GeoCoPS (2.0)©: Supplemental Notes©

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ABOUT THIS DOCUMENT

These supplemental notes are an *edited* reproduction of the following public domain publications:

1. Leshchinsky, D. and Leshchinsky, O., "Geosynthetic Confined Pressurized Slurry (GeoCoPS): Supplemental Notes for Version 1.0," *Report TR CPAR-GL-96-1*, September 1996, US Army Engineer Waterways Experiment Station, Vicksburg, Mississippi.
2. Leshchinsky, D., Leshchinsky, O., Ling, H.I. and Gilbert, P.A., "Geosynthetic Tubes for Confining Pressurized Slurry: Some Design Aspects," *Journal of Geotechnical Engineering*, ASCE, Vol. 122, No. 8, 1996, pp. 682-690.

1.0 ABSTRACT

Geosynthetic tubes in the context of this paper are made of several geosynthetic sheets sewn together to form a shell capable of confining pressurized slurry. The slurry is sufficiently fluid so that it is possible to hydraulically fill the tube. After pumping the slurry in, the geosynthetic shell acts as a 'cheese cloth' allowing seepage of liquid out and retaining the solid particles. The availability of a wide selection of geosynthetics in terms of strength, durability and permeability enables the use of hydraulically filled tubes in many applications, some of which may be considered critical (e.g., encapsulate contaminated soil). This paper presents an overview of an analysis to calculate both stresses in the geosynthetic and geometry of the tube. It also verifies the correctness and validity of the results obtained from a computer program developed to solve the problem. An instructive parametric study implies that the most critical factor needed to assure successful construction is the pumping pressure; a slight accidental increase in this pressure may result in a very significant stress increase in the encapsulating geosynthetic. Pressure increase beyond a certain level, however, has little influence on the storage capacity of the tube. Guidance in selecting an adequate geosynthetic, including reduction factors and filtration properties, is also presented. Design aspects associated with required spacing of inlets and head loss of the slurry as it flows through the tube are considered outside the scope of this paper.

2.0 INTRODUCTION

Construction in environmentally sensitive areas (e.g., wetlands) requires techniques causing minimum disturbance and damage. One such technique can be achieved with the aide of dikes made of geosynthetic tubes. A flat tube can be placed with little disturbance to the foundation and then be filled with slurry by pumping. The quickly formed dike then may retain water on one side while allowing construction on the other. Over time, vegetation may grow over the exposed tube surface. Geosynthetic tubes can also be used to contain or cap contaminated soil, form a 'working table' over very soft soil facilitating the construction of an embankment, and construct groins for controlling beach erosion. Varies interesting case histories are reported by Silvester (1986), Bogossian et al. (1982), Perrier (1986), Ockels (1991), Sprague and Fowler (1994), and de Bruin and Loos (1995).

The tubes are made of sewn geosynthetic sheets. Inlet openings on top allow for the attachment of a pipe that transports hydraulic fill into the tubes (see Figure 1a and Figure 1b) . If the fill is sandy and the geosynthetic is very pervious (e.g., geotextile), these inlets should be spaced closely (say, 10 m apart) to assure uniform filling of the tubes (i.e., water will seep through the tubes hindering the hydraulic transport of sand over a long distance). If clayey slurry is used, the inlets can be located as far as 150 m apart. The fine clayey particles tend to rapidly blind the fabric slowing down the water escape through the geotextile.

The scope of this paper is limited to the design aspect of selecting a geosynthetic. Important aspects associated with actual construction are available in the literature (e.g., Pilarczyk, 1994, and Sprague, 1993). To assure successful installation, construction aspects must be accounted for in the design (e.g., locations and type of tube inlets).

Figure 1a: Sand-Filled Tubes (Groins) to Control Erosion, Destine, Florida:
Left: Distant View, and Right: Close-up View

Figure 1b: Clayey Slurry Filled Tubes, Gaillard Island, Mobile, Alabama: Upper Left: Consistency of Dredged Slurry, Upper Right: 8-inch Division Pipe to Supply Slurry to Tube, Middle Left: Flexible Pipe Attached to Inlet Before Pumping of Slurry, Middle Right: Clayey Slurry Pumped through Single Inlet for 2 Hours to Form 150 m Long, 1.5 m High, and 3.6 m Wide Tube, Lower Left: Appearance of Tube Immediately After Completion of Pumping, and Lower Right: Tube Acts as a Filter Allowing Clear Water to Seep Out While Retaining Clayey Particles

3.0 OVERVIEW OF ANALYSIS

Formulation of a geosynthetic tube, filled with pressurized slurry or fluid, is based on equilibrium of the encapsulating flexible shell. The results of this formulation provide both the circumferential tensile force in and the cylindrical geometry of the encapsulating shell material. It should be pointed out that the formulation appears in numerous articles (e.g., Liu 1981, Kazimierowicz 1994, Carroll 1994). For the sake of completeness, only an overview of the basic formulation is reproduced later. The following assumptions govern the formulation:

1. The problem is two-dimensional (i.e., plane strain) in nature. That is, the tube is long and all cross-sections perpendicular to the long axis are identical in terms of geometry and materials. Hence, the pressure loss due to drainage through a geotextile tube during filling and possible material segregation is ignored. The pressure at the inlet (i.e., the pumping pressure) is the basis for analysis.
2. The geosynthetic shell is thin, flexible and has negligible weight per unit length.
3. The material filling the tube is slurry (i.e., a fluid) and therefore, a hydrostatic state of stresses exists inside the tube.
4. No shear stresses develop between the slurry and the geosynthetic.

Refer to Figure 2 for notation and convention. For clarity of presentation, the tube considered is surrounded by air and is filled with only one type of slurry. However, extension of the formulation to include layers of slurry inside and layers of fluid outside is straightforward. Note that the cross section is symmetrical, having a maximum height of h at the centerline, maximum width B, and a flat base that is in contact with the foundation soil and is b wide. The pumping pressure of the slurry into the tube is p_o. The average unit weight (density) of the slurry is γ. Hence, the hydrostatic pressure of the slurry at any depth x, as measured from point O, is $p(x)=po+\gamma x$.

The geometry of the geosynthetic shell is defined by an unknown function $y=f(x)$. At a point of contact $S(x,y)$, the radius of curvature of the geosynthetic is r. The center of this curvature is at point $C(x_c,y_c)$. Both r and C vary along $y(x)$. Consider the forces on an infinitesimal arc length, ds, of the geosynthetic at S (see inset in Figure 2). Since it is assumed that the problem is two-dimensional and that no shear stresses develop between the slurry and the geosynthetic, it follows that the geosynthetic tensile force, T, must be constant along the circumference. Assembling the force equilibrium equation in either x or y direction leads to the following relationship:

$$r(x) = \frac{T}{p(x)} \quad \text{..} \quad (1)$$

Equation 1 is valid at any point along $A1OA2$. To simplify the analysis, it is assumed (conservatively) that the calculated T from Equation 1 is carried solely by the geosynthetic along the flat base b. That is, no portion of T is transferred to the foundation soil due to shear along the interface between the geosynthetic and soil (this shear can be mobilized only as the geosynthetic deforms relative to the foundation).

