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Numerical and field test verifications for the deformation behavior of geotextile tubes considering 1D and areal strain

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ABSTRACT

Two-dimensional analytical and numerical solutions for determining the geometric dimensions and stresses of geotextile tubes are reviewed. Conventional one-dimensional (1D) approximation of the average drop in height (consolidated height) of geotextile tubes was also reviewed in this study. Densification modeling of the fill material based on areal-strain analysis is introduced. Leshchinky et al.'s approximation method considers only the vertical movement of the densifying material in the analysis. The areal-strain method offers an alternative analysis approach wherein both the vertical and lateral movements of the densifying fill material are considered. The geotextile tube is assumed to be resting on a rigid horizontal foundation and analyses for both filling and densified stages treats the internal material as liquid in order to apply normal pressure to the tube. Parametric cases for the densification of geotextile tube fill are presented. Results show that the degree of tube height reduction decreases as the density of the slurry fill is increased. Large-scale tests have been conducted on composite geotextile tubes made of outer woven and inner non-woven polyester (PET) material. The tubes were 10 m and 25 m long having theoretical diameters of 3.0 m and 5.0 m, respectively. The validity of the solution for densification analysis was demonstrated by comparing the numerical results to those of the field test. The agreement between the numerical results and field measurement data is fairly acceptable.

1. Introduction

Presently, a massive reclamation project is being implemented at Saemangeum in South Korea. Saemangeum is famous for its dike, considered as the longest in the world, constructed between 1991 and 2010. The reclamation is projected to reclaim approximately 280 m^2 of land on the Saemangeum estuary which will be developed into various hubs for business, industry, agriculture and tourism in the near future. As part of the reclamation effort, containment dikes will be used to partition the areas to be reclaimed. Currently, however, the supplies for cement and construction aggregates such as rocks, gravel and sand are declining due to the restrictions in the quarry site. The traditional practice of constructing shoreline protection, marine embankments, breakwaters, revetments, and dikes in reclamation areas involves the use of rocks, gravel aggregates or precast concrete. The materials for this conventional construction practice are usually quarried and sourced from distant mountains and rivers. Such practice has a significant environmental impact. Construction cost also increases with respect to the additional transportation expenses from the source to the site. The duration of the construction period is also longer due to the lengthy process of material production and equipment involved.

Revetments, breakwaters, levees, groins and dikes constructed from sand-filled geotextile tubes could be a viable alternative to the conventional rubble-mound structures in cases where temporary protection is required or rock is not obtainable and too difficult to transport to the site. Due to the increasing demand of construction materials used to build the conventional structures, geotextile tube technology is an inexpensive solution and a strong contender to replace the more conventional hard engineering solutions. Environmental impacts for geotextile tubes are less than that of the rubble mound structures, as the quarrying and transporting of rocks are not required and these structures can be easily removed in the case of adverse unforeseen impacts. Also, the ability to use local material and unskilled labor makes construction easier and faster.

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Geotextile tubes are tubular structures made of strong permeable material and are hydraulically or mechanically filled with dredged material. These tubes have been widely applied in environmental and coastal engineering (Restall et al., 2002; Lawson, 2008; Lee and Douglas, 2012) as alternatives for the conventional concrete-made structures such as containment dikes, revetments, levees, groins, seawalls and breakwaters. Geotextile tubes are conventionally pumped with slurry to efficiently distribute the fill material inside the tube. This means that tubes have to be dewatered and possibly refilled again in order to attain the desired filled height. However, presently, the knowledge about the consolidation or the densification behavior of geotextile tubes filled with fine-grained slurries is limited. Consolidation and permeability characteristics of the fill material are important to quantify stress–strain relations such as settlements, and the time-dependent behavior of very soft cohesive soils (Abu-Hejleh and Znidarčić, 1995). The nature of the consolidation/densification process of geotextile tubes needs to be studied. Laboratory tests have been conducted to provide design parameters for the geotextile tube dewatering process (Moo-Young et al., 2002; Koerner and Koerner, 2005, 2006; Recio and Oumeraci, 2008; Cantre and Saathoff, 2011; Khachan et al., 2014; Guimarães et al., 2014). There are a number of experimental and analytical studies regarding geotextile tube available in the literature (Choi, 2013; Górniak et al., 2015; Guo et al., 2015). Several significant closed-form solutions for geotextile tube filling analysis has been presented in the works of Liu and Silvester (1977), Leshchinsky et al. (1996), Kazimierowicz (1994), Carroll (1994), Plaut and Suherman (1998), Ghavanloo and Daneshmand (2009), Malík (2009) and Guo et al. (2013b, 2014b). Geotextile tube modeling using continuum mechanics has been conducted by Seay (1998), Seay and Plaut (1998), Cantré (2002), and Kim et al. (2013, 2014). Studies on geotextile tubes considering the consolidation/densification of the fill material have been conducted previously by Leshchinsky et al. (1996), Shin and Oh (2004), Cantré and Saathoff (2011), Plaut and Stephens (2012), Yee and Lawson (2012), Brink et al. (2013) and Guo et al. (2013a, 2014a).

The research and development of the geotextile tube technology for the Saemangeum development project is conducted at the nearby university (Kunsan National University). This study presents: (1) a review of the analytical and numerical solutions for geotextile tube analysis; and, (2) non-time dependent consolidation or densification analysis method based on the deformation behavior (strain) of the fill material. Because the nature of the analysis is not time dependent, the authors use the term “densification” instead of “consolidation” in the following sections to describe the solidification of the fill material (slurry). Conventional one-dimensional (1D) approximation of the average drop in height (consolidated height) of geotextile tube is also reviewed. Densification modeling of the fill material based on areal-strain analysis is introduced. Parametric studies, comparison between the results of the present study and the conventional method, and field test verifications of the numerical results are presented and discussed in the following sections.

