Comparison of consolidation parameters measured by laboratory and *in-situ* tests

Comparaison des paramètres de consolidation mesures par des tests en laboratoire et *in situ*

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ABSTRACT: Both laboratory and in-situ tests were conducted to measure the consolidation properties of Singapore marine clay. These measurements were also compared with that back calculated from field monitoring data. It is concluded from the study that the horizontal coefficient of consolidation, c_h, measured by piezocone tests are in good agreement with that by Rowe cell, when Teh and Houlsby's method is used for interpretation. When vertical drains are installed, the global c_h value of the soil layer as back calculated from field monitoring data, is lower than that obtained from either the in-situ or laboratory measurements.

1 INTRODUCTION

The existing Changi Airport of Singapore was constructed on about 700 ha of reclaimed land in the early 1980's. In order to cater for future expansion of the Airport, a further 1500 ha of land is currently being reclaimed at Changi East next to the existing Changi Airport. This offshore land reclamation is carried out by firstly placing hydraulic sand fill on to seabed marine clay and then consolidating the clay by mean of vertical drains and surcharge. As vertical drains were used to accelerate the consolidation process, the permeability and consolidation properties of the soil in both vertical and horizontal directions became important design parameters. Although various laboratory and in-situ testing methods have been used to determine the coefficient of consolidation, there are uncertainties involved in each method. The objective of this paper is to compare the consolidation parameters of Singapore marine clay measured by laboratory and in-situ tests. The laboratory tests were oedometer and Rowe cell tests on good quality undisturbed samples. The in-situ tests included BAT permeameter, piezocone (CPTU), flat dilatometer (DMT), and self-boring pressuremeter (SBPT) tests. In addition, the consolidation parameters were also back calculated using the field monitoring data.

2 THE BASIC SOIL PROPERTIES

The Singapore marine clay at Changi is a Quaternary deposit that lies within valleys cut in the Old Alluvium. The soil profile can be divided into three layers, the upper marine clay, the intermediate, and the lower marine clay layers. The thickness of each layer varies with locations. Typically, the upper marine clay layer ranges from 0 – 5.5 m to about 10 – 25 m below the seabed. It is generally overconsolidated with OCR ranging from slightly large than 1 to 4. The undrained shear strength of the upper marine clay varies from 10 to 30 kPa. The liquid limit of the clay is between 70 to 80% and the plastic limit 20 to 30%. The natural water content is in the range of 68 to 75%. Marine or organic matters are often found in the upper marine clay layer. Below the upper marine clay layer is the intermediate layer which is a moderately overconsolidated stiff sandy silt or sandy clay layer of a thickness of 3 to 5 m. Below the intermediate clay layer is the lower marine clay layer ranging to a depth of 40 to 50 m below the seabed. The lower marine clay layer is not homogeneous, but occasionally interbeded with sandy clay, peaty clay, and sand layers. This layer has a natural water content of between 50% to 65% and plasticity index (PI) of 45% to 65%. The clay is lightly overconsolidated with an undrained shear strength varying from 30 to 60 kPa. More information on the soil profile and soil properties is described in Bo Myint Win et al (1998).

3 LABORATORY MEASUREMENTS

Large diameter thin wall samples of nature seabed marine clay were taken from an offshore pontoon and used for this study. For the upper marine clay ranging up to 7 m below the sea bed, 180 mm in diameter samples were retrieved in order to minimize the sample disturbance and enable Rowe cell tests to be conducted on 150 mm diameter specimens. Below 7 m, 100 mm in diameter thin wall stationary piston samples were recovered. All the samples were carefully sealed on site immediately after sampling. The fresh samples were wire trimmed carefully into specimens and tested in the site laboratory.

Oedometer tests were used to determine the coefficient of consolidation of soil in the vertical direction, c_v. Rowe cells with diameters of both 70 mm and 150 mm were used to determine the coefficient of consolidation in the horizontal direction, c_h.

3.1 Measurement of c_v

The c_v versus depth profiles as measured by oedometer tests on samples taken from five locations are presented in Fig. 1. The five locations were taken along the proposed runway with a distance of 30 to 90 m apart. As c_v is dependent on the vertical stress, only the c_v values at a vertical stress of 400 kPa, i.e., in the virgin compression range, are presented and used in the subsequent discussion. For Location 1C, the data obtained from two boreholes which were only a few meters apart are presented in Fig. 1 and a good agreement is evident. The variation in the data obtained from different locations reflects the natural variability of the soil properties and the differences in the soil profiles at the reclamation site. Generally, it can be seen from Fig. 1 that the c_v values are in the range of 0.5 to 1.7 m^2/yr for the upper and 0.5 to 2.3 m^2/yr for the lower marine clay.