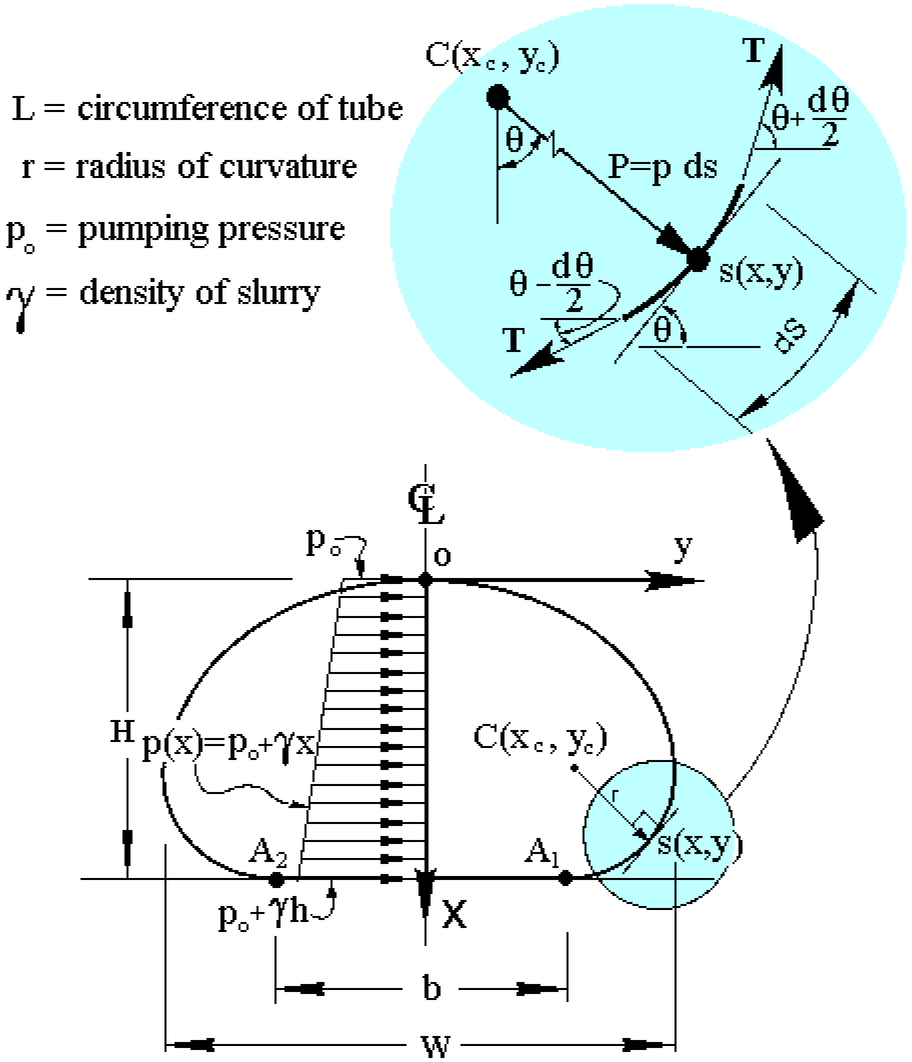


Figure 2. Cross-Sectional View of Geosynthetic Tube: Convention and Notation

Consequently, Equation 1 expresses the complete solution for the problem. Differential calculus gives the radius of curvature as:

$$r(x) = \frac{[1+(y')^2]^{3/2}}{y''} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

where $y'=dy/dx$ and $y''=d^2y/dx^2$.

Substituting Equation 2 and $p(x)$ into Equation 1 yields:

$$T\cdot y'' - [p_o+\gamma\cdot x]\cdot[1+(y')^2]^{3/2} = 0 \quad \ldots\ldots\ldots\ldots (3)$$

Equation 3 is a non-linear differential equation that, in general, has no closed-form solution; that is, it has to be solved numerically. Its solution produces the relationships between the geometry of the tube *y(x)*, the circumferential tensile force *T*, the pumping pressure p_o, the unit weight of the slurry γ, and the height of the tube *h* (note that *x* varies only between zero and *h*):

$$y = f(x \mid T, p_o, h, \gamma) \quad \text{.............................} (4)$$

Since the unit weight of the slurry γ is normally known, Equation 4 implies that *y* is a function of the independent variable *x* and the three parameters *T*, p_o and *h*. Typically, *y(x)* is sought for a given (design) parameter; i.e., either *T*, or p_o or *h* is given. The other two parameters are part of the solution of the problem. To obtain such an explicit solution, constraints must be imposed. Two such constraints will produce a solution where for a selected design parameter, the geometry of the tube, as well as the other two parameters, will be obtained. Two physical constraints will replace two unknown parameters that currently are part of the solution.

One constraint is the geometrical boundary condition at point *O*. Physically, the geosynthetic at *O* must be horizontal to assure a smooth transition from one half tube of the symmetrical problem to the other half. That is:

$$1 / y'(0) = 0 \quad \text{..} (5)$$

The second constraint can be introduced through the specification of the flat base length *b*. In this case, vertical force equilibrium along *b* requires that:

$$b = \frac{W}{p_o + \gamma \cdot h} \quad \text{..} (6a)$$

where *W* is the weight, per unit length, of the slurry filling the entire section of the tube. That is:

$$W = 2\gamma \int_0^h y(x) \cdot dx \quad \text{..................................} (6b)$$

Combining Equation 6a and 6b gives:

$$b = \frac{2\gamma}{p_o + \gamma \cdot h} \int_0^h y(x) \cdot dx \quad \text{..........................} (7)$$

Prescribing *b* and simultaneously solving Equations 3, 5 and 7 for a single selected design parameter (either *T*, or p_o or *h*) will result in a tube having a certain length of circumference *L*. However, it is more practical to specify the circumference of a tube rather than *b* since the tube is manufactured from a prescribed number of geosynthetic sheets sewn together. If *L* is specified, the value of *b* will then be the outcome of the analysis. Hence, Equation 7 can be replaced by the following constraint:

$$L = b + 2\int_S ds \tag{8}$$

where *s* represents the arc *A1OA2* (Figure 2), and *ds* is the differential arc length and, from differential calculus, is equal to $[1+(y')^2]^{1/2}$. Using this definition of *ds* in Equation 8 combined with substitution of Equation 7 (i.e., this equation represent the vertical force equilibrium along *b*) results in:

$$L = \frac{2\gamma}{p_o+\gamma\cdot h}\cdot\int_0^h y(x)\cdot dx + 2\int_0^h [1+(y')^2]^{1/2} dx \tag{9}$$

Now for a prescribed *L*, simultaneous solution of Equations 3, 5 and 9 yields the relationship between *T*, *h*, p_o and *y(x)*; i.e., the explicit form of Equation 4. This solution is complete if one of the design parameters (either *T*, or *h* or p_o) is specified. The numerical process involved with such a solution is rather tedious requiring a trial and error procedure. Several computational schemes are available in the literature (e.g., Liu 1981, Kazimierowicz 1994, Carroll 1994). The procedure used in this work is a modification of that proposed by Carroll (1994). For given circumference *L*, and say, *T* (or *h* or p_o), the computer program GeoCoPS, developed by Leshchinsky and Leshchinsky (1996), computes the geometry of the tube *y(x)* and the other two parameters. This program was developed as a design tool and it allows the user to specify various reduction factors related to the geosynthetic strength. The calculated results can be viewed graphically for easier interpretation.

Finally, there is also a practical need to assess the axial tensile force per unit length, T_{axial}, in the geosynthetic encapsulating the slurry. Refer to Figure 3 for definition of this force. The total force *P* acting on a vertical plane signifying the end of a tube, resulting from pressurized slurry, is:

$$P = 2\cdot\int_0^h (p_o+\gamma\cdot x)\cdot y(x)\cdot dx \tag{10}$$

The tube in the z-direction (i.e., axial direction) carries the force *P*. The force T_{axial} per unit length then is *P* divided by the circumference, *L*, of the tube. That is:

$$T_{axial} = \frac{2}{L}\cdot\int_0^h (p_o+\gamma\cdot x)\cdot y(x)\cdot dx \tag{11}$$

Once the geometry of the tube has been determined through the solution of Equation 3, the value of T_{axial} can then be computed by solving Equation 11.

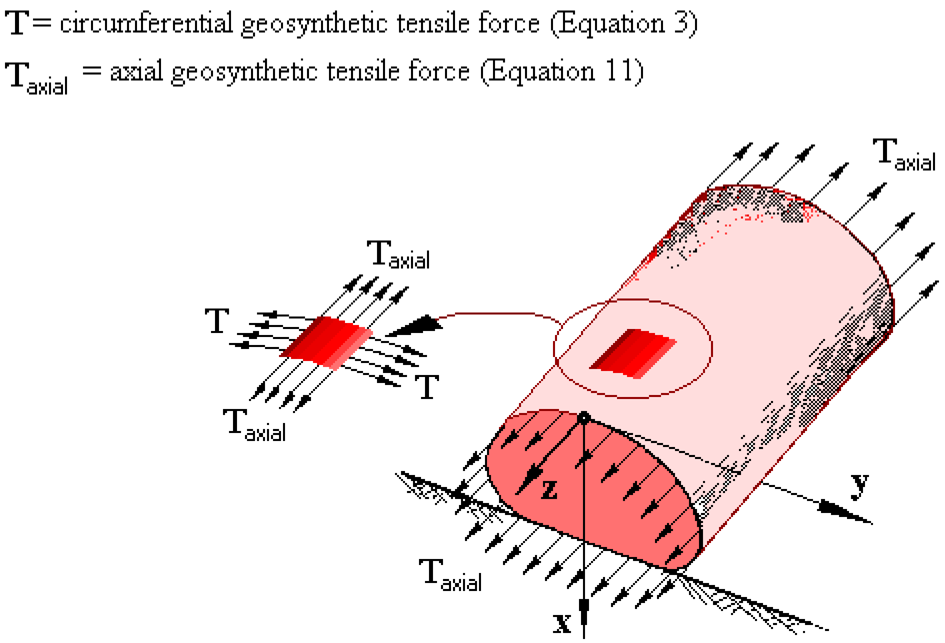


Figure 3. Axial Tensile Force in Geosynthetic Tube [T = Circumferential Geosynthetic Tensile Force (Eq. 1); T_{axial}=Axial Geosynthetic Tensile Force (Eq. 11)]

