Geotech Geol Eng
DOI 10.1007/s10706-007-9137-4

ORIGINAL PAPER

Dissipation Testing of Singapore Marine Clay by Piezocone Tests

A. Arulrajah · M. W. Bo · H. Nikraz · A. S. Balasubramaniam

Received: 2 August 2006 / Accepted: 5 July 2007

Abstract In situ dissipation tests provide a means of evaluating the in situ coefficient of consolidation due to horizontal flow and hydraulic conductivity in horizontal direction in marine clays formation. Dissipation tests by means of piezocone were utilised in the characterisation of the coefficient of consolidation due to horizontal flow and the hydraulic conductivity in horizontal direction of Singapore marine clay at Changi. Piezocone dissipation tests were carried out prior to reclamation as well as after ground improvement with vertical drains to compare the changes in the coefficient of consolidation due to horizontal flow and hydraulic conductivity in horizontal direction prior to and after ground improvement. The quasi-static piezometric pressures from the dissipation tests were compared with piezometric pressures from piezometers to determine their possibility of future use as an alternative to piezometers. Post-improvement CPTU dissipation tests were carried out in the treated "Vertical Drain Area" as well as in an adjacent untreated "Control Area" for comparison purposes. This study provides support for the use of piezocone dissipation testing methods for the determination of the coefficient of consolidation due to horizontal flow and hydraulic conductivity in horizontal direction of marine clays in the region as well as an alternative to piezometer instrumentation for monitoring of piezometric pressure during consolidation.

Keywords Piezocone · Dissipation · In situ · Marine clay · Pore pressure

A. Arulrajah (✉)
Faculty of Engineering and Industrial Sciences, Swinburne University of Technology, P.O. Box 218, Hawthorn, Melbourne, VIC 3122, Australia
e-mail: aarulrajah@swin.edu.au

M. W. Bo
DST Consulting Engineers Inc, Gloucester, ON, Canada

H. Nikraz
Department of Civil Engineering, Curtin University of Technology, Building 204, Level 3, Bentley, Perth, WA 6102, Australia

A. S. Balasubramaniam
School of Engineering, Griffith University, Gold Coast Campus, PMB 50 GCMC, Gold Coast, QLD 4215, Australia

1 Introduction

To allow for the future expansion of Changi International Airport in Singapore, an additional 2,000 ha of land is currently being reclaimed next to the existing airport. The offshore land reclamation is being carried out by the hydraulic filling of sand which is followed by the installation of vertical drains and subsequently surcharge loading. As vertical drains are used to accelerate the consolidation of the marine clays, the permeability and consolidation properties of the soil particularly in the horizontal direction become important design parameters.

In the last two decades, there has been an emergence of in situ testing methods as an alternative to laboratory testing methods. In situ dissipation tests have emerged as a useful method to obtain the required consolidation due to horizontal flow and horizontal permeability parameters for the design of vertical drain projects. The coefficient of consolidation due to horizontal flow and horizontal hydraulic conductivity are important parameters for the design of vertical drain projects. The determination of these parameters is traditionally based on laboratory consolidation tests with the use of vertically cut samples. However laboratory testing does not yield appropriate properties of soil due to different loading, drainage conditions and sample disturbance as compared to the actual in situ soil condition.

Piezocone dissipation test (CPTU) is an alternative to these traditional laboratory testing methods. These dissipation tests can be conducted at various levels in the marine clay and hence variations of the coefficient of consolidation due to horizontal flow and horizontal hydraulic conductivity with depth can be obtained. In addition, by allowing the pore water pressure to reach the quasi-static state, the dissipation test may be used as an alternative to piezometer instrumentation in measuring piezometric pressure in consolidation stage.

In situ piezocone dissipation tests were conducted for the characterisation of Singapore Marine Clay at Changi East Reclamation project site located next to the existing Changi Airport in the eastern part of Singapore. In situ piezocone dissipation tests were carried out prior to reclamation. In situ piezocone dissipation tests were also carried out after a surcharge period of 23 months in a vertical drain treated "Vertical Drain Area" as well as in an adjacent untreated "Control Area" where the same magnitude of surcharge load was applied for comparison purposes.

In situ dissipation tests by means of CPTU were utilised in the characterisation of the coefficient of consolidation due to horizontal flow and horizontal hydraulic conductivity of Singapore marine clay in the land reclamation project. In addition, the degree of consolidation of the "Vertical Drain Area" was compared to that of the untreated "Control Area" to ascertain the performance of the vertical drains. The degree of consolidation of the improved ground was also compared with field instrumentation results of piezometers and deep settlement gauges. Studies have been carried out previously by Bo et al. (1998b) and Chu et al. (2002) in the reclamation site for CPTU dissipation tests carried out prior to land reclamation. However, only brief discussion on comparisons of the dissipation test results prior to and after surcharge loading has been made by Bo et al. (1997). This paper focuses primarily on the in situ piezocone dissipation test comparisons prior to reclamation and between vertical drain treated and untreated areas after surcharge loading.