2. Theoretical background

The geotextile tube modeling during the filling stage is based on the analytical solution formulated by Plaut and Suherman (1998). In the adopted analysis method presented in this paper, the geotextile tube is assumed to be resting on a rigid horizontal foundation. The geotextile tube is assumed to be sufficiently long in order to appropriately perform a two-dimensional analysis of the tube's cross-section. Analyses for both filling and densified stages treat the internal material as liquid in order to apply normal pressure to the tube. The tube material is modeled as an inextensible membrane with negligible weight and bending stiffness. The friction between the slurry and the tube, and between the densified fill and the tube, is neglected, so that the internal material only exerts a normal pressure on the tube. The solid particles are incompressible and the time-dependence of the permeation of liquid out of the tube is not investigated. The governing equations for determining the cross-sectional geometry of the tube and applied forces are defined as follows:

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

$$\frac{dX}{dS} = \cos\theta \tag{2}$$

$$\frac{dY}{dS} = \sin\theta \tag{3}$$

$$\frac{dT}{dS} = 0 \tag{4}$$

where T = circumferential tensile stress (constant due to Eq. (4)), 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} = unit weight of the fill material, Y = vertical coordinate, X = horizontal coordinate and H is the tube height, as shown in Fig. 1. The elliptic integral parameter k derived by Namias (1985, as cited by Plaut and Suherman 1998) was applied to solve for the non-dimensional membrane force t using the following expression:

$$k = \frac{2\sqrt{t}}{p_{bot}} \tag{5}$$

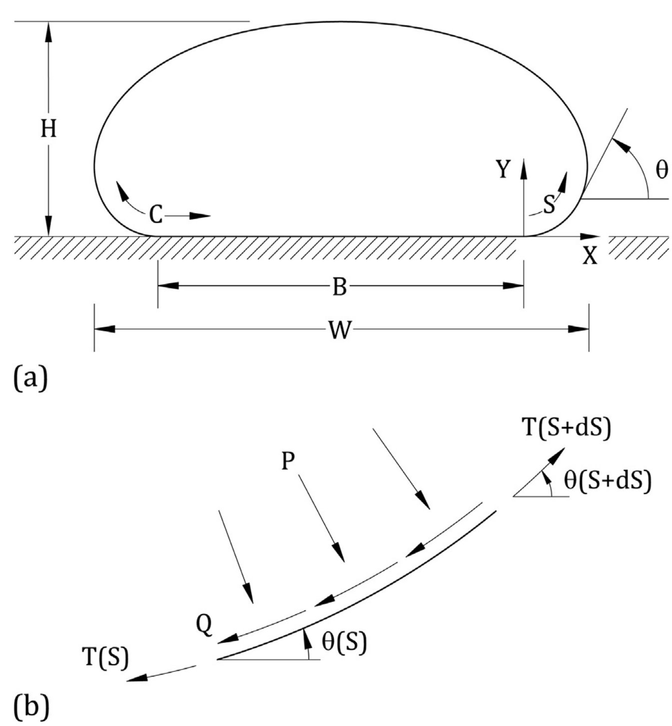

Fig. 1. (a) Tube cross-section and (b) forces acting on the differencross-sectional area of tube, tial element (after Plaut and Suherman, 1998).

$$p_{bot} = \frac{P_{bot}}{\gamma_{int} C} \quad (6)$$

where k is the elliptic integral parameter and p_{bot} is the non-dimensional bottom pressure. To determine the parameter k, the following equation must be satisfied:

$$2p_{bot}[K(k) - E(k)] - 1 = 0 \quad (7)$$

where $K(k)$ and $E(k)$ are the complete elliptic integrals of the first and second kind, respectively. The basic equations for non-dimensional geometric properties with respect to the elliptic integral parameter k and tube circumference C are tabulated in Table 1 (please refer to the Notations section for the definition of symbols used). Please refer to the original publication (Plaut and Suherman, 1998) for more detailed information of the basic solution.

After the slurry pumping, water permeates from the tube and a significant drop in the tube height is attained. Leshchinsky et al. (1996) proposed a non-time dependent approximation method to predict the densified geotextile tube height H_f using basic volume–weight relationships in soil mechanics expressed by the following equation:

$$\varepsilon_h = \frac{\Delta H}{H_0} = \frac{G_s\left(\omega_0 - \frac{\omega_f}{S_f}\right)}{1 + \omega_0 G_s} \quad (22a)$$

$$\omega_0 = \frac{G_s - G_0}{G_s(G_0 - 1)} \quad (22b)$$

Table 1
Non-dimensional quantities for the basic solution to geotextile tube analysis after Plaut and Suherman (1998).

Non-dimensional geometric properties with respect to elliptic integral parameter k		Non-dimensional geometric properties with respect to the geotextile tube circumference C	
$t = \left(\frac{k \cdot p_{bot}}{2}\right)^2$	(8)	$t = \frac{T}{\gamma_{int} C^2}$	(9)
$b = 1 - 2k\sqrt{t}K(k)$	(10)	$b = \frac{B}{C}$	(11)
$a = b \cdot p_{bot}$	(12)	$a = \frac{A}{C^2}$	(13)
$h = \left(1 - \sqrt{1-k^2}\right)p_{bot}$	(14)	$h = \frac{H}{C}$	(15)
$w = b + 2\left[E\left(\frac{\pi}{4}, k\right) - \left(1 - \frac{k^2}{2}\right)F\left(\frac{\pi}{4}, k\right)\right]p_{bot}$	(16)	$w = \frac{W}{C}$	(17)
$x = \left[E(\phi, k) - \left(1 - \frac{k^2}{2}\right)F(\phi, k)\right]p_{bot}$	(18)	$x = \frac{X}{C}$	(19)
$y = \left(1 - \sqrt{1 - k^2 \sin^2\phi}\right)p_{bot}$	(20)	$y = \frac{Y}{C}$	(21)

$$\omega_f = \frac{S_f\left(G_s - G_f\right)}{G_s\left(G_f - 1\right)} \quad (22c)$$

where H_0 = initial tube height containing the slurry; $\Delta H = (H_0 - H_f)$ = amount of the decrease in tube height; G_s = specific gravity of soil solids; G_0 = unit weight ratio of slurry and water, $(\gamma_{slurry}/\gamma_w)$; G_f = unit weight ratio of solidified fill and water, (γ_{soil}/γ_w); ω_0 and ω_f are the initial and final water contents of fill material; S_f = degree of saturation of solidified fill; and γ_{slurry}, γ_{soil} and γ_w are the unit weights of initial slurry, densified soil fill and water, respectively. Leshchinsky et al.'s (1996) basic assumption states that the densifying fill material only moves in the vertical direction (i.e., one-dimensional [1D] movement; lateral movement is neglected). In the present study, a densification modeling approach based on areal-strain adapted from the conventional one-dimensional (1D) strain method (Leshchinsky et al., 1996) is introduced. Areal strain is defined as the two-dimensional change in area caused by deformation (Twiss and Moores, 2006), a measure of relative area change that combines the effects of vertical and longitudinal strain. The basic assumptions are: [1] the initial slurry fill is fully saturated (S_0 = 100%); [2] the densified fill material is either fully saturated (S_f = 100%) or saturated to a certain degree ($0 < S_f < 100\%$); and, [3] the solid particles are incompressible.

