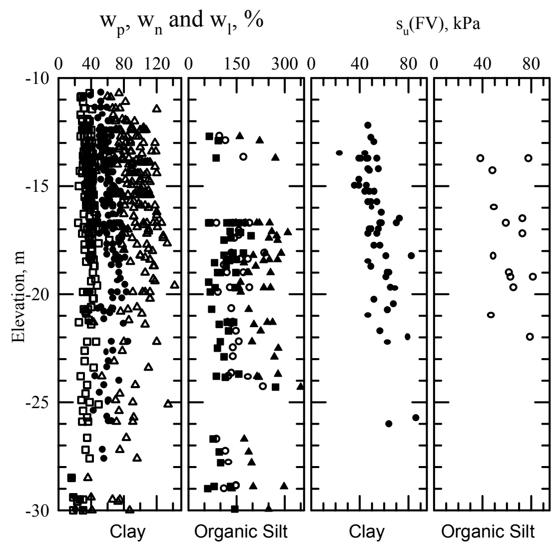


Figure 2. Index properties and undrained shear strength in site A

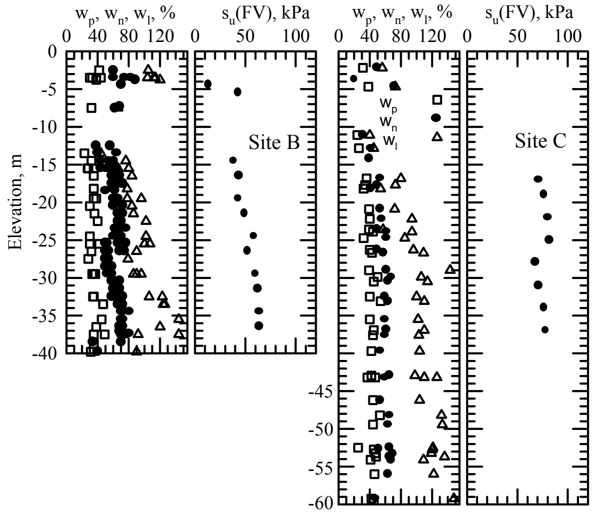


Figure 3. Index properties and undrained shear strength in sites B and C.

2.2 *Site B*

The top sand layer is loose to medium dense, poorly graded, silty fine sand (2-5 m) with few shell fragments and traces of mica. The sand layer is underlain by a transition layer (3-11m) that comprises inter-bedded loose silt, silty to very silty sand and soft clay. The transition layer is underlain by dark grey soft to firm high plasticity clay (24-32m). The clay is micaceous calcareous with few shell fragments. It is inter-bedded with thin laminae of fine sand. In similarity to Site A, shell fragments and traces of mica may be found along the entire deltaic deposit.

2.3 *Site C*

The top hydraulic fill layer (3 to 5m) is underlain by slightly micaceous medium dense to dense sand layer with broken shells layer (5 to 6m). Silt and clay may be occasionally found in this layer. The sand layer overlies a transition layer (5 to 7m), which includes inter-bedded sandy silts, clayey slits and clay sublayers. The transition layer is underlain by plastic organic clay (10 to 16m) with possible crust at the top. Occasional sand and silt seams may be encountered in the layer. The plastic layer is underlain by very plastic organic clay (24 and 35m). The organic clay may be described as fissured.

3 CPTU, CHARTS, AND SOIL CLASSIFICATION

The CPTU tests in the three sites were performed using a 20-ton nominal capacity machine with penetration rate of 2 cm/sec. Electric cones with tip area of 10 cm^2 and with 100 MPa maximum capacity were used to carry out the test. Records were made at 2 cm intervals. At each depth, cone resistance (q_c), inclination and side friction (f_s) were measured. Penetration induced pore water pressures were measured behind the cone (u_2) when CPTU was carried out.

After a series of CPT based soil classification charts in the literature, Robertson (1990) provided CPT and CPTU based soil classification charts that are global to be used as a guide to define soil behavior type. Occasionally, judgment is required to correctly classify the soil behavior type, as soils may fall within different zones (Lunne at al. 1997). Robertson charts are examined in this paper. The CPT base chart relies on the normalized cone resistance (Q_t) and the normalized friction ratio (F_r), while the CPTU based chart relies on Q_t and pore pressure ratio (B_q).

The three quantities are calculated using the expressions shown on the charts in Fig. 7. The corrected cone resistance (q_t) that is used to calculate Q_t is calculated using the expression

$$q_t = q_c + (1 - \alpha)\ u_2 \qquad (1)$$

where α is the net area ratio of the cone.

