LABORATORY STUDY ON THE CONSOLIDATION SETTLEMENT OF CLAY-FILLED GEOTEXTILE TUBE AND BAGS

Soon Hoe Chew [1], Piow Yang Pang [2], Czhia Yheaw Tan [3], and Kok Eng Chua [4]

ABSTRACT

One of the newer families of geosynthetic product is geotextile tube, container and bag which could be effectively used in the containment of dredged material or clayey soils. In the recent decade, geotextile tube, container and bag with various dimension and shape are widely applied for offshore protection and land reclamation project. From geotechnical engineering point of view, the estimation of the settlement and the prediction of consolidation process of clay-filled geotextile bag would be an important aspect in the design of the geotextile containment system. The application of geotextile tubes and bags often involves the stacking of these units in multiple layers. Two critical issues in its design are the consolidation settlement of the bags and tubes; and the strain development of the geotextile. In order to study the consolidation behavior of the geotextile-clay system, modified triaxial tests have been conducted in the National University of Singapore. The modeled geotextile tubes filled with clay have been subjected to different confining pressure and the rate of consolidation has been monitored and compared with established consolidation theory. For the strain development of the geotextile subjected to loading pressure arising from the stacking of geotextile bags, laboratory tests were conducted to evaluate the strain development in scaled-geotextile bags. These geotextile bags were filled with soft slurry clay and submerged in water; and have been loaded using vertical pressure. The strain development of the geotextile and the rate of settlement of the geotextile bags were monitored. This paper presents the findings and the results of the above mentioned laboratory tests and the comparison with existing consolidation theories.

Key words: Laboratory study, geotextile tube, geotextile bag, consolidation.

1. INTRODUCTION

Geotextiles can be sewn into various types of containment units, namely geotextile bag, geotextile tube and geotextile container. These three types of containment units are differentiated by their shapes and sizes. In this application, geotextiles function as a permeable boundary that allow water to escape freely, meanwhile serve as a constructive barrier to confine the soil from contaminate the natural environment (Koerner 2005). The stacking of geotextile containment units could be used as a retaining structure for land reclamation or coastal line protection. When these geotextile containment units are filled with clayey soils, the estimation of the settlement and the prediction of consolidation process of clayey-filled geotextile bag would be an important aspect in the design of the geotextile containment system.

In order to study the consolidation behaviour of the geotextile-clay system, modified triaxial tests have been conducted in the National University of Singapore. The modeled geotextile tubes with a 100 mm height and 50 mm diameter and filled with clay have been subjected to different confining pressure and the rate of consolidation has been monitored and compared with established consolidation theory. The triaxial tests results are shown and discussed in this paper.

The second part of the research consists of scaled geotextile bags that were subjected to a series of loading tests in the laboratory. These scaled geotextile bags were filled with soft slurry clay and submerged in water; and then being loaded with different vertical pressure. The strain development of the geotextile, as well as the pore pressure inside the clayey fill was monitored throughout the loading tests. The loading force applied onto the geotextile bag is a simulation of the overburden pressure generated from the stacking of multiple units of geotextile bags above the tested/instrumented geotextile bag.

2. EXPERIMENTAL SETUP

In this section, the methodology and apparatus used in the modified triaxial test and geotextile bag loading test is presented and discussed.

2.1 Modified Triaxial Test Setup and Procedure

The experimental setup for the modified triaxial test is shown in Fig. 1. This is a standard consolidation drained triaxial compression test setup, with the exception that a modelled geotextile tube of 100 mm height and 50 mm diameter is placed inside the triaxial chamber, replacing the usual triaxial soil sample. Clayey soil is filled into the geotextile tube. The geotextile provides an all-round permeable boundary for the excess pore pressure to be dissipated in all directions.

Once the modelled geotextile tube is completely saturated (*i.e.* Skempton's B parameter larger than 0.95), then the cell pressure will immediately increase to specified confining pressures. Pore pressure transducer and volume change indicator would connect to data logger for readings monitoring.

