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RECENT STUDIES OF GEOSYNTHETIC TUBES AND MATTERRES: AN OVERVIEW

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ABSTRACT : Geosynthetic tubes have been used in recent years in many projects related to coastal protection, dike construction, flood control and waste sludge dewatering purposes. The geosynthetic mattress method that uses flat mattress like geosynthetic containers have also been developed and used in several projects. The applications of geosynthetic tubes and geosynthetic mattresses are summarized in this paper. The existing analytical methods for different kinds of geosynthetic tubes are also summarized and critically reviewed in this paper. Methods for experimental studies and numerical analysis of geosynthetic tubes and mattresses are also reviewed and discussed.

KEYWORDS: Geotextile tube, geosynthetic tube, geosynthetic mattress

1. INTRODUCTION

Geosynthetic tubes are normally formed by inflating the tubes with water, clay slurry, sand or waste sludge. They have been used in recent years for many projects including coastal protection, dike construction, flood control and waste sludge dewatering in Australia, Brazil, China, France, Germany, Indonesia, Korea, Japan, Malaysia, Netherlands, USA and some other countries (Davis et al., 1992; Bogossian et al., 1982; Miki et al., 1996; Nickels and Heerten, 1996; Leshchinsky et al., 1996; Saathoff et al., 2007; Katoh et al., 1994; Lee, 2009; Cho et al., 2009; Yan and Chu, 2010; Shin and Oh, 2004). The geosynthetic mattress method that uses flat mattress like geotextile bags have also been developed and used in several coastal projects (Yan and Chu, 2010).

Geosynthetic tubes can be grossly classified into three categories: (1) impermeable geosynthetic tubes or bags made of very low permeability geomembranes, such as butyl rubber, EPDM rubber, PVC, polypropylene, polyurethane, Elvaloy, liner or fluid containment materials; (2) permeable geosynthetic tube made of geotextiles, such as synthetic polymers-polypropylenes, polyesters, polyethylene, or polyamides woven or non-woven geotextile with high tensile strength, high geotextile permeability and good soil retention characteristics; and (3) inflatable rubber dam made of impermeable and high strength synthetics but supported and anchored onto a permanent concrete foundation. Although rubber dams are also impermeable geosynthetic tubes, they need to be categorized separately due to the following reasons: (1) The impermeable geosynthetic tubes are mainly used for temporary or short term purposes, whereas the rubber dams are used more for permanent or long term purposes and thus, the materials used for rubber dams are different from the materials for impermeable geosynthetic tubes. The materials used for rubber dams are much thicker and are sometimes reinforced. (2) The bottom of a rubber dam has to be supported and anchored onto a permanent concrete foundation (as illustrated in Figure 9), whereas a permanent concrete foundation is normally not used for impermeable geosynthetic tubes. The typical applications of each category are also listed in Table 1. An overview of the different applications, the methods adopted for

Table 1 Classification of geosynthetic tube

Category	Applications
A. Impermeable Geosynthetic Tube or Geosynthetic tube made of membranes	A1. Flood control
	A2. Contain contaminated materials
	A3. Form working table
	A4. Water level control
	A5. Water diversion
B. Permeable Geosynthetic Tube or Geosynthetic tube made of geotextiles	B1. Dikes construction
	B2. Beach restoration
	B3. Coastal erosion prevention
	B4. Breakwater
	B5. Dewatering waste sludge
	B6. Water level control
C. Inflatable Rubber Dam	C1. Small dams
	C2. Elevating existing dams or spillways
	C3. Water diversion
	C4. Recreational basins
	C5. Contamination prevention
	C6. Groundwater supply
	C7. Hydroelectricity
	C8. Tidal control or flood control

analytical, experimental and numerical studies of the geosynthetic tubes are presented in this paper.

2. IMPERMEABLE GEOSYNTHETIC TUBES

2.1 Applications

As global warming has caused the sea level to rise in recent years, the river or coastal related disasters such as tsunami and flood have become higher in frequency and stronger in intensity. The traditional method of using sandbags to build temporary barriers may no longer be adequate for server flooding events. To fill, transport and stack a large amount sandbags need huge amount of manpower and time which are limited during a disaster. Furthermore, these sandbags are also difficult to be disposed after flood has receded.

An alternative method is to use water or slurry filled impermeable geosynthetic tube (Application A1 in Table 1) to build barrier. One example for the use of geosynthetic tube to protect the house from the damage of flood is shown in Figure 1. The advantage of this method is that the tubes can be inflated quickly and re-used in the future. However, the disadvantage is that the dike made of the geosynthetic tubes cannot be too tall. The water pressure acting on one side may also cause stability problems. Several methods have been developed to increase the lateral bearing capacity such as using a wedged single or stacked tubes (Huong et al., 2002), attaching a piece of geosynthetic material on the headwater side, stacking the tubes in 1-2 shapes and hold them together with straps, baffle tube dam and sleeved tube dam (Kim, 2003)

Figure 1 Geosynthetic tubes used for flood control (Howard and Trainer, 2011)

When construction needs to be carried out in lake, river or sea, a cofferdam is required to be constructed first to protect the equipment, working table or human activity from the action of tides and waves. The impermeable geosynthetic tubes filled with sand or water has been used (Application A3 in Table 1). One example is shown in Figure 2. The advantages of this method are the tube is lightweight, easy to transport, reusable in future and can be constructed in virtually any location. The on-site required equipment is just a portable pump. Furthermore, there must have sufficiently slurry or sand supply.

