Geotechnical Engineering Journal of the SEAGS & AGSSEA Vol. 42 No.1 March 2011 ISSN 0046-5828

Geosynthetic Tubes and Geosynthetic Mats: Analyses and Applications

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ABSTRACT: In recent years, there has been an increasing use of geotextile or geosynthetic materials for the construction of river or coastal structures. In this paper, a review of different applications of geotextile or geosynthetic tubes and geosynthetic mats is presented. The types of geotextile or geosynthetic tubes and geosynthetic mats are classified. A summary of different analytical methods for geosynthetic tubes is also provided. So far, there are few analytical or numerical methods available for geosynthetic mats as it is a relatively new technique. Several new analytical or numerical methods have therefore been developed recently for geosynthetic mats. Some of these methods are presented in this paper.

1. INTRODUCTION

As a counter measure against river and coastal related disasters in recent years, there has been an increasing use of geotextile and geosynthetic materials for river and coastal construction. Rubber dam, geotextile or geosynthetic tube, and more recently geosynthetic mats (or geomats) are a few examples. As dikes or other types of coastal protection structures normally extend longitudinally over a long distance, a small improvement in the design could result in a significant amount of saving. Therefore, it will have a great economical benefit if a more cost-effective method could be established. In this paper, the applications of geosynthetic tubes and geosynthetic mats for the construction of river or coastal protection structures are reviewed. The methods for the analysis of geosynthetic tubes and geosynthetic mats are summarized. A few new analytical or numerical methods for geosynthetic mats are also introduced.

The geosynthetic tube method has been used for hydraulic and coastal engineering projects for a long time. For engineering design of geosynthetic tubes, a number of analytical methods have also been proposed. Among these methods, almost all are proposed based on some simplified assumptions and therefore are applicable only to certain conditions. For this reason, it is necessary to classify the types of geosynthetic tubes and provide a critical review on the applicability of each analytical method to each type of geosynthetic tubes. Part of the work is reported in this paper.

Geosynthetic tubes or geosynthetic mats can be grossly classified into three categories: permeable geosynthetic tube or mat, impermeable geosynthetic tube or inflatable rubber dam according to the fill materials, the materials used for the tubes and the types of base, as listed in Table 1. References for examples of applications of each type of geosynthetic tubes or geosynthetic mats are also given in Table 1.

2. APPLICATIONS

The traditional method of constructing shoreline structures is to use rock or precast concrete units. In recent years, several methods have been developed to use geotextile or geosynthetic materials for the construction of coastal structures such as breakwaters and dikes. One of them is to use geotextiles acting as formwork for cement mortar units cast in situ (Silvester and Hsu, 1993). Water or air inflated rubber bags or rubber dams have also been used to provide a flexible and sometimes temporary barrier (Zheng et al., 2002; Chu et al., 2009). A difference between rubber dams and impermeable geosynthetic tubes is that the former is normally supported and anchored on to a permanent concrete base. One example of rubber dam is shown in Fig. 1 which is used for adjusting the water level in a river for flood control or irrigation purposes in China. Rubber dams have also been used for relatively large scale projects in recent years. One of the largest so far is the rubber dam used for the Ramspol storm surge barrier in Netherlands. To protect West Overijssel, a province in The Netherlands, against flooding due to high water at the Jsselmeer and Ketelmeer, a storm surge barrier has been constructed. The barrier uses three identical inflatable rubber dams. The dimensions of each rubber dam are 75 m long, 13 m wide and a design height of 8.35 m. A unique feature of this project is that a combination of air and water was used as the inflation medium. This minimized the dimensions of the rubber body and also allowed the height of the dam to be adjusted quickly. More information on this project can be found in (Jongeling and Rövekamp, 1999).

Figure 1. A rubber dam crossing a river

Similar methods, but using sand or clay slurry as fill materials, have also been used for dike construction (Kazimierowicz, 1994; Miki et al., 1996; Leshchinsky et al., 1996). Sand or sandy soil is the most ideal fill material for this purpose. For near shore or offshore project, a suction dredger can be used to pump sand from the seabed or a sand pit directly into the geosynthetic tubes. One example is shown in Fig. 2 where sand filled geosynthetic tubes were used for shoreline protection. When sand fill is not readily available, silty clay or soft clay may also be used. In this case, the clayey fill would have to be in a slurry state in order to be pumped in the tube. The slurry then has to be dewatered in the geosynthetic tube or geosynthetic mat to reduce the water content and allow excess pore pressures to dissipate. In this case, the selection of the geotextile used for the tubes or mats becomes important. The geotextile has to be chosen to meet both the strength and filter design criteria. Some analytical methods have been developed to estimate the required tensile strength for the geotextile (e.g., Kazimierowicz, 1994; Miki et al., 1996). The apparent opening size (AOS) of the geotextile needs to be selected to allow the pore pressure to dissipate freely and yet retain the soil particles in the geosynthetic tubes or geosynthetic mats.