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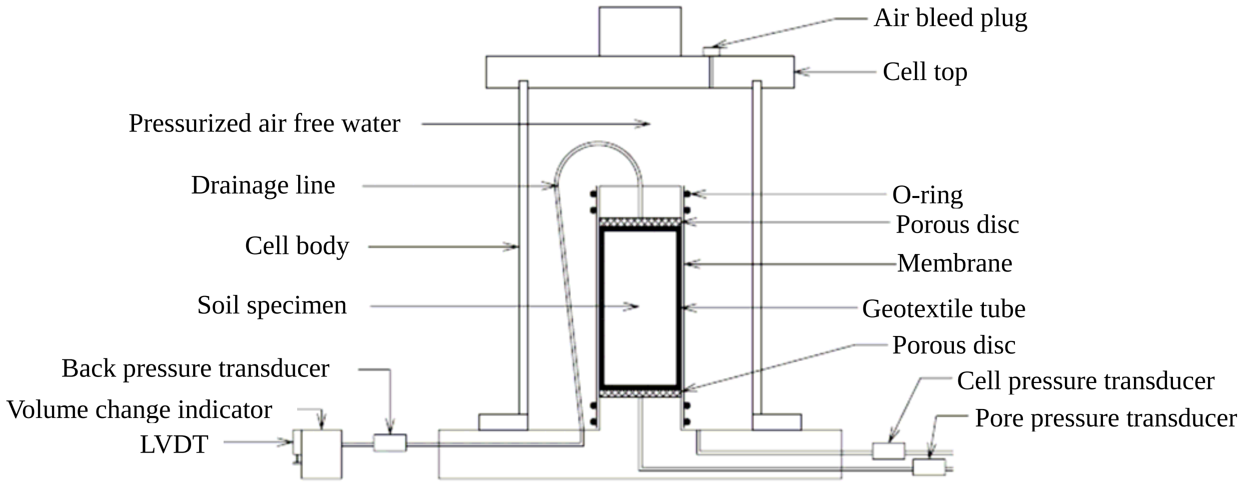

Fig. 1 Experimental setup for modified triaxial test

Three tests were conducted with the testing condition of confining pressure and existence of geotextile boundary as shown in Table 1. The experimental variable for T1 and T2 is the difference in confining pressure; while the variable for T1 and T3 is the existence of geotextile boundary.

The confining pressure of 100kPa (Sample T2) simulates a geotextile tube that is being laid into seawater depth of about 10 m and is being stacked onto by many layers of geotextile tube above itself, which is similar to some field applications. The confining pressure of 400kPa (Sample T1 and T3) was used to evaluate the efficiency of the geotextile layer in conditions that a geotextile tube is being subjected to a much deeper sea.

2.2 Geotextile Bag Loading Test Setup and Procedure

The experimental setup for the geotextile bag loading test is shown in Figs. 2 and 3. A special water tank (850 × 850 × 500 mm) was fabricated with a Perspex plate in the front face. This allows visual observation to be made during the loading process. A steel frame with a design capacity of up to 25 kN was used.

The geotextile bag was sewn into its shape using non-woven geotextile, Polyfelt TS 20. This material is made of 100% polypropylene. It has a bi-directional ultimate tensile strength of 9.5 kN/m^2 in the machine direction at 35% strain and in the cross machine direction at 70% strain. One side of the geotextile bag was left open for in-filling of clay into the bag.

Upon completing the filling process of clay, the geotextile bag was sealed and placed in the water tank. The water tank would then be filled with water, up to a height of 300 mm. A loading plate was used to load this geotextile bag.

