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The optimization of arc length for composite geotextile tube using by geometric parameters analysis

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ABSTRACT

This study represents the optimization of arc length with respect to combination of woven and nonwoven geotextile tube by the analysis method which was performed by Geotextile Tube Design Software(GeoTDS Ver.3.0). The software program was developed in order to perform the following specific functions: non-time dependent consolidation analysis and a new proposed method, time-dependent consolidation analysis based on generalized one dimensional consolidation theory which analyzes and predicts the densified or consolidated tube geometry after the dewatering process. Geotextile tube strain varies depending on the amount of soil in the cross section as well as the percentage length of radius of (Woven and Non-Woven) Geotextile tube material. The variation of deformation occurs with respect to cross sectional area and permeability of filling material are discussed.

1. INTRODUCTION

Geotextile tubes are made of water permeable, sand-sealed geotextile filled with sand or other granular materials. They are often used in coastal areas, functioning as beach groynes, breakwaters, dune toe protection, submerged reefs, containment dikes or core structures (Bezuijen & Vastenburg 2013). Numerous studies on geotextile tubes published in the literature as well as several analytical solutions were proposed (Lui & Silvester 1977; Kazimierowicz 1994; Leshchinsky et al. 1996; Plaut & Suherman 1998; Ghavanloo & Daneshmand 2009; Malik 2009; Cantre & Saathoff 2011; Gou et al. 2014a, 2014b). Plaut and Suherman (1998) formulated a design method to calculate the shape of geotextile tubes filled with an incompressible fluid having a specific weight and pressure head relative to the

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external air pressure. Plaut and Suherman's formulation is well explained and is relatively easy to produce, hence, the same method is adopted in the present study. The basic assumptions for the analysis are: (1) the geotextile tube is considered to be sufficiently long so that a two-dimensional (2D) analysis of its cross section will be appropriate (plane strain problem); (2) The tube material is modeled as a flexible and inextensible membrane with negligible weight and bending stiffness; (3) The tube is assumed to be filled with an incompressible fluid having a specific weight and pressure head relative to the external air pressure; (4) The tube is resting on a rigid foundation and is subjected to an internal (and possibly in some cases, external) hydrostatic pressure; (5) There is no friction between the geotextile material and fill material, or between the geotextile material and the rigid foundation; and lastly, (6) the tensile force around the geotextile tube is constant.

2. PROGRAM ALGORITHM

2.1 Geotextile Tube Geometry

The nomenclatures for the geotextile tube geometry and forces acting on its differential membrane element are shown in Figs. 1(a) and 1(b), respectively. Equilibrium analysis of Fig. 1 yields the following governing equations:

$$P = T\frac{d\theta}{dS} = P_{bot} - \gamma_{\text{int}} Y \tag{1}$$

$$\frac{dX}{dS} = \cos\theta; \quad \frac{dY}{dS} = \sin\theta; \quad \frac{dT}{dS} = 0 \qquad \text{(2a, 2b, 2c)}$$

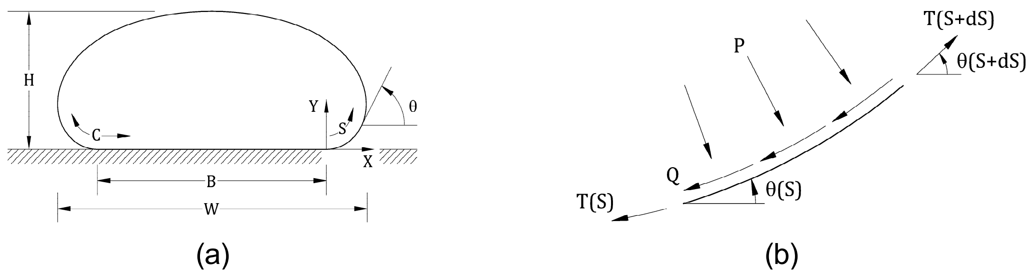


Fig. 1 (a) Tube cross-section and (b) forces acting on the differential element (after Plaut and Suherman 1998)