Figure 2. Use of sand filled geotextile tubes for shoreline protection in Malaysia (after Lee, 2009)

Table 1. Classification of Geosynthetic Tubes

Type	Material for tube	Fill material	Applications
Impermeable Geosynthetic Tube	Very low permeability liner or fluid containment materials requiring high tensile strength made of Butyl Rubber, EPDM Rubber, PVC, Polypropylene, Polyurethane, and Elvaloy	Water, clay slurry, sludge or other waste materials	Flood control (Fowler, 1997; Plaut and Suherman, 1998); Contain contaminated materials (Szyszkowski and Glockner, 1987); Form "working table"; Beach erosion Control; Breakwater (Alvarez et al., 2007); Water level control (Sehgal, 1996); Water Divertion (Tam, 1997)
Permeable Geosynthetic Tubes or Mats	Woven or non-woven geotextile, usually made of synthetic polymers-polypropylenes, polyesters, polyethylene, and polyamides with high tensile strength, high geotextile permeability and good soil retention characteristics.	Mainly sand, clay slurry, cement mixed clay. Mortar has also been used	Dikes (Fowler, 1997; Yan and Chu, 2005); Underwater breakwater (Kim et al., 2004); Beach restoration (Oh and Shin, 2006; Alvarez et al., 2007); Coastal erosion prevention (Koerner and Koerner, 2006; Shin and Oh, 2007); Dewatering contaminated high water content waste (Fowler et al., 1996; Perry, 1993).
Inflatable Rubber Dam	High strength synthetics, such as macromolecule compound materials. A permanent concrete base is normally used.	Water and/or air	Small dams (Sehgal,1996; Zhang et al. 2002); Height elevation for existing dams or spillways; Water diversion (Tam, 1997); Recreational basins; Contamination prevention, Groundwater supply; Hydroelectricity; Tidal control or flood control (Watson et al.,1999)

One technique of using clay slurry fill geosynthetic mats for dike construction was developed in Tianjin, China, and used for one land reclamation project along the coast of Tianjin (Chu and Yan, 2007; Yan and Chu, 2010). The cross-section of the dike is illustrated in Fig. 3 and a picture showing the alignment of the bags is shown in Fig. 4. It can be seen that large flat geotextile bags in the form of geosynthetic mats, instead of geosynthetic tubes, were adopted for this project. As shown in Fig. 3, the designed height of the dike was 4.8 m with base and top elevations at 0.7 m and 5.5 m respectively. The top width of the dike was 2.43 m. The water levels were at 4.7 m elevation during high tide and at nearly 0.7 m elevation during low tide. The outer and inner slopes of the dike were chosen to be 2L:1H and 1.5L:1H, respectively. For the bottom bag, the dimension used was 30 m in circumference. Clay slurry was dredged from the seabed of a selected area and pumped directly into the bags through an injection hole. The height of the bag after consolidation was around 0.5 m. Nine layers of geosynthetic mats were used.

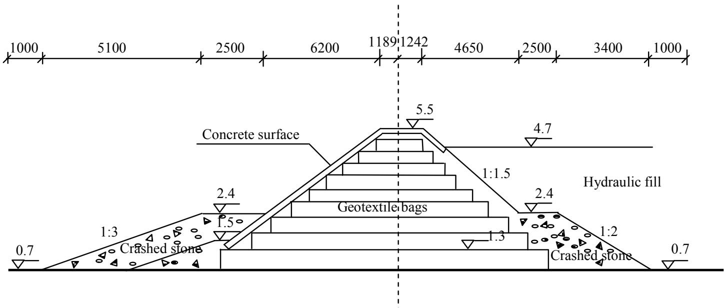


Figure 3. Schematic illustration of a dike made of clay slurry filled geotextile bags

Figure 4. Dike constructed using clay slurry filled geosynthetic mats

The dike built with the large size geosynthetic mats was then protected by casting a 25 mm thick grouted geotextile mattress on top of the surface after the settlement of dike stabilized. The grouted geotextile mattress was formed by pumping lean concrete into a mould made of geotextile. Berms were used to enhance the stability of the dike and to protect the toes of the slopes. A more detailed description of this method can be found in Yan and Chu (2010).

There are a number of advantages for using mats for dike construction. Firstly, as the lateral dimension is very large comparing to its height, geosynthetic mat has no laterally stability problems. Secondly, construction can also be speedier as pumping can be carried out at a number of points. Thirdly, the dike made of geosynthetic mats can accommodate relatively large differential settlement. This may result in savings in the foundation treatment. Despite of the various advantages, there is a lack of design or analysis method for dikes constructed using this method. To overcome this problem, some analytical methods are being developed. Finite element methods have also been used. Some of these methods are presented in the next section.

3. EXISTING ANALYTICAL METHODS

Various analytical or numerical methods have been proposed for the analysis of different types of geosynthetic tubes. A summary of some of the analytical methods for rubber dam and impermeable geosynthetic tubes on rigid foundation are given in Tables 2 and 3, respectively. For rubber dams, the tube is normally fixed to a rigid concrete base, whereas a geosynthetic tube is resting on foundation soil. Therefore, the analytical methods adopted for rubber dams and impermeable geomembranes are different. The differences among the different analytical methods are mainly in the assumptions which are listed in both Tables 2 and 3.

The analysis for permeable geosynthetic tube is more difficult as a consolidation process is involved. At present, there is no suitable theoretical method to analyze the consolidation process of tube after it is filled. Most of the existing solutions are to calculate the critical dimension of cross section after the geosynthetic tube is filled. The axis tension force will also be the largest at this state. Leshchinsky et al. (1996) used volume-weight relationships to calculate the height variation of the geotexile tube by assuming that the width of the geotextile tube does not change during consolidation process. Shin and Oh (2004) presented a new approach to calculate the consolidation process of geotexile tube called the settling and self-weight consolidation method. They separates the consolidation process into four basic processes, namely dispersed free settling, flocculated free settling, zone settling, and consolidation settling. Because the first two processes were difficult to calculate, the authors only gave the calculation methods for the zone settling and self-weight consolidation processes. The details of these analytical methods are summarized in Table 4.

