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Derivation of design charts based on the two-dimensional structural analysis of geotextile tubes

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Abstract. Analytical solutions for modeling geotextile tubes during the filling process and approximation method to determine the densified tube shape are reviewed. The geotextile tube filling analysis is based on Plaut & Suherman's two-dimensional solution for geotextile tubes having a weightless and frictionless inextensible membrane resting on a rigid horizontal foundation subjected to internal and external hydrostatic pressures. The approximation for the densified tube shape developed by Leshchinsky *et al*. was adopted. A modified method for approximating the densified tube shape based on an areal-strain deformation analysis is introduced. Design diagrams useful for approximating geotextile tube measurements in the design process are provided.

Keywords: geotextile tube; membrane structure; analytic solution; structural analysis; design charts

1. Introduction

Geotextile tubes are tubular membrane structures made of thin permeable and flexible sheets inflated with slurry, waste sludge or soil. These structures are widely utilized in the present because they are economical and easy to construct. In civil engineering, geotextile tubes has been utilized as alternatives to the conventional concrete or rubble mound hydraulic and marine structures. Some of its applications includes: gyrone; breakwater; dune foot protection; exposed or submerged revetments; channel repair; land reclamation; artificial reef; sill structures; containment dikes; sediment management; river training; and, bank protection (Silvester 1986, Cantre 2002, Fowler *et al*. 2002a, 2002b, Alvarez *et al*. 2007, Lawson 2008, Bezuijen and Vantenburg 2013).

Numerous studies have been conducted in the past and several analytical solutions for liquid or slurry filled geotextile tubes have been proposed (Lui and Silvester 1977, Kazimierowicz 1994, Leshchinsky *et al*. 1996, Plaut and Suherman 1998, Ghavanloo and Daneshmand 2009, Malik

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2009, Cantre and Saathoff 2011, Gou *et al*. 2014a, 2014b). Seay (1998), Cantre (2002), Kim *et al*. (2013a, 2015) applied continuum mechanics to model the behavior of geotextile tubes. Model tests and large-scale experiments on geotextile tubes can be found in the literature (Recio and Oumeraci 2009, Kriel 2012, Kim *et al*. 2013b, 2014a, 2014b). Brink *et al*. (2013) proposed a method for consolidation modeling of geotextile tubes filled with fine-grained materials.

This paper presents a study on the two-dimensional structural analysis for geotextile tubes. Existing methods for determining the geotextile tube shape during filling and densification (dewatered) stages were adopted and improved. Based on these methods, design diagrams useful for approximating geotextile tube measurements in the design process are provided.

2. Theoretical background on the structural analysis of geotextile tubes

2.1 Formulation for geotextile tubes resting on rigid foundation during filling in terms of bottom pressure

2.1.1 Existing calculation methods

There are several calculation methods to estimate the cross-sectional dimensions of a geotextile tube, resting on a rigid foundation, during the filling and densification process (Cantre 2002). The earliest analytical formulation was proposed by Liu and Silvester (1977) using elliptic integrals to determine the shape of the tube based on its circumference, pressure head, contact base length of tube with the foundation, height and width after filling. A geometrical solution for geotextile tube problem was also introduced by Kazimierowicz (1994) using an analytical function for low external pressures. Kazimierowicz's solution is a differential equation in terms of the given tube height, hydrostatic pressure and the computed membrane force. Leshchinsky *et al*. (1996) derived a differential equation to determine the geometrical properties of a pressurized slurry filled geotextile tube. 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 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.

2.1.2 Governing assumptions of Plaut and Suherman's analytical solution

The basic assumptions adopted from Plaut and Suherman's (1998) analytical solutions 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), hence, the following design criteria, with respect to the geotextile tube length L_t and circumference C, should be satisfied (Cantre and Saathoff 2011)

$$\frac{L_t}{C} \geq 2.5 \tag{1}$$

(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;

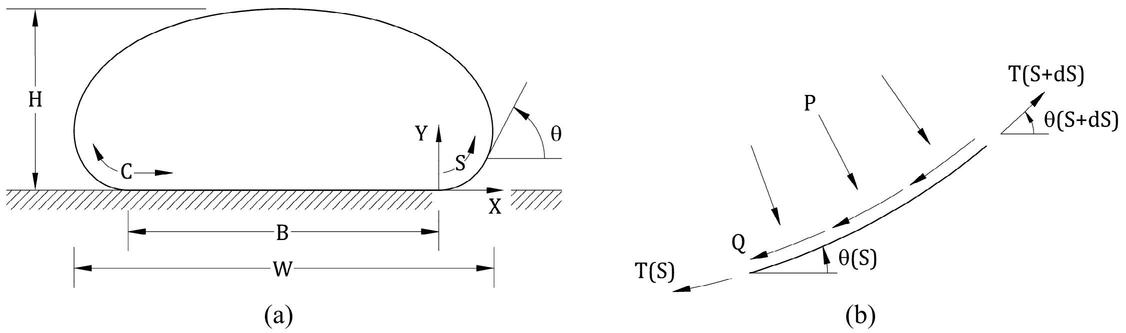


Fig. 1 (a) Tube cross-section and (b) forces acting on the differential element (after Plaut and Suherman 1998)

(5) There is no friction between the geotextile material and fill material, or between the geotextile material and the rigid foundation.