According to the description in section 2 and considering the sub-layers that are thicker than or equal to 1 m, the Nile deltaic soils may be divided to four categories; a) sand: sand/silty sand in the top layer or within the alternating sequence or transition layers, b) clay in the bottom layers or within the alternating sequence or transition layers, c) organic silt within the alternating sequence in site A and d) mixture: of sandy/silty/clayey sand/silt/clay in thin sub-layers within the transition layers.

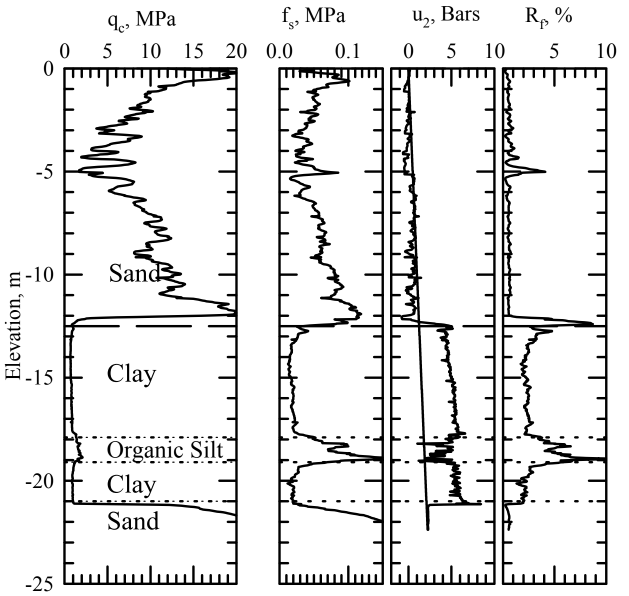


Figure 4. Typical CPTU record in site A.