2.2 Analytical Methods

The analytical solution at the equilibrium state for the geometry of the cross-section of an impervious geosynthetic tube filled with water can be derived based on the differential equations. In deriving the solution, the geosynthetic tube is often assumed to be a plane strain problem. Other assumptions made include the geosynthetic sheet is thin, flexible so that its weight and extension can be neglected; the friction between the geosynthetic tube and the fill material, or that between the geosynthetic tube and the rigid foundation are often assumed to be neglected; and the geosynthetic tube is filled with water or slurry with a unique unit weight. Based on the property of the foundation soil or the stacked pattern, the analytical methods could be separated into several cases as discussed below.

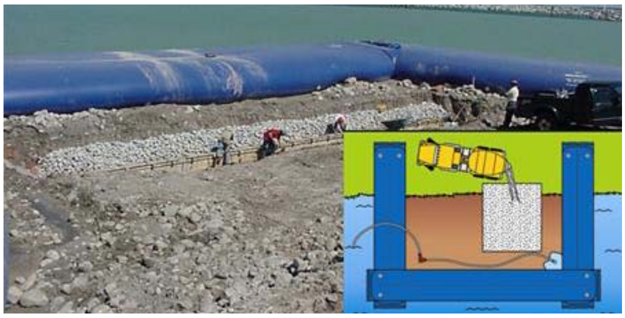


Figure 2 The geosynthetic tubes used for temporary barrier (www.aquabarrier.com)

2.2.1 Geosynthetic Tube Resting on Rigid Foundation

The first analytical formulas for liquid inflated impermeable geosynthetic tubes resting on rigid foundation were derived by Liu and Silvester (1977). In this solution, elliptic integrals are used to describe the shape function of the shell. The other analytical solutions have also been proposed by Leshchinsky et al. (1996), Kazimirowicz (1994), Malík (2009), Malik and Sysala, (2010). Dimensionless parameters are often used (Plaut and Suherman, 1998). A computer program GeoCoPS has been coded by Leshchinsky and Leshchinsky (1996) to analyze the cross-section of geosynthetic tube. The geosynthetic tube containing slurry and consolidated filling material was also analyzed by Plaut and Stephens (2012). In this analyzing method, the filling slurry behaves like a liquid but the consolidated filling materials on the bottom behaves like a solid material. The interacts between consolidated filling material with the internal tube surface were in a friction-like manner which have normal and tangential force components.

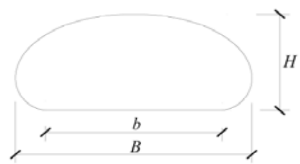
Recently, a coefficient method has been proposed by Guo (2012). In this method, relationships between the geometry parameters of the cross-section of geosynthetic tube and a factor related to the pumping pressure (Q) are established as shown in Figure 3 where γ is the unit weight of the filling slurry; p_0 is written as the pumping pressure; H, B, b, L and A present as the height, width, contact length with ground surface, the perimeter, and area of cross-section respectively; Q denotes the factor of pumping pressure; C_B, C_b and C_L are factors related to factor Q; T is tensile force along the cross-section. The values of the factor of pumping pressure (Q) and the responding three geometry parameters (B, b, L) are presented in Figure 3. The Q value are separated into 25 intervals. If the required Q value locates between the endpoints, the linear interpolation method can be used by assuming their value are linear in the intervals. The calculation procedure can be further simplified using Microsoft Office Excel because the linear interpolation method can be solved automatically by a subroutine, such as micro function *Qmatch*() shown in Figure 3. Generally, there are two cases of calculation based on the inputs: (1) when H, γ and p_0 are taken as inputs, the calculation can be carried out directly using the calculation procedure as shown in Figure 3; (2) when L, γ and p_0 are taken as inputs, the "Goal Seek" function in Microsoft Office Excel 2010 can be used to search the value of L to the desired magnitude by changing H.

When the pumping pressure equals to zero ($p_0 = 0$) or height to width ratio less than 0.163, which is typically the case of geosynthetic mattresses, their differential equations could be solved analytically (Chu et al., 2011; Guo, 2012). All the basic geometry parameters such as the area, A, the perimeter of cross-section, L, and the contact width with ground, b, are easily calculated using close-.

Coefficient Methods

INPUTS		
γ	H	p_0
12	1	10
(kN/m3)	m	kPa

OUTPUTS								
T	Q	B		L		b		A
8	1.520833	B	C_B	L	C_L	b	C_b	
		1.395	1.207764	3.903	3.380304	0.634	0.549049	1.162
kN/m		m		m		m		m2



