Analysis of Dilatometer Test in Clay

Laifa Cao
SPL Consultants Limited, Toronto, Canada. E-mail: lcao@splconsultants.ca

Ming-Fang Chang
CivilTech Engineering, USA. E-mail:changmf@gmail.com

Cee Ing Teh
Nanyang Technological University, Singapore. E-mail: cciteh@ntu.edu.sg

Keywords: dilatometer, cavity expansion, modified Cam clay, clay, OCR, undrained shear strength

ABSTRACT: This paper presents an interpretation of the flat dilatometer test in clay based on simplified theoretical solutions of cavity expansion in modified Cam clay. The lift-off pressure and pressure for 1.1 mm membrane deflection are interpreted using the framework of cavity expansion theories with due consideration of the effect of strain rate and the initial stress state. Methods for estimating the overconsolidation ratio and undrained shear strength are presented. A comparison of results obtained from the proposed correlations with limited data collected in the Singapore marine clay indicates the validity of the proposed analysis methods.

1 INTRODUCTION

The flat dilatometer test (DMT) (Marchetti 1980) produces two pressure measurements, namely p_0, the lift-off pressure, and the pressure corresponding to 1.1 mm (1.0 mm in the early stage of the DMT) of membrane deflection, p_1. Results of the DMT are commonly presented in three indices, the material index, I_D, the horizontal stress index, K_D and the dilatometer modulus, E_D, calculated from p_0 and p_1. These indices are used to interpret various soil parameters. Empirical correlations are often used in the interpretation.

Wroth (1984) indicated that correlations for estimation of soil parameters from in-situ test results can be used with confidence only if the interpretation procedure is set against a background of theory, however idealized this may be.

The analysis of soil response in a DMT can be performed using either a numerical simulation or the cavity expansion theory. An example of the numerical simulation of the dilatometer blade insertion in clay using a general finite element program was presented by Yu et. al. (1993). Insertion was modelled as the expansion of a flat cavity. A plane strain condition with no strain permitted in the vertical direction was assumed. The soil mass was idealized as an elastic-perfectly plastic medium deforming under a constant volume or undrained condition. The lift-off pressures, or the ultimate pressures, in an expansion of a cylindrical cavity and a flat cavity were found to be very close. This finding is consistent with that indicated in the field. Lutenegger & Blanchard (1990) reported similar results based on several tests with both full-displacement cylindrical pressuremeter and flat dilatometer in a number of clay deposits with the stiffness ranging from very soft sensitive marine clays to very stiff glacial clays.

Whittle & Aubeny (1993) presented a strain path method simulating the soil disturbance caused by insertion of a penetrometer. The Modified Cam Clay (MCC) model was used to predict excess pore pressures generated by the insertion of a flat plate. Whittle & Aubeny (1993) found that the length-to-width aspect ratio of the flat plate had little influence on the magnitude of excess pore pressure acting at the center of the plane. The distribution of excess pore pressure around a Marchetti dilatometer is almost the same as that around a simple pile with both showing an isotropic distribution of pore pressure in the surrounding soil. A similar distribution was obtained in a laboratory chamber test involving insertion of a flat blade into kaolin (Huang et. al. 1991).

The p_0, which is considered to be equal to the ultimate pressure, is relatively independent of the shape of the cavity. The cavity expansion theory may be used to analyze the DMT. Pool (1994), on the basis of the spherical cavity expansion theory, attempted to express p_0 as the sum of the ultimate pressure for the expansion of a spherical cavity and the shear-induced excess pore pressure. However, the ultimate pressure for the expansion of a spherical cavity is a total stress which has already included the excess pore pressure due to shear (Cao 1997). Pool's attempt was unsuccessful.

Due to the highly empirical nature, existing methods of interpretation of the DMT have not been universally accepted. Although the penetration of the dilatometer blade and the subsequent lateral expansion of the steel membrane are difficult to model, an approximate theoretical analysis may be useful in providing a practical framework for interpretation of test results.

In this paper, the flat DMT test in clay is analyzed using the cavity expansion theory. The soil is idealized as a homogeneous elasto-plastic material described by the MCC model. Both p_0 and p_1 are analyzed and related to the fundamental soil parameters and the in-situ stress state. Semi-theoretical formulas for estimating overconsolidation ratio, OCR and undrained shear strength, s_u from p_0 and p_1 are developed. These formulas are evaluated by comparing OCR and s_u profiles interpreted from dilatometer measurements with corresponding direct measurements from the field vane tests and the odometer tests in Singapore marine clay.

2 THEORETICAL ANALYSIS

Although an elaborate strain path approach, such as that considered by Whittle & Aubeny (1993), or a finite element approach such as that proposed by Yu et. al. (1993), may eventually be developed for interpreting DMT results, experimental studies indicated that a less-rigorous approach may be sufficient for practical use. One such approach is described in the subsequent paragraphs based on the following assumptions:

(1) The blade geometry is unimportant for the initial penetration stress response of the soil around the blade. This assumption has been validated by the numerical analysis (Whittle & Aubeny 1993) and results of the laboratory chamber test (Huang et. al. 1991).

(2) The lift-off pressure (p_0) is analogous to the limit pressure in a pressuremeter test. This assumption has been confirmed in the field (Lutenegger & Blanchard 1990).

