Effective Stress Shear Strength Parameters From Piezocone

M. Hamza
Faculty of Engineering, Suez Canal University & Chairman of Hamza Associates, Egypt

M. Shahien
Faculty of Engineering, Tanta University, Egypt

ABSTRACT
Effective stress shear strength parameters for cohesive soils are important parameters in geotechnical analysis and design. These parameters can be determined by carrying out consolidated undrained tests with porewater pressure measurements. Those parameters can be also determined based on interpretation of piezocone penetration tests. The current state of the art status had not reached to a level where reliable estimate of effective stress shear strength parameters can be made from the CPTU data. The aim of this paper is to provide additional data on both effective stress shear strength data measued from isotropically consolidated undrained triaxial tests and CPTU data for normally consolidated to slightly overconsolidated clay from the Nile delta deposits based on geotechnical investigations in nine major sites in Egypt. It is beleived that the addition of this data to the literature provides a better ground for improving the current state of the art of estimating effective stress shear strength parameters from the CPTU data. With such beleif, the data are used to evaluate and modify the available method(s). Such an exercise empirically contributed to judgment of angle of plastification and modification of bearing capacity factor, N_q, in the Senneset-Janbu method.

Keywords : effective stress, shear strength, piezocone, clay.

1 INTRODUCTION

Effective stress shear strength parameters for cohesive soils are important parameters in geotechnical engineering analysis and design. The parameters are useful in carrying out both long term and/or short term analyses. The short term analysis, however, requires estimation of shearing induced excess porewater pressure. Such an estimation can be done empirically with different degrees of success.

Effective stress shear strength parameters can be determined by carrying out consolidated undrained tests with porewater pressure measurements. Those parameters can be also determined based on interpretation of piezocone penetration tests

This paper aims to provide additional data on both effective stress shear strength data measued from isotropically consolidated undrained triaxial tests and CPTU data for normally consolidated to slightly overconsolidated clay from the Nile delta deposits. The authors beleive that the addition of the data to the literature provides a better ground for improving the current state of the art of estimating effective stress shear strength parameters from the CPTU data. With such beleif, the data are used to evaluate and modify the available method(s).

2 EFFECTIVE STRESS SHEAR STRENGTH

Effective stress shear strength parameters can be determined by carrying out consolidated undrained tests with porewater pressure measurements. The consolidated undrained tests could be isotropically or K_o consolidated undrained trixial or direct simple shear tests with porewater pressure measurements. The triaxial test could be either in compression or extention modes.

The Mohr-Coulomb failure envelop of normally consolidated or slightly overconsolidated young clays at yield is linear with a constant friction angle ϕ'_m and zero or relatively small values of cohesion intercept. The values of maximum available friction angle, ϕ', determined by effective stress path tangency for normally consolidated young clay occurs at larger values of axial strain. Mesri and Ali (1999) reported values of ϕ'_m for Boston Blue Clay in the K_o triaxial compression test 4-5^o lower than that in isotropically consolidated triaxial compression. Values of ϕ'_m measured for the same clay in triaxial compression tests are 3^o and 8^o less than those in isotropic and Ko triaxial extension, respectively.

3 INTERPRETATION OF PIEZOCONE DATA

Effective stress shear strength parameters can be also determined based on interpretation of piezocone penetration test. Method of interpretation was originally established by Janbu and Senneset (1974) to be applicable in both cohessionless and cohesive soils. The method was further illustrated by Senneset et al. (1982) with no verification with field and laboratory measurements. The method relies on the simple approach for analyzing the cone resistance utilizing the traditional bearing capacity expression. The method was further developed by Senneset et al. (1988) utilizing the same approach leading to the following bearing capacity formula in terms of effective overburden pressure, σ'_{vo},:

$$q_t - \sigma_{vo} = N_m(\sigma'_{vo} + a)$$

where
q_c= measured cone resistance
q_t= corrected cone resistance = $q_c+(1-\alpha)u_2$
α= area ratio of the cone
σ_{vo}=total overburden pressure

$$N_m = \frac{N_q - 1}{1 + N_u B_q}$$

$$B_q = \frac{u_x - u_o}{q_t - \sigma_{vo}}$$

u_o=insitu pore pressure
u_x=penetration induced pore pressure measure by the cone, it can be u_2 or u_1
u_1=penetration induced pore pressure measured at the head of the cone
u_2=penetration induced pore pressure measured behind the cone
N_u = bearing capacity factor = 6 $\tan\phi'(1+\tan\phi')$
N_q = bearing capacity factor to be calculated

$$N_q = \tan^2\left(45 + \frac{\phi'}{2}\right)e^{(\pi - 2\beta)\tan\phi'}$$

β = angle of plastification
a = soil attraction

Proceedings of the 17th International Conference on Soil Mechanics and Geotechnical Engineering
M. Hamza et al. (Eds.)

