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Geotextile containment for hydraulic and environmental engineering

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ABSTRACT: Historically, geotextile containment has been used to encapsulate sandy soils to enable their use as flexible, erosion-resistant, mass-gravity structures in hydraulic and marine applications. More recently, geotextile containment has been used as a means of disposing of, and dewatering, waste and contaminated sediments. The paper reviews the three main geotextile containment units in use – geotextile tubes, geotextile containers and geotextile bags – and discusses relevant performance criteria for their wide range of hydraulic and environmental applications. Special attention is given to the use of geotextile containment for the isolation of, dewatering, and disposal of specific waste streams and contaminated sediments.

1 INTRODUCTION

Geotextile containment is used for an increasing range of applications. Table 1 summarises the current three main application areas – hydraulic and marine, foundations and environmental. In hydraulic and marine applications geotextile containment prevents the erosion of sand fill thereby enabling its use in erosion-resistant structures. In foundation applications geotextile containment improves the bearing capacity of stone and sand columns in low shear strength foundation soils. In environmental applications geotextile containment enables controlled dewatering of waste and contaminated sediments thereby substantially reducing their volume and rendering them manageable for disposal. Also, geotextile containment can be used for the controlled offshore disposal of contaminated soil and sediments.

The application of geotextile containment in foundations may be considered more a case of geotextile confinement rather than containment because the aim is to improve bearing capacity of the columns by generating confining tensions in the geotextile skin, and consequently, this application is not considered further in this paper. Thus, the paper will concentrate on two of the applications for geotextile containment listed in Table 1, that of hydraulic and marine applications and that of environmental applications.

Table 1. Range of applications of geotextile containment.

Geotextile containment applications	Examples
Hydraulic and marine	Mass-gravity revetment and dyke structures. Mass-gravity offshore structures. Surface protection to stream banks.
Foundations	Encasing of stone and sand columns.
Environmental	Dewatering of waste and contaminated sediments. Offshore disposal of contaminated soil and sediments.

2 TYPES OF GEOTEXTILE CONTAINMENT UNITS

Geotextile containment, in one form or another, has been used for many years for a wide variety of hydraulic and marine applications. The most universal, and widely used, geotextile containers are the well-known, ubiquitous sand bags which are seen the world over shoring up flood defences in times of natural calamity.

Three fundamental types of geotextile containment units exist, differentiated by geometrical shape and volume. These are geotextile tubes, geotextile containers and geotextile bags. Geotextile tubes, fig: 1a, are tubular containers that are formed insitu on land or in water. Geotextile containers, fig: 1b, are large-volume containers that are filled in barges above water and then deposited into submarine environments. Geotextile bags, fig: 1c, are small-volume containers that are filled on land or above water and then pattern-placed either near water or below water level.

a) Geotextile tubes

b) Geotextile containers

c) Geotextile bags

Figure 1. Types of geotextile containment units.

Geotextile tubes are laid out and filled onsite to their required geometrical form. The tubes are filled by hydraulically pumping fill into the tube. Geotextile tubes range in size from 1 m to 10 m in diameter, and up to 200 m in length.

Geotextile containers are large-volume containers that are filled above water and then positioned and placed at water depth. The volumes of these containers more commonly range from 100 m^3 to 700 m^3, although containers as large as 1,000 m^3 have been installed. To facilitate the installation of geotextile containers of this magnitude an efficient and practical installation system must be utilised. To date, this has been accomplished by means of split-bottom barges.

Geotextile bags are manufactured in a range of shapes, and they are installed in a pattern-placed arrangement that greatly improves their overall stability and performance. Today, geotextile bags range in volume from 0.05 m^3 to around 5 m^3, and may be pillow-shaped, box-shaped or mattress-shaped depending on the required application.

When considering geotextile containment, distinction must be made between those applications where the geotextile containment is required for only temporary or expedient use and those applications that require long-term performance. For example, for temporary or expedient works the requirements of the geotextile container is fairly basic as it only has a short life expectancy over which it has to perform; however, for long-term applications the performance requirements of the geotextile container are more severe. With regard to long-term performance, distinction also must be made according to the type of hydraulic environment acting on the geotextile container. For example, the action of still water will have a different effect on the geotextile container than the action of breaking waves.

3 GEOTEXTILE CONTAINMENT FOR HYDRAULIC AND MARINE APPLICATIONS

In a modern context geotextile containment has been used for hydraulic and marine applications for approximately 40 years. The most common types used are geotextile tubes followed by geotextile bags and then geotextile containers.

3.1 *Geotextile tubes*

3.1.1 *Introduction*

Geotextile tubes first began to be used for hydraulic and marine structures in the 1960's. These tubes (Longard tubes) were of small diameter (less than 2 m) and proved of limited use, especially in hydraulic environments, due to instability. Longard tubes utilised an impermeable inner lining to the woven geotextile skin in order to pressurise the tube with water before introduction of the sand fill.

During the late 1980's large diameter geotextile tubes were developed using strong woven geotextiles as the tube skin (and with no impermeable inner liner). The major advantage of these later-developed tubes is that a large protected mass, tubular structure could be designed directly to meet many hydraulic and marine stability requirements. Also, during the late 1980's, heavy weight nonwoven geotextiles were developed for small diameter (less than 1.5 m) geotextile tubes. Today, geotextile tubes ranging in diameters from 1.0 m to 5.5 m are used in many hydraulic and marine applications the world over.

3.1.2 *Engineering features of geotextile tubes*

Geotextile tubes are laid out and filled hydraulically onsite to their required geometrical form. The typical features of a geotextile tube are shown in fig: 2. Hydraulic fill is pumped into the geotextile tube through specially manufactured filling ports located at specific intervals along the top of the geotextile tube. During filling, the geotextile tube, being permeable, allows the excess water to pass through the geotextile skin while the retained fill attains a compacted, stable mass within the tube. For hydraulic and marine applications the type of fill used is sand, or a significant percentage of sand. The reasons for this are that this type of fill can be placed to a good density by hydraulic means; this type of fill has good internal shear strength; and this type of fill, once placed, will not undergo further consolidation, which would change the filled shape of the geotextile tube. Once filled, the geotextile tube behaves as a mass-gravity unit and can be designed accordingly.

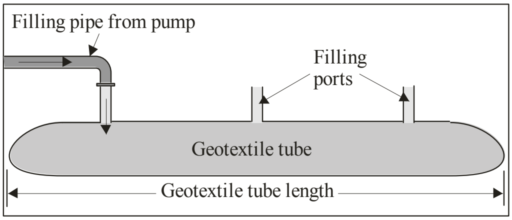
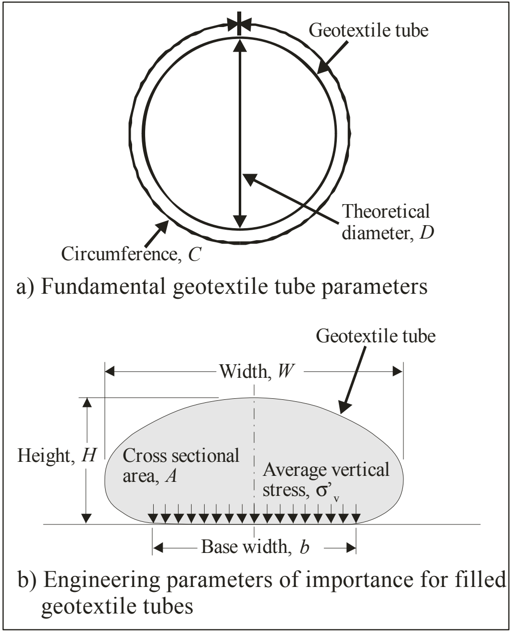


Figure 2. Typical features of geotextile tubes.

The geotextile skin performs three functions that are critical to the performance of the filled geotextile tube. First, the geotextile skin must have the required tensile strength and stiffness to resist the mechanical stresses applied during filling and throughout the life of the units, and must not continue to deform so that the geotextile tube changes shape over time. Second, the geotextile skin must have the required hydraulic properties to retain the sand fill and prevent erosion under a variety of hydraulic conditions. Third, the geotextile skin must have the required durability to remain intact over the design life of the units.

Geotextile tubes are normally described in terms of either a theoretical diameter, *D* (in Europe, Middle East and Asia) or a circumference, *C* (in North and South America), fig: 3a. While these two properties represent the fundamental parameters of geotextile tubes they are not of direct interest when it comes to the engineering parameters for hydraulic and marine applications where the geotextile tube in its filled condition is of prime importance. The various engineering parameters of importance are shown in fig: 3b.



a) Fundamental geotextile tube parameters

b) Engineering parameters of importance for filled geotextile tubes

Figure 3. Various parameters associated with geotextile tubes.

Table 2 lists approximate relationships between the fundamental geotextile tube parameters of theoretical diameter and circumference (fig: 3a) and the engineering parameters of importance depicted in fig: 3b. The relationships are applicable to geotextile tubes that have a maximum strain ≤15%, low unconfined creep, and are filled to maximum capacity with sand-type fill. Furthermore, it is also assumed that the foundation beneath the tube is a flat, solid surface.

Table 2. Approximate relationships between fundamental and engineering parameters of geotextile tubes (After Lawson 2003).

Engineering parameter	In terms of theoretical diameter, D	In terms of circumference, C
Maximum filled height, H	$H \approx 0.6\,D$	$H \approx 0.19\,C$
Filled width, W	$W \approx 1.4\,D$	$W \approx 0.45\,C$
Base contact width, b	$b \approx 0.9\,D$	$b \approx 0.29\,C$
Cross sectional area, A	$A \approx 0.65\,D^2$	$A \approx 0.07\,C^2$
Average vertical stress at base, σ'_v	$\sigma'_v \approx 0.72\,\gamma D$	$\sigma'_v \approx 0.24\,\gamma C$
Note: γ = bulk density of the geotextile tube fill.		

3.1.3 *Applications for geotextile tubes*

Geotextile tubes are used for a range of hydraulic and marine applications where mass-gravity barrier-type structures are required. These applications are shown in fig: 4 and described briefly below.

3.1.3.1 *Revetments, fig:4a*

Geotextile tubes are used for revetment structures where their contained fill is used to provide mass-gravity stability. They are used for both submerged as well as exposed revetments. For submerged revetments the geotextile tube is covered by local soil and is only required to provide protection when the soil cover has been eroded during periods of intermittent storm activity. Once the storm is over the revetment is covered by soil again either naturally or by maintenance filling. For exposed revetments the geotextile tube is exposed throughout its required design life.

To prevent erosion of the foundation soil in the vicinity of the geotextile tube it is common practice to install a scour apron (see fig: 4a). This scour apron usually consists of a geotextile filter layer that passes beneath the geotextile tube and is anchored at the extremity by a smaller, filled, geotextile tube.

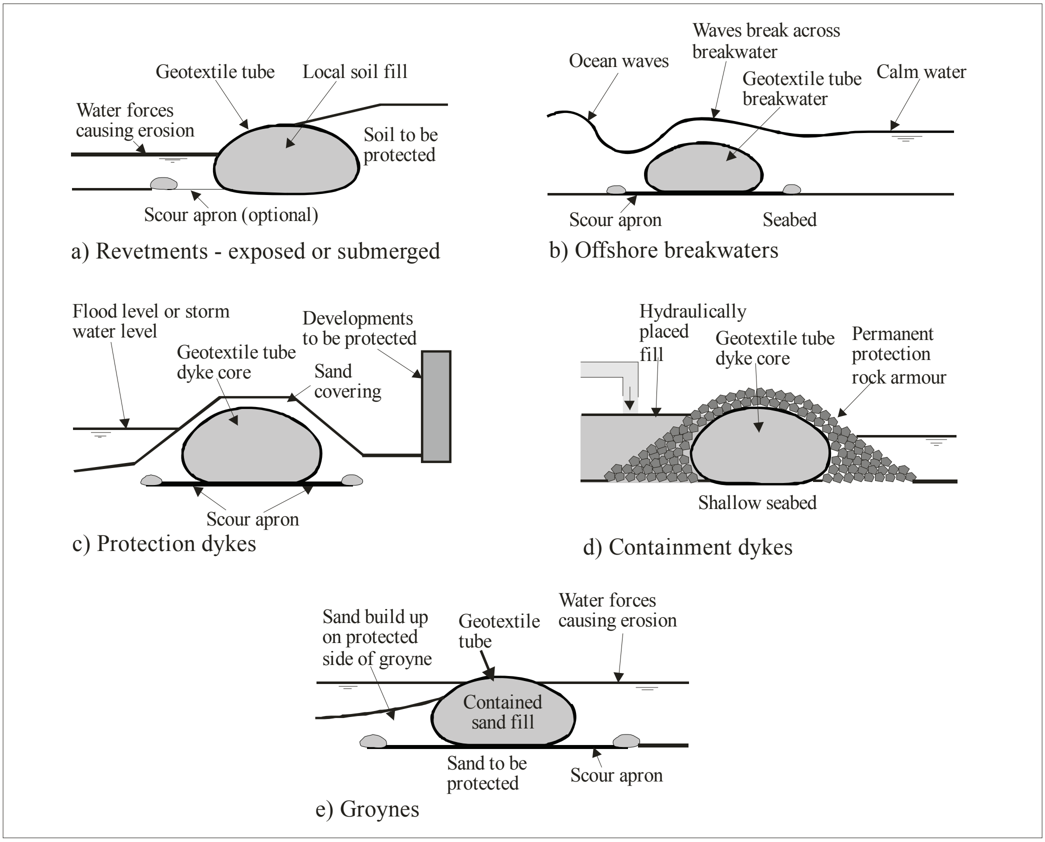


Figure 4. Hydraulic and marine applications for geotextile tubes.

Revetments are also constructed using multiple-height geotextile tubes. Here the geotextile tubes are staggered horizontally to achieve required stability. Considerable care should be exercised during construction of these types of revetments to ensure the water emanating from the hydraulic filling of the upper geotextile tubes does not erode the soil and undermine the lower geotextile tubes in the multiple-height revetment structure. Examples of use are given by Nickels & Heerten (1996) and Artières (2005).

3.1.3.2 *Offshore breakwaters, fig:4b*

Geotextile tubes are used for offshore breakwaters to prevent the erosion of shoreline developments. Here the filled geotextile tube is located a certain distance offshore in order to dissipate wave forces before they can reach the shoreline. Again, scour aprons are used beneath the geotextile tube breakwater to ensure local erosion does not undermine the breakwater structure.

In many instances the geotextile tube is left exposed which consequently affects its design life. Additional techniques or treatments may be applied to the geotextile tube breakwater to increase its exposed design life. These are discussed in more detail in section 3.1.8. Examples of use are given by Townsend (2005) and Oh et al. (2006).

3.1.3.3 *Protection dykes, fig: 4c*

Geotextile tubes are used for protection dykes where they prevent flood and storm damage to valuable structures and real estate. Protection dykes also may be used for river, lake or stream training works.

Where geotextile tube protection dykes are constructed it is common to cover the geotextile tube with local soil. The geotextile tube is only required to function intermittently during storm or flood periods when the soil cover is eroded. The use of the soil cover provides a number of advantages to the geotextile tube core. First, the soil cover hides the geotextile tube core thereby providing an aesthetic environment and ensuring no damage due to vandalism. Second, the soil cover protects the geotextile tube from long-term exposure to the atmosphere (UV degradation).

Where geotextile tubes are used for river, lake or stream training works it is common to leave the tube exposed except for major structures where rock armour layers may be placed over the geotextile tube to dissipate hydraulic forces. Where the tubes are left exposed a geotextile shroud may be used across the top of the tube, or a coating applied, to enhance its longevity in an exposed environment. Examples of use are given by Austin (1995), Fowler (1997) and Nor Hisham et al. (2006).

3.1.3.4 *Containment dykes, fig: 4d*

Geotextile tubes are used for the cores of containment dykes where water depths are relatively shallow. Here, the tube structure contains a filled reclamation area - the reclamation fill being dry dumped or placed hydraulically. The advantage of this approach is that the same hydraulic fill used in the reclamation can also be used inside the geotextile tubes for the containment dykes thus avoiding the need to import rock fill for the dykes. Where water forces dictate, and where longevity is required, rock armouring can be placed around the geotextile tube core, e.g. fig: 4d. Examples of use are given by de Bruin & Loos (1995), Spelt (2001), Fowler et al. (2002) and Yee (2002).