where P = internal hydrostatic pressure, T = circumferential tensile stress (constant throughout the tube circumference due to Eq. (2c), θ = tangential angle with respect to the horizontal axis, S = arc length of the cross-sectional element, C = tube circumference, P_{bot} = pressure at the bottom of the tube, γ_{int} = specific weight of the fill material, Y = vertical coordinate and X = horizontal coordinate. The general solution is achieved using elliptic integrals which was formulated by Liu and Silvester (1977). The complete detail of the basic solution can be found in the original publication of Plaut and Suherman (1998).

The solution presented above is generally used for geotextile tube analysis during the filling stage. For densification (consolidation) analysis, Leshchinsky et al. (1996) proposed a one-dimensional (1D) strain approach (i.e., downward movement only; lateral movement is neglected) to estimate the final height of the tube containing the solidified slurry at a certain desired density. The original expression proposed by Leshchinsky et al. extended equation proposed by the authors are written as follows, respectively:

$$\frac{H_f}{H_0} = 1 - \frac{G_s\left(\omega_0 - \dfrac{\omega_f}{S_f}\right)}{1+\omega_0 G_s}; \quad \frac{A_f}{A_0} = 1 - \frac{G_s\left(\omega_0 - \dfrac{\omega_f}{S_f}\right)}{1+\omega_0 G_s} \tag{3}$$

where H_0 = initial tube height before the densification of the fill material; H_f = final tube height filled with solidified material; A_0 = initial tube area before the densification of the fill material; A_f = final tube area filled with solidified material; G_s = specific gravity of the fill material's solid particles; ω_0 and ω_f are the initial and final water contents of the fill material, respectively; and S_f = degree of saturation of the solidified fill. The basic assumptions for the analysis are: (1) The initial fill (slurry) is assumed to be fully saturated; (2) The densified fill material (after dewatering) is either fully saturate (S_f = 100%) or saturated to a certain degree (S_f < 100%); and (3) The soil particles are incompressible., the soil is section in consideration is a non-rectangular shaped soil section bounded by the confining geotextile membrane. Assuming a segment of a geotextile tube with a unit length of L_s and a cross-sectional area A shown in Fig. 2. As the material fill in the tube consolidates, the cross-sectional area A decreases homogenously along L_s. Based on these assumptions the volumetric strain relationship (Das 2010) is; where A_0 is the cross-sectional tube area after the final filling process or the initial cross-sectional tube area at the start of the consolidation process; ΔA is the amount of the decrease in the geotextile tube's cross-section after consolidation. The fundamental assumption for this analysis is that the circumference of the tube remains constant during the process of consolidation.

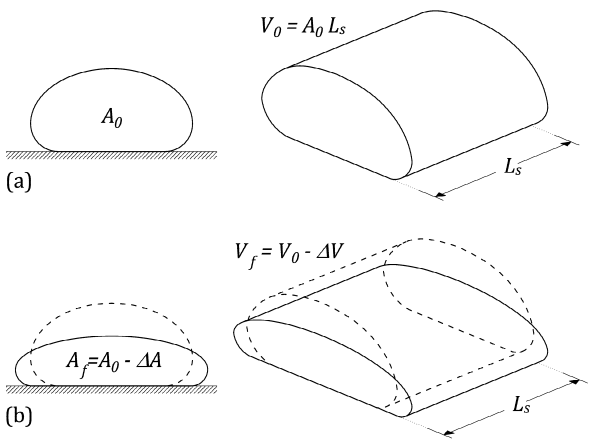


Fig. 2 Geotextile tube segment: (a) Final filling state and (b) final consolidation state