2 Description of Project Site and Research Area

The site for this research study is located in the Changi East Reclamation Project in the Republic of Singapore. The area is submerged underwater with seabed elevation varying from 2 m to 8 m below Admiralty Chart Datum. The northern part of the project area is underlain by marine clay up to 40 m thickness in certain areas and the research area is located in this part of the area. Figure 1 shows the location of the project site.

The research area is located in an area where the thickest compressible layers existed and a portion of where the future airport runway would be located. The original seabed elevation in the research area is 3 m below Admiralty Chart Datum (−3 mCD). A pre-reclamation borehole was carried out prior to the commencement of land reclamation works to

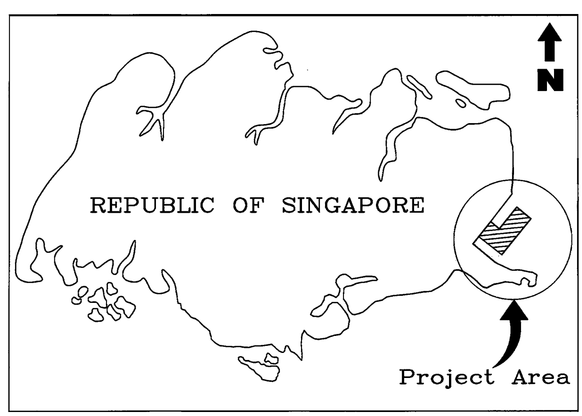

Fig. 1 Location of project site

characterize the marine clay properties. The research area consists of two adjacent sub-areas namely the "Vertical Drain Area" where vertical drains were installed and the "Control Area" where vertical drains were not installed. The two sub-areas are located adjacent to each other and are subject to the same soil conditions. Furthermore, the construction sequence and surcharge heights for these two sub-areas are the same and as such a comparison could be carried out of the treated "Vertical Drain Area" with the untreated "Control Area". Prefabricated vertical drains were installed at +4 mCD in the Vertical Drain Area and surcharge was subsequently placed to +10 mCD in both the areas. The vertical drains were installed at 1.5 by 1.5 m square spacing to depths of up to 35 m. Figure 2 shows the location of the research site comprising the Vertical Drain Area and the adjacent untreated Control Area.

Singapore marine clay at Changi is a quartenary deposit that lies within valleys cut in the Old Alluvium. It is locally known as Kallang formation. Figure 3 shows the soil profile and geotechnical properties of the research area prior to reclamation. As evident in the figure, the research area comprises of two distinct layers of marine clay which are the Upper Marine Clay (−3.29 mCD to −14 mCD) and the Lower Marine Clay (−19 mCD to −28 mCD). Intermediate Stiff Clay (−14 mCD to −19 mCD) separates these two distinct marine clay layers. The upper marine clay is soft with undrained shear strength values ranging from 10 kPa to 30 kPa. Marine or organic matter is found in the upper marine clay. The intermediate layer is a silty clay layer. Its formation is believed to have occurred

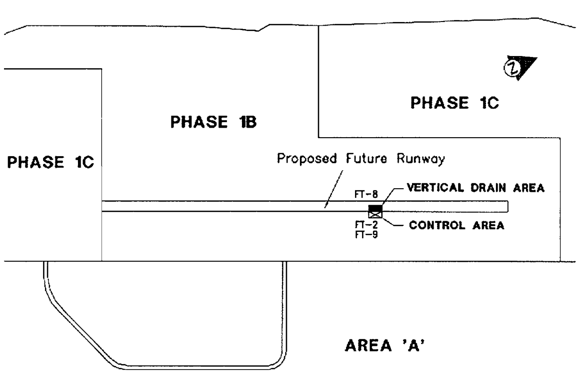

Fig. 2 Location of research site comprising Vertical Drain Area and Control Area

during the lowering of sea level, which was subsequently followed by a sea level rising and further deposition of the upper marine clay layer. The lower marine clay is lightly overconsolidated with an undrained shear strength varying from 30 kPa to 50 kPa. It is not homogeneous but occasionally interbeded with sandy clay, peaty clay and sand layers. Below the lower marine clay is a stiff sandy clay layer locally known as Old Alluvium. Details on the characteristics of Singapore Marine Clay has been discussed by Bo et al. (1998a, 2000).

3 Theories of Piezocone Dissipation Test

The c_h values of natural soils can be affected considerably by the stratification or the fabric of the soils which are relatively difficult to be characterised by laboratory tests. As an alternative, in situ dissipation tests using the piezocone were carried out to determine the horizontal coefficient of consolidation and hydraulic conductivity of the marine clay due to horizontal flow prior to reclamation and after ground improvement. The horizontal coefficient of consolidation, c_h, can be determined from the CPTU as well as laboratory tests.

The type of instrument used in the CPTU dissipation test was a Gouda dutch cone. The cone used was capable of registering a cone resistance of up to 50 MPa, sleeve friction of up to 500 kN/m^2 and a maximum pore pressure of 2000 kN/m^2. The cone had a 60° cone penetrometer, projected cross-section area of 10 cm^2, friction sleeve area of 150 mm^2 and an unequal area ratio "a" of 0.8035. The pore pressure filter was located at the base immediately behind the cone penetrometer. Figure 4 shows the geometry and dimensions of the piezocone penetrometer used in this study (De Beer et al. 1988).

