Stress history profiling of Nile delta clay deposits: Determination and challenges

Le profilage des dépôts d'argile du delta du Nil: détermination et défis

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ABSTRACT: Stress history of geo-material is one of the most important parameters required for both geotechnical analysis and design. Stress history is often expressed in terms of OCR that is defined as the ratio of pre-consolidation pressure to effective overburden pressure. The OCR is usually determined using one dimensional consolidation tests carried out on "undisturbed" samples in the Oedometer. One of the major challenges in determination of the OCR is sample disturbance during and after sampling. This paper shall show the challenges in OCR determination in a conventional manner, and discuss all other alternative approaches used to complement and confirm the determination of stress history of clay deposits. These approaches include in-situ and laboratory tests. This will be demonstrated through examples from two sites of major projects in Egypt during the last 15years.

RÉSUMÉ : L'historique des contraintes du géomatériau est l'un des paramètres les plus importants pour l'analyse et la conception géotechniques. L'histoire du stress est souvent exprimée en termes de OCR qui est définie comme le rapport de la pression de pré-consolidation à la pression effective de surchargement. L'OCR est généralement déterminé à l'aide de tests de consolidation unidimensionnels effectués sur des échantillons «non perturbés» dans l'oedomètre. L'un des principaux défis dans la détermination de la OCR est la perturbation des échantillons pendant et après l'échantillonnage. Cet article doit montrer les défis dans la détermination OCR d'une manière conventionnelle et discuter de toutes les autres approches alternatives utilisées pour compléter et confirmer la détermination de l'histoire de stress des dépôts d'argile. Ces approches incluent des tests in situ et de laboratoire. Cela sera démontré à travers des exemples de grands projets en Egypte au cours des 15 dernières années.

KEYWORDS: Stress History, OCR, Oedometer, Sample Disturbance, In-situ Tests, Laboratory Tests.

1 INTRODUCTION

Drained compressibility and strength including stress history in particular for cohesive soils are very important in geotechnical design and analysis. Stress history provides key parameters in determining geo-material strength and strain and compressibility (Urbaitis et al., 2016). It can be used to obtain stress-strain relationship (e.g. Viggiani and Atkinson, 1995; and Vardanega et al., 2012). Drained parameters and stress history are useful in; a) carrying out long term settlement analysis, b) stability analysis c) providing key parameters for analysis and design of ground improvement, d) carrying out stress-deformation analysis for geotechnical problems, and e) profiling undrained shear strength parameters with the aid of other insitu field investigation equipments such as field vane and piezocone.

2 DEFINITION AND MECHANISMS

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.

3 DETERMINATION OR ESTIMATION

3.1 *Conventional approach*

3.1.1 *Oedometer test*

Stress history or OCR and drained compressibility parameters for cohesive soils can be best determined from End of Primary (EOP) void ratio versus effective stress relationship that extends beyond the preconsolidation pressure, σ'_p in the compression range. Such a relationship is conventionally obtained by carrying out incremental load (IL) one dimensional consolidation tests on "undisturbed" samples in Oedometer with appropriate load increment ratio (Mesri, 1990). The most common Casagrande method is used to determine σ'_p from the EOP e-log σ'_v curves from the Oedometer tests carried out. Other means of determining EOP e-log σ'_v curve and thus σ'_p could be constant rate of strain CRS tests and Ko consolidation in traxial cell (Mesri et al.1994, and DeGroot 2014).

3.1.2 *Challenges*

Obtaining relatively "undisturbed" samples is the most challenging part toward determination reliable σ'p and compressibility parameters for cohesive soils. There are many factors that mainly contributes to sample disturbance and thus reliable evaluation of OCR in the laboratory (Mesri, 1990; DeGroot 2014; Urbaitis et al., 2016). These factors include a) change in state of stress on the soil from anisotropic state to isotropic state upon soil extraction from the ground and thus stress releif, b) proper soil extraction from the sampling tube, c) sample preservation, d) sample transportation, e) sample storage, and f) sample placement in the ring. One of the possible major source for sample disturbance in Nile Delta deposits is the natural gas ex-solution in the pore water (Hight et al., 2000).