2.2 Time-Dependent Consolidation Analysis

Mikasa (1963) derived a generalized nonlinear one-dimensional (1D) consolidation equation for clay layers having homogeneous consolidation properties throughout its depth that is initially in equilibrium with its self-weight and effective overburden stress as follows:

$$\frac{\partial \varepsilon}{\partial t} = C_v \frac{\partial^2 \varepsilon}{\partial z^2} + \frac{dC_v}{d\varepsilon}\left(\frac{\partial \varepsilon}{\partial z}\right)^2 - \frac{d\left(C_v \cdot m_v \cdot \gamma'\right)}{d\varepsilon}\left(\frac{\partial \varepsilon}{\partial z}\right) \tag{4}$$

where ε is the natural strain, t is the consolidation time, and z is the depth, Eq. (4) considers the changes of the coefficient of consolidation C_v, coefficient of volume compressibility m_v, and coefficient of permeability k with the decrease in the void ratio e during the progress of consolidation.

Generally, the void ratio-effective stress relationships for normally consolidated homogenous soils is linear in semi-logarithmic space of an *e-log* σ' diagram (Mission, 2011; Burland, 1990; Lambe and Whitman, 1969). The relationship between the coefficient of consolidation C_v and natural strain ε is derived as follows,

$$C_v = \frac{k}{m_v \gamma_w} = \frac{k_0}{m_{v0}\gamma_w}\phi = C_{v0}\phi \tag{5}$$

$$\phi = \frac{10^{\left[\left(1-\frac{1}{\exp(\varepsilon)}\right)(1+e_0)\left(\frac{1}{C_c}-\frac{1}{C_k}\right)\right]}}{\exp(\varepsilon)} \tag{6}$$

Applying above Eqs. The finite difference equation becomes,

$$\Delta\varepsilon = C_{v0}\Delta t\left\{\phi\left[\frac{\left(\frac{\varepsilon_{z+\Delta z}-\varepsilon_z}{\Delta z_{z+\Delta z}}\right)-\left(\frac{\varepsilon_z-\varepsilon_{z-\Delta z}}{\Delta z_{z-\Delta z}}\right)}{\left(\frac{\Delta z_{z-\Delta z}+\Delta z_{z+\Delta z}}{2}\right)}\right]+\frac{d\phi}{d\varepsilon}\left(\frac{\varepsilon_{z+\Delta z}-\varepsilon_{z-\Delta z}}{\Delta z_{z-\Delta z}+\Delta z_{z+\Delta z}}\right)^2\right\} \tag{7}$$

where Δt is the time step and Δz is the depth increment as shown in Fig. 3. If H_0 is the initial thickness of the clay layer and n is the number of elements in the finite difference grids, then the initial element thickness is $\Delta z_0 = H_0/n$. After the strain value has been determined for the time $t = \Delta t$, it is used to determine the nodal coordinates for the new grid to be used to predict the value of the strain at the next time step (Fig. 3a).

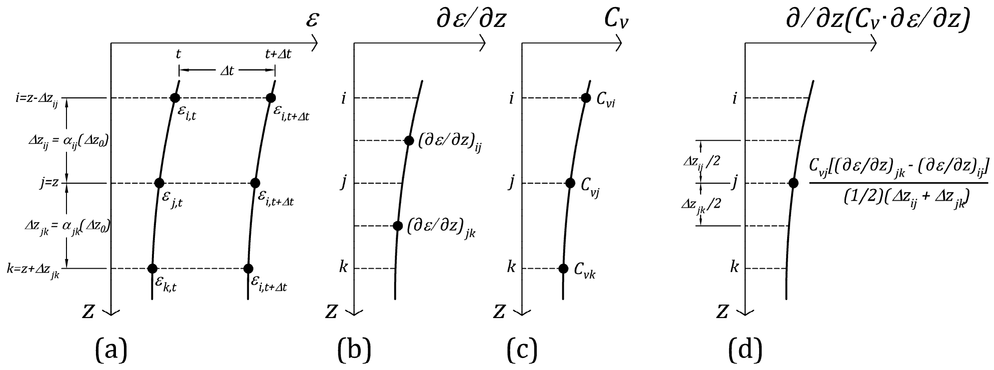


Fig. 3 (a) Variation of strain ε with depth, (b) first derivative of strain, (c) variation of strain C_v with depth and (d) second derivative of strain