Table 1 Summary of confining pressure and geotextile boundary in test series

Sample	Confining pressure (kPa)	Geotextile boundary
T1	400	Yes
T2	100	Yes
T3	400	No

Fig. 2 Geotextile bag loading test apparatus

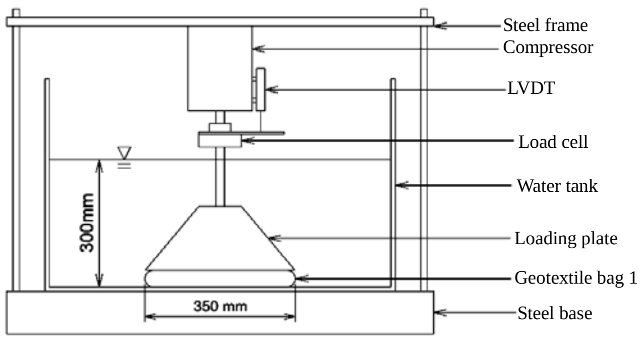

Fig. 3 Schematic diagram of experimental setup for geotextile bag loading test

At the beginning of the experiment, a 2kN load (equals to vertical pressure of 16 kPa) was applied onto the geotextile bag. This load is equivalent to a stacking of 20 layers of the same bag above the tested bag, and was maintained for the first 24 hours. After that, the load was increased to 8 kN (equals to vertical pressure 65 kPa) and maintained until the end of the experiment.

2.3 Instrumentation for Geotextile Bag Loading Test

A total of 4 strain gauges were installed onto the geotextile bag at locations shown in Fig. 4. The strain gauge locations are selected based on the anticipated high strain development area. The method of installation of strain gauge is according to Chew *et al.* (2000).

A load cell was placed between the loading plate and the hydraulic compressor to monitor and control the loading onto the geotextile bag. The vertical movement of the loading plate was measured by the linear variable differential transducer attached to the side of the hydraulic compressor.

In order to measure the rate of consolidation, pore pressure transducers (PPTs) were attached inside the geotextile bag and secure at 6 mm distance from the surfaces of geotextile layer (Fig. 5).

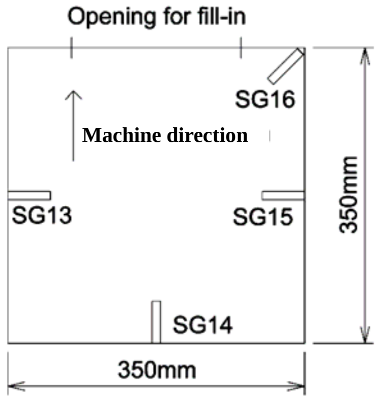

Fig. 4 Schematic diagram of strain gauges location

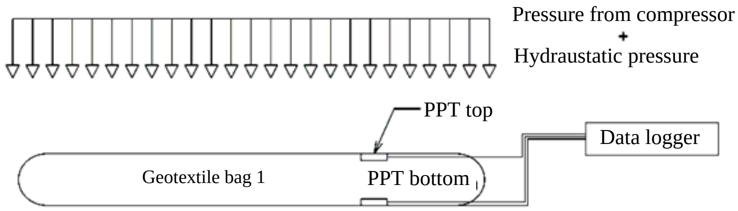

Fig. 5 Schematic diagram of pore pressure transducers location

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1 Modified Triaxial Test

Experimental results obtained from modified triaxial test were compiled in Fig. 6. Result showed that test T1 with higher confining pressure has a shorter period for consolidation than that of test T2 (refer Fig. 6). This is because the high confining pressure accelerates the rate of consolidation by increasing the rate of excess water dissipation. Referring to Table 2, the duration to complete consolidation for T1 was two times shorter than T2.

On the other hand, by comparing the results between test T1 and T3 (refer to Fig. 6), the existence of all-round geotextile boundary could effectively speed up the consolidation process by reducing drainage path. This phenomena could be explained by Terzaghi's consolidation theory as the duration t of consolidation is proportional to the square of drainage path d for a given time factor T_v corresponding to unique U_v, degree of consolidation. The drain path for T1 is 23 mm, on the other hand, the drain path for T3 is 100 mm. Thus, the longer drain path in T3 lead to longer duration of consolidation.