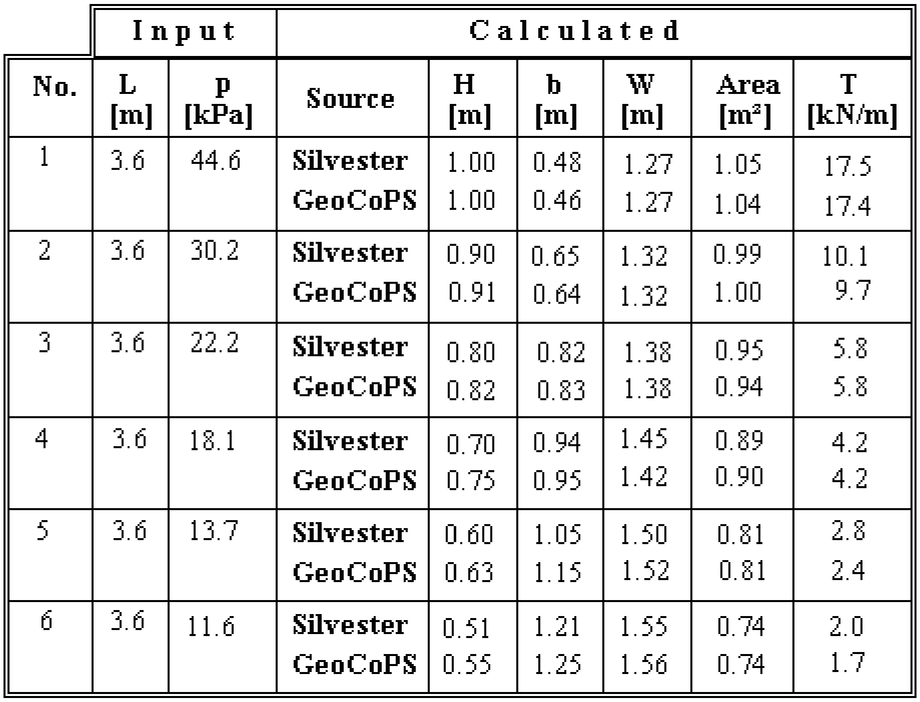
Typically, the circumferential force T is larger than T_{axial}. Hence, if a geosynthetic having isotropic strength is considered, the value of T_{axial} is not needed in design. However, frequently geosynthetics are anisotropic; i.e., their strength in the warp direction (usually corresponds to the tube's circumferential direction) is different than that in the fill direction (usually corresponds to the tube's axial direction). This anisotropy is particularly common in medium to high strength geotextiles, where different types and number of yarns per unit width are used in each of the principal directions in the fabrication process. The end product may have either significantly higher or worse, lower strength in the axial direction as compared to the circumferential one. Consequently, to assure economical selection of a geosynthetic, producing a safe structure, the value of T_{axial} should always be considered. Program GeoCoPS provides the values of both T and T_{axial}. These values are adjusted by user-prescribed reduction factors that account for the de facto reduction in geosynthetic strength due to seams and possible construction damage. The end result allows for the selection of an adequate geosynthetic.

4.0 VERIFICATION OF ANALYSIS

4.1 Numerical

Silvester (1986) presented the results of a numerical analysis in a format of a non-dimensional chart and a table for a particular circumference of a tube. It was stated that the numerically resulted shapes of the tube had been verified experimentally. The references imply that the experimental work used for verification was conducted by Liu, some of which are reported by Liu (1981). The input data for the tabulated results was the circumference, L=3.6 m (12 ft), and the pressure at the bottom of the tube (i.e., $p=p_o+\gamma h$); the unit weight of the slurry used (mortar) relative to that of water was 2.0. Table 1 shows the comparison between values calculated by Silvester (1986) and those computed using program GeoCoPS for the same input data. As evident from the table, the numerical agreement of computed results is very good.

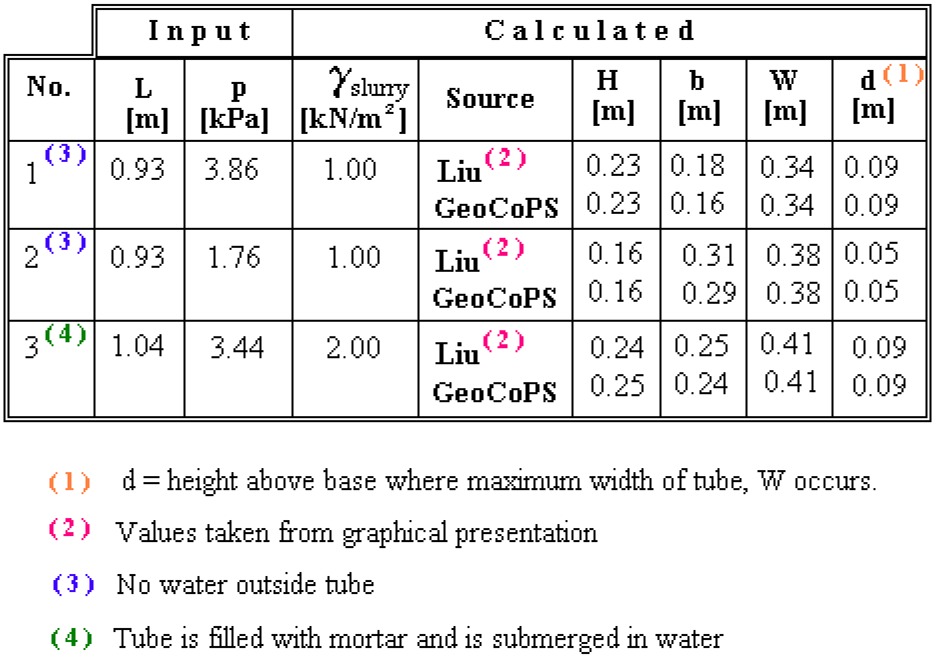
Table 1. Comparison of results obtained from GeoCoPS and Silvester (1986)
[$\gamma_{slurry}=2\gamma_w$; see Figure 2 for notation]



	Input		Calculated					
No.	**L [m]**	**p [kPa]**	**Source**	**H [m]**	**b [m]**	**W [m]**	**Area [m^2]**	**T [kN/m]**
1	3.6	44.6	**Silvester** **GeoCoPS**	1.00 1.00	0.48 0.46	1.27 1.27	1.05 1.04	17.5 17.4
2	3.6	30.2	**Silvester** **GeoCoPS**	0.90 0.91	0.65 0.64	1.32 1.32	0.99 1.00	10.1 9.7
3	3.6	22.2	**Silvester** **GeoCoPS**	0.80 0.82	0.82 0.83	1.38 1.38	0.95 0.94	5.8 5.8
4	3.6	18.1	**Silvester** **GeoCoPS**	0.70 0.75	0.94 0.95	1.45 1.42	0.89 0.90	4.2 4.2
5	3.6	13.7	**Silvester** **GeoCoPS**	0.60 0.63	1.05 1.15	1.50 1.52	0.81 0.81	2.8 2.4
6	3.6	11.6	**Silvester** **GeoCoPS**	0.51 0.55	1.21 1.25	1.55 1.56	0.74 0.74	2.0 1.7

Liu (1981) showed the results of analysis and experimental work. Two types of 'slurry' were used: water and mortar. One reported case was for a tube filled with mortar and submerged in water. No values of calculated T were reported. Table 2 indicates, once again, a very good numerical agreement.

Table 2. Comparison of results obtained from GeoCoPS and Liu (1981) [see Figure 2 for notation]



	Input		Calculated					
No.	**L [m]**	**p [kPa]**	γ_{slurry} **[kN/m^2]**	**Source**	**H [m]**	**b [m]**	**W [m]**	**d (1) [m]**
1 (3)	0.93	3.86	1.00	**Liu (2)**	0.23	0.18	0.34	0.09
				GeoCoPS	0.23	0.16	0.34	0.09
2 (3)	0.93	1.76	1.00	**Liu (2)**	0.16	0.31	0.38	0.05
				GeoCoPS	0.16	0.29	0.38	0.05
3 (4)	1.04	3.44	2.00	**Liu (2)**	0.24	0.25	0.41	0.09
				GeoCoPS	0.25	0.24	0.41	0.09

(1) d = height above base where maximum width of tube, W occurs.

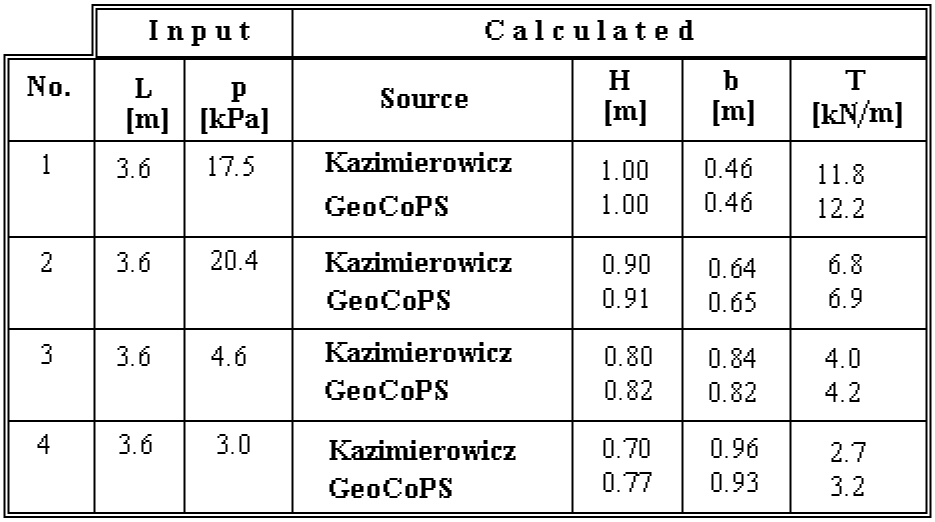
(2) Values taken from graphical presentation

(3) No water outside tube

(4) Tube is filled with mortar and is submerged in water

Kazimierowicz (1994) presented an instructive numerical approach to solve the problem. Table 3 shows a comparison of results for one type of slurry and different pumping pressures. Generally, the agreement here is good.