There is no definitive method for determination of sample quality. However, examination of sample X-rays may provide a valuable qualitative evaluation of sample quality (DeGroot,2014). On the other hand, sample quality was evaluated quantitatively on the basis of the magnitude of the volumetric strains, ε_{vo}, during reconsolidation to σ'_{vo} in oedometer tests (Andresen and Kolstad, 1979). The Sample Quality Designation (SQD) scale using ε_{vo} was modified by Terzaghi et al. (1996). Mesri et al. (1994) used the modified scale to evaluate the Oedometer clay sample disturbance for Check Lap Kok, Hong Kong. For Oedometer testing of soft clays, A (ε_{vo}<1) and B (ε_{vo}=1~2) quality specimen are required and specimens with SQD less than C (ε_{vo}=2~4) are unacceptable (Mesri et al. 1994).

Large dimeter or block hand carved samples obtained from open excavation, shafts or tunnels may be less disturbed than samples recovered by any other procedure (Terzaghi et al.,1996). One exception is related to stress relief associated with carved samples. The Sherbrook sampler was developed to recover samples of quick clay with a diameter of 250mm and a height of about 350mm from the bottom of a 400-mm diameter fluid filled borehole to reduce the influence of stress relief on sample quality (Lefebvre and Poulin 1979).

Mesri et al. (1997) carried out one dimensional EOP IL tests on samples of Pancon clay from Pisa, Italy. The tests were performed on samples in Oedometer and on Ko consolidated samples in Triaxial cell. The samples were obtained from large diameter samples recovered using Sherbrook sampler. The samples quality was evaluated using the Terzaghi et al (1996) scale to be A to B with very few samples had SQD of C.

The experience of the authors in Egypt is to obtain high quality samples to be collected by means of 79 mm inner diameter, 83 mm outer diameter and 700mm long stainless steel thin wall Shelby tubes with cutting edge sharpened to approximately 5^{o}. Hamza and Shahien (2013) evaluated SQD of samples extracted from several sites of Nile Delta Clay deposits using the thin wall Shelby tube sampler with sharpened cutting edge. Figure (1) shows the OCR values of Delta Clay deposits 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 with few samples with the undesired D quality. As sample disturbance increases (i.e. ε_{vo} increases), OCR value decreases due to de-structuring of samples during sampling.

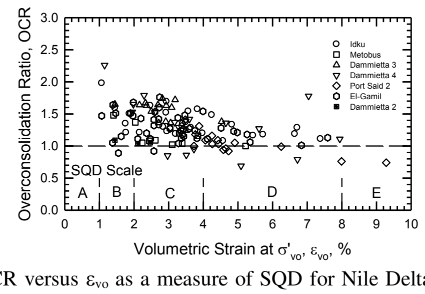

Fig. 1 OCR versus ε_{vo} as a measure of SQD for Nile Delta Clay (after Hamza and Shahien, 2013).

Sample disturbance is not the only challenge for determination of σ'_p. The Casagrande (1936) method is the most widely used technique for estimating σ'_p, however, it can be quite individual dependent and difficult to apply in case of rounded compression curves. The strain energy method of Becker et al. (1987) (DeGroot, 2014) or Wang and Frost (2004) that use work per unit volume as the criterion for estimating σ'_p from a plot of strain energy versus effective vertical stress σ'_v in linear scales.

In order to investigate the sensitivity of determining σ'_p from Oedometer tests, Oedometer tests results from the authors' files from Idko site (2013) were used. The σ'_p were determined by Becker et al. (1987) and Wang and Frost (2004) methods as well as by the Casagrande (1936) method. The resulting OCRs were compared in Figure (2). In general, the OCR based on the three methods were comparable with an acceptable scatter. However, Figure (2) suggests that the work based methods may provide OCR values that were higher than those determined by the Casagrande (1936) method. The ratio of increase could reach to as high as 50% with an average increase ratio of 20%.

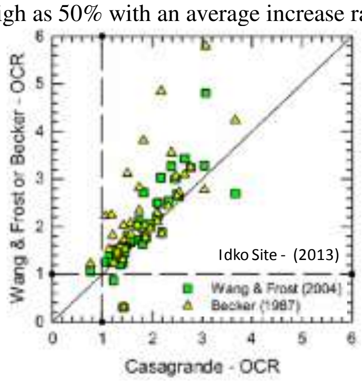

Fig. 2 OCR using work based methods compared to those using the Casagrande (1936) (Data from authors' personal files).

