Compressibility Parameters of Cohesive Soils From Piezocone

Paramètres de compressibilité de sols cohésifs au piézocone

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ABSTRACT: Drained compressibilty parameters for cohesive soils can be determined by carrying out one dimensional consolidation tests on “undisturbed” samples. The compressibility parameters include the compression and recompression indices, overconsolidation ratio and coefficient of consolidation. Some of these parameters or in other forms have been already correlated in the literature to results of piezocone. The aim of this paper is to provide additional data on drained compressibility parameters, focusing on constrained modulus and overconsolidation ratio, for cohesive soils from geotechnical investigations in seven major sites of river Nile Delta deposits in Egypt where piezocone CPTU data are also available. The results of consolidation tests are used to evaluate and modify the available correlations(s) with CPTU data. It is believed that the data and analysis in this paper shall be a valuable contribution to the literature by providing a better ground for improving the current state of the art of estimating the compressibility parameters from the CPTU data.

RÉSUMÉ : Les paramètres de compressibilité drainée pour les sols cohérents peuvent être déterminés en exécutant un test de consolidation unidimensionelle sur les échantillons « intacts ». Ces paramètres incluent les indices de compression et de recompression, le taux de surconsolidation et le coefficient de consolidation. Certains de ces paramètres ont déjà été corrélés dans la bibliographie aux résultats du piézocone. L'objectif de cet article est de fournir des données supplémentaires sur les paramètres de compressibilité drainée en se concentrant sur le module contraint et sur le taux de surconsolidation pour des sols cohérents étudiés dans sept sites majeurs des dépôts du Delta de Nil en Egypte, où des données de CPTU sont aussi disponibles. Les résultats d’essais de consolidation sont utilisés pour évaluer et modifier les corrélations disponibles avec les données de CPTU. On estime que les données et l'analyse présentées ici seront une contribution valable à la bibliographie en fournissant de meilleurs fondements pour améliorer l’état de l’art actuel concernant l'estimation des paramètres de compressibilité à partir de données de CPTU.

KEYWORDS: constrained modulus, overconsolidation ratio, sample quality designation, piezocone, clay

1 INTRODUCTION

Drained compressibilty parameters for cohesive soils are useful in; a) carrying out long term settlement analysis, b) providing key parameters for analysis and design of ground improvement, and c) profiling undrained shear strength parameters with the aid of other insitu field investigation equipments such as field vane and piezocone.

Drained compressibility parameters for cohesive soils can be determined from End of Primary (EOP) void ratio versus effective stress relationship that results from carrying out incremental load one dimensional consolidation tests on “undisturbed” samples. The drained compressibility parameters include the compression and recompression indices, overconsolidation ratio and coefficient of consolidation. These parameters can be influenced with variable degrees by quality of samples used in the tests. (Jamiolkowski et al., 1985 and Terzaghi et al., 1996). Empirical correlations to estimate these parameters or equivalent in other forms, from insitu tests such as piezocone are available in the literature (e.g. Jamiolkowski et al, 1985, Lunne et al., 1997 and Mayne, 2009). Availability of such correlations provides a great aid for geotechnical engineers to estimate such parameters in continuous profiles for a site in relatively short period of time and perform fewer consolidations tests for confirmation. However, estimating drained parameters from undrained piezocone test results could be complicated and sometimes may have various degrees of uncertainties (Lunne etl. 1997). Therefore, there is a need for continuous feed of data from local experiences to confirm, validate, and even modify the existing correlations.

The aim of this paper is to provide additional data on both constrained modulus and overconsolidation ratio as determined from oedometer consolidation tests on “undisturbed” samples of cohesive soils and CPTU data from seven sites from the Nile Ddelta deposits. The authors believe that the addition of the data presented in this paper to the literature provides a better ground for improving the current state of the art of estimating drained compressibility parameters from the CPTU data. With such belief, the data are used to evaluate and modify the available correlations.

