Overconsolidation ratio of a seabed clay from in-situ tests

La rapport de surconsolidation d'une argile d'un fond de mer par des essais en place

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ABSTRACT: The overconsolidation ratio (OCR) of a soil is important in that the ratio affects the initial stress state and the compression and shear behaviour of the soil. The assessment of the OCR traditionally by means of oedometer tests on "undisturbed" samples has not always been successful due to inevitable sample disturbance. One alternative is to estimate the OCR from in-situ tests. Three tests including the field vane, the piezocone, and the dilatometer tests were used for evaluating the OCR profiles of a seabed clay at a huge reclamation site in Singapore. The marine clay layers were found to be lightly overconsolidated except for the upper few metres where the clay was moderately to heavily overconsolidated. Values of OCR interpreted using recently developed correlations were found to compare well with oedometer data, although some existing correlations failed to provide reasonable estimates of OCR for the moderately to heavily overconsolidated seabed clay.

RESUME: Le rapport de surconsolidation du sol (OCR) est important, comme ce rapport affecte l'état initial de contrainte, la compression et le comportement de cisaillement du sol. La prédiction traditionnelle de l'OCR par des essais oedométrigue de l'échantillon non remanié, nè donne pas toujours un bon résultat, dû au dérangement de l'échantillon gui est inévitable. L'une de solution est l'estimation de l'OCR par des essais in-situ. Trios types d'essais (field vane, piezocone et dilatomèter) ont été utilise pour évaluer les profils de l'OCR de l'argile au fond de sous marin à un immense site de réclamation à Singapour. Les couches de l'argile sous marin sont trouvées faiblement surconsolidés sauf guelgues mètres de la couche supérieure où les argile sont de modérément à fortement surconsolidés. L'interprétation des valeurs de'OCR utilise de corrélation gui est développée récemment est en bon accordavec celles des données oedométrigues; bien gue guelgues corrélations existants ne sont pas suffisamment bien pour donner l'estimation raisonnable de l'OCR pour les argiles de modérément à fortement surconsolidés.

1. INTRODUCTION

The overconsolidation ratio (OCR) of a natural soil is defined as the ratio of the vertical preconsolidation pressure (p'_c) to the in-situ vertical effective stress (σ'_{vo}). The OCR which reflects the stress history and dictates the in-situ stress state of the soil is one of the most important parameters in goetechnical engineering.

Traditionally, the overconsolidation ratio is often assessed by means of oedometer tests on "undisturbed" samples. This method of assessment has not always been successful due to inevitable sample disturbance and the relative high cost of a detailed investigation. This is particularly the case in a foreshore land reclamation project involving the placement of sandfill over a seabed clay for which undisturbed sampling is expensive and the stress history of the clay may be complex. The difficulty of determining the OCR profiles in this case could be overcome by the use of selected in-situ tests that can provide nearly continuous measurement data with depth.

This paper describes the use of three in-situ tests for the evaluation of OCR profiles for a seabed clay at a huge reclamation site in the eastern part of Singapore prior to land reclamation. Values of OCR are interpreted from measurements made in the tests using both existing semi-empirical correlations and recently developed, theoretical-based correlations and results are compared with oedometer data. Porewater pressure changes as observed in the field during reclamation are also used to deduce reference in-situ OCRs for verification purposes.

2. SITE GEOLOGY AND SUBSURFACE CONDITIONS

A huge reclamation work at Changi East right adjacent to the existing Changi Airport in the eastern end of Singapore was embarked on in 1993 for future development of the third airport runway and other related facilities. The site is underlain by Recent deposits of Kallang Formation consisting primarily members of the Singapore marine clay and the Old Alluvium (made up of clayey sand) which rests directly on the Pleistocene siltstone and shale.

Prior to reclamation, a site investigation program including boring and in-situ testing was carried out at test clusters FT-1, FT-2, FT-3, FT-4 located in the area of the proposed runway for Changi Airport for the characterization of the site. Borehole exploration revealed that the Singapore marine clay at the site consists of two marine members locally known as the upper and the lower marine clay layers with an overall thickness ranging from 25 to over 35 metres. These soft to medium stiff clay members are separated by an intermediate layer of generally medium stiff to stiff sandy clay and/or medium dense sand typically 2 to 5 m in thickness. The whole or lower part of clayey intermediate layer directly in contact with the lower marine clay is believed to be the desiccated layer of lower marine clay. The mean sea level in the area was about to 6 to 8 m above the seabed at the time of investigation.