3.2 *Alternative approaches*

3.2.1 *Undrained shear strength testing in the laboratory*

The undrained shear strength of most clays and silts, for a given mode of shear, is controlled by the stress history (or σ'_p) of the soil (Ladd and Foott 1974, Ladd 1991, Mesri 1991, Terzaghi et al 1996, DeGroot 2014). Thus the concept of undrained shear strength to preconsolidation pressure ratio is constant. This can be explained by the fact that both conditions; loading to stress passing σ'_p in the laterally constrained condition and shearing the soil to the undrained shear strength; represent yield conditions (Terzaghi et al 1996). Test specimens with appropriate quality are Ko consolidated to stress levels (σ'_{vc}) greater than σ'_p to measure the undrained shear strength in the normally consolidated range. Thus obtaining the ratio of s_u/σ'_{vc}. Therefore, for a given mode of shear, the following expression can be written (Terzaghi et al 1996):

$$s_{uo} = (s_u/\sigma'_{vc})\ \sigma'_p \qquad (1)$$

where s_{uo} is in situ undrained shear strength. The expression in Equ. (1) can be used to estimate either s_{uo} or σ'_p with the knowledge of the other one. The expression in Equ. (1) can be rewritten to utilize the same concept estimating σ'_p using isotropically consolidated undrained triaxial compression shear strength measurement :

$$\sigma'_p = [s_{uo}(TC)\ (\sigma'_{Ic}/s_u(TC))]\ /\ [(1+2K_o)/3] \qquad (2)$$

where $s_{uo}(TC)$ is undrained triaxial compression shear strength measured at in situ effective mean overburden pressure, $s_u(TC)$ is undrained shear strength measured at isotropic pressure in the compression range σ'_{Ic}, and Ko is coefficient of earth pressure at rest that can be estimated as 1-sin(ϕ'). The effective friction angle, ϕ', can be estimated by effective stress interpretation of the undrained triaxial testing with shear-induced excess pore water pressure measurement.

3.2.2 *Field Vane Test (FV)*

The undrained shear strength as measured by field vane test, $s_u(FV)$ can be used to estimate σ'_p and thus OCR. The ratio $s_u(FV)/\sigma'_p$ is constant that is dependent on plasticity index based on Bejrum-Mesri empirical relationship in Terzaghi et al 1996) (Figure 3). Based on the authors' experience, the lower bound of the relationship best fits the Nile Delta Clays in Egypt.

3.2.3 *Piezocone Penetration Test (CPTU)*

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), Mayne (2009), Robertson (2012) and Hamza and Shahien (2013). The most common and widely used correlation is (e.g. Lunne et al. 1997):

$$\sigma'_p = k\,(q_t-\sigma_{vo}) \text{ or } OCR = k(q_t-\sigma_{vo})/\sigma'_{vo} \quad (3)$$

Where σ_{vo} is the total overburden pressure and q_t is the corrected cone tip resistance. According to the review of Hamza and Shahien (2013), the reported k values in the literature is in the range of 0.14 to 0.5 which coincides with range of values back–calculated for Nile Delta clay with an average of 0.32.

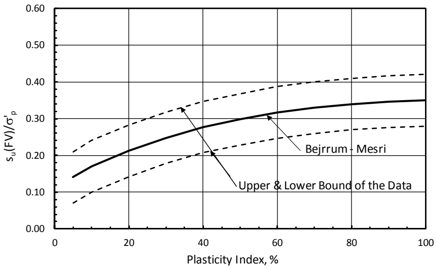

Fig. 3 Empirical correlation between $s_u(FV)/\sigma'_p$ and plasticity index for inorganic soft clay (After Terzaghi et al, 1996).

3.2.4 *Dilatometer Test (DMT)*

Marchetti (1980) proposed that OCR in fine-grained soils can be estimated from the dilatometer test utilizing the DMT dilatometer horizontal stress index K_D, together with, the following empirical expression:

$$OCR = (0.5\,K_D)^{1.56} \quad (4)$$

3.2.5 *Shear Wave Velocity (V_s)*

Mayne (2007) showed that OCR can be estimated empirically using the following expression:

$$OCR = 0.101\,(\sigma'_{atm})^{0.102}\,(G_{max})^{0.478}\,(\sigma'_{vo})^{-0.580} \quad (5)$$

$$G_{max} = (\gamma_b/g)\,V_s^2 \quad (6)$$

Where σ_{atm} is reference pressure=95.8 kPa, G_{max} is the small strain shear modulus. γ_b is the bulk unit weight, g is the ground acceleration=9.8 m^2/sec, and V_s is the shear wave velocity measured in down hall seismic test.