By definition, geotextile tubes are cylindrical tubes with a wide range of diameters depending on their application and have theoretically infinite length (Cantré, 2002). Consider the geotextile tube segment in Fig. 2 with a unit length of L_s and cross-sectional area A. The initial cross-sectional area of the tube after slurry filling is denoted as A_0. As the fill material consolidates, the filled tube area A decreases until a certain density of the fill material is achieved and the final cross-sectional area of the tube becomes A_f. Assuming the circumference C (Fig. 1) of the tube remains constant during the densification process, the volumetric strain (Das, 2010) of the segment in consideration can be defined as:

$$\Delta V = \Delta A(L_s) = \frac{A_0(L_s)}{1 + e_0}\Delta e \quad (23)$$

$$\frac{\Delta A}{A_0} = \frac{\Delta e}{1 + e_0} \quad (24)$$

where ΔV = volumetric change; $\Delta A = (A_0 - A_f)$ = change in the cross-sectional area (areal change); Δe = change in void ratio; and

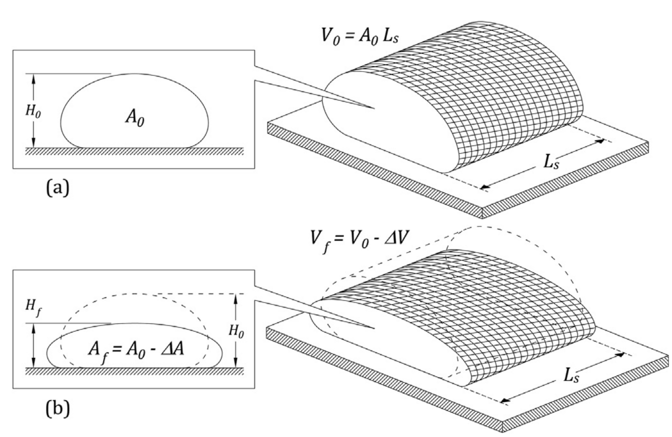

Fig. 2. Geotextile tube segment: (a) fully-filled with slurry and (b) densified tube.

e_0 = initial void ratio. Analogous to Eq. (22a), Eq. (24) can be expressed in terms of areal strain ε_a as follows;

$$\varepsilon_a = \frac{\Delta A}{A_0} = \frac{\Delta a}{a_0} = \frac{G_s\left(\omega_0 - \frac{\omega_f}{S_f}\right)}{1+\omega_0 G_s} \tag{25}$$

Therefore,

$$a_f = a_0\left[\frac{S_f + \omega_f G_s}{S_f(1+\omega_0 G_s)}\right] \tag{26}$$

where a_0 and a_f are respectively the initial and final non-dimensional cross-sectional areas of the tube. In order to calculate the geometric dimensions of the densified tube, the solution must satisfy the following condition:

$$a_f = b\cdot p_{bot} \tag{27}$$

2.1. Programming the basic formulations with matlab

Eqs. (5)–(7) and the formulas tabulated in the left column of Table 1 contain elliptic integrals which have no closed form solutions. This means that a computer is needed when designing geotextile tubes using Plaut and Suherman's (1998) method. In this paper, a numerical algorithm, shown in Fig. 3, was developed for a computer program using Matlab language (MATLAB 8.1). The initial input parameters used in the modeling of a geotextile tube during filling are: (1) theoretical diameter D_T or circumference C of the tube; (2) unit weight γ_{slurry} or the initial water content ω_0 of the slurry fill; and (3) initial bottom pressure P_{bot} or the initial tube height H. The corresponding non-dimensional bottom pressure p_{bot} and tube height h can be calculated using Eqs. (6) and (14), respectively. Using either of these initial dimensionless parameters, the integral parameter k is solved numerically using Eq. (7). Eq. (8) gives t, Eq. (10) gives b, Eq. (12) gives a, Eq. (16) gives w, and Eqs. (18) and (20) respectively gives the dimensionless x and y coordinates of the tube. The dimensional quantities can be obtained

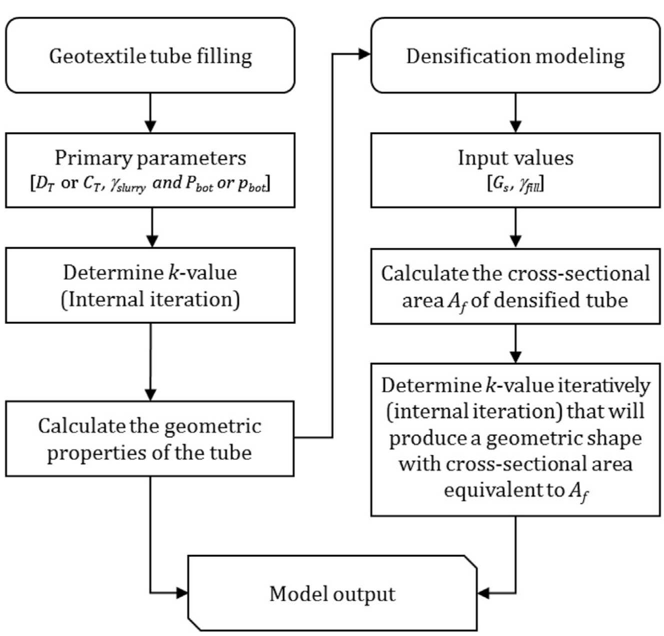

Fig. 3. Program algorithm of the areal-strain method.