3.1.3.5 *Groynes, fig: 4e*

Geotextile tubes can be used as groynes to prevent the littoral movement of sediment. In most cases the geotextile tubes are left exposed, but coatings or a rock covering may be applied depending on the circumstances and the required life expectancy. Examples of use are given by Jackson (1987) and Fowler et al. (2002).

3.1.4 *Limit state design modes*

Since geotextile tubes behave as mass-gravity units the conventional approach to design follows a standard procedure of assessing the possible modes of failure or deformation in order to arrive at a safe design solution. Fig: 5 lists the various limit state modes that are assessed and these are divided into external modes (those modes affecting the performance of the geotextile tube structure overall) and internal modes (those modes affecting the performance of the internal structure of individual geotextile tubes). Either a global factor of safety or a partial factor of safety approach can be applied when assessing the various limit state modes.

3.1.4.1 *External modes*

There are six external limit state modes to be assessed, fig: 5a. These are sliding resistance, overturning resistance, bearing resistance, global stability, scour resistance and foundation settlement.

Geotextile tubes are very stable units with high base contact width to height ratios, e.g. in Table 2 b/H = 1.5. Geotextile tubes should be checked for sliding and overturning stability, especially if the tubes are of small theoretical diameter, $D \leq 2$ m.

Bearing stability (e.g. fig: 5a(iii)) may be of importance if the foundation is very soft and the geotextile tube is very large. However, experience has shown that the distribution of weight of geotextile tubes on soft foundation soils is very efficient.

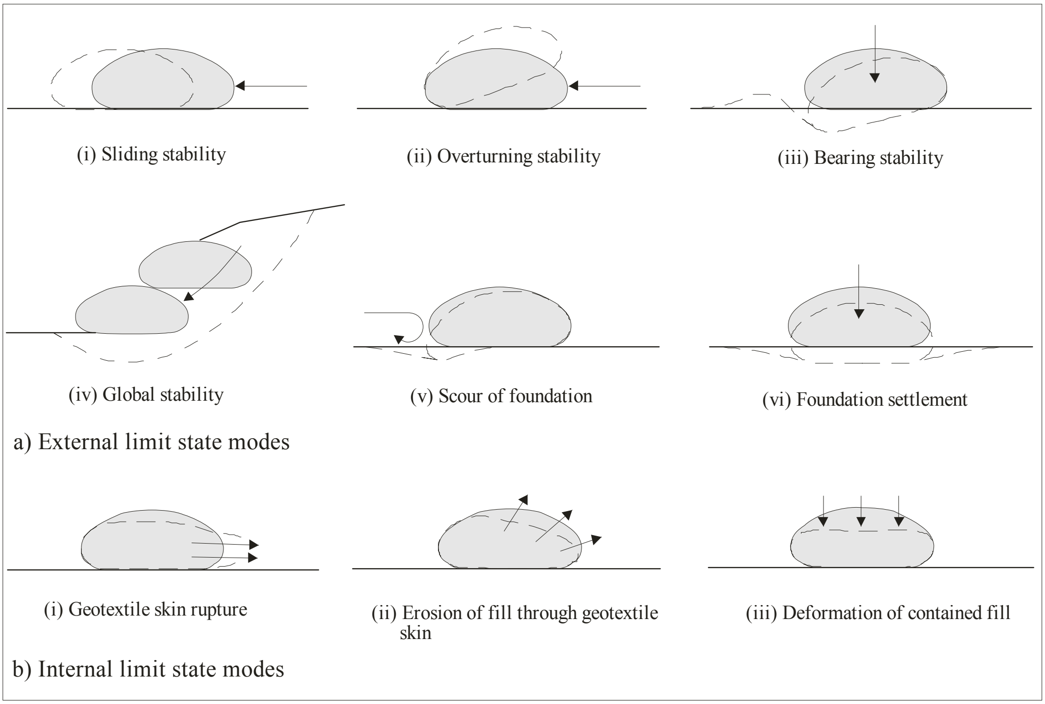


Figure 5. Limit state modes for geotextile tubes.

Global stability only needs to be taken into account when multiple geotextile tubes are used, e.g. fig: 5a(iv). Here, the stability analysis should take into account changes in both the external water level and the groundwater level within the geotextile tube structure. Also, potential weak planes between adjacent geotextile tubes should be assessed.

Scour of the foundation around the edges of geotextile tubes (e.g. fig: 5a(v)) can lead to undermining, and the geotextile tube overturning. Scour may occur either during the filling process or during the life of the tube. During filling, a large amount of water is expelled through the geotextile skin and this can cause erosion and undermining of the geotextile tube if measures are not taken to prevent this. To prevent scouring of the foundation during filling it is common practice to first install a geotextile or geomembrane layer beneath the geotextile tube prior to tube placement and filling. This procedure is very important where multiple-height geotextile tubes are installed in order to prevent the filling water of the upper tubes causing erosion and instability of the lower tubes in the structure.

Where there is potential for foundation scour during the life of the geotextile tube structure it is common practice to install a scour apron during construction, see fig: 4. The scour apron consists of a geotextile filter anchored at the extremities by means of a small diameter geotextile tube manufactured as an integral part of the geotextile filter base.

Where geotextile tubes are constructed on compressible foundations, and where they are required to meet specific height requirements for hydraulic structures (e.g. breakwaters), an assessment of the effect of foundation settlement should be performed, fig: 5a(vi).

3.1.4.2 *Internal modes*

There are three internal stability modes to be assessed, fig: 5b. These are geotextile skin rupture resistance, geotextile skin hydraulic resistance and deformation of the contained fill. These are discussed in detail in sections 3.1.5, 3.1.6 and 3.1.7.

3.1.5 *Required tensile properties of geotextile tubes*

3.1.5.1 *Tensions generated in geotextile tubes*

During the filling process and throughout the life of filled geotextile tubes tensions are generated in three areas of the tube unit, fig: 6. These locations are around the circumference of the geotextile tube ($[T]_c$), along the length, or axis, of the geotextile tube ($[T]_a$) and at the connection of the filling ports with the geotextile tube ($[T]_p$).

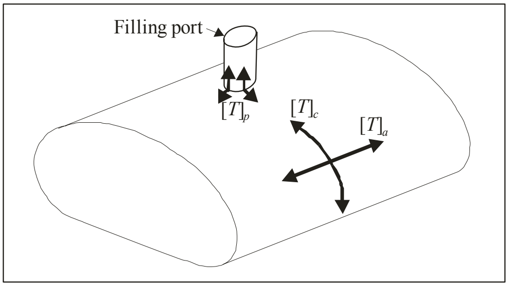


Figure 6. Locations of tensions generated in geotextile tubes.

The analysis of tensions generated in geotextile tubes is complicated due to the effect of geotextile tube geometry. Further, the fill contained within geotextile tubes starts as a liquid, i.e. with zero shear strength, and then over time reverts to a solid, i.e. with internal shear strength. This change in phase of the contained fill, the amount of filling and pumping pressure applied, and the time over which the contained fill changes in phase all affect the magnitudes of the tensions generated in geotextile tubes. For hydraulic and marine structures where the contained fill consists of sand, the time it takes to change to a solid material is very short (unlike finer fills) and thus analysis methods based on the assumption of a shear resistant fill are more appropriate for this type of application.

The procedure normally used to determine the tensions in geotextile tubes is to first determine the circumferential tension $[T]_c$, then the axial tension $[T]_a$, and finally the port connection tension $[T]_p$.

Two approaches have been used to analyse the circumferential tensions generated in geotextile tubes. These are membrane theory and continuum mechanics.

Membrane theory methods have been proposed by a number of researchers, e.g. Liu (1981), Kazimierowicz (1994), Leschinsky et al. (1996) and Palmerton (2002). An important feature of membrane theory methods is that the contained fill is assumed to act as a liquid with no internal shear resistance. The filling procedure can be modelled along with the resulting filled shape. While these methods appear to reasonably determine the filled shape of geotextile tubes, they do not determine the circumferential tension in the geotextile skin too well where sand is used as the confined fill. The reason for this is that sand fill reverts to a solid phase relatively quickly once entering the geotextile tube, with the subsequent stresses acting on the geotextile skin quite different to that when in the liquid phase. The author has found that the procedure proposed by Palmerton (2002) appears to provide the most reasonable results when calculating maximum circumferential tensions in filled geotextile tubes.

Continuum mechanics have also been used to model geotextile tube behaviour, e.g. Seay (1998) and Cantré (2002). While this approach can model the tension distribution around the circumference of a geotextile tube containing a shear resistant fill, it is virtually impossible to model the filling process, which also affects the final filled shape and consequently the geotextile skin tensions. Where continuum methods have proved very beneficial is in the modelling of settlements of geotextile tube structures on soft foundations as they can account for the complex vertical stress distribution at the base of a filled geotextile tube reasonably well.

Fig: 7 shows the maximum circumferential tension $[T_{max}]_c$ for filled geotextile tubes having theoretical diameters D = 3.0 m, 4.0 m and 5.0 m using the procedure of Palmerton (2002). As noted in Table 2 the maximum filling height is $H \approx 0.6D$, which results in maximum circumferential tensions $[T_{max}]_c$ of 22 kN/m, 39 kN/m and 61 kN/m respectively for the three geotextile tube sizes.

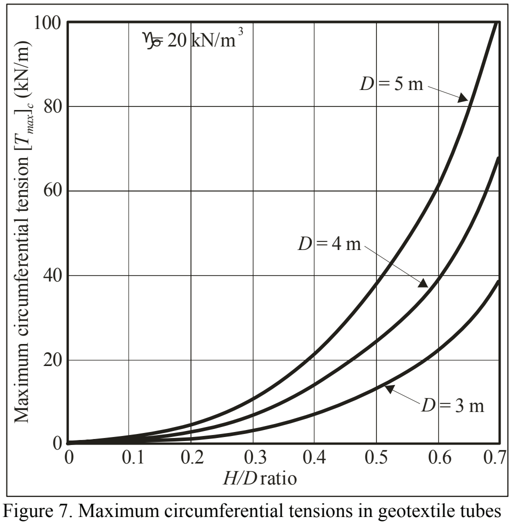
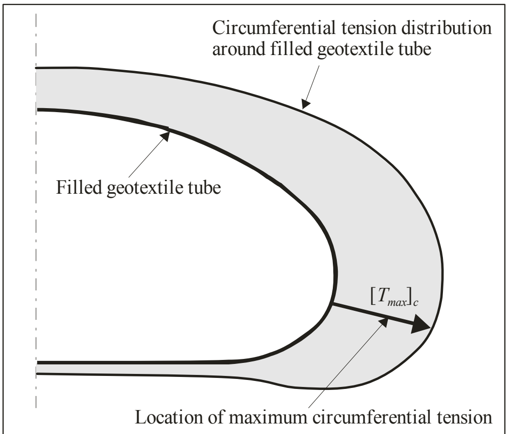
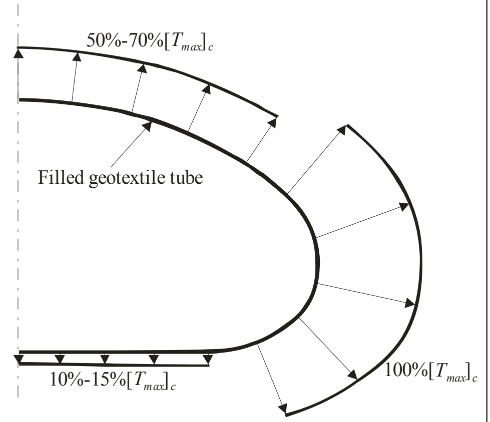


Figure 7. Maximum circumferential tensions in geotextile tubes according to Palmerton (2002).

The magnitude of the circumferential tension around a filled geotextile tube is a function of the curvature of the geotextile skin, with the highest tension $[T_{max}]_c$ coinciding with the location of highest curvature. This occurs at the sides of the filled geotextile tubes, fig: 8a. Elsewhere around the filled geotextile tube the circumferential tension is lower, and especially across the base of the geotextile tube where the circumferential tension is very low because the geotextile skin is essentially flat in this location.



a) Circumferential tension distribution around a filled geotextile tube



b) Approximation of circumferential tension distribution in terms of $[T_{max}]$

Figure 8. Distribution of circumferential tensions around the exterior of filled geotextile tubes.

Fig: 8b shows an approximation of the distribution in circumferential tension expressed in terms of the percentage of the maximum circumferential tension $[T_{max}]_c$. When designing a geotextile tube the magnitude of the circumferential tension and its location needs to be kept in mind when seaming geotextile sheets together to form the resulting geotextile tube.

The axial tensions generated along the length of filled geotextile tubes are a function of the filling pressure and the height of the tube. Fig: 9 shows the maximum axial tension $[T_{max}]_a$ expressed in terms of the maximum circumferential tension $[T_{max}]_c$ using the procedure of Palmerton (2002). A relationship of $[T_{max}]_a = 0.63\ [T_{max}]_c$ would appear a very good fit.

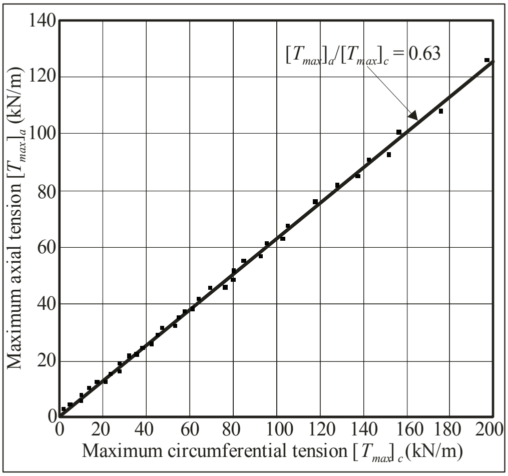


Figure 9. Maximum axial tensions in geotextile tubes according to Palmerton (2002).

The magnitude of the port connection tension $[T]_p$ is a function of the filling pressure and the height of the geotextile tube. In general, $[T]_p \approx 0.3\ [T_{max}]_c$.

3.1.5.2 *Integrity of geotextile tube seams*

Geotextile tubes are manufactured by seaming together sheets of geotextile. Thus, the integrity of geotextile tube seams is crucial to the performance of the tube. Not only are the seams required to meet specific strengths but are also required to do this without the seams separating and thus allowing loss of hydraulic fill during the filling process.

The use of special seaming technology to produce high capacity seams and the judicious location of seams both combine to produce a geotextile tube that must meet the tension requirements in all locations.

3.1.5.3 *Ultimate strength requirements of geotextile tubes*

The geotextile tube skin and its component parts must have adequate tensile strengths to resist the tensions generated during the filling process and throughout the life of the filled geotextile tube. The required ultimate tensile strength of the geotextile tube skin (including geotextile and any seams) is:

$$[T_u]_c \, or [T_u]_a \geq FS\left([T]_c \, or [T]_a\right) \tag{1}$$

Where, T_u = ultimate tensile strength required in the circumferential or axial direction of the geotextile tube; T = tensions at locations around the geotextile tube skin in the circumferential or axial direction; FS = global factor of safety.

The global factor of safety FS must account for factors, such as, unknowns in the determination of geotextile skin tensions, creep of geotextile and seams, seam strength inefficiencies, durability, etc. Unless a specific analysis is undertaken of the various factors that comprise FS a default value of 4.0 to 5.0 is normally applied.

