Journal of the Korean Geo-Environmental Society
22(12): 25～32. (December 2021) http://www.kges.or.kr

ISSN 1598-0820 (Print)
ISSN 2714-1233 (Online)
DOI https://doi.org/10.14481/jkges.2021.22.12.25

Consolidation Analysis of Geotextile Tubes Filled with Highly Compressible Sludge Using Variable Coefficients of Consolidation

Hyeongjoo Kim[1)]· Hyeongsoo Kim[†]

Received: October 18th, 2021; Revised: November 4th, 2021; Accepted: November 19th, 2021

ABSTRACT : Geotextile tube technology has been perceived as an economical solution for liquid sludge treatment, and analyzing its consolidation behavior is necessary to be able to evaluate the dewatering capabilities of large geotextile tubes filled with contaminated soil, tailings, sewage sludge, and so on. The objectives of this study are to present a method that can adequately convey the consolidation behavior of geotextile tubes filled with sewage sludge, and to investigate the effects of various geotextile tube consolidation parameters. In this study, variable coefficients of consolidation are utilized to analyze the consolidation process of geotextile tubes filled with sewage sludge. The consolidation solution was verified by comparing the measured and predicted data from a hanging bag test conducted in the literature. After verifying the proposed solution, the consolidation parameters of a geotextile tube composed of a woven polypropylene outer layer and a non-woven polypropylene layer filled sewage sludge were obtained. Using the obtained parameters, the consolidation behavior of a large-scale composite geotextiles tube was predicted.

Keywords : Geotextile tubes, Liquid sludge, Compressibility, Two-dimensional drainage, Variable coefficient of consolidation, Consolidation analysis

1. Introduction

Due to rapid development and industrialization, large quantities of waste, including those that take the form of slurries with high water and fines content, are produced (Moo-Young et al., 2002; Muthukumaran & Ilamparuthi, 2006), and efficient disposal of these materials is one of the many problems faced today (Bourgès-Gastaud et al., 2014). Geotextile tube technology has been regarded as one that could be an economical solution for waste disposal. The technology utilizes geotextiles to encapsulate the fill materials, becoming tubular containers, as shown in Fig. 1. However, the utilization of these tubes is not straightforward as assessment of its dewatering capabilities and consolidation performance is necessary.

Fig. 1. Geotextile tube filled on land

Many consolidation theories (Terzaghi, 1943) have been proposed in the past and most of these theories have been applied to predict the settlement of a consolidating soil in the field under surcharge or under its own weight. However, consolidation solutions for geotextile tubes have been limited. Leshchinsky et al. (1996) have used basic-weight volume relationships to predict the drop in height of the geotextile tube by assuming that the soil in the tube is only moving downward, with the belief that the lateral movement of the tube during consolidation is negligible. However, various model tests and field tests conducted by Kim et al. (2016, 2018) have shown that in some or most cases, the tube width increases due to consolidation. In addition, the solution presented by Leshchinsky et al. (1996) is not concerned with the consolidation time. Kim et al. (2018) were able to present

1) Member, Professor, Department of Civil and Enviromental Engineering, Kunsan National University
† Post-Doctoral Researcher, Department of Civil and Enviroment Engineering, Kunsan National University (Corresponding Author : gudtn3004@kunsan.ac.kr)

a time-dependent geotextile tube consolidation procedure that utilizes the areal method to account for the vertical and horizontal deformation of the tube. However, the procedure neglects the horizontal drainage length in the consolidation equation. Recently, Kim et al. (2021) proposed a consolidation solution that takes into account the changes in the horizontal drainage length of geotextile tubes, and applied it for modified geotextile tubes, in which they analyzed the consolidation of modified geotextile tubes filled with silty sand. The solution also takes into account the variation of the coefficient of consolidation with time. The variation of the coefficient of consolidation in highly compressible materials were reported by Lee & Lee (2011), in which they concluded that the water content and sedimentation coefficient of consolidation (C_s) in the case of a clayey soil both rapidly decrease with time.

In this study, a consolidation solution for geotextile tubes filled with very soft sludge is presented using variable coefficients of consolidation that depend on the volume ratio. The solution is based on a combination of various methods that were modified or extended to take into account the change in tube shape, the nonlinear interaction between the soil and geotextile, and the water content distribution of the tube during consolidation. Thereafter, the performance of composite geotextile tubes filled with sewage sludge is investigated theoretically so that compatibility between the fill material and the geotextile can be evaluated for use in large-scale dewatering applications.