(6) The tensile force around the geotextile tube is constant.

2.1.3 Formulation of the analytical solution

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

$$P = T\frac{d\theta}{dS} = P_{bot} - \gamma_{\text{int}}Y \tag{2}$$

$$\frac{dX}{dS} = \cos\theta;\quad \frac{dY}{dS} = \sin\theta;\quad \frac{dT}{dS} = 0 \qquad \text{(3a, 3b, 3c)}$$

where P=internal hydrostatic pressure, T=circumferential tensile stress (constant throughout the tube circumference due to Eq. (3c)), 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 as Liu and Silvester (1977). The elliptic integral parameter k (Namias 1985, as cited in Plaut and Suherman 1998) is applied to determine the non-dimensional membrane force t in terms of the non-dimensional bottom pressure p_{bot} (normalized in terms of the tube circumference C).

$$p_{bot} = \frac{P_{bot}}{\gamma_{\text{int}}C} = \frac{H_{\text{int}}}{C} \tag{4}$$

$$t = \left(\frac{k \cdot p_{bot}}{2}\right)^2 = \frac{T}{\gamma_{\text{int}}C^2} \tag{5}$$

where P_{bot}=pressure at the bottom of the tube; H_{int}=pressure head of the fill material relative to the external air pressure; T=geotextile sheet tension generated during the filling process. The solution for parameter k follows

$$2p_{bot}\left[K(k)-E(k)\right]-1=0 \tag{6}$$

where *K(k)* and *E(k)* are the complete elliptic integrals of the first and second kind, respectively. The derivation for the basic solutions are discussed in detail in the works of Plaut & Suherman (1998). The governing equations for the non-dimensional geometric properties with respect to the elliptic integral parameter *k* and tube circumference *C* are as follows:

$$h=\left(1-\sqrt{1-k^2}\right)p_{bot}=\frac{H}{C} \tag{7}$$

$$b=1-2k\sqrt{t}K(k)=\frac{B}{C} \tag{8}$$

$$a=b\cdot p_{bot}=\frac{A}{C^2} \tag{9}$$

where h=non-dimensional tube height; H=actual tube height; b=non-dimensional base with in contact with the foundation; B=contact base width; a=non-dimensional tube cross-sectional area; and A=cross-sectional area. Note that the expressions given in Eqs. (7)-(9) are expressed in terms of the elliptic integral parameter k (middle expression) and geotextile tube circumference (right expression).

The solution discussed above can be implemented using the initial input parameters: D_T (theoretical diameter of the tube) or C; unit weight of the fill material γ_{slurry}; pumping pressure P_0; desired tube height H or the bottom pressure P_{bot}.

2.2 Formulation for geotextile tube deformation during densification (dewatering) process

Approximation method for predicting the final tube height during dewatering is presented in the works of Leshchinsky *et al.* (1996). The analysis is based on the assumption that the tube only changes height during the dewatering stage (right after the filling process). The equation for the drop in the height of the tube is given as

$$\varepsilon_h=\frac{\Delta H}{H_0}=\frac{G_s\left(\omega_0-\omega_f\right)}{1+\omega_0 G_s} \tag{10}$$

where ε_h=1D strain; ΔH=(H_0-H_f)=decrease in tube height; H_0=initial tube height before the densification of the fill material; H_f=final tube height 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.

In this paper, modifications were made on the assumptions made by Leshchinsky *et al*. (1996). These assumptions 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%);

(3) The soil particles are incompressible.

Leshchinsky *et al.* (1996) considered 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. In this study, the effects of lateral movement during the tube densification is taken into consideration. In order to do this, areal strain is adopted. 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 effect of vertical and longitudinal strain. Considering the deformation of the tube area (areal strain) during the densification process, the equations proposed by Leshchinsky *et al.* becomes

$$\varepsilon_a = \frac{\Delta A}{A_0} = \frac{G_s\left(\omega_0 - \dfrac{\omega_f}{S_f}\right)}{1+\omega_0 G_s} \tag{11}$$

$$\omega_0 = \frac{G_s - G_0}{G_s\left(G_0 - 1\right)} \tag{12}$$

$$\omega_f = \frac{S_f\left[G_s - G_f\right]}{G_s\left[G_f - 1\right]} \tag{13}$$