3.2 Measurement of c_h

As the conventional oedometer cell only permits drainage in the vertical direction, a vertically trimmed (i.e., along the axis of the sample tube) specimen has to be used to measure the c_h of soil. However, this method is questionable, as the principal stress direction applied to the oedometer specimen is 90^0 different from that in the field. The c_h and c_v values measured by oedometer

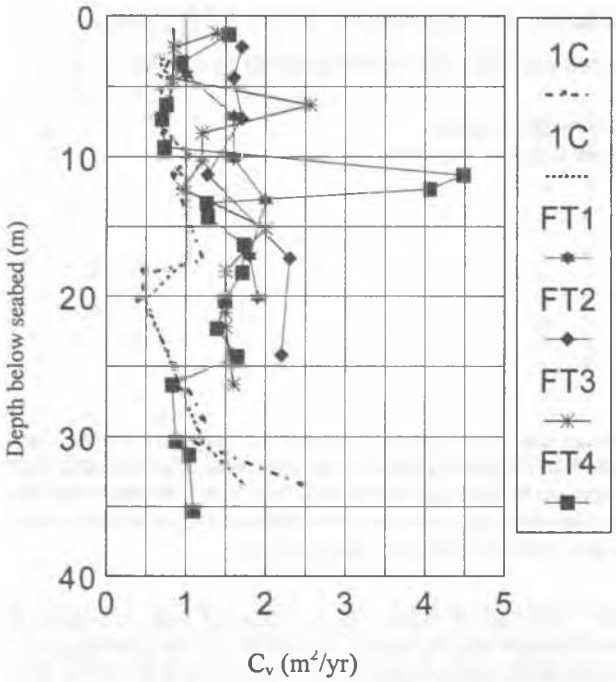

Figure 1 The C_v profiles at 5 different locations measured by oedometer tests.

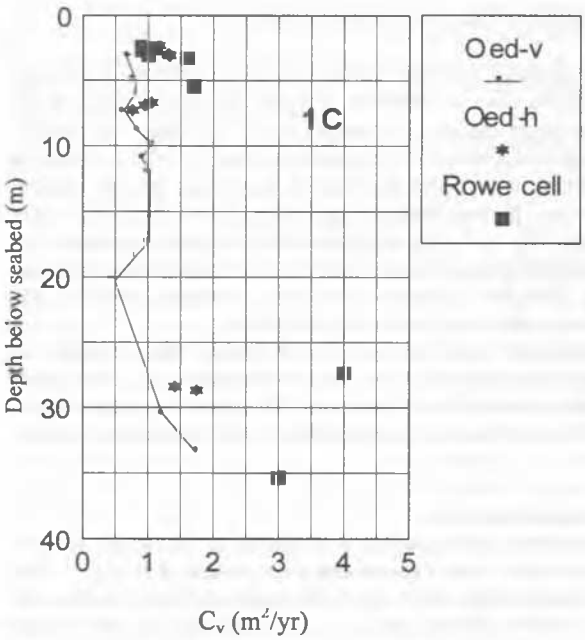

Figure 2 The C_v and C_h profiles at location 1C measured by oedometer and Rowe cell tests.

tests with both vertically and horizontally cut specimens and Rowe cell tests on samples taken from Location 1C are compared in Fig. 2. It can be seen that the c_h value is about two times larger than the c_v value for the upper marine clay and is about 3 to 4 times larger for the lower marine clay. The c_h value appears to increase with depth.

4 IN-SITU TESTS

The c_h values of natural soils can be affected considerably by the stratification or the fabric of the soils which may not be measured by laboratory tests because the dimensions of the specimens are normally small. Therefore, in-situ tests including CPTU dissipation, DMT and SBPT holding tests were also conducted to measure the c_h values of soil at different depths. In-situ permeability tests using the BAT permeameter were also conducted to determine the in-situ permeability in the horizontal direction, k_h.

4.1 *Piezocone (CPTU) Dissipation Test*

The CPTU used had a standard cone tip area of 1000 mm^2 and an apex angle of 60^0. The pore pressure filter was located just behind the cone tip. CPTU dissipation tests were carried out at various depths along a borehole. Both the methods proposed by Baligh and Levadoux (1980) and Teh and Houlsby (1991) were used to calculate the c_h values.

As postulated by Baligh and Levadoux (1980), c_h obtained from early stages of dissipation corresponds to the c_h values in the OC range. Therefore, a conversion was made to convert the measured c_h to the values in the NC range. One method suggested by Baligh and Levadoux (1980) is as follows:

$$c_h(NC) = \frac{RR}{CR} c_h(CPTU) \tag{1}$$

where: $$RR = \frac{C_r}{1+e_0} \quad \text{and} \quad CR = \frac{C_c}{1+e_0} \tag{2}$$

in which RR and CR are respectively recompression and compression ratios, C_r and C_c are recompression and compression indices measured from the e – log σ'_v curve, and e_0 is the initial void ratio of the soil.