2 INVESTIGATED SITES

Comprehensive geotechnical investigation campaigns were carried out in seven sites of major projects along the north coast and within the Delta of the Nile River of Egypt. The seven 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 Delta. Three of these sites were reported in Hight et al. (2000), Hamza et al. (2002), (2003) and (2005). The seven sites were used by Hamza and Shahien (2009) to investigate the correlations of estimating the efective stress friction angle from piezocone data. The stratifications of the sites are shown in Fig. (1).

The statification of the 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 tends to thicken as moving from west to east of the Delta (Hamza et al., 2005).

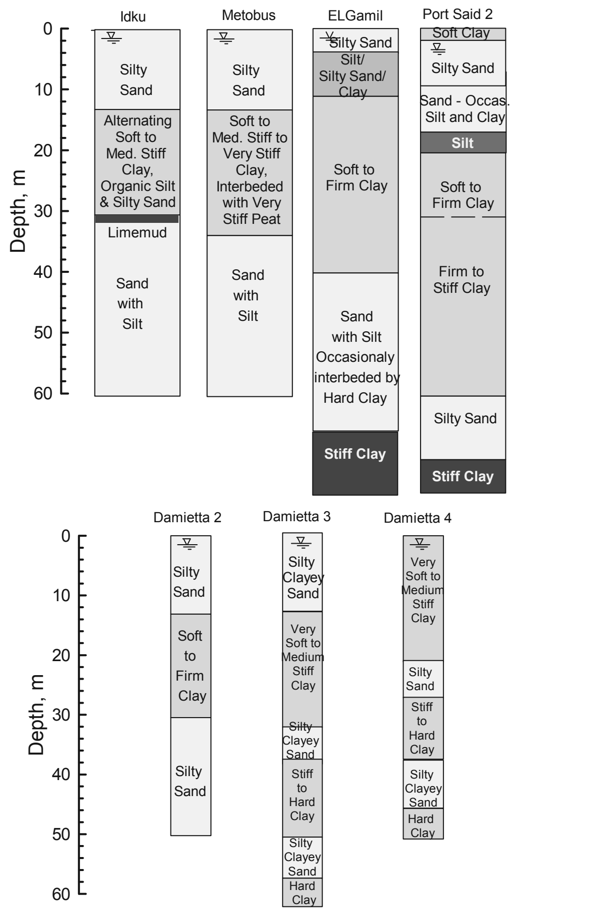

Figure 1. Stratigraphy of the soil formations in the seven sites.

3 COMPRESSIBILITY PARAMETERS FROM OEDOMETER TESTS

3.1. General

The results of total 125 consolidation tests were used in this study. The tests were carried out on clay “undisturbed” samples that were collected by means of stainless steel thin wall Shelby tubes with cutting edge sharpened to approximately 5^{o}. Incremental loading procedure was utilized with a load increment ratio of 2. End Of Primary (EOP) consolidation was determined for each load increment using the Taylor method. EOP void ratio versus logarithm of effective vertical pressure (e-log σ'_v) curves were plotted for each test.

3.2. Overconsolidation Ratio

The overconsolidation ratio, OCR, is defined as the ratio between the preconsolidation or yield pressure, σ'_p, to in situ effective overburden pressure, σ'_{vo}. The σ'_p is the pressure that distinguishes between low compressibility in the recompression range and the high compressibility in the compression range. There are several mechanisms for a deposit to demonstrate a σ'_p (Jamiolkowski et al., 1985 and Mayne et al., 2009). Those mechanisms include; decrease in vertical effective stress, freeze-thaw cycles, repeated wetting-drying, tidal cycles, earthquake loading, desiccation, aging, cementation or geotechnical bonding. The decrease in effective stress could be caused by; mechanical removal of overburden, overburden erosion, rise in sea level, increased groundwater elevations, glaciation, and mass wasting. The conventional and most common Casagrande method is used to determine σ'_p from the EOP e-log σ'_v curves from the Oedometer tests carried out.