3.1.6 *Required hydraulic properties of geotextile tubes*

Geotextile tubes are constructed to perform in a variety of hydraulic environments ranging from still or slow moving water, to fast moving currents, to wave environments. In many of these applications the geotextile tube skin is exposed directly to the hydraulic environment. Two aspects of the hydraulic environment should be taken into account when considering the use of geotextile tubes. These are the type of hydraulic regime acting on the geotextile tube and the time period of exposure to the hydraulic regime. As stated already, a variety of hydraulic regimes can act on geotextile tubes depending on their use. The severity of these hydraulic regimes governs the hydraulic properties of the geotextile skin as well as whether the geotextile tube can perform suitably in an unprotected manner (i.e. with the geotextile skin exposed directly to the hydraulic regime). The time period of exposure can also have an effect on the severity of the hydraulic environment, for example, exposure to intermittent storm activity will not have the same effect as continual exposure to the same types of waves. Table 3 summarizes the recommended hydraulic properties of the geotextile skin, and whether additional protection measures are required, according to the mode of hydraulic regime and the period of exposure. For the purposes of Table 3, intermittent exposure refers to exposure for several days at a time to the specific hydraulic regime (not for several weeks or months). An example would be the effects of storm activity that is periodic but only acts over a short period of time.

Table 3 indicates that geotextile tubes can perform in an exposed state in a variety of hydraulic regimes except where continual water currents greater than 1.5 m/s and continual wave heights > 1.5 m occur. In these extreme hydraulic environments additional protection is required in order for the geotextile tube to perform acceptably. Examples of additional protection measures can be rock armour or wire gabions and mattresses placed around the exposed surface of the geotextile tube. At the low end of the performance spectrum an additional sacrificial covering may be used. These additional protection measures dissipate much of the hydraulic forces before they reach the geotextile tube skin. For other, less intense, hydraulic regimes described in Table 3, the geotextile tube may perform well structurally in an unprotected state, but some loss in serviceability (i.e. change in shape) may occur over time.

Table 3. Geotextile hydraulic properties and required protection according to hydraulic regime for geotextile tubes.

Hydraulic regime	Period of exposure to hydraulic regime	
	Intermittent	Continual
Still, or slow moving water	No protection required. $AOS \leq 0.5$ mm $q_{n,100} \geq 10$ L/m^2.s	No protection required. $AOS \leq 0.5$ mm $q_{n,100} \geq 10$ L/m^2.s
Water current < 1.5 m/s	No protection required. $AOS \leq D_{85}$ fill $q_{n,100} \geq 10$ L/m^2.s	No protection required. $AOS \leq D_{85}$ fill $q_{n,100} \geq 30$ L/m^2.s
Water current ≥ 1.5 m/s	No protection required, but some change in shape may occur after repeated events. $AOS \leq D_{85}$ fill $q_{n,100} \geq 30$ L/m^2.s	Protection required and some change in shape may occur. $AOS \leq D_{50}$ fill $q_{n,100} \geq 30$ L/m^2.s
Waves < 1.5 m	No protection required. $AOS \leq D_{50}$ fill $q_{n,100} \geq 30$ L/m^2.s	No protection required, but change in shape may occur over time. $AOS \leq D_{50}$ fill $q_{n,100} \geq 30$ L/m^2.s
Waves ≥ 1.5 m	No protection required, but considerable change in shape may occur after repeated events. $AOS \leq D_{50}$ fill $q_{n,100} \geq 30$ L/m^2.s	Protection required and change in shape may occur. $AOS \leq D_{50}$ fill $q_{n,100} \geq 30$ L/m^2.s
Note: AOS = apparent opening size of the geotextile tube skin; $q_{n,100}$ = volume flow rate at 100 mm constant head through the geotextile tube skin.		

3.1.7 *Deformations of geotextile tubes*

Geotextile tube structures can undergo deformation due to scour of the foundation beneath the tubes and due to deformation of the contained fill within the geotextile tubes. In this section consideration is given to deformation of the contained fill only.

Deformations of the contained fill can arise due to the following:

- incomplete filling of the geotextile tubes;
- liquefaction of the contained fill;
- the contained fill undergoes consolidation;
- the geotextile skin continues to deform over time.

Incomplete filling of geotextile tubes can result in deformations which may be exacerbated by liquefaction of the sand fill due to wave activity. Good filling practice must be observed in order to ensure the sand fill is in a dense, confined state.

For hydraulic and marine structures sand fill is used inside geotextile tubes. This fill type is relatively incompressible and, provided it achieves good density within the geotextile tube, will not undergo consolidation.

The geotextile skin must have good tensile strength and stiffness in order to maintain the sand fill in a confined state. The geotextile skin should not undergo elongation or relaxation over time, which then allows the sand fill to deform, and the geotextile tube to lose its shape and height.

3.1.8 *Protection measures applied to geotextile tubes*

External protection measures are applied to geotextile tubes for a variety of reasons, namely:

- to reduce the impact of the hydraulic forces acting directly on the geotextile tube;
- to enhance the design life of the geotextile tube in an exposed environment;
- to protect from extreme natural occurrences, e.g. ice flows, etc;
- to protect from vandalism.

Section 3.1.6 discusses the types of protection measures used to reduce the impact of hydraulic forces.

In many instances geotextile tubes are required to perform over a relatively long design life in an exposed environment. In this environment UV degradation can occur, with the geotextile tube design life dependent on the level of UV radiation and the resistance of the geotextile tube skin to this radiation. If the geotextile tube is located in a marine environment, marine growth generally occurs quickly on the outer surface and this tends to mask the geotextile skin somewhat from the effects of UV radiation. However, for good long term performance in an exposed environment additional protection measures are normally required for the geotextile tube skin. These measures are listed below in order of providing longer term performance.

- Additional stabilizer packages in the geotextile tube skin – where the enhanced performance of the stabilizer package improves the performance of the geotextile tube skin over time.
- More robust, or multi-layer geotextile skin – where extra design life is achieved by the use of more robust or multi-layer geotextile skins that degrade over a longer period of time.
- Geotextile shrouds - where the outer geotextile shroud provides protection for the inner geotextile tube skin. The geotextile shroud becomes sacrificial over the design life of the geotextile tube structure. These are used where the geotextile tube structure is continually exposed to the environment and where the hydraulic forces are not severe.
- Geotextile coating – where a robust coating is applied to the geotextile tube to protect it. Coatings can be applied in a variety of colours.
- Soil covering – where the geotextile tube is covered by soil or sand to prevent long term UV exposure. Here the geotextile tube structure performs intermittently during periods of storm activity and is then covered over again by soil or sand.
- Armour covering – where a flexible armour covering is used around the geotextile tube structure to prevent long term exposure to UV light. This is normally used in hydraulic and marine applications where severe hydraulic forces occur.

Extreme natural occurrences can also affect the long term performance of exposed geotextile tubes. Examples include the damaging effects of ice flows, and trees carried in water during floods, on the exposed surface of geotextile tubes. Where this is known to be a problem then the geotextile tube structure must be protected. The form of protection from this type of exposure is normally armour covering.

Vandalism can also affect the long term performance of geotextile tubes. This type of damage is normally in the form of localised cuts and tears. The best way of protecting against this likelihood is to cover the geotextile tube so it is out of sight. Alternatively, robust coatings can be applied which prevent vandalism. Failing this, a good maintenance scheme should be put in place to correct any acts of vandalism.

3.1.9 *Geotextile tubes for Naviduct Project, Enkhuizen, The Netherlands*

This project, originally reported on by Spelt (2001) and Lawson (2003), is an example where geotextile tubes were used for containment dykes in an environmentally sensitive lake in The Netherlands.

The Krabbersgat Lock at Enkhuizen is an important bottleneck in the main network of waterways in The Netherlands. Due to an increase in shipping and road traffic at the lock significant time delays were occurring for both shipping and road transport. To ensure smooth movement of shipping and road traffic it was decided to construct a combination of an aqueduct and a lock below which a tunnel for road traffic could pass (this structure is known as a “Naviduct”).

For cost and environmental reasons a crescent-shaped containment area was constructed in the lake adjacent to the Naviduct site. This containment area acted as a local disposal for the spoil material from the adjacent construction site. Once finished, the partially filled containment area will be vegetated and will act as a bird sanctuary. Further, the crescent-shape of the containment area is to act as a barrier to drifting ice during winter.

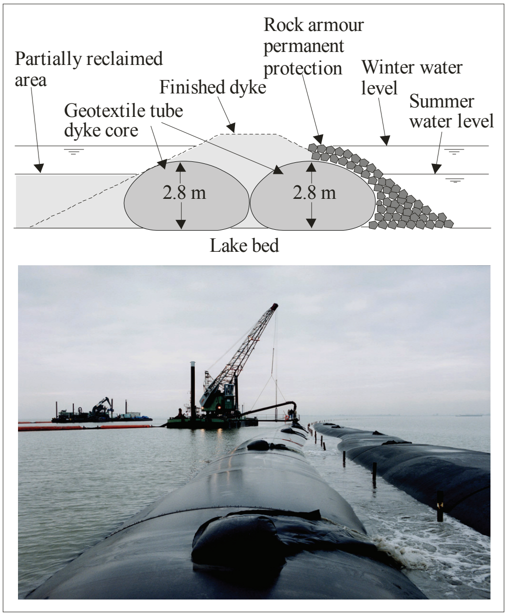


Figure 10. Use of geotextile tubes to construct containment dyke, Naviduct project, Enkhuizen, The Netherlands.

The construction of the containment dykes was carried out using a double layer of geotextile tubes of filled height 2.8 m, fig: 10. The reason why geotextile tubes were used for the containment dykes was because the locally available sand fill from the Naviduct site was too fine and uniform to be used by itself as the structural component of the containment dykes. Instead, the geotextile tubes were filled with the local fine sand, and this provided the structural basis for the containment dykes.

The crescent-shaped containment area utilized 7.5 km of geotextile tubes, two abreast, in the containment dyke. Before placement of the geotextile tubes a geotextile filter layer was placed on the lake bed at the base of the containment dykes for erosion control purposes. The geotextile tubes were laid out in the water, anchored in place, and then filled by connecting the exit pipe of the dredger directly into the inlets of the geotextile tubes.

Once filled, the geotextile tubes were covered with a geotextile shroud to protect the tube from long-term UV exposure. On the outside of the containment dyke the tubes were covered with rock armour for the final protection, fig: 10. Finally, the dyke was raised to its finished height by using the local fine sand fill, and vegetated.

3.2 *Geotextile containers*

Geotextile containers, as already stated, are large-volume containers that are filled above water and then positioned and placed at water depth. The volumes of these containers commonly range from 100 m^3 to 700 m^3.

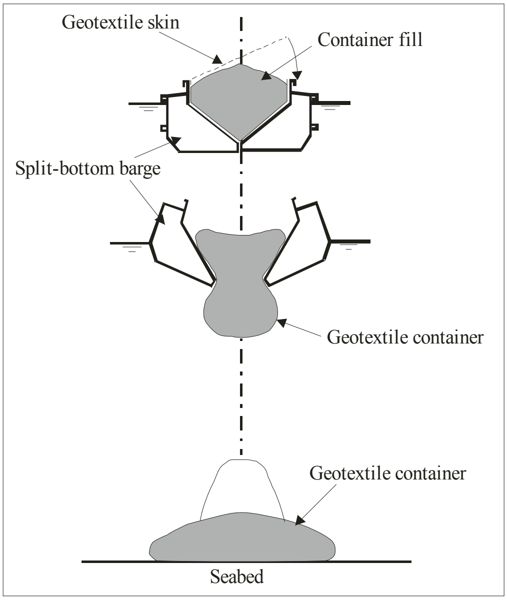


Figure 11. Installation procedure for geotextile containers (After Pilarczyk 2000).

The procedure for installation of geotextile containers is shown in fig: 11. This entails the filling of the geotextile container in a split-bottom barge; the container is then sealed and the barge positioned at the correct dumping location. The split-bottom barge opens and the geotextile container passes through and descends through the water to the seabed.

Depending on its source, the container fill can be dry-dumped, wet-dumped or hydraulically pumped into the container. The types of fills placed in geotextile containers have ranged from mixed soil (ranging from small boulders to sandy silt) to sand to overconsolidated clay.

3.2.1 *Engineering features of geotextile containers*

Geotextile containers are used as mass-gravity, structural components in hydraulic and marine applications. Once installed, the containers are required to maintain volume and shape stability over the required design life of the overall structure.

For hydraulic and marine applications the volumes of the geotextile containers are normally limited to less than 400 cubic metres to ensure a well-defined shape results. Further, the installation depths are normally limited to less than 20 m, as these types of structures are commonly located at relatively shallow water depths. The type of fill used is sand, or a high percentage of sand, to ensure long-term volume and shape stability of the installed containers. The use of this type of fill also reduces the tensions generated in the geotextile skin during installation as considerable drop energy is absorbed by the shear resistance of the fill.

To create effective submarine structures geotextile containers must be installed to defined accuracies and tolerances, especially if multiple container layers are required. Herein lies one of the major limitations of this technique because placing accuracy is dependent on a number of factors that may be difficult to control on site. These include accuracy of barge location and orientation, water currents, placing depths, seabed conditions, etc. Several of the factors affecting geotextile container placement have been studied by Bezuijen et al. (2002b) and Bezuijen et al. (2005).

Bezuijen et al. (2005) also has investigated the stability of multiple geotextile container layers and has presented calculation models for this.

3.2.2 *Applications for geotextile containers*

Geotextile containers are used for a range of hydraulic and marine applications where submarine mass-gravity support or barrier type structures are required. These are shown in fig: 12 and described briefly below.

3.2.2.1 *Offshore breakwaters, fig:12a*

Geotextile containers are used as part of offshore breakwaters to prevent the erosion of the shoreline. The technique here is the same as that for geotextile tube offshore breakwaters except that geotextile containers are used at greater water depth and a rock covering is normally placed across the top of the containers to raise the breakwater to its required height.

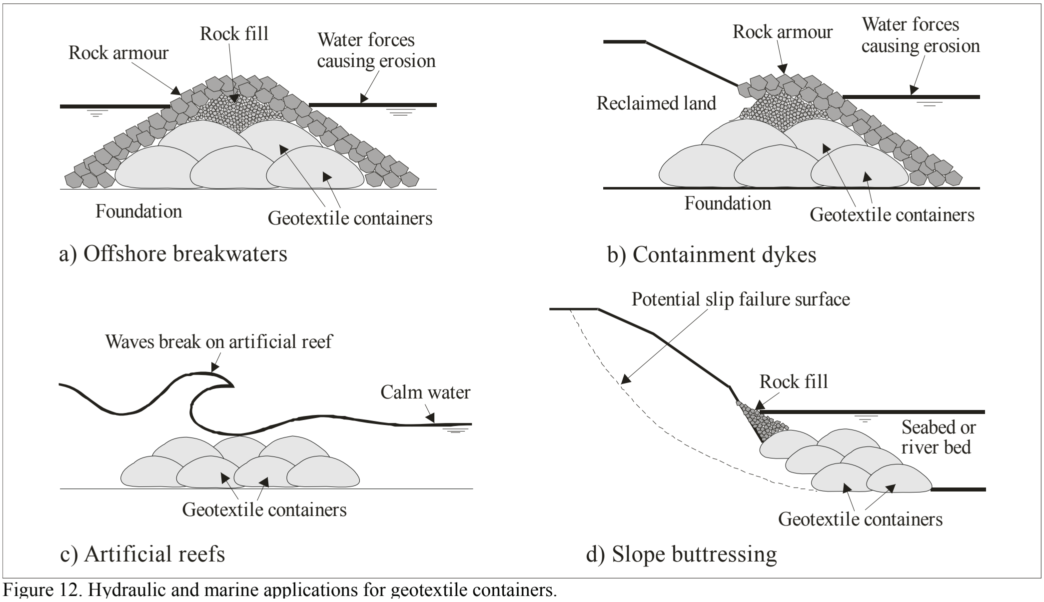


Figure 12. Hydraulic and marine applications for geotextile containers.

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3.2.2.2 *Containment dykes, fig: 12b*

Geotextile containers are used for containment dykes where the water depth facilitates the placement of the containers. The technique is the same as that for geotextile tubes except that the geotextile containers are used at greater water depth. A rock covering is normally placed across the top and down the outer face of the geotextile containers to raise the containment dyke above water level. Where the dyke is to remain submerged geotextile containers may be the sole units. Examples of use are given by Wei et al. (2001), Yee (2002) and Bezuijen et al. (2002a).