2. Theoretical Background

In this study, it is assumed that the material inside the tube during consolidation is saturated. This assumption is typically true for undrained tubes (tubes filled with fine-grained materials or tubes composed of low permeability geotextiles), hence, the solution presented in this study is suited for dewatering applications. However, the solution can also be used in shoreline applications by using very large coefficient of consolidation (c_v and c_r) values while assuming that the material inside the tube after filling is saturated. Assuming that the tube is resting on a rigid permeable foundation and that the tube is sufficiently long with negligible deformation along its length, a half cross-sectional representation of the tube is used in the consolidation analysis, as shown in Fig. 1. The geotextile tube dimensions such as the tube height (H), final tube height (H_f), tube area (A), initial tube area (A_0), final tube area (A_f), initial horizontal drainage lengths (e.g. y_{01} to y_{010}), and initial vertical drainage lengths (e.g. x_{01} to x_{05}) are obtained using the discrete membrane element method (DMEM) proposed by Yee (2012). The horizontal lengths y_{01} to y_{010} are discretized into dy_{01} to dy_{010}, and the horizontal drainage direction is assumed eastward. The vertical lengths x_{01} to x_{05} are also discretized into dx_{01} to dx_{05}, and the vertical drainage direction is assumed downward. A sample discretization of the horizontal drainage length y_{02}, discretized into dy_{02}, is shown in Figure 1(a). Also, a sample discretization of the vertical drainage length x_{01}, discretized into dx_{01}, is shown in Figure 1(b). The values of dy_0 and dx_0 depend on the number of horizontal nodes (n_r) and vertical nodes (n_v), respectively. The horizontal nodes are assigned with horizontal consolidation ratios (ζ_r), as shown in Fig. 2(a). Similarly, vertical consolidation ratios (ζ_v) are assigned to each of the vertical nodes, as shown in Fig. 2(b). The first number assignment in Fig. 2 for the consolidation ratios represents the drainage length number and the second number assignment represents the node number. For example, the consolidation ratio at the 3rd horizontal node at drainage

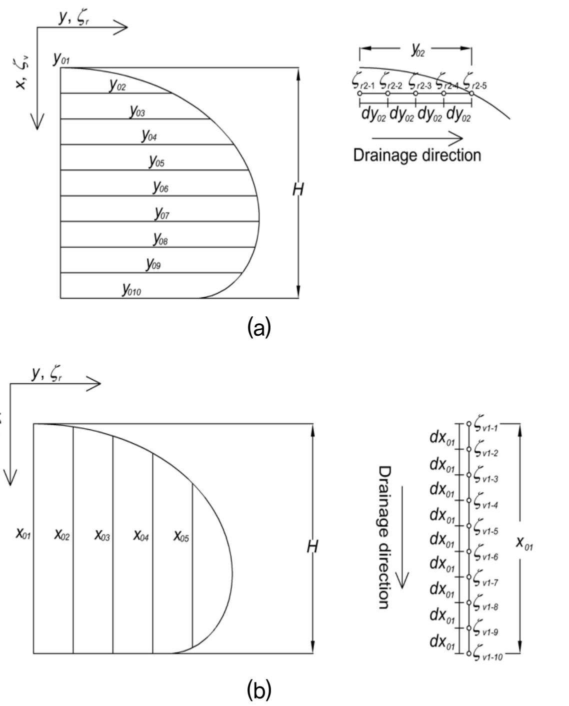

Fig. 2. Required dimensions for consolidation analysis: (a) horizontal drainage direction and discretization, and (b) vertical drainage direction and discretization

length y_{02} is $\zeta_{r2\text{-}3}$. After discretizing the drainage lengths, the consolidation of the geotextile tube can now be predicted using Eq. (1). Eq. (1) is based on the finite strain consolidation theory proposed by Mikasa (1963), which was mainly applied for one-dimensional problems such as the settlement of soil in the field. Since the soil in a geotextile tube deforms in such a way that the height decreases and that the width increases during consolidation, the second term was added to be able to consider horizontal drainage, and the terms $[\zeta + (H_0/H_f - \zeta_f)(\zeta - 1)/(\zeta_f - 1)]^2$ and $[\zeta + (y_0/y_f - \zeta_f)(\zeta - 1)/(\zeta_f - 1)]^2$ were incorporated into the original consolidation equation to take into account the change in vertical and horizontal dimensions, respectively. Detailed solution and the finite difference form of Eq. (1) can be found in the works of Mikasa (1963), and Takada & Mikasa (1984).