Data from computer program

Q	C_L	Q	C_B	Q	C_b
1.00000	18.67328	1.00000	8.67616	1.00000	7.92242
1.00600	9.29226	1.00600	3.99218	1.00600	3.25369
1.01706	7.83738	1.01706	3.27401	1.01706	2.53554
1.06329	6.03762	1.06329	2.40270	1.06329	1.67097
1.13746	5.00516	1.13746	1.91990	1.13746	1.20078
1.18377	4.62974	1.18377	1.74918	1.18377	1.04173
1.30681	3.98810	1.30681	1.46510	1.30681	0.77730
1.38389	3.71750	1.38389	1.34886	1.38389	0.67063
1.56957	3.26030	1.56957	1.15755	1.56957	0.50578
1.70547	3.02372	1.70547	1.06138	1.70547	0.42737
1.84318	2.83344	1.84318	0.98548	1.84318	0.36956
2.12222	2.54244	2.12222	0.87203	2.12222	0.28605
2.26302	2.42750	2.26302	0.82810	2.26302	0.25925
2.54633	2.23833	2.54633	0.75691	2.54633	0.20895
2.88844	2.06130	2.88844	0.69152	2.88844	0.16960
3.11741	1.96442	3.11741	0.65624	3.11741	0.15233
3.40435	1.86072	3.40435	0.61885	3.40435	0.13084
3.69192	1.77196	3.69192	0.58717	3.69192	0.11825
3.97997	1.69487	3.97997	0.55988	3.97997	0.10552
4.55711	1.56686	4.55711	0.51502	4.55711	0.08303
5.13525	1.46414	5.13525	0.47943	5.13525	0.07117
5.42459	1.41984	5.42459	0.46419	5.42459	0.06471
6.00367	1.34213	6.00367	0.43760	6.00367	0.05881
7.30798	1.20555	7.30798	0.39132	7.30798	0.04488
9.48423	1.04860	9.48423	0.33879	9.48423	0.03286

Notes

1. input data of of the pumping pressure, p_0, unit weight of filling slurry, γ, and height of geosynthetic tube, H

2. Calculate tensile force, T, and factor of pumping pressure, Q.

$$T = (p_0 H + \frac{1}{2}\gamma H^2)/2$$

$$Q = (p_0^2 + 2\gamma T)/2\gamma T$$

3. get the desired factors such as CL=Qmatch(F5,A10:B34), CB=Qmatch(F5,C10:D34) or Cb=Qmatch(F5,E10:F34) using the following micro function, Qmatch()

```
Function Qmatch(ByVal xvalue, ByVal sordata As Range)
With sordata
If xvalue < .Cells(1, 1) Or xvalue > .Cells(.Rows.Count, 1) Then
Qmatch = "Overflow"
Else
 Set Bmatch = .Find(xvalue)
 If Bmatch Is Nothing Then
  RowIndex = Application.Match(xvalue, .Columns(1), True)
 Qmatch = (.Cells(RowIndex + 1, 2) - .Cells(RowIndex, 2)) * (xvalue - .Cells(RowIndex, 1)) /
            (.Cells(RowIndex + 1, 1) - .Cells(RowIndex, 1)) + .Cells(RowIndex, 2)
 Else
 Qmatch = Application.VLookup(xvalue, sordata, 2, False)
End If
End If
End With
End Function
```

$$B = C_B\sqrt{\frac{2T}{\gamma}} \qquad L = C_L\sqrt{\frac{2T}{\gamma}}$$

$$b = C_b\sqrt{\frac{2T}{\gamma}} \qquad A = \frac{p_0 + \gamma H}{\gamma} b$$

4. calculate the desired parameter as length, L, width, B, contact width with ground, b, or area of cross-section, A

Figure 3 Coefficient method for geosynthetic tube designing (Guo, 2012)

form solutions when the unit weight of the filling slurry, γ, and the height H, and width B of cross-section are taken as inputs . The analytical solutions have also been verified by model tests where a good agreement has been gotten

2.2.2 Geosynthetic Tube Resting on Deformable Foundation

When geosynthetic tubes are used for coastal construction projects, they are often laid on soft ground where large settlement may take place. The ground settlement will influence the performance of the geosynthetic tube. The only analytical method was given by Plaut and Suherman (1998) in which the basement was assumed to be a tensionless Winker foundation. They used non-dimensional parameters in which the height of the tube, H, and settlement, H_f, are normalized by the length of cross-section, L; the pumping pressure, p, by γL; the tensile force, T, by γL^2; and the modulus of subgrade reaction, K_f, by γ. The tube was modeled as an inextensible membrane and filled with an incompressible fluid. The geometry of the geosynthetic tube was resolved by partial differential equations. In Plaut and Suherman's solution, the perimeter of the cross-section of the tube and the pumping pressure (expressed as pressure head) are assumed to be known. The height and width of the geosynthetic tube are the results of the solutions. An improved method was proposed by Guo et al. (2011) where the height of the geosynthetic tubes above ground surface and the pumping water pressure are taken as the design parameters. However, the use of Winkler model has the following limitations: 1) it is difficult to determine the stiffness of subgrade reaction; 2) the soil is modeled as a linear elastic material; and 3) the variation of stress in the soil cannot be considered.

To overcome the limitations in the use of Winkler model, a nonlinear method by using the *e-log p* consolidation curve to model the settlement of soil foundation has been proposed by Guo (2012). In this method, the foundation soil was divided into finite slices. The surcharge distribution within the soil mass induced by the weight of geosynthetic mattress is calculated with the Boussinesq solution. It should be pointed out that the e-log *p* method is only an approximate method because the e-log *p* curve is established under 1-D condition only. The advantage of this method is that the parameters used for calculation are easier to be obtained from laboratory tests. The surcharge pressure distribution within soil mass, the over consolidation ratio and the external water level are considered. The e-log *p* method can be used to calculate the cross-section of impervious geosynthetic mattresses or rubber dams.