Based on assumption (1), the penetration of a DMT in clay can be evaluated through the cavity expansion theory. From assumption (2), the lift-off pressure, p_0 can be estimated from the ultimate pressure during the expansion of a cylindrical cavity. The ultimate pressure, p_0 in the MCC (Cao 1997; Cao et. al. 2001) can be approximately expressed as

$$p_0 = \sigma_o + \frac{\sqrt{3}}{3} M \sigma'_o \left(\frac{R}{2}\right)^{\Lambda} (\ln I_r + 1) \qquad (1)$$

where σ_o = initial mean total stress; σ'_o = initial mean effective stress; M = critical state parameter or slope of critical state line and is equal to $6\sin\phi'/(3-\sin\phi')$; ϕ' = effective friction angle determined from conventional triaxial compression tests; R = isotropic overconsolidation ratio; Λ = plastic volumetric strain ratio I_r = rigidity index = G/s_u; G = shear modulus; s_u = undrained shear strength in plane strain compression.

For practical purposes, Eq. (1) can be simplified by substituting the in-situ vertical stress, σ_{vo} for σ_o, the in-situ effective vertical stress, σ'_{vo} for σ'_o and the conventional OCR for R and expressed as

$$p_0 = \sigma_{vo} + \frac{\sqrt{3}}{3} M \sigma'_{vo} \left(\frac{OCR}{2}\right)^{\Lambda} (\ln I_r + 1) \qquad (2)$$

The undrained shear strength in the plane strain compression condition, s_u, may be expressed approximately in terms of the in-situ effective vertical stress σ'_{vo} as (Chang et. al. 1999)

$$s_u = \frac{\sqrt{3}}{3} M \sigma'_{vo} \left(\frac{OCR}{2}\right)^{\Lambda} \qquad (3)$$

It is interesting that the combined equation from Eqs. (2) and (3) resembles Vesic's (1972) solution for the cylindrical cavity expansion, even though, Eq. (2) was derived purely from the MCC theory and s_u was defined by the MCC theory as the undrained shear strength under the plane strain compression condition. The difference between Eq. (1) and Eq. (2) is insignificant as discussed by Cao (1997).

As the undrained shear strength of clay is widely recognized to be affected by the strain rate imposed during shear, it is reasonable to expect that the measured lift-off pressure is similarly affected by the dilatometer penetration rate. In the DMT, the rate of advancing the dilatometer blade ranges from 10 to 40 mm/s. This speed of penetration corresponds to a strain rate that is much faster than the strain rate adopted in a typical laboratory triaxial compression test for clays.

The measured undrained strength generally increases with increasing strain rate. Kulhawy & Mayne (1990), by reviewing data from 26 clays tested in triaxial compression, confirmed that each log cycle increase of strain rate was accompanied by a 10% change in s_u. Cao (2003) reported that the undrained shear strength of Singapore marine clay determined from direct simple shear tests typically

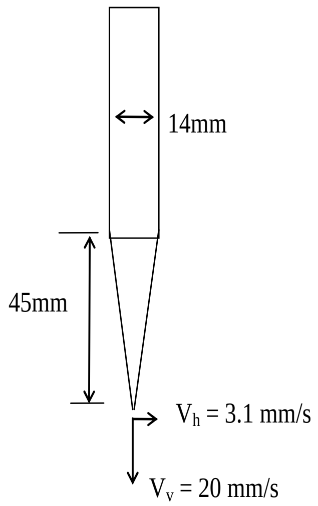

Fig. 1. Penetration velocity at a standard dilatometer test.

increased 10% with each log cycle of shear strain rate, which is consistent with Kulhawy & Mayne's (1990) finding from the triaxial compression test.

Corresponding to the vertical penetration velocity of 20 mm/s in the DMT, the horizontal penetration velocity is 3.1 mm/s, as illustrated in Fig. 1. The relevant horizontal strain rate is approximately 44.4% per second or 160,000% per hour during blade installation.

Since p_0 is measured after the blade penetration stops, the measured pressure may be assumed to be equal to the pressure acting on the membrane during blade penetration. Thus the strain rate related to p_0 is approximately 160,000% per hour.

Assuming s_u increases at 10% with per log cycle of increase in shear strain rate and no pore water dissipation from the stopping of blade penetration to the measurement of p_0, the prevailed s_u in the DMT will be about 57% higher than that from a laboratory undrained compression test at a typical strain rate of 0.5% per hour. Thus a strain rate factor, α_d, of 1.57 is appropriate for DMT and Eq. (2) can be modified as

$$p_0 = \sigma_{vo} + \frac{\sqrt{3}}{3}\alpha_d M\sigma'_{vo}\left(\frac{OCR}{2}\right)^{\Lambda}(\ln I_r + 1) \qquad (4)$$

Based on a similar argument, p_1 can be considered as the ultimate pressure during the undrained expansion of a spherical cavity as the pressure working on a circle plate is equal to the pressure working on half of a spherical surface. The ultimate pressure for a spherical cavity expansion in the MCC (Cao 1997; Cao et. al. 2001) with the consideration of the effect of strain rate can be expressed approximately as

$$p_1 = \sigma_{vo} + \frac{2}{3}\alpha_d M\sigma'_{vo}\left(\frac{OCR}{2}\right)^{\Lambda}(\ln I_r + 1) \qquad (5)$$

Similar to the undrained compression condition, the undrained shear strength in the triaxial compression condition may be expressed approximately in terms of the in-situ effective vertical stress σ'_{vo} as (Chang et. al. 1999)

$$s_u = \frac{1}{2}M\sigma'_{vo}\left(\frac{OCR}{2}\right)^{\Lambda} \qquad (6)$$

3 SITE CONDITION AND TESTING

The test site, located at Changi East, Singapore, is underlain by up to 25 meters of soft to stiff marine clays that were lightly to moderately overconsolidated. At some locations, the upper marine clay is overlain by a sand layer. The sea water level was about 3.8 to 6.0 meters above the seabed at the time of investigation.

