

A study on the mechanical and hydraulic properties of geotextile tube structure filled with high plasticity clay

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ABSTRACT

The utilization of geotextile tubes in coastal areas have been increasing over the years. Stacked geotextile tubes have been envisioned to replace conventional structures as long-term slope structures for a variety of reasons. In this study, the internal stability of a single geotextile tube is analyzed by considering the coefficient of soil pressure. The coefficient of soil pressure is an important design parameter because it affects the circumferential tension force and the overall stability of stacked geotextile tube structures during multi-stage construction. Furthermore, it is important to predict the consolidation time of a single geotextile tube which is of great importance in developing the construction schedule of large scale projects. In order to investigate the change in circumferential tension force, shape, and water content of clay-filled geotextile tubes, a half cross-section test was conducted. The test is unique because it can quantitatively measure the tension force of the geotextile tube. The results of the test show the importance of advancing the geotextile tube design analysis by developing accurate representations and predictions of the geotextile tube behavior.

1. INTRODUCTION

Planning, designing, scheduling, and costing are essential in geotextile tube projects. In designing, predicting the geometric dimensions and stresses of geotextile tubes are important in order to evaluate its capacity and strength. Also, prediction of the filling, dewatering and consolidation time of geotextile tubes are crucial in developing the construction schedule. Therefore, a standard approach in designing geotextile tubes in the geotechnical aspect must be established considering soil-geotextile interaction.

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Many researchers have proposed several theoretical concepts in determining the geometric dimensions, stresses, deformation, or capacity of geotextile tubes. However, the coefficient of soil pressure (K), which may affect the prediction of the geotextile tension, tube stresses, and overall stability of geotextile tube structures, has not been considered by previous methods. Furthermore, time-dependent analysis on the shape variation of geotextile tubes during consolidation has not been fully extended considering areal strain and horizontal drainage.

2. THEORETICAL BACKGROUND

2.1 Calculation of circumferential tension force and tube geometry

As shown in Eq. (1), the coefficient of soil pressure, which is expressed as K , is the ratio of horizontal stress (σ_h) to the vertical stress (σ_v). In calculating the circumferential tension force, previous methods assume that the coefficient of soil pressure (K) is equivalent to 1.0. Thus, K is usually omitted in the calculations, as shown in Fig. 1. Considering half the cross section of the geotextile tube and the coefficient of lateral soil pressure (K), the circumferential tension force (T) can be calculated using Eq. (2). In Eq. 1, P_p is the pumping pressure, H is the tube height, and γ is the unit weight of the soil fill. In cases where the pumping pressure is negligible and when pumping pressure is removed after filling, the tension force (T) is calculated using Eq. (3).

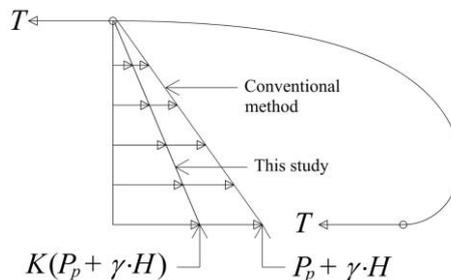


Fig. 1 Half cross-section geotextile tube force diagram

$$K = \frac{\sigma_h}{\sigma_v} \quad (1)$$

$$T = 0.5 \cdot K \cdot P_p \cdot H + 0.25 \cdot K \cdot \gamma \cdot H^2 \quad (2)$$

$$T = 0.25 \cdot K \cdot \gamma \cdot H^2 \quad (3)$$

From the Eq. (2), the geometry of a geotextile tube filled with pressurized slurry can be obtained. The formulation follows the discrete membrane elements method (DMEM) which was proposed by Yee et al. (2012) with slight modifications to the formulas by incorporating K .

2.2 Areal method

Kim et al. (2016) conducted several parametric studies and field test verifications on the densification analysis of geotextile tubes using the areal method. The areal method is a densification modeling approach based on areal-strain and is defined as the two – dimensional change in area caused by deformation. Fig. 2 shows the filled and consolidated cross-section of a geotextile tube along with its consolidation properties. The areal method is expressed in Eq. (4). Eq. (4) relates the initial area (A_0) and final area (A_f) to the initial water content (ω_0), final water content (ω_f), specific gravity (G_s), initial void ratio (e_0), final void ratio (e_f), initial volume ratio (f_0), and final volume ratio (f_f).