3. NUMERICAL ANALYSIS AND RESULTS

3.1 Parametric Properties

The parametric properties for the clayey soils given in Table 1 are inputted in the GeoTDS program as shown in Fig. 4. Dredged soil obtained from Pyeongtaek, South Korea was considered as the fill material for the geotextile tube time-dependent consolidation parametric study presented in this section. The clay parameters used in the GeoTDS program were initially given in Table 1. Other physical properties of the clayey fill material in its natural state (during dredging) are listed in Table 2. In this parametric study, the geotextile tube was simulated to be filled with slurry on dry area (surface filling) until the circumferential tensile stress reaches 90%$T_{c(ALOWABLE)}$. The simulation results at the end of the geotextile tube filling are summarized in Table 2.

3.2 Time-Dependent Consolidation

The results of the time dependent consolidation are presented in Table 3. Notice how the analysis results on stress and pressures at Table 2. Differs to the results at the beginning of the time-dependent consolidation analysis (i.e., time = 0, U_{avg} = 0%). The resulting values at the beginning of the time-dependent consolidation are higher than the simulated results of the filled-tube prior to the consolidation analysis. This can be attributed to the type of fill material used in the analysis. For instance, a slurry material is used during the geotextile tube filling. Due to its material composition (liquid and solid), slurry fills are less dense compared to the solidified fills. Hence, during the tube filling simulation, the unit weight of the slurry fill is used in the analysis. For the consolidation modelling, on the other hand, the unit weight of the solidified fill material is used in the analysis.

In Table 3 the geotextile tube geometric properties, stresses and pressures are shown corresponding to 0%, 15%, 30%, 45%, 60%, 75%, 90% and 100% average degree of consolidation of the solidified fill. The time at which each average degree of consolidation is attained is also given. For the type of fill material and tube dimension used in the parametric study, it would take approximately about 1 year for the geotextile tube to fully consolidate. The geometric shapes of the geotextile tube at each stage corresponding to the average degree of consolidation of the solidified fill are illustrated in Fig. 5.

Predictions for the development of excess pore water pressures, degree of consolidation, and tube settlement profile are shown in Figs. 6-8.

The detailed lists of the physical properties for the geotextile tube and fill material used in the parametric study are shown in Table 1.

Table 1 The properties for Geotextile tube and Pyeongtaek's dredging clay

Description	Unit	Quantity
Theoretical diameter, D_T	m	3
Tube length, L_{tube}	m	25
Max. allow. circumferential tensile stress, $T_{c(ALLOWABLE)}$	kN/m	25
Slurry		
Specific gravity of soil solids, G_s	-	2.7
Specific weight, γ_{slurry}	kN/m^3	14
Water content , ω_0	%	300
Solidified fill (clay and sand, non-time-dependent consolidation analysis)		
Specific weight, γ_{fill}	kN/m^3	18
Water content, ω_f	%	38.4
Time-dependent consolidation analysis (only applicable to clayey fills)		
Liquid Limit, LL	%	43
Plastic Limit, PL	%	20
#200 passing	%	92.1
USCS		CL
Compressibility index, C_c	-	0.79
Permeability index, C_k	-	0.53
Coefficient of consolidation, C_v	m^2/yr	2.5229
Coefficient of volume compressibility, m_v	m^2/kN	0.0044