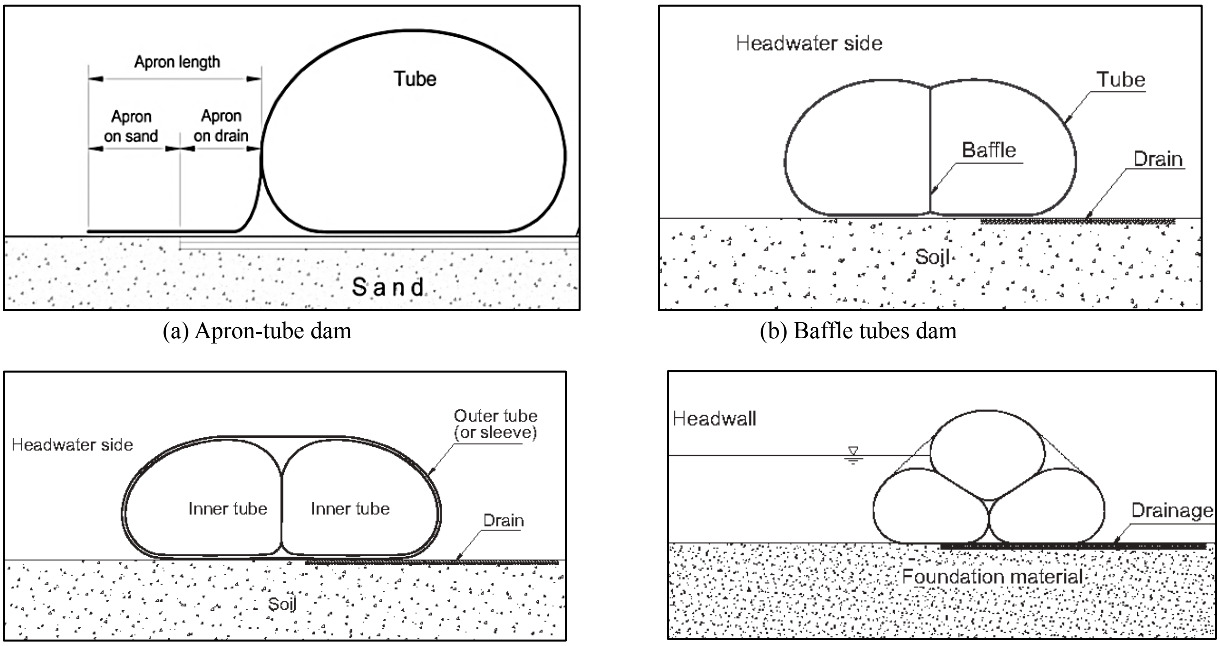
2.2.3 Stacked Geosynthetic Tube

The geosynthetic tubes can be stacked in several layers to construct a higher dike or to dewater waste sludge. Two cases, (1) one tube stacks on top of another (1-1 stacked) and (2) one tube straddles two tubes (1-2 stacked) resting on rigid and deformable foundation were proposed and analyzed by Plaut & Suherman (1998) and Plaut & Klusman (1999). In the two methods, the geosynthetic tubes were assumed to have the same perimeters. Both the two methods cannot be directly applied to the cases when the pumping pressure of the top geosynthetic tube is zero.Theoretical solutions for the case of 1-1 stacked geosynthetic tubes have also been proposed by Guo (2012). The solutions were derived for three cases of stacked patterns based on their different contact conditions: horizontal, convex, or concave contact. It was assumed that the geosynthetic tubes were impermeable or watertight and inflated with same water or slurry. The method was applicable for the two layer stacked geosynthetic tubes with different perimeters. Furthermore, it also considered the case when the pumping pressure of the top geosynthetic tube is zero. The developed solutions were compared with the solutions given by Plaut & Klusman (1999) where the two layers tubes were assumed to have same geometry. The solutions have also been compared with model tests results. Good agreements were obtained.

2.2.4 Other Types of Geosynthetic Tubes

The analysis of some other types of impermeable geosynthetic tubes have also been carried out. The cross-section of the geosynthetic tube with a piece of apron attached to the tube and placed it along the ground on the headwater side (see Figure 4(a)) was analyzed by Kim (2003) by assuming the foundation is rigid. The friction between tube and foundation was neglected but that between the apron and foundation was involved. Thus, the axial tensile forces were different along the apron and the tube cross-section.

Multi-chambered geosynthetic tubes resting on rigid foundation were studied by Kim (2003). The first case is that the tube is perforated by an internal baffle (baffle tube) as see in Figure 4(b). The second case is two tubes surrounded by a larger tube outside (sleeved dam) as shown in Figure 4(c). The third case is 1-2 stacked tubes surrounded by a larger tube outside as shown in Figure 4(d). In these solutions, the axial tensile forces in the circumference direction are taken as constant because the frictions between the foundation and the tube are neglected. The geometry of the tube and the tension force of tubes are calculated using finite difference program FLAC (Itasca Consulting Group, 2000). Geosynthetic tubes strapped together were also studied by Kim (2003).



(a) Apron-tube dam

(b) Baffle tubes dam

(c) Sleeve tube dam

(d) Stacked tubes

Figure 4 Four types of water-filled geomembrane tubes (after Kim, 2003)

2.3 Experimental Studies

Experimental studies of geosynthetic tube include model tests and the basic property tests for geosynthetic materials or filling slurry. The geosynthetic sheets used for gluing impermeable geosynthetic tubes must have enough tensile strength to sustain the pressure applied during pumping and stacking periods. The details of these testing standards for impermeable geomembrane (or plastic) materials are summarized in Table 2

The model tests for impermeable geosynthetic tubes include the measurement of the cross-section geometry, the tensile force along geosynthetic sheet and the pumping pressure inside. The strain of the geosynthetic sheets during a model test was often measured by the waterproof strain gauges (Cantré and Saathoff, 2011). Since geosynthetic sheet is a thin and flexible material, a contact-free measure system has to be used to measure the cross-section of geosynthetic tube. A highly accurate low-budget photogrammetric system was adopted for this purpose by Cantré and Saathoff (2011) as shown in Figure 5. This highly accurate low-budget photogrammetric system included four digital cameras to capture approximately half of a tube's circumference during filling and dewatering while resting on a plane table.