3.2.5 *Aging law of compressibility*

Minimum OCR of a layer in a site can be estimated using the aging law of compressibility (Mesri, 1987):

$$OCR_{Aging} = (t/t_p)^{\kappa} \qquad \kappa=(C_\alpha/C_c)/(1-C_r/C_c) \quad (7)$$

where t is time, t_p is the time required for the layer to reach end of primary consolidation, C_α is secondary compression index, C_c is the compression index and C_r is the recompression index. Using Terzaghi's theory of consolidation, t_p is estimated using coefficient of consolidation, c_v, and maximum drainage distance, H, as determined by the layer drainage boundaries. The time is estimated based on the geologic age. The C_α/C_c ratio for clay is 0.04 +/- 0.01 (Mesri et al., 1994). The ratio C_r/C_c can be estimated from results of Oedometer test.

4 APPLICATIONS TO SITES IN EGYPT

Geotechnical investigation campaigns were carried out in two sites of major projects (Table 1) along the north coast in Idko (Hamza et al., 2003) and El-Gamil (Hamza et al, 2002) at west and east of the Nile River Delta, respectively. The stratifications and typical CPTU profiles of the two sites are shown in Fig. (4). The geotechnical parameters of the clay layer in the two sites are summarized in Table(2). All means presented in this paper were used to determine or estimate OCR profiles for both sites. The resulting OCR profiles are shown in Figure (5).

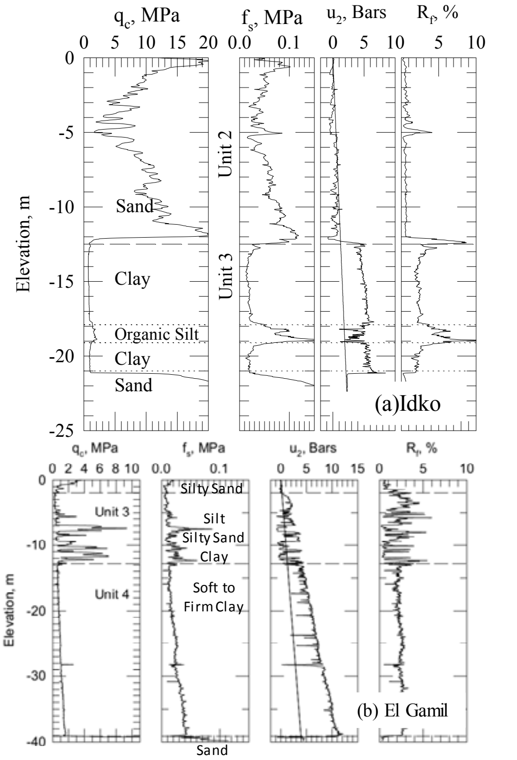

Figure 4. Stratigraphy and typical CPTU profiles in the two sites.

Table 1. Summary of field and lab. Tests carried out at the two sites.

Site or Laboratory	*Idko*	*El Gamil*
Boreholes	61	8
CPTU	55	11
Field Vane Profile	23	8
Down Hole Seismic	3	-
Dilatometer	-	1
Oedometer Tests	87	35
Triaxial compression	Few	Few

Table 2 Summary of in geotechnical parameters in the two sites

Parameter of Clay Layer	*Idko*	*El Gamil*
Thickness to Clay Layer	3 - 14	28
Natural Water Content, %	17-86	35-81
Unit Weight, kN/m^3	14.1-16.9	14.1-16.8
Liquid Limit, %	32-142	44-144
Plasticity Index, %	24-05	21-99
Oedometer OCR	1.01-1.76	1.08-2.3
c_v, m_2/year	0.5-16	0.73-7.3
C_α/C_c	0.03-0.05	0.05-0.07
C_r/C_c	0.15	0.14
Max. Drainage Distance, m	1.5-7.0	14
Age of layer (Holocene), year	5000 - 10000	
Undrained Shear s_{uo}(TC), kPa	36-57	28-80
$s_u(TC)/\sigma'_{Ic}$	0.30-0.32	0.29-0.35
Effective Friction Angle, ϕ', °	20	23
s_u(FV), kPa	13-77	24-86
CPTU $_{qt}$, MPa	0.9-1.1	0.8-1.7
DMT K_D	-	2.2-3.0
Vs	180-340	-

5 SUMMARY AND CONCLUDING REMARKS

The chalenges associated with determination of OCR from the Oedometer include influence of sample disturbance and the subjectiveness of the method used to determine σ'_p.