$$\frac{\partial\zeta}{\partial t}=\left[\zeta+\left(\frac{H_o}{H_f}-\zeta_f\right)\left(\frac{\zeta-1}{\zeta_f-1}\right)\right]^2\left[c_v\frac{\partial^2\zeta}{\partial x_0^2}+\frac{dc_v}{d\zeta}\left(\frac{\partial\zeta}{\partial x_0}\right)^2\right]+\left[\zeta+\left(\frac{y_0}{y_f}-\zeta_f\right)\left(\frac{\zeta-1}{\zeta_f-1}\right)\right]^2\left[c_r\frac{\partial^2\zeta}{\partial y_{0^2}}+\frac{dc_r}{d\zeta}\left(\frac{\partial\zeta}{\partial y_0}\right)^2\right] \quad (1)$$

where ζ is the consolidation ratio; ζ_f is the final consolidation ratio; t is time; c_v and c_r are the vertical and horizontal coefficients of consolidation, respectively; x_0 and y_0 are the initial depth and initial horizontal length, respectively; H_0 and H_f are the initial and final heights of the tube, respectively; y_f is the final horizontal length.

Because the volume of soft soils changes rapidly during the consolidation process, Mikasa (1963) introduced the consolidation ratio (z), which is equal to the ratio of the initial volume (V_0) and the final volume (V_f), and is also equal to the quotient of the initial volume (f_0) and the final volume ratio (f_f). Assuming that geotextile tube consolidation is a plane strain problem, the consolidation ratios ζ and ζ_f are related to the tube area (A), initial tube area (A_0), and final tube area (A_f), as shown in Eq. (2). The volume ratio (f) in Eq. (2) is equal to quotient of the soil mass volume (V) and the volume of solids (V_s). This relationship can be derived by taking the sum of the volume of voids (V_v) and volume of solids (V_s), which is equal to the volume of the soil mass (V). Replacing V_v with the product of the void ratio (e) and the volume of soil (V_s), then $V = V_s(1 + e)$. Rearranging, $V/V_s = (1 + e)$. The term $(1 + e)$ is defined as the volume ratio (f).

$$\zeta=\frac{f_0}{f}=\frac{A_0}{A};\ \zeta_f=\frac{f_0}{f_f}=\frac{A_0}{A_f} \quad (2)$$

Since drainage takes place in both the horizontal and vertical directions at the same time, drainage is assumed to occur around the geotextile tube, as shown in Fig. 3(a). However, due to the complex shape of the tube and varying drainage lengths, solving the consolidation of the tube using a grid by grid procedure can be complicated. As a result, node analysis is used in this study, in which the vertical consolidation ratios (ζ_v) and the horizontal consolidation ratios (ζ_r) are calculated independently. Shown in Fig. 3(b) is the concept of the solution. The vertical drainage is affected by the vertical coefficient of consolidation (c_v) and the horizontal drainage is affected by the horizontal coefficient of consolidation (c_r). The boundary conditions are as follows: at $t = 0$, the consolidation ratio (ζ) is equal to 1 at all points in the tube; at $t > 0$, the consolidation ratio (ζ) at the boundary of the geotextile tube is equal to the final consolidation ratio ζ_f.

After obtaining the consolidation ratio at each drainage length, the progress of consolidation must be assessed collectively. To take into account simultaneous drainage in the horizontal and vertical directions, Eq. (3), which is the formula proposed by Carillo (1942), is used to calculate for the degree of consolidation (U). The degree of consolidation (U), the horizontal degree of consolidation (U_r), and the vertical degree of consolidation (U_v) are related to the cross-sectional area and volume ratio, as shown in Eq. (4). In Eq. (4), DA_r and Df_r are the change in cross-sectional area and change in volume ratio due to horizontal consolidation, respectively; DA_v and Df_v are the change in cross-sectional area and change in volume ratio due to vertical consolidation, respectively. Since the consolidation ratio (z) is related to volume ratio (f), as shown in Eq. (2), the horizontal volume ratio (f_r) and the vertical volume ratio (f_v) can be obtained