A laser sensor and movable scanner were used to simplify the contact-free testing procedure, see Figure 6(a), (Guo, 2012). The laser sensor (model ILD1700-750 by Micro-Epsilon Company) had a range of 750 mm and resolution of 50 μm. The laser sensor is fixed on an x-beam made of an aluminum alloy bar that could move from left to right. When the laser sensor moved horizontally along the x-beam, the vertical distance between the laser sensor and the top

Table 2 Test standards for tensile strength of geomembrane material

	Name of standard		Specimen size		Loading rate
			Dumb-bell	Rectangular ($W\times L^{(1)}$, *mm*)	
ASTM	D638-03		$13^{(2)}\times 57^{(2)}$		10±3 *%/min*
	D882-02		---	5~25.4×50	$25^{(3)}$ *mm/min*
British Standard	BS EN 12311-2: 2010	Method A:	---	50×200	100±10 *mm/min*
		Method B	$6^{(4)}\times 115$	---	500±50 *mm/min*
				15×170	200±20 *mm/min*

Notes: *(1)The length of specimen, L, is the gauge length between clamps;*
(2)The width and length are determined by the thickness of specimen; for more details refer to ASTM D638-03;
(3)The load rate is determined by percent elongation at break when test for other than elastic modulus;
(4)The width is the smallest width; for more details refer to BS EN 12311-2: 2010.

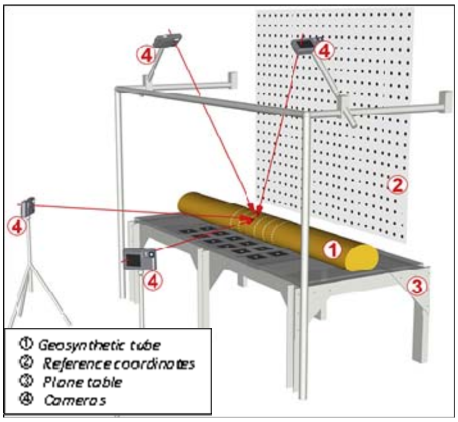
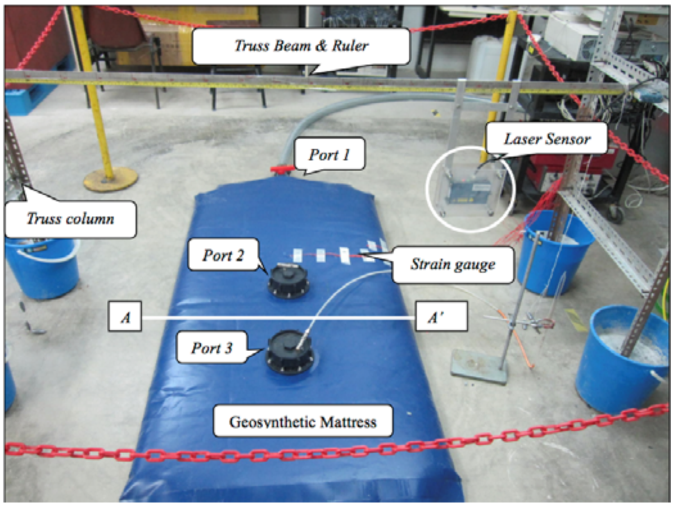
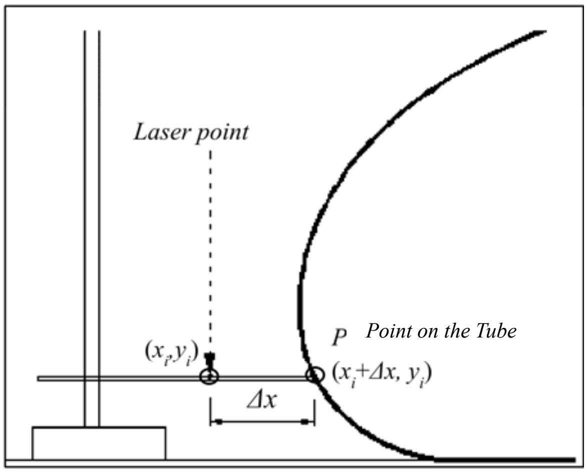


Figure 5 Geometry measurement using photogrammetric system (Cantré and Saathof, 2010)



(a) Photo of geometry measurement system



(b) Measurement method for bottom points

Figure 6 Geometry measurement method using laser sensor (Guo, 2012)

each model test, the distance between the concrete floor and laser sensor was measured. Then, the vertical position of a point on the top surface of the geosynthetic mattress was calculated by the distance to the floor minus the laser sensor reading. The horizontal position of the testing point was measured using a ruler attached to the beam as shown in Figure 6(a). To measure the position of the geosynthetic mattress along the bottom half, another laser sensor can be used. However, when a second laser sensor is not available, an indirect method as shown in Figure 6(b) canalso be used. A ruler was placed on the side of the geosynthetic tube with its edge contacting with the geosynthetic tube. The point on the ruler (such as point (xi, yi) in Figure 6(b)) could be measured by the laser sensor directly. The distance from the laser point (xi, yi) to the edge of the geosynthetic tube, denoted as Δx as shown in Figure 6(b), can be measured by the ruler. Then the target point on the geosynthetic mattress could be calculated as (xi+ Δx, yi). This contact-free measuring system avoided the contact effect to the flexible geosynthetic mattress. However, as the laser sensor could not move longitudinally, it could only measure one profile of the mattress along a center cross-section such as the section A-A' shown in Figure 6(a)

2.4 Numerical Studies

The numerical methods used for simulating the geosynthetic tubes can directly provide the geometry of the cross-section and the tensile force distribution in the geosynthetic tube. Some commercial computer software such as FLAC and ABAQUS (ABAQUS, 1998) can be used for the analysis.