The CPTU dissipation tests were carried out at various elevations. Coefficient of consolidation due to horizontal drainage was estimated from method suggested by Baligh and Levadoux (1986). The first step in the prediction method consists of normalizing dissipation records and plotting the normalized excess pore pressure versus log time. In general, the normalized excess pore pressure decreases monotonically from 1.0 (at t = 0) to 0 (at t approaching infinity).

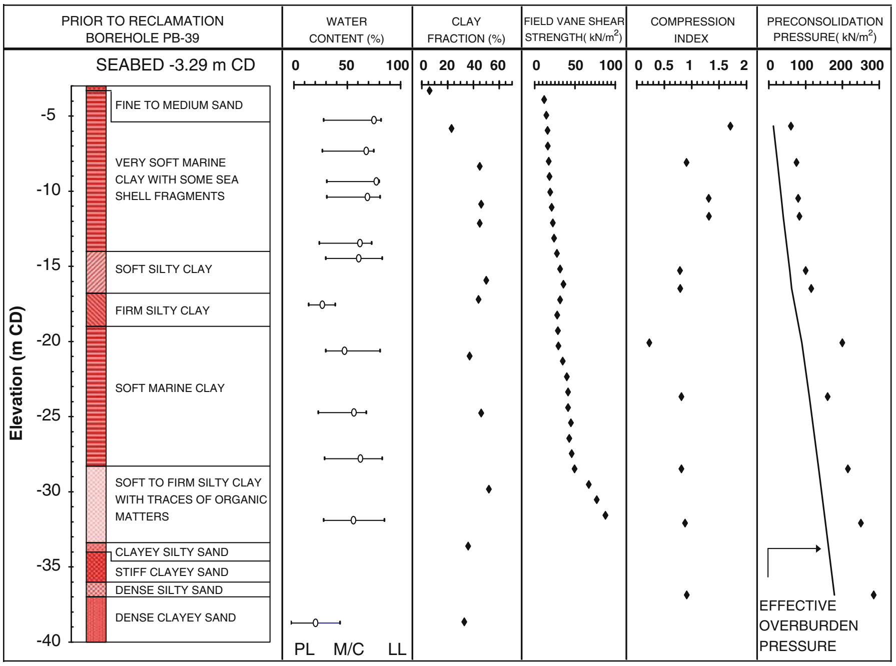

Fig. 3 Typical soil profile and geotechnical parameters at research area

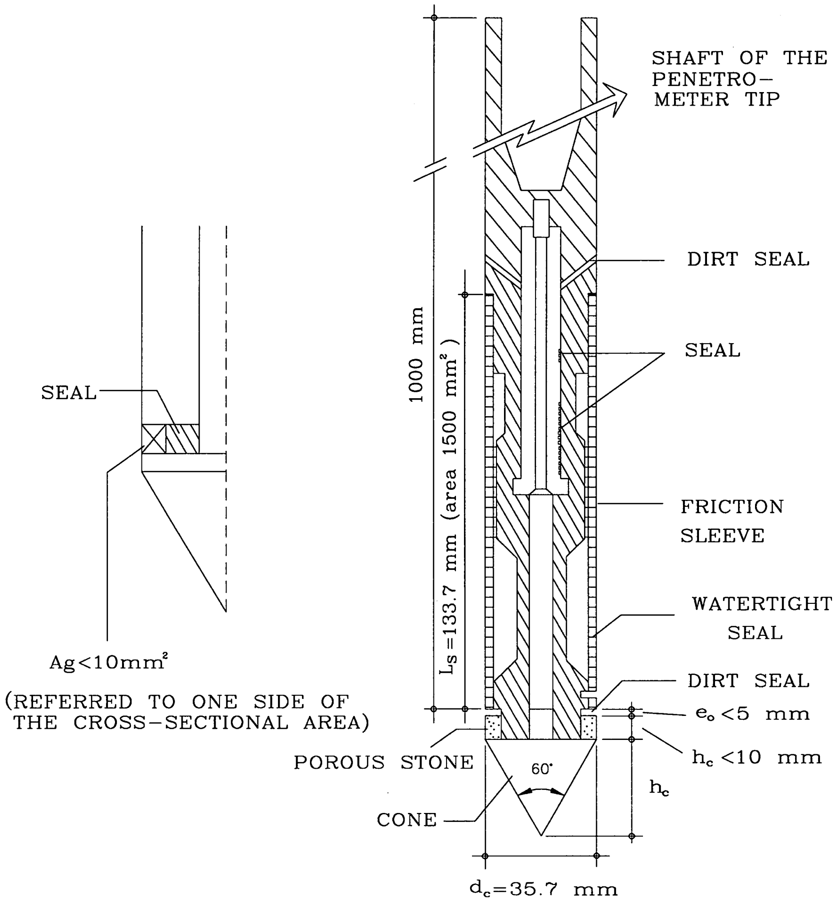

Fig. 4 Geometry and dimensions of piezometer tip (De Beer et al. 1988)

$$\bar{u} = (u - u_0)/(u_i - u_0) \quad (1)$$

where $\bar{u}$ is the normalized excess pore pressure at time t; u_0, static pore pressure; u_i, initial or penetration pore pressure (at t = 0); u, pore pressure recorded at time t.