Table 3. Comparison of results obtained from GeoCoPS and Kazimierowicz (1994) [γ_{slurry}=1.4γ_w ; see Figure 2 for notation]



	Input		Calculated			
No.	**L [m]**	**p [kPa]**	**Source**	**H [m]**	**b [m]**	**T [kN/m]**
1	3.6	17.5	**Kazimierowicz**	1.00	0.46	11.8
			GeoCoPS	1.00	0.46	12.2
2	3.6	20.4	**Kazimierowicz**	0.90	0.64	6.8
			GeoCoPS	0.91	0.65	6.9
3	3.6	4.6	**Kazimierowicz**	0.80	0.84	4.0
			GeoCoPS	0.82	0.82	4.2
4	3.6	3.0	**Kazimierowicz**	0.70	0.96	2.7
			GeoCoPS	0.77	0.93	3.2

These comparisons are for results obtained from different numerical procedures solving, essentially, the same governing equation (i.e., Equation 3). The closeness of results can serve as an indication that the numerical procedure utilized in this paper leads to the correct geometry and the associated tensile force (within an acceptable numerical margin of error).

4.2 Experimental

Liu (1981) conducted experiments on PVC tubes, each about 2.5-m long, filled either with water or mortar. The mortar-filled tubes were submerged in water. A transparent Plexiglas 'foundation' supported the tubes so that b could be measured accurately. Liu also traced the geometry of the tube. Figures 4, 5 and 6 show the measured points along the circumference versus the calculated geometry by program GeoCoPS. The three cases also correspond to the input data in Table 2; however, in the figures the comparison is restricted to Liu's experimental data.

Clearly, the agreement between predictions and measured data is very good. This increases the confidence in the practical value of the analysis and its associated numerical procedure and thus making the analysis and its associated program GeoCoPS suitable tools for designing geosynthetic tubes subjected to slurry pressure.

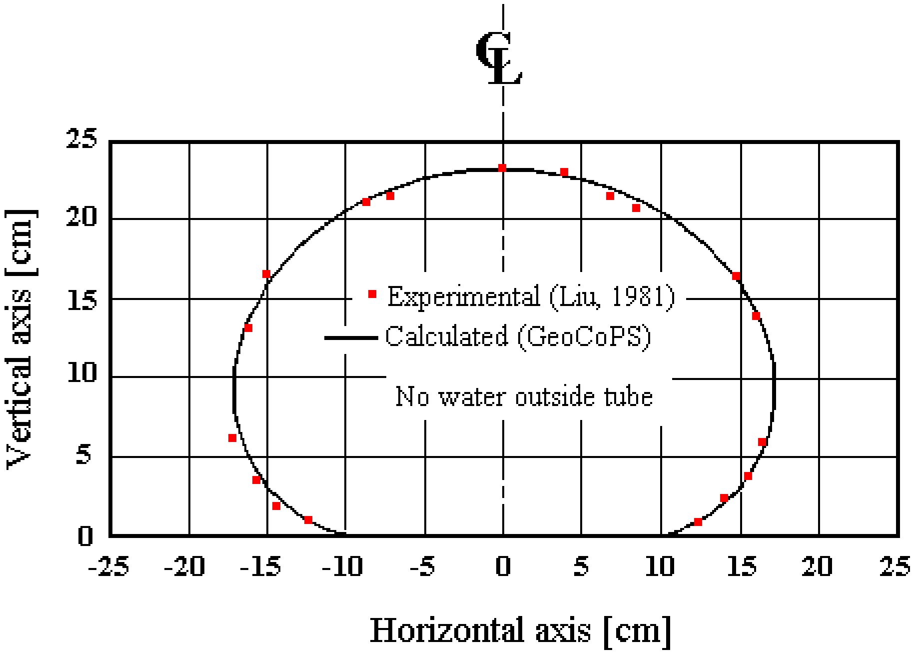


Figure 4. Measured Points Along Circumference Tube (Liu 1981) versus Computed Geometry by GeoCoPS (L=0.93m; $p=p_o+\gamma h$=3.86 kPa; $\gamma=\gamma_w$)

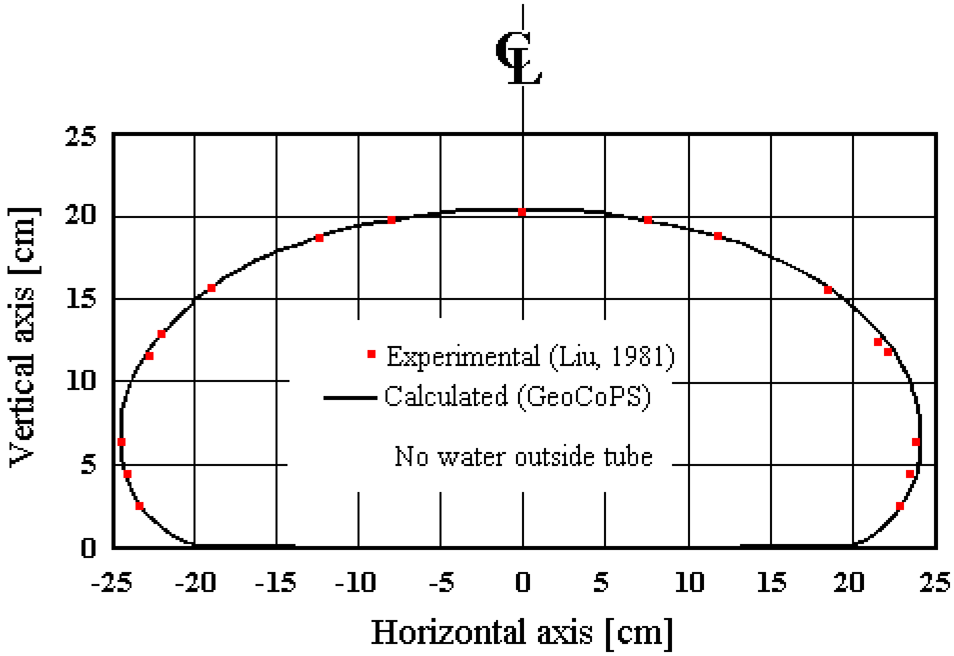


Figure 5. Measured Points Along Circumference Tube (Liu 1981) versus Computed Geometry by GeoCoPS (L=0.93m; $p=po+\gamma h$ =1.73 kPa; $\gamma_{slurry}=\gamma_w$)

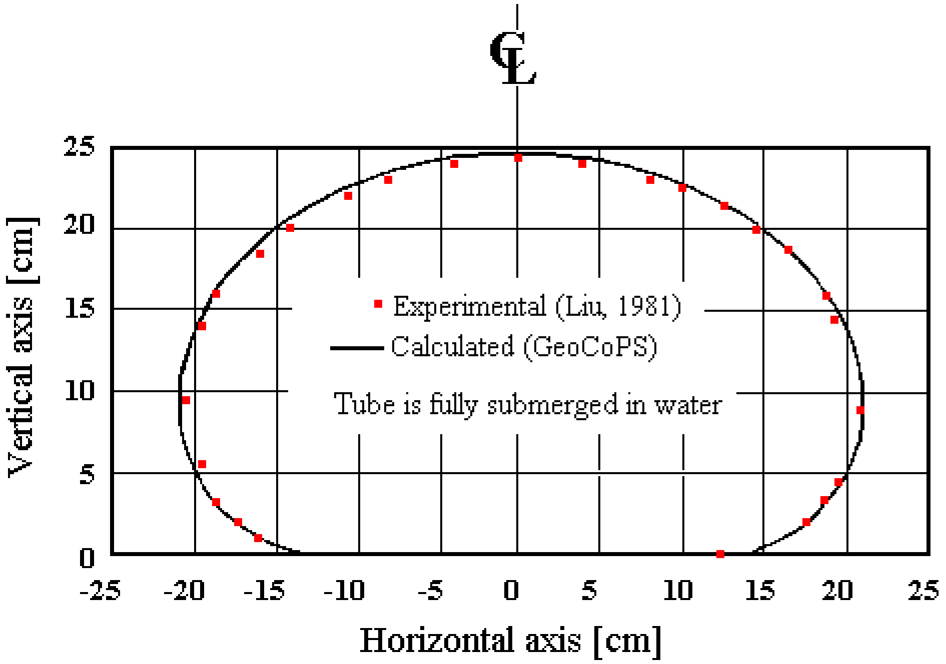


Figure 6. Measured Points Along Circumference Tube (Liu 1981) versus Computed Geometry by GeoCoPS (L=1.04m; $p=po+\gamma h$ =3.45 kPa; $\gamma_{slurry}=2\gamma_w$)

5.0 PARAMETRIC STUDY

To realize how sensitive the solution for the geosynthetic tube is with respect to the design parameters, a parametric study was conducted. This instructive study was conducted using program GeoCoPS. For all cases, the circumference of the tube was chosen as L=9 m (30 ft), the unit weight of slurry relative to water was taken as 1.2, no water outside the tube was considered, and all reduction factors on geosynthetic strength were set to 1.0.