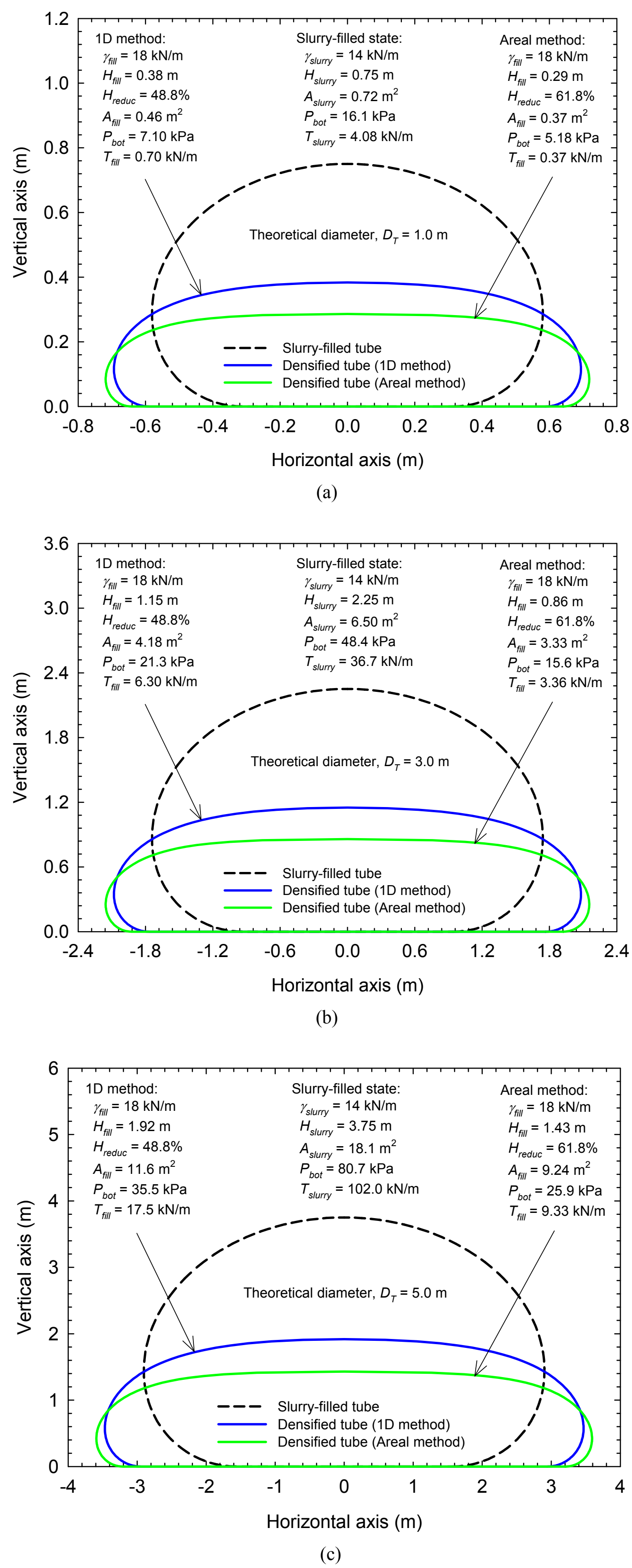

Fig. 4. Case 1: Geometric properties of the slurry-filled and densified tubes (G_s = 2.7; S_f = 100%; γ_{slurry} = 14 kN/m^3; γ_{fill} = 18 kN/m^3): (a) 1.0 m tube, (b) 3.0 m tube and (c) 5.0 m tube.

from their non-dimensional counterparts using the appropriate equations.

During filling, the input parameters are: (1) unit weight γ_{fill} or the final water content ω_f of the solidified fill; (2) specific gravity of the soil solids G_s; and (3) degree of saturation S_f of the solidified fill. It is assumed that the circumference of the tube C during filling and densification remains the same. The tube is filled with slurry having a specific gravity of soil solids G_s and unit weight ratio of slurry to water G_0. After filling, the densified tube has a unit weight ratio of solidified fill to water G_f. The densified geometric properties of the tube can be determined numerically in terms of the calculated tube height H_f obtained using Eq. (22a) for the 1D strain method, or tube area A_f obtained from Eq. (25) for the areal-strain method. For the densification analysis using the 1D strain method, the calculated H_f-value is used in the numerical calculation and Eq. (7) is solved for p_{bot} in terms of k, this is substituted into Eq. (14), then Eq. (14) is solved for k, and p_{bot} is obtained from Eq. (7). On the other hand, the A_f-value is used to determine the non-dimensional geometric properties of the tube for the densification analysis using the areal-strain method. The normalized densified tube area a_f can be determined using Eq. (26). The corresponding k, p_{bot}, t, and b values are solved numerically using Eqs. (7), (8), (10) and (12). Finally, the dimensional quantities can be determined from their non-dimensional counterparts using the appropriate equations tabulated in the right column of Table 1.

3. Results and analysis

3.1. Parametric study

3.1.1. Case 1: different-size tubes filled with the same slurry mixture

Three geotextile tubes are considered in the parametric study. Sandy materials are pumped into tubes having theoretical diameters of 1.0 m, 3.0 m and 5.0 m. The unit weights of the slurry and the solidified fill material are assumed to be 14 kN/m^3 and 18 kN/m^3, respectively. The specific gravity G_s of the material fill solids is 2.70 and the degree of saturation S_f of the solidified fill is 100%. The tubes are pumped until the filled height (H_{fill}) reaches 75% of the theoretical diameter (D_T). The subsequent geometric properties for the 1.0 m, 3.0 m and 5.0 m tubes before and after consolidation are shown graphically in Fig. 4a, b and c, respectively. The results show that the tube size (e.g., theoretical diameter D_T, tube circumference C) does not directly affect the degree of geotextile tube height reduction. Case in point, the tubes considered in this section having different sizes pumped with the same type of fill material exhibited the same results in the percentage tube height reduction (i.e., 48.8% using the 1D method; 61.8% using the Areal method) at the end of the densification process. This implies that no matter what tube size is used as long as it is filled with the same type of material, the percentage degree of tube height reduction will remain approximately the same. Also, in comparison with the 1D method for densification analysis, the calculation output using the areal-strain method always yields the following results: (1) smaller values for the final tube height H_f, area A_f, bottom pressure P_{bot}, top pressure P_{top}, and tension T_f, and (2) higher magnitudes for the values of final tube width W_f and contact base width B_f.

3.1.2. Case 2: same-size tubes filled with slurries at different densities

For this parametric study, three tubes with similar theoretical diameters of 3.0 m are pumped with slurry having unit weights of 14 kNm^3, 15 kN/m^3 and 16 kN/m^3, respectively. The specific gravity G_s of the material fill solids is 2.70 and the degree of saturation S_f of the solidified fill is 100%. Similar to the previous section, the tubes are pumped with slurry up to 75% of the theoretical diameter.