The Singapore marine clay is the marine member of a local geologic unit known as the Kallang Formation. It consists of two members: the upper member (or the upper marine clay) and the lower member (or the lower marine clay). The upper marine clay was deposited 11 thousands years ago at the initiation of Holocene times and deposition continued until about 5 thousands years ago. The lower marine clay lies unconformably over the valley floors or dense fluvial sediments, which was believed to have been deposited during the Riss-Wurm interglacial period, about 120 thousands years ago (Tan & Lee 1977; Tan 1983). Near the top of the lower member, the soil is stiff and has a distinctive pale-red mottled appearance. This stiff layer, locally known as the intermediate layer, is believed to have derived from desiccation and weathering of the lower member when the sea level dropped during the Wurm glacial period. The stiffer layer is overlain by silty clay, beach sand or river sediments. These deposits form a boundary between the upper and lower members. Through differing in age, the two members share similarities in appearance and texture. They are laminated and are pale grey to dark grey in appearance. Both marine members are rich in kaolinite with moderate amount of montmorillonite and illite (Tan 1983), highly plastic, and have high water contents. The upper member occasionally contains sand lenses and shell fragments whereas the lower member has fine silt partings.

DMTs were conducted at four test clusters. The results expressed as p_0, p_1 and I_D with depth are shown in Fig. 2 to Fig. 5, where I_D, the material index, is defined as $(p_1 - p_0)/(p_0 - u_o)$ and u_o is the in-situ pore water pressure. The pressure p_1 which was

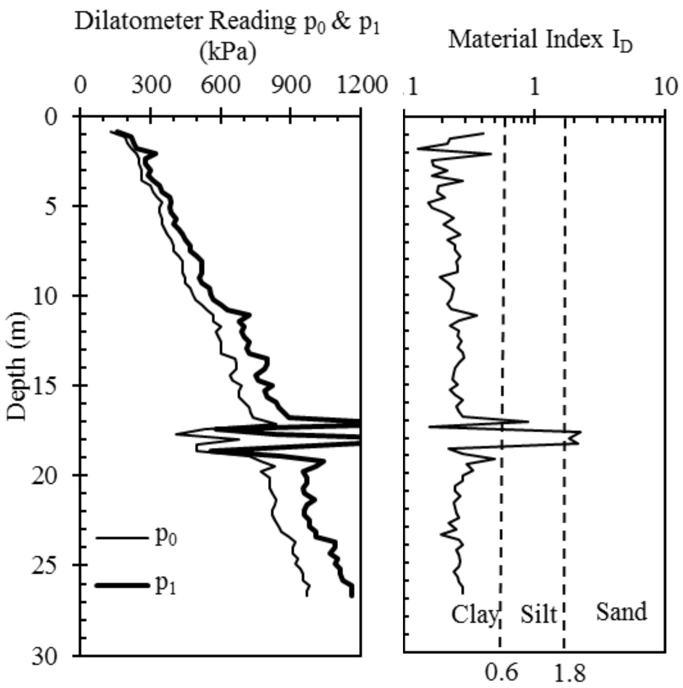

Fig. 2. Dilatometer test at test cluster 1.

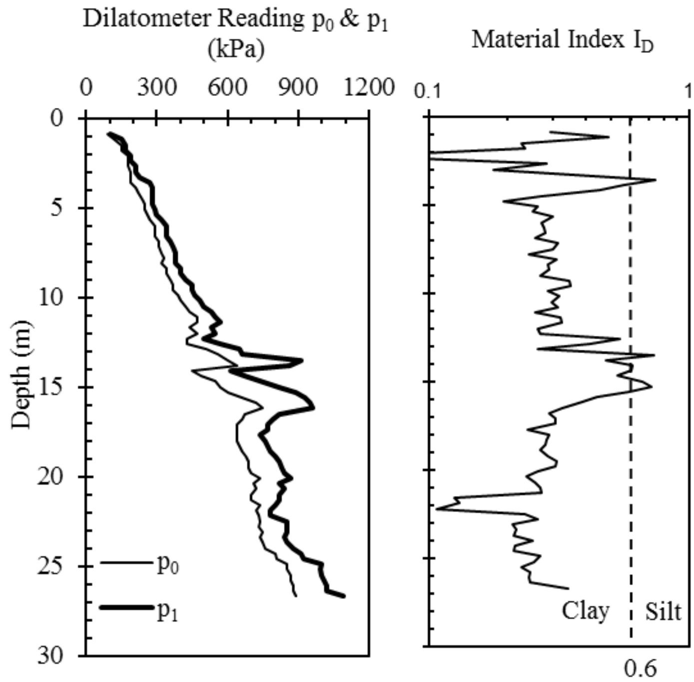

Fig. 3. Dilatometer test at test cluster 2.