At a given degree of consolidation, the predicted coefficient of consolidation due to horizontal flow can be obtained from the following expression given by Baligh and Levadoux (1986). The time factor, T has been validated for Singapore marine clay by Arulrajah et al. (2005).

$$c_h(\text{probe}) = (R^2T)/t \quad (2)$$

where R is radius of cone shaft in meters which is 0.01785 m for the cone used; T, time factor which is 3.65 for a 60° tip at 50% normalised excess pore pressure; t, time elapsed to reach given degree of consolidation in years.

For clays consolidated in the normally consolidated range, estimates of the horizontal coefficient of consolidation can be estimated from c_h(probe) by means of the following expression (Baligh and Levadoux 1986):

$$c_h(\text{NC}) = (Cr/Cc).c_h(\text{probe}) \quad (3)$$

where Cr is the recompression index; Cc, compression index.

The horizontal hydraulic conductivity can be estimated from:

$$k_h = (\gamma_w/2.3\sigma'_v)(RR)c_h \quad (4)$$

where k_h is horizontal hydraulic conductivity; γ_w, unit weight of water in kN/m^3; RR, recompression ratio = Cr/Cc; σ'_v, mean effective vertical stress of soil in kPa.

When the piezocone is penetrated into soft soil, some excess pore pressure will generate due to penetration. However if the cone is held in the same elevation, pore pressures will dissipate until it reaches the equilibrium pore pressure. This equilibrium pore pressure will be the same as pore pressure in the soil at the time of testing (Bo et al. 1997). With this measured equilibrium pore pressure from CPTU tests, a counter check can be done for piezometer reading and the average degree of consolidation can be computed from the following equation;

$$U(\%) = 1 - (U_t/U_i) \quad (5)$$

where U_t = excess pore pressure at time "t", U_i = initial excess pore pressure which is equal to additional load ($\Delta\sigma'$).

4 Assessment of Piezometric Heads and Degree of Consolidation

Figure 5 presents the dissipation curves of the piezocone dissipation tests prior to reclamation. The dissipation test were carried out at various elevations for periods of up to 3½ h.

Figure 6 shows the CPTU dissipation test curves in the Vertical Drain Area after ground improvement with vertical drains and surcharge loading for 23 months. The piezocone dissipation test in the vertical drain treated "Vertical Drain Area" was carried out at the centroid of the vertical drain grid. The dissipation tests were carried out for up to 50 h. It can be seen that the normalized excess pore pressures at all elevations have stabilised close to this time period. Figure 7 provides a comparison of the piezometric heads of piezometers at the Vertical Drain Area with the CPTU long term holding test results. It is evident that the ground improvement with vertical drains has significantly dissipated the excess pore water pressures built up due to the surcharging load. Furthermore, the CPTU dissipation test and piezometer readings indicate good relationship with similar readings.

Figure 8 shows the CPTU dissipation test curves in the Control Area after surcharge loading for 23 months. The dissipation tests here were carried out for up to 42 h. The normalized excess pore pressures at all elevations have stabilised after 1000 min. Figure 9 provides a comparison of the piezometric heads of piezometers at the Control Area without vertical drains with the CPTU results. Without ground improvement, a slight dissipation of the excess pore water pressures built up due to consolidation was observed. The CPTU dissipation test and piezometer readings indicate good agreement in piezometric pressures.

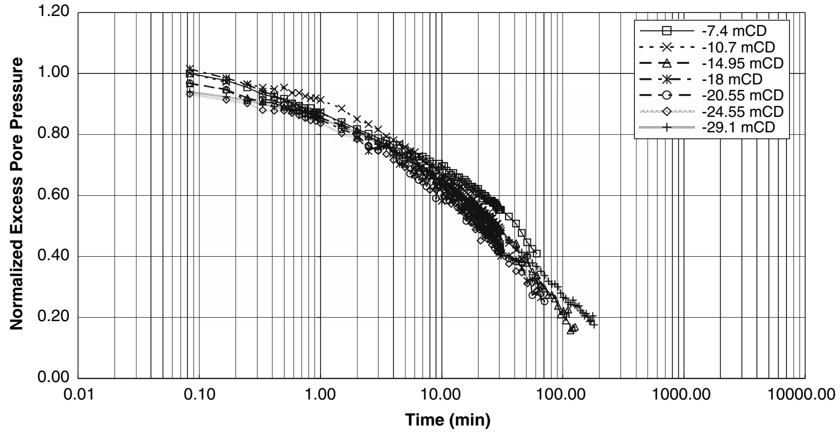

Fig. 5 Pre-reclamation CPTU dissipation tests with normalized excess pore pressures