Since manual solution is tedious using the discrete membrane elements method, a computer program was used to obtain the tube areas (A) at specific tube heights (H). Data obtained from the program was saved in a matrix for easy data acquisition of the relationship between the tube height and tube area. A graph of the relationship between A and H , as shown in Fig. 3, was obtained by normalizing the tube height (H) with the maximum tube height (D), and tube area (A) with the maximum tube area (A_{max}). The curve in Fig. 3 was derived to approximate the area of the geotextile tube in cases where computers are unavailable, especially in the field, where the required volume of slurry needs to be estimated. For every ratio of H/D , an equivalent ratio of A/A_{max} is obtained, where the maximum height (D) is the theoretical diameter and the maximum area (A_{max}) is the area of the circle.

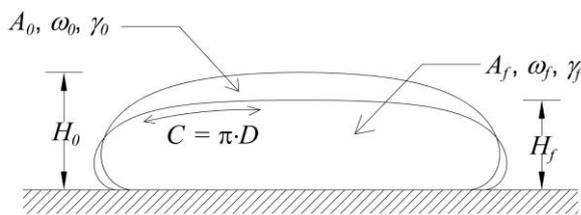


Fig. 2 Filled and consolidated cross-section of geotextile tube

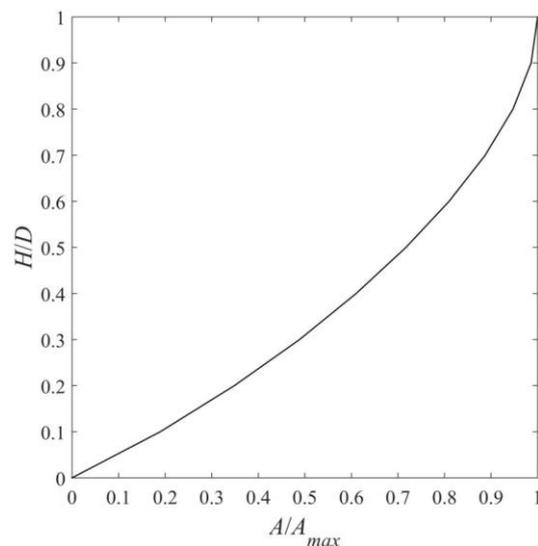


Fig. 3 Relationship between height and area of tube

$$\frac{A_f}{A_0} = \frac{1 + \omega_f \cdot G_s}{1 + \omega_0 \cdot G_s} = \frac{1 + e_f}{1 + e_0} = \frac{f_f}{f_0} \quad (4)$$

3. HALF-CROSS SECTION TEST SETUP

The clay soil material was obtained near a train station in Gunsan, South Korea. The properties of the clay soil are shown in Table 1. Since the clay soil was not workable, water was added. Clay soil and water was mixed using an agitator and clay slurry was produced with a water content (ω_0) of 108.94% and a saturated unit weight (γ_0) of 13.96 kN/m³. The half cross-section tube was filled by buckets. A total of 60 buckets was used to fill the tube with each bucket weighing 14-15 kgs. The measured tube height after filling was 0.67 m and the tube area was 0.60 m², calculated by theoretical analysis. The total weight (W_{t0}) of the tube was 8.36 kN, which was calculated using Eq. (6). L in Eq. (6) is the tube length. However, since the tube length used in the analysis is only 1.0 m, the initial tube area (A_0) was multiplied by the slurry unit weight (γ_0) to obtain the total tube weight. The theoretical weight of the tube was confirmed by multiplying the weight of each bucket to the total buckets. The total weight of the buckets range between 840-900 kg, which is almost equivalent to 8.36 kN. To obtain the initial weight of water and soil of the slurry mixture, Eq. (7) was used. During consolidation, the weight of soil was assumed to be constant. Thus, any change from the tube weight comes from water discharge (Q_{out}). From this, the weight of water (W_w) during consolidation can be calculated using Eq. (8) and the water content (ω) during consolidation can be calculated using Eq. (9). The unit weight of the soil was calculated using Eq. (10).