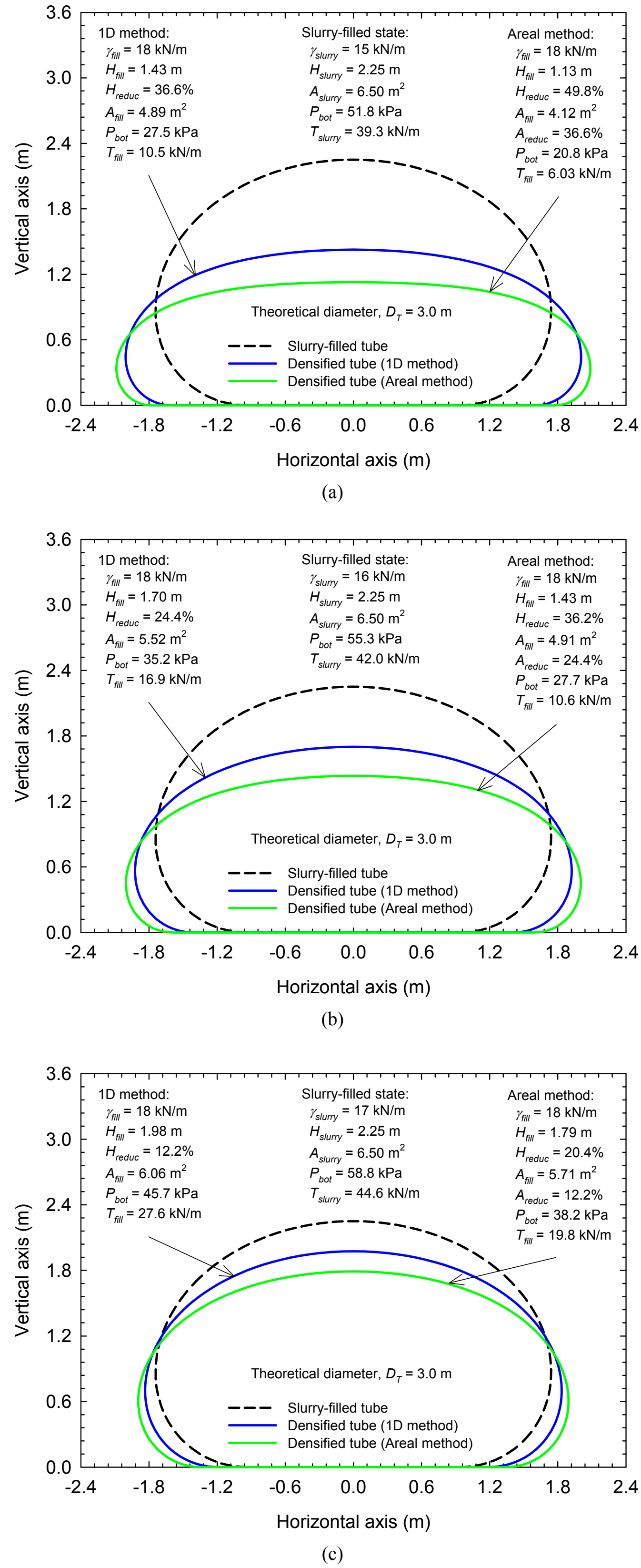

Fig. 5. Case 2: Geometric properties of the slurry-filled and densified tubes (theoretical diameter, $D_T = 3.0$ m; $G_s = 2.7$; $S_f = 100\%$; $\gamma_{fill} = 18$ kN/m^3): (a) $\gamma_{slurry} = 15$ kN/m^3, (b) $\gamma_{slurry} = 16$ kN/m^3 and (c) $\gamma_{slurry} = 17$ kN/m^3

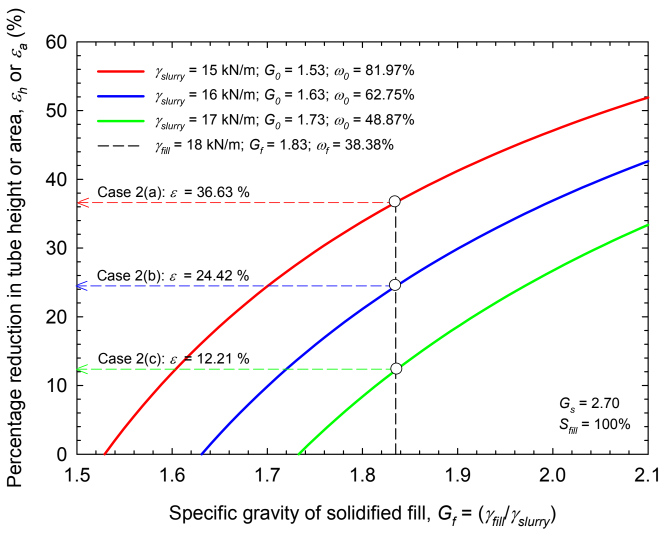

Fig. 6. Percentage reduction of tube geometry (in terms of tube height ε_h or tube area ε_a) with respect to the initial and final unit weight ratio of fill material and water, G_0 & G_f.

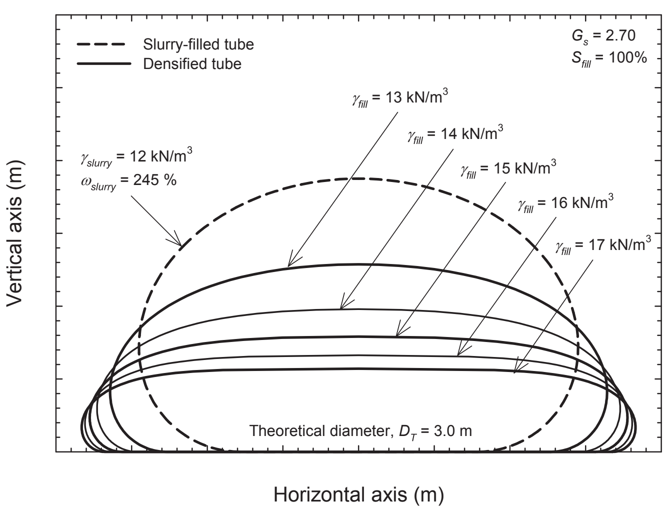

Fig. 7. Case 3: Tube shape variation with respect to the density of the densified material.

Densification analysis was conducted for each tube. Results presented in Fig. 5 show that the degree of tube height reduction decreases as the density of the solidified fill material is increased. However, it should be noted that other significant factors such as filter cake formation and the apparent opening size (AOS) of the tube may also affect the rate of densification process. Moreover, the denser the slurry mixture, the more viscous it becomes and this may present problems during tube pumping. As mentioned earlier in Section 2, Eq. (22a) is analogous with Eq. (25), therefore the percentage reduction in tube height ε_h using the 1D method is equal to the percentage reduction in tube area ε_a obtained from the areal-strain analysis.

Fig. 6 shows the relationship between the percentage reduction in terms of tube height or area and the specific gravity of the fill material when it solidifies to a certain density (similar relationships using one-dimensional strain were presented by Leshchinsky et al., 1996). For example, in the areal-strain analysis, the percentage reduction in the cross-sectional area of a geotextile tube filled with slurry of $\gamma_{slurry} = 15$ kN/m^3 ($\omega_0 = 81.97\%$) is roughly 36.63% when the density of the solidified fill becomes 18 kN/m^3 ($G_f = 1.835$; $\omega_f = 38.38\%$). Likewise, using the 1D strain analysis, a tube height reduction of 36.63% will be attained when the density of a geotextile tube filled with the same material reaches 18 kN/m^3.