When using FLAC for simulation, the geosynthetic tubes can be modeled as linearly elastic beam elements and the extension, bending effect and weight of geosynthetic sheet are neglected (Huong, 2001; Kim, 2003; Kim et al., 2005, a; Kim et al., 2005, b). The following calculation steps are conducted: 1) to build the initial equilibrium between gravity, hydraulic pressure distribution and deformation of soil subgrade, and 2) to apply the node forces onto the beam element and transfer the stress to the soil subgrade till the whole system is balanced. The special shape or assembled geosynthetic tubes, such as attached with an apron (Kim et al., 2004), baffle tube dam, sleeved tube dam and the stacked tube dam (Kim, 2003; Kim, et al. 2005a; Kim, et al. 2005b) and a wedge holding on side (Huong, 2001) were also analyzed with this software.

The computer software ABAQUS was also used to calculate the geometry of the cross-section and the tensile force in geosynthetic tube. Seay and Plaut (1998) used it to model the geosynthetic tubes three-dimensionally. They modeled the geosynthetic tube in a flat shape at the beginning and then applied an internal hydraulic pressure to check the final shape of cross-section. The pressures on bottom of the tube versus its heights curves obtained from this study were almost linear. This is different from the results presented by Malik (2009) or Leshchinky et al. (1996) in which the relationships between pumping pressure and the heights were nonlinear.

3. PERMEABLE GEOSYNTHETIC TUBES

3.1 Applications

In recent years, many methods have been developed to use geosynthetic or geosynthetic materials for the construction of coastal structures. One of the applications is to use geosynthetics as formwork to build mortar filled mattress or concrete bags for coastal erosion prevention (Application B3 in Table 1). The exterior geosynthetic materials serve primarily as a form until the internal cement mortar hardens. The concrete bags can also be reinforced and connected by driving steel rods through them (Pilarczyk, 2000).

The geosynthetic tube can also be inflated using sand to form breakwaters as shown in Figure 7(a) or for beach restoration as shown in Figure 7(b). Similarly, geosynthetic tubes inflated using sand have also been used for artificial islands projects and river breakwater projects. Compared with the traditional ways of constructing shoreline structures using rock or precast concrete units, the use of geosynthetic tubes offers a number of advantages. Firstly, it is cost-effective. The use of a layer of geosynthetic to form a tube with soil (either sand or clay slurry) as fill materials is often more economical than the use of concrete or rocks. Secondly, the construction process can be made simpler and faster. Thirdly, it enables local soils and even slurry materials to be used as fill materials for construction. The high tensile strength of geosynthetic materials offers the best combination with any kinds of soil.

If sand is not readily available, it is possible to use silty clay or clay slurry as fill materials (application B1 in Table 1). One example was presented by Yan and Chu (2010) for dike construction in Tianjin, China. As shown in Figure 8, large flat geosynthetic mattresses or mats were adopted for this project. The use of geosynthetic mattresses for dike construction offers the following advantages: (1) geosynthetic mattress has no lateral stability problems as the lateral dimension is very large compared to its height; (2) the filling process of a geosynthetic mattress can be more convenient as more filling points can be used; and (3) the dike made of geosynthetic mattresses can accommodate relatively large differential settlement which may result in savings the foundation treatment.

Geosynthetic tubes have also being used for dewatering waste sludge such as digested biosolids, sewage sludge (Bowles and Fleischer, 1999;Fowler et al., 1996), dredged materials (Moo-Young and Tucker, 2002;Worley et al., 2004; Zhu et al., 2010), industrial solid wastes (Worley et al., 2004; Worley et al., 2008), fly ash (Kutay et al., 2005; Muthukumaran and Ilamparuthi, 2006) and coal slurry (application B5 in Table 1). The waste sludge is firstly filled into a geosynthetic tube by pumping. Under the pumping pressure and confinement of the geosynthetic sheet, the water seeps through the permeable geosynthetic sheet and the sludge consolidates. In most of the cases, these high water content wastes are exposed to sunlight for the formation of desiccation crust. After dewatering, the dewatered materials can be transported to a dry disposal area or be possibly reused if the dewatered materials are some kinds of beneficial materials. Sometimes, the geosynthetic tubes can be stacked together to save resting space and accerate the dewatering process.

3.2 Analytical Studies

The analysis of a permeable geosynthetic tube is more difficult than that of an impermeable one as the consolidation process of the internal soil during or after filling is involved. Leshchinsky et al. (1996) used volume-weight relationships to calculate the height variation of the geosynthetic tube by assuming that the width of geosynthetic will not change during consolidation process. Shin and Oh (2004) presented a new approach to calculate the consolidation process of geosynthetic tube called settling and self-weight consolidation methods. The consolidation process was separated into four stages: (1) dispersed free settling during which the soil particles disperse and freely settle without mutual interactions; (2) flocculated free settling during which the soil particles flocculate and form flocs of different sizes; (3) zone settling during which the flocs are formed due to flocculation and settle with a strong mutual interaction and (4) consolidation settling during which the visible flocs cannot be formed and the mixture settles as a whole (Shin and Oh, 2004). Only the methods for the calculation of the zone settling and self-weight consolidation processes were given. There are no solutions for the first two processes yet.