Figure 1 shows the typical soil and water content profiles at the site of the proposed runway. In general, the liquid limit w_P and the plastic limit w_L are similar in the upper and the lower marine clay layers. The water content w is slightly lower in the lower marine clay than in the upper marine clay. The values of w_P, w_L and w are much lower for the intermediate clay layer.

3. IN-SITU TESTS AND INTERPRETATION METHODS

Three in-situ tests including the field vane test (FVT), the piezocone test (CPTU), and the dilatometer test (DMT) were carried out in the Singapore marine clay at each of the four test clusters in the proposed runway area. The fact that the response

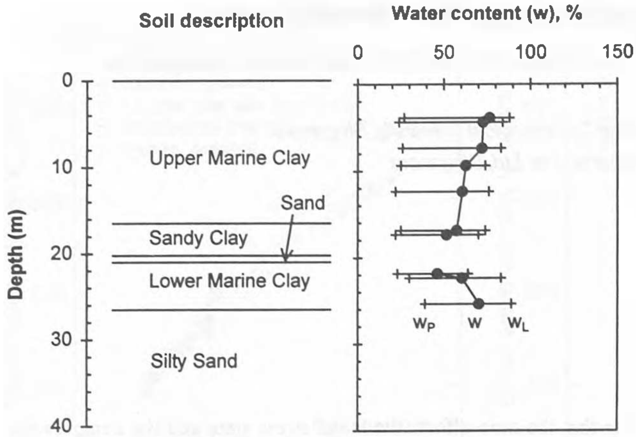

Fig. 1 Typical soil and water content profiles

of a soil to the actions prevailed in these tests is affected predominantly by the in-situ horizontal effective stress which is dictated by the OCR of the soil allows the interpretation of OCRs from results of these tests.

3.1 *Field vane test*

The field vane test (FVT) is commonly used for determining in-situ undrained shear strength in soft to medium stiff clays in Singapore. The interpretation of OCR from the undrained shear strength measured in the FVT, $(s_u)_{fv}$, is based on a consideration that the undrained strength of a clay, when normalized with the in-situ vertical effective stress (σ'_{vo}), is a direct function of the OCR.

Based on an experimental observation that the normalized undrained strength ratio, s_u/σ'_{vo} correlates strongly with the plasticity index (I_p), Mayne and Mitchell (1988) suggested a correlation as follows for estimating OCR:

$$OCR = 22(I_p)^{-0.48}\frac{(s_u)_{fv}}{\sigma'_{vo}} \tag{1}$$

There is however no unique correlation between OCR and $(s_u)_{fv}/\sigma'_{vo}$. The stress condition in the soil is very complex in the field vane test and a certain form of simplification or approximation is required in the interpretation of FVT results.

A recent theoretical study carried out by Cao (1997) on the basis of the modified Cam clay concept indicated that $(s_u)_{fv}$ can be correlated to the OCR by

$$OCR = 2\left(\frac{\sqrt{3}(s_u)_{fv}}{\sigma'_{vo}M\cos\phi'_{ps}}\right)^{1/\Lambda} \tag{2}$$

where Λ is the plastic volumetric strain ratio with a typical value of 0.75, M is the slope of the critical state line, and ϕ'_{ps} is the effective friction angle in the plane strain compression condition. Note that M and ϕ'_{ps} can be calculated or estimated from the conventional angle of internal friction in the triaxial compression condition ϕ' using $M = 6\sin\phi'/(3-\sin\phi')$ and $\phi'_{ps} = 1.12\phi'$, respectively.

3.2 *Piezocone test*

The standard piezocone test (CPTU) involves penetrating a standard electric cone with a filter element immediately behind the conical tip into the soil at a standard rate of 20 mm/s and measuring the tip resistance (q_c), the sleeve friction (f_s) and the penetration pore pressure (u_{bt}).

Various methods have been proposed to correlate piezocone data such as the corrected cone resistance (q_t) and the pore pressure ratio B_q, which is defined as $(u_{bt} - u_o)/(q_t - \sigma_{vo})$, where u_o is the in-situ porewater pressure and σ_{vo} is the total vertical stress, to OCR. Chang (1991) presented a simple correction between B_q and OCR for a conservative estimate of OCR for clays with sensitivity $S_t \leq 8$, and OCR ≤ 8. The correlation is as follows

$$OCR = 2.3B_q/(3.7B_q - 1) \tag{3}$$

A theoretical method based on the expansion of cavity in the modified Cam clay has been developed by Cao et al.(1996) for the estimation of OCR of clay directly from the q_t and the u_{bt}. The proposed expression is as follows:

$$OCR = 2\left[\frac{0.866q_t + 0.134\sigma_{vo} - u_{bt}}{\alpha_\varepsilon\sigma'_{vo}(1+0.66M)}\right]^{1/\Lambda} \tag{4}$$

where α_ε is the strain rate correction factor for cone which can be taken as 1.64, $M = 6\sin\phi'/(3-\sin\phi')$, and Λ can be assumed as 0.75 in the absence of experimental data. According to Cao et al. (1996), Eq. (4) is suitable for $B_q < 0.75$ and, for B_q from 0.75 to 0.85, the following equation should be used:

$$OCR = 2\left[\frac{q_t - u_{bt}}{\alpha_\varepsilon\sigma'_{vo}(1+0.67M)}\right]^{1/\Lambda} \tag{5}$$

3.3 *Dilatometer test*

The conventional dilatometer test (DMT) involves penetrating a dilatometer blade with a steel membrane on one side into soil at a standard rate of 20 mm/s and measuring the lift-off pressure P_o when the membrane is being inflated after the penetration stops.

Current methods for the interpretation of DMT results are highly empirical. Marchetti (1980) proposed the following correlation for the estimation of OCR for clay

$$OCR = (0.5K_D)^{1.56} \tag{6}$$

where $K_D = (P_o - u_o)/\sigma'_{vo}$ is the horizontal stress index. However, based on oedometer data at three test sites in Singapore, Chang (1991) suggested that $OCR = (0.5K_D)^{0.84}$ is more suitable for application in the Singapore marine clay.

Due to the empirical nature, existing methods of interpretation have not been universally accepted. A theoretical method has recently been developed by Cao (1997) based on the cavity expansion theory and the modified Cam clay model for estimating the OCR directly from the lift-off pressure P_o using the following expression:

$$OCR = 2\left[\frac{\sqrt{3}(P_o - \sigma_{vo})}{\alpha_d\sigma'_{vo}M(\ln I_r + 1)}\right]^{1/\Lambda} \tag{7}$$

where I_r is the rigidity index and α_d is the strain rate correction factor for flat dilatometer which can be taken as 1.57 (Cao, 1997).

For lightly to moderately overconsolidated Singapore marine clay with I_r ranging from 50 to 100, ϕ' from 19 to 25° (based on triaxial compression tests) and Λ averaging 0.85, Cao (1997) suggested that the following simplified equation deduced from Eq. (7) can be used:

$$OCR = 2\left(\frac{P_o - \sigma_{vo}}{4.13\sigma'_{vo}}\right)^{1.18} \tag{8}$$

It is interesting that the above equation is similar to Marchetti's (1980) proposed correlation between the horizontal stress index K_D and the OCR.

4. RESULTS AND DISCUSSIONS

Results of the OCR values interpreted from various in-situ tests were compared primarily with those deduced from standard oedometer tests on specimens prepared from 76.2mm or 100mm diameter undisturbed samples recovered from the reclaimed site.

Figure 2 shows the OCR profiles interpreted from the FVT data using both Mayne and Mitchell's (1988) correlation in Eq. (1) and Eq. (2), compared with the oedometer data at the four test locations. The seabed Singapore marine clay at the site is lightly overconsolidated with the OCR decreases gently from approximately 2 at around 5 m below seabed to a value ranging from 1.2 to 1.8 near the bottom of the clay. The upper part of the upper marine clay immediately beneath the seabed is moderately to heavily overconsolidated.

The comparison in Fig. 2 shows that the OCR-profile estimated from Eq. (2) proposed by Cao (1997) is very close to the oedometer profile and is consistently higher than that interpreted using Mayne and Mitchell's correlation for both the upper and the lower marine clay layers.

Figure 3 shows the OCR profiles interpreted from the CPTU data using both the B_q-method in Eq. (3) and Eqs. (4) and (5) compared with the same set of oedometer data at different locations. The presence of the moderately to heavily overconsolidated intermediated clay layer or desiccated crust of the lower marine clay is clearly shown in these continuous profiles interpreted from the CPTU data.

Equations (4) and (5) as proposed by Cao et al. (1996) appear to have provided a fairly good estimate of the OCR-profile for the upper marine clay and a very good estimate for the lower marine clay. On the other hand, the B_q-method appears to have underestimated the OCR particularly in the moderately to heavily overconsolidated part of upper marine clay immediately below the seabed. The water depth at the test site was between 6 and 8m. The high in-situ water pressure is believed to have an effect on the reliability of B_q and consequently the estimated OCRs.