3.2.2.3 *Artificial reefs, fig: 12c*

Geotextile containers can be used to construct artificial reefs. Here, the containers provide a raised platform (a reef) that forces waves to break over the top of the reef. This prevents erosion of the protected shoreline.

As well as dissipating wave energy artificial reefs also can be used to refract waves and alter the normal waveform. However, to do this successfully requires the reef to be constructed to a specific plan geometry with specific side slopes and platform height. This level of placement accuracy is normally outside the limits of large-volume geotextile container placement, and is more suited to the application of smaller-volume geotextile bags.

Further, the nature of geotextile containers makes it difficult to fill them to maximum volume and density. Consequently, it is to be expected that if the filled geotextile containers are to be exposed to continual wave activity then liquefaction of the sand fill will cause a change in shape of the exposed containers and a subsequent lowering of the surface level of the artificial reef. This then alters the shape of the waveform across the top of the reef, and thus the structure may require periodic maintenance to maintain the existing waveform. Examples of use are given by Fowler et al. (1995a), Black (1998) and Restall et al. (2002).

3.2.2.4 *Slope buttressing, fig: 12d*

Geotextile containers are used for the underwater buttressing of unstable slopes. Here, the weight of the geotextile containers is utilized to provide a counter-weight to a potentially unstable slope. The advantage of using geotextile containers is that a "soft" buttress structure is provided that won't damage shipping. An example of use is given by Jagt (1988).

3.2.3 *Tensions generated in geotextile containers and ultimate tensile strength requirements*

The tensions generated in a geotextile container vary throughout the installation procedure. Fig: 13 shows the five stages of geotextile container installation, namely; filling of the geotextile container in the barge; reshaping of the geotextile container to exit the barge; free-fall of the geotextile container through the water; impact of the geotextile container on the seabed; and the installed shape of the geotextile container on the seabed. All five installation stages generate different tensions in the geotextile container as shown in fig: 13. These are discussed in further detail below.

The tensions developed in geotextile containers are complex and are dependent on many factors. Several researchers have attempted to quantify the tensions generated in geotextile containers during installation. Bezuijen et al. (2005) summarises the relationships developed by a number of Dutch researchers using analytical models to calculate geotextile container tensions during the installation procedure. An analytical calculation is provided to describe each of the installation stages shown in fig: 13. Palmerton (2002) has applied the distinct element method to model the procedure of geotextile container installation. While in its early stages of development, this method shows particular promise as it can model all stages of installation in one progressive modelling process.

3.2.3.1 *Filling of geotextile container in barge*

The first stage of geotextile container installation involves the laying out of the container in the split-bottom barge, its filling, and the final sealing of the geotextile container. The tensions generated in the geotextile container are relatively low during this stage and are due primarily to draw-down of the container in the barge during filling. De-stressing the container during filling can alleviate much of these tensions.

3.2.3.2 *Reshaping of geotextile container to exit barge*

As the split-bottom barge opens the geotextile container undergoes a change in shape in order to exit the barge, fig: 13. This change in shape and the exiting of the container creates significant tensions in the geotextile skin.

The magnitude of the tensions generated in the geotextile skin of the container is affected by the following:

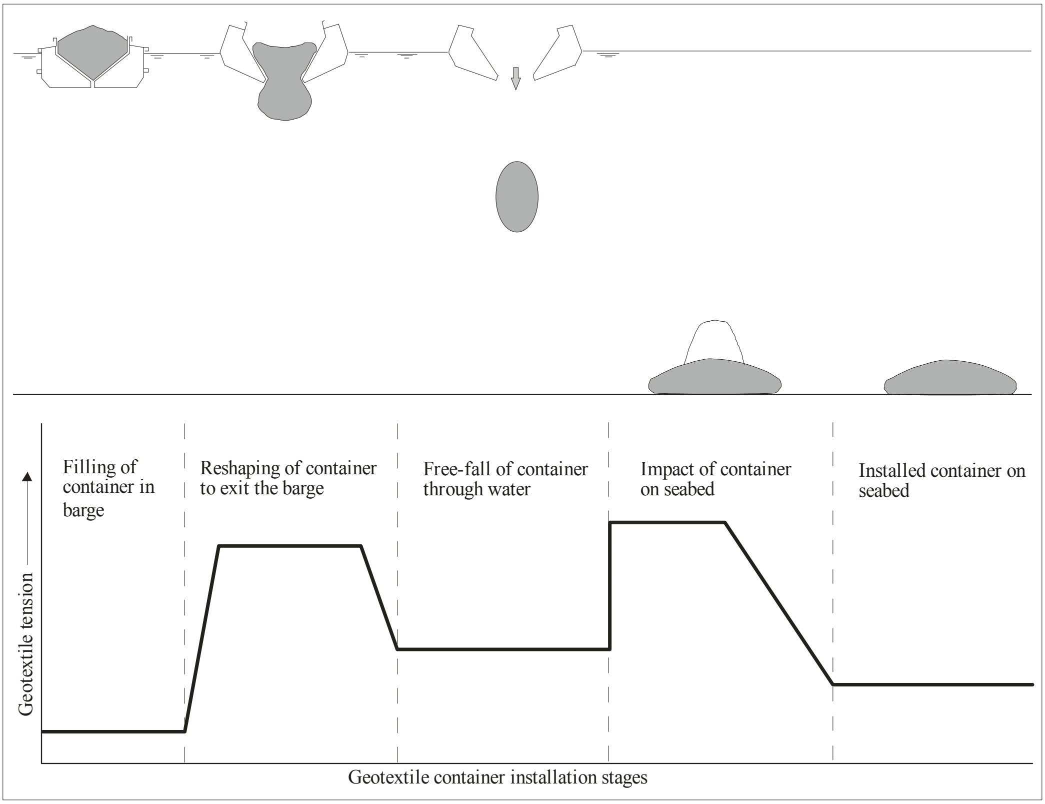

Figure 13. Geotextile tensions generated at various stages of geotextile container installation.

- The ratio of the internal width of the barge to the width of the opening in the split-bottom barge.
- The speed of opening of the split-bottom barge.
- The surface condition of the inside of the barge.
- The surface condition of the gate in the split-bottom barge.

The change in shape of the geotextile container is minimised if the split-bottom barge can open quickly to an amount equivalent to its internal width. In practice, this is not possible as the most common split-bottom barges open slowly and only by an amount approaching 50% of the internal width. Thus, to exit the barge, the geotextile container has to undergo a considerable change in shape, which can generate significant tensions in the geotextile skin.

When exiting the barge, frictional forces are generated between the inner surface of the barge and the geotextile container. This increases further the tensions generated in the container. To minimise the effects of friction the inner surface of the barge should be smooth, or alternatively, a woven geotextile sheet should be used on the inner barge surface to decrease friction effects.

The narrowest point of exit of the geotextile container occurs at the lips of the barge. Here the condition of the lips of the barge greatly influences the localised tensions generated in the geotextile skin. For best performance the lips should be smooth and free of any sharp surfaces and rough surfaces.

Three-dimensional effects also generate tensions in the geotextile container when exiting the barge. The rate of exit is generally not the same along the length of the container. This causes the filled container to bend which generates significant tensions in the geotextile skin along its length. This effect can be reduced by decreasing the length of the containers in relation to their diameter and closely controlling the filling of the container.

3.2.3.3 *Free-fall of geotextile container through water*

On exiting the barge the geotextile container falls through the water gaining in velocity. If the depth of

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water is great enough then the container may reach a terminal velocity before reaching the seabed floor. Normally, terminal velocity is reached within 10 m of exiting the barge. The magnitude of terminal velocity of the geotextile container depends on the type of fill used (whether it is wet or dry) and the amount of drag on the container, but is normally between 5 and 8 m/s.

During fall, tensions are generated in the geotextile container due to balancing the forces of fill weight, buoyancy, drag, etc.

3.2.3.4 *Impact of geotextile container on seabed*

As the geotextile container falls through the water it gains in energy. On impacting the seabed floor this energy is dissipated instantaneously in the form of a change in shape of the geotextile container (it flattens) with a resulting quick increase in tension in the geotextile skin, fig: 13.

The magnitude of the tensions generated in the geotextile skin of the container on impacting the seabed is affected by the following:

- The mass, i.e. size, of the container.
- The velocity at impact.
- The container angle at impact.
- The internal shear resistance of the container fill.
- The condition of the seabed at impact.

The size of the container and its velocity at impact generate energy that is dissipated by a change in shape of the container and an increase in tensions in the container skin. The size of the containers is normally decided on the basis of balancing the geometry of the overall container structure with the availability of suitable split-bottom barge sizes. For most hydraulic and marine applications this results in container sizes ranging between 100 m^3 and 700 m^3.

The greater the water depth the greater the velocity of the geotextile container at impact up until a terminal velocity is reached. As stated in section 3.2.3.3 terminal velocity occurs at around 10 m of water depth, thus the impact energy should not increase for water depths greater than this.

If the container remains horizontal during fall then this generates lower tensions in the geotextile skin on impact with the seabed. However, if the container impacts at an angle then greater localized tensions are generated. For best performance it is important for the container to remain near horizontal during fall. Reasons for angled fall of containers are uneven distribution of fill in the containers, uneven exit from the split-bottom barge and water currents during fall. Obviously, greater water depth allows more opportunity for the falling container to change alignment.

The internal shear resistance of the container fill helps to dissipate the energy resulting from seabed impact. The change in shape of the installed container will not be as extensive if the container fill consists of granular material compared to soft clay, and thus, the tensions generated will not be as great. For hydraulic and marine structures the fill within geotextile containers is normally always granular material, e.g. sand.

If the seabed is soft then there will be some cushioning for the container when it impacts the seabed. This results in lower induced tensions than if the seabed had a hard and/or rough surface.

3.2.3.5 *Installed shape of geotextile container on seabed*

Once settled on the seabed floor the geotextile container assumes its final shape, fig: 13. The final shape attained depends on a number of interrelated factors, namely:

- The volume/unit length of the geotextile container.
- The amount of fill placed in the geotextile container compared to the container volume.
- The internal shear resistance of the container fill.
- The tensile stiffness of the geotextile skin.

The greater the volume/unit length of the geotextile container the greater the height of the contained fill on the seabed (in conjunction with the other factors listed here). But, the greater the volume/unit length the greater the tensions generated in the geotextile skin during installation.

The height of the contained fill on the seabed will be reduced if the amount of fill placed in the geotextile container is less than the container volume. But, the tensions generated in the geotextile skin will be reduced if the amount of fill is reduced.

As stated in section 3.2.3.4 the internal shear resistance of the contained fill helps to dissipate the container impact energy and so affects the final shape of the contained fill on the seabed. Sand and other granular fills are used for hydraulic and marine structures as these have good internal shear resistance and thus maximise the height of the contained fill once installed.

The geotextile skin should have adequate tensile stiffness to provide some confinement to the contained fill. This prevents the contained fill from spreading over time and the resulting structure losing height.

3.2.3.6 *Ultimate tensile strength requirements of geotextile containers*

Fig: 13 shows the relative tensions generated in the geotextile skin of the container during the various installation stages. The highest tensions are generated during the exiting of the container from the split-bottom barge and impacting of the container on the seabed. Specific individual circumstances will dictate which of these two stages generates the highest tensions for a particular project.

As stated previously, the tensions generated in geotextile containers are complex and are dependent on many factors. Analytical solutions that exist to calculate the tensions in geotextile containers, e.g. Bezuijen et al. (2005), require the application of large factors of safety (around 4.0 to 5.0) to determine the required tensile strengths of the geotextile skin. This is to account for the many unknowns. High tensile strengths are required in both the circumferential and the longitudinal directions of the geotextile skin. Geotextile strengths of 100 kN/m to 200 kN/m along with high capacity seams are common for geotextile containers.

3.2.4 *Effect of different hydraulic environments on geotextile containers*

Geotextile containers are required to perform in a variety of hydraulic environments as evidenced by the applications shown in fig: 12. For the majority of applications the geotextile containers are either part of a larger mass-gravity structure or are located at some water depth beneath the surface. In these instances the hydraulic forces acting directly on the geotextile containers are limited and as such the geotextile skin only has to have limited hydraulic properties.

However, where geotextile containers are located in the vicinity of breaking waves and high water flows special attention should be paid to the long term performance of the containers for the following reasons. First, geotextile containers, unlike geotextile tubes, cannot be filled to maximum density with sand fill and consequently, are more prone to liquefaction and change of shape over time. This change in shape may result in a critical loss of height of the structure. Second, consideration needs to be given to the required hydraulic properties of the geotextile container skin to ensure the container fill is not eroded out of the container. The relationships given in Table 3 for geotextile tubes also apply to geotextile containers when subjected to the same hydraulic conditions.

Where the hydraulic regime is severe additional protection measures may be warranted. These normally involve the use of armour layers to protect the geotextile container structure. In some instances it may be impractical to use armour layers to enhance the protection for geotextile containers. An example of this is where geotextile containers are used for artificial reefs that also serve as surfing reefs. Here armour protection is a safety hazard to surfers and cannot be used. Consequently, a more robust geotextile skin is normally used for the containers in addition to a commensurate future maintenance programme. For these types of structures a limited design life is accepted.

3.2.5 *Protection measures applied to geotextile containers*

External protection measures are applied to geotextile containers for two reasons, namely:

- To reduce the impact of the hydraulic forces acting directly on the geotextile containers;
- To enhance the design life of the geotextile container in an exposed environment.

Section 3.2.4 discusses the types of protection measures used to reduce the impact of hydraulic forces.

In a number of instances geotextile containers may be required to perform over a relatively long design life in an exposed environment. In this environment UV degradation can occur, with the geotextile container design life dependent on the level of UV radiation and the resistance of the geotextile container skin to this radiation. If the geotextile container is located in a healthy aquatic environment, marine growth generally occurs quickly on the outer surface and this tends to mask the geotextile skin from the effects of UV radiation. However, for good long term performance in an exposed environment additional protection measures are normally required for the geotextile container skin. These measures are listed below in order of providing longer term performance.

- Additional stabilizer packages in the geotextile container skin – where the enhanced performance of the stabilizer package improves the performance of the geotextile container skin over time.
- More robust geotextile skin – where extra design life is achieved by the use of more robust geotextile skins that degrade over a longer period of time.
- Geotextile coating – where a robust coating is applied to the geotextile container to protect it.
- Armour covering – where a flexible armour covering is used around the geotextile container structure to prevent long term exposure to UV light. This is normally used in hydraulic and marine

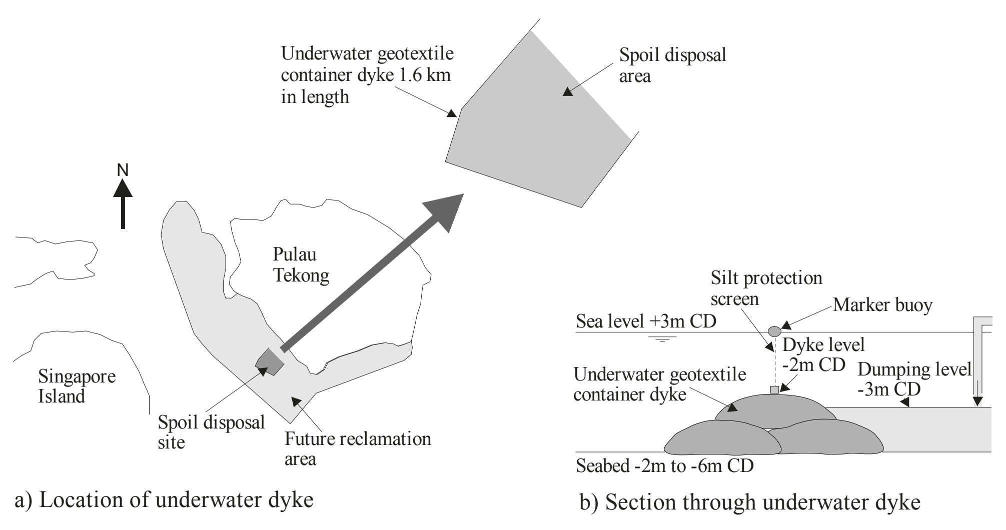


Figure 14. Geotextile containers to construct underwater containment dyke, Pulau Tekong offshore disposal site, Singapore.

applications where severe hydraulic forces are possible, and where long design life is required.