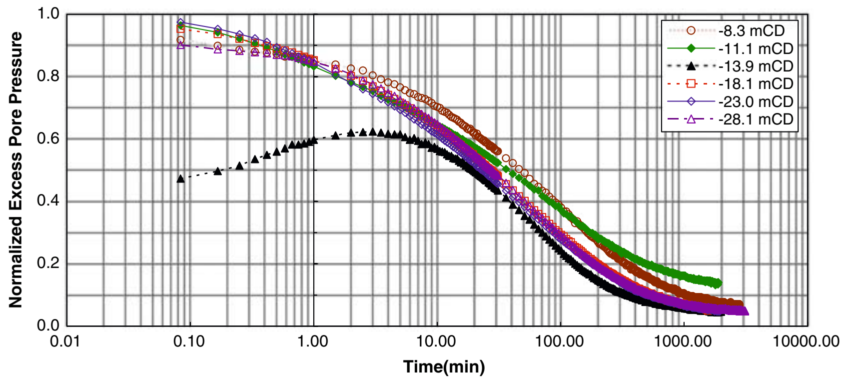

Fig. 6 CPTU dissipation tests carried out after 23 months of surcharge loading at Vertical Drain Area (FT8)

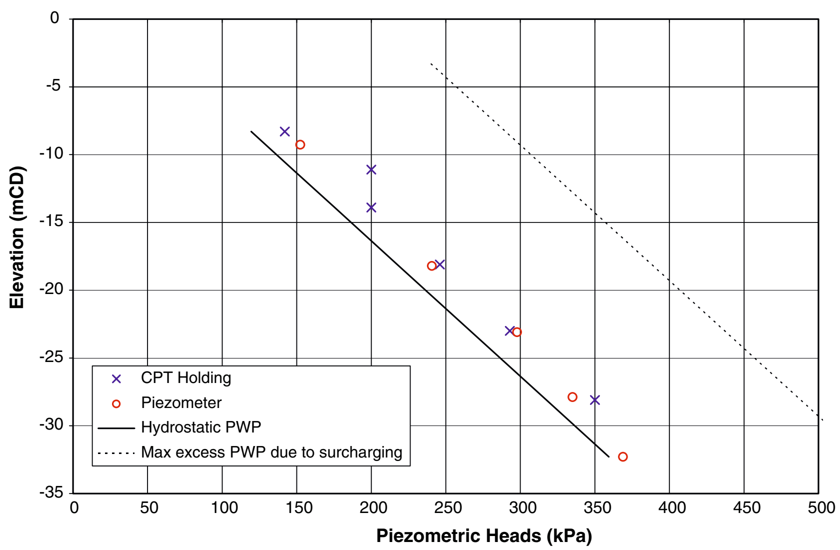

Fig. 7 Comparison of piezometric heads at Vertical Drain Area after 23 months of surcharge loading

Figure 10 shows the degree of consolidation from the CPTU dissipation tests for the Vertical Drain Area and Control Area as compared to the field instrumentation results. The CPTU dissipation test and piezometer readings are in good agreement for both the Vertical Drain Area and Control Area. The

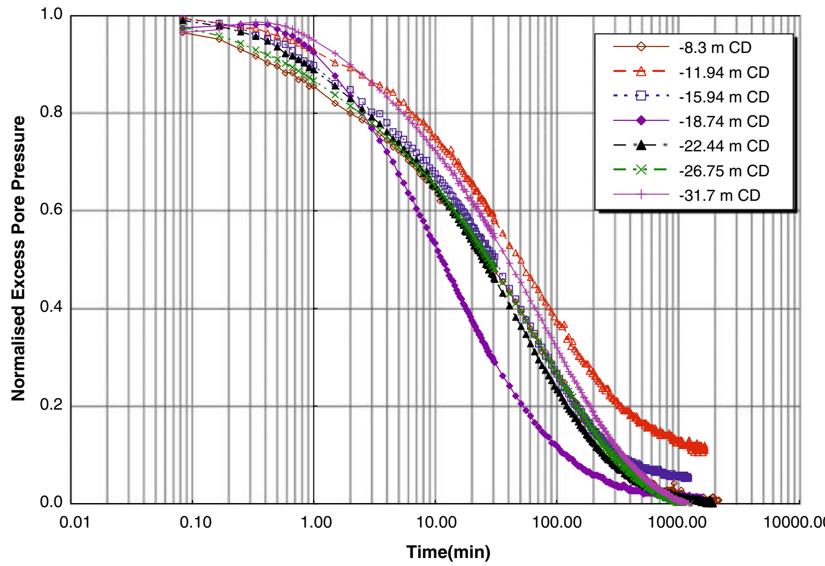

Fig. 8 CPTU dissipation tests carried out after 23 months of surcharge loading at Control Area (FT9)