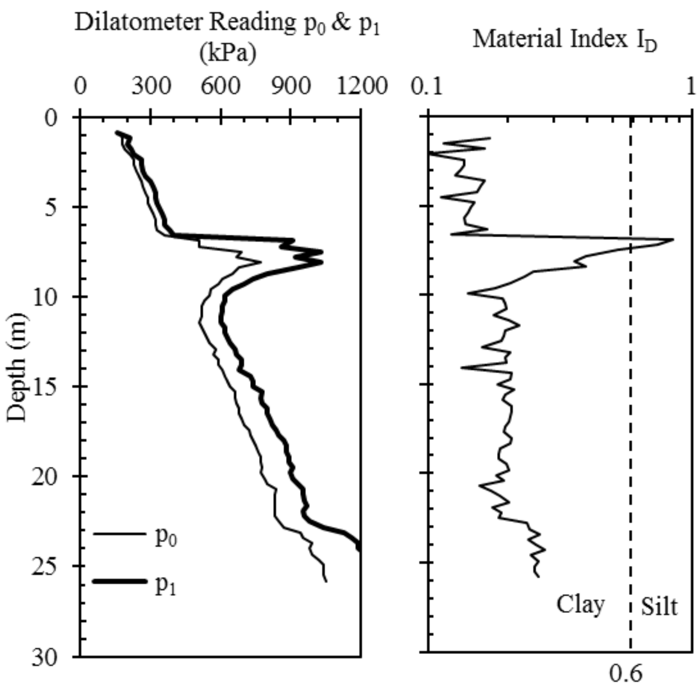

Fig. 4. Dilatometer test at test cluster 3.

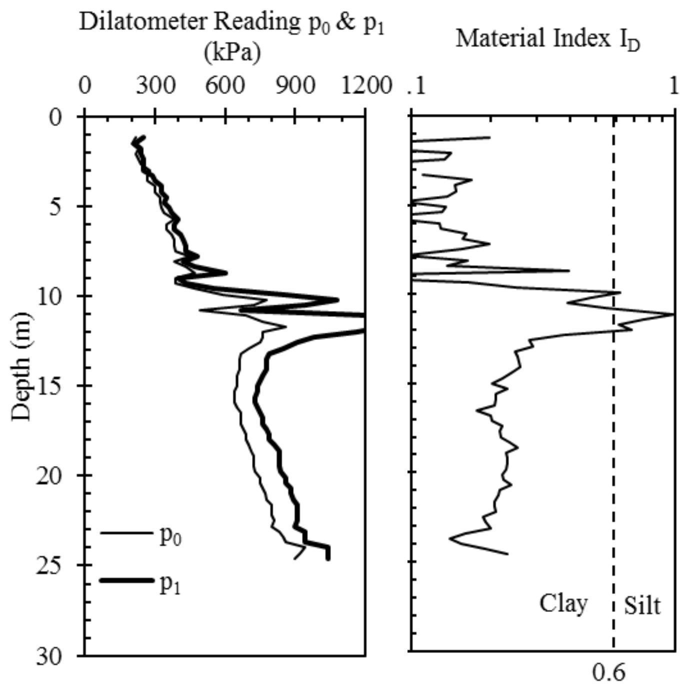

Fig. 5. Dilatometer test at test cluster 4.

the pressure corresponding to 1.0 mm of membrane deflection, is generally greater than the lift-off pressure p_0. The I_D profile shows distinctively the intermediate layer consisting of clayey to sandy silt which separates the upper and lower marine clays.

A series of laboratory tests were carried out to determinate the soil characteristics. For the upper marine clay, the plastic limit, PL ranges from 22 to 31 and the liquid limit, LL ranges from 74 to 88. The natural water content of the upper marine clay varies from 59% to 77%, which is close to LL. For the lower marine clay, PL ranges from 22 to 37, LL ranges from 63 to 90 and its natural water content varies from 44% to 70%. According to the Unified Soil Classification System, the marine clay may be classified as highly plastic clay (CH). At the site, the average bulk densities are 1.57 Mg/m^3 for the upper marine clay, 1.64 Mg/m^3 for the lower marine clay, and 1.86 Mg/m^3 for the intermediate silty clay.