4. NEW METHODS FOR IMPERMEABLE GEOSYNTHETIC TUBE AND GEOSYNTHETIC MAT

4.1 Closed Form Solutions for Geosynthetic Mat on Rigid Foundation

A geosynthetic mat is different from a geosynthetic tube as its horizontal dimension is much greater than the vertical one which makes it more stable than the sausage shaped geosynthetic tube. The existing analytical or numerical methods developed for the sausage shaped geosynthetic tube may not be always applicable directly to geosynthetic mat as the solution may not converge when the ratio between the height and width of the tube is very small as is typically the case for geosynthetic mats. As an approximation, a closed form solution for geosynthetic mat can be derived with the following assumptions:

(1) The problem is two-dimensional (2D) (i.e., plane strain) in nature;

(2) The geosythetic shell is thin, flexible. Its weight and extension is neglected;

(3) Frictions between the fill and geotextile and between the geosynthetic mat and foundation are negligible;

(4) The tensile stress of the geotextile along its circumference is constant;

(5) All the geosynthetic mats are filled with the same material and no water pressure is applied externally.

The detailed derivation is presented elsewhere (Guo, 2009). The solution is given below:

$$\begin{cases} x = 0, \quad y = 0 \\ x \neq 0, \quad y = H[\sqrt{1 - \dfrac{x^2}{H^2}} - \dfrac{1}{2}\ln(\dfrac{H}{x} + \sqrt{\dfrac{H^2}{x^2} - 1}) \\ \qquad + \dfrac{1}{2}(\dfrac{1}{k} - \sqrt{2} + \ln(\sqrt{2}+1))] \end{cases} \tag{1}$$

$$A = H^2(\frac{1}{k} - (\sqrt{2} - \ln(\sqrt{2}+1))) \tag{2}$$

$$L = 2H(\frac{1}{k} + 1 - (\sqrt{2} - \ln(\sqrt{2}+1)) \tag{3}$$

$$b = H(\frac{1}{k} - (\sqrt{2} - \ln(\sqrt{2}+1)) \tag{4}$$

$$T = \frac{1}{4}\gamma H^2 \tag{5}$$

where: k = height to width ratio and $k = H/B$;
H = height of geosynthetic mat,
A = cross-section area
L = perimeter of cross-section;
b = contact width with the ground;
T = tensile force along the geotextile sheet.

The above solution gives the geometry of the cross-section of the mat. The unit weight of the filling liquid γ, height and width of cross-section of designed geosynthetic mat are taken as input parameters. The tensile force along the geotextile sheets, the area and perimeter of cross-section can be calculated using Eq. (2) to Eq. (5).

As an example, the cross-sections of geosynthetic mats are calculated and plotted in Fig. 5 using the closed-form equations for a filled height of 1 m with the height to width ratio, *k*, of 0.1, 0.125 and 0.163 respectively. In the calculation, the unit weight of the filling liquid was assumed as 12 kN/m^3.

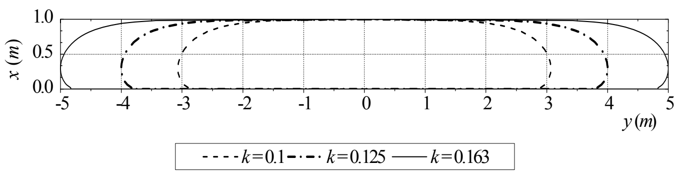
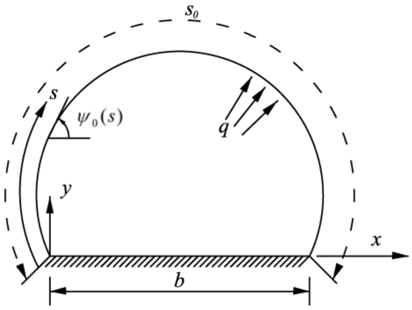
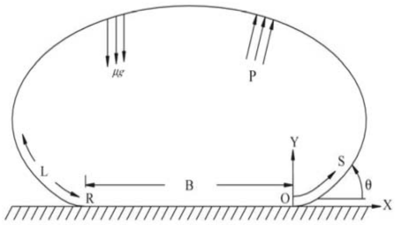
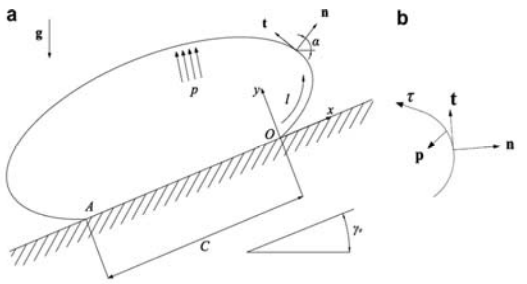


Figure 5. Changes in the cross-section of geosynthetic mat with height to width ratio, k, (for γ = 12 kN/m^3, H = 1 m, k= 0.1, 0.125 and 0.22 respectively)