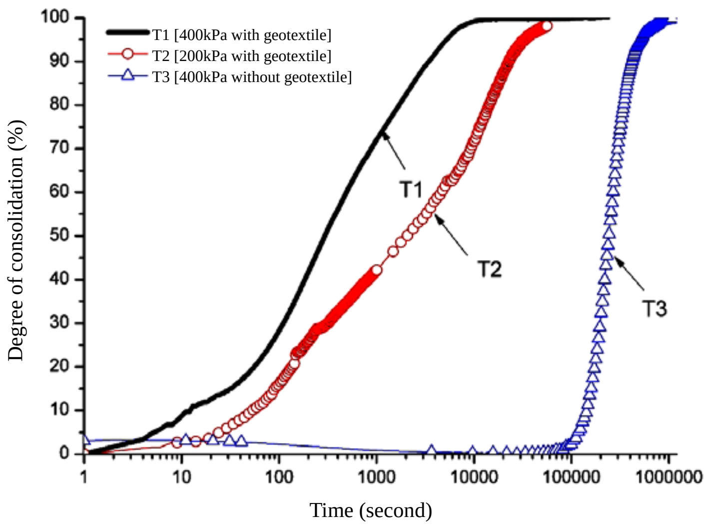

Fig. 6 Comparison of the degree of consolidation for sample T1, T2 and T3

Table 2 Summary for water dissipation in modified triaxial test

Test	Duration to complete consolidation $U = 99\%$ (day)	Total amount of water dissipated (cm^3)	Average rate of dissipation (cm^3/hr)
T1	0.29	85.9	12.34
T2	0.63	71.2	4.71
T3	12.51	80.5	0.27

3.2 Geotextile Bag Loading Test

In each geotextile bag loading test, pore pressures in the soil, settlement of the geotextile bag and the strain development in the geotextile have been recorded. Comparison has been made between the experimental results and established theories.

The following section shows the comparison of experimental results with existing theories such as Terzaghi's consolidation theory; Carrilo's combined flow theory and Hyperbolic method for soil consolidation analysis.

Estimation of Pore Pressure by Terzaghi's Consolidation Theory

Two pore pressure transducers were installed at the bottom and top of the inner surface of the instrumented geotextile bag.

From Fig. 7, we can observe that excess pore pressure was generated immediately upon the loading of 2 kN at $t = 0$ hours and during the increase of loading from 2 kN to 8 kN at $t = 24$ hours.

According to Terzaghi's theory of consolidation, the exact solution of excess pore pressure, u could be expressed as Eq. (1) The pore pressure in the soil at any instance can be calculated using this equation.

$$u = \sum_{n=1}^{\infty} \frac{2u_i}{n\pi}(1-\cos n\pi)\left(\sin\frac{n\pi z}{2d}\right)\exp\left(-\frac{n^2\pi^2 c_v\, t}{4d^2}\right) \quad (1)$$

where d is the drainage depth and t is the particular time, u_i being the initial excess pore pressure.

The theoretical calculation of excess pore pressure at time t is shown in Fig. 7 together with the experimental data points. It can be seen that the theoretical estimation showed good agreement with the experimental results, for $t = 0$ to 24 hours. In the loading at 8 kN, the theoretical estimation is the upper bound of the two PPTs at the first 6 hours.

Estimation of Degree of Consolidation by Carillo Combined Flow Method

The degree of consolidation estimation from vertical and radial flow with radial drainage, as suggested by Barron (1948), could be expressed as

$$\frac{\delta u}{\delta t} = c_v\left(\frac{\delta^2 u}{\delta z^2}\right) + c_r\left(\frac{\delta^2 u}{\delta r^2} + \frac{1}{r}\frac{\delta u}{\delta t}\right) \quad (2)$$

where z and r are the vertical and radial distance respectively.