doi:10.3233/978-1-60750-031-5-3451

Sandven et al. (1988) suggested that angle of plastification, β, to be chosen from tentative suggested narrow ranges based on type of soil. On the other hand, Lunne et al. (1997) stated that angle of plastification and bearing capacity factor were associated with large degrees of uncertainities.

The expression for computing bearing capacity factor N_q is valid for plane strain conditions, the method suggests no correction for a cylindrical cone (Lunne et al., 1985).

Another aspect that is not addressed by the method is the location of measurement of the penetration-induced excess porewater pressure. Such measurement is dependent on the location wether at the head of the cone or behind the head (Campanella and Robertson, 1988).

Additional difficulty can be added to the approach is that the mode of undrained shear around the cone head does correspond to single mode of shear but rather complex behavior (Keaveny and Mitchell, 1986).

Keaveny and Mitchell (1986) suggested an alternative approach to estimate effective strength shear strength paprameters from piezocone results. The approach utilizes the Vesic's cavity expanssion method to estimate su, combined with empirical correlations to estimate OCR and A_f. Such combination provides an estimate of effective stress shear strength parameters. The semi-empirical approach by Keaveny and Mitchel (1986) is reported to provide good results for silts and overconsolidated clays. However, poor results are reported for normally consolidated clay.

Campanella and Robertson (1988) stated that current status at the time had not reached a level where a reliable estimate of "drained" shear strength parameters can be made from "undrained" CPTU data. The authors beleive that this statement still valid till the current status even for the estimation of effective stress shear strength parameters from the CPTU data.

4 AIM OF THE PAPER

This paper aims to provide additional data on both effective stress shear strength data measued from isotropically consolidated undrained triaxiala tests and CPTU data for normally consolidated to slightly overconsolidated clay form the Nile delta deposits. The authors beleive that the addition of the data to the literature provides a better ground for improving the current state of the art of estimation effective stress shear strength parameters from the CPTU data. With such beleif, the data are used to evaluate the mentioned available method(s). Such an exercise empirically contributed to judgment of angle of plastification and modification of bearing capacity factor, N_q.

5 SITES INVESTIGATED

Comprehensive geotechnical investigation campaigns were carried out in nine sites of major projects along the north coast of Egypt. The nine sites provide full coverage of the Nile Delta deposits starting from Idku at west of the Nile Delta, to Metobus within the Nile Delta, to Damietta, to El-Gamil and Port Said further east of the Nile Delta. Three of these sites were reported in Hight et al. (2000), Hamza et al. (2002), (2003) and (2005). The stratifications in the nine sites are shown in Figures 1a, 1b and 1c.

The statification of the Nile Delta from the nine sites consists of silty sand top layer over very soft to medium stiff clay layer over sand over stiff to hard clay. The thickness of the soft clay layer to tends to thicken in moving from west to east of the delta (Hamza et al., 2005).