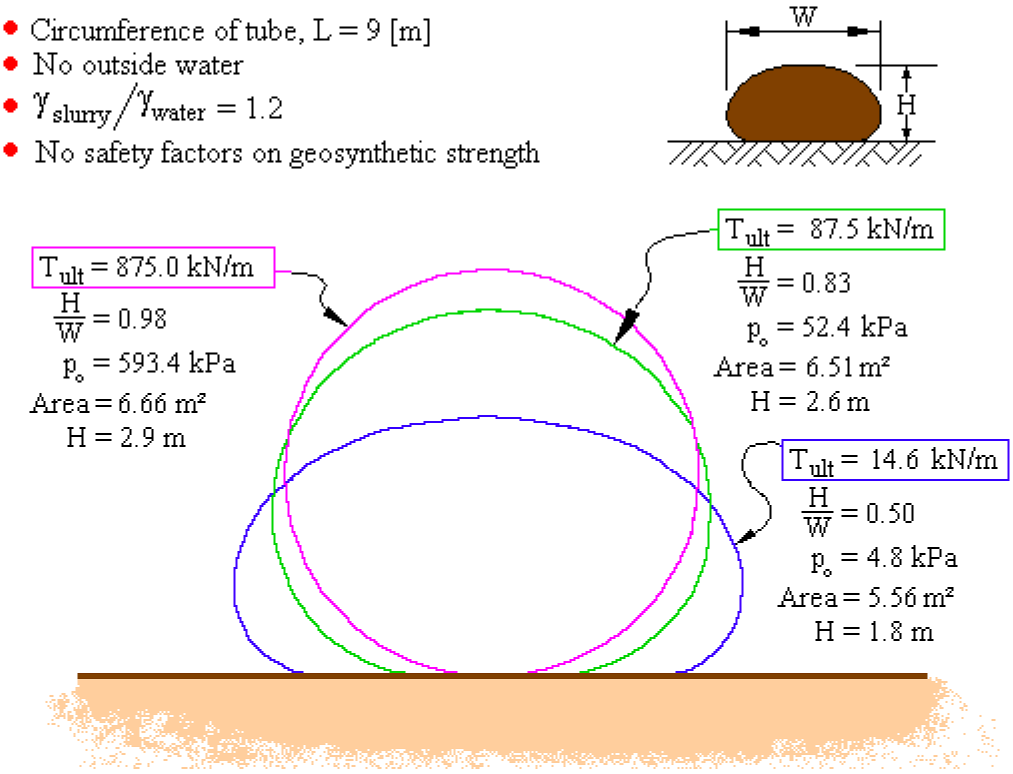


Figure 7. Effects of *Tult* on Geometry of Tube

Figure 7 shows the effects of the specified tensile force of the geosynthetic (circumferential strength) on the geometry of the tube. To get a perfect circular cross section, having a diameter equal to $D=L/\pi=2.9$ m, the required T (or p_o) must approach infinity. However, at T as low as 14.6 kN/m (1,000 lb/ft) the height h is 1.8 m. That is, h is 63% of the maximum theoretical height, D. Increasing T to 87.9 kN/m (6,000 lb/ft) will produce a height of 2.6 m or 89% of D. There is little influence on the cross-sectional area as the height changes. This has clear design implications if storage of a certain volume of slurry is needed.

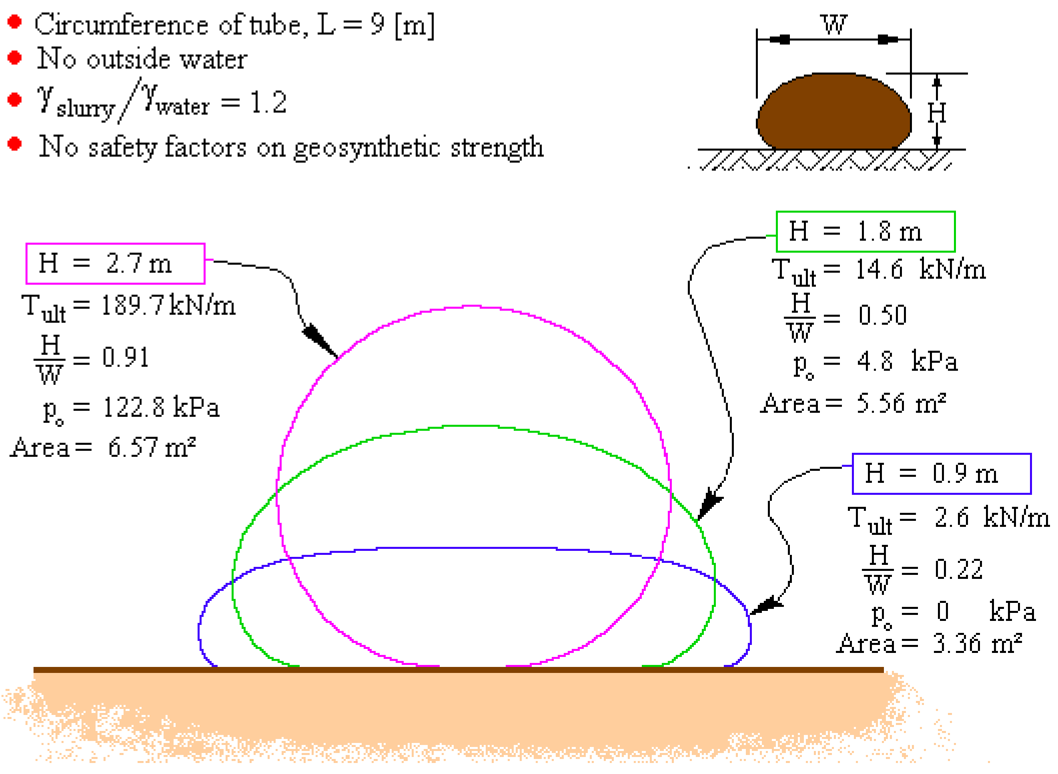


Figure 8. Effects of *H* on Geometry of Tube

Figure 8 illustrates the effects of a designed height h on the geometry of the tube. For a desired height of 0.9 m (about 31% of *D*), the required pumping pressure is nearly zero, and the required circumferential force is only 2.6 kN/m. However, for a desired height of about 94% of *D* (*h*=2.7 m), the required pumping pressure is about 122.8 kPa (17.8 psi), and the required circumferential force is substantially larger, approximately 190 kN/m.

Figure 9 depicts the effects of the pumping pressure on the geometry of the tube. It is apparent that at low pressures, a small increase in p_o will result in significant increase in height h. However, beyond a certain value (say, 35 kPa), the increase in height is insignificant (i.e., the tube's section approaches a circle) while the increase in required strength of geosynthetic is exponential. It should be noted that the pump pressure in a typical dredge line is quite high (300 kPa and more). Without an adequate field control, the pumping pressure may build up toward that of the pump and consequently, can rupture the encapsulating geosynthetic. Hence, to reduce the risk of excessive pumping pressure, a strict control of pressure at the tube's inlet is essential.