Table 1. Clay Soil Properties

Property	Unit	Quantity
Specific gravity, G_s	N/A	2.637
Percent passing #200 sieve	%	97
Soil classification (USCS)	N/A	CH

$$W_{t0} = A_0 \cdot \gamma_0 \cdot L = A_0 \cdot \gamma_0 \quad (6)$$

$$W_{w0} = W_{t0} - \frac{W_{t0}}{1 + \omega_0}; W_s = W_{t0} - W_{w0} \quad (7)$$

$$W_w = W_{w0} - Q_{out} \cdot \gamma_w \quad (8)$$

$$\omega = \frac{W_w}{W_s}; f = 1 + \omega \cdot G_s \quad (9)$$

$$\gamma = \frac{G_s + \omega \cdot G_s}{1 + \omega \cdot G_s} \gamma_w \quad (10)$$

The test tank and the experimental setup are shown in Figs. 4 and 5. The dimensions of the observation tank are 1.0 m in length, 1.5 m in width, and 1.0 m in height. The tank, which was supported by steel bar framing, consists of a transparent glass for easy viewing of the test specimen. The glass was marked with lines spaced at 5 cm for tube geometry measurement. A 5 cm thick sand layer was placed at the

bottom of the tank to allow drainage at base of the tube. The woven polyester (PET) half-cross section tube was installed and supported by two load cells at the top and bottom to monitor the tensile and compressive forces developing in the tube. The top load cells, which represent the tension force, were labeled as LC1 and LC2 while the bottom load cells, which represent bottom compression from the soil were labeled as LC3 and LC4. To obtain the measured tension force ($T_{measured}$), Eq. (10) was used. The pressure gauges and load cells were connected to a data logger which transmits the data readings into a desktop PC.

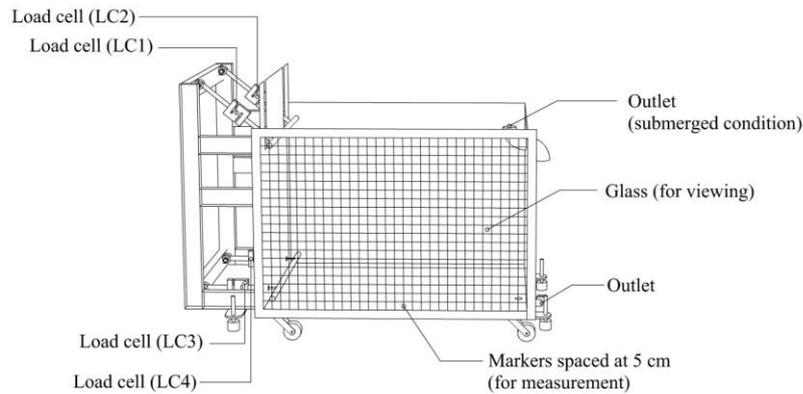


Fig. 4. Test tank used for half cross-section test

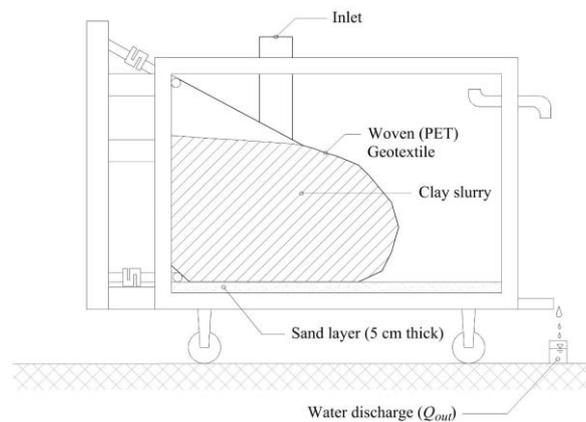


Fig. 5. Clay half cross-section test setup

$$T_{measured} = \frac{LC1 + LC2}{L} = LC1 + LC2 \quad (10)$$

4. HYDRAULIC PROPERTIES OF HALF CROSS-SECTION TUBE

The measured tube settlement and water discharge are shown in Fig. 6. The tube settlement was measured by inserting a stick into the inlet of the tube and was confirmed by viewing the specimen through the glass. The tube settled to about 18.8 cm after 21 days. Water discharge was measured using a graduated cylinder by