where ε_a=areal strain; ΔA=(A_0-A_f)=decrease in tube area; A_0=initial tube area before the densification of the fill material; A_f=final densified tube area; S_f=degree of saturation of the solidified fill; G_0 (=$\gamma_{slurry}/\gamma_{water}$) and G_f (=$\gamma_{fill}/\gamma_{water}$) are the ratio of the unit weight of slurry and solidified fill to the unit weight of water, respectively. Therefore, the final area of the tube A_f, once a certain density of the densified fill material is achieved, can be expressed as:

$$A_f = A_0\left[1 - \frac{G_s\left(\omega_0 - \dfrac{\omega_f}{S_f}\right)}{1+\omega_0 G_s}\right] \tag{14}$$

2.3 Numerical procedure

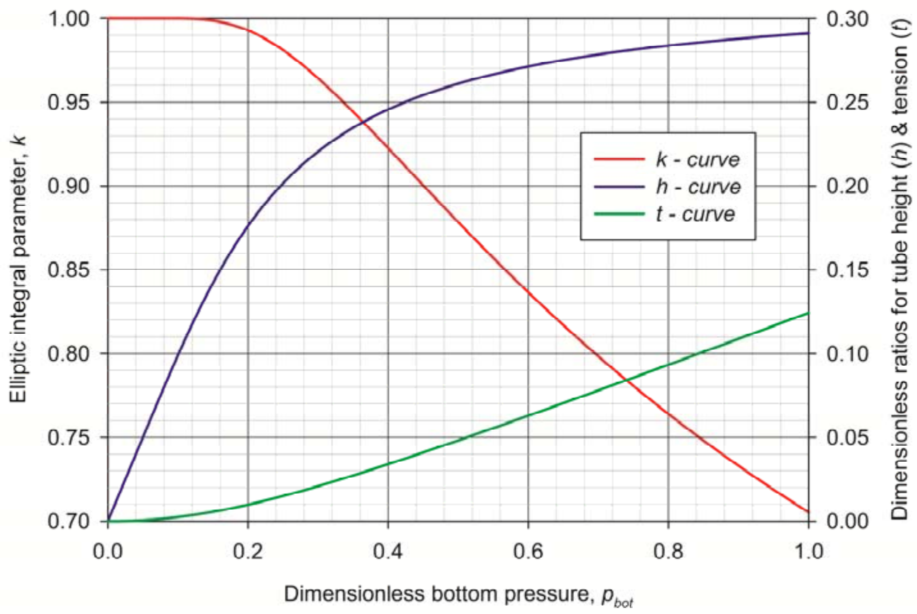
Eqs. (5)-(9) contains elliptic integrals which have no closed form solutions. This means that a computer is needed when designing geotextile tubes using Plaut and Suherman's (1998) method. In some cases, like in the construction field, computers might be unavailable. Hence, design diagrams – the simplest way for approximation measures in the design process-might come in handy in the construction site. However, in order to derive these design diagrams, a computer program needs to be written first. In this paper, a numerical algorithm was developed using the Matlab language (MATLAB 8.1). The initial input parameters used are:

(1) Tube theoretical diameter D_T or circumference C;

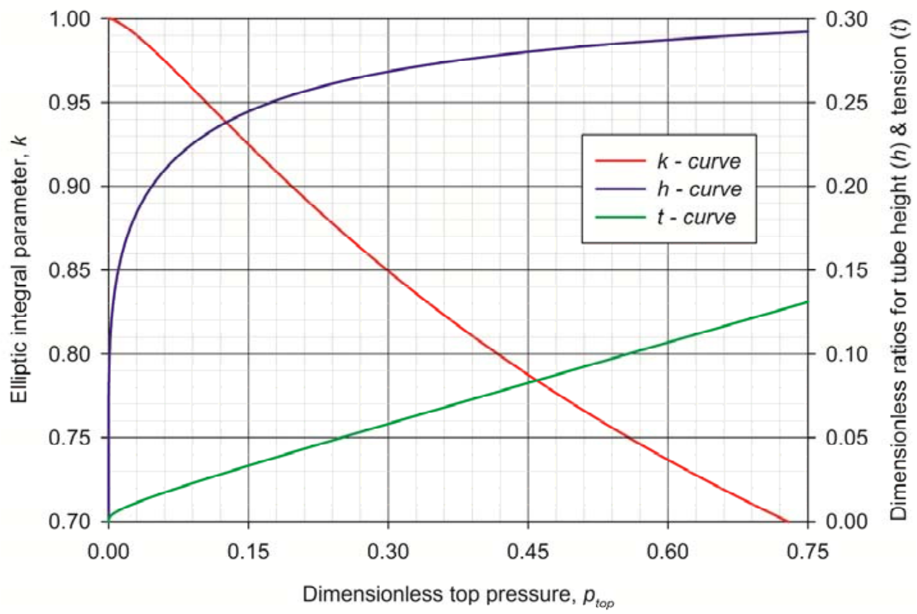
(2) Unit weight γ_{slurry} or the initial water content ω_0 of the slurry fill;

(3) Bottom pressure P_{bot} or the dimensionless bottom pressure p_{bot}.