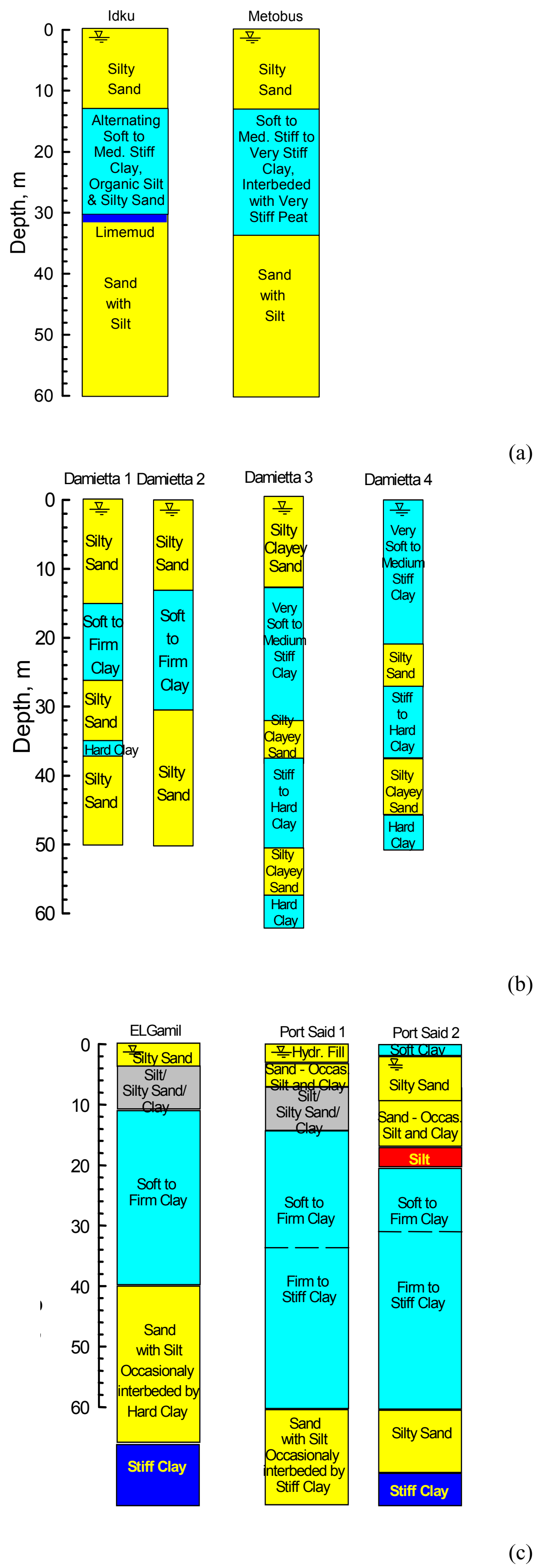

Figure 1. Stratigraphy of the soil formations in the nine sites.

Table (1) shows summary of the ranges of of the physical and index properties, effective stress shear strength parameters and CPTU data for the soft to medium clay in the nine sites.

Table 1. Physical and index properties, effective stress friction angle, overconsolidation ratio and CPTU data. .

Site		Depth, m	No. of Samples	No. of tests	w_o, %	γ_b, kN/m^3	w_l, %	Ip, %
Idku	mir	14.7	5	12	56	14.8	78	43
	ma:	19.1			74	16.1	106	68
Metobus	mir	13.2	3	7	47	16.3	54	26
	ma:	25.5			54	16.8	95	61
Damietta	mir	17	3	6	60	14.7	74	41
	ma:	27.2			69	16.1	90	52
Damietta	mir	15.7	3	6	43	15.9	74	40
	ma:	22.7			63	16.7	85	48
Damietta	mir	13.2	16	48	44	15.5	67	37
	ma:	30.7			69	17.3	123	77
Damietta	mir	17.7	3	9	57	15.5	68	43
	ma:	19.7			66	16.1	101	63
El-Gamil	mir	13.7	10	24	41	14.7	44	21
	ma:	36.7			73	16.8	125	82
Port Said	mir	19.4	10	13	53	14.9	80	44
	ma:	57.0			65	16.4	150	91
Port Said	mir	20.7	10	29	41	15.1	60	31
	ma:	56.7			69	17.1	133	90

Site		$\sigma'_{3c}/\sigma'_{vo}$	ϕ', o	σ'_{vo}, kPa	OCR	q_c, MPa	q_t, MPa	Bq
Idku	mir	1	13.8	113	1.2	0.77	0.91	0.5
	ma:	4	27.3	168	1.5	0.93	1.1	0.62
Metobus	mir	1	19.8	133	1	0.6	0.7	0.56
	ma:	3	23.8	209	1.1	0.7	0.8	0.73
Damietta	mir	0.8	18.5	150	1.0	0.75	0.85	0.50
	ma:	2	23.5	240	1.1	1.15	1.3	0.77
Damietta	mir	0.7	18.5	150	1.00	0.85	1	0.5
	ma:	1.6	29.8	200	1.25	0.9		0.6
Damietta	mir	0.82	13	123	1.24	0.59	0.71	0.3
	ma:	3.25	24.6	253	1.74	1.44	1.63	1.1
Damietta	mir	1	15.8	120	1.0	0.5	0.6	0.7
	ma:	3.5	23	150	1.1	0.6	0.7	0.73
El-Gamil	mir	0.73	18.2	92	1.0	0.7	0.81	0.4
	ma:	3	29.5	229	1.9	1.44	1.67	0.87
Port Said	mir	0.79	14.9	145	1.13	0.98	1.10	0.37
	ma:	1.95	29.8	602	1.91	1.64	1.89	0.46
Port Said	mir	0.67	19.7	192	1.0	1.02	1.14	0.39
	ma:	2.27	27.8	418	1.4	1.53	1.75	0.48