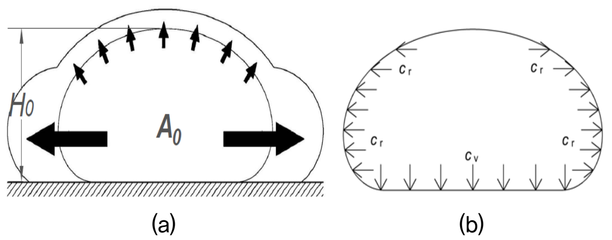

Fig. 3. Drainage conditions: (a) simultaneous vertical and horizontal drainage, (b) independent vertical and horizontal drainage

using Eq. (1). Thereafter, DA_r and DA_v can be obtained using Eq. (6). In Eq. (6), the mean volume ratio is utilized for the reason that the strain of the tube is evaluated based on the change in cross-sectional area, and therefore, it is suggested to analyze the deformation of the tube as a whole. Substituting Eq. (4) into Eq. (3), the cross-sectional area (A) at any time during consolidation can be calculated using Eq. (7). Similarly, the volume ratio (f) at any point in the tube can be obtained using Eq. (8). Thereafter, the water content distribution can now be obtained using Eq. (10). It should be noted that Eq. (8) can only be used if the horizontal and vertical volume ratios are situated at the same points in the tube. Therefore, it may be necessary for the calculated horizontal and vertical consolidation ratios to be converted or interpolated based on the chosen points of analysis. For additional procedures in solving Eq. (1), please refer to the work of Kim et al. (2020).

$$U = 1-(1-U_r)(1-U_v) \tag{3}$$

$$U = \frac{A_0 - A}{A_0 - A_f} = \frac{f_0 - f}{f_0 - f_f};$$
$$U_r = \frac{\Delta A_r}{A_0 - A_f} = \frac{\Delta f_r}{f_0 - f_f};\ U_v = \frac{\Delta A_v}{A_0 - A_f} = \frac{\Delta f_v}{f_0 - f_f} \tag{4}$$

$$f_r = \frac{f_0}{\zeta_r};\ f_v = \frac{f_0}{\zeta_v} \tag{5}$$

$$\Delta A_r = A_0 - \frac{A_0}{f_0/mean(f_r)};\ \Delta A_v = A_0 - \frac{A_0}{f_0/mean(f_v)} \tag{6}$$

$$A = A_0 - \frac{(\Delta A_r + \Delta A_v)(A_f - A_0) + \Delta A_r \Delta A_v}{A_f - A_0} \tag{7}$$

$$f = f_o - \frac{(\Delta f_r + \Delta f_v)(f_f - f_0) + \Delta f_r \Delta f_v}{f_f - f_0} \tag{8}$$

$$\Delta f_r = f_0 - f_r;\ \Delta f_v = f_0 - f_v \tag{9}$$

$$w = \frac{f-1}{G} = \frac{e}{G} \tag{10}$$

3. Consolidation Solution by Variable Coefficients of Consolidation

Fowler et al. (1996) conducted hanging bag tests on two geotextile bags filled with sewage sludge for the purpose of evaluating the dewatering capabilities and effluent water quality for design and filling of a large geotextile tube. The bags were made of composite geotextiles in which the outer layer of both the bags were woven polyester (PET). The first geotextile bag (geobag 1) was composed of a non-woven polyester (PET) inner layer while the second bag was composed of a non-woven polypropylene (PP) layer. The properties of the outer woven PET geotextile and the inner non-woven geotextiles are shown in Tables 1 and 2, respectively. The circumference of the bags were the same at 1.22 m, hence the diameter (D) of the bags were 0.39 m. The first bag (geobag 1) was used to obtain the consolidation parameters while the second geobag (geobag 2) was used to validate the obtained consolidation parameters. Geobag 1 was filled with sludge up to a height of 1.57 m with an initial void ratio (e) of 35.4 or an initial volume ratio (f_0) of 36.4. At the end of consolidation, the average final volume ratio (f_f) was 9.03 based on the height and void ratio relationship. Geobag 2 was filled up to a height of 1.55 m with an initial void ratio (e) of 21.9 or an initial volume ratio (f_0) of 22.9. At the end of consolidation, the average final volume ratio (f_f) was 7.65. The specific gravity (G) of the sludge was assumed to be 2.65. It should be noted that horizontal drainage length (D/2 = 0.195 m) remained constant throughout the test.