Sample quality was evaluated on the basis of the magnitude of the volumetric strains, ε_{vo}, during reconsolidation to σ'_{vo} in oedometer tests as suggested by Andresen and Kolstad (1979). The Sample Quality Designation (SQD) scale using ε_{vo} suggested by Andresen and Kolstad (1979) and modified by Terzaghi et al. (1996) is used in this paper. Figure (2) shows the OCR values in this study versus ε_{vo}. Shown also on the plot, is the above mentioned SQD scale. The scale suggests that the majority of samples have quality B to C. Such sample qualities correspond to verbal scale of very good to good samples.

The OCR values for the clay are in the range of 1 to 2. It should be noted that OCR values might be influenced by sample disturbance. As sample disturbance increases (i.e. ε_{vo} increases), the OCR value decreases due to the de-structuring of the samples during sampling. One possible major source for sample disturbance in Nile Delta deposits is the natural gas exsolution in the pore water (Hight et al., 2000). The OCR values, for the very few tests, that are less than 1 were corrected to 1 for use in evaluations and correlations developed in this study.

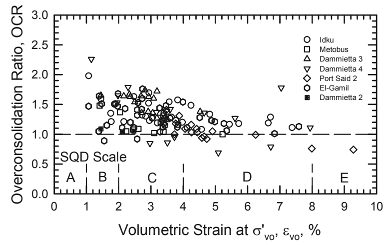

Fig. 2 Overconsolidation ratio (OCR) versus ε_{vo} as a measure of SQD

3.3. Compression Indices and Moduli

The compression, C_c, and re-compression, C_r, indices were calculated for each test as the slopes of the e-log σ'_v curve in the normally consolidated and the re-compression ranges, respectively. The recompression index, C_r, was calculated as the average slope of the unloading-reloading cycle of e-log σ'_v curve between vertical effective stress value of twice of the preconsolidation pressure, σ'_p, and effective overburden pressure, σ'_{vo} or the average slope of the unloading curve from consolidation pressure of 3200 kPa.

Compression index values in this study are plotted in Figure (3) versus natural water content, the Terzaghi et al. (1996) plot for filling and reference. The water content is a major variable as it reflects how much water held in the deposit to be squeezed out upon the increase in effective stress. As expected, the data show a band that compares relatively well with data from all over the world as collected originally by Terzaghi et al. (1996). The overall average of ratio of re-compression to compression indices C_r/C_c is calculated to be about 0.1.

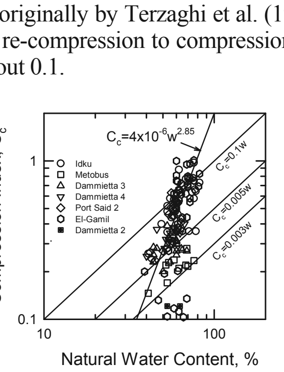

Figure.3 Data of this study on the compression index versus natural water content Terzaghi et al (1996) relationship

Constrained modulus is another form of compressibility parameter instead of the recompression or compression indices. The following expression is used to estimate the tangent constrained modulus:

$$M= \delta\sigma'_v/\delta\varepsilon = 2.3(1+e)\sigma'_v/C_c \quad (1)$$

The general definition of constrained modulus in Equ. (1) is used in the literature (e.g. Kulhawy and Mayne 1990). There are several definitions for the constrained modulus depending on which σ'_v and which index, C_c or C_r, used in Equ. (1). It is expected that the modulus in the compression range is different than that in the re-compression range. Even in the compression range, the constrained modulus is dependent on σ'_v level (Janbu, 1963). Figure (4) introduces the several definitions of the constrained modulus using consolidation test data from the Idku site as an example. The Janbu (1963) approach can be used to define three constrained moduli as defined in Figure (4) and Equs. (2) to (4); M_i in the recompression range, M_{np} or $M_{n@\sigma'p}$ at σ'_p and M_n in the compression range that is dependent on level of σ'_v:

$$M_i = 2.3(1+e)\sigma'_p/C_r \quad (2)$$

$$M_{np} = M_{n@\sigma'p} = 2.3(1+e)\sigma'_p/C_c \quad (3)$$

$$M_n = 2.3(1+e)\sigma'_v/C_c \quad (4)$$

There are investigators (e.g. Sanglerat, 1972, and Abdelrahman et al., 2005) that are using M_o at σ'_{vo} as in Equ (5)(Fig. 4):

$$M_o = 2.3(1+e)\sigma'_{vo}/C_c \quad (5)$$

The geotechnical engineer should be cautious as what modulus is reported or estimated and how it is used in settlement analysis, because in a lot of literature the reference is given to M without specifying which modulus is meant such as in Equ. (1). M_o modulus can be used to estimate both M_i and M_n using Equs. (6) and (7) to be used for settlement analysis in the recompression and compression ranges, respectively.

$$M_i = M_o OCR(C_c/C_r) \quad (6)$$

$$M_n = M_o(\sigma'_v/ p_a) \quad (7)$$

where σ'_v is the average pressure between σ'_p and the final pressure due to surface load causing the settlement.

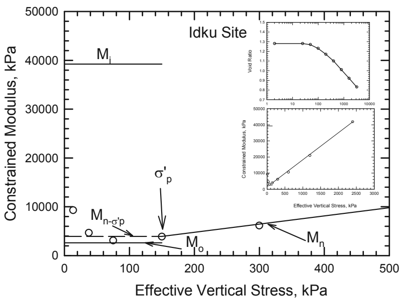

Figure 4 Definition of tangent constrained modulus concept

4 PEIZOCONE PENETRATION TESTS

Piezocone Penetration Tests with pore water pressure measurements (CPTU) were performed at the sites. A l0 cm^2 Piezocone was used to carry out the testing. Records were made at 2 cm intervals. At each tested depth, cone resistance (q_c), pore water pressures behind cone (u_2) and side friction (f_s) were measured. Typical CPTU records at some of the sites under study are shown in Hight et al. (2000), Hamza et al. (2003) and Hamza et al. (2005). The corrected tip resistance, q_t, can be calculated as $q_t=q_c+(1-\alpha)u_2$, where $\alpha=0.75$ is a cone factor. The net cone resistance, q_n, can be calculated as $q_n= q_t-\sigma_{vo}$, where σ_{vo} is the total overburden pressure.

5 PEIZOCONE PENETRATION TESTS

5.1. Stress History or Overconsolidation Ratio

Review of the available correlations between σ'_p or OCR and Piezocone results was carried out by Lunne et al. (1997), Mayne (2001), Ladd and DeGroot (2003), Powell and Lunne (2005), Pant (2007), Mayne (2009), Becker (2010) and Robertson (2012). The cone parameters used in the correlations include q_c, q_t, q_t-σ_{vo}, q_t-u_2, Δu. Some of these parameters were used with or without normalization by σ'_{vo}. According to Campanella and Robertson (1988), there is no unique relationship between OCR or σ'_p and measured penetration induced pore water pressures and if exists, it is poor because the pore pressures measured is influenced by the location of the u measurement (i.e. u_1, u_2 or u_3), clay sensitivity, over consolidation mechanism, soil type and local heterogeneity. The most common and widely used correlation is (e.g. Lunne et al. 1997):

$$\sigma'_p = k\,(q_t-\sigma_{vo}) \quad \text{or} \quad OCR = \sigma'_p/\sigma'_{vo} = k(q_t-\sigma_{vo})/\sigma'_{vo} \quad (8)$$

It should be noted that empirical constant k in both expressions in Equ. 8 is the same. Table (1) shows a summary of k values reported in the literature. According to the table, k is in the range of 0.14 to 0.5. Mayne (2001) showed that k is slightly dependent on plasticity index, while Becker (2010) showed that k is slightly dependent on coefficient of horizontal pressure at rest. Robertson (2012) suggested an expression that is dependent on $(q_t-\sigma_{vo})/\sigma'_{vo}$ and sleeve friction ratio, F_r. The empirical constant is calculated for the data in this study and is plotted versus F_r in Figure (5). The expression suggested by Robertson (2012) was also plotted on the same plot. Figure (5) shows that the Robertson (2012) predicts well the range of k. However, it seems that k is slightly increasing with F_r. The calculated k values are in the range of 0.1 to 0.6 (0.18 to 0.4, if scatter is ignored) with an average of 0.32, which is consistent with the existing correlations in the literature.