3.2.6 *Geotextile containers for Pulau Tekong offshore disposal site, Singapore.*

Singapore is an island nation located at the Southern tip of Peninsular Malaysia in Southeast Asia. Economic and developmental expansion has necessitated the large-scale adoption of land reclamation schemes. Offshore spoil disposal sites are also a necessity because of the lack of land area. A major offshore disposal site, South of Pulau Tekong, was constructed during 2001 to contain spoil from foundation excavations at a major reclamation project, Southern Islands, South of Singapore. This project has already been reported on in detail by Wei et al. (2001) and Yee (2002), consequently, it is proposed to paraphrase this project here for illustrative purposes.

The location of the offshore disposal site at Pulau Tekong to the East of Singapore Island is shown in fig: 14a. To accommodate the spoil from the Southern Islands reclamation site the disposal site required a capacity of 420,000 m^3 (45 hectares in plan area). This was accomplished by the construction of a 1.6 km long, U-shaped, underwater containment dyke around the spoil disposal area.

Sand dykes, instead of rock dykes, were judged the appropriate type of containment structure because underwater rock structures would pose a safety hazard to shipping. However, the cost of sand, which had to be imported from neighbouring countries, was very expensive. Consequently, an alternative solution was decided upon utilizing geotextile containers for the underwater containment dyke. The geotextile container dyke gave a number of advantages. First, the geotextile containers were to be filled with the material and dead coral spoil from the Southern Islands reclamation project thus, imported sand was not required. Second, geotextile container dykes could be constructed at a steeper side-slope angle than sand dykes giving a greater disposal area capacity. Third, geotextile containers are not subject to erosion, unlike sand dykes, thus they did not require additional erosion protection.. Fourth, geotextile container dykes can be constructed relatively accurately regardless of water and weather conditions, unlike sand dykes.

A typical cross-section through the geotextile container, underwater containment dyke is shown in fig: 14b. In deeper water depths three geotextile containers were used to construct the containment dyke cross-section, while in shallow water depths a single geotextile container was used. The size of the geotextile containers was 650 m^3 capacity, with the geotextile being woven polypropylene of tensile strength 120 kN/m in both the length and cross directions.

The intended fill for the geotextile containers was to be primarily sandy fill from the reclamation excavation. However, it became apparent at the start of the works that the excavated fill was highly variable including marine clay, residual soils, weathered rock, small boulders and large clumps of dead coral. This highly variable fill was used throughout the container installation operation.

At peak installation, two split-bottom barges were employed for filling, transport and installation of the geotextile containers. This enabled a filling, transportation and installation cycle time to fit with the contractor's mode of operations.

The 1.6 km long containment dyke was formed using 108 geotextile containers and took 85 days to construct. This was despite initial delays due to the contractor learning the procedures involved, and the 5 hour transport time between the container filling site and the container installation site.

3.3 *Geotextile bags*

Geotextile bags, in the form of the ubiquitous "sand bags", can be considered the common ancestor of all geotextile containment techniques with many of the traits common to both geotextile tubes and geotextile containers. For example, geotextile bags are filled offsite and then installed to the geometry required in a similar manner to geotextile containers. Further, for best performance they have to be filled to maximum volume and density with sand in an identical manner to geotextile tubes. However, geotextile bags have two distinct differences to other geotextile containment techniques inasmuch as they can be manufactured in a range of shapes, and they are installed in a pattern-placed arrangement that greatly improves their overall stability and performance. Today, geotextile bags range in volume from 0.05 m^3 to around 5 m^3, and are pillow-shaped, box-shaped or mattress-shaped depending on the required application.

3.3.1 *Engineering features of geotextile bags*

For best performance it is essential that the geotextile bags be filled to maximum density and volume. This becomes more difficult as the volume of the bag increases, but can be enhanced by using water to compact the sand fill hydraulically within the geotextile bag. Filled density and volume is important from the viewpoint of maximising stability, but it is also important from the viewpoint of minimising the effects of fill liquefaction and loss of shape of the geotextile bags. To ensure the contained fill is maintained in its dense state the geotextile skin should have adequate tensile stiffness and not undergo deformation over time.

One major advantage of geotextile bags is that these small-volume units can be used to construct hydraulic and marine structures that require good geometrical tolerances. This can make them preferable to large-volume units such as geotextile containers when specific slope and height tolerances are required. Another advantage of the small-volume geotextile bag units is that maintenance and remedial works can be carried out easily by replacing the failed bag(s). This is much simpler than carrying out remedial works on larger-volume containment units such as geotextile containers.

3.3.2 *Applications for geotextile bags*

Geotextile bags are used for a range of hydraulic and marine applications. These are shown in fig: 15 and described briefly below.

3.3.2.1 *Revetments, fig: 15a*

Geotextile bags are used for revetments where their contained fill is used to provide stability and prevent erosion. Geotextile bags have been used for both submerged as well as exposed revetments, the same as with geotextile tubes. Much of the details concerning geotextile tube revetments also apply to geotextile bag revetments.

To prevent erosion of the foundation soil at the toe of the revetment it is common practice to extend the bottom layer of geotextile bags so the main revetment cannot be undermined.

Examples of use are given by Perrier (1986), Gadd (1988), das Neves et al. (2005), Restall et al. (2005) and Buckley & Hornsey (2006).

3.3.2.2 *Groynes, fig: 15b*

Geotextile bags may be used as groynes to prevent the shoreline movement of sediment. Here, the same conditions apply for geotextile bags as for geotextile tubes. Examples of use are given by Fowler et al. (1995), Restall et al. (2002), Restall et al. (2005) and McClarty et al. (2006).

3.3.2.3 *Artificial reefs, fig: 15c*

Geotextile bags can be used to construct artificial reefs. Here, the same conditions apply for geotextile bags as for geotextile containers. A major advantage of geotextile bags is that they can be installed to better geometric tolerances than relatively large-volume geotextile containers. Also, being relatively small in volume and having considerably better fill density, the geotextile bags are less prone to liquefaction from waves (or its effects) than the relatively large-volume geotextile containers.

Artificial reefs are normally required to dissipate wave energy and thus prevent erosion of the protected shoreline. Here, the reef has only to have basic geometrical requirements of height and area, with the geotextile bags providing a mass-gravity structure. However, artificial reefs have been used more recently to also refract waves and alter their shape to make them better suited for surfing, e.g. Black (1998). For this application the reef has to be constructed to good geometrical tolerances of height and shape as well as side-slope tolerances, and these tolerances have to be maintained throughout the design life of the reef. For this application geotextile

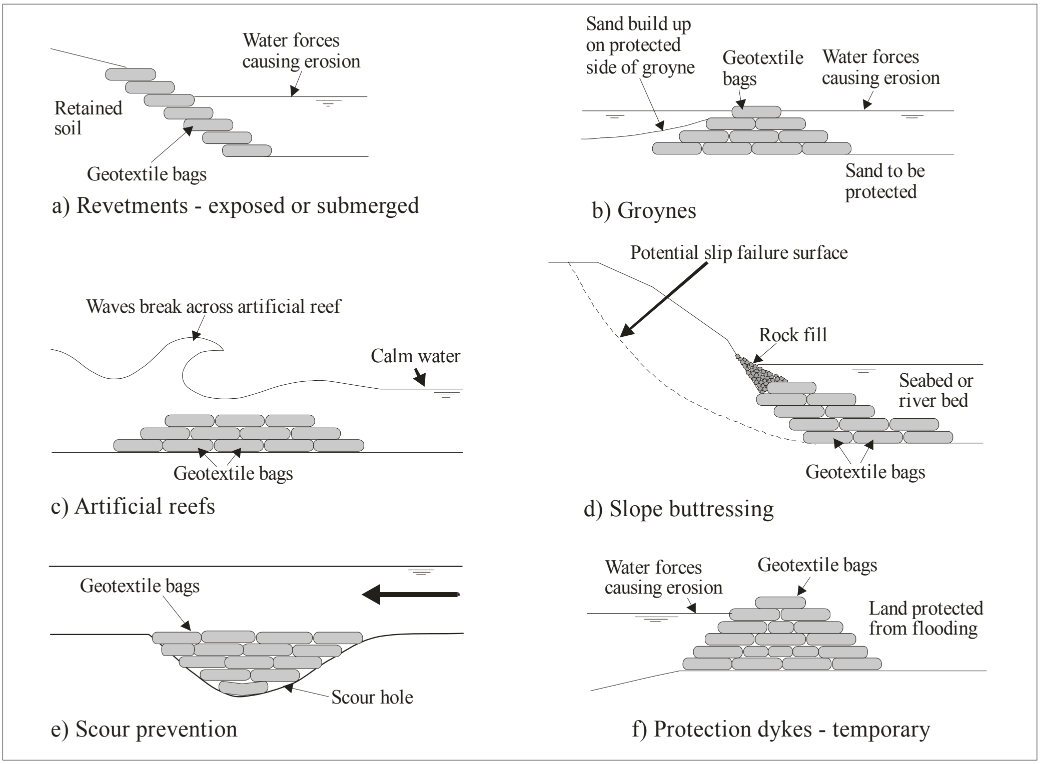


Figure 15. Hydraulic and marine applications for geotextile bags.

bags have to be of a specific geometry and have to be installed carefully in order to meet the required geometrical tolerances of the reef. An example of use is given by Borrero & Nelson (2002).

3.3.2.4 *Slope buttressing, fig: 15d*
As with geotextile containers, geotextile bags can be used to provide buttress support to an unstable slope in a hydraulic environment. Here, the geotextile bags act as a mass-gravity structure providing additional restraint to the toe of the unstable slope.

One advantage of geotextile bags for this application is that installation can be carried out by simple lifting equipment; thus geotextile bags can be installed at shallow water depths if necessary, unlike geotextile containers, which have to be installed at relatively greater water depth. An example of use is given by Zhang et al. (2006).

3.3.2.5 *Scour prevention, fig: 15e*
Geotextile bags are used as expedient means of scour prevention. This is the original application for these units. The bags can be used as expedient means to prevent undermining of nearby structures.

Geotextile bags can be easily installed using simple machinery. The bags conform to the shape of the scour hole and thus provide good sealing qualities. An example of use is given by Heibaum (1999).

3.3.2.6 *Protection dykes, fig: 15f*
Protection dykes are one of the original applications for geotextile bags. These bags, in the form of small sand bags, can be seen the world over shoring flood defences during times of natural calamity. This expedient use of geotextile bags comprises the most basic, and common, form of geotextile containment application. One example of use is given by Tonks et al. (2005).

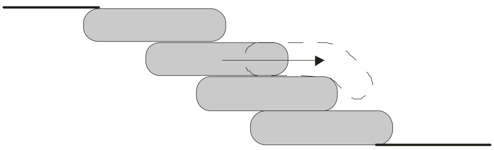
However, geotextile bags may be used for more sophisticated and substantial protection dyke structures where they may be required to perform over long periods of time. Here, the geotextile bags are required to perform in the same manner as geotextile tubes for this same application. The pattern-placement of geotextile bags forms a stable mass-gravity structure that is resistant to erosion when subjected to hydraulic forces.

3.3.3 *Limit state design modes*

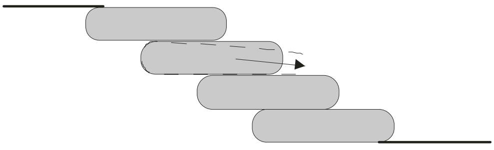
As with geotextile tubes (see section 3.1.4), packed geotextile bags behave as mass-gravity structures and the approach to design follows an identical process to other structural-type applications where each stability and deformation mode is assessed and rendered safe. These limit state design modes can be divided into external and internal modes.

3.3.3.1 *External modes*

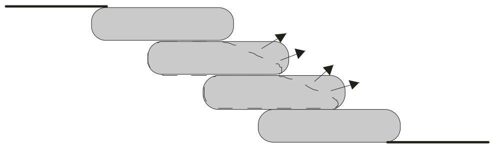
There are six external stability modes for geotextile bag structures and these are identical to those for geotextile tubes, fig: 5a. These are sliding stability, overturning stability, bearing stability, global stability, scour of foundation and foundation settlement. Each external stability mode is assessed in the same manner as for geotextile tubes with the geotextile bag structure considered a homogenous, flexible structure.



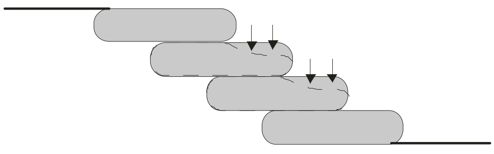
a) Local instability



b) Geotextile bag rupture



c) Erosion of fill through geotextile bag



d) Deformation of contained fill

Figure 16. Internal stability modes for geotextile bags.

3.3.3.2 *Internal modes*

There are four internal stability modes to be assessed, fig: 16. These are local instability, geotextile bag rupture, erosion of fill through the geotextile bag and deformation of the contained fill.

For stability of the structure, geotextile bags must not undergo local instability, fig: 16a. The geotextile bag mass (i.e. volume), its shape, along with its pattern-placement controls the local stability of the geotextile bag structure when it is subject to hydraulic forces. For good local stability it is important to ensure that the geotextile bags are packed densely together in an efficient pattern.

The geotextile bag must be strong enough to resist tensile rupture, fig: 16b. The filled geotextile bag mass, its shape and the method of placement influences the required strength of the geotextile bag. Other variables, such as exposure conditions, may also influence the strength requirements of the geotextile bag. One advantage geotextile bags have over other mass-gravity containment units, e.g. geotextile tubes, is if there is a geotextile skin rupture then geotextile bags are relatively easy to replace.

The type of fill used in geotextile bags along with the magnitude and type of hydraulic forces acting on the geotextile bag structure, and their duration, affects the required hydraulic properties of the geotextile skin, fig: 16c. Recognised geotextile filter criteria should be used to determine the hydraulic property requirements of the geotextile bags.

Deformation of the contained fill within geotextile bags should be kept to a minimum, fig: 16d. Hydraulic conditions can cause movement of sand fill inside the geotextile bags which causes the bags to change shape and diminish their stability. For maximum stability it is important that the sand fill be placed at maximum density in the geotextile bags and that the geotextile bags not undergo deformation to allow relaxation of the sand fill following placement.

3.3.4 *Required hydraulic properties of geotextile bags*

Geotextile bags, like geotextile tubes, are constructed to perform in a variety of hydraulic environments ranging from still or slow moving water, to fast moving currents, to wave environments. In all applications the geotextile bag skin is exposed directly to the hydraulic environment. As with geotextile tubes, the type of hydraulic regime and the time period of exposure to the hydraulic regime need to be considered when using geotextile bags. Consequently, the details contained in Table 3 relating to required geotextile skin hydraulic properties and whether additional protection measures are required also apply to geotextile bags when they are used for long term applications.

Water currents ≥ 1.5 m/s and waves can affect the long-term performance of geotextile bags by causing liquefaction and internal movement of the sand fill, especially if the geotextile bags have not been filled properly, or the geotextile skin undergoes significant deformation or creep. This effect is more pronounced with geotextile bags than with the greater-mass geotextile tubes. Fill liquefaction and internal movement causes a loss of stability in the pattern-placed geotextile bags, which may lead to premature failure of the overall structure. The possibility of this needs to be accounted for at the design stage, see fig: 16d. However, a major advantage with geotextile bags is that they can be easily replaced should they show distress under a specific hydraulic regime.

4 GEOTEXTILE CONTAINMENT FOR THE DEWATERING OF WASTE AND CONTAMINATED SEDIMENTS

4.1 *Introduction*

Many industries utilize water for processing and for the movement and storage of by-products and waste. This results in large volumes of liquid or slurry-like materials being stored in containment areas, or being treated before discharge into lakes, rivers and streams. In the past many industry by-products were discharged directly into water courses where they have settled, and over time, have contaminated the sediments of these water courses.