Table 2. A list of analytical methods for rubber dam on rigid base

Method	Notation	Calculation Profile	Assumptions
Hsieh and Plaut (1989, 1990)	Water filled rubber dam resting on rigid base	Where: x, y is the horizontal and vertical coordinate; *s* is the arc length from the origin; s_0 is the perimeter; b is the base length; the angle between the horizontal and the membrane tangent is $\psi_0(s)$.  $\begin{cases} T_1 \dfrac{d\psi_0}{ds} = \gamma(y-h) \\ \dfrac{dx}{ds} = \cos\psi_0, \dfrac{dy}{ds} = \sin\psi_0 \end{cases}$ Where, T_1 is the tension and constant along the circle; *h* is the internal pressure head; γ is the specific weight of liquid.	• The geomembrane tube is 2D (plane strain) problem; • The membrane is anchored along two of its generators to a rigid horizontal base; • The filling liquid is incompressible and uniform with a specific unit weight; • The membrane is inextensible and negligible weight; • The friction between tube and foundation was neglected. No shear stresses develop between the slurry and the geosynthetic.
Plaut and Cotton (2005)	Dynamic quantities of air filled rubber dam	Where, θ is the angle between tangent and *horizontal*; s is arc length; L is the total perimeter; B is the contact width; P is internal air pressure; μ is the mass per length of the tube; Q is the tension along the tube;  Subscripts *e* and *d represents* equilibrium and dynamic quantities, respectively. The parameters are non-dimensional with $x = X/L, y = Y/L, q = Q/\mu g L^2, \sigma = S/L, \varpi = \Omega\sqrt{L/g}$ $\begin{cases} \dfrac{dx_d}{ds} = -\theta_d \sin\theta_e \\ \dfrac{dy_d}{ds} = -\theta_d \cos\theta_e \\ \dfrac{d\theta_d}{ds} = \dfrac{1}{q_e}[\varpi^2(x_d \sin\theta_e - y_d \cos\theta_e) - \theta_d \sin\theta_e - q_d \dfrac{(p+\cos\theta_e)}{q_e}] \\ \dfrac{dq_d}{ds} = -\varpi^2[\varpi^2(x_d \cos\theta_e + y_d \sin\theta_e) + \theta_d \cos\theta_e] \end{cases}$	• The tube was filled with air and its weight was considered. • The foundation is rigid and friction with tube is neglected; • The membrane is inextensible and with no bending stiffness;
Ghavanloo, and Daneshmand (2009a)	Air filled rubber dam resting on inclined rigid plane base	 Where, L is the total perimeter; C is the contact width between tube and inclined plane; P is internal air pressure; μ is the mass per length of the tube; t is the tension along the tube; $\begin{cases} x = -\tau_0(1+p)\int_{-\frac{\pi}{2}}^{\alpha} \dfrac{\sin(\delta-\gamma_0)}{(p-\sin\delta)^2} d\delta \\ y = -\tau_0(1+p)\int_{-\frac{\pi}{2}}^{\alpha} \dfrac{\cos(\delta-\gamma_0)}{(p-\sin\delta)^2} d\delta \\ \tau_0 = [(1+p)(\int_{-\frac{\pi}{2}}^{\frac{3\pi}{2}} \dfrac{1+\sin(\delta-\gamma_0)}{(p-\sin\delta)^2} d\delta)]^{-1} \end{cases}$ Where, The parameters are non-dimensional with $x=X/L$, $y=Y/L$, $p=P/\lambda g$, $\varpi = \Omega\sqrt{L/g}, \tau = \tau/\lambda g L$	• The geomembrane tube is 2D (plane strain) problem and filled with air; • The membrane is inextensible and with no bending stiffness; • The tangential strain of tube equals to zero; • The internal air pressure is assumed constant within the cross section area.

<table>
<tr>
<td rowspan="2">Ghavanloo, and Daneshm (2009b)</td>
<td>Air filled rubber dam resting on straight line rigid base</td>
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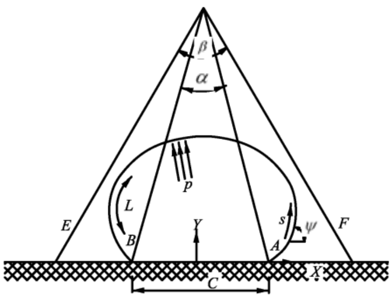

$$\begin{cases} x(s)=\dfrac{p}{2(\pi-\psi_0)(p+1)}[\sin(\dfrac{2(\pi-\psi_0)(p+1)s}{p}+\psi_0)-\sin\psi_0]+\dfrac{1}{2(p+1)} \\ y(s)=\dfrac{p}{2(\pi-\psi_0)(p+1)}[\cos\psi_0-\cos(\dfrac{2(\pi-\psi_0)(p+1)s}{p}+\psi_0] \end{cases}$$

where, x, y is the horizontal and vertical coordinate; *p* is the internal pressure; ψ_0 is the tangent *angle* at lift-off point; s is arc length.
</td>
<td rowspan="2">
The shape function of rigid foundation *f(x)* should satisfy the following conditions:

- *f*(*x*) is even function in (-*H*,*H*); it is symmetric with *Y* axis;
- *f*(*x*) must be at least twice difference on (-*H*,*H*);
- $f'(x)\geq 0$

The assumption of this paper:

- The tube is 2D (plane strain) problem and filled with air;
- The membrane is inextensible and with no bending stiffness;
- The tangential strain of tube equals to zero;
- The internal air pressure is assumed constant within the cross section area.
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<tr>
<td>Air filled rubber dam resting on trapezoidal rigid base</td>
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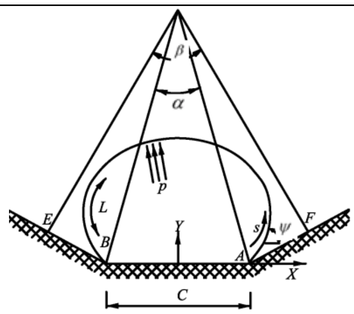