4.2 *Dilatometer (DMT) Dissipation Test*

A Marchetti type DMT with a blade 96 mm in width, 230 mm in length, and 14 mm in thickness was used in the study. A 60 mm diameter membrane with a sensing disc behind was attached on one side of the blade. In the DMT test, only the lateral total stress (σ_h) but not the pore-water pressure is measured. According to Marchetti and Totani (1989), for tests in soft clays, a significant proportion of the measured total lateral stress against the blade is the pore-water pressure. The decay of σ_h corresponds largely to the decay of pore-water pressure generated from penetration of the blade. An approximate relationship can be established between the rate of decay of σ_h and the c_h of the soil. The c_h of the soil can then be estimated using either the *A*-reading (DMTA) or the *C*-reading (DMTC) obtained from a DMT dissipation test. Similar to CPTU tests, the c_h values determined from either DMTA or DMTC correspond to the unloading/reloading range. Corrections were made to obtain the in-situ c_h values using a relation similar to Eq. (1).

4.3 *Self-Boring Pressuremeter (SBPT) Holding Test*

A special version of the Cambridge *SBPT MKX(D)* was used in this study. The probe was 83 mm in diameter, 1.4 meters long. During a SBPT holding test, the pore-water pressure dissipation was measured by a pore-water pressure cell. The c_h was calculated based on the pore water pressure measurment. Similar to the CPTU and the DMT, the c_h values determined from SBPT tests correspond to the unloading/reloading range and were corrected to obtain the c_h values for the NC range using the conversion shown in Eq. (1).

4.4 *BAT Permeability Test*

The BAT permemeter developed by Torstensson (1983) was used to directly determine the in-situ k_h values. The BAT filter was 30 mm in diameter and 40 mm in length. The tests were carried out as an 'inflow' test. As water flowed into the probe, the air pressure in the chamber changed.

4.5 *Back Calculation Based on Field Data*

The settlement and pore water pressure responses during consolidation under surcharge were monitored at several selected locations. These monitoring data enable the field c_h values to be back calculated. At Location FT2 where vertical drains were installed, the c_h values were back calculated based on the settlement monitored at different elevations and are in the range of 0.7 to 1.2 m^2/yr (Bo Myint Win et al, 1997). In the back calculation, the ultimate settlement was estimated based on Asoka's method (Asoka, 1978). The settlement data of up to 15 months or roughly 90% of degree of consolidation were used in constructing the Asoka plot. The ultimate consolidation settlement obtained from the Asoka plot was checked using SAGE CRISP.

5 COMPARISONS OF DIFFERENT MEASUREMENTS

The c_h values measured by various methods at Location FT2 are compared in Fig. 3. At FT2, the soil improvement scheme was designed for the underlying clay to reach a 90% average degree of consolidation within 18 months and a c_h value of 1.0 m^2/yr and 2.0 m^2/yr was used for the upper and the marine clay layers respectively. Based on the laboratory and in-situ measurements shown in Fig. 3, the design values were on the conservative side. Even though, the field consolidation rate was slower than expected. This is reflected in the back-calculated c_h values that are lower than the c_h values adopted in the design. This observation indicates that the c_h value of the soil – vertical drain system could be lower than the c_h value measured for the soil.

A comparison of the c_h values obtained by various methods at Location 1C is shown in Fig. 4. It is again observed that the back-calculated c_h values are lower than those measured by in-situ tests. Similar cases have also been reported by Balasubraniam et al (1995) and Chun et al (1997).

The lower c_h values could be mainly due to the smear and disturbance effect to the soil caused by the installation of vertical drains. A study made by Bo Myint Win et al (2000) has shown that the permeability of the soil can be reduced by an order of magnitude due to smear effect and the k_h of the soil in the smear zone is as small as the k_h of the remolded clay. The smear zone is about 4 to 5 times the equivalent diameter of the vertical drain (Bo Myint Win et al, 2000). For vertical drains installed at a spacing of 1.5 m, the soil layer can be much disturbed. Therefore, it is understandable that the overall c_h values of the soil as back calculated are likely to be much smaller than that of the intact soil. For the same reason, the k_h or c_h values measured by the CPTU or the BAT permeameter may also be affected by the smear effect. This is because the piezocone or the BAT permeameter has to be pushed into the clay, hence the clay adjacent to the piezometer tip has been smeared. The smear effect for BAT permeameter may be larger than that for the CPTU as the BAT permeameter used had a filter with a larger surface area. On the other hand, the c_h derived from the total pressure decay in the DMT dissipation test may not be greatly affected by the smear effect as the flow of water is not directly measured. The results of SBPT holding tests are much less affected by the smear effect due to its self-boring mechanism. This may have explained why the c_h values measured by CPTU and BAT permeability are normally lower than the measurements by DMT and SBPT.