(4) Unit weight γ_{fill} or the final water content ω_f of the solidified fill;
(5) Specific gravity of the soil solids G_s.
(6) Degree of saturation S_f of the solidified fill.



(a)



(b)

Fig. 2 Design diagram to determine the elliptic parameter k, non-dimensional tube height h and tensile force t with respect to the (a) normalized bottom pressure p_{bot} and (b) normalized top pressure p_{top}

An algorithm of a computer code was developed by the authors to find the solution of Eq. (6). Using predetermined p_{bot}-values ranging from 0 to 1 at an increment of 0.00001, the parameter k and the complete elliptic integrals of the first $K(k)$ and second $E(k)$ kinds were determined iteratively using Eq. (6). The dimensionless tension t can then be determined using Eq. (5). Subsequently, the non-dimensional geometric properties such: (1) tube height h; (2) base width in contact with the foundation b; and (3) cross-sectional area a, can then be computed using Eqs. (7), (8) and (9), respectively.

During filling, the circumference of the tube is C and 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_{fill} obtained using Eq. (10) for 1D strain method, or tube area A_{fill} obtained from Eq. (14) for areal-strain method. For the densification analysis using the 1D strain method, the calculated H_{fill}-value is used in the numerical calculation of its corresponding k and p_{bot} values using Eqs. (6) and (7). Eqs. (8) and (9) will give the values for the non-dimensional geometric properties b_f and a_f of the densified tube. On the other hand, the A_{fill}-value obtained fron Eq. (14) 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. (9). The subsequent k, p_{bot}, t, and b values are solved numerically using Eqs. (5), (6) and (8).