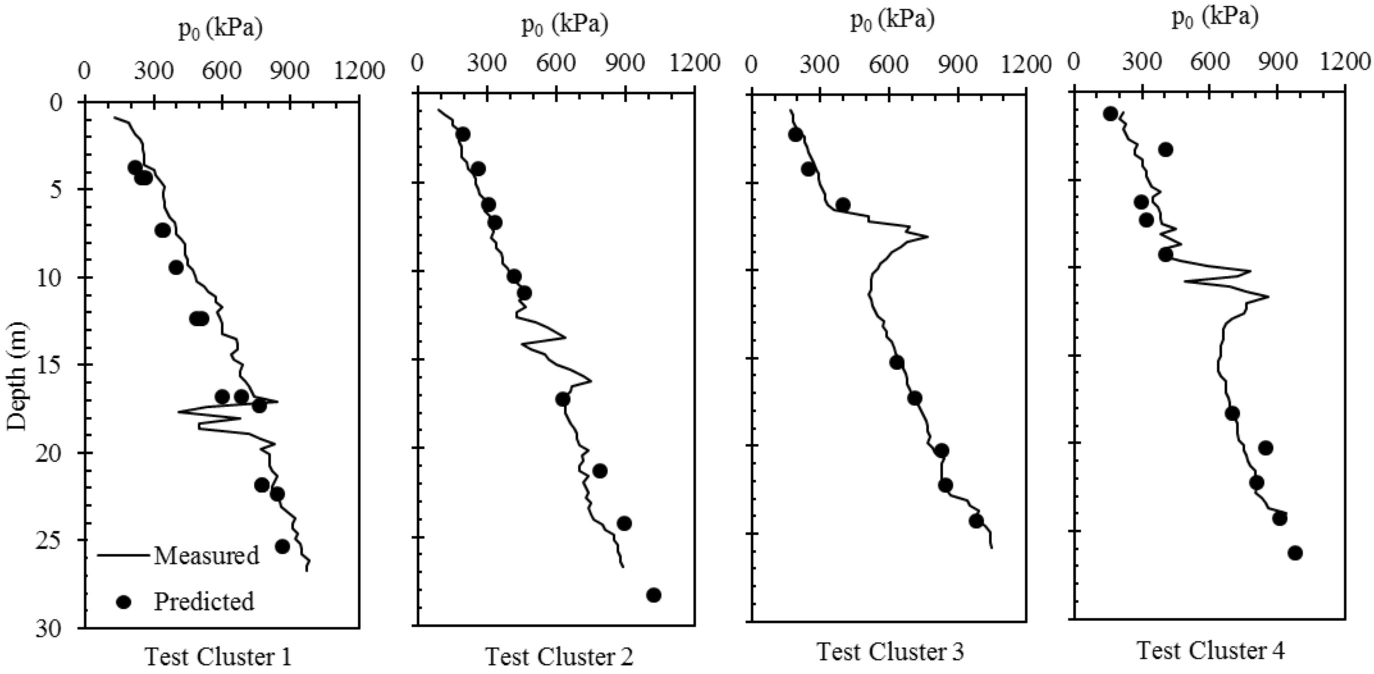

Fig. 6. Predicted versus measure p_0.

The marine clay is lightly to moderately overconsolidated with the OCR decreasing with depth in general. For the upper marine clay, OCR ranges from 1 to 3. The top part of the upper marine clay is heavily overconsolidated and the OCR is as high as 10 at some locations. The intermediate layer of silty clay is moderately overconsolidated with the OCR ranging from 2.4 to 5. The lower marine clay is slightly overconsoldiated with the OCR ranging from 1 to 2. For the upper marine clay, the magnitude of the compression index, C_c ranges from 0.31 to 1.71 and the swelling index, C_s varies from 0.044 to 0.209. The average value of Λ estimated from C_s and C_c is 0.89. For the lower marine clay, C_c range from 0.47 to 1.14 and C_s ranges from 0.038 to 0.161. The average value of Λ is 0.89. For the silty clay of the intermediate layer, C_s ranges from 0.17 to 0.40 and C_c ranges from 0.026 to 0.06. The average value of Λ is 0.86.

For the upper marine clay, the I_r calculated from the G at half of the maximum shear stress and s_u varies from 32 to 100 with an average value of 66. The s_u obtained from the samples isotropically consolidated under the respective effective in-situ vertical stress ranges from 13.6 to 36.2 kPa. The effective friction angle ϕ' is between 20 and 25°. For the lower marine clay, the I_r value ranges from 47 to 108 with an average value of 79, which is slightly higher than that of the upper marine clay. The s_u obtained from the samples isotropically consolidated under the respective effective in-situ vertical stress ranges from 54.7 to 60.3 kPa. The value ϕ' ranges from 20^o to 24^o, which is similar to that for the upper marine clay.

The M determined from the effective stress paths on the plane of mean effective stress and deviator stress is 0.91 for the upper marine clay and 0.89 for the lower marine clay. These M values correspond to effective friction angles of 23.2^o for the upper marine clay and 22.8^o for the lower marine clay at the critical state. At the failure state, the stress paths normally fall on the critical state line.

4 INTERPRETATION OF TEST RESULTS

4.1 *Comparison of predicted and measured p_0 and p_1*

Eq. (4) was used to calculate the lift-off pressure p_0. Fig. 6 shows the predicted and the measured values of p_0 at four test clusters. The soil parameters M, and I_r were based on the triaxial shear strength test and the values of OCR and Λ were obtained from oedometer tests. At test cluster 1, the values of p_0 predicted by Eq. (4) are slightly lower than those measured by the DMT. The values of the predicted p_0 are close to the measured data for the upper marine clay and slightly greater than the measured data for the lower marine clay at test cluster 2. At test clusters 3 and 4, the predicted p_0 values are in good agreement with those measured by the DMT.