A relatively simple relationship between the final volume and solids concentration of geosynthetic tubes have also been proposed by Yee et al. (2012). This empirical relationship between the volume of the tube and its height has also been verified by the solutions given by the more rigorous analyses of Leshchinsky et al. (1996). The rates of volume reduction and solid concentration increase during dewatering have also been established by Yee and Lawson (2012). In this method, the final geometry was estimated using the change in void ratio plus assumptions regarding the variation in the geometry of the tube. The fundamental mathematical formulas were derived empirically. The main factors for determining the accuracy of the analytical model are the flow quality factor, Ap, during the filling phase and the power factor, q, during the dewatering stage. These two factors are obtained from large-scale or full-scale prototype model tests.

(a) Breakwater in the sea (Lee and Douglas, 2012)

(b) Beach restoration (Harris and Sample, 2009)

Figure 7 Permeable geosynthetic tubes used for coastal structures

Figure 8 Dike constructed using clay slurry filled geosynthetic mattresses (Yan and Chu, 2010)

3.3 Experimental Studies

Experimental studies of geosynthetic tube include model tests and the basic property tests for geosynthetic materials or filling slurry. The geosynthetic sheets used for seaming or gluing geosynthetic tubes must have enough tensile strength to sustain the pressure applied during pumping and stacking periods. For permeable geosynthetic tube, the geosynthetic sheet must also have enough retention properties to block the fine particles in the geosynthetic tube. Therefore, the basic properties of geosynthetic material for permeable geosynthetic tubes include not only tensile strength but also filtration properties.

3.3.1 Basic Properties Test

The experimental studies of permeable geosynthetic materials include not only tensile strength but also the filtration properties. Several standards have been developed for tensile strength testing. The details of these testing standards are summarized in Table 3. As geosynthetic specimens tend to contract or necking in the central area when stretched, a specimen with a width of 20 cm and gauge length of 20 cm were suggested for tensile strength testing because the results achieved can correlate better with the tensile strength values anticipated in the field (ASTM D4595). The methods for filtration test can be classified into four types according to the ways pressure is applied. The first method is to test the filtration properties by hanging geosynthetic bags on a frame (Koerner and Koerner, 2006a, 2006b). The second method is the vacuum filtration test which applies vacuum pressure to suck the excess pore water out of fixed geosynthetic specimen (Moo-Young and Tucker, 2002; Tucker, 2000). The third method is to apply an air pressure on the top of sludge surface to force the excess pore water to seep through the fixed geosynthetic specimen (Moo-Young et al. 2002; Muthukumaran and Ilamparuthi, 2006). Furthermore, the filtration properties can also be determined through geosynthetic tube model tests as described by Fowler et al. (1996).

3.3.2 Mosel Test

The model test for a permeable geosynthetic tube includes the measurement of displacement of cross-sectional geometry, tensile force along the geosynthetic sheet and pumping pressure inside. The strain or tensile force of the geosynthetic sheets during a model test was often measured by waterproof strain gauges. A contact-free displacement measure system also has to be used to measure the cross-section of the geosynthetic tube. The consolidated geosynthetic tubes will more or less be affected by the properties of the filling materials. Based on the field test conducted by Shin and Oh (2003), the height of dredge sand filled geosynthetic tube settled about 40% within 2 days from the time after being filled. But for silty clay, the tube dropped off 50% within a month after filled. When the permeable geosynthetic tube is filled with sand, the consolidation process is quick and the unit almost maintains its original cross-section (Lawson, 2008). When the tube was filled with silty clay or waste sludge, the final geometry may be estimated by using the change in sludge water content or void ratio plus assumptions regarding the variation in the geometry of the tube(Leshchinsky et al. 1996; Yee et al. 2012). Some case studies were performed to verify these assumptions (Yee and Lawson, 2012). When using geosynthetic tubes for waste sludge dewatering, the dewatering time and water content of the dewatered soil are two important dewatering parameters. The longer dewatering time constrains the speed and volume of waste that can be treated. Therefore, acceleration of this dewatering process is necessary. There are at least two kinds of accelerating methods: 1) add chemical as dewatering accelerant; and 2) use electro-osmosis. The chemical dewatering accelerant can accelerate the dewatering time for organic waste such as sewage sludge, lagoon solids but has no benefit with fly ash (Worley et al., 2008). The electro-osmotic dewatering method utilizes an electric potential between anode and cathode to accelerate the pore water moving through the fine-grained particles. The method has already been applied to dewater sewage sludge (Jones et al., 2006; Miller et al., 1998), waste water sludge (Tyagi, 2006), lagoon sewage (Glendinning et al., 2006) and fine-grained residue from mine tailings (Fourie et al., 2004; Fourie et al., 2002).

3.4 Numerical Studies

Two dimensional analysis of geosynthetic tube resting on rigid foundation was carried out by Cantré (2002) using ABAQUS. The initial geometry of stacked geosynthetic tubes was obtained using the formula proposed by Plaut and Suheman (1998) and then the shapes at equilibrium were analyzed with ABAQUS. The consolidation process of permeable geosynthetic tube was also modeled using this procedure by assuming the modulus and saturation of slurry changed with the dissipation of the pore water pressure.