Figure 4 shows the OCR profiles interpreted from the DMT data using both Chang's (1991) correlation in Eq. (6) and Eq. (8) proposed by Cao (1997) compared with the same set of

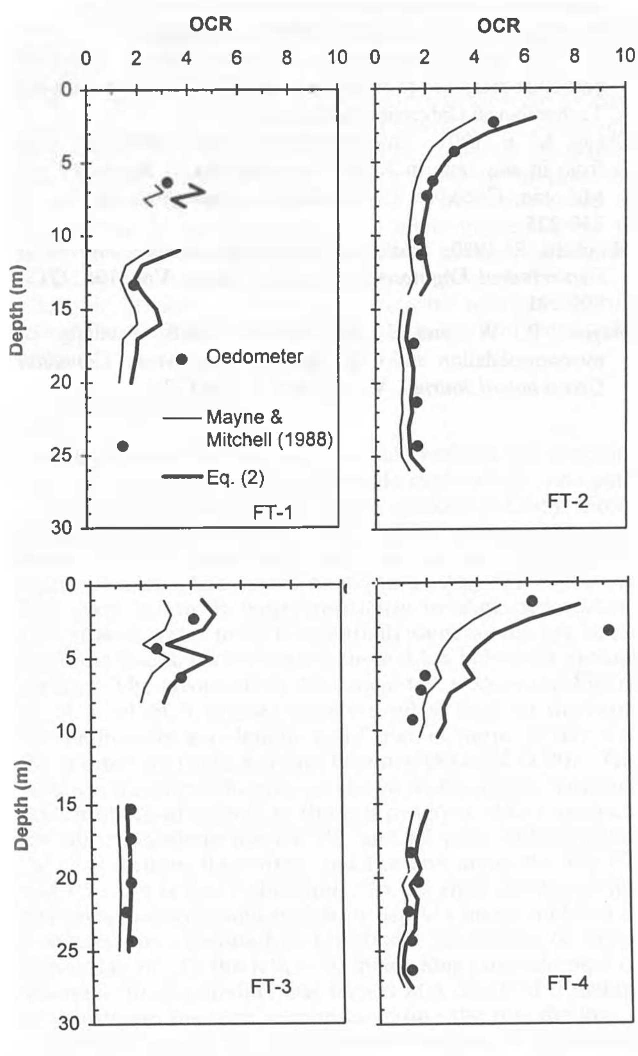

Fig. 2 Predicted OCR-profiles from FVT compared with oedometer data

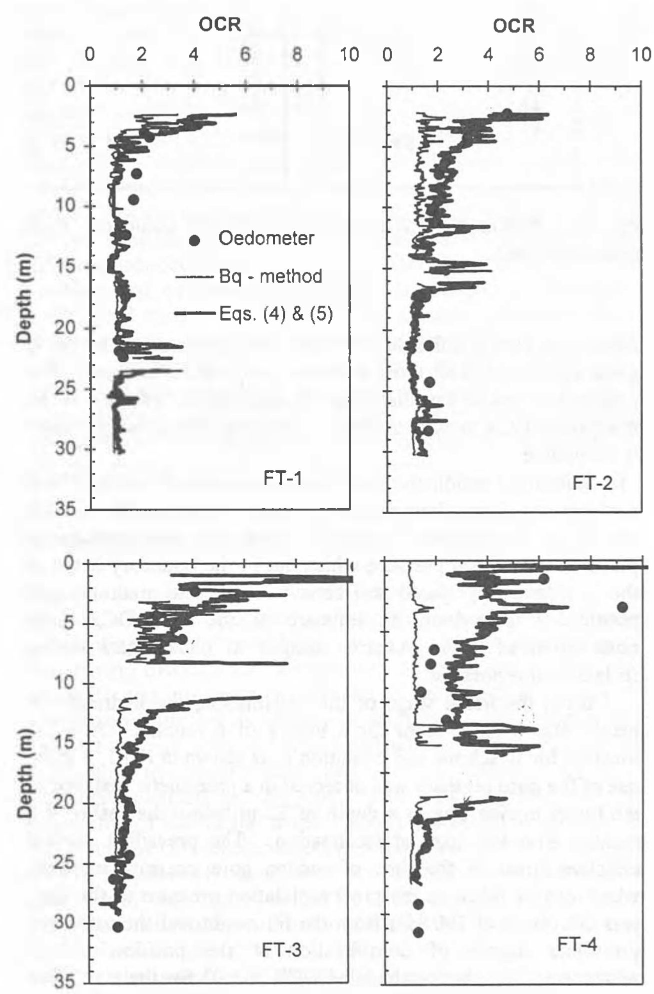

Fig. 3 Predicted OCR-profiles from CPTU compared with oedometer data

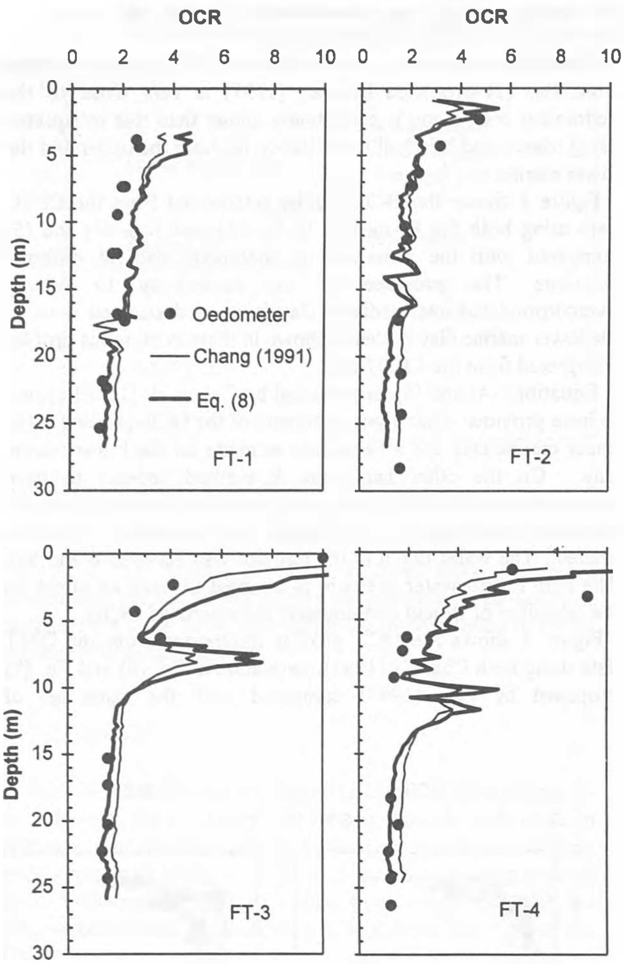

Fig. 4 Predicted OCR-profiles from DMT compared with oedometer data

oedometer data at different locations. The estimated OCRs are in good agreement with those measured in oedometer tests. The presence of the intermediate layer is also clearly reflected in the interpreted OCR profiles at the two locations where the clay layer is distinctive.

In addition to oedometer data, back-calculated OCRs from field performance obervations provide reference in-situ OCRs that are useful for verification purposes. Since the preconsolidation pressure is a critical pressure which marks the boundary between the predominantly elastic soil behaviour and the predominantly plastic soil behaviour, an estimate of the field OCR from observation of pore pressure changes in piezometers during reclamation is possible.

During the initial stage of the reclamation, the hydraulic fill height was hold at 4.5m for a period of 6 months. At FT-1 location for which the soil condition is as shown in Fig.1, a sharp rise of the pore pressure was observed in a piezometer installed in the lower marine clay at a depth of 22 m below the seabed 4.5 months after the start of reclamation. The prevailing vertical effective stress at the