Where the shape function of trapezoidal shaped rigid foundation is defined as:

$$f(x)=-ax-\frac{ab}{2},\text{ if }\frac{-\text{b}}{2}\geq x;\ 0,\text{ if }\frac{-\text{b}}{2}\leq x\leq\frac{\text{b}}{2};\ ax-\frac{ab}{2},\text{ if }x\geq\frac{\text{b}}{2}$$

if $p<p_0$

$$\begin{cases} x(s)=\dfrac{p(1-b+b\sqrt{1+a^2})}{2(\pi-\psi_0)(p+\sqrt{1+a^2})}[\sin(\dfrac{2(\pi-\psi_0)(p+\sqrt{1+a^2})s}{p(1-b+b\sqrt{1+a^2})}+\psi_0) \\ \qquad -\sin\psi_0]+\dfrac{1+b(\sqrt{1+a^2}-1)}{2(p+\sqrt{1+a^2})} \\ y(s)=\dfrac{p(1-b+b\sqrt{1+a^2})}{2(\pi-\psi_0)(p+\sqrt{1+a^2})}[\cos\psi_0-\cos(\dfrac{2(\pi-\psi_0)(p+\sqrt{1+a^2})s}{p(1-b+b\sqrt{1+a^2})} \\ \qquad +\psi_0)]+\dfrac{a(1-b-pb)}{2(p+\sqrt{1+a^2})} \end{cases}$$

if $p\geq p_0$

$$\begin{cases} x(s)=\dfrac{p}{2(\pi-\psi_0)(p+1)}[\sin(\dfrac{2(\pi-\psi_0)(p+1)s}{p}+\psi_0) \\ \qquad -\sin\psi_0]+\dfrac{1}{2(p+1)} \\ y(s)=\dfrac{p}{2(\pi-\psi_0)(p+1)}[\cos\psi_0-\cos(\dfrac{2(\pi-\psi_0)(p+1)s}{p}+\psi_0] \end{cases}$$

where, x, y is the horizontal and vertical coordinate; *p* is the internal pressure; p_0 is limit pressure defined as the pressure a t which the contact width equal to b; ψ_0 is the tangent angle at lift-off point; s is arc length.
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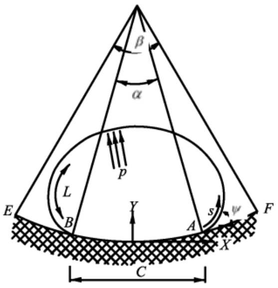
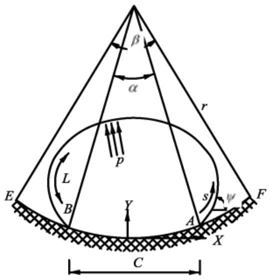
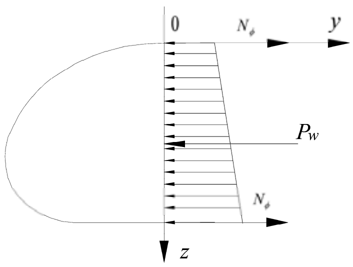
Ghavanloo, and Daneshm (2009b)	Air filled rubber dam resting on parabolic rigid foundation	 Where the parabolic function can be presented by the simplest form, $f(x) = X^2$. $\begin{cases} x(s) = \dfrac{(1-[\frac{c}{2}\sqrt{1+c^2}+0.5\ln(c+\sqrt{1+c^2})])}{2(\pi-\psi_0)} \cdot \\ \quad [\sin(\dfrac{2(\pi-\psi_0)s}{(1-[\frac{c}{2}\sqrt{1+c^2}+0.5\ln(c+\sqrt{1+c^2})])}+\psi_0)-\sin\psi_0]+\dfrac{c}{2} \\ y(s) = \dfrac{(1-[\frac{c}{2}\sqrt{1+c^2}+0.5\ln(c+\sqrt{1+c^2})])}{2(\pi-\psi_0)}[\cos\psi_0 - \\ \quad \cos(\dfrac{2(\pi-\psi_0)s}{(1-[\frac{c}{2}\sqrt{1+c^2}+0.5\ln(c+\sqrt{1+c^2})])}+\psi_0)]+\dfrac{c^2}{4} \end{cases}$	
	Air filled rubber dam resting on circular rigid foundation	 Where r is radius of this circular foundation; α is central angle of the contact arc; β is the central of this rigid base. $\begin{cases} x(s) = \dfrac{1-r\alpha}{2(\pi-\psi_0)}[\sin(\dfrac{2(\pi-\psi_0)s}{1-r\alpha}+\psi_0)-\sin\psi_0]+\dfrac{r\sin(\frac{\alpha}{2})}{2} \\ y(s) = \dfrac{1-r\alpha}{2(\pi-\psi_0)}[\cos\psi_0-\cos(\dfrac{2(\pi-\psi_0)s}{1-r\alpha}+\psi_0)]+r(1-\cos(\dfrac{\alpha}{2})) \end{cases}$	

Table 3. A list of analytical methods for impermeable geosynthetic tube on rigid foundation

Method	Calculation Profile	Assumptions
Kazimirowicz (1994)	 Where r=radius of curvature, N_Φ=Tensile force; p_r=Hydraulic water pressure. Case A ($p_0 >> \gamma H$) $r = H/2$; Which means a circular cross section Case B ($p_0 \neq 0$) and C ($p_0 = 0$) $\dfrac{d^2z}{dy^2} = -\dfrac{p_r}{N_\phi}[1+(\dfrac{dz}{dy})^2]^{3/2}$	• There is only the membrane state of stress at the covering materials • Plane strain state (2D) • No concentrated loads acting on a structure • Shell's own weight is neglected • Filling material has a specific unit weight • Friction between the structure and subsoil is neglected.