The pressures for 1 mm membrane deflection

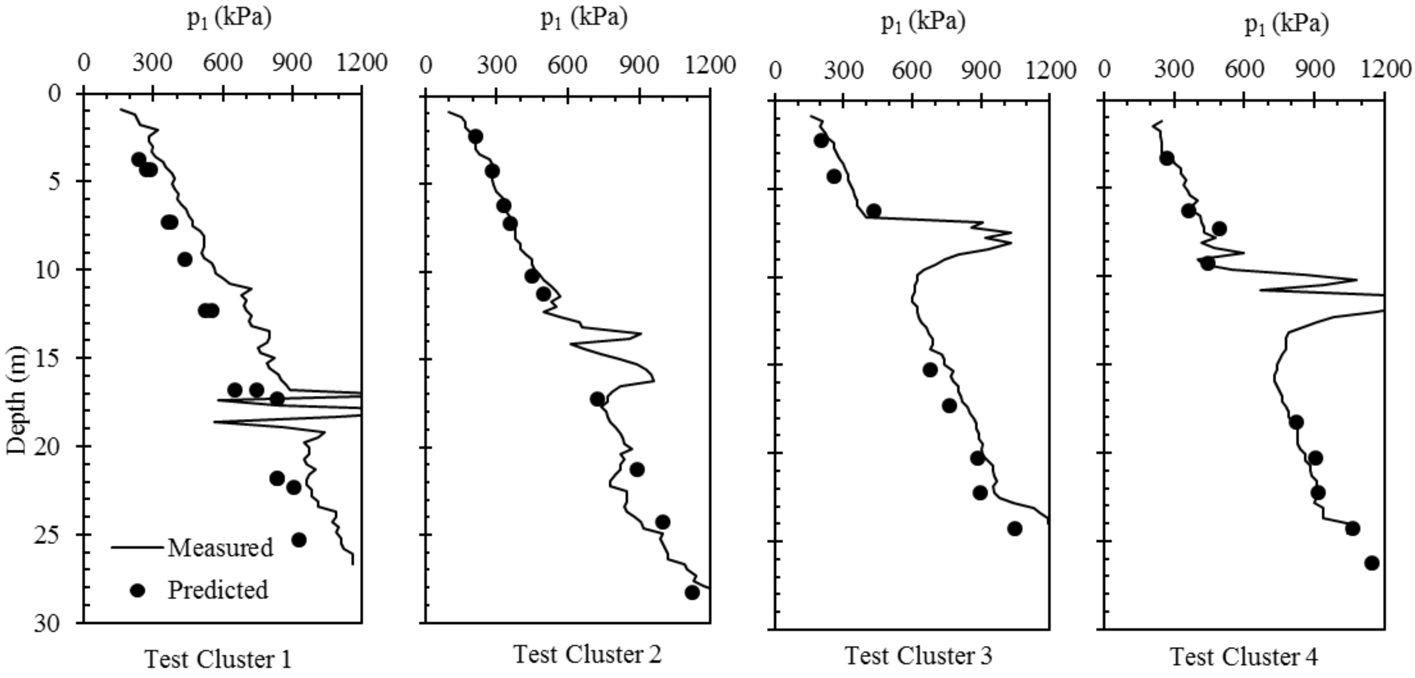

Fig. 7. Predicted versus measure p_1.

predicted by Eq. (5) with the measured p_1 at four test clusters are shown in Fig. 7. At test clusters 1 and 3, the values of p_1 predicted by Eq. (5) are slightly lower than those measured by the DMT. At test clusters 2 and 4, the predicted p_1 is in good agreement with those measured by the DMT.

The good agreement between p_0 or p_1 and the ultimate pressure for a cavity expansion indicate that the difference between p_0 and p_1 is not a good indicator of the elastic modulus for the soft to stiff clayey soils. This confirms the finding of Marchetti et. al. (2001) who suggested that E_D defined as $34.7(p_1 - p_0)$ should not be usable directly as a soil modulus, but first be corrected, by using the correction factor which depends on OCR or stress history (K_D) and type of material (I_D).

4.2 *Estimation of OCR and s_u from p_o and p_1*

Since the p_o and p_1 can be reasonably interpreted by the theories of cylindrical and spherical cavity expansions in the MCC, respectively as presented in Eqs. (4) and (5), the OCR and s_u can be estimated from p_0 and p_1 as follows

$$OCR = 2\left[\frac{\sqrt{3}(p_0 - \sigma_{vo})}{1.57\sigma'_{vo} M(\ln I_r + 1)}\right]^{1/\Lambda} \tag{7}$$

$$OCR = 2\left[\frac{1.5(p_1 - \sigma_{vo})}{1.57\sigma'_{vo} M(\ln I_r + 1)}\right]^{1/\Lambda} \tag{8}$$

$$s_u = \frac{p_0 - \sigma_{vo}}{1.57(\ln I_r - 1)} \tag{9}$$

$$s_u = \frac{p_1 - \sigma_{vo}}{2.09(\ln I_r - 1)} \tag{10}$$

Theoretically, the s_u estimated from Eq. (9) corresponding to the plane strain compression condition is slightly greater than the s_u estimated from Eq. (10) corresponding to the triaxial compression condition (Chang et. al. 1999).

Note that Eqs. (7) to (10) are dependent on I_r, M, and/or Λ which are not readily available. For the Singapore marine clay, I_r normally ranges from 30 to 110 and the effective friction angle ranges from 20^o to 25^o. In cases where the soil properties are not available, average values of $I_r = 75$, $\phi' = 23^o$ and $\Lambda = 0.85$ can be adopted in Eqs. (6) to (9) for an approximate estimate of OCR and s_u profiles for soft to stiff clay deposits using the reading p_0 and p_1 measured from the DMT. The simplified expressions of Eqs. (7) to (10) become

$$OCR = 2\left(\frac{p_0 - \sigma_{vo}}{4.13\sigma'_{vo}}\right)^{1.18} \tag{11}$$

$$OCR = 2\left(\frac{p_1 - \sigma_{vo}}{4.77\sigma'_{vo}}\right)^{1.18} \tag{12}$$

$$s_u = 0.12(p_0 - \sigma_{vo}) \tag{13}$$

$$s_u = 0.09(p_1 - \sigma_{vo}) \tag{14}$$

4.3 *Comparison of predicted and measured OCR and s_u*

Fig. 8 shows the OCR profiles developed using Eqs.