The result of curve fitting for geobag 1 is shown in Fig. 4, wherein a C_{cv} of 32.39 was obtained. C_{cv} is a constant that defines the change in coefficient of consolidation, which

Table 1. Properties of the outer woven PET geotextile used in hanging bag test

Description		Test method	Unit	Quantity
Tensile strength:	Weft	ASTM D4595	kN/m	227.76
	Warp	ASTM D4595	kN/m	218.12
Elongation:	Weft	ASTM D4595	%	13.6
	Warp	ASTM D4595	%	13.1
Apparent opening size (AOS)		ASTM D4751	μm	250

Table 2. Properties of the inner geotextiles used in hanging bag test

Description		Unit	Quantity
Average thickness:	Polyester	mm	5.08
	Polypropylene	mm	4.70
Apparent opening size (AOS):	Polyester	μm	149
	Polypropylene	μm	149

is given by Eq. (11). Using C_{cv}, the relationship between the volume ratio (f) and the coefficient of consolidation is obtained, as shown in Fig. 4. Using the same C_{cv} and the c_v-f or c_r-f relationship obtained in Fig. 4, the change in soil height of geobag 2 was predicted and compared, as shown in Fig. 5. The result shows that the predicted soil height matches well with the measured data. Since the measured and predicted data for geobag 2 matched well with each other using the consolidation parameters obtained from geobag 1, based on the results, it seems that the effect of the inner layer on the consolidation behavior is negligible. The predicted geometry of the sludge in geobag 1 and its water content distribution during dewatering, which was obtained using Eqs. (3-10), is shown in Fig. 6. As shown, the average water content (w_{ave}) in geobag 1 was reduced to 1,088%, 759%, and 431% from an initial water content of 1416% after t = 1.74 days, 8.54 days, and 27 days, respectively. Volume loss in the bag was mainly attributed by radial flow owing to the fact that the drainage length in the horizontal direction was significantly smaller than the vertical drainage length. Low water content, which is represented by the darker color in the figure, rapidly spread from the sides to center of the geobag while the change in water content starting from the