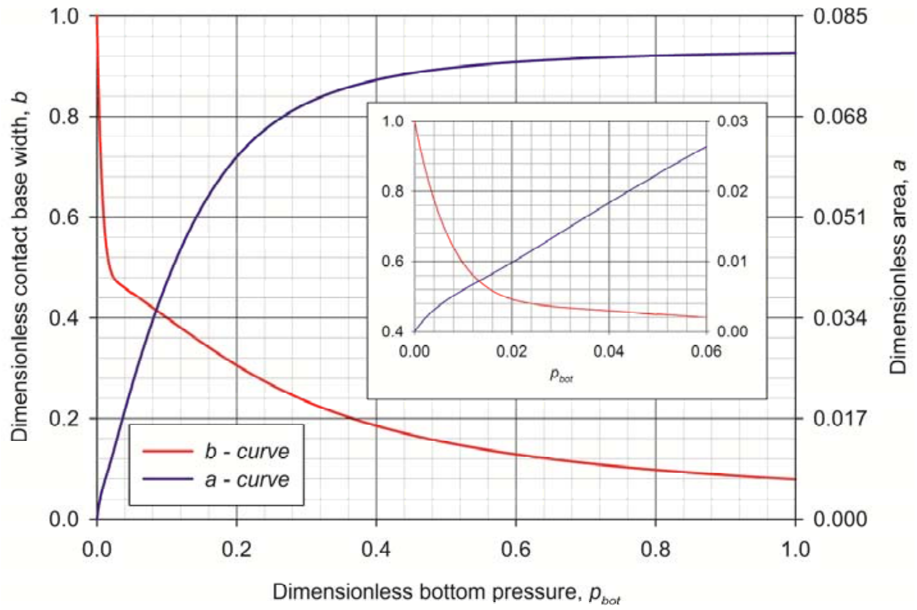
3. Design diagrams

3.1 Tube geometry

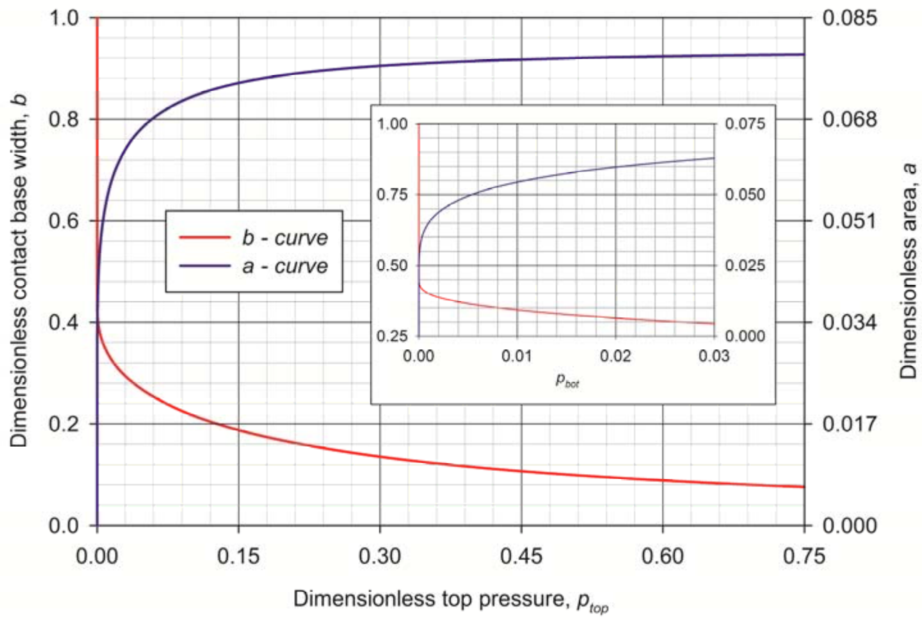
Non-dimensional design diagrams can be created based on the calculation methods developed by Plaut and Suherman (1998). These non-dimensional diagrams could be useful in estimating geometric shapes of geotextile tubes when computer programs are unavailable. According to Cantre (2002), considerable deviants to the calculated values can be encountered in analyses made on very large diameter tubes. Fig. 2(a) illustrates the relationship between the dimensionless bottom pressures to the elliptic integral parameter k, non-dimensional tension t and non-dimensional tube height h. Given the desired bottom pressure and the specific weight γ_{int} of the material fill, the geotextile tube height H and generated tension T can be approximated using Fig. 2(a). Moreover, in some cases where the given initial parameter is the pumping pressure (pressure on top of the tube), which can be easily controlled or monitored by the operators in the construction site, relationships between the top pressure and the non-dimensional geometric and stress properties needs to be established. Hence, a design chart illustrating the relationship between the dimensionless top pressure to the elliptic integral parameter k, non-dimensional tension t and non-dimensional tube height h are given in Fig. 2(b). Furthermore, given the desired bottom or top pressure as the initial design parameter, the dimensionless contact base width b and tube area a can be determined from the design charts shown in Fig. 3.

3.2 Approximation of tube geometry during densified state

The formulation for densification of geotextile tubes were discussed in section 2.2. Design charts of tube densification can be derived by combining Eqs. (10)-(14). Fig. 4 shows the



(a)



(b)

Fig. 3 Design diagram to determine the non-dimensional base width *b* and tube cross-sectional area *a* with respect to the (a) normalized bottom pressure p_{bot} and (b) normalized top pressure p_{top}

relationship between the percentage-reductions in terms of the areal strain of the slurries used in this parametric study to its relative density when it solidifies to a certain density (similar relationships using one-dimensional strain was presented by Leshchinsky *et al.* 1996). For example,

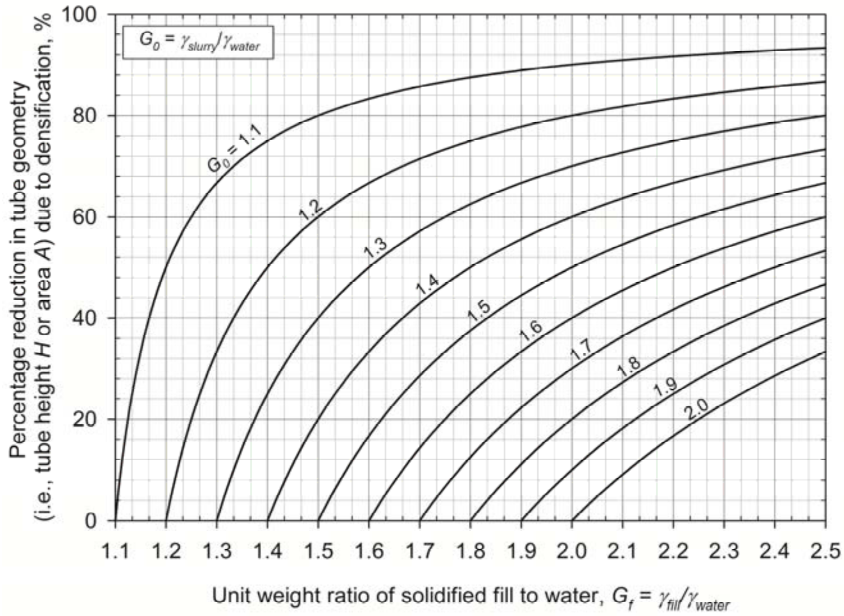


Fig. 4 Reduction in the tube geometry (i.e., tube height and area) with respect to the initial and final unit weight ratios (relative to water) of the fill material