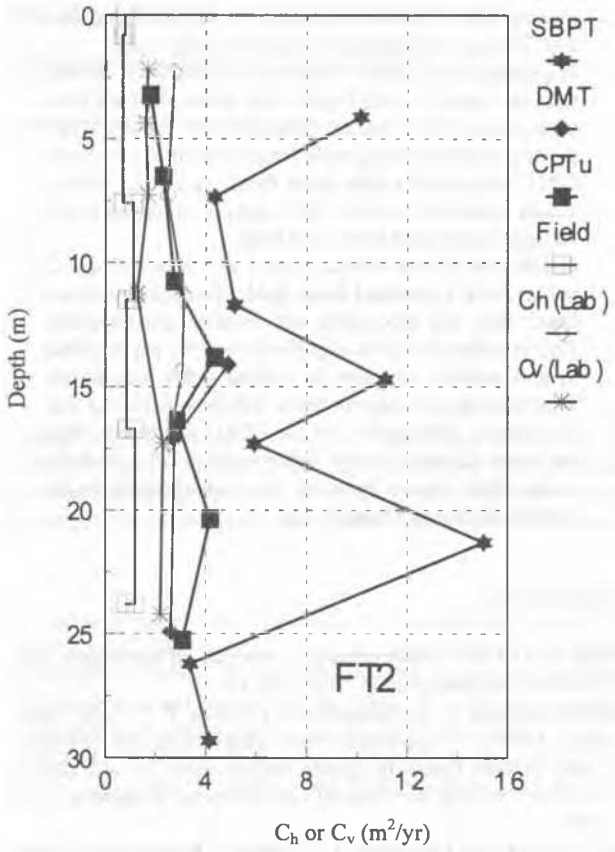

Figure 3 Comparison of C_h profiles measured by different methods and back calculation at location FT2

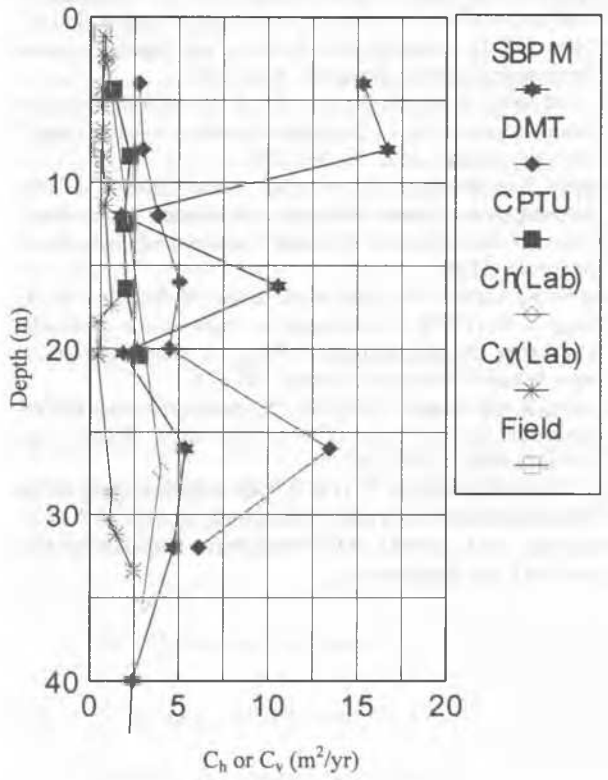

Figure 4 Comparison of C_h profiles measured by different methods and back calculation at location 1C

6 CONCLUSIONS

The following conclusions can be drawn from the study:

1. The c_h values derived from the CPTU dissipation tests generally agree well with those from Rowe cell tests, when Teh and Houlsby's interpretation method is used.
2. The c_v value of Singapore marine clay at the NC state is in the range of 0.5 to 2.0 m^2/yr. The c_h value of the soil at NC state is in the range of 2.0 to 5.0 m^2/yr as

measured by the Rowe cell and the CPTU dissipation test. The c_h value generally increases with depth.

3. In general, the c_h values measured by the SBPT holding tests are usually much higher than those obtained from other tests. The c_h values deduced from the DMT dissipation tests are marginally larger than those from the CPTU, but smaller than those from the SBPT. The c_h values obtained from the DMT appear to have a larger variation compared with other tests.
4. In the area where vertical drains are installed, the c_h values back calculated from field monitoring data are lower than the laboratory and in-situ measurements. This is indicative of the significance of the smear effect in soft marine clay due to vertical drain installation. When design soil improvement schemes involving vertical drains, laboratory and the CPTU dissipation tests are more suitable for the determination of c_h and the smear effect has to be taken into consideration in selecting the design values for c_h.

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