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Evaluating the in-situ hydraulic conductivity of soft soil under land reclamation fills with the BAT permeameter

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ABSTRACT

In-situ tests were undertaken with a BAT permeameter as part of a hydrogeological study to determine the horizontal hydraulic conductivity of Singapore marine clay at Changi. BAT permeameter tests were undertaken in marine conditions prior to land reclamation at a Test Site. An additional series of tests were undertaken after land reclamation and subsequent ground improvement works with prefabricated vertical drains after 23 months of surcharge loading. The BAT permeameter results were compared to laboratory test results carried out using a Rowe consolidation cell as well as hydraulic conductivity tests interpreted from other in-situ dissipation tests including Piezocone Penetration Test (CPTU), Dilatometer Test (DMT) and Self-Boring Pressuremeter Test (SBPMT). The BAT permeameter was found to be suitable for horizontal hydraulic conductivity measurements. The BAT permeameter has the advantage that it measures horizontal hydraulic conductivity directly whereas other in-situ test methods require the introduction of additional parameters to evaluate the hydraulic conductivity indirectly. The horizontal hydraulic conductivity measured using the BAT permeameter was however lower than that expected which is attributed to smear effect. The horizontal hydraulic conductivity was found to decrease in the vertical drain treated area as compared to the prior to reclamation results which is attributed to the significant void ratio reduction at the vertical drain treated area.

1. Introduction

The hydraulic conductivity in the horizontal flow direction is an important parameter for the engineering geology interpretation of land reclamation projects on soft marine clay deposits. Laboratory tests are commonly used for determination of the hydraulic properties of soft soils and rocks (Heister et al., 2005; Ponziani et al., 2011). In-situ tests are commonly used for determination of the hydraulic conductivity of rocks and sands (Mollah and Sayed, 1995; Meijas et al., 2009; Chapuis, 2012) but are not commonly used for soft soils.

The determination of hydraulic conductivity parameters of soft soils is traditionally based on laboratory consolidation tests or falling head tests (Nayak et al., 2007). Prototype cells have also been developed in recent years for monitoring the hydraulic conductivity of soft soils such as peat (Ponziani et al., 2011). The Rowe consolidation cell (Rowe and Barden, 1966) has provisions for horizontal drainage, which enables the determination of the horizontal hydraulic conductivity indirectly from coefficient of horizontal consolidation values. The usage of the Rowe consolidation cell for the determination of the horizontal consolidation and hydraulic conductivity properties of Singapore marine clay has been discussed previously by Bo et al. (2003) and Chu et al. (2002). The standard test methods for undertaking the Rowe consolidation test are specified by ASTM D-2435 (2004) and BS1377-6 (1990). These laboratory tests for soft soils are however subject to uncertainties due primarily to sample disturbances. In recent years, in-situ testing methods have become increasingly popular for the determination of hydraulic conductivity of soft soils. In the determination of hydraulic conductivity by laboratory testing methods, with an increase in sample disturbance the void ratio and yield stress subsequently reduce and the compression curve tends toward the remolded line (Nagaraj et al., 1990; Shogaki and Kaneko, 1994; Horpibulsuk et al., 2007). Sample disturbance therefore causes a significant difference in hydraulic conductivity between the in-situ and laboratory test methods.

There has been an increasing emergence of in-situ testing methods as an alternative to laboratory testing and field instrumentation methods for assessing the hydraulic characteristic of soft marine clays in land reclamation projects. Ground improvement with prefabricated vertical drains (PVDs) is a widely used technique for the treatment of soft soil deposits in land reclamation projects (Holtz et al., 1991; Bergado et al., 1996; Choa et al., 2001; Bo et al., 2003; Arulrajah el al., 2004a; Chu et al., 2004; Chu et al., 2006; Arulrajah et al., 2009a; Chu

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et al., 2009a; Bo et al., 2012). Field instrumentation with the usage of settlement gages and piezometers is frequently used to assess the degree of consolidation of soft soils in these land reclamation projects after ground improvement with prefabricated vertical drains (Bergado et al., 1996; Arulrajah et al., 2004b; Bo et al., 2007; Arulrajah et al., 2009b; Chu et al., 2009a; Arulrajah et al., 2013).

In-situ testing equipments such as the Piezocone Penetration Test (CPTU) with pore pressure measurements (Baligh and Levadoux, 1986; Bo et al., 2003; Arulrajah et al., 2009a; Cai et al., 2010; Arulrajah et al., 2011; Bo et al., 2012; Cai et al., 2012), Dilatometer Test (DMT) (Marchetti, 1980; Bo et al., 2003; Arulrajah et al., 2006a; Bo et al., 2012) and Self-Boring Pressuremeter Test (SBPMT) (Mair and Wood, 1987; Arulrajah et al., 2011) have been previously used as alternative methods to field instrumentation in the determination of the hydraulic characteristics of soft soils.

In-situ dissipation tests are particularly useful in the determination of the in-situ hydraulic conductivity of soft soils at various depths (Chu et al., 2002; Bo et al., 2012). In-situ dissipation tests have been undertaken previously in ground improvement projects in soft soils with equipment such as the SBPMT (Arulrajah et al., 2011; Bo et al., 2012), DMT (Marchetti and Totani, 1989; Arulrajah et al., 2006b; Bo et al., 2012) and CPTU (Arulrajah et al., 2007; Cai et al., 2010; Cai et al., 2012). However, hydraulic conductivity is only measured indirectly by these in-situ test methods.

The BAT permeameter system has the advantage over these other in-situ testing equipments because it can directly measure the in-situ hydraulic conductivity (Torstensson, 1984). The key objective of this paper is to compare the results of the horizontal hydraulic conductivity (k_h) from the BAT permeameter tests to laboratory testing results undertaken with a Rowe consolidation cell as well as to in-situ testing results with the SBPMT, CPTU and DMT.