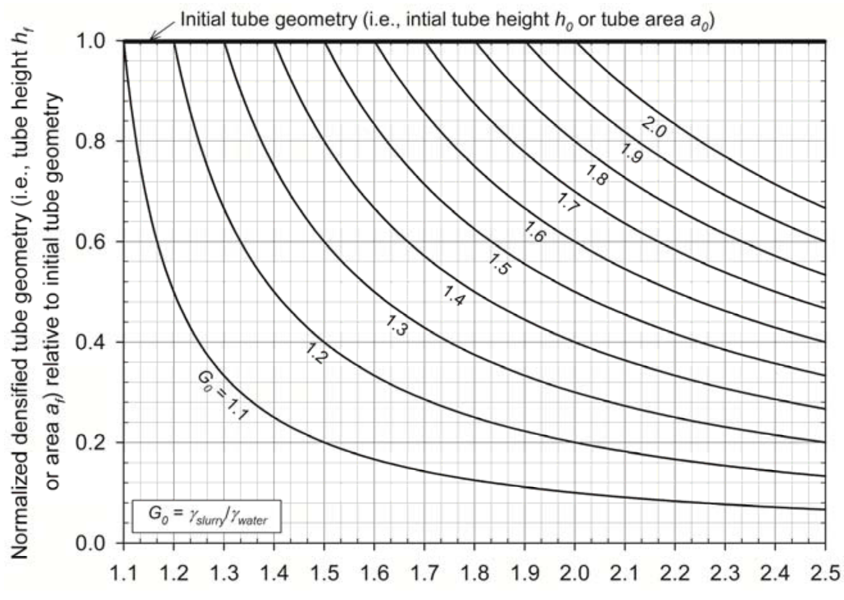


Fig. 5 Normalized densified tube geometry (in terms of tube height or area) with respect to the initial and final unit weight ratios (relative to water) of the fill material

the percentage reduction in the tube height (1D-strain method) or cross-sectional area (areal-strain method) of a geotextile tube filled with slurry having unit weight ratio of slurry to water G_0=1.4

and specific gravity of soil solids G_s=2.7 (γ_{slurry}=13.734 kN/m^3; ω_0=120.37%) is roughly 40% when the unit weight ratio of solidified fill to water becomes G_f=1.667 (γ_{fill}=16.353 kN/m^3; ω_f=57.36%).

In Fig. 5, the relationship between the normalized densified tube geometry (i.e., densified tube height h_f for 1D strain analysis or densified tube area a_f for areal-strain analysis; relative to the normalized initial tube geometry h_0 and a_0, respectively) is shown as a function of the initial and final unit weight ratios (relative to water) of the fill material. Going back to the previous example, the tube height reduction (for 1D-strain analysis) or tube area reduction (for areal-strain analysis) is 40% its initial geometry (i.e., 0.4h_0 for 1D strain; 0.4a_0 for areal-strain). Hence, referring to Fig. 5, the normalized densified tube geometry is h_f=0.6h_0 for the 1D-stain analysis and a_f=0.6a_0 for the areal-stain analysis.

4. Numerical validation

4.1 Tube filling

Plaut and Suherman (1998) presented a problem of a tube having a circumference C=3.658 m filled with slurry having a specific weight $\gamma_{slurry}=2\gamma_{water}$. To verify the soundness of the numerical solutions in this study, the calculated results from Plaut and Suherman (1998) and from the present study are tabulated in Table 1. The closeness of the results presented indicates that the numerical solution applied in this study is appropriate.

4.2 Tube densification

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 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

Table 1 Comparison of results obtained from the present study and Plaut and Suherman (1998)

Properties	This study	Plaut and Suherman (1998)	Percent difference (%)
Dimensionless parameter:			
k	0.98109024	0.9811	0.0010
p_{bot}	0.25	0.25	0
Geometric properties:			
H (m)	0.73750	0.737	0.0678
W (m)	1.44282	1.44	0.1956
B (m)	0.97513	0.975	0.0133
A (m)	0.89176	0.892	0.0269
Stresses:			
P_{bot} (kPa)	17.94253	17.94	0.0141
P_{top} (kPa)	3.47279	3.47	0.0804
T (kN/m)	3.94845	3.95	0.0392

Table 2 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 filling state:							
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 state:							
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	-	-

Note: [a] Plaut and Suherman (1998) solution;
[b] Values obtained using GeoCoPS 3.0 Software

having densified unit weight of 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 computer program developed by Leshchinsky's *et al.* (1996, GeoCoPS 3.0). The calculated outputs are tabulated in Table 2. For the tube modeling during pumping, the results for tube width (W), base contact length (B) and cross-sectional area (A) based on Leshchinsky *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 *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 decreases while the maximum tube width W and contact base length B remains constant in the densified state). On the other hand, for both the 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 2. Since the 1D strain method is based on the concept introduced by Leshchinsky *et al.* (1996), the results from their analysis and from present study are in close agreement and have an acceptable numerical margin of error. Results obtained from the areal strain analysis, however, yields smaller outputs for the tube height, area, and generated stresses (i.e., bottom pressure, top pressure and tensile force).