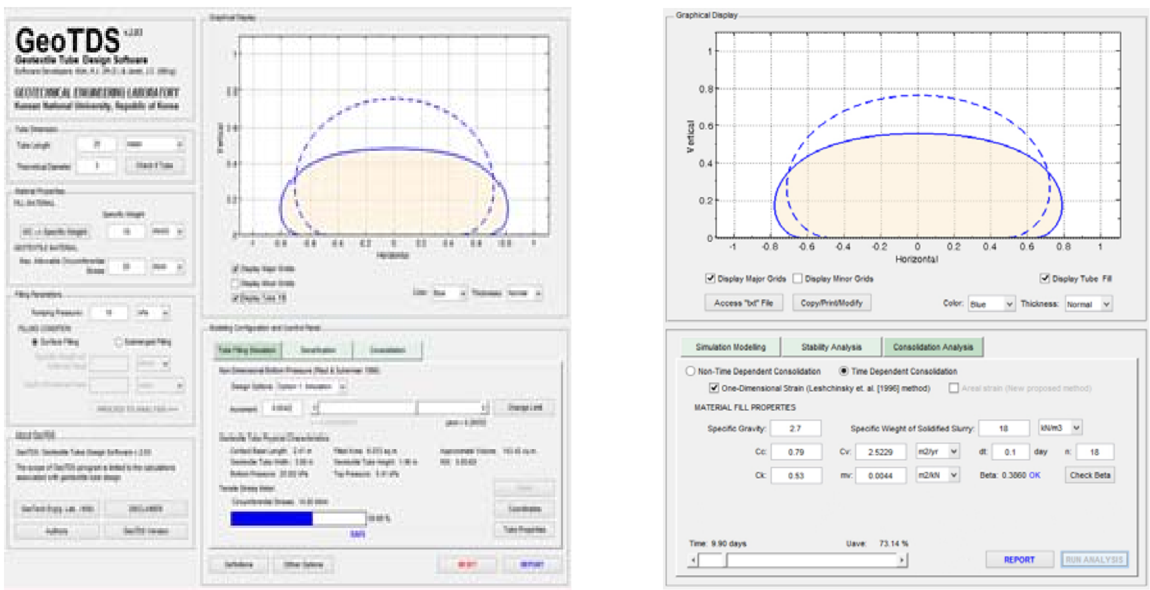
Table 2 Simulation results after geotextile tube filling simulation

Description	Unit	Quantity
Geometric properties:		
Tube height, H	m	2.0
Tube width, W	m	3.65
Contact base, width B	m	2.34

Cross-sectional area, *A*	m^2	6.09
Pressures and stresses:		
Circumferential stress	kN/m	22.5
Percentage achieved circumferential stress with respect to $T_{c(ALLOWABLE)}$	%	90

Table 3 Simulation results for geotextile tube time-dependent consolidation analysis

Time (days)	U_{avg} (%)	Geometric properties				Stress and pressures		
		H (m)	*W* (m)	*B* (m)	*A* (m^2)	*T* (kN/m)	P_{bot} (kPa)	P_{top} (kPa)
		2.00	3.64	2.33	6.08	28.9	46.9	10.8
3	15	1.86	3.73	2.57	5.81	22.3	40.7	7.3
11	30	1.71	3.83	2.80	5.51	17.1	35.4	4.7
24	45	1.56	3.92	3.01	5.20	13.3	31.1	3.0
42	60	1.42	4.00	3.19	4.85	10.4	27.4	1.8
60	75	1.32	4.05	3.32	4.59	8.6	24.9	1.2
124	90	1.12	4.14	3.52	4.05	5.9	20.7	0.5
364	100	1.03	4.21	3.65	3.81	4.9	18.8	0.3



(a) Non-time dependent (b) time-dependent

Fig. 4 Interactive graphical display for non-time and time-dependent consolidation analysis