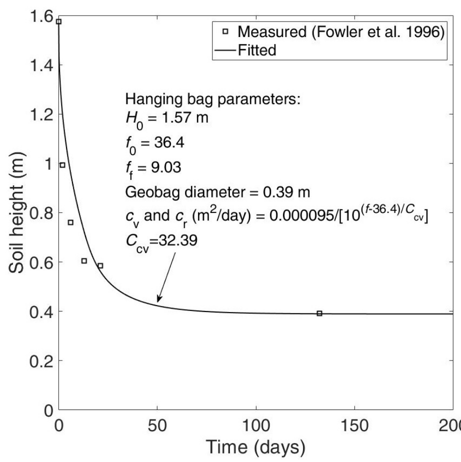

Fig. 4. Hanging bag test curve fitting for geobag 1

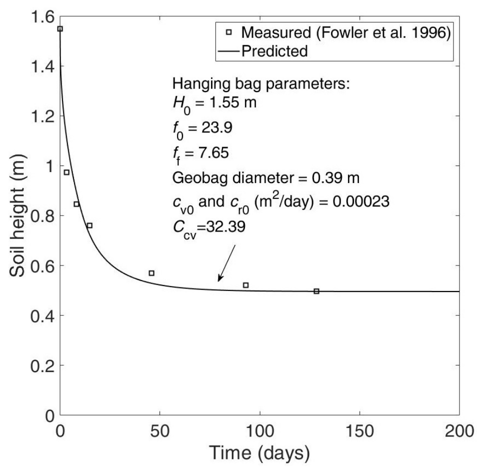

Fig. 5. Comparison of measured and predicted data of geobag 2

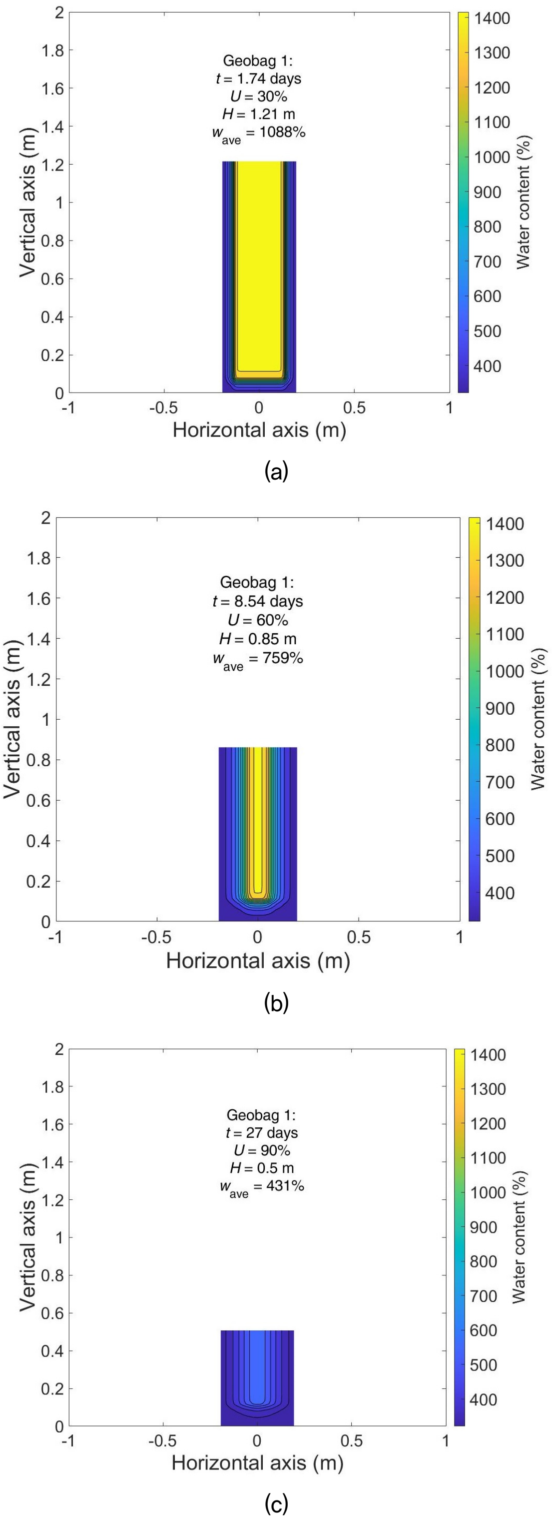

Fig. 6. Predicted geometry of sludge in geobag 1 and its water content distribution: (a) U = 30%, (b) U = 60%, (c) U = 90%

bottom to the top did not progress until the height of the sludge was only 0.5 m. Hence, the drainage path greatly influences the dewatering behavior of geotextile tubes.

$$c_{cv} = \frac{f_0 - f_f}{\log(\delta)} \tag{11}$$

where,

$$\delta = \frac{c_{vf}}{c_{v0}} \tag{12}$$

4. Consolidation Simulation of Geotextile Tubes Filled With Highly Compressible Sludge

Fowler et al. (1996) conducted a field test on a composite geotextile tube filled with sewage sludge. The outer layer consisted of a woven polypropylene (PP) geotextile while the inner layer consisted of non-woven polypropylene (PP) geotextile. The properties of the outer woven PP geotextile and the inner non-woven PP geotextile are shown in Tables 3 and 2, respectively. The geotextile tube circumference (C) and length (L) were both 9.14 m. The tube was filled up to a height of 1.52 m using sewage sludge with an initial water content of 1282%. After 53 days, the volume ratio reduced to 12.05 from 32.05, and the height of tube was reduced to about 29.17% of the original height. Using the method proposed in this study, the consolidation parameters were obtained by curve fitting, as shown in Fig. 7. The predicted geometry and water content distribution of the geotextile tube filled with sludge is shown in Fig. 8. As

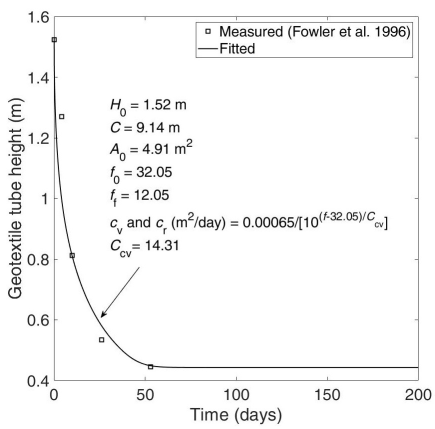

Fig. 7. Curve fitting for a composite geotextile tube (woven PP+non-woven PP) filled with sewage sludge

Table 3. Properties of the outer woven PP geotextile used in the geotextile tube demonstration test filled with sewage sludge

Description		Test method	Unit	Quantity
Tensile strength:	Weft	ASTM D4595	kN/m	70
	Warp	ASTM D4595	kN/m	70
Elongation:	Weft	ASTM D4595	%	20
	Warp	ASTM D4595	%	20
Apparent opening size (AOS)		ASTM D4751	μm	420