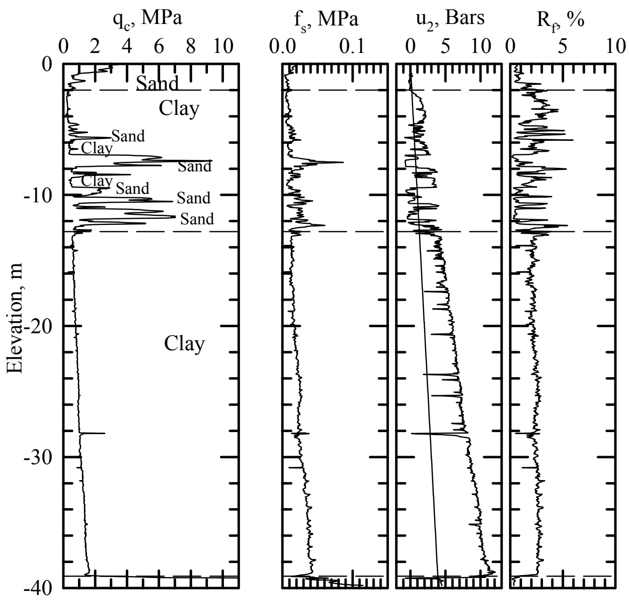


Figure 5. Typical CPTU record in site B

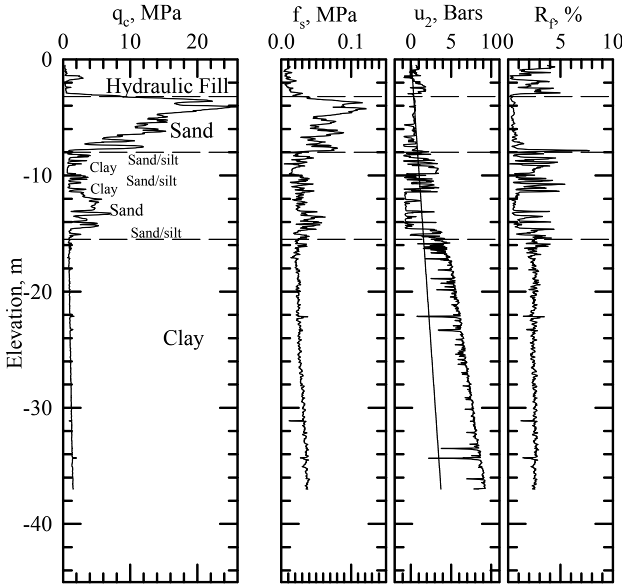


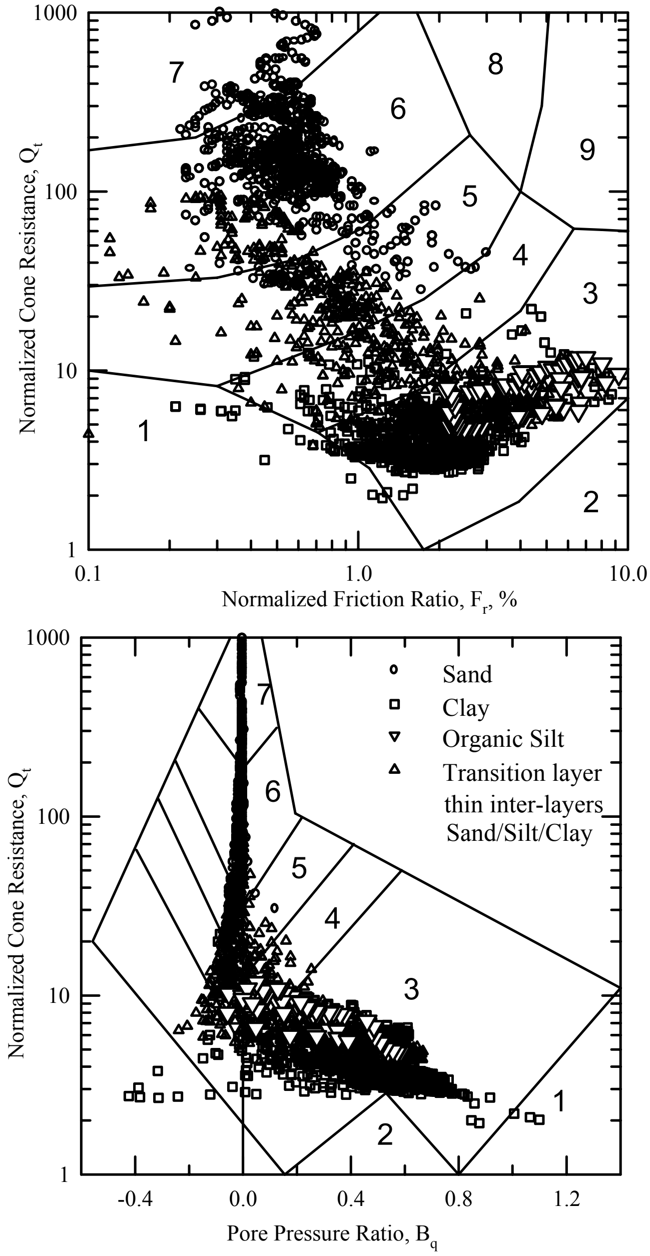
Figure 6. Typical CPTU record in site C

The Robertson charts (Fig. 7) suggest that the soil behavior types of the above-mentioned four soil categories would be predicted as; a) sand: (5, 6 and/or 7), b) clay: (3 and/or 4), c) organic silt: (2 if not then 4) and d) mixture: (3, 4, 5 and/or 6). Typical CPTU profile from each site are plotted on the Robertson charts (Fig. 7). Each soil of the four categories is designated with a different symbol. Examining the plotted data on Fig. 7, there is a very good to excellent agreement between the prediction of the charts and the classification based on bore holes information. However, the organic silt is not well predicted by the charts. The organic silt data are plotted on zones clay(3) and clay-silt(3-4) on the CPT and CPTU charts, respectively. The organic nature of the soil is missed. The organic nature of the silt could be recognized during the investigation by comparing/calibrating the bore hole information, the behavior of the field CPTU record, and published behavior of CPTU record in similar material by Vos (1982) and Lunne et al. (1997).

4 UNDRAINED SHEAR STRENGTH

Figures 2 and 3 show s_u(FV) of the clays with elevations in the three sites. In general, the values of s_u(FV) tend to increase with depth. The undrained shear strength is measured in the sites by other laboratory means. However, emphasis is given in this paper to the shear strength measured using field vane.

The undrained shear strength, s_u, depends on mode of shear or failure, soil anisotropy, sample disturbance, and strain rate effect (Terzaghi et al. 1996). The measured s_u, therefore, should be corrected before it is used for design. The s_u mobilized at failure in the field, s_u(mob), may be estimated by multiplying s_u(FV) by a correction factor μ. That factor was obtained by comparing s_u(FV) and s_u(mob) back-calculated form records of failures in the field. The correction is dependent on the plasticity of the clay (Bjerrum 1973, and Terzaghi et al. 1996). The measured s_u in the laboratory could be also corrected to obtain design values (Mesri 1989). The next section of the paper, however, is focusing on using the corrected field vane measurement, $\mu.s_u$(FV).



$$Q_t = \frac{q_t - \sigma_{vo}}{\sigma'_{vo}} \quad F_t = \frac{f_s}{q_t - \sigma_{vo}} \times 100\% \quad B_q = \frac{u_2 - u_o}{q_t - \sigma_{vo}}$$

1. Sensitive, fine grained
2. Organic soils – peats
3. Clays-clay to silty clay
4. Silt mixtures; clayey silt to silty clay
5. Sand mixtures; silty sand to sandy silt
6. Sands; clean to silty sands
7. Gravelly sand to sand
8. Very stiff sand to clayey sand
9. Very stiff fine grained

(after Robertson, 1990)

Figure 7 CPTU classification chart – Soils from all the sites.