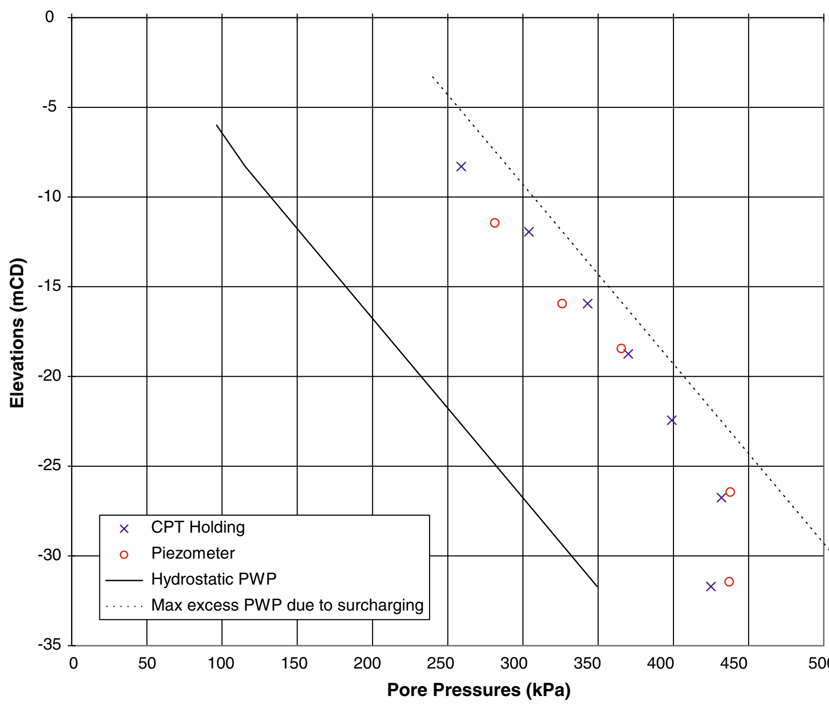

Fig. 9 Comparison of piezometric heads at Control Area after 23 months of surcharge loading

deep settlement gauges in the Vertical Drain Area were also analysed by both the Asaoka and hyperbolic methods to attain the ultimate settlement and subsequently the degree of consolidation from the settlement gauges were computed. The method of analysis of the deep settlement gauges was carried out by the method proposed by Bo et al. (1997). These too were in good agreement with the CPTU dissipation test results in the Vertical Drain Area. The Vertical Drain Area has attained a degree of consolidation of 80–85% based on the CPTU results. The Control Area without vertical drains on the other hand has attained a degree of consolidation of 10–22% based on the CPTU results.

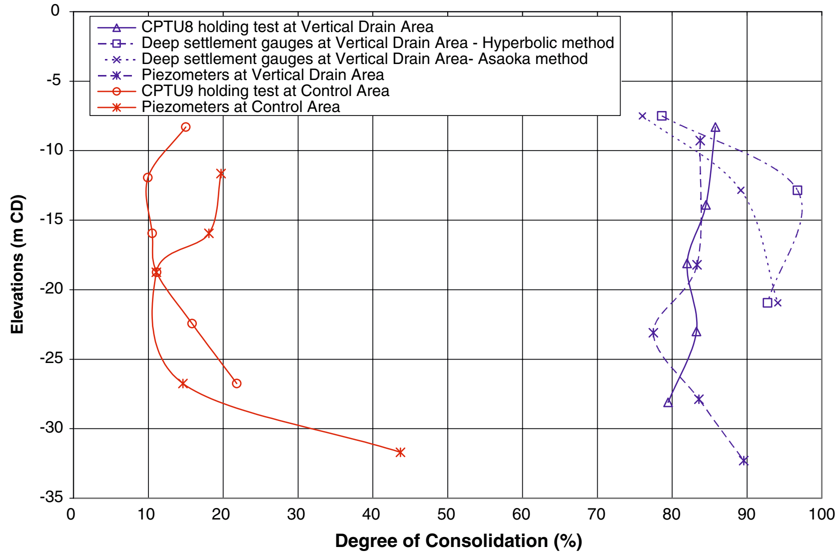

Fig. 10 Comparison of degree of consolidation from CPTU dissipation test between Vertical Drain Area and Control Area after 23 months of surcharge loading

5 Assessment of Coefficient of Consolidation due to Horizontal Flow and Horizontal Hydraulic Conductivity

Figure 11 presents the c_h results from the CPTU dissipation tests for the Vertical Drain Area and Control Area after 23 months of surcharge loading as compared to the pre-reclamation dissipation test. The c_h results have been selected based on 50% normalised excess pore pressure based on a time factor, T as indicated in Eq. 2. The pre-reclamation dissipation tests indicate large c_h values in the intermediate stiff clay layer. The c_h values for the laboratory tests were obtained from radial flow Rowe cell of 75 mm diameter and 30 mm thickness and also from horizontally cut 63.5 mm oedometer test samples and were found to be in the same range as that of the CPTU. The c_h value seems to be higher in the Vertical Drain Area at some elevations as compared to the Control Area. This is due to the greater reduction in the coefficient of volume change, m_v after consolidation or it was simply affected by the correction factors