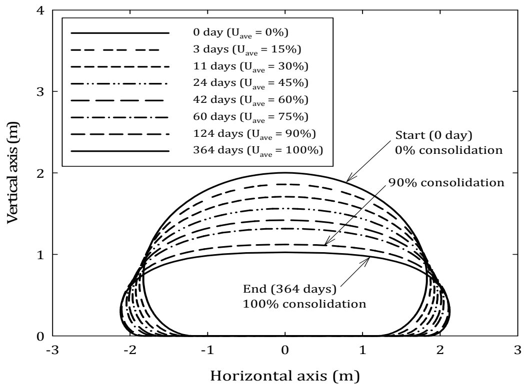


Fig. 5 Geotextile tube geometric shapes during the consolidation process

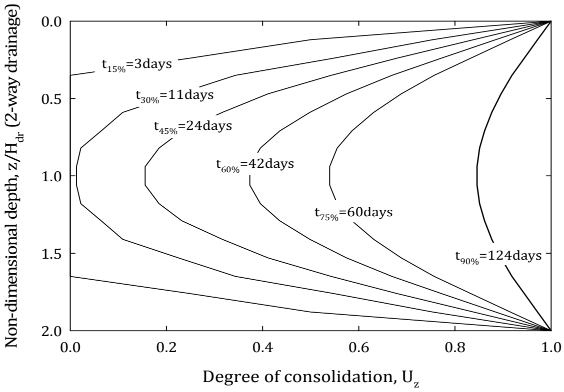


Fig. 6 Projected development of the degree of consolidation isochrones

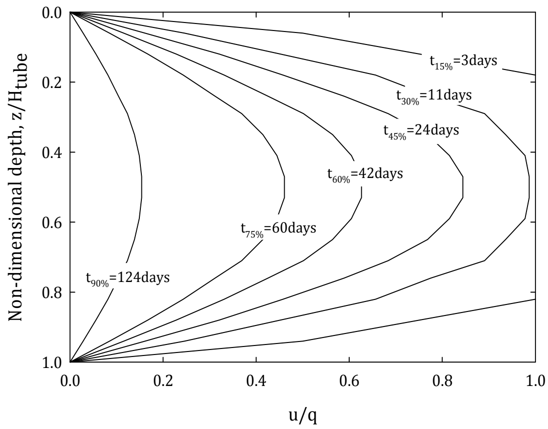


Fig. 7 Projected development of excess pore water pressure isochrones

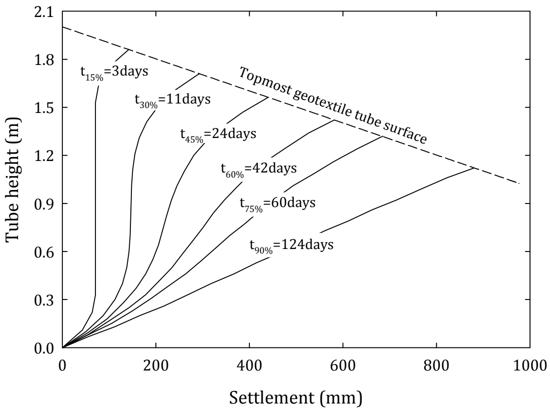
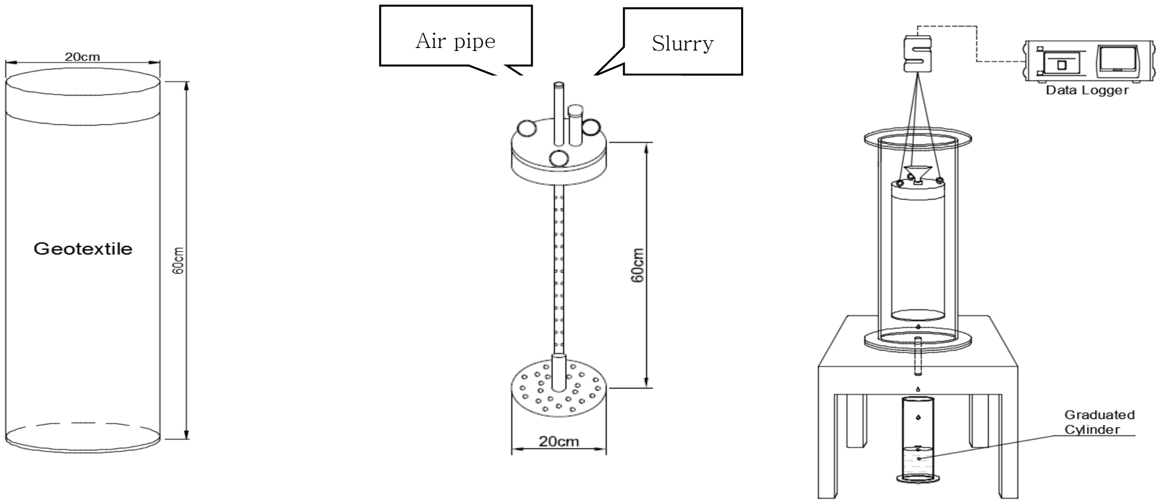