Over time, many of these slurry waste impoundments require cleaning to remove the sludge, and to enable the impoundment to accept further waste flows. The removal and disposal of sludge and waste from lagoons and ponds, and contaminated sediments from mines, lakes and rivers presents a major environmental problem because of the large volumes involved and the fact that these wastes are in liquid form which presents problems in handling and disposal.

With government legislation, liquid or slurry-like wastes now have to be stored, or disposed of, in special containment facilities and cannot be discharged directly into water courses. This has lead to several major environmental issues, namely; how best to store, or dispose of, these slurry-like by-products and wastes, and how best to remediate existing containment facilities and contaminated sediment sites. Land filling has become the disposal facility of choice, however, with the huge volumes of slurry-like wastes and contaminated sediments produced; direct land filling is not practical. Further, these wastes, in their natural state, are in liquid form which makes their handling, transport and disposal difficult. Thus, a preliminary treatment stage has to be employed in order to significantly reduce the volume of the slurry waste prior to disposal by land filling, and to render it manageable for handling, transport and disposal. Dewatering is commonly applied as this preliminary treatment.

Dewatering accomplishes two primary objectives with regard to the treatment and disposal of slurry-like waste and contaminated sediments. First, a large reduction in volume of the slurry-like material is achieved as water is removed from the waste. Second, the consistency of the waste or contaminated sediment is changed from a liquid to a semi-solid or solid material that can be easily handled, transported and disposed of in waste storage facilities. Dewatering, if done in a controlled manner, may also achieve two important secondary objectives; that of retention of the solids and of the contaminants within the containment medium during the dewatering process.

4.2 *Geotextile tubes for dewatering waste streams and contaminated sediments*

Geotextile tubes provide an ideal medium for the dewatering of slurry-like waste streams and contaminated sediments because of the following. First, they provide a large contact surface area with the slurry to enable efficient dewatering. Second, they utilize geotextiles that enable efficient dewatering of the slurry. Third, they can be fabricated in sizes, and used in numbers, that fit into the scale of required dewatering operations. Fourth, they are relatively simple to employ and utilize unlike other, more complex, mechanical dewatering technologies, and therefore cheaper.

Geotextile tubes were first used for dewatering waste slurry during the mid 1990’s, e.g. Fowler et al. 1996, where trials involving the dewatering of municipal sewage sludge were performed. This provided much of the initial understanding of how geotextile tubes may be employed for waste dewatering applications. Since that time, geotextile tubes have been used to dewater many slurry-like wastes and contaminated sediments.

In many respects the use of geotextile tubes to dewater waste streams and contaminated sediments is still developing with new applications arising frequently. For example, industries that produce significant quantities of slurry waste and where geotextile tubes have been successfully utilized for dewatering, are municipal waste treatment, agriculture waste treatment, food and food processing waste treatment, industrial and mining waste treatment, construction industry waste treatment and the treatment of contaminated sediments.

It is important to recognise that geotextile tubes are used *as part of the system* of disposal of slurry-like waste and contaminated sediments. Fig: 17 shows the different stages in the dewatering process and the various options involved. Basically, the slurry is introduced into the system where it is first mixed with a dewatering accelerant (if required). The slurry is then pumped into the geotextile tubes where dewatering occurs. Over time, the water passing out of the tubes can be pumped to a water treatment plant where it is cleaned further, or it may be recirculated to the original slurry ponds, or it may exit directly to the environment (if it is clean enough). At the end of dewatering the contained solids may be left in-place, or they may be transported to an off-site disposal facility, or they may be recycled for other uses. The overall system includes combinations of pumping equipment and pipelines; geotextile type, tube sizes and numbers; accelerant additives; water treatment processes; and specific disposal facilities for the final dewatered waste stream.

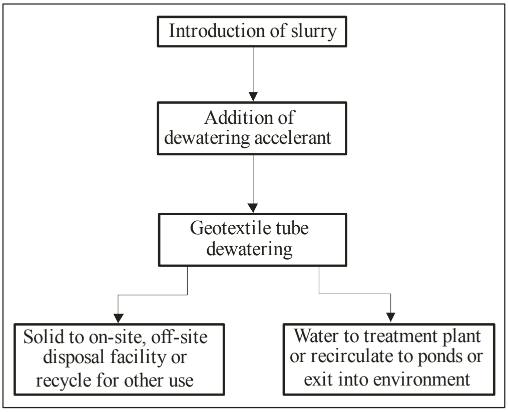
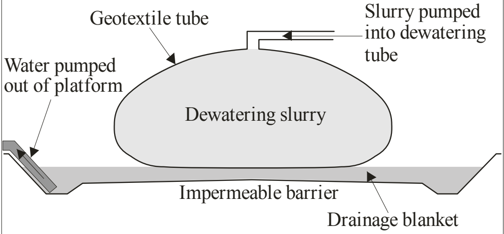


Figure 17. Diagram of the overall dewatering system using geotextile tubes.

To dewater effectively a geotextile tube dewatering platform needs to be provided in the manner shown in fig: 18a. The base of the platform should consist of a stable, impermeable barrier to support the geotextile tube dewatering units and prevent loss of the effluent water from the tubes into the foundation. The surface of the impermeable barrier should have a slight cross-fall to enable water flows to any lateral drainage sumps. The impermeable barrier can consist of compacted earth, or can be concrete, or can be a composite clay-geomembrane base liner. The choice of the base barrier depends on the nature of the dewatering operation and the importance of collecting the water emanating from the geotextile tubes.

Above the impermeable barrier a drainage blanket is installed in order to facilitate full-circumferential drainage from the geotextile tube. The drainage blanket also enables the water to flow easily to any sumps at the periphery of the platform. The upper surface of the drainage blanket should be level to prevent the geotextile tubes from moving during filling. Either granular drainage blankets or geocomposite drainage blankets are used.



a) Details of geotextile tube dewatering platform

b) Multiple geotextile tubes used to dewater slurry waste

Figure 18. Geotextile tube dewatering platform.

To match the volume requirements of the slurry pumping operation single or multiple geotextile tubes of varying sizes and lengths are used. Thus, where multiple geotextile tubes are used in a single layer, an extensive dewatering platform may be required. Fig: 18b shows a large scale layout where multiple geotextile tubes are used for dewatering. However, many small scale operations employ only a single geotextile tube, or even a single geotextile bag, to effectively dewater the waste volume.

The overall dewatering process using geotextile tubes encompasses three stages – the containment stage, the dewatering stage and the consolidation stage. The containment stage involves the filling of the geotextile tubes with slurry waste. The geotextile tube must have the necessary strength to withstand the tensile stresses generated during filling. The dewatering stage involves the drainage of excess *free* water out through the pores of the geotextile tube resulting in effective dewatering and large volume reduction. Normally, there are several containment and dewatering cycles before the process progresses to the final consolidation stage. The consolidation stage involves the final consolidation (the drainage of *pore* water) and desiccation of the contained waste into a form that can be transported and disposed of, or recycled using downstream activities.

Fig: 19 shows the various stages of filling, dewatering and consolidation in a typical geotextile tube dewatering operation. The first stage involves the initial filling of the geotextile tube with slurry. The amount of slurry pumped into the geotextile tube will depend on its volume capacity, which is governed by its dimensions, and tensile strength of the geotextile skin and seams. Once maximum volume has been reached the geotextile tube is left to dewater for a period of time. This dewatering and resulting volume reduction must occur over a practical time period in order to optimize the overall dewatering process. Normally this is between 2 weeks and 2 months depending on the type of operation.

Once dewatering has proceeded, the geotextile tube is refilled with slurry to its maximum volume capacity, and the process of refilling and dewatering is repeated between 4 and 6 times until such time as refilling becomes inconsequential with regard to volume off-take. The geotextile tube is left to go through its final dewatering stage and then its consolidation stage. During the consolidation stage water passes out of the geotextile tube much more slowly that during the dewatering stages. The reason for this is that pore water is released much more slowly than free water. The consolidation stage may take between 2 months to 6 months depending on the type of contained slurry and the target final solids concentration.

Finally, the geotextile tube skin is removed if the dewatered waste is to be transferred off-site or recycled. In some instances the exposed dewatered waste is left in-place for further drying by evaporation before removal.

4.3 *Geotextile tube dewatering fundamentals*

As stated in section 4.1, dewatering accomplishes two primary objectives with regard to the treatment and disposal of slurry-like waste and contaminated sediments – that of a significant reduction in volume of the slurry-like material and a resulting improvement in its consistency (i.e. level of solidification). In dealing with slurries where there are large amounts of water present it is common to refer to the solid component in the slurry in terms of a solids concentration which is the weight of solids present divided by the total weight of the slurry. This is a little different to geotechnical engineering practice where the term water content is normally

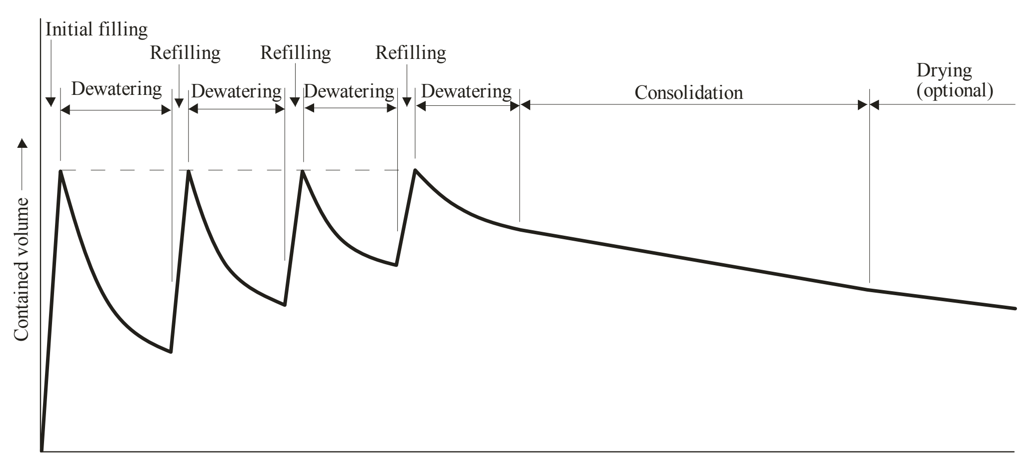


Figure 19. Filling, dewatering and consolidation stages when using geotextile tubes.

used to describe the water-to-solids relationship. However, there is a relationship between solids concentration and water content, and this is:

$$S = \frac{1}{1+w} \qquad (2)$$

Where, S = solids concentration (by weight) of the slurry; w = water content of the slurry. For example, using eq: 2, a solids concentration of 5% equates to a water content of 1900%. Clearly, the term solids concentration is more reasonable when dealing with slurry-like materials than the term water content.

The fundamental principles of dewatering using geotextile tubes are shown in fig: 20. The slurry waste, or sediment, is pumped into the geotextile tube at a specific solids concentration filling it to a specific volume. Over time, water passes out of the slurry through the skin of the geotextile tube resulting in a reduction of the contained slurry volume and a resulting increase in solids concentration within the geotextile tube, fig: 20a. The rate at which the volume reduction occurs diminishes over time as the contained slurry inside the geotextile tube reduces in hydraulic conductivity, and consequently, the rate of increase in solids concentration also slows.

The change in contained slurry volume within the geotextile tube and the change in solids concentration are inter-related. Suppose the geotextile tube is filled to an initial volume V_o with slurry of initial solids concentration S_o, fig: 20b. The geotextile tube is then allowed to dewater for a period of time t at which the contained volume of slurry within the geotextile tube has reduced to V_t with a resulting solids concentration increase to S_t. If it is assumed that negligible solids escape from the geotextile tube during the dewatering process, and the solids concentration is constant throughout the contained mass, then the following relationships between contained slurry volume change and solids concentration change apply.

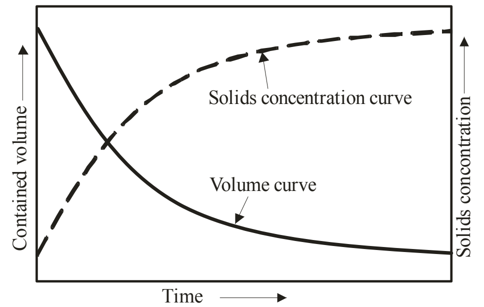
The ratio of the contained slurry volume at time t compared to that at time $t = 0$ is:

$$\frac{V_t}{V_o} = \frac{\left[\dfrac{1-S_t}{S_t}+\dfrac{1}{G}\right]}{\left[\dfrac{1-S_o}{S_o}+\dfrac{1}{G}\right]} \qquad (3)$$

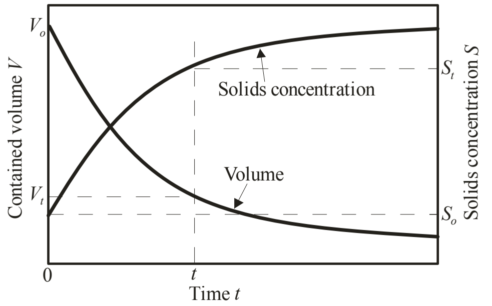
Where, V_t, V_o, S_t and S_o are as shown in fig: 20b; G = specific gravity of the contained slurry. The term $1/G$ has only a minor influence and eq: 3 can be simplified as follows:

$$\frac{V_t}{V_o} = \frac{\left[\dfrac{1-S_t}{S_t}\right]}{\left[\dfrac{1-S_o}{S_o}\right]} \qquad (4)$$

Fig: 21 shows the comparison in results between eq: 3 and eq: 4 using an initial solids concentration S_o = 5% and a slurry specific gravity G = 1.2. The two equations yield very similar results and thus eq: 4 may be used more readily for simplicity.



a) Decrease in volume and increase in solids concentration with time



b) Volume change and solids concentration change parameters

Figure 20. Fundamental principles of dewatering using geotextile tubes.

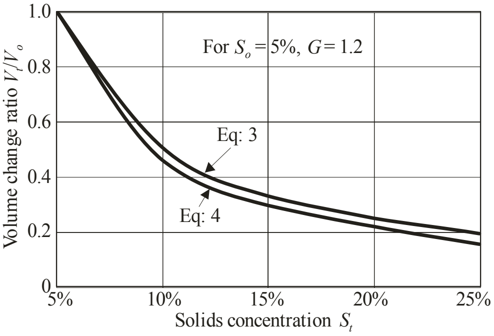


Figure 21. Comparison between eq: 3 and eq: 4.

In some instances it may be important to know what contained slurry volume reduction will occur for a given increase in solids concentration of the contained slurry. This can be determined from the following relationship:

$$\Delta V_t = \frac{V_o - V_t}{V_o} = 1 - \frac{\left[\dfrac{1-S_t}{S_t}\right]}{\left[\dfrac{1-S_o}{S_o}\right]} \qquad (5)$$

Where, ΔV_t = contained slurry volume reduction over time t. For example, if the initial slurry solids concentration S_o = 5%, and the slurry solids concentration at time t was S_t = 15%, then this would result in a 70% reduction in the contained slurry volume.

Alternatively, it may be important to know what would be the expected increase in solids concentration for a given reduction in contained slurry volume. This can be determined as follows:

$$S_t = \frac{\left\{\dfrac{1}{1-\Delta V_t}\right\}\left\{\dfrac{S_o}{1-S_o}\right\}}{\left[1+\left\{\dfrac{1}{1-\Delta V_t}\right\}\left\{\dfrac{S_o}{1-S_o}\right\}\right]} \qquad (6)$$

For example, for an initial slurry solids concentration S_o = 5%, and reduction in contained slurry volume ΔV_t = 50%, the slurry solids concentration at time t would be S_t = 9.5%.

Eqs: 3 to 6 relate to a single filling/dewatering cycle. In practice, four to six filling/dewatering cycles are carried out before the geotextile tube is left to finally consolidate (see fig: 19). The solids concentration and contained volume reduction during these multiple filling/dewatering cycles can be determined using relatively simple numerical progression relationships.