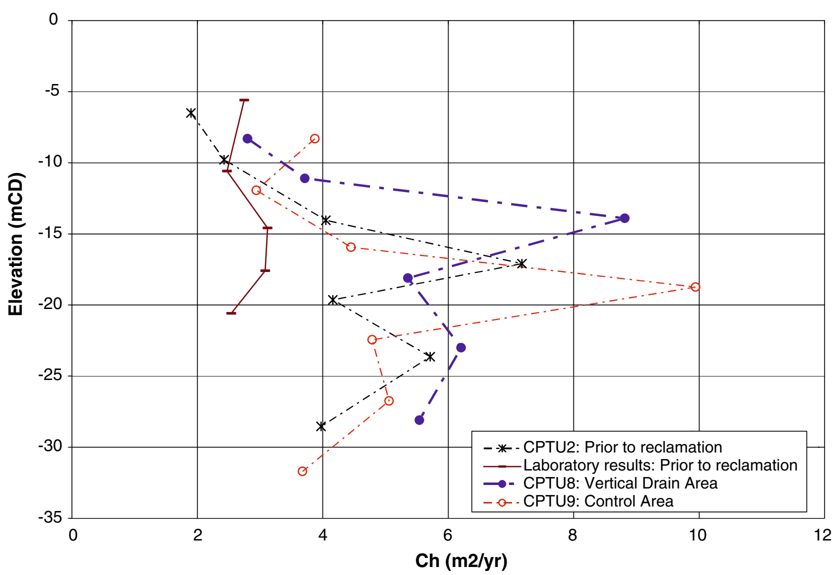

Fig. 11 Comparison of horizontal coefficient of consolidation from CPTU dissipation test prior to reclamation and after 23 months of surcharge loading

used. A clear increase in the c_h values is obtained in the intermediate marine clay layer.

Figure 12 shows the k_h results from the CPTU dissipation tests for the Vertical Drain Area and Control Area after 23 months of surcharge loading as compared to the pre-reclamation dissipation test. The k_h values were obtained by using Eq. 4 and compared to the k_h results obtained from the prior to reclamation oedometer tests. It can be observed that the pre-reclamation k_h values are decreasing with depth. The piezocone test results also show high k_h values in the intermediate desiccated zone. It is apparent that the prior to reclamation k_h is higher than that of the Vertical Drain Area and Control Area after 23 months of surcharge loading. This is expected due to reduction in the void ratio after surcharge loading. It is also apparent that the k_h in the Vertical Drain Area is lower than that in the Control Area which is expected due to higher void ratio changes and smear effect. Smear effect also affects the k_h in the vertical drain treated area due to insertion of the mandrel into the ground.

The c_h of the upper and lower marine clay prior to reclamation varies between 2 m^2/year and 6 m^2/year. The pre-reclamation dissipation tests indicate large c_h values in the intermediate stiff clay layer. The pre-reclamation CPTU indicates that k_h varies between 10^{-8} m/s and 10^{-9} m/s.

c_h varies between 3 m^2/year and 6 m^2/yr in the Vertical Drain Area and between 3 m^2/year and 5 m^2/yr in the Control Area, after 23 months of surcharge loading. k_h varies between 10^{-9} m/s and 10^{-10} m/s in the Vertical Drain Area and Control Area, after 23 months of surcharge loading.

6 Back Calculation Based on Field Monitoring Data

The settlement and pore-water pressure response during consolidation under the surcharge were monitored at the test location. This monitoring enabled the field c_h values to be back calculated. Bo et al. (1997) has reported that the c_h values back calculated from settlement measured at different elevations at the test location are in the range of 0.78–1.2 m^2/year. In the back calculation, the ultimate settlement was estimated based on Asaoka method using the settlement data for the surcharge loading duration, which corresponds to a degree of consolidation of about 90%.

7 Observations and Discussions

The major factor that accounts for the lower c_h values back calculated from field settlement measurements is the smear effect incurred from the insertion of the mandrel during the installation of vertical drains. For soft marine clay, the smear effect can be quite significant as the spacing of the drains is normally 1.5 m (Chu et al. 2002). Bo et al. (1998b) has reported that the permeability of soil in the smear zone could be reduced by 1 order of magnitude or to

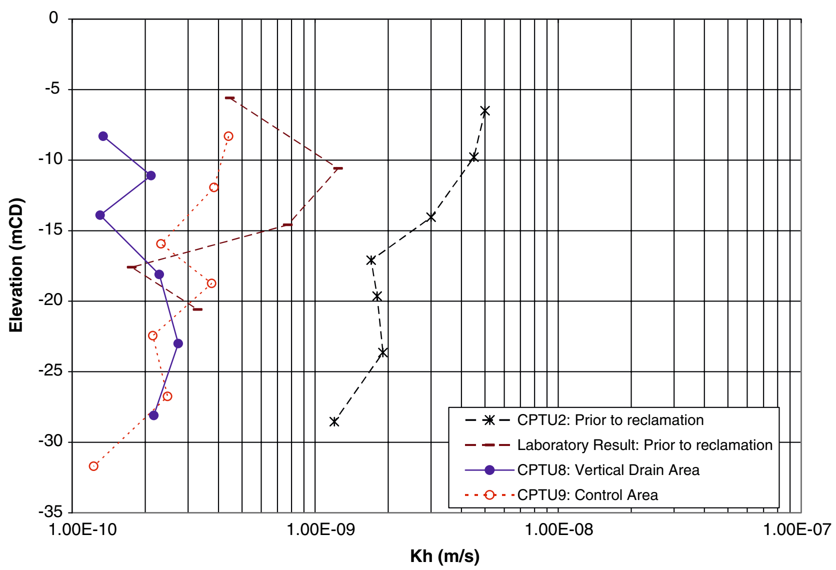

Fig. 12 Comparison of horizontal hydraulic conductivity from CPTU dissipation test prior to reclamation and after 23 months of surcharge loading