2. BAT permeameter testing method

The BAT permeameter developed by Torstensson (1984) was used in this study for in-situ measurements of horizontal hydraulic conductivity of the soft marine clay at Changi, Singapore. The BAT permeameter results can be considered as the baseline measurements of horizontal hydraulic conductivity as this is directly measured. This contrasts with dissipation testing by other in-situ testing methods such as CPTU, DMT or SBPMT where the horizontal hydraulic conductivity is indirectly evaluated from the coefficient of horizontal consolidation. The BAT permeameter measures the pore pressure locally in the soil, with little water movement, resulting in a quick reaction time in soft soils (Torstensson and Schellingerhout, 1999). The BAT permeameter also has the ability to sample ground water, measure pore water pressure and determine in-situ hydraulic conductivity of soft soils. The BAT permeameter in this research was used to determine the in-situ hydraulic conductivity of the soft marine clay prior to land reclamation and after ground improvement.

The key element in the BAT system is the filter tip, which consists of a thermoplastic body and a porous plastic filter tip (Torstensson, 1984). The diameter of the BAT filter was 30 mm and the length is 40 mm. The different test adapters make a tight temporary connection to the filter tip with the aid of a hypodermic needle. The pore pressure adaptor contains a hypodermic needle and an electronic pressure transducer, connected to a battery-operated digital readout unit. The pore pressure adaptor is threaded to an extension pipe, lowered into a prebored borehole and placed at the desired elevation. When the pore pressure adaptor is lowered down the borehole, it is coupled to the nozzle in the filter tip and gravity draws the hypodermic needle downward, penetrating the rubber disk mounted in the filter tip. The needle provides a hydraulic connection between the interior of the filter tip and the test adapter (Torstensson, 1984). In the BAT permeameter test, the penetrometer has to be pushed into the soft clay and this results in smearing around the BAT permeameter. Smearing affects the k_h measurement, similar to the insertion of a mandrel (Bo et al., 2003). Fig. 1 shows the geometry and dimensions of the BAT permeameter.

The in-situ measurement of hydraulic conductivity can be carried out either as an inflow test or as an outflow test. In the former case, the gas/water container is completely gas-filled at the start of the test. An inflow test can be conducted simultaneously with extraction of pore water sample. In an outflow test, the container is partially filled with compressed gas. The air in the chamber is evacuated (or pressurized) to any desired pressure. As water flows into (or out of) the probe, this results in a change in air pressure in the chamber. A pressure transducer monitors the pressure change. The test is based on measurement of flow into and out of a sample container. This rate is computed by the pressure change measured in the container using Boyle's Law, which can be translated into a volume change and analysis of the time-pressure record yields the horizontal hydraulic conductivity. The quantity of flow and heads is computed from the change in the gas pressure measured in the chamber using Boyle's Law (Torstensson, 1984).

$$k_h = \frac{P_0 V_0}{Ft}\left[\frac{1}{P_0 U_0} - \frac{1}{P_t U_0} - \frac{1}{U_0^2}\ln\left(\frac{P0 - U_0}{P0} \times \frac{P_t}{P_t - U_0}\right)\right] \quad (1)$$

$$F = \frac{2\Pi L}{\ln\left[\frac{L}{d} + \sqrt{1 + \left(\frac{L}{d}\right)^2}\right]} \quad (2)$$

where k_h is the horizontal hydraulic conductivity in m/s; P_0 is the absolute initial system pressure; V_0 is the initial gas volume in ml; F is the shape factor and is calculated as 228.76 mm for the current test; U_0 is the static pore water pressure; P_t is the absolute pressure at time t; L is the length of filter in mm and d is the diameter of filter in mm. All pressures are measured in meter.

3. Results and discussions

The Test Site comprises of two distinct layers of marine clay, which are the upper marine clay layer and the lower marine clay layer (Arulrajah and Bo, 2008). These two layers are separated by an intermediate stiff clay layer, which in reality is the desiccated crust of the lower marine clay (Arulrajah and Bo, 2008). The original seabed elevation at the site was −3.29 mCD (CD refers to Admiralty Chart Datum). Prefabricated vertical drains were installed in the Vertical Drain Area at 1.5 m by 1.5 m square spacing at the installation platform level of +4 mCD to an elevation of −25 mCD (29 m length of vertical drains). The Test Site was subsequently surcharged, with the placement of additional reclamation sandfill to an elevation of +10 mCD and surcharge left in place for a period of 23 months. The purpose for the surcharge was for preemptive settlement to take place during this temporary surcharging period under the load greater than future loads so as to minimize post-construction settlement. An adjacent Control Area (where no vertical drains were installed) was constructed similarly for BAT permeameter result comparison purposes. The implementation of land reclamation and ground improvement with prefabricated vertical drains in the Test Site has been discussed by Bo et al. (2003), Bo and Choa (2004) and Bo et al. (2007) and Chu et al. (2009b).

Fig. 2 presents the geotechnical borelog of the Test Site. The upper marine clay is very soft clay with some sea shell fragments. This upper clay layer is from the seabed to 11 m depth. Its water contents are close to the liquid limits and the clay fractions increase with depth while the compression indices tend to decrease with depth. The undrained shear strengths are 18–20 kN/m^2. The lower marine clay, from 16 m to 25.2 m in depth, comprises of soft clay with water contents lower than the liquid limits. The compression indices are almost constant with depth. An intermediate stiff clay layer, with undrained shear strength larger than 75 kN/m^2, is present between the upper and lower marine clay layers. Field vane shear tests could not be undertaken below this intermediate stiff clay layer due to its relative stiffness and was terminated in this layer. The BAT permeameter tests were