Fig. 8 Projected settlement profile

3.3 Program Analysis on GeoTDS by Hanging Test

Geobag set up is shown in Fig. 9 and results of the tests are shown Figs. 10-11. It is observed that water content on the woven material is lesser compared to the nonwoven material. The variation of water content depends on retained fine soils in the hanging bag by geotextile dewatering and by hydraulic compaction due to pumping pressure. Lesser water content for the woven material means a higher degree of compaction and conversely more fine soils means lower degree of compaction for the nonwoven material.



Geobag dimensions Geobag contraption (c) Geobag filling set up

Fig. 9 Geobag set up

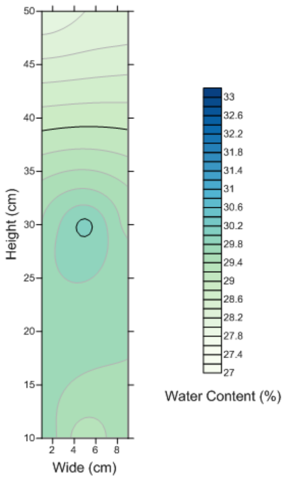


Fig. 10 Water content of woven material

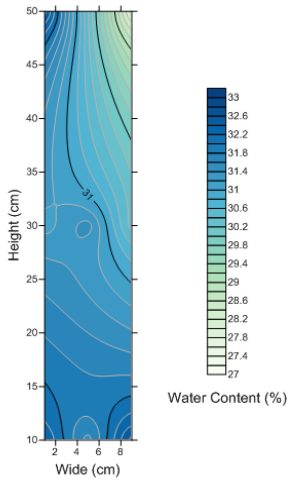


Fig. 11 Water content of nonwoven material

The numerical analysis was done in the concept of consolidation in a layered soil. The lower area of the cross section was assumed to be permeable. In this case, the geotextile material used was assumed to be woven. On the other hand, the upper area was assumed to be impermeable thus the use of nonwoven material. There are several variables involved, such as different coefficients of permeability, thickness of layer (percentage of woven and nonwoven material around the circumference), and different values of coefficient of consolidation. Results of the tests as shown in Figs. 12-14 imply that the geobag with the higher coefficient of consolidation allows the soil particles to settle faster.