5 UNDRAINED SHEAR STRENGTH FROM CPTU

One of the available empirical approaches for interpretation of s_u from CPTU records (Lunne et al. 1997) is the one based on correlating q_t (equ. 1) to s_u measured by one method or corrected to mobilized values. Therefore, the type of s_u interpreted from a certain correlation is dependent on the reference s_u used in the correlation. Therefore, s_u(Test) is estimated from CPTU results using the following equation:

$$s_u(\text{Test}) = \frac{q_t - \sigma_{vo}}{N_{KT}(\text{Test})} \qquad (2)$$

where σ_{vo} is the total vertical stress, and N_{kt}(Test) is an empirical cone factor.

Aas et al. (1986) reported a correlation between N_{kt}(Corrected FV) and plasticity index based on 9 Norwegian Clays. The correlation suggests that N_{kt}(Corrected FV) increases with the increase in plasticity index for normally consolidated to slightly overconsolidated clays. Aas et al. (1986) reasoned this correlation to the influence of strain rate.

The results of field vane tests are used together with CPTU records from the three sites to calculate values of N_{kt}(Corrected FV) for the Nile Delta Clay deposit. The values of N_{kt}(Corrected FV) are plotted on the correlation suggested by Aas et al. (1986) in Fig. 8. Plotted also on Fig. 8, are N_{kt}(Corrected FV) values calculated for three Canadian clays (La Rochelle et al., 1988). It should be noted that the existing data are for clays with plasticity index lower than 45%. The Nile Delta clay data updated the correlation to plasticity index of about 80%. The data in this paper, together with data on Norwegian and Canadian clays, are within a relatively narrow range. Therefore, N_{kt}(Corrected FV) may be estimated from plasticity index using the updated correlation in Fig. 8.

6 SUMMARY AND CONCLUSIONS

The data accumulated from three comprehensive geotechnical investigations for major projects on Nile Delta deposits are used in this paper. The sites are from both the west and east sides of the Nile delta. The investigations included results of Piezocone, Field Vane tests and continuous "undisturbed"/disturbed sampling to establish the stratigraphy, soil properties, and natural variability.

Extensive Nile Delta deposits present at the sites and extend to depths from 30 to 60 m below ground level. The Holocene Deltaic deposits tend to thicken moving from west to east, with a common trend a sand to silty sand layer underlain by alternating sequence of layers of organic silt/sand/clay on the west side of the delta. The alternating sequence changes on the east side of the delta to thinner transition zones with thin sub-layers of sand/silt/clay that could be sandy/silty/clayey. On the east side of the delta, the transition zone is underlain by thick clay layer.

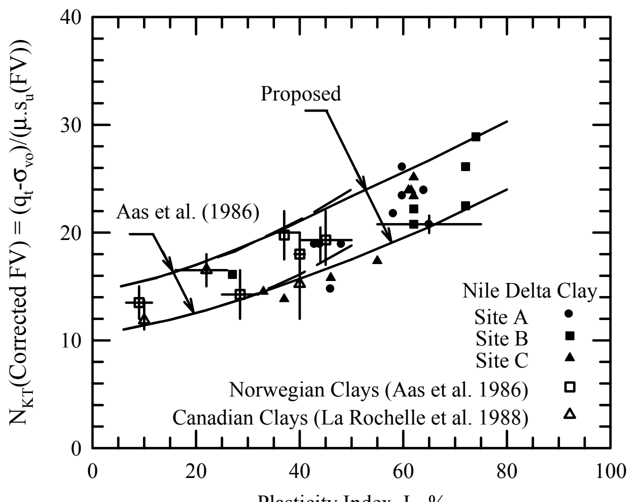


Figure 8. Cone factor N_{kt}(Corrected FV) versus plasticity index

The Robertson (1990) CPT and CPTU based soil classification charts are examined. With the exception for organic silt, there is a very good to excellent agreement between the prediction of the charts and the classification based on bore holes information for Nile delta deposits.

The undrained shear strength from Field Vane tests of the Nile delta clay in this paper, together with data of Norwegian and Canadian clays, are used to provide an updated-new correlation between N_{kt}(Corrected FV) and plasticity index, for normally to slightly overconsolidated clays. The correlation may be used to estimate corrected s_u(FV) from CPTU results.

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