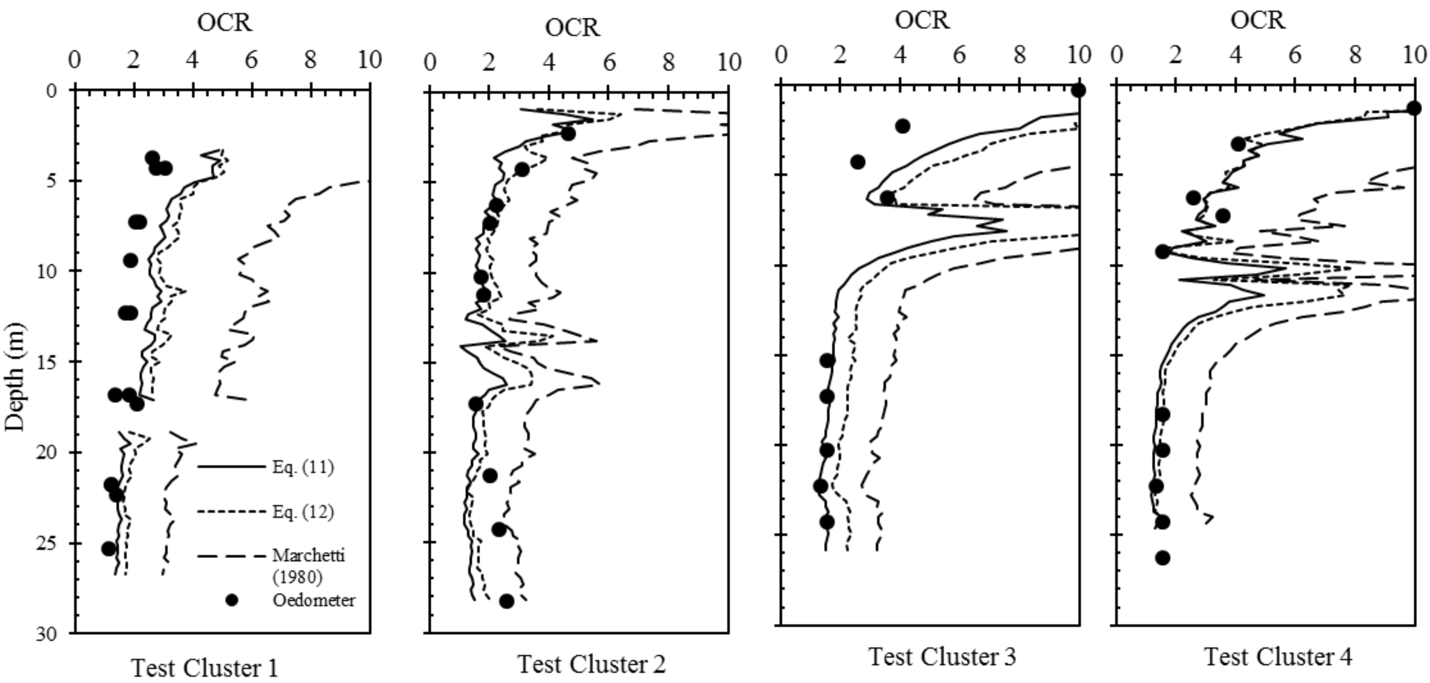

Fig. 8. Predicted versus measure OCR.

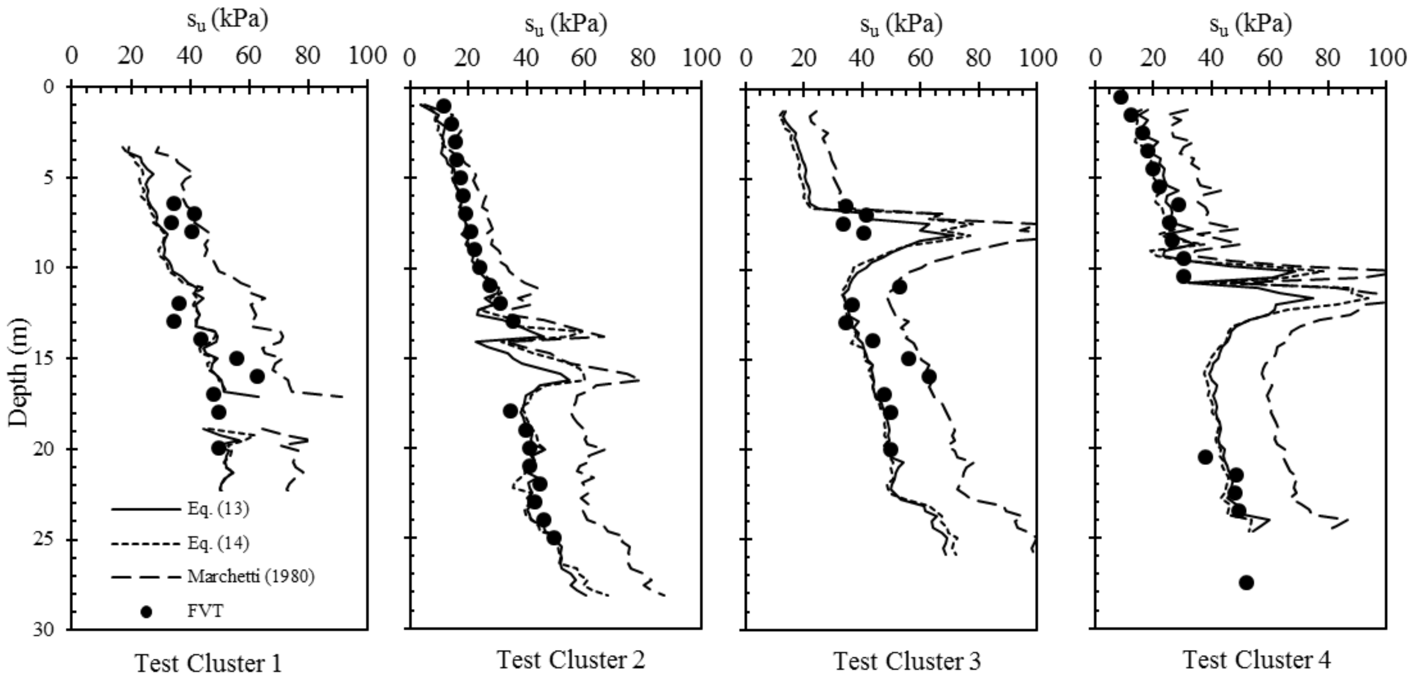

Fig. 9. Predicted versus measure OCR.