collecting the water from the bottom outlet. The measured water discharge was 0.11 m^3 after 21 days. Shown in Fig. 7 is the geometry of the tube after filling and during consolidation. The measured geometry was compared using the method discussed in Section 2. Results show that the calculated data are in agreement with the measured data, thus, validating the theoretical dimensioning method. After validating the theoretical dimensioning method, the measured heights during consolidation, which was calculated from the measured settlement, were converted to tube area. After converting the measured heights into tube area, the average water content was calculated using Eq. (4). A comparison between the average water content obtained from the areal method and water discharge is shown in Fig. 8. A slight discrepancy between the results could be a result from the underestimation of the tube area, or due to water not being able fully flow out from the bottom of the tank.

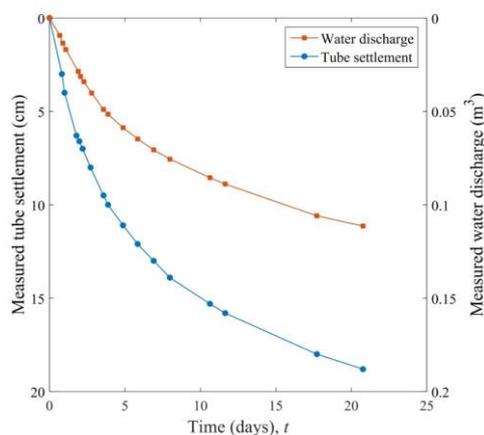


Fig. 6. Measured settlement and discharge

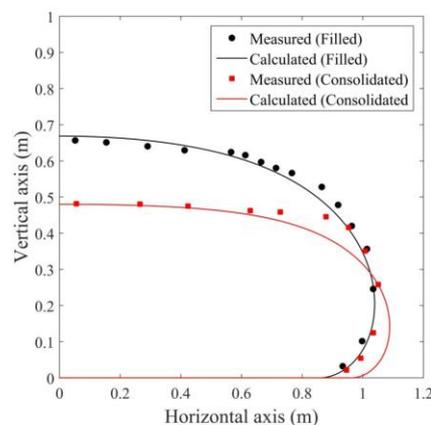


Fig. 7. Geometry of half cross-section tube after filling and during consolidation

After the test, the water content was measured. The water content with depth and the average water content after 29 days are shown in Table 2. The water content distribution inside the tube after 29 days is also shown in Fig. 9. Results of the test show that the water content at the top of the tube is 1.67 times more than at the bottom of the tube. Furthermore, at depth 0.22 m, the water content at the center of the tube is 1.13 times more than the right side which is nearer to the geotextile boundary. This indicates that a two-dimensional solution with acceptable boundary conditions must be proposed to accurately predict the consolidation of the tube. Furthermore, the average water content from Table 2 also agrees with the result in Fig. 8.

Table 2. Measured water content and average water content after 29 days

Depth (m)	Water content (%)	Average water content (%)
0	101.5	
0.125	91.2	
0.22	86.6 (center), 76.3 (right)	82.28
0.34	71.5	
0.48	60.6	

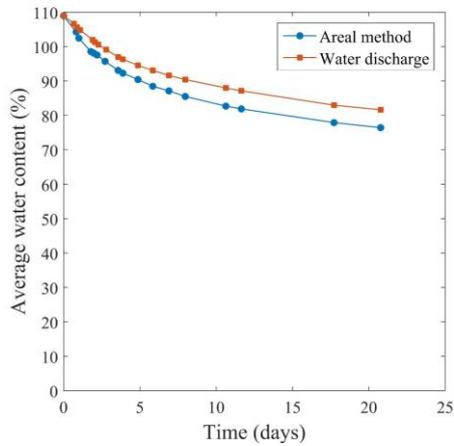


Fig. 8. Calculated average water content from tube settlement (areal method) and measured water discharge