6 EFFECTIVE STRESS SHEAR STRENGTH DATA

Sixty three high quality tube samples were collected by means of 700mm long stainless steel thin wall Shelby tubes with cutting edge sharpened to approximately 5^o. The samples were extracted from nine sites (Table 1). The samples were extracted from depths in the range from 13.2 m to 57.0 m. The samples had water content in the range of 41% to 74 % with liquid limit in the range of 44% to 150% and plasticity index in the range of 21% to 91%. Based on Oedometer tests on undisturbed samples, the samples had overconsolidation ration in the range of 1.00 to 1.91. The samples were used to carry out 154 isotropically consolidated undrained triaxial compression tests with porewater pressure measurements. In these tests the samples were isotropically consolidated to equal all around effective stress in the range of 57 kPa to 413 kPa. This range corresponds to effective all around pressure to effective overburden pressure in the range of 0.67 to 4.00. The samples were then brought to failure in undrained condition. The shear induced excess porewater pressure at failure was in the range of 59 kPa to 303 kPa. This range corresponds to Skempton coefficient at failure, A_f, in the range of 0.52 to 0.87. The shear strength envelops of the tested samples resulted on effective stress shear strength friction angle and effective cohesion intercept in the ranges 13.5^o to 23.5^o and 0 kPa to 23.5 kPa, respectively.

It should be noted that the mentioned ranges of both effective shear strength friction angle and effective cohesion intercept are dependent of the ranges effective consolidation pressure range. It should be noted the for normally consolidated to slightly overconsolidated, clays the effective cohesion intercept is about zero and the shear strength envelop may be slightly nonlinear.

The following expression is used to estimate the effective stress shear strength friction angle assuming a zero effective cohesion intercept:

$$\phi = \sin^{-1}\left(\frac{\sigma'_{1f} - \sigma'_{3f}}{\sigma'_{1f} + \sigma'_{3f}}\right)$$

where

σ'_{3f}=effective equal all around pressure at failure

σ'_{1f}=effective axial stress at failure

The resulting secant effective stress friction angle was in the range of 12.8^o to 30^o. The average effective stress friction angle for each every strength envelop was calculated in the range of 12.8^o to 28.5^o. The resulting range of secant effective friction angle and the average effective tress friction angle were plote versus plasticity index in Figure (2). Shown also on the same figure is the empirical relationship between the drained friction angle and plasticity index after Terzaghi et al. (1996). It should be noted that the main reason for the plot is to file the effective stress friction angle data in the graph and to compare between the data and the drained friction angle. It is interesting to note that there is a rough correlation between effective stress friction angle and plasticity index with considerable scatter. The comparison with the drained friction angle leads to the conclusion that the drained friction angle is a rough upper bound estimate for the effective stress friction angle.

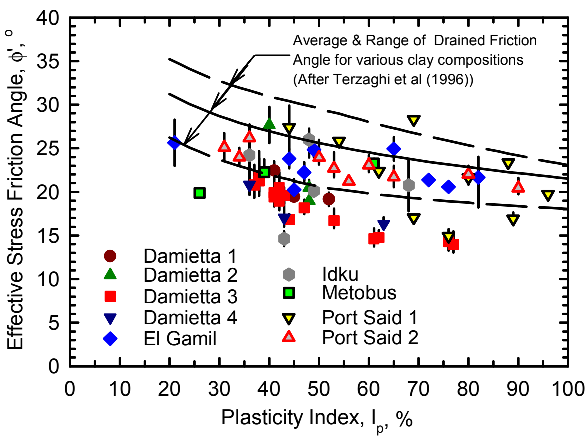

Figure 2. Effective stress friction angle of Nile Delta Deposits versus plasticity index.