(11) and (12) for the marine clay at the Changi East site. At test cluster 1, the predicted OCR values are slightly lower than those measured by the oedometer tests. The values of the predicted OCR are close to the oedometer measured data for the upper marine clay and slightly greater than the oedometer measured data for the lower marine clay at test cluster 2. The values of the predicted OCR are close to the oedometer measured data for the lower marine clay and slightly lower than the oedometer measured data for the upper marine clay at test cluster 3. At test cluster 4, the predicted OCR values are in good agreement with those measured by the oedometer tests. The OCR values estimated using Marchetti's (1980) correlations, $OCR = (0.5K_D)^{1.56}$ and $K_D = (p_0 - u_o)/\sigma'_{vo}$, are found to have overestimated the OCR values for the Singapore marine clay, as illustrated in Fig. 8.

Fig. 9 shows the s_u profiles estimated using Eqs. (13) and (14) for the marine clay at the Changi East site. The predicted s_u values are generally in good agreement with those measured in the field vane test (FVT). The s_u values deduced from Marchetti's (1980) correlation $s_u = 0.22\sigma'_{vo}(0.5K_D)^{1.25}$ generally overestimated the s_u values for the Singapore marine clay, as shown in Fig. 9.

5 CONCLUSIONS

The theoretical solutions for the expansions of cylindrical and spherical cavities in an unbounded modified Cam clay are applied to the interpretation of the flat dilatometer test in clay. The initial stress state of the material is incorporated in the derivation of the theoretical solution. The proposed approach takes into account the effect of the strain rate imposed by pushing the dilatometer blade at a penetration rate of 20 mm/s. The approximate analogy between the cylindrical cavity expansion and blade penetration enables the modification of the theoretical solution for the interpretation of the lift-off pressure, p_0. Similarly, the approximate analogy between the spherical cavity expansion and membrane expansion enables the modification of the theoretical solution for the interpretation of the pressure that corresponds to 1.1 mm (or 1.0 mm in the early stage of the DMT) membrane deflection, p_1. Correlations have been proposed for the interpretation of the overconsolidation ratio, OCR and the undrained shear strength, s_u from p_0 and p_1.

The proposed framework has been applied to the data collected in the Singapore marine clay. A comparison of OCR and s_u values estimated based on the proposed methods with direct measurements by other independent means indicates the validity of the proposed approach. Further verification of the proposed methods for other clays is needed.

6 REFERENCES

Cao, L. F. (1997). “Interpretation of in-situ tests in clay with particular reference to reclaimed sites.” *Ph.D. Thesis*. Nanyang Technological University, Singapore.

Cao, L. F., Teh, C. I. and Chang, M. F. (2001). “Undrained cavity expansion in modified Cam clay I: Theoretical analysis.” *Géotechnique*, 51(4), 323-334.

Cao, L. F. (2003). “Soil investigation in land reclamation.” *Proc. 1st World Forum of Chinese Scholars in Geotechnical Engineering*, Shanghai, China, 334-360.

Chang, M. F., Teh, C. I. and Cao, L. F. (1999). “Critical state strength parameters of saturated clays from modified Cam clay.” *Canadian Geotechnical Journal*, 36(5), 876-890.

Huang, A. B. and Bunting, R. D. and Carney, T. C. (1991). “Piezoblade tests in a clay calibration chamber.” *Calibration Chamber Testing*, Elsevier, New York, 161-173.

Kulhawy, F. H. and Mayne, P. W. (1990). “Manual on estimating soil properties for foundation design.” *Report EL-6800*, Electric Power Research Institute, Palo Alto, California.

Lutenegger, A. J. and Blanchard, J. D. (1990). “A comparison between full displacement pressuremeter tests and dilatometer in clay.” *Proc. 3rd International Symposium on Pressuremeter*, Oxford, 309-320.

Marchetti, S. (1980). “In situ test by flat dilatometer.” *Journal of Geotechnical Engineering*, ASCE, 106(3), 299-321.

Marchetti, S., Monaco P., Totani G. and Calabrese M. (2001). “The flat dilatometer test (MDT) in soil investigation.” A Report by the ISSMGE Committee TC16. *Proc. IN SITU 2001 Intnl. Conf. On In Situ Measurement of Soil Properties*, Bali, Indonesia,41.

Pool, R. G. (1994). “Rational framework for interpreting overconsolidation ratio, undrained strength ratio, and lateral stress coefficient from flat dilatometer tests in clay.” *Master Thesis*, Georgia Institute of Technology, Atlanta, Georgia.

Tan, S. B. and Lee, K. W. (1977). “Engineering geology of the marine member of the Lallang Formation.” *Proc., International Symposium of Soft Clay*, Bangkok, 75-88.

Tan, S. B. (1983). “Geotechnical properties and laboratory testing of soft soils in Singapore.” *Proc. International Seminar on Construction Problems in Soft Soils*, Singapore, 1-47.

Vesic, A. S. (1972). “Expansion of cavities in infinite soil mass.” *Journal of the Soil Mechanics and Foundations Division*, ASCE, 98(SM3), 265-290.

Whittle, A. J. and Aubeny, C. P. (1993). “The effects of installation disturbance on interpretation of in situ tests in clay.” *Predictive Soil Mechanics, Proc. Wroth Memorial Symposium*, Thomas Telford, London, 742-767.

Wroth, C.P. (1984). “The interpretation of in situ soil test.” *Géotechnique*, 34(4), 449-489.

Yu, H. S., Carter, J. P. and Booker, J. R. (1993). “Analysis of the dilatometer test in undrained clay.” *Predictive Soil Mechanics, Proc. Wroth Memorial Symposium*, Thomas Telford, London, 783-795.