5. Parametric study

5.1 Geotextile tube filling

A 3.0 m diameter (theoretical) tube having a sufficient length is considered. The unit weight of the slurry fill was taken as 14 kN/m^3 and the specific gravity of its solid particles is 2.7. The maximum allowable tensile stress is 25 kN/m. Four analyses were performed based on the attained tensile stress T_c of the filled geotextile tube with respect to the maximum allowable circumferential stress $T_{c(ALLOWABLE)}$ (i.e., 25%, 50%, 75% and 100%, respectively). The corresponding geometric properties of the tube relating to the attained tensile stress T_c (25%, 50%, 75% and 100% of

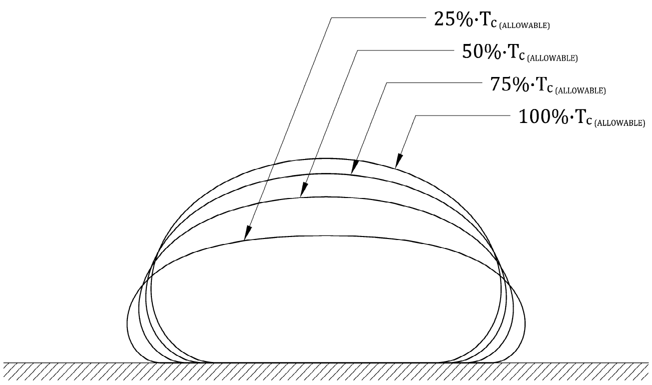


Fig. 6 Geotextile tube geometry with respect to the attained circumferential tensile stress

Table 3 Summary of the results for geotextile tube filling

Descriptions	Units	Percentage achieved circumferential stress with respect to $T_{c(ALLOWABLE)}$			
		25%	50%	75%	100%
Geometrical dimensions:					
Tube height, *H*	m	1.280	1.671	1.902	2.058
Tube width, *W*	m	4.092	3.863	3.716	3.613
Contact base, width *B*	m	3.381	2.865	2.510	2.243
Cross-sectional area, *A*	m^2	4.522	5.455	5.922	6.201
Pressures and stresses:					
Circumferential stress	kN/m	6.249	12.500	18.750	24.999
Bottom, P_{bot}	kPa	18.72	26.66	33.032	38.703

$T_{c(ALLOWABLE)}$) are determined and comparisons are made. The geometric graphical representation for the case of surface-filled geotextile tube resting on a rigid foundation is shown in Fig. 6. To attain a circumferential stress equivalent to 25%$T_{c(ALLOWABLE)}$, the geotextile tube must achieve a filled height and width equivalent to 1.280 m and 4.092 m, respectively. The corresponding geometric dimensions, stress and pressures are tabulated in Table 3. For this case, the maximum capacity of the slurry-filled geotextile tube (in terms of cross-sectional area) is equivalent to 6.20 m^2 (H=2.058 m; W=3.613 m). Beyond that, failure on the geotextile tube membrane is inevitable.

5.2 Densification of geotextile tube

A sufficiently long geotextile tube having a theoretical diameter of 3.0 m is considered. The tube is pumped with a high moisture content slurry of γ_{slurry}=12 kN/m^3 (ω≈245%; G_s=2.7). The tube is filled with slurry up to 75% its theoretical diameter. The corresponding stress and geometric properties of the tube are tabulated in Table 2. Generally, the average drop in height for a soil layer in soil mechanics are about 10% for sandy fills and 50% clayey fills. In analysis used in the present study, however, during the filling process the slurry is assumed to be a highly saturated viscous material and behaves like a liquid. Hence during the process of densification, depending on the amount of water content of the initial slurry, it is possible that the amount of tube

Table 4 Summary of the parametric study results for geotextile tube using 1D-strain densification analysis

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	245.0	1.986	-	6.078	-	30.80	18.75
Tube densification:							
13	156.6	1.364	31.32	4.737	22.06	18.78	6.762
14	110.4	1.038	47.73	3.862	36.46	14.78	3.902
15	81.97	0.838	57.80	3.261	46.35	12.64	2.663
16	62.75	0.703	64.60	2.822	53.17	11.26	1.982
17	48.87	0.605	69.54	2.486	59.10	10.29	1.557

Notes: H_{reduc}=Percentage reduction in tube height; A_{reduc}=Percentage reduction in tube area.