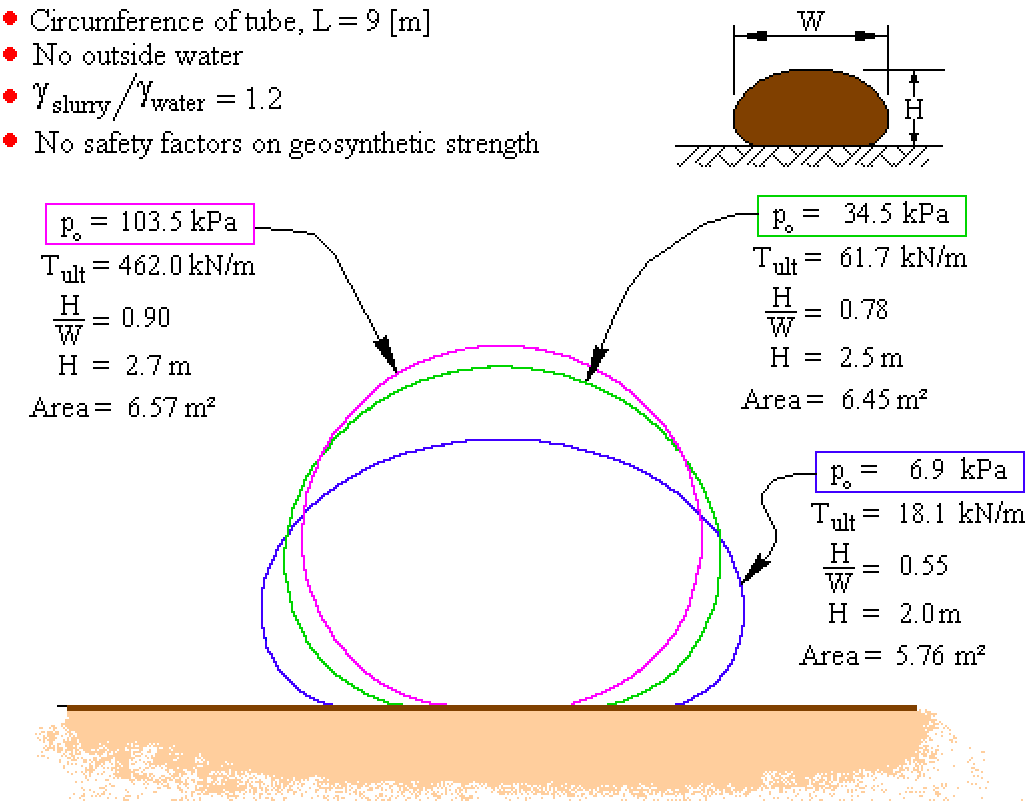


Figure 9. Effects of p_o on Geometry of Tube

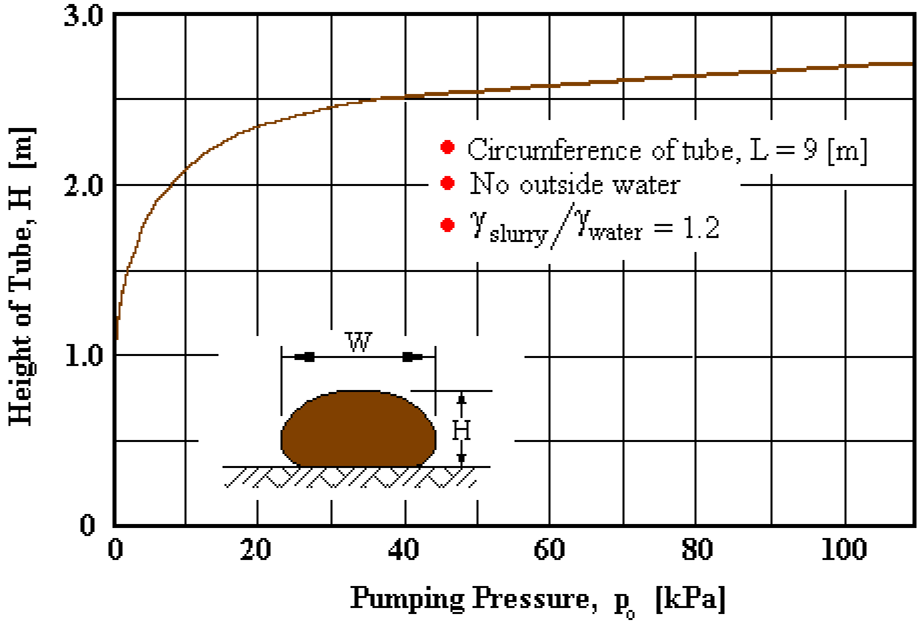


Figure 10. Height of Tube versus Pumping Pressure

Figure 10 demonstrates the relationship between the height of the tube and the pumping pressure. It can be seen that p_o is most significant at low pressures; as the pressure increases, its effect on h becomes negligible. At a pumping pressure of 35 kPa, 87% of the theoretical height is achieved. In fact, the relationship approaches an asymptote of $h=D$ that will be met only when p_o is at infinity.

Figure 11 illustrates the effects of pumping pressure on both T and T_{axial} For the selected parameters in the parametric study, it can be seen that as p_o decreases, the axial force approaches the value of the circumferential force. This figure is particularly instructive in the context of design; it illustrates the potential economy when selecting a geosynthetic having an anisotropic strength that correspond to both tensile forces T and T_{axial} when those are significantly different. Since these strengths must develop through the seams, one can also realize the critical importance of seam strength and efficiency.

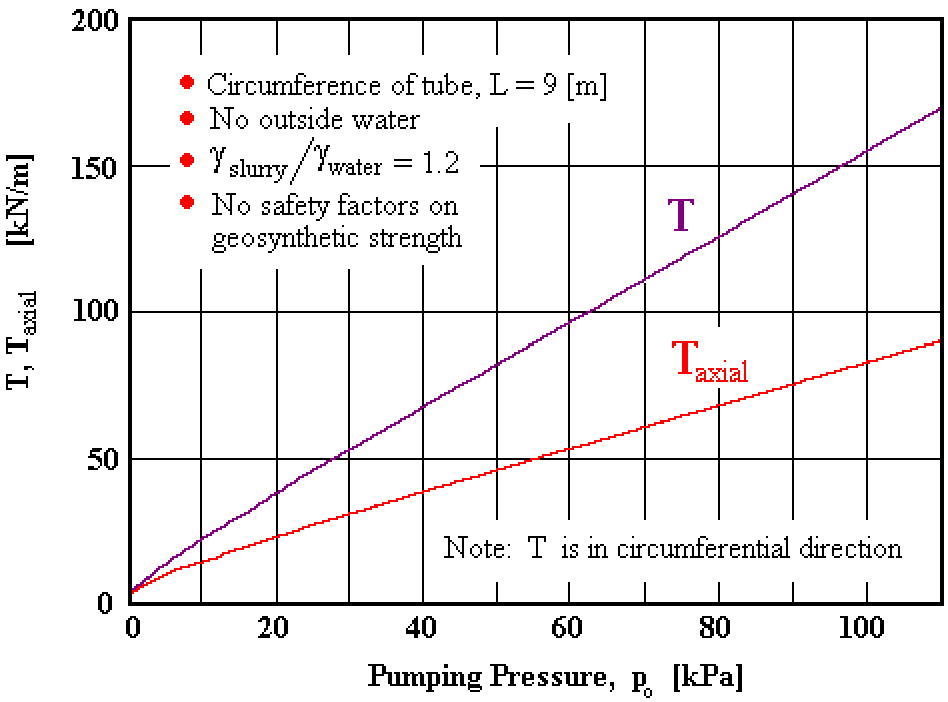


Figure 11. T and T_{axial} versus Pumping Pressure

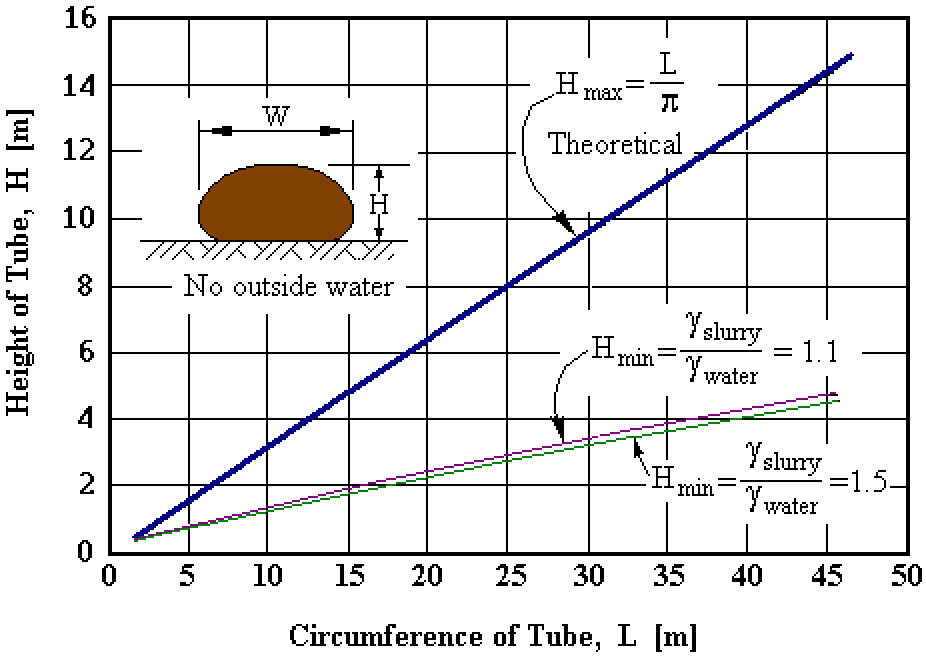


Figure 12. Extreme Values of Heights of Tube (No Water Outside)