7 PIEZOCONE PENETRATION DATA

Piezocone Cone Penetration Tests with measurement of penetration induced pore water pressure (CPTU) were carried out in the above mentioned nine sites by means of a 15-cm2 piezocone with the porous stone located behind the cone tip base (u_2). The measured records of piezocone data were noted from profiles that were located as close as possible to boreholes and depths from which undisturbed samples were extracted for triaxial testing to obtain effective stress shear strength data. According to Table (1), the ranges of q_c, q_t and B_q of the obtained PCPT recods were 0.5 MPa to 1.64 MPa, 0.6 MPa to 1.89 MPa and 0.3 to 1.1, respectively.

8 EVALUATION OF THE SENNESET-JANBU METHOD

In order to evaluate the Senneset-Janbu method as listed in the above sections, the following data were used (Abdelrahman et al., 2005):

1) ground stress data including σ_{vo} and u_o which were measured or interpreted from borehole logs,
2) CPTU records including (q_c and u_2),
3) effective stress shear strength data including ϕ' and c' (in this study c' was taken 0 for normally consolidated to slightly overconsolidated clays, and ϕ' was taken as the average friction amgle from laboratory measured envelop), and
4) angle of plastification, β, the angle that is related to bearing capacity failure under the cone during penetration.

Looking at the above mentioned groups of data, it is obvious that the only unknown parameter is β. In the developed Senneset-Janbu method, a tentative value of β is chosen from a very narrow range of values (-5° to +5°) suggested by Sandven et al. (1988) for the clays considered in this study. An a approach to evaluate the method is to choose b (assuming it is in a narrow range) and then effective stress friction angle is estimated and then compared to friction angles measured in the triaxial tests. Alternatively, the measured values of friction angles are used to backcalculate β. Such an approach was used by both Powel et al. (1988) and Abdelrahman et al. (2005). The backcalculated values of β, using the alternative approach, can be then judged and used to check the supposed values to be chosen.

The values of β backcalculated using the data in this study were plotted versus plasticity index in Figure (3). The back calculated values of angle β are in the range of 0° to -140°. Those values are required to obtain the measured effective stress friction angles from the measured CPTU data using the Senneset-Janbu method. It should be noted that negative values of β that are higher than -90 is not physically possible. The back calculated values with the shown range reflect the uncertainties and the accuracy of the original method with the suggestion of Sandven et al. (1988).

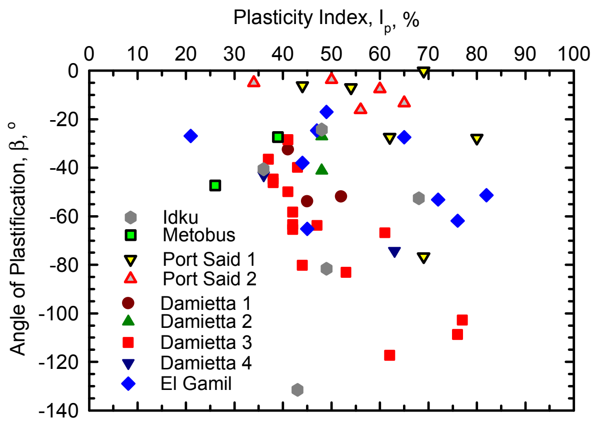

Figure 3. Plastification angle of Nile Delta deposits versus plasticity index.

Abdelrahman et al. (2005) carried out geotechnical investigation in a site west of Port Said, Egypt, in which both in situ CPTU tests and consolidated undrained triaxial compression tests with porewater pressure measurements on "fairly" undisturbed samples were performed. The angles of shearing resistance obtained from triaxial tests, together with CPTU results, were used to backcalculate β for the studied clay. The values were in the range of -20o to -55o. The backcalculated values were higher than those proposed by Sandven et al. (1988).

The values of β backcalculated using the data in this study were also plotted effective stress friction angle in Figure (4). The plot shows that with some scatter in the data, the plastification angle or its required values is dependent on the effective stress friction angle. Such dependence can be utilized to introduce a method of calculation that requires iteration between the required β for calculations and ϕ'. Such iterative procedure deserves evaluation in future investigation.