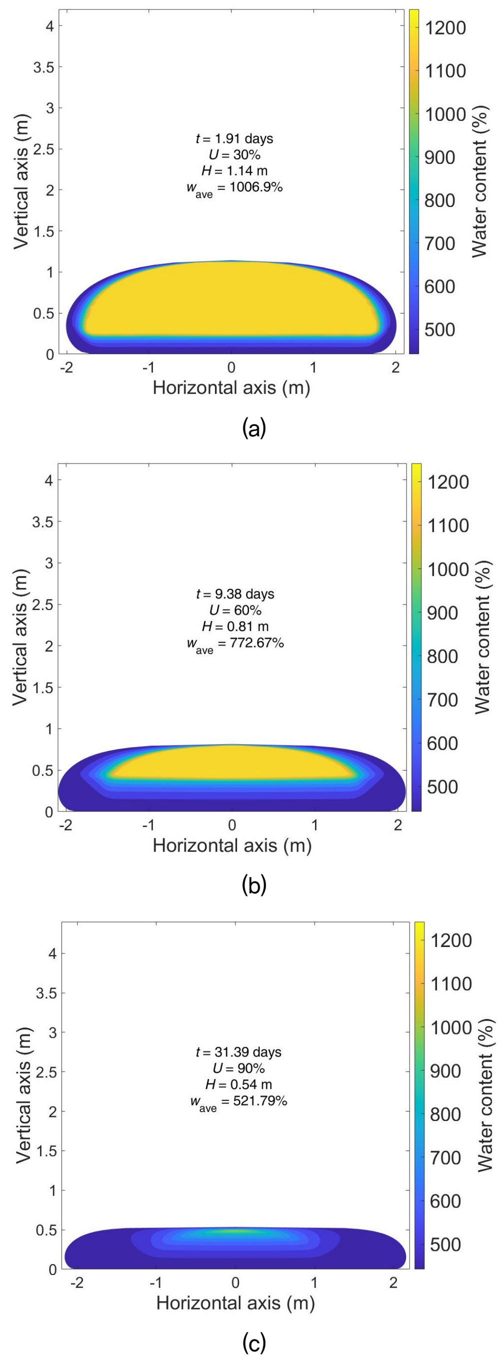

Fig. 8. Predicted geometry and water content distribution of geotextile tube filled with sludge: (a) U = 30%, (b) U = 60%, (c) U = 90%

shown, the width of the tube increased slightly while the height of tube decreased drastically after about 31 days. In addition, the average water content (w_{ave}) was greatly reduced from 1282% to 1007%, 773%, and 522% after t = 2 days, 10 days, and 32 days respectively, as shown in Fig. 8.

After obtaining the consolidation parameters, the consolidation of two composite geotextile tubes filled with sewage sludge was simulated. The first simulation uses the consolidation parameters obtained from the geobag experiment. Hence, the first simulated geotextile tube is composed of a woven PET outer layer and a non-woven PET inner layer. The second simulation uses the consolidation parameters obtained from the geotextile tube field test. Hence, the second simulated geotextile tube is composed of a woven PP outer layer and a non-woven PP inner layer. Both the tubes have similar initial heights (H_0), initial volume ratio (f_0), final volume ratio (f_f), initial area (A_0), final area (A_f), and circumference (C). The result of the consolidation simulation is shown Fig. 9. Results show that the consolidation performance of the woven PP+non-woven PP geotextile tube was better than the woven PET+non-woven PET geotextile tube. This is because the outer PP geotextile used in the simulation is more permeable than the outer PET geotextile due to its large apparent opening size (see Tables 1 and 3). Based on the results, the geotextile tube composed of PP geotextile fully consolidated in about 190 days while the geotextile tube composed of PET geotextile was still consolidating. Using the method proposed in this study, it is projected that the PET geotextile tube will reach a degree of consolidation of 90% in about 5.36 years. This shows the importance of obtaining consolidation parameters so that compatibility between the fill material and the geotextile material can be assessed for use in large scale dewatering applications.