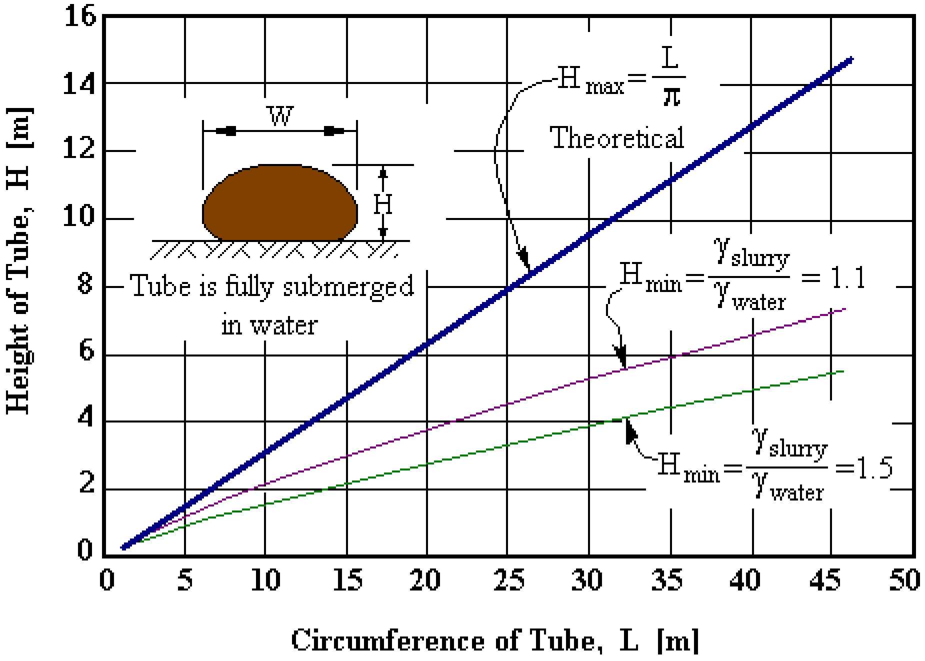


Figure 13. Extreme Values of Heights of Tube (Tube is Submerged in Water)

Finally, Figures 12 and 13 show the maximum theoretical height and minimum feasible height of a tube having a given circumference L. The maximum theoretical height, h_{max}, is equal to the diameter of a tube having a circular cross section and a circumference L. The minimum feasible height, h_{min}, was calculated using program GeoCoPS. It corresponds to a case where the pumping pressure is just zero. It signifies the limit for which the curvature of a segment along the top portion of the encapsulating tube is zero (i.e., no "sagging" of the tube occurs at its top). That is, within the accuracy limit of the numerical procedure used, the tube is turning flat at its top. A flat top geometry will render the mathematical solution of the problem of pressurized slurry tube invalid. Figures 12 and 13 also indicate the range of feasible heights for given circumferences. When the tube is not submerged (Figure 12), the slurry unit weight has negligible effects on h_{min}. However, full submergence (Figure 13) produces some limited effects on the minimum height. Also, h_{min} for the submerged tube is higher than for the non-submerged one. This is a result of reduction in effective stresses within the slurry as the tube becomes submerged. Reduced slurry stresses allow the tube to maintain a cross section that is nearly circular.

6.0 DESIGN CONSIDERATIONS

6.1 Geosynthetic Strength

The tube analysis renders the circumferential and axial force in the geosynthetic at working load conditions. However, to select a geosynthetic possessing adequate ultimate strength, practical factors should be superimposed on either calculated force. Program GeoCoPS uses the following reduction factors:

$$T_{ult} = T_{work}(RFid \cdot RFd \cdot RFc \cdot RFss) \cdots\cdots (12)$$

Where:

- T_{work} = the calculated tensile force in the geosynthetic at working load conditions, either in the circumferential direction ($T_{work} = T$) or in the axial direction ($T_{work} = T_{axial}$).
- RF_{id} = reduction factor for installation damage. In the context of tubes, this factor refers to an accidental increase of pumping pressure and therefore it could be termed also as a factor of safety for pumping pressure uncertainties, Fs-ppu. As shown in the parametric study, a slight increase of pressure beyond a certain value implies exponential increase in geosynthetic stresses. Field experience, however, indicates that excessive pumping pressure may occur as a result of poor control by the contractor. This excessive pressure may cause local rupture of the seam or of the geosynthetic in the vicinity of the seam. It is recommended to use a preliminary minimal value of RF_{id}=Fs-ppu=1.3.
- RF_{ss} = reduction factor for seam strength. Seam efficiency may be quite low for high-strength woven geotextiles. A minimum preliminary value of 2.0 is recommended. The exact value should be determined using the test specified in ASTM D 4884-90 (Standard Test Method for Seam Strength of Sewn Geotextiles); i.e., this test provides the seam efficiency and RF_{ss} is, by definition,

equal to 1/(seam efficiency). It should be noted that defective seam may render a geotextile tube somewhat ineffective, especially if slurry comprised of clayey soil is used (see Figure 14).

Figure 14. Local Rupture of Defective Seam Due to Slurry Pressure, Gaillard Island, Mobile, Alabama

- *RFd* = reduction factor for chemical and biological degradation. For typical slurry, most geosynthetics are inert. To verify whether a slurry may cause damage, the test specified in ASTM D 5322-92 (Standard Practice for Immersion Procedures for Evaluating the Chemical Resistance of Geosynthetics to Liquids) can be used as a guidance. However, to make the test meaningful, the actual slurry should be used. Furthermore, chemical degradation can be caused externally by a direct exposure to the sun (ultraviolet radiation, UV). To assess the tendency for such degradation, the test procedure specified in ASTM D 4355-92 (Standard Test Method for Deterioration of Geotextiles from Exposure to Ultraviolet Light and Water), can be used. Biological degradation does not seem to be a problem in most cases where tubes are used. Assuming that the geosynthetic is indeed chemically inert, that biological degradation is not an issue, and that the strength of the portions exposed to the sun is needed only during construction (and shortly after as the slurry solidifies), a minimum preliminary value of $RF_d = 1.0$ is recommended. It should be pointed out that most geosynthetics either contain carbon black or are inherently resistant to photo-oxidation and therefore, deteriorate slowly (typically years) when exposed to UV.
- RF_c = reduction factor for creep. It signifies the required reduction of the ultimate strength so that at the end of the designed life of the structure, the no rupture will occur. The creep behavior of a geosynthetic can be determined using the test specified in ASTM D 5262-92 (Standard Test Method for Evaluating the Unconfined Tension Creep Behavior of Geosynthetics). However, this factor

should be evaluated in the context of tubes and their applications. That is, maximum tensile force in the geosynthetic will be mobilized during pumping. After pumping, as the slurry solidifies, this force relaxes. Consequently, this maximum force will exist over a short period of time and a relatively small creep reduction factor can be assigned. Its value must assure that the tensile creep rupture strength (see ASTM D 5263-92 for definition) will be larger than T_{work} within the time this force exists (i.e., during pumping and shortly after, as the excess pore water pressure dissipates and the slurry solidifies). The minimum value of RF_c would depend on the type of polymer; it is recommended that the minimum preliminary value of RF_c for all polymers should exceed 1.5.

- T_{ult} = the ultimate strength of the required geosynthetic. Its value should be in the circumferential direction if $T_{work}=T$ is used in Equation 12. If $T_{work}=T_{axial}$ is used, then T_{ult} is in the axial direction. A geosynthetic possessing, at least, these ultimate strengths in its warp and fill directions, with correspondence to the circumferential and axial directions, should be specified. The ultimate strength should correspond to the test specified in ASTM D 4595-94 (Standard Test Method for Tensile Properties of Geotextiles by the Wide-Width Strip Method).

6.2 Geosynthetic Retention of Soil Particles

Typically, the geosynthetic encapsulating the slurry has to function also as a filter. That is, allow the fluid transporting the solids into the tube to drain slowly out while retaining the solid particles (i.e., perform as a 'cheese cloth'). As is the usual case with filters, the geosynthetic must possess two required properties that are opposing each other: be pervious and simultaneously, have a 'perfect' retention of solids. This perfect retention is particularly important in case contaminated soil is to be contained by the tube or when the tube is subjected to hydrodynamic forces associated with coastal environment. In such cases, filtration criteria that are stricter than those presented here may be needed.

Using the geosynthetic to retain the solid particles in the slurry necessitates compatibility between it and the solids in the slurry. Using ASTM D 4751-93 (Standard Test Method for Determining Apparent Opening Size of a Geotextile) gives the apparent opening size, AOS, of the geosynthetic. AOS (or $O95$) indicates the approximate largest solid particle that would effectively pass through the geosynthetic. Koerner (1994) provides an instructive table showing different design methods to assure the retention of a soil having a particular grain size distribution considering a given AOS. The method recommended here was developed by *Task Force #25*, AASHTO, and published in 1991:

1. For soil with 50% passing sieve No. 200: $O95 < 0.59$ mm (i.e., AOS sieve No. 30)
2. For soil with > 50% passing sieve No. 200: $O95 < 0.30$ mm (i.e., AOS sieve No. 50)

Consequently, upon using conventional test to determine the distribution of grain size of the slurry, one can specify the maximum allowed AOS of a geosynthetic. It should be noted that when the slurry is comprised of clayey soils, experience indicates (Leshchinsky, 1992) the passage of particles through the geotextile rapidly stops while water continue to seep clean outside. In case of contaminated slurry, however, the

AOS criteria may have to be modified to assure a truly perfect retention. Such modification can be done through experiments simulating the insitu conditions.