Table 5 Summary of the parametric study results for geotextile tube using Areal-strain densification analysis

Specific weight (kN/m^3)	Water content (%)	A (m^2)	A_{reduc} (%)	H (m)	H_{reduc} (%)	P_{bot} (kPa)	T (kN/m)
Tube filling:							
12	245.0	6.078	-	1.986	-	30.80	18.75
Tube densification:							
13	156.6	4.172	31.36	1.148	42.20	15.35	4.526
14	110.4	3.176	47.75	0.811	59.16	11.41	2.325
15	81.97	2.564	57.82	0.627	68.43	9.417	1.478
16	62.75	2.150	64.63	0.512	74.22	8.188	1.048
17	48.87	1.851	69.55	0.432	78.25	7.346	0.794

Notes: H_{reduc}=Percentage reduction in tube height; A_{reduc}=Percentage reduction in tube area.

reduction (i.e., height, area, volume) will exceed beyond the average normal drop. The higher the quantity of water are dissipated during the densification process, 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. In this parametric study, the water content of the slurry during tube filling is significantly high (i.e., 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. In the numerical results are presented in Table 4 using 1D densification analysis, the tube would have lost 57.8% of its initial filled height. The current water content at this state would be 82%. As more water elements seeps through the geotextile membrane the more compact and denser the densified fill becomes, thereby, decreasing the cross-sectional area of the tube. Numerical results for the densified tube having unit weights of 13 kN/m^3, 14 kN/m^3, 16 kN/m^3 and 17 kN/m^3, are presented. Also, for comparison, the numerical results of densification analysis using the areal-strain method are tabulated in Table 5. As mentioned in section 4.2, in comparison with the densification analysis results using 1D-strain, the results from the areal-strain analysis yields smaller outputs for the tube height, area, and generated stresses.

Table 6 Comparison of values from design chart and numerical analysis in terms of h and p_{bot}

Properties	Design chart values	Numerical values	Percent difference (%)
Dimensionless parameter:			
h (intial input value)	0.15915	0.1591549431	0.0031
k	[0.995]	0.9966614145	0.0017
p_{bot}	[0.170]	0.1733	1.9225
Geometric properties:			
H (m)	1.500	1.500	0
B (m)	3.110 [b = 0.330]	3.103	0.2253
A (m)	5.063 [a = 0.057]	5.068	0.0987
Stresses:			
P_{bot} (kPa)	19.23 [p_{bot} = 0.170]	19.60	1.9057
T (kN/m)	7.994 [t = 0.0075]	7.950	0.5519

Note: Values inside [ ] are the non-dimensional geometric properties obtained from their respective design charts (i.e., Figs. 2 and 3).

5. Design chart validation

For this section, a tube having a theoretical diameter of 3.0 m filled with slurry (γ_{slurry}=12 kN/m^3; ω≈245%; G_s=2.7) up to 1.5 m (filled tube height) is considered. Using Eq. (7), the normalized filled tube height relative to the tube circumference is h_0=0.15915. Using this value, the elliptic integral parameter k and normalized quantities such as p_{bot} and t can be approximated using Fig. 2(a). Next, using Fig. 2(b), the normalized quantities b and a can be estimated. The approximations made by the authors for the present problem are tabulated in Table 6. The dimensional quantities can then be calculated using Eqs. (4)-(5) and Eqs. (7)-(9). Results obtained using the numerical procedure are also provided for comparison. From the tabulated results, it can be seen that the values drawn from the design charts and calculated numerical values are generally in good agreement.

6. Conclusions

Methods for analyzing the cross-sectional shapes, circumferential tension, top and bottom pressures are presented in this study. The geotextile tubes are modeled as weightless and inextensible membranes resting on a rigid foundation using approximate solutions based on the non-dimensional geometric properties with respect to the tube circumference C and elliptic integral parameter k. The basic assumption for the problem is that tension is constant all throughout the circumference of the geotextile tube at a given specific internal pressure.

Existing method for the one-dimensional (1D-strain) approximation of geotextile tube densification based on the basic volume-relationships in soil and fluid mechanics are reviewed and improved. A new calculation approach for the densification of geotextile tubes based on areal-strain analysis is introduced. In comparison with the densification analysis results using 1D-strain, the results from the areal-strain analysis yields smaller outputs for the tube height, area, and generated stresses (i.e., bottom pressure, top pressure and tensile force).

Design diagrams were created based on the existing and modified analytical and approximate solutions for geotextile tubes. These non-dimensional diagrams could be useful in estimating geometric shapes of geotextile tubes in construction sites where computer programs are unavailable.

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