the k_h of the remoulded clay as a result of the smear zone. The smear zone was reported by Bo et al. (1998b) to be 4–5 times the equivalent diameter of the vertical drain. When drains are installed at close spacing, the back-calculated c_h values will generally be greatly influenced by this smear zone (Chu et al. 2002).

The smear effect also affects the CPTU measurements for k_h and c_h. In the CPTU dissipation test, a penetrometer has to be pushed into the clay and a smear effect similar to the insertion of a mandrel could have been introduced prior to the measurements. This finding also indicates that when vertical drains are used in soft clay, the smear effect on the consolidation properties of soil has to be taken into consideration in the design (Chu et al. 2002).

8 Conclusion

Piezocone dissipation tests have been utilised as a tool to obtain the piezometric heads of marine clays after ground improvement as well as to assess the degree of consolidation of the improved marine clay. Piezocone dissipation tests were also used to characterise the horizontal coefficient of consolidation and horizontal hydraulic conductivity of Singapore marine clay at Changi in a land reclamation project prior to reclamation and after 23 months of surcharge loading.

The results indicated that pore pressure measured from the CPTU holding tests are in agreement with those measured by the piezometers tests in both the Vertical Drain Area and adjacent untreated Control Area. The CPTU test results were also successfully used for the determination of the equilibrium pore pressure and degree of consolidation of the improved areas as confirmed by the field instrumentation results. This confirms that long term piezocone holding tests can be used as an alternative to piezometers in marine clays. The Vertical Drain Area was found to have attained a degree of consolidation of 80–85% based on the CPTU results. The Control Area without vertical drains on the other hand has attained a degree of consolidation of 10–22% based on the CPTU results.

The c_h of the upper and lower marine clay prior to reclamation was found to vary between 2 m^2/year and 6 m^2/year. The pre-reclamation CPTU indicates that k_h varies between 10^{-8} m/s and 10^{-9} m/s.

c_h varies between 3 m^2/year and 6 m^2/year in the Vertical Drain Area and between 3 m^2/year and 5 m^2/yr in the Control Area, after 23 months of surcharge loading. k_h varies between 10^{-9} m/s and 10^{-10} m/s in the Vertical Drain Area and Control Area, after 23 months of surcharge loading.

The c_h value seems to be higher in the Vertical Drain Area at some elevations as compared to the Control Area. This is due to the greater reduction in the coefficient of volume change, m_v after consolidation or it was simply affected by the correction factors used.

It is apparent that the prior to reclamation k_h is higher than that of the Vertical Drain Area and Control Area after 23 months of surcharge loading. This is expected due to reduction in the void ratio after surcharge loading. It is also apparent that the k_h in the Vertical Drain Area is lower than that in the Control Area which is expected due to higher void ratio changes and smear effect.

References

Arulrajah A, Nikraz H, Bo MW (2005) In-situ testing of Singapore marine clay at Changi. Geotech Geol Eng 23:111–130

Baligh MM, Levadoux JN (1986) Consolidation after undrained piezocone penetration. II: interpretation. J Geotech Eng ASCE 112:727–745

Bo MW, Arulrajah A, Choa V (1997) Assessment of degree of consolidation in soil improvement project. Proceedings of the international conference on ground improvement techniques, May, Macau, pp 71–80

Bo MW, Arulrajah A, Choa V, Chang MF (1998a) Site characterization for land reclamation project at Changi in Singapore. In Roberson and Mayne (eds) Proceedings of the 1st international conference on site characterization (geotechnical site characterization), April 1998. Balkema, Rotterdam, Atlanta, USA, pp 333–338

Bo MW, Arulrajah A, Choa V (1998b) The hydraulic conductivity of Singapore marine clay at Changi. Q J Eng Geol 31:291–299

Bo MW, Chang MF, Arulrajah A, Choa V (2000) Undrained shear strength of the Singapore marine clay at Changi from in-situ tests. Geotech Eng 31(2):91–107

Chu J, Bo MW, Chang MF, Choa V (2002) Consolidation and permeability properties of Singapore marine clay. J Geotech Geoenviron Eng 128(9):724–732

De Beer EE, Goelen E, Heynew WJ Joustra K (1988) Cone penetration test (CPT): international reference test procedure. Proceedings of the 1st international symposium on penetration testing, vol 2. Orlando, USA, pp 737–744