Using the on-site slurry, one can evaluate whether the selected geosynthetic will not clog. This performance feature can be determined using ASTM D 5101-90 (Standard Test Method for Measuring the Soil-Geotextile System Clogging Potential by the Gradient Ratio). Typically, clogging should not be a problem if the *AOS* criteria were used in selecting a geosynthetic. If, however, the slurry will result in a biological activity on the geosynthetic, the clogging potential then can be evaluated using ASTM D 1987-91 (Standard Test Method for Biological Clogging of Geotextile or Soil/Geotextile Filters). Biological activity is typically a long-term concern whereas the filtration capacity in a tube is usually a short-term (a few months) issue.

It is quite possible that the conflicting requirements of 'perfect' particles retention and high permeability, combined with a required high-strength material, will result in a geotextile that is not available in the market. In this case, a nonwoven geotextile can be used as a liner to retain the fine particles. The outside geosynthetic can then be a high-strength woven (and very pervious) geotextile. This combination will produce an acceptable encapsulating material. Furthermore, the nonwoven geotextile will also serve as a safety feature in case of a locally defective seam as the one shown in Figure 14. The cost of nonwoven geotextile liner is quite low as compared with the cost of high-strength woven geotextile.

6.3 Consolidated Height of Tube

After the pumping and as the slurry consolidates (i.e., solidifies), experience indicates that the height of the tube drops while its maximum width increases very little. The drop in height can be very significant, especially when fine soil slurry is pumped in. The following approximate procedure allows for an estimate of the average drop in height once a certain density of the fill material is achieved.

Assuming the solidified slurry is fully saturated (S=100%) and using basic volume-weight relationships, it can be shown that:

$$\omega_o = \frac{G_s - \frac{\gamma_{slurry}}{\gamma_w}}{G_s\left(\frac{\gamma_{slurry}}{\gamma_w} - 1\right)} \quad \cdots\cdots\cdots\cdots (13)$$

and

$$\omega_f = \frac{G_s - \frac{\gamma_{soil}}{\gamma_w}}{G_s\left(\frac{\gamma_{soil}}{\gamma_w} - 1\right)} \quad \cdots\cdots\cdots\cdots (14)$$

where ω_o and ω_f are the initial and final water content of the fill material, respectively; G_s is the specific gravity of solids (constant for same soil particles regardless of change in water content); γ_{soil}, γ_{slurry} and γ_w are the unit weights of the soil (solidified slurry), slurry and water, respectively.

Assuming the consolidating material is moving only downwards (i.e., one-dimensional movement; negligible lateral movement especially when compared with the vertical drop) and making use of the relationship *[*$\Delta e/(1+e_o)$*]*$=\Delta h/h_o$, the following equation is obtained:

$$\frac{\Delta h}{h_o} = \frac{G_s(\omega_o - \omega_f)}{1 + \omega_o G_s} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (15)$$

where Δh and h_o are the decrease in height of tube and initial height of tube, respectively.

Combining Equation 13, 14 and 15, one can estimate the drop in the height of the tube as the material inside densifies. Figure 15 illustrates the result of combining these equations, assuming G_s=2.70. Note, for example, that when a slurry having (γ_{slurry}/γ_w)=1.1 consolidates to (γ_{soil}/γ_w)=1.2 (i.e., 9% increase in density), the resulted decrease in height is about 50%. Experience indicates (e.g., Leshchinsky, 1992) that when fine grain material is pumped in, the tube will drop about 50% in height within about a month. At this stage, a solid soil is formed over which a person can walk. If the objective is to form a tube of a certain desired height, than additional slurry can be pumped in. This process can be repeated until the final desired height is attained. Alternatively, pumping sand (or soil with more than 50% of the particles greater than sieve No. 200) will result in final tube dimensions acceptable typically after only one pumping.

7.0 CONCLUSION

An overview of analysis to calculate the geometry and stresses of a geosynthetic encapsulating pressurized slurry has been presented. The validity of the numerical procedure utilized to solve the resulted equations has been verified against numerical and experimental results obtained by other investigators.

Parametric studies indicate that stresses in the encapsulating geosynthetic are very sensitive to the pumping pressure. Consequently, during construction it is extremely important to safeguard against accidental increase in the slurry pumping pressure. The parametric studies also reveal that a significant increase in pumping pressure will only slightly increase the tube's cross sectional area and hence, its storage capacity.

A guide to selecting a geosynthetic is provided. It is based on reduction factors. These reduction factors address the seam strength (i.e., the 'weak link'), potential installation damage (i.e., accidental increase in pumping pressure), treachery creep, and possible chemical and biological degradation. Also addressed is the required permeability of the geosynthetic so as to perform as a filter; i.e., drain the fluid while retaining the solid particles. Finally, a simple procedure to assess the final height of a tube filled up with clayey slurry is proposed.

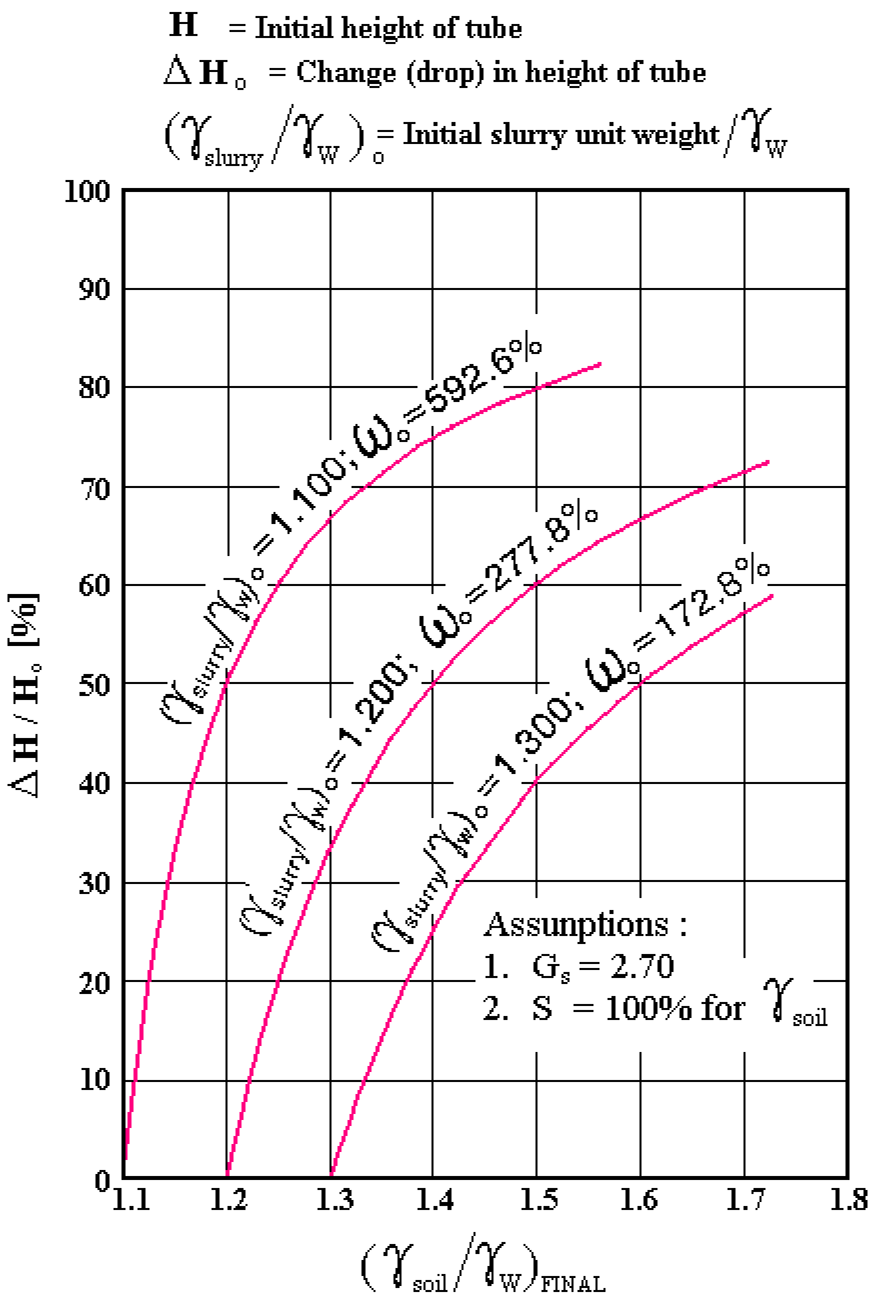


Figure 15. Drop in Height of Tube as Function of Density of Soil

It should be pointed out that complete design of geosynthetic tubes has to also include the head loss occurring as the slurry flows away from the inlet. This aspect of design, which will determine either the maximum length of a tube or the distance between inlets along the tube, has not been addressed.

8.0 ACKNOWLEDGMENTS

This work resulted from research conducted under the Construction Productivity Advancement Research (*CPAR*) program partially sponsored by the U.S. Army Corps of Engineers. The authors appreciate the constructive review provided by the anonymous reviewers and the ASCE Publication Committee Member; their promptness is commended.

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