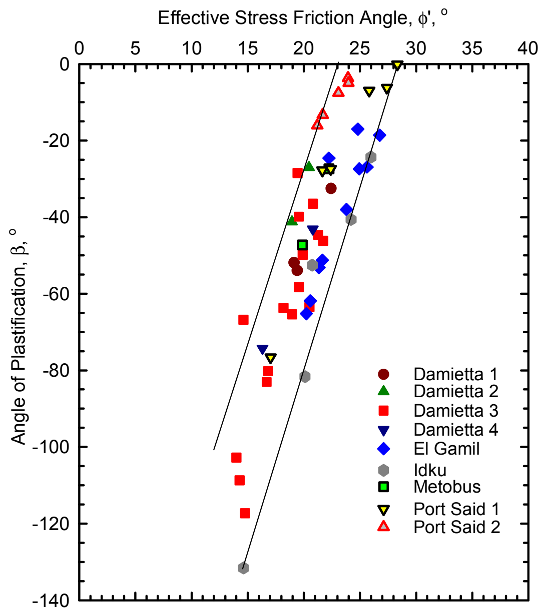

Figure 4. Plastification angle of Nile Delta deposits versus effective stress friction angle.

9 EVALUATION OF THE MAYNE AND CAMPANELLA (2005) SEMI-EMPIRICAL METHOD

Mayne and Campanella (2005) showed that the Senneset-Janbu theory could be approximated by the following expression for $0.1<B_q<1$ and $20°<\phi'<45°$:

$$\phi' \approx 29.5^{o} \cdot B_q^{0.121} \cdot \left[0.256 + 0.336 \cdot B_q + \log Q\right]$$

The data in this study were used to evaluate the above mentioned expression. The expression was used to calculate the effective stress friction angle for the data in the nine sites in this study. The computed values of ϕ' were compared to those measured in the laboratory triaxial compression tests. The comparison is shown in Figure (5). The data in Figure (5) show that the Mayne and Campanella (2005) method overestimates the measured effective stress friction angle of the clays in this study. The comparison suggests that the estimated friction angle by the method could be multiplied by a correction factor of about 0.75 to predict with some scatter the mesaured values of the effective stress friction angle.

10 MODIFICATION OF THE BEARING CAPACITY FACTOR EXPRESSION

The following alternative expression to estimate the bearing capacity factor N_q in the Senneset-Janbu method is proposed.

The proposed expression is empirically based on the data from the nine sites in this study.

$$N_q = \tan^2\left(45 + \frac{\phi}{2}\right) e^A$$

where

$$A = 2.4\ \sqrt[4]{\tan\phi'}$$

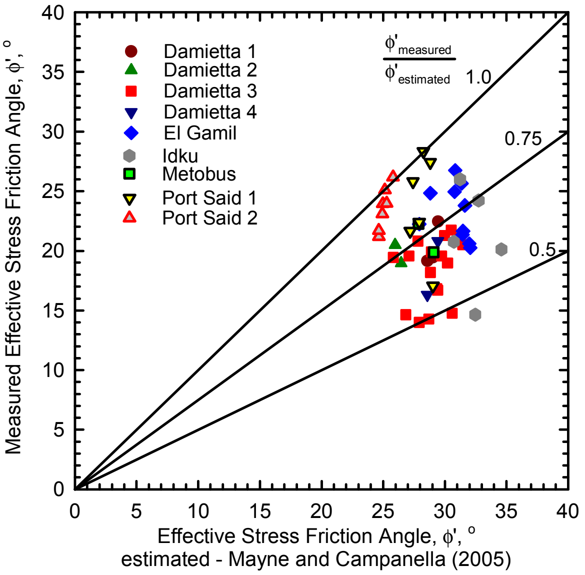

Figure 5. Comparison between measured effective stress friction angle and that estimated by the Mayne and Campanella (2005) method.