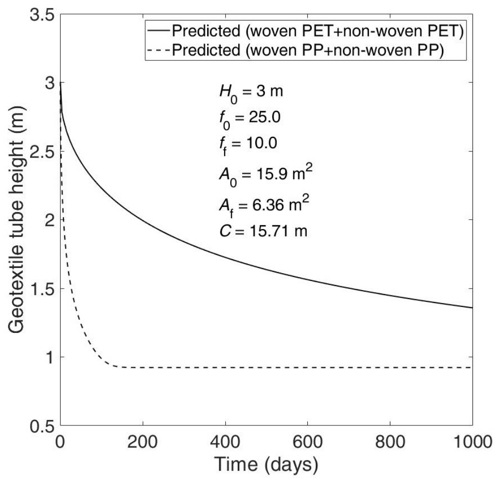

Fig. 9. Consolidation simulation of two composite geotextile tubes filled with sewage sludge

5. Conclusions

The performance of geotextile tubes is affected by many factors. Hence, obtaining hydraulic compatibility between geotextiles and fill materials is complex. To assess the behavior of geotextile tubes filled with sewage sludge during consolidation, theoretical analysis was conducted. In this study, a two-dimensional consolidation solution for geotextile tubes was proposed. The proposed method was verified by comparing the measured data from a hanging bag test with the predicted data. After verifying the proposed method, the consolidation of two composite geotextile tubes filled with sewage sludge was simulated based on the parameters obtained in this study. The results showed the importance of obtaining consolidation parameters so that compatibility between the soil and the geotextile material can be assessed for use in large scale dewatering applications.

Acknowledgment

This research was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education (NRF2021R1A6 A1A0304518511).

References

1. Bourgès-Gastaud, S., Stoltz, G., Sidjui, F. and Touze-Foltz, N. (2014), Nonwoven geotextiles to filter clayey sludge: an experimental study, Geotextiles and Geomembranes, Vol. 42, No. 3, pp. 214~223.
2. Carrillo, N. (1942), Simple two and three dimensional case in the theory of consolidation of soils, Journal of Mathematics and Physics, Vol. 21, No. 1~4, pp. 1~5.
3. Fowler, J., Bagby, R. M. and Trainer, E. (1996), Dewatering sewage sludge with geotextile tubes, Proc. 49th Canadian Geotechnical Conference, St John's, Canada, pp. 1~31.
4. Kim, H. J., Won, M. S., Jamin, J. C. and Joo, J. H. (2016), Numerical and field test verifications for the deformation

behavior of geotextile tubes considering 1D and areal strain, Geotextiles and Geomembranes, Vol. 44, No. 2, pp. 209~218.
5. Kim, H. J., Park, T. W., Dinoy, P. R., Kim, H. S. and Kim, H. J. (2018), Design and consolidation analysis of geotextile tubes for the Saemangeum project in Korea, Geosynthetics International, Vol. 25, No. 5, pp. 507~524.
6. Kim, H. J., Park, T. W., Dinoy, P. R. and Kim, H. S. (2021), Performance and design of modified geotextile tubes during filling and consolidation, Geosynthetics International, Vol. 28, No. 2, pp. 125~143.
7. Lee, S. H. and Lee, J. H. (2011), An experimental research about settling and consolidation characteristics of dredged soil in west coast, Journal of the Korean Geo-Environmental Society, Vol. 12, No. 5, pp. 29~36 (In Korean).
8. Leshchinsky, D., Leshchinsky, O., Ling, H. I. and Gilbert, P. A. (1996), Geosynthetic tubes for confining pressurized slurry: some design aspects, Journal of Geotechnical Engineering, Vol. 122, No. 8, pp. 682~690.
9. Mikasa, M. (1963), The consolidation of soft clay - a new consolidation theory and its application, Kajima Institution Publishing Co., Ltd., Tokyo Japan.
10. Moo-Young, H. K., Gaffney, D. A. and Mo, X. (2002), Testing procedures to assess the viability of dewatering with geotextile tubes, Geotextiles and Geomembranes, Vol. 20, No. 5, pp. 289~303.
11. Muthukumara, A. E. and Ilamparuthi, K. (2006), Laboratory studies on geotextile filters as used in geotextile tube dewatering, Geotextiles and Geomembranes, Vol. 24, No. 4, pp. 210~219.
12. Takada, N. and Mikasa, M. (1984), Consolidation of multi - layered clay, In: Proceedings of a Symposium on Sedimentation Consolidation Models - Prediction and Validation, New York, USA, pp. 216~228.
13. Terzaghi, K. (1943), Theoretical soil mechanics, John Wiley and Sons, New York.
14. Yee, T. W. (2012), Analysis of geotextile tube using discrete membrane elements method. In: 5th European Geosynthetics Congress, Valencia, 2012, pp. 583~587.