To facilitate slurry movement, it is pumped into the geotextile tubes at relatively low solids concentrations. Table 4 lists typical initial solids concentrations ranging between 1% and 12% for various waste streams. One major goal of dewatering is to increase the solids concentration until the contained waste behaves like a gelatinous or solid material that can be handled and transported to a permanent disposal facility or used for other purposes. Table 4 lists final solids concentrations of the same waste streams that result in gelatinous or solid behaviour. There is a wide range of final solids concentrations and this is dependent on the type of waste stream. The more inorganic particulate wastes (e.g. mineral processing, some industrial by-products and contaminated sediments) yield higher final solids concentrations.

Table 4. Typical initial and final solids concentrations during the dewatering of various waste streams.

Waste material	Initial solids concentration S_o	Final solids concentration S_f
Biosolids	1% to 4%	15% to 25%
Agriculture	2% to 4%	20% to 25%
Mineral processing	3% to 10%	40% to 70%
Industrial by-products	4% to 10%	25% to 75%
Contaminated sediments	10% to 14%	35% to 70%

4.4 *Dewatering performance of geotextile tubes*

4.4.1 *Filtration through geotextile tubes*

Geotextiles are used successfully to filter intact soils. Here the soils consist of particles of varying sizes in a supporting structure. Geotextile filter criteria exist to enable the determination of suitable geotextile hydraulic properties to filter effectively a wide range of intact soil types. More recently, geotextile filter criteria have been extended to situations where appreciable quantities of organic matter exist in the draining medium, e.g. in landfills. Here it has been demonstrated that geotextile filters with open pores and simple pore structures work most effectively, Giroud (1996).

In dewatering applications the slurry waste or contaminated sediment consists of little intact solid matter (the solids are in a non-supporting structure, i.e. in water), but may comprise large amounts of suspended solids, colloids and suspended organic matter. To further complicate matters, quantities of heavy metals and organic contaminants may also be present. Because of this very different filtration environment (c.f. conventional soil filtration) conventional geotextile filter criteria has little relevance. Further, the governing performance criteria for the dewatering of waste are different to that of conventional soils.

There are three overall performance criteria for dewatering waste. These are:

1. There must be a significant reduction in contained volume (and a comparable gain in solids concentration), and this must occur over a relatively short time period.
2. There can be an initial loss of solids through the geotextile tube but this must stop a relatively short period after dewatering begins.
3. The effluent quality must remain constant with time.

These three performance criteria are discussed in more detail in sections 4.4.1.1, 4.4.1.2 and 4.4.1.3 below.

4.4.1.1 *Reduction in contained volume*

The reduction in contained volume in a controlled manner is the fundamental performance criterion for geotextile tube dewatering.

During dewatering, volume reductions in geotextile tubes result from two phases – a dewatering phase and a consolidation phase (e.g. see fig: 19). These two phases are shown diagrammatically in fig: 22. The dewatering phase involves the movement of free water to the geotextile tube surface. This movement of water occurs over a relatively short period of time (anything from 1 week to 2 months depending on the type of waste and the size of the geotextile tubes) and results in a relatively large loss in contained volume in the geotextile tube. If the waste is in its natural state inside the tube then the movement of significant quantities of suspended solids can also occur and this may form a cake at the geotextile surface, which may impede further flows. The loss of this free water collapses the waste into a semi-coherent mass, and if allowed to drain further, the geotextile tube enters the consolidation phase.

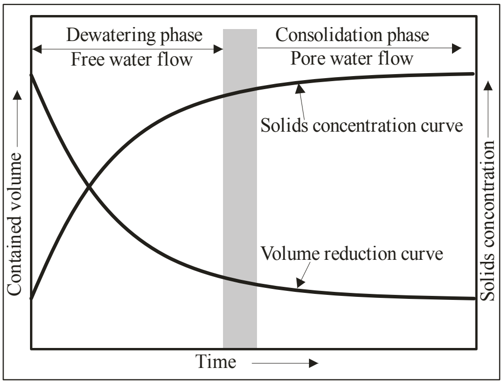


Figure 22. Dewatering and consolidation phases in geotextile tube dewatering.

During the consolidation phase water movement occurs along and through the pores in the contained waste. The rate at which water is lost is relatively slow compared to the dewatering phase, and is governed by the hydraulic conductivity of the waste and the effect of any filter cake build up on the inside of the geotextile surface during the loss of the free water. If allowed to proceed, the consolidation phase results in a relatively small volume reduction over an extended length of time (again, this is dependent on the type of waste and the size and type of the geotextile tubes).

The transition between the dewatering phase and the consolidation phase is ill-defined, and as such, is difficult to determine. Also, the time it takes for this transition to occur can vary considerably depending on the type and consistency of the waste stream, the use of dewatering accelerants, the size and type of geotextile tubes, etc. In practice, where dewatering times are limited because of project time constraints the consolidation phase is rarely allowed to occur, and thus, little pore water is actually drained from the contained waste. Consequently, the final solids concentration attained normally reflects the loss of free water only (see Table 4 for the final solids concentration of various wastes).

4.4.1.2 *Loss of solids*

During the dewatering phase when free water passes from the waste and out of the geotextile tube suspended solids and organic matter may also be carried out of the tube. So as not to adversely affect effluent quality it is important that this loss of solids decreases to zero relatively quickly. Normally, if the dewatering process is operating correctly the time taken to reach zero loss of solids is between 1 hour and 1 day depending on the nature of the waste being dewatered and the type of geotextile being used for the tube.

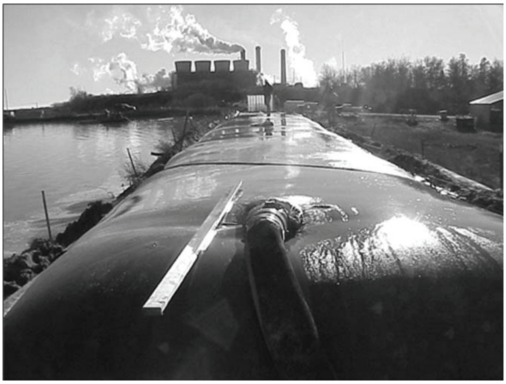
If solids and suspended organic matter continually flow out of the geotextile tube with the effluent water this may have implications on any downstream effluent treatment. As downstream effluent treatment processes can be relatively costly it is important to minimise suspended solids and suspended organic matter loss from the dewatering tubes.

4.4.1.3 *Effluent quality*

Effluent quality is governed by the presence of suspended matter and dissolved solids and compounds. The effluent quality determines whether further downstream effluent treatment is required before the water is passed into the environment or recirculated.

To best control effluent quality it is important that no suspended solids and organic matter are allowed to pass out of the geotextile tubes during dewatering. One way of achieving this is to use chemical dewatering accelerants in the contained waste to collapse any suspended matter and prevent its loss. This has an important secondary effect as the collapsed waste structure also reduces significantly the loss of other pollutants (e.g. heavy metals, organic compounds) from the tubes, thus improving effluent quality. Dewatering chemical accelerants have also proved beneficial in reducing significantly the amount of organic nitrogen and phosphorus in the effluent from dewatering animal waste, Worley et al. (2004).

a) Cone test



c) Full-scale prototype test

b) Hanging bag test

Figure 23. Different levels of evaluating the performance of geotextile tube dewatering.

4.4.2 *Evaluating geotextile tube performance*

Wastes and their behaviour vary considerably, not only between different waste streams but also from site to site. Consequently, each new dewatering application should undergo an evaluation programme in order to arrive at the optimal geotextile tube dewatering solution. Fig: 23 shows the three stages of evaluation in order of complexity – cone test, hanging bag test, full-scale prototype test.

The cone test (fig: 23a) consists of a 0.3 m diameter geotextile tube sample that is formed into a cone shape. The waste is poured into the cone and the drained liquid is collected in a container below the geotextile sample. The test is very simple and can be performed in the laboratory or in the field. It is useful for screening chemical accelerants and can give insight into final percent solids concentration, effluent quality and contained volume reduction.

Once the simple screening tests have been done it is normal to continue to the next level of testing which utilises the hanging bag test, fig: 23b. This is a field test and utilises a 1.7 m long by 0.6 m wide piece of the planned dewatering geotextile fashioned into a bag. The slurry waste is poured into the top of the bag and the amount of effluent, its quality and the contained volume (or solids concentration) is recorded over time. A draft ASTM standard exists for this test as well as a draft GRI Standard Test Method (GRI GT12 : 2004). This test is normally always used at the evaluation stage of every planned geotextile tube dewatering project. It provides valuable performance information relating to dewatering rates and effluent quality. A more recent appraisal of the hanging bag test is given by Koerner & Koerner (2006).

For new projects it is normal to carry out full-scale prototype testing whether by using a separate prototype tube or combining this testing with the first dewatering tube of the project. The scale of the prototype testing can range from a small-size tube to the full-size planned dewatering tube, e.g. fig: 23c. The full-scale prototype testing is used to confirm, or modify, the design assumptions derived from smaller scale testing, e.g. hanging bag testing, and allow the new assumptions to be incorporated into the main project.

4.4.3 *Rate of dewatering*

The rate at which the dewatering process occurs is dependent on the change in hydraulic conductivity of the contained waste during dewatering and the filtration performance of the geotextile skin in the geotextile tube. The filtration performance is dependent on the hydraulic properties of the geotextile, the nature of the pore structures within the geotextile, and its interaction with the contained slurry waste. This filtration performance is governed by the filter cake formation on the inside of the geotextile, Moo-Young et al. (2002).

An important dewatering performance parameter is the time over which dewatering occurs. The dewatering time must be consistent with the overall dewatering operation. Normal dewatering operations require the dewatering time to be between 1 and 2 months. Longer dewatering times constrain the speed of waste processing and the volumes that can be treated.

Maintaining the dewatering period within a relatively short time-frame normally requires the use of dewatering accelerants, as the time-frame associated with the dewatering of sludges under normal conditions can be long and the process inefficient.

4.5 *Use of dewatering accelerants*

As stated in section 4.4 slurry waste or contaminated sediment consist of little intact solid matter, but is comprised of large amounts of suspended solids, colloids and (maybe) suspended organic matter. Also present can be significant quantities of heavy metals and/or organic contaminants. To dewater efficiently, the geotextile tube must retain much of the solids and organic matter and control the passage of any heavy metals and organic contaminants; and at the same time allow the water to pass. Further, the loss of water must occur in a relatively short time period for practical purposes. Meeting these two conflicting requirements has lead to the use of dewatering accelerants.

Currently, there are two ways to accelerate the rate of dewatering. These are;

- the addition of chemical dewatering accelerants into the slurry prior to entering the geotextile tube, and;
- the use of an electro-osmotic potential within the geotextile tube to accelerate dewatering.

(A third acceleration method also exists, that of pressure, but is not discussed here because it is not considered feasible to geotextile tube dewatering.)

4.5.1 *Chemical dewatering accelerants*

Chemical flocculating agents have been used for many years in the water treatment industry to separate suspended solids, colloids and organic matter from water. These chemical agents neutralize the inter-particle charges and consequently collapse the suspended solids and organic matter. The collapse of the slurry structure also traps heavy metals and organic contaminants within the collapsed structure, and produces relatively large amounts of free water.

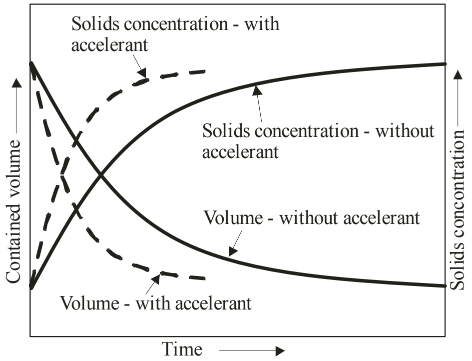
Flocculating agents can be used in geotextile tube dewatering to accelerate the dewatering rate and enable effective dewatering over a relatively short period of time. The chemical accelerant is introduced to, and mixed with, the waste prior to its entry into the geotextile tubes. The type of accelerant used and its dosage rate is critical to the performance of the chemical accelerant, and this is highly dependent on the type of waste being treated.

Water-soluble organic polymers known as polyelectrolytes are very effective chemical dewatering accelerants. They usually have ion exchange sites, which gives the molecule an ionic charge. Those with a positive charge are cationic; those with a negative charge are anionic; others that are neutral are non-ionic. These molecules react with colloidal material in the slurry by neutralizing the charge and bridging individual particles to form flocs.

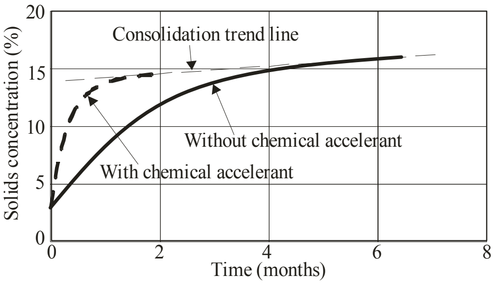
Cationic polyelectrolytes are either polyamines or acrylamides and are generally most effective at higher pH. Anionic polyelectrolytes are acrylates and are most effective at lower pH. Non-ionic polyelectrolytes are typically polyacrylamides. By tailoring structures and molecular weights it is possible to design a polymer dewatering accelerant for most coagulation and flocculation problems.

The chemical dewatering accelerant that works best in any system can be determined only through experimental screening by small-scale filtering or hanging bag tests (see section 4.4.2). Waste streams are highly variable, not only across different waste streams, but also within specific waste groups. Chemical accelerant addition is highly specific not only from the type of accelerant applied but also its dosage rate. Consequently, the only way of arriving at an optimal specific waste/chemical accelerant combination is by way of small-scale filtration testing.

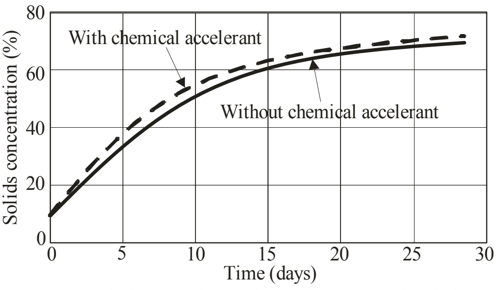
Fig: 24a shows the effect of chemical accelerants on the dewatering rate of geotextile tubes. The accelerant collapses the solid and suspended matter structure in the waste releasing free water. This free water then drains relatively quickly through the geotextile tube resulting in an accelerated volume reduction (and a comparable accelerated increase in solids concentration). If no chemical accelerant is used the waste drains much more slowly due to its natural hydraulic conductivity, self weight and internal water head, and the waste structure compresses over a longer time frame to reach a structure similar to the collapsed structure when the accelerant is used. Thus, the total volume reduction (and solids concentration increase) will be of similar magnitude for the accelerated and the normal dewatered waste, however, the accelerated dewatered waste will achieve this in a much shorter time-frame.



a) Effect of chemical accelerants on rate of solids concentration increase and rate of volume decrease



b) Effect of chemical accelerant on rate of solids concentration increase of sewage sludge



c) Effect of chemical accelerant on rate of solids concentration increase of fly ash slurry

Figure 24. Effect of chemical dewatering accelerants on rate of geotextile tube dewatering.

Chemical dewatering accelerants perform differently on different waste streams. Fig: 24b shows the geotextile tube dewatering of sewage sludge taken directly from the digester of a municipal waste water treatment plant. Two dewatering treatments are performed – one with the addition of the correct chemical dewatering accelerant and one without. The geotextile tube containing the waste with the accelerant dewaters to around 15% solids concentration after 1.5 to 2 months. The geotextile tube containing the waste, but with no accelerant, dewaters to the same solids concentration, but takes 4 months to do it. Clearly, the addition of the chemical dewatering accelerant is of benefit here.

Fig 24b shows both the accelerated and the non-accelerated waste trending to a consolidation trend line where any further increase in solids concentration is governed by loss of pore water only from the waste. Both have the same consolidation trend line but the waste with the accelerant reaches this trend line much sooner.