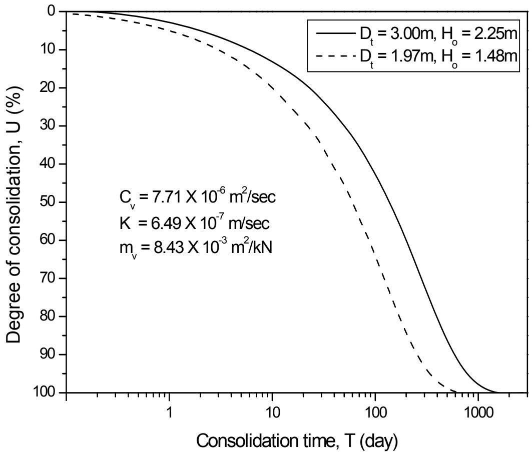


Fig. 12 Degree of consolidation with respect to time with different diameters

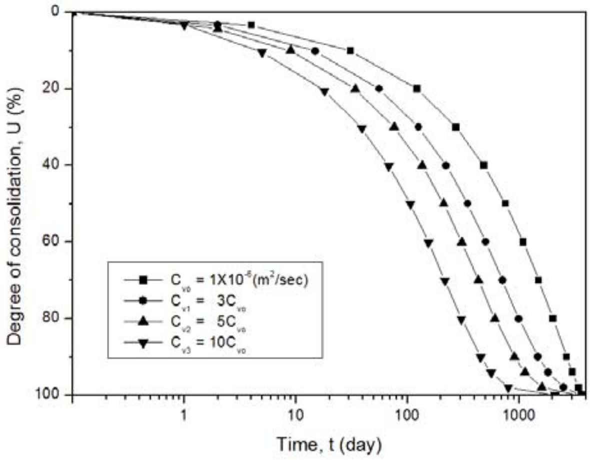


Fig.13 Degree of consolidation and time comparison with increasing C_v

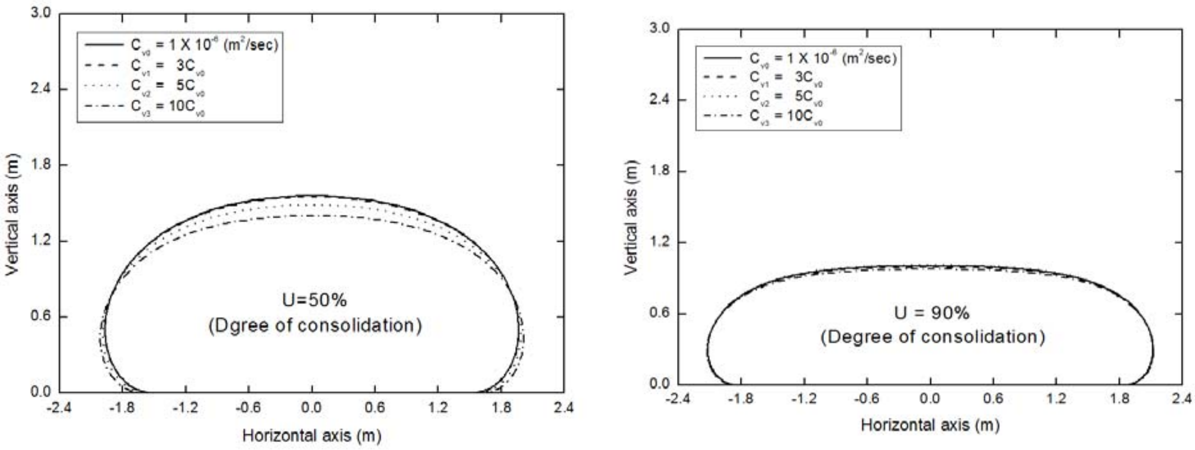


Fig. 14 Geotextile shape comparison with increasing C_v (U=50%, 90%)

4. CONCLUSION

This paper presents a introduction of the development of the Geotextile Tube Design Software (GeoTDS). GeoTDS is a computer program utilizing a GUI environment intended for simulation of geotextile tube geometry, two-dimensional analysis of deformation, and simulation by field data as case study. There were several cases involved, such as increasing coefficient of consolidation by using woven and nonwoven material around the circumference.

The following conclusions were obtained from the results of the study:

- Geotextile tube filling simulations for tubes filled under surface and/or submerged condition.
- Prediction of densified or consolidated tube geometry after the dewatering process.

- Higher coefficient of consolidation(C_v) allows geotextile tube to horizontally deform faster, vertical settlement increases by time, and geotextile horizontal deformation is the same at U=90%.

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