The three-dimensional consolidation equation including vertical and radial flow can thus be expressed by Carillo's Equation

(3)

Using the pore pressure experimental results, the degree of consolidation of the soil in the geotextile was plotted in Fig. 8. By comparing Carillo's combined flow method with the experimental results, we observed that the degree of consolidation of the clayey soil can be well represented by this theory. It also proves that the consolidation process inside the geotextile bag is a three-dimensional consolidation process with radial and vertical flow.

Estimation of Settlement by Hyperbolic Method

The estimation of ultimate settlement by using hyperbolic method was suggested by Tan *et al*. (1992). In Hyperbolic method, the graph of t/δ versus t was plotted, where δ is the cumulative settlement at that particular instant. The ultimate settlement could be estimated from $1/\beta$, where β is the gradient of the line from hyperbolic plot.

Figure 9 shows the hyperbolic plot and Table 3 summarised theoretical estimation and experimental data. The calculation shows that these two results are close. The good accuracy is partly due to the fast achievement of 60% consolidation, of which hyperbolic method requires for good prediction of settlement.

Strain Development Versus Loading

Figure 10 shows that the strain increment for geotextile bag while being loaded. Experimental evidence shows that the

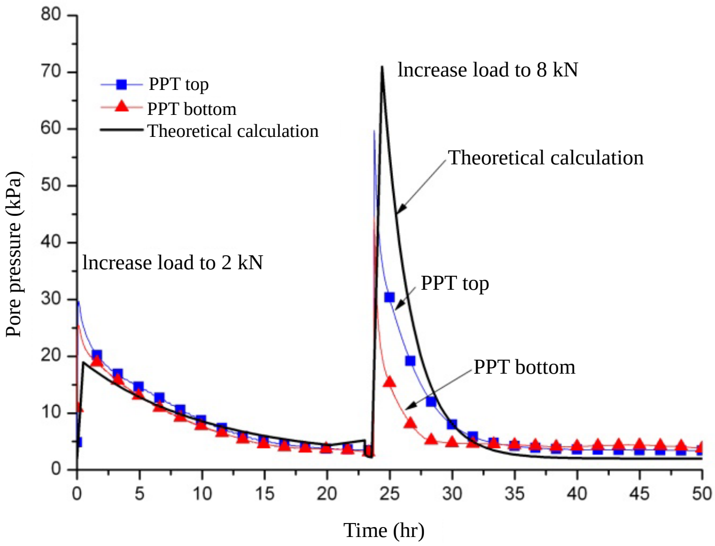

Fig. 7 Comparison of theoretical calculation with experimental data for pore pressure

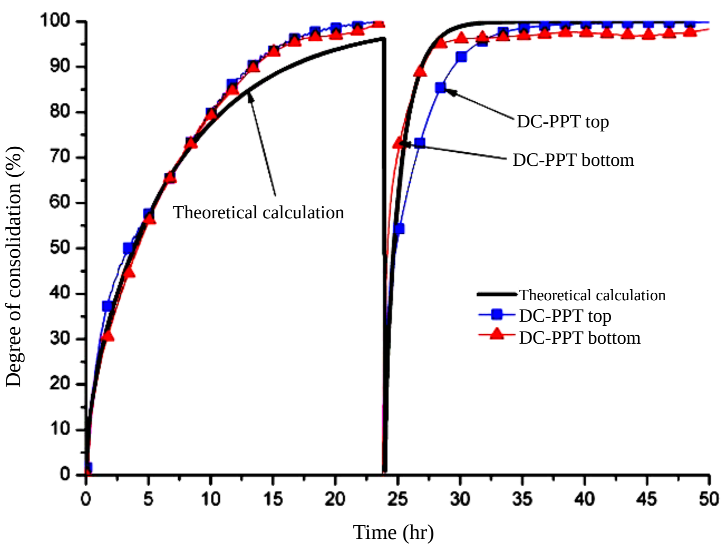

Fig. 8 Comparison of theoretical calculation with experimental data for degree of consolidation