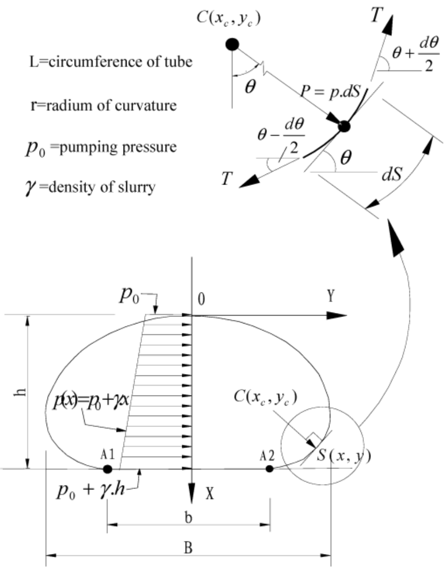
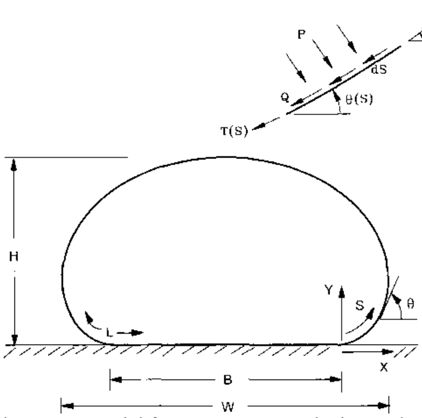
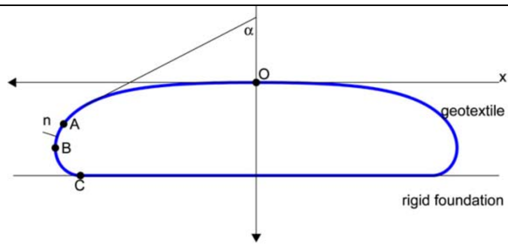
Leshchinsky et al. (1996)	 $Ty'' - (p_a + \gamma x)[1+(y')^2]^{3/2} = 0$	• The geomembrane tube is 2D (plane strain) problem; the pressure loss due to drainage through the tube during filling is ignored; • The sheet of tube is modeled as thin, flexible and has negligible weight per unit weight ; • No shear stresses develop between the slurry and the geosynthetic • The friction between tube and foundation was neglected. Then the tensile force is assumed as constant.
Plaut and Suherman (1998)	 Where: Q=The net tangential force per area; P=The internal pressure; T=The circumferential tension per width perpendicular to the cross section; W=Width of tube; H=The height of tube; L=Total perimeter of cross section; B=The contact length; s= The arc length from the origin lift-off point. $\begin{cases} \frac{dT}{ds}=Q, \quad T\frac{d\theta}{ds}=P \\ \frac{dx}{ds}=\cos\theta, \quad \frac{dy}{ds}=\sin\theta \end{cases}$	• The geomembrane tube is 2D (plane strain) problem;; • The sheet of tube is modeled as extensibility and negligible weight; • No shear stresses develop between the slurry and the geosynthetic • The friction between tube and foundation was neglected.
Malík (2009)	 Where α = the angle between the tangential bector and the axis y. H=the tensile force; ρ =density of water of slurry; g=the gravitational acceleration; p=the pressure of water or slurry at the point O. $\begin{cases} x(\alpha) = -\int_{-\frac{\pi}{2}}^{\alpha} \frac{H\sin\theta d\theta}{(p^2+2g\rho H(1+\sin\theta))^{\frac{1}{2}}} \\ y(\alpha) = \int_{-\frac{\pi}{2}}^{\alpha} \frac{H\cos\theta d\theta}{(p^2+2g\rho H(1+\sin\theta))^{\frac{1}{2}}} \end{cases}$	• The geosynthetic is inextensible and flexible and its weight can be neglected. • The filling medium (water or slurry) behaves as an ideal liquid which generates hydrostatic pressure in every point and acts in the perpendicular direction to the geosynthetic. • There is no friction between the foundation and the geosynthetic.

Table 4. A list of analytical methods for permeable geosynthetic tube on rigid foundation