3.1.3. *Case 3: densified tube shape variation at different densities*

A 3.0 m diameter (theoretical) tube is considered. The tube is pumped with a high moisture content slurry of $\gamma_{slurry} = 12$ kN/m^3 ($\omega \approx 245\%$; $G_s = 2.7$). The tube is filled with slurry up to 75% of its theoretical diameter. The variation in the shape of the densified tube is shown in Fig. 7. The corresponding stress and geometric properties of the tube are tabulated in Table 2. As shown in Fig. 7, the tube height decreases as the filling material densifies. Generally, the average drop in height for a soil layer in soil mechanics is about 10% for sandy fills and 50% clayey fills. For geotextile tube analysis, however, the slurry fill is assumed to be a highly saturated viscous material and behaves like a liquid. Hence, during the densification process, the larger the quantity of permeated water, the further the tube drops. As the water content decreases, the soil particles are condensed and densified, hence increasing the density of the tube fill. For Case 3, the initial water content of fill material is significantly higher than in the previous cases ($\omega_0 = 245\%$). Suppose the engineer/designer wanted to determine the stress and geometric properties of the tube when the densified fill material attains a unit weight of 15 kN/m^3. Based on the calculated results presented in Table 2, using 1D strain analysis, the tube would have

Table 2
Case 3: Geotextile tube stress and geometric properties at varying fill densities.

Specific weight (kN/m^3)	Water content (%)	H (m)	H_{reduc} (%)	A (m^2)	A_{reduc} (%)	P_{bot} (kPa)	T (kN/m)
Tube filling:							
12[a]	245	2.25	–	6.50	–	41.5	31.5
Tube densification:							
13[b]	157	1.54	31.4	5.17	20.4	22.1	9.31
13[c]	157	1.26	44.2	4.46	31.4	17.0	5.56
14[b]	110	1.18	47.7	4.25	34.7	17.0	5.14
14[c]	110	0.88	60.8	3.40	47.7	12.4	2.76
15[b]	82	0.95	57.8	3.60	44.6	14.4	3.45
15[c]	82	0.68	69.8	2.74	57.8	10.2	1.73
16[b]	63	0.80	64.6	3.13	51.9	12.8	2.55
16[c]	63	0.55	75.4	2.30	64.6	8.84	1.22
17[b]	49	0.69	69.5	2.76	57.5	11.7	2.00
17[c]	49	0.47	79.3	1.98	69.5	7.92	0.92

H_{reduc} = Percentage reduction in tube height.
A_{reduc} = Percentage reduction in tube area.
[a] Values obtained using Plaut and Suherman (1998) method.
[b] Values obtained using 1D strain analysis.
[c] Values obtained using Areal-strain analysis.

Table 3
Comparison between results of this study and Leshchinsky et al. (1996)/GeoCops 3.0

Description/Method	Specific weight (kN/m^3)	H (m)	W (m)	B (m)	A (m^2)	T (kN/m)	P_{bot} (kPa)
Slurry-filled tube:							
This study[a]	14	2.30	3.45	1.78	6.57	40.9	51.7
Leshchinsky et al. method[b]	14	2.30	3.80	2.30	7.20	34.0	–
Densified tube:							
Areal-strain (this study)	16	1.25	4.11	3.42	4.45	6.76	20.8
1D-strain (this study)	16	1.55	3.93	3.03	5.20	11.7	27.5
1D-strain[b]	16	1.50	3.80	2.30	4.90	–	–
Areal-strain (this study)	18	0.87	4.30	3.84	3.4	3.45	15.8
1D-strain (this study)	18	1.17	4.15	3.50	4.25	6.62	21.8
1D-strain[b]	18	1.20	3.80	2.30	3.70	–	–
Areal-strain (this study)	20	0.67	4.40	4.04	2.70	2.23	13.4
1D-strain (this study)	20	0.95	4.27	3.76	3.59	4.57	19.1
1D-strain[b]	20	0.90	3.80	2.30	3.00	–	–

[a] Plaut and Suherman (1998) solution.
[b] Values obtained using GeoCops 3.0 Software.

lost 57.8% and 44.6% its initial filled height and cross-sectional area, respectively. On the other hand, using the areal-strain method, the tube would have lost 69.8% and 57.8% of its initial filled height and cross-sectional area, respectively. The current water content of the fill material at this state would be 82%. As more water seeps through the geotextile membrane, the more compact and denser the densified fill becomes, thereby decreasing the cross-sectional area of the tube.

3.2. Numerical validation

3.2.1. Comparison of the results the present study to conventional solution

A 3.0 m diameter (theoretical) tube is considered in this study. The tube is sufficiently long and two-dimensional analysis of the cross-section is applicable. The geotextile tube is pumped with slurry up to the height of 2.3 m. The unit weight of the slurry fill is