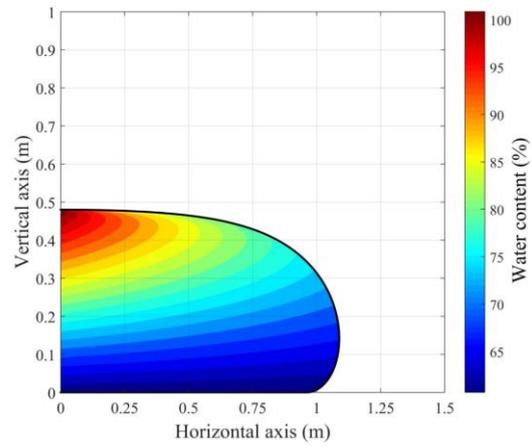


Fig. 9. Measured water content distribution after 29 days

5. MECHANICAL PROPERTIES OF HALF CROSS-SECTION TUBE

The measured loads per unit length with time obtained from the load cells were calculated, as shown in Fig. 10. As shown, the tension force is larger compared to the compression force located at the bottom of the tube. Using Eq. (10), the measured tension force was compared with the theoretical tension force (T), which was calculated using Eq. (3). In Eq. (3), H during consolidation was obtained by subtracting the measured tube settlement to the initial tube height (H_0). Also, γ was obtained using Eqs. (4) and (10). In this study, K values of 0.71 and 1.0 were chosen and compared with the measured data. Contrary to previous methods proposed in literature which assumes that K is equal to 1.0, the method proposed in this study ($K = 0.71$) is in better agreement with the measured data, thus, validating the theoretical method proposed in this study.

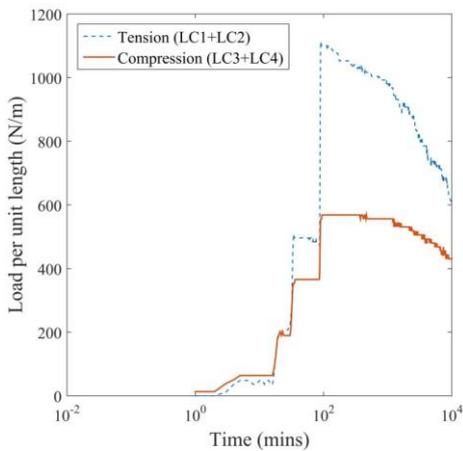


Fig. 10. Measured load per unit length with time

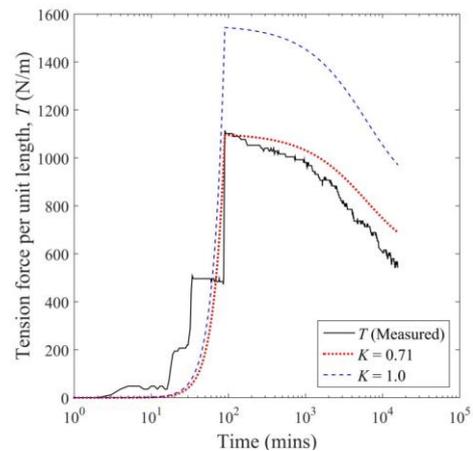


Fig. 11. Comparison between measured and theoretical tension force

6. CONCLUSIONS

In this study, a geotextile tube modeling solution which considers the soil pressure coefficient (K) was developed. The half cross-section test was conducted to determine the coefficient of soil pressure (K) of a clay soil and to validate the theoretical method presented in this study. Based on the half cross-section test, the follow conclusions are drawn:

- The measured and calculated tube geometry fairly agree with each other, thus, validating the theoretical method.
- After validating the theoretical method, the measured heights during consolidation, which was calculated from the measured settlement, were converted to tube area. From this, average water content was calculated and the average water content between the areal method and water discharge was compared. A slight discrepancy between the results could be a result from the underestimation of the tube area, or due to water not being able fully flow out from the bottom of the tank.
- Results of the test showed that the water content at the top of the tube is 1.67 times more than at the bottom of the tube. At depth 0.22 m, the water content at the center of the tube is 1.13 times more than the right side which is nearer to the geotextile boundary. This indicates that a two-dimensional solution with acceptable boundary conditions must be proposed to accurately predict the consolidation of the tube.
- From the test, an average K value of 0.71 was obtained. Contrary to previous methods proposed in literature which assumes that K is equal to 1.0, the method proposed in this study ($K = 0.71$) is in better agreement with the measured data, thus, validating the theoretical method proposed in this study.

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