Table 1. Summary of the parameter k from the literature..

Reference	k	Comment
Lefebvre & Poulin (1979)	0.25- 0.4	Norway & UK sites
Mayne & Holtz (1988)	0.4	World Data
Larson & Mulabdic (1991)	0.29	Scandinavian Soils
Mayne (1991)	0.33	Cavity Expansion & Critical State Soil Mechanics Analysis
Leroueil et al. (1995)	0.28	Eastern Canada Clays
Chen & Mayne (1996)	0.305	205 Clay sites
Lunne et al. (1997)	0.2 – 0.5	
Mayne (2001)	$0.65(I_p)^{-0.23}$	
Mesri (2004)	0.25 – 0.32	s_u/σ'_p=constant interpretation
Abdelrahman et al. (2005)	0.2 – 0.5	Port Said Site, Egypt
Pant (2007)	0.14	Louisiana Soils – 7 Sites
Becker (2010)	0.3	Beaufort Sea Clays K_o=1.5
	0.24	Beaufort Sea Clays K_o=2.0
Robertson (2012)	*	SHANSEP & CSSM

* $k = [\,[(q_t-\sigma_{vo})/\sigma'_{vo}]^{0.2} / (0.25(10.5+7\log F_r))\,]^{1.25}$ where $F_r = f_s/(q_t-\sigma_{vo})$

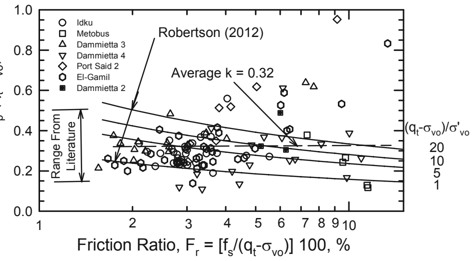

Figure (5) Empirical constant k for the sites in this study

Ladd and De Groot (2003) proposed the following SHANSEP type of expression to estimate OCR:

$$OCR = k_{OCR}[(q_t-\sigma_{vo})/\sigma'_{vo}]^{1.25} \quad (9)$$

Ladd and De Groot reported a value of 0.192 for k_{OCR} based Boston Blue clay experience. Robertson (2009) suggested general k_{OCR} value of 0.25. Robertson (2012) suggested the expression in Equ. (10) to estimate k_{OCR} based on F_r:

$$k_{OCR} = (2.625+1.75\log F_r)^{1.25} \quad (10)$$

The data of Delta clay sites was used to back calculate k_{OCR} and was plotted versus Fr in Fig. (6). The Robertson (2012) expression was also plotted on Fig. (6). Figure (6) shows that Equ. (10) predict well the range of k_{OCR}. However, it seems that k_{OCR} is slightly increasing with F_r. The average k_{OCR} of the data in this study was about 0.23 that is consistent with data in literature.

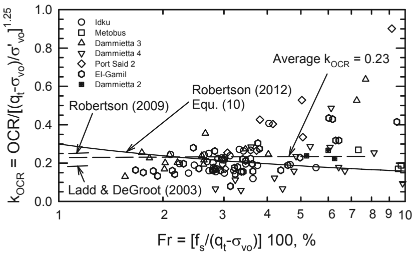

Figure (6) Empirical constant k_{OCR} for the sites in the study

5.2. Constrained Modulus

Review of the available correlations between M and cone results for cohesive soil was carried out by Lunne et al. (1997), Mayne (2001), Pant (2007), and Robertson (2009). Attempts to correlate M of cohesive soils to cone results have started since mid sixties of the last century (Sanglerat, 1972). The following expression shows the general form of the empirical correlation:

$$M_{Subscript} = \alpha_{Subscript}[q_{Parameter}] \quad (11)$$

The subscript in Equ (11) could be nothing, i, np, n, or o as in Equs (1 to 5). The empirical constant α as well as the cone parameter, $q_{Parameter}$, used in Equ (11) as reported in literature is summarized in Table (2). According to the table, α_o is in the range of 1 to 14. Sanglerat (1972) showed that α_o is inversely dependent on q_c. Robertson (2009) suggested that α_o is directly related to $(q_t-\sigma_{vo})/\sigma'_{vo}$ with an upper limit of 14. The empirical constant α_o is calculated for the data in this study and is plotted versus $(q_t-\sigma_{vo})/p_a$ in Figure (7), where p_a is a reference pressure of 100 kPa.. Ignoring some scatter, the calculated α_o values are in the range of 1 to 8 with an average of 3.5, which is consistent with the existing correlations in the literature. Sources of scatter in Figure (7) include but not limited to; sample disturbance with its influence on the measured compressibility and natural variation between the location of borehole from which the samples were extracted and that of the CPTU testing.

Table (2) Summary of components of empirical Equ. (11) in literature

Reference	$\alpha_{Subscript}$	α Range	$q_{Parameter}$	Comment
Bachelier and Parez (1965)	α_o	2.3-7.7	q_c	Flanders Clay
Sanglerat (1972)	α_o	1-8 *	q_c	France & Spain Clays
Jones & Rust (1995)	α_o	2.2-3.3	q_c	South African Clays
Pants (2007)	α_{np}	3.1	q_t	Louisiana Clay
	α_{np}	3.27	$q_t-\sigma_{vo}$	Louisiana Clay
Kulhawy & Mayne (1990)	α	8.25	$q_t-\sigma_{vo}$	
Senneset et al. (1989)	α_i	5-15	$q_t-\sigma_{vo}$	Glava Clay
	α_{np}	8	$q_t-\sigma_{vo}$	Glava Clay
Abdelrahman et al. (2005)	α_o	1.25	$q_t-\sigma_{vo}$	Port Said Clay
Mayne (2009)	α	5	$q_t-\sigma_{vo}$	Vanilla Clays
Robertson (2009)	α_o	**	$q_t-\sigma_{vo}$	

* Dependent on type of soil and on q_c values
** For Clays (Ic > 2.2) $\alpha_o = (q_t-\sigma_{vo})/\sigma'_{vo}$ $\alpha_o \le 14$

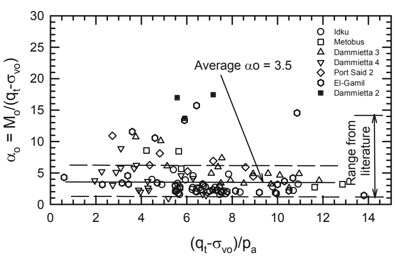

Figure (7) Empirical constant α_o for the sites in the study

6 SUMMARY AND CONCLUSIONS

1) The results of geotechnical investigations in seven sites in the Nile Delta clays were used in this paper.
2) The compressibility parameters; OCR, C_c and C_r, and M_o, were calculated from EOP e-logσ'_v curves of total 125 consolidation tests carried out on "undisturbed" samples. The SQD of the majority of the samples was B to C.
3) The compressibility parameters of each test were paired with results from neighboring or adjacent piezocone test that were recorded at the same depths of the samples. Such pairing allowed for comprehensive review of the existing empirical correlations to predict compressibility parameters from in-situ piezocone results.
4) The OCR of the Nile Delta clays can be best predicted using Equs. (8) and (9) using average k of 0.32 and average k_{OCR} of 0.23. Figs (5) & (6) suggest that k and k_{OCR} have the general tendency to slightly increase with friction ratio, F_r.
5) The M_o can be best predicted using Equ. (11) with average value of α_o of 3.5. Settlement analysis can then be carried out using M_i and M_n that can be calculated using Equs (6) and (7).

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