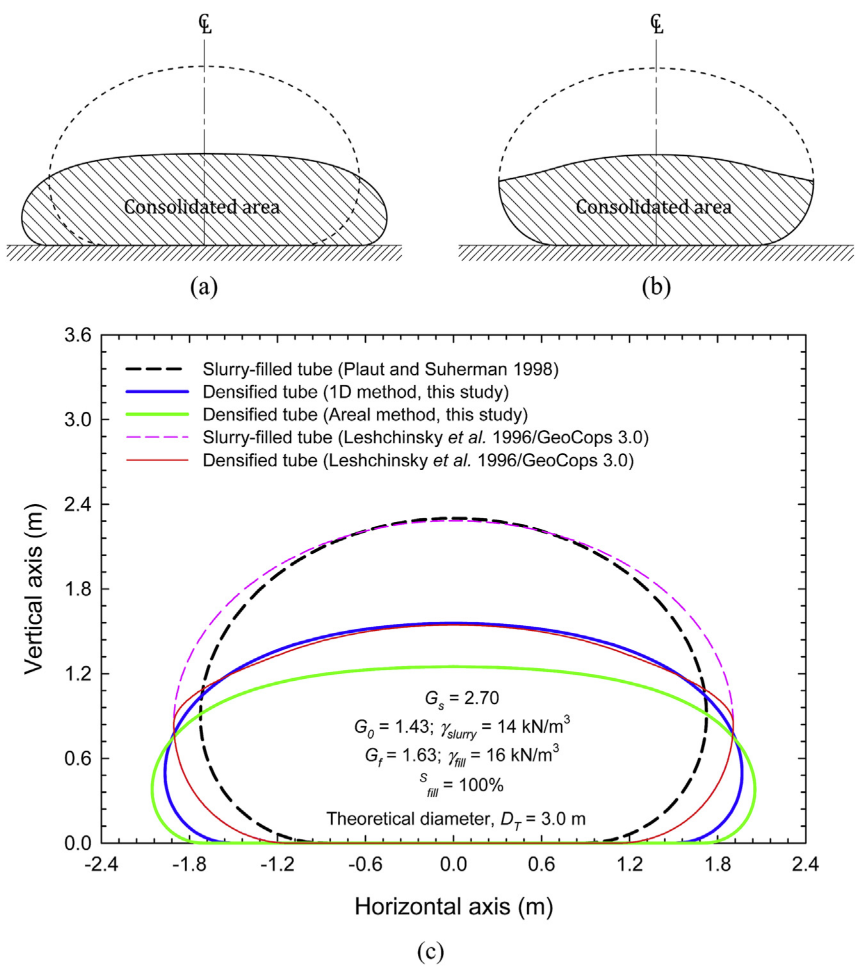

Fig. 8. Geometric output of the densified tube using methods in (a) present study and (b) GeoCops (Leshchinsky et al., 1996; GeoCops 3.0). (c) Graphical comparison between results of present study and computed geometry by GeoCops

Table 4
Composite geotextile properties.

Description/Test method		Unit	Quantity
Apparent opening size, AOS (ASTM D4751)		μm	145
Permeability, $k_{Geotext}$ (ASTM D4491)		cm/s	5.8×10^{-2}
Tensile strength (ASTM D4595):	Weft	kN/m	178
	Warp	kN/m	186

14 kN/m^3 and the specific gravity of soil solids is 2.7. The objective is to determine the geometric properties of the tube having densified unit weights of 16 kN/m^3, 18 kN/m^3 and 20 kN/m^3. The numerical analysis results obtained from the 1D and areal-strain methods presented in this study are compared with the results of the GeoCops program (Leshchinsky et al., 1996; GeoCops 3.0). The calculated outputs are tabulated in Table 3. For the tube modeling during pumping, the results for tube width (W), base contact length (B) and cross-sectional area (A) based on Leshchinsky's et al. (1996) analysis are slightly larger than the results in the present study. For densification modeling, it can be observed in the results of Leshchinsky's et al. (1996) analysis that only the downward movement of the densifying material is considered (i.e., the tube height H and filled area A decrease while the maximum tube width W and contact base length B remain constant in the densified state). On the other hand, for both methods used in the present study, the vertical and lateral tube deformations are considered in the analysis as demonstrated in the geometric output results in Table 3. The maximum tube width W and contact base length B increase as the tube height H and cross-sectional area A decrease after the densification process. A graphical comparison of the geometric shape of the tubes obtained from the present approach and that of Leshchinsky et al. (1996) is illustrated in Fig. 8.

3.2.2. Field test verifications

Two large-scale field tests were conducted at the Saemangeum area near Gunsan City in South Korea. The geotextile tubes used in the field test were 10 m and 25 m long having approximate diameters of 3.0 m and 5.0 m, respectively. The tubes are made of composite outer woven and inner non-woven polyester (PET) material. The physical properties of the geotextile and fill materials are given in Tables 4 and 5, respectively. The grain size distribution of the fill material is shown in Fig. 9. A 0.5 m thick compacted sand base was prepared prior to the slurry pumping of each geotextile tube. The average water content of the slurry fill is approximately 150% for the 3.0 m diameter tube and 170% for the 5.0 m diameter tube. The geometry of the tube's cross-section along the port location was measured though a Total Station Theodolite (TST). The tube measurements were taken at the end of the 1st filling phase and before the start of the 2nd filling phase. Prior to the second filling stage, soil samples were taken from the filling ports of the tubes to determine the current state of water content of the densifying fill along the port section. The average water content of the samples was used to estimate the drop of the cross-sectional area of the densified fill inside the tube.

The measured and predicted points for the tubes are shown in Figs. 10 and 11. The measured points and predicted geometry are

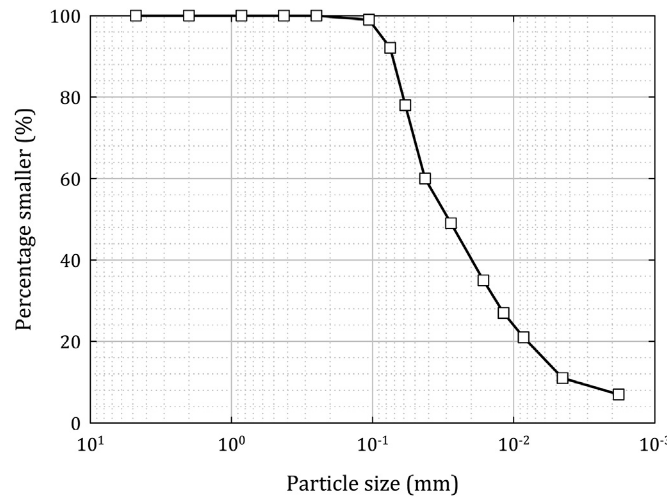

Fig. 9. Particle size distribution of the fill material.

Table 5
Fill properties (Natural, slurry and densified states).

Description/Property		Unit	Quantity
Natural condition:			
Natural water content, ω_n		%	20.0
Specific gravity of soil solids, G_s		–	2.705
Plasticity index, PI		%	NP[a]
Percent passing#200 (U S.) sieve		%	26.2
Soil classification (USCS)		–	SM[b]
Slurry form:			
Tube 1 (3.0 m)	Water content, ω_{slurry}	%	150
	Unit weight, γ_{slurry}	kN/m^3	13.1
Tube 2 (5.0 m)	Water content, ω_{slurry}	%	170
	Unit weight, γ_{slurry}	kN/m^3	12.8
Densified state:			
Tube 1 (3.0 m)	Water content, ω_{fill}	%	84
	Degree of saturation, S_f	%	100
	Unit weight, γ_{fill}	kN/m^3	14.9
Tube 2 (5.0 m)	Water content, ω_{fill}	%	92
	Degree of saturation, S_f	%	100
	Unit weight, γ_{fill}	kN/m^3	14.6

[a] Non-plastic.
[b] Silty-sand.