Method	Calculation Profile	Assumptions
Leshchinsky et al. (1996)	$\begin{cases} \frac{\Delta h}{h_0} = \frac{\Delta e}{1+e_0} = \frac{e_0 - e_f}{1+e_0} = \frac{G_s(w_0 - w_f)}{1+w_0 G_s} \\ w_0 = \frac{G_s - \gamma_{slurry}/\gamma_w}{G_s(\gamma_{slurry}/\gamma_w - 1)} \\ w_f = \frac{G_s - \gamma_{soil}/\gamma_w}{G_s(\gamma_{soil}/\gamma_w - 1)} \end{cases}$ Where, Δh and h_0 are the decrease in height and initial height of the tube; *Gs* the specific gravity of solid; e_0 , the initial void ratio; w_0 and w_f , the initial and final water content of filling material; γ_{slurry} and γ_{soil} are the unit weight of slurry and consolidated soil.	• The width of tube is constant during the consolidation process; • The consolidation process is 1-dimension; • The filling material is full saturated; • The filling material is uniform and during consolidation process its water content is uniform.
Shin and Oh (2004)	*Direct calculation from measured soil properties and equations*: $C_F = \frac{-k}{\rho_f(1+e)} \frac{d\sigma'}{de}$ (1) Where *σ'* is the effective stress, *e* the void ratio, *k* the permeability, and ρ_f the pore fluid density; • *By comparison of self-weight consolidation curve:* $C_F = \frac{Tz_0^2}{t}$ (2) Where, *T* is time factor, *t* real time, z_0 total thickness of the soil and C_F coefficient of consolidation. • *Comparison of pore pressure dissipated curve:* Plot the isochrones of excess pore water pressure(pwp) with factor *T*; Real pwp at a particular time are then compared with these isochrones to find a value of time factor *T* corresponding to the real time; Then C_F can be calculated with Eq. (2).	• The large strain consolidation theory was used; • The instant deposition of tube is a zero effective stress state; • The filling material is uniform. During consolidation process, its water content, pore water pressure and density are uniform. • The void ratio/effective stress and the permeability/void ratio relationship are linear, and that the coefficient of consolidation CF is a constant.

4.2 Solution for Geosynthetic Mat on Deformable Foundation

A calculation process for geosynthetic mat resting on deformable foundation is developed. The same assumptions adopted for the calculation of geosynthetic mat resting on rigid foundation are made. Furthermore, the deformable foundation is assumed to be elastic Winkler Foundation with foundation stiffness of K_f. The tensile force along geotextile sheet can be divided into two parts. The first is the part above the ground which is constant. The second is below the ground in which the tensile strength increases with the depth of foundation (Plaut et. al. 1998). The values of the tensile force are given by the following equations:

$$T_{x=0\sim H} = \frac{1}{4}\gamma(H+H_f)^2 - \frac{1}{4}K_f H_f^2 \quad (6a)$$

$$T_{x=H\sim(H+H_f)} = K_f(\frac{1}{2}x^2 - Hx) + \frac{1}{4}\gamma(H+H_f)^2 - \frac{1}{4}K_f(H_f^2 - 2H^2) \quad (6b)$$

The geometry of the cross-section of the geosynthetic mat can be derived as Eq. (7). This is a nonlinear differential equation. It has to be resolved numerically as it contains an elliptical differential equation that has no closed form solution:

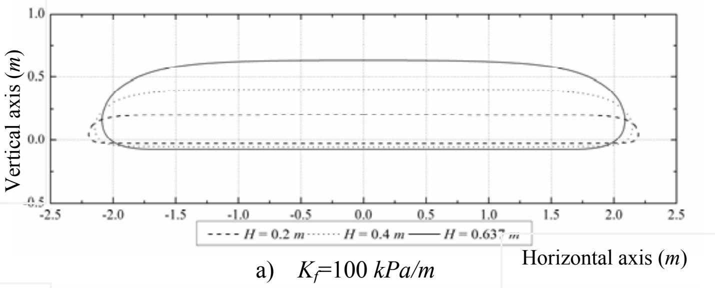
$$y'' = \frac{1}{T}[\alpha K_f(x-H)\left|y'\right|(1+y'^2)^{\frac{1}{2}} - \gamma x](1+y'^2)^{\frac{3}{2}} \quad (7)$$

In Eq. (7), the unit weight of filling slurry, *γ*, the height and width of geosynthetic mat above ground surface, *H* and *B*, are taken as inputs. The tensile force, *T*, can be calculated using Eqs. (6a) and (6b). The following two initial boundary conditions can be established to resolve this equation:

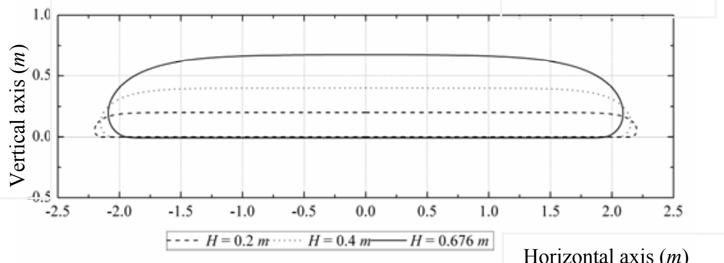
1). When $x = 0$, then $y = 0$, $dy/dx = \infty$, $\theta = 0$.

2). When $x=H+H_f$, then y = 0, $dy/dx = -\infty$, and $\theta = \pi$.

Using the above method, the geometry of cross-section for a geosynthetic mat with a perimeter of 9 m resting on deformable foundation can be calculated and shown in Fig. 6 for different heights. The effect of the modulus of subgrade reaction of a specific geosynthetic mat can also be evaluated as shown in Fig. 6. In the analysis, the unit weight of filling material is taken as 12 kN/m^3. A modulus of subgrade reaction of 100 and 1000 *kPa/m* are used for Fig. 6a and Fig. 6b respectively.



a) K_f=100 *kPa/m*



b) K_f = 1000 *kPa/m*

Figure 6. The cross section of geosynthetic mat resting on deformable foundation (for *L*=9.0 *m*, γ=12 kN/m^3; unit, *m*)

The relationship between the height of geomat below the ground surface, H_f, and the height above the ground surface, *H*, is presented in Fig. 7 for a given geomat with the perimeter of cross-section of 9 *m* and the unit weight of slurry of 12 kN/m^3. For the modulus of subgrade reaction ranging from 100 to 5000 *kPa*/*m*, there is a linear relationship between *H* and H_f as shown in Fig. 7. It can be seen that for this particular case, the subgrade reaction does not affect much the settlement of the geomat unless the foundation soil is very soft with a K_f value of 100 kPa/m or less. Based on calculations for other cases (Guo 2009), it may be concluded in general that when the modulus of subgrade reaction is greater than 1000 *kPa/m*, the foundation can be assumed as rigid in the analysis.