4. RUBBER DAMS

4.1 Applications

The rubber dams are installed to function as low level weirs or barrages across a river to raise the water level for the use of diverting flow into a supply canal, conduit for irrigation, domestic, or industrial (Paul, 1998). The water or air inflated rubber bags or rubber dams have also been used as a flexible and sometimes temporary barrier (Chu et al., 2009; Zhang et al., 2002). The difference between rubber dams and impermeable geosynthetic tubes is that the rubber dam is normally supported and anchored onto a permanent concrete foundation such as the one shown in Figure 9 that is used for Ramspol storm surge barrier in the Netherlands.

Table 3 Test standards for tensile strength of woven geosynthetic material

	Name of standard	Specimen size ($W \times L^{(1)}$, mm)	Loading rate
ASTM	D4595-09	200×200	10±3 %/*min*
	D5034–09	100×75	300±10 *mm*/*min*
British Standard	EN ISO 10319: 1996	200×100	20±5 %/*min*

Note: $^{(1)}$ *L is the gauge length between clam*

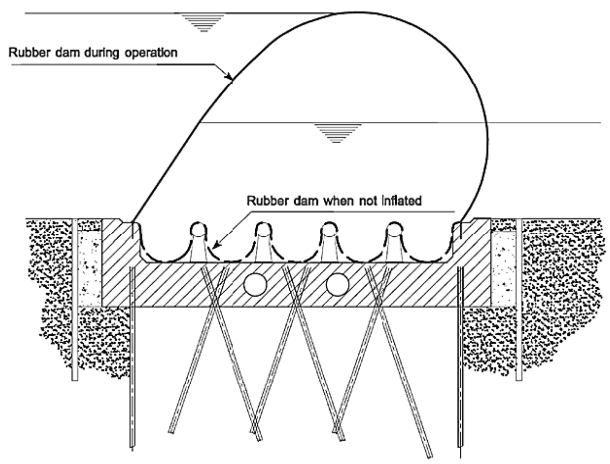


Figure 9 Rubber dam used for surge barrier (Jongeling and Rövekamp, 1999)

The Ramspol storm surge barrier is one of the largest rubber dams in the world so far. It used three identical inflatable rubber dams. The dimensions of each rubber dam were 75 *m* in length, 13 *m* in width and 8.35 *m* in height. A unique feature of this project is that a combination of air and water was used as the inflation medium. This minimizes the dimensions of the rubber body and also allows the height of the dam to be adjusted quickly by pumping air into or sucking it out of the dam. More information on this project can be found in Jongeling and Rövekamp (1999). The major advantage of the rubber dam is that it can be easily deflated or inflated. The major disadvantage is its vulnerability against punching or UV.

4.2 Analytical Studies

The analytical method for rubber dam is similar to that used for analyzing the impermeable geosynthetic tube resting on rigid foundation. The only difference is that the water head on one side has to be considered because the rubber dam is installed across the river for raising water level. The balance shapes of the cross-sections when facing water on one side become important considerations (Hsieh et al., 1989; Hsieh and Plaut, 1990). The dynamic pressures from the tidal or wave action have to be considered too (Plaut, 1990). The response amplitudes as a function of fundamental parametric resonances had also been charted. Wu and Plaut (1996) analyzed the rubber dams under overflow conditions. They solved the governing differential equations numerically on steady state and dynamic state of the rubber dam. The static and dynamic behavior of rubber dam resting on deformable foundation was studied by Plaut and Cotton (2005). Ghavanloo and Daneshmand (2009a) considered the weight of the heavy thin-wall membrane resting on an inclined or horizontal plane. Ghavanloo and Daneshmand, (2009b) also developed a new analytical method to determine the equilibrium shape of rubber dam filled with air and rested on rigid foundations of an arbitrary shape.

5. CONCLUDING REMARKS

Geosynthetic tubes can be classified into three categories: impermeable geosynthetic tubes, permeable geosynthetic tubes and rubber dams. Applications of each type of geosynthetic tubes were introduced. Different analytical and numerical methods adopted for the analysis of each type of geosynthetic tubes were also reviewed. Experimental studies and some recent techniques applied were also discussed in this paper.

The impermeable geosynthetic tubes have been used in recent years in many projects related to flood control, contain contaminated materials, form work table, water level control and water diversion. Several solutions for impermeable geosynthetic tubes resting on rigid foundation have been developed. The coefficient method for impermeable geosynthetic tube and the closed-from solution for geosynthetic mattress have also been proposed for preliminary designs. For settlement prediction of geosynthetic tubes on soft ground, the *e-log p* method has also been proposed. This method has a number of advantages over the Winkler method.

The permeable geosynthetic tubes have been adopted for dike construction, beach restoration, breakwater construction and dewatering waste sludge. The analysis of a permeable geosynthetic tube is more difficult than that of an impermeable one as the consolidation process of the internal soil during or after filling is involved. The easiest method is to calculate the tube height using void ratio changes by assuming the tube width change little during consolidation process.

The rubber dams are installed to function as low level weirs or barrages across a river to raise the water level for the use of diverting flow into a supply canal, conduit for irrigation or water supply. The analytical method for rubber dam is similar to that for analyzing the impermeable geosynthetic tube resting on rigid foundation. The only difference is that the water head on one side has to be considered because the rubber dam is installed for raising water level.

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