Those challenges necessitate the use of alternative approaches for estimating OCR such as those presented in this paper. The estimated values of OCR are used to reinforce, check and supplement the values obtained in the Oedometer.

This paper presents model for determining OCR values from Oedometer and for estimating OCR values using the alternative approaches presented in this paper utilizing the comprehensive date available from two well investigated sites in Egypt.

The following remarks can be made about the resulting OCR values shown in Fig. (5):

a) In general, OCR values resulting from all methods are very comparable with acceptable level of scatter.
b) The scatter is more pronounced in Idko site as compared to that in El Gamil site. This could be related to the heterogeneity in the clay layer in Idko as it is characterized as repeated alternating layers of clay/organic silt/silty sand.
c) The undrained shear strength from Triaxial compression tests, field vane, shear wave velocity, CPTU and DMT approaches predict predict very well the range of OCR values obtained from Oedometer tests. Few exceptions are in shear wave velocity approach.
d) It is interesting that the range of OCR estimated using the aging law of compressibility (Mesri, 1987) coincide very well with the majority of data obtained from Oedometer tests.

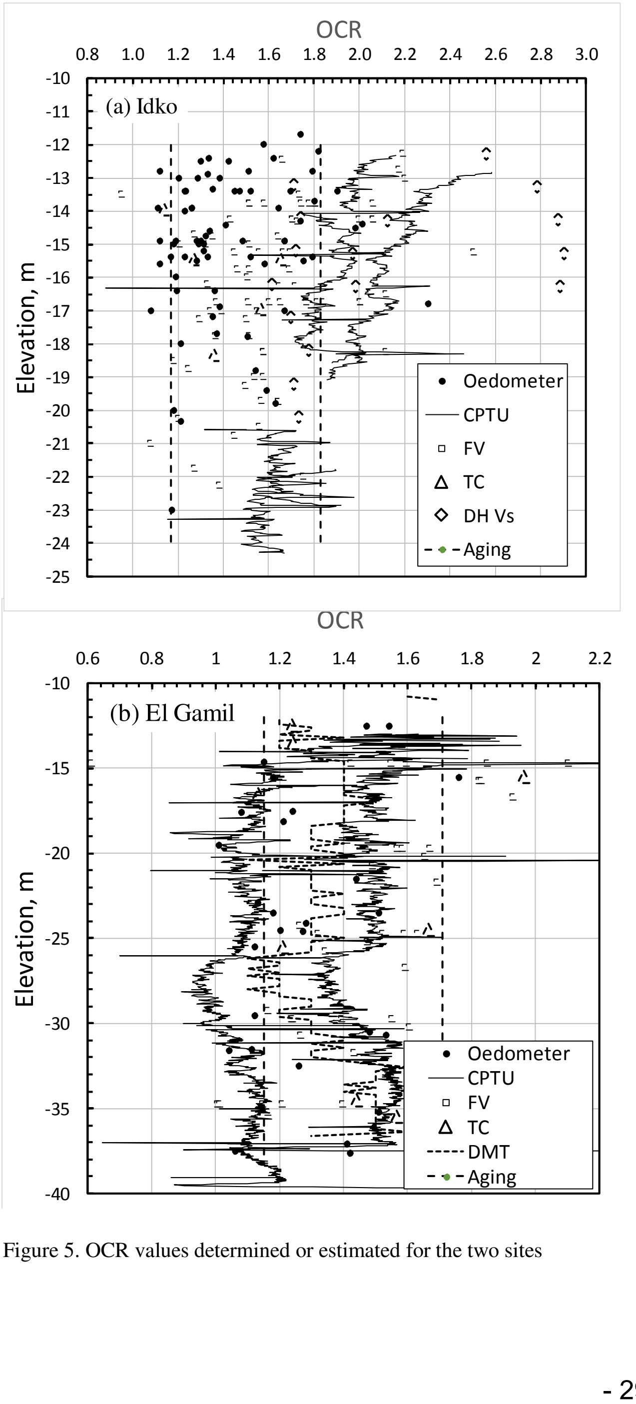

Figure 5. OCR values determined or estimated for the two sites

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