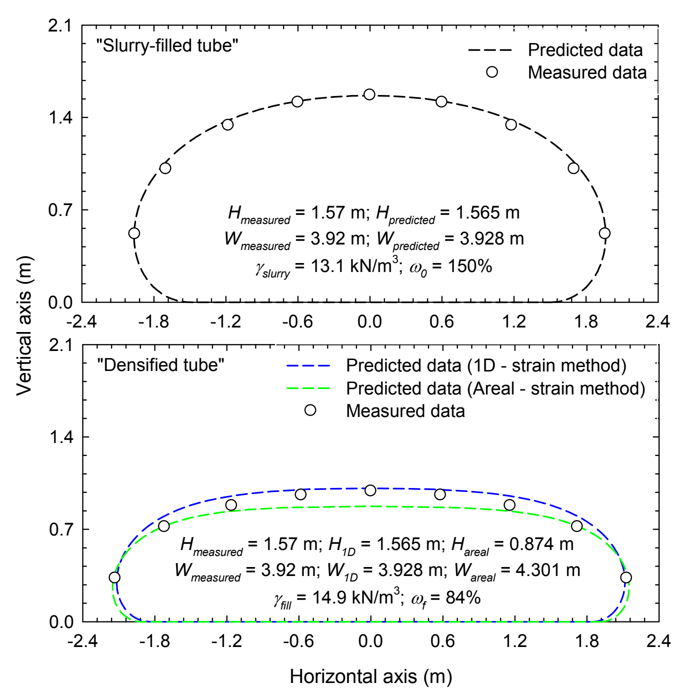

Fig. 10. Measured and predicted points for 3.0 m – diameter tube.

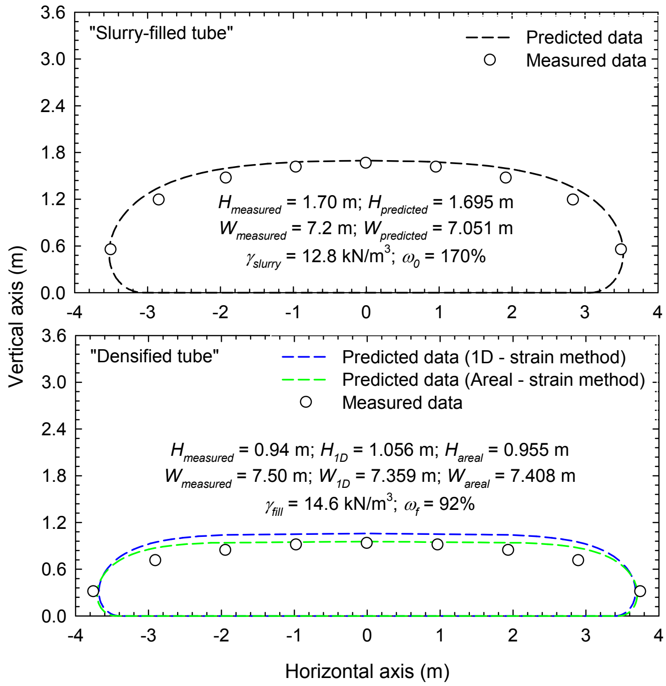

Fig. 11. Measured and predicted points for 5.0 m − diameter tube.

represented by the circular marks and dashed lines, respectively. The measured and calculated geometry of the 3.0 m diameter tube before and after consolidation is shown in Fig. 10. The average water content of the densified tube was approximately 84% before the next slurry refilling. The measured tube height and width are 1.57 m and 3.92 m, respectively. The results of the 1D-strain analysis for the densified tube (in terms of tube height and width) closely correspond to the actual measured values. Fig. 11 shows the measured and predicted geometry of the 5.0 m diameter tube before and after densification. For this tube, the average water content of the densified tube (before refilling) was approximately 92%. For the 5.0 m tube, the results of the areal-strain analysis for the densified tube (in terms of tube height and width) closely correspond to the actual measured values.

Based on the results presented, some of the measured points do not closely agree with the predicted values. It should be noted that the tube in the analysis was considered to be resting on a rigid foundation. In the actual construction site, however, external factors such as foundation settlement and/or ground erosion during the filling process have a significant effect on the final shape of the tube. Considering these factors, the authors believe that the analytical approach presented in this paper is adequately applicable in the design and densification modeling of geotextile tubes.

4. Conclusions and recommendations

The geotextile tube in the analysis was considered to be resting on a rigid horizontal foundation and the internal material was treated as liquid for both filling and densification analyses in order to apply normal pressure to the tube. The tube material was modeled as an inextensible membrane with negligible weight. Densification analysis considering one-dimensional and areal strain was incorporated into the earlier two-dimensional closed-form solutions for geotextile tubes.

The parametric studies showed that tubes of different sizes filled with similar type of material will attain the same percentage degree of tube height reduction. Also, the degree of tube height reduction decreases as the density of the material fill used is increased. The validity of the solution for densification analyses is confirmed by comparing the results to actual field test data. The agreement between the numerical results and field measurement data is fairly acceptable. Hence, the areal-strain method introduced in this paper offers an alternative analysis approach where both the vertical and lateral movements of the densifying material are considered in the analytical and numerical solution.

External factors such as the effects of deformable foundation and geotextile strain are not considered in this study. Such factors should be included in the future studies. In some cases, the tube requires multiple filling to attain a certain desired tube height. This means that multiple layers of material fill should be considered in the densification analysis (e.g., fill material on the upper layer has less density than the material fills deposited at the bottom). It is therefore recommended to consider this type of analysis in forthcoming research.

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Notations

A, A_0, A_f: cross-sectional area of tube, cross-sectional-area of slurry-filled tube, cross-sectional area of densified tube (m^2)
a: non-dimensional cross-sectional area
B: contact base length of tube with foundation (m)
b: non-dimensional contact base length
C: tube circumference (m)
D_T: theoretical diameter of the geotextile tube
$E(k)$: complete elliptic integral of the second kind
$F(\phi, k)$: incomplete elliptic integral of the first kind
$E(\phi, k)$: incomplete elliptic integral of the second kind
H: tube height (m)
h, h_d: non-dimensional tube height, non-dimensional densified tube height
G_0, G_f, G_s: unit weight ratio of slurry and water, unit weight ratio of solidified fill and water, specific gravity of soil solids
$K(k)$: complete elliptic integral of the first kind
k: elliptic integral parameter
$k_{Geotext}$: permeability of the geotextile membrane (cm/s)
L_s: length of the tube segment
P_{bot}: pressure at the bottom of the tube (kPa)
p_{bot}: non-dimensional pressure at the bottom of the tube
S: arc length of the cross-sectional element (m)
T: circumferential tensile stress (kN/m)
t: non-dimensional circumferential stress
W: maximum tube width (m)
w: non-dimensional maximum tube width
X: horizontal coordinate (m)
x: non-dimensional horizontal coordinate
Y: vertical coordinate (m)
y: non-dimensional vertical coordinate
γ_{int}: specific weight of the fill material (kN/m^3)
θ: tangential angle with respect to the horizontal axis