Table 3 Summary of settlement measurement

Load (kN)	Hyperbolic method		Measured ultimate settlement (mm)	% of difference
	β	Ultimate settlement, $1/\beta$ (mm)		
2	0.0325	30.79	28.50	+7.72
8	0.0252	39.68	38.59	+2.79

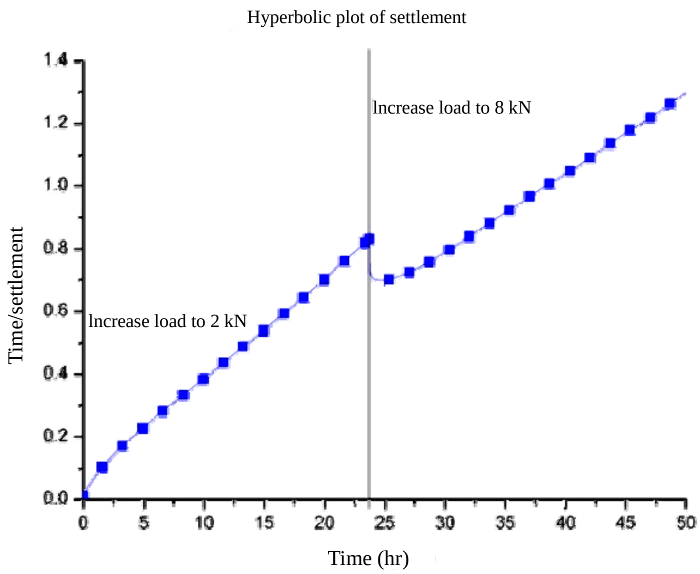

Fig. 9 Hyperbolic plot of settlement for loading test

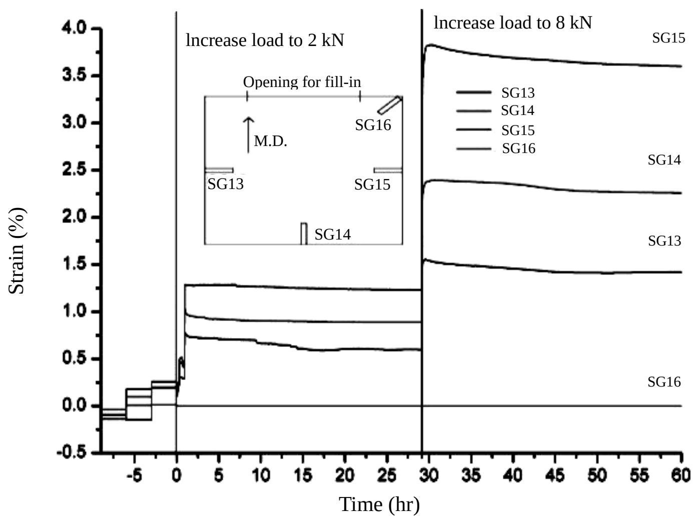

Fig. 10 Relationship of strain development of geotextile bag against time

maximum strain is 3.83% measured by strain gauge 15 and this happened while the compression loading increase to 8 kN. In contrast, the corners of geotextile bag experienced minimum strain development as recorded by strain gauge 16. The general strain level is about 0.5% to 1.3% when load is 2 kN, and about 1.5% to 3.8% when load increased to 8 kN. This shows that the geotextile bag is still behaving within elastic range, where geotextile material has not been stretched to yielding.

4. CONCLUSIONS

According to the tests on modified triaxial test and a geotextile bag loading test, the conclusions are:

1. In modified triaxial test, geotextile layer and the confining pressure are proven to be an important factor affecting the result of consolidation.
2. In the loading test conducted, experimental data proved that Terzaghi's Theory of Consolidation and 3D Carillo's combined flow theory could accurately predict the dissipation of excess pore pressure in geotextile bag.
3. The ultimate settlement of this geotextile bag filled with clayey soil can be predicted via Hyperbolic theory.
4. Experimental results from geotextile bag loading test shows that the strain development is directly proportional to the compressive load applied.

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