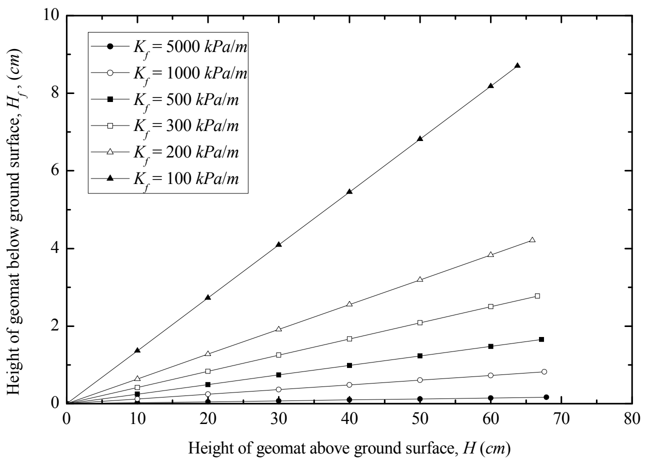


Figure 7. Relationships between H and H_f (For L = 9 m, γ=12kN/m^3)

4.3 Alternative Solutions for Geosynthetic Tube and Geosynthetic Mat on Deformable Foundation

The analysis presented above assumes the soil base to be Winkler foundation. In this case, the soil has to be assumed to be linear elastic. An alternative solution can be developed by assuming that the settlement of the tube can be calculated using the one-dimensional settlement theory. This assumption is reasonable for geosynthetic mat as its width is large enough for the settlement in the centre part to be assumed to be independent of any lateral deformation. The overburden pressure of soil layer induced by the weight of the geomat can be calculated using the Boussinesq solution. This method can be used to calculate the cross section shape of impervious geosynthetic tube or rubber dam. It can also be used to calculate the cross section of permeable geotextile tube filled with sand where consolidation is very fast and does not affect much the consolidated geometry of the geotextile tubes.

The calculated cross-sections for a pumping pressure of zero are shown in Fig. 8. In the calculation, the compression index C_c of the soil is assumed to be 1.05, void ratio of 2.0 and the unit weight of soil layer of 15kN/m^3 which are taken as the mean value of the Singapore Upper Marine Clay (Bo et al. 2007). The circumference of the geomat analysis is taken as L = 9 m. The geomat is filled with slurry of a unit weight of 12 kN/m^3. The height of the geomat is used as an input parameter.

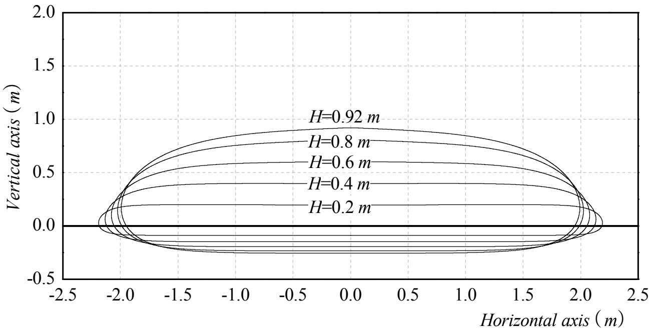


Figure 8. Shape of cross section of geotextile tubes when p_0=0 and H=0.2m, 0.4m, 0.6m, 0.8m, 0.92m,respectively

5. SUMMUARY

Geosynthetic tubes or geosynthetic mats have been used for many hydraulic and marine engineering projects. Some examples of applications have been illustrated in this paper. It should be pointed out that different methods are suitable only to different site conditions. The cost effectiveness of each method also depends on the cost and availability of the materials and construction machines as well as the construction processes. For example, the geosynthetic mat method is suitable for the construction of a breakwater or dike in relatively shallow water. It has the advantage of providing good lateral stability and ease of construction. The case study presented in this paper shows that clay slurry can also be used as fill material for the mats. However, design and analysis methods for the use of clay slurry as filling for the geosynthetic mat have not been fully established yet and more studies and field verifications are required. Normally, the dike constructed using this method needs to be covered by a thin layer of grouted geotextile mattress after the settlement of the dike stabilized.

Different analytical or numerical methods for different types of geosynthetic tubes (geotextile tube, geomembrane tube and rubber dam) or geosynthetic mats are classified and summarized in this paper. Not all the existing analytical or numerical methods are applicable directly to geosynthetic mats. A few new analytical or numerical methods for the analysis of geosynthetic mats are also presented. These include a closed form solutions for geosynthetic mat on rigid foundation, solution for geosynthetic mat on deformable foundation, and alternative solutions for geosynthetic tube and geosynthetic mat on deformable foundation. The study shows that the foundation can be assumed to be rigid when the modulus of subgrade reaction is greater than 1000 *kPa/m*.

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