time of sudden pore pressure increase, which can be taken as the preconsolidation pressure of the clay, was calculated at 190 kPa from the fill height and the estimated prevailing degree of consolidation at the position of the piezometer. The back-calculated OCR is 1.43 for the clay. The measured OCR of 1.47 from an oedometer test on a sample recovered from a depth of 22.4m and the OCRs predicted from CPTU and DMT appear to agree with this back-calculated OCR value.

It should be noted that the OCR profiles provided by all the three in-situ tests are nearly continuous, especially those from the CPTU and the DMT. These continuous profiles of OCR are important particularly when the soil deposit, such as the seabed clay, has a complicated stress history in that a full detailed understanding of the soil stratification is possible.

5. CONCLUSIONS

Results of this investigation show that in-situ tests such as the FVT, the CPTU, and the DMT are useful and economical alternatives to oedometer tests for the evaluation of OCR profiles in the lightly to moderately overconsolidated seabed clay at Changi East in Singapore. With the use interpretation methods developed on the basis of sound soil mechanics principles, the reliability of these interpreted results can be improved even in the moderately to heavily overconsolidated clay. Besides important considerations such as cost and sample disturbance, the continuous OCR profiles offered by in-situ tests could also make the in-situ test based investigation methods more attractive than the traditional laboratory based methods.

6. REFERENCES

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