11 SUMMARY AND CONCLUSIONS

The following summary and concluding points are based on the data, analysis and discussion presented in this paper:

1) Data on effective stress friction angle and piezocone data for clays from nine sites were used in this paper.
2) The Senneset-Janbu method to estimate the effective friction angle from piezocone data was evaluated by back calculating required angle of plastification.
3) The required values of plastification angle to obtain effective stress friction angle are in the range of 0o to -140o, while those suggested by Sandven et al (1988) is in the range of -5o to +5o for the clays studied in this paper.
4) The plastification angle or its required values for the Senneset-Janbu method is dependent on the effective stress friction angle.
5) The Mayne and Campanella (2005) expression overestimates the measured effective stress friction angle data in this paper.
6) An alternative expression for the bearing capacity factor is empirically proposed based on the data in this paper to be used with the Senneset-Janbu method to estimate eefective stress friction angle.

REFERENCES

Abdelrahman, M. , O. Ezzeldine and M. Salem (2005). "The Use of Piezocone in Characterization of Cohesive Soil West of Port Said – Egypt," Proceedings of Fifth International Geotechnical Engineering Conference – Cairo University – Egypt, pp. 201-219.

Campanella, R.G. and P. K. Robertson (1988). "Current status of piezocone test" Proceedings of International Symposium on Penetration Testing. ISOPT-1, Orlando, Vol. 1, pp. 1-24.

Janbu, N. And K. Senneset (1974). "Effective stress interpretation of in-situ static penetration tests," ESOPT Stockholm, Vol. 2.2, pp. 181-193.

Hamza, M., M. H. Ibrahim and M. Shahien (2002). "Ground characterization of the East Nile Delta Clay," Proc. Of 3rd Regional Middle East Civil Engineering Conference, ASCE-ES, Cairo (CD-ROM).

Hamza, M., M. Shahien and M. Ibrahim (2005). "Characterization and undrained shear strength of Nile delta soft deposits using piezocone," 16th International Conference on Soil Mechanics and Geotechnical Engineering, Osaka, Japan

Hamza, M., M. Shahien and M. H. Ibrahim (2003). "Ground characterization of Soft Deposits in Western Nile Delta," Proc. Of 13th Regional African Conference on Soil Mechanics and Geotechnical Engineering, Morocco.

Hight, D. W., M. M. Hamza, and A. S. El Sayed (2000). "Engineering characterization of the Nile Delta clays," Proc. of IS Yokohama 2000.

Keaveny, K.M. and J.K. Mitchell (1986), "Strength of fine grained soils using the Piezocone," Proceedings of In-Situ '86, ASCE Speciality Conference, Blacksburg, Virginia.

Lunne, T., T.I. Tjelta and H.P. Christoffersen(1985). "Engineering use of piezocone data in north sea clays," Proceedings of 11th Int. Conference on Soil Mechanics and Foundations Engineering, San Francisco, Vol. 2, pp. 907-912.

Lunne, T., P.K. Robertson, and J.J.M. Powell (1997). Cone Penetration Testing. Blackie Academic and Professional- London, p. 312.

Mayne, P.W. and R. G. Campanella (2005). "Versatile site characterization by seismic piezocone," Proceedings of Int. Conference on soil Mechanics and Geotechnical Engineering, Vol. 2, pp. 721-724.

Mesri, G. and S. Ali (1999). "Undrained shear strength of a glacial clay overconsolidated by desiccation," Georechnique, Vol. 49, No. 2, pp. 181-198.

Powel J.J.M., R.S.T. Quarterman and T. Lunne (1988). "Interpretation and use of the piezocone test in UK clays," Proceedings of the Geotechnology Conference on Penetration Testing in The UK, Birmingham, pp. 151-156.

Sandven, R., K. Senneset, and N. Janbu (1988). "Interpretation of Piezocone Tests in Cohesive Soils," Proceedings of International Symposium on Penetration Testing. ISOPT-1, Orlando, Vol. 2, pp. 939-953.

Senneset, K., N. Janbu, and G. Svan□ (1982). "Strength and Deformation Parameters from Cone Penetration Tests," Proceedings of 2nd European Symposium on Penetration Testing, ESOPT-II, Amestrdam, Vol. 2, pp. 863-870.

Senneset, K., R. Sandven, T. Lunne, T. By, and T. Amundsen (1988). "Piezocone Tests in Silty Soils," Proceedings of International Symposium on Penetration Testing. ISOPT-1, Orlando, Vol. 2, pp. 955-966.

Terzaghi, K., R. B. Peck, and G. Mesri (1996). Soil Mechanics in Engineering Practice, 3rd Edition, John Wiley and Sons, Inc., p. 549.