Fig: 24c shows the geotextile tube dewatering of fly ash slurry from a thermal power station. Again, the best performing chemical dewatering accelerant has been added to the slurry in one tube and none has been used in the other tube. The results show that both tubes dewater at a similar rate and achieve a maximum solids concentration of around 70% after only 30 days. Clearly, the addition of the chemical dewatering accelerant has no benefit here.

The difference in performance of the chemical accelerants for the two waste streams may be rationalised as follows. The sewage sludge is composed of significant quantities of suspended solids and organic matter and the chemical accelerant collapses this structure producing free water that can be readily drained out of the tube. On the other hand, the fly ash slurry is particulate in nature and has negligible suspended solids and nil organic matter, and so the chemical accelerant has negligible effect on its dewatering capability.

An important secondary consideration in the use of chemical dewatering accelerants concerns the ability of the treated waste to trap and contain contaminants within the geotextile tube and not allow them to pass out with the effluent water. This has major implications when considering effluent quality. Examples exist of the ability of appropriate chemical dewatering accelerants to contain heavy metals, e.g. mercury, lead, zinc, and arsenic, and non-soluble organic compounds, e.g. polychlorinated biphenyls (PCB's), polycyclic aromatic hydrocarbons (PAH's), pesticides and dioxins. The ability of the accelerant addition to trap these heavy metals and non-soluble compounds depends on how the accelerant reacts with the waste stream overall. If the accelerant can collapse the waste stream structure then high percentages of these contaminants can be contained within the geotextile tube.

This ability of chemical dewatering accelerants to trap organic compounds has also been demonstrated in the geotextile tube dewatering of animal waste where compounds of organic nitrogen and phosphorus have been fully contained within the geotextile tubes, Worley et al. (2005).

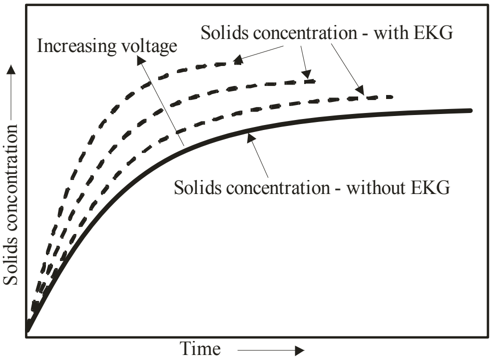
4.5.2 *Electro-osmotic dewatering accelerants*

The use of chemical dewatering accelerants is far more developed than the use of electro-osmotic dewatering accelerants. Electro-osmosis has been used on a limited scale as a means of accelerating the dewatering of fine-grained soils for some time, e.g. Bjerrum et al. (1967). This technique utilises an electric potential between anode and cathode electrodes to accelerate the movement of pore water through fine-grained soils. Heat is dissipated as a by-product of this mechanism. Results indicate that the rate of pore water movement can be up to five times that of normal pore water flows. Limitations of this technique are the cost of electricity to drive the process and attrition of the anode electrodes which degrade as part of the process.

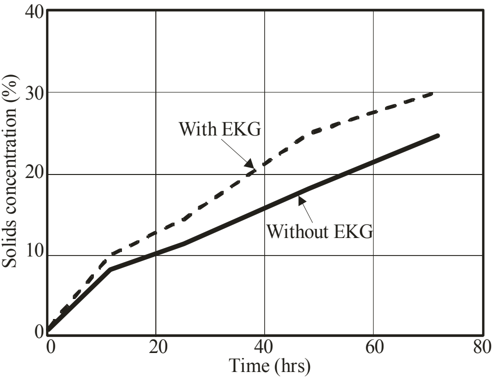
More recently, electro-osmosis has been used to accelerate the insitu dewatering of sewage sludge, Miller et al. (1998), Jones et al. (2006). Both cases demonstrated that the solids concentration increased at a greater rate, and achieved a higher value, when the electro-osmosis process was applied compared to normal dewatering conditions.

The term Electro-Kinetic Geosynthetics (EKG) was first used by Jones (1996) to describe geosynthetics that can be used for electro-osmotic applications in soils. This is of particular interest to geotextile tube dewatering because the electro-osmotic elements can be integrated within the geotextile tube itself. By incorporating the cathode into the geotextile skin of the tube and using a non-degrading anode in the centre much of the problems associated with conventional electro-osmotic dewatering are overcome.

Fig: 25a shows the fundamental principles of EKG accelerant use with geotextile tube dewatering. The application of voltage causes an increase in the rate of dewatering which causes a consequent increase in the rate of solids concentration. This also results in an increase in the final solids concentration compared to normal dewatering conditions. The greater the voltage applied, the higher the rate of dewatering, and the higher the final solids concentration for the same dewatering time (or conversely, the shorter the time required to reach a specific solids concentration).



a) Effect of EKG accelerant on rate of solids concentration increase



b) Effect of the application of EKG on dewatering rate of sewage sludge

Figure 25. Effect of EKG accelerant on rate of geotextile tube dewatering.

The effect of the EKG accelerant shown in fig: 25a should be contrasted with that of the chemical accelerant in fig: 24a. The chemical accelerant does not increase the natural final solids concentration although it does increase the dewatering rate, whereas the EKG accelerant can increase both the dewatering rate and the final solids concentration.

Fig: 25b shows the results of small-scale geotextile tube (approximately 1 m dia.) dewatering tests on activated municipal sewage sludge. The sewage sludge was placed in the geotextile tubes and allowed to dewater (initial solids concentration = 0.7%). One test had no EKG while the other had an EKG potential equivalent to 30 V/m and a current of 0.5 Amps applied. The results clearly demonstrate the increase in dewatering of the EKG test compared to the normal case. Both an increase in the rate of dewatering as well as an increased level of final solids concentration was obtained.

Glendinning et al. (2006) also report on dewatering tests of digested lagoon sewage sludge using EKG in the laboratory. Using an applied voltage of 100 V/m solids concentration increased from around 14% (initially) to 23% and 27% (for the two tests) after 21 days. This results in a volume reduction of 40% and 50% respectively for the two tests.

Fourie et al. (2002) and Fourie et al. (2004) have used the EKG technique to dewater insitu fine-grained residue from mineral sands processing, diamond mine tailings and lead-zinc mine tailings. All results showed increased dewatering rates and higher final solids concentration when the EKG technique was applied. While the test programme did not include geotextile tubes, it is considered that the results would be comparable had they been used as the containment/dewatering medium.

Accelerated dewatering using the EKG technique with geotextile tubes has very interesting potential. However, more work is required to quantify the performance benefits for a range of slurry-like waste streams.

4.6 *Volumes of slurry dewatered and flow rates*

To ensure a dewatering operation proceeds as planned a volume or rate balance between the amount of slurry entering the geotextile tube dewatering system and the amounts of liquid and solids exiting the system must be maintained. The whole dewatering system has to be designed in an effective hydraulic manner to ensure this balance is maintained.

The amount of slurry waste to be dewatered and treated is normally expressed in terms of a total volume or a known flow rate. Volume amounts are usually given if a specific volume is to be removed from lagoons, digesters, lakes, rivers, etc. Alternatively, known flow rates are usually given if it involves output from a process such as an industrial or mining operation or a treatment plant.

The characteristics of the waste slurry should be known, such as specific gravity, the solids concentration during pumping, the solids concentration in place in the geotextile tubes, the target dewatered solids concentration, dewatering rate, and the concentration of coarse material (sand, etc.). The target dewatered solids concentration and dewatering rate should be derived from an evaluation of geotextile tube dewatering performance with the specific waste stream (see section 4.4.2) and account for the effect of dewatering accelerants, etc., if relevant. Coarse material in the waste does not undergo a volume change during dewatering, but does affect the total volume of dewatered solids produced.

The above parameters enable the determination of the dewatered solids volume and rate of effluent water production. The dewatered solids can be disposed of on-site or off-site, or may be recycled, etc. The quality of the effluent water produced determines its use and whether further downstream treatment is required. The effluent water may be recirculated or if it is of good quality can be passed to the environment.

The above parameters also enable the determination of the quantity and sizes of geotextile tubes required to dewater the waste stream. The capacity of the geotextile tubes is also affected by the heights to which they can be filled. The allowable geotextile tube filling height also influences the size of tube used as this governs the magnitude of the tensions generated in the tube during filling, and affects the required ultimate tensile strength of the geotextile skin. This is discussed in the section below.

While geotextile tubes are the most common means of dewatering, geotextile bags have also been used if the volumes are small. In some instances, to aid portability, geotextile bags are maintained inside steel containers during filling and transport to an of-site disposal facility.

4.7 *Filling heights and tensions generated in geotextile tubes during dewatering and ultimate tensile strength requirements*

The tensions generated in geotextile tubes for dewatering are similar to those for hydraulic and marine applications, section 3.1.5. During filling tensions are generated in three locations in the tube units - around the circumference of the tubes, along the length of the tubes, and at the connection of the filling ports with the tubes, see fig: 6.

When slurry waste is used for filling the tubes the tensions generated in the circumferential and longitudinal directions can be readily analysed by use of the membrane theory methods of Leschinsky et al. (1996) and Palmerton (2002). Fig: 26 shows the maximum circumferential tensions generated in 4 m, 6 m and 8 m diameter geotextile tubes at different filling heights (the density of the slurry is assumed to be 11 kN/m^3). It is observed that for *H/D* ratios > 0.4 the circumferential tensions increase significantly for increasing filling heights.

The maximum longitudinal tension generated in the tube can be approximated using the same relationship as presented in section 3.1.5.1, i.e. the longitudinal tension is approximately 63% of the maximum circumferential tension.

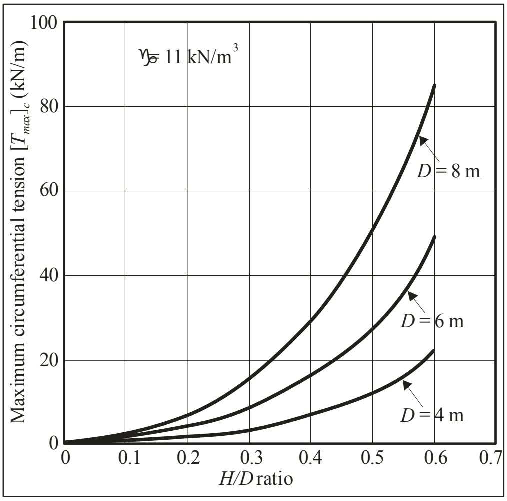


Figure 26. Maximum circumferential tensions in geotextile tubes according to Palmerton (2002).

The magnitude of the port connection tensions can be significant especially if the dewatering tubes are filled to maximum filling heights. To prevent rupture at the ports, and to enable greater filling heights, special metallic port connections have been developed to resist the high stresses in these locations.

The resulting tensile strengths of geotextile tubes are determined by applying a safety factor between 3.5 and 5 times the maximum tensions generated. As with geotextile tubes for hydraulic and marine applications the judicious application of high capacity geotextile seams is crucial to the structural performance of the dewatering tubes.

To maximise dewatering capacity it is important for the geotextile tubes to be filled to a maximum safe height in order to maximise the volume throughput. Safety is important here in order to ensure the tubes do not rupture and discharge the waste in an uncontrolled manner. Good control over pumping during the filling stages is very important to ensure the tubes are not overstressed.

Where the dewatering platform area is limited it may be necessary to stack multiple dewatering tubes on top of each other. The loads exerted by the upper geotextile tubes must be taken into account when determining the required tensile strengths of the lower tubes.

4.8 *Dewatering applications using geotextile tubes*

Currently, geotextile tubes are used to dewater a wide range of slurry-like wastes and contaminated sediments. Virtually any industry that generates slurry waste can utilise geotextile tubes for dewatering and post-processing of the waste. Listed below are the major industry groupings that have used geotextile tube dewatering to date.

4.8.1 *Municipal waste and water treatment*

The dewatering of municipal waste (sewage) sludge was an early application for geotextile tube dewatering, e.g. Fowler et al. (1996). Most municipal sewage treatment plants store the generated sludge from the sewage treatment processes in ponds where further anaerobic processes take place. Over time, these ponds fill with sludge and require cleaning. Further, these ponds are not engineered containment facilities, and consequently, may leak and pollute local water courses, etc. Thus, the cleaning and reclamation of these ponds has become an important environmental issue. Geotextile tubes have been used extensively for dewatering sludge from these containment ponds. The effluent water is normally recirculated to the ponds and the dewatered solids disposed.

Sludges are produced at several stages of the sewage treatment process (known as primary and secondary sludges). Primary sludges are generated in clarifiers and are the result of flocculation sedimentation. Secondary sludges are also generated in clarifiers by flocculation sedimentation but follow biological treatment. There is considerable regulatory pressure for the conversion of sewage sludges to clean biosolids as this can be used for fertiliser, etc. Geotextile tubes also have been used to dewater sludges emanating directly from clarifiers. Some examples of use are given by Fowler et al. (2002).

In a number of instances geotextile tubes have been connected directly to digesters. Here the effluent water is recirculated within the treatment process and the humic solids removed for disposal or allowed to compost.

One limitation on the use of geotextile tubes to dewater sewage sludge is that a flat area has to be available to carry out the dewatering. Space limitations exist with many metropolitan sewage treatment plants because of encroaching development and treatment plant capacity expansion. In these cases alternative dewatering treatment technologies may be more appropriate.

More recently, geotextile tubes have been used to dewater alum sludge, the waste by-product of fresh water treatment plants. In many locations the direct disposal of this sludge is not allowed, and dewatering it to solid form and then disposal in an off-site landfill is the only cost-effective alternative.

4.8.2 *Agricultural animal waste*

Cattle, chicken and hog farms produce large amounts of waste that is commonly stored in sludge ponds near the animal housing facility. The floor of the animal housing is washed out daily with all the waste being washed into retention ponds. Over time these ponds become filled with sludge, and they have to be cleaned out periodically.

Animal waste is more difficult to dewater than sewage waste. It normally has to be treated with a conditioning agent as well as a chemical accelerant to ensure colloids and nutrients are contained within the geotextile tubes during dewatering.

It is reasonably common for the dewatered animal waste to be recycled as fertilizer on pastures. An example of use is given by Worley et al. (2004) where geotextile tubes are used to dewater dairy cattle waste.

4.8.3 *Food processing*

Food processing produces large quantities of slurry-like waste whether it is part of the manufacturing process, or part of the growing process. Examples of food processing industries that have used geotextile tubes to dewater waste are potato processing (washing and skin waste), cheese processing, wine processing and abattoirs. Many other possibilities exist.

Intensive aquaculture activities generate considerable waste from the high-growth feeding of fish and shrimps. This benthic waste can be toxic to fish and shrimps and has to be removed from the aquaculture impoundments at frequent intervals. Dewatering of this waste and subsequent disposal in containment facilities is becoming the practice where environmental regulations exist.

4.8.4 *Mining waste*

Various types of waste are produced from the mining of minerals. Examples include, tailings, mineral fines, processing sludge, etc. Large mining activities produce large amounts of tailings that are stored in open tailings dams in isolated locations. However, there are many instances where tailings are produced in relatively small amounts from small mines that are close to population or environmentally sensitive areas. The management of these tailings or their reclamation and remediation provides many opportunities because in many cases the tailings have to be first dewatered before they can be rendered stable and inert. An example of geotextile tube dewatering of lead and zinc mining tailings for a small capacity mine in Greece is given by Newman et al. (2003).

Other mining activities produce mineral fines as part of the washing process, e.g. coal mining, that can be reclaimed and reused following dewatering.

4.8.5 *Industrial waste*

Many industrial processes produce waste that is stored in waste ponds on the industrial site. Over time these ponds fill with waste and have to be cleaned to enable the ponds to continue to function.

A common form of waste reclamation is to dewater the waste from the ponds and, depending on the nature of the dewatered waste, then dispose of it in landfill, incinerate it, use it for other applications, or recycle it back through the industrial plant.

4.8.6 *Construction waste*

A number of construction activities generate slurry waste that for environmental reasons is becoming increasingly difficult to dispose of directly. Examples include drilling, grouting and diaphragm wall muds. Because the quantities of slurry produced are relatively small, small-sized geotextile tubes have been used to dewater the slurries on-site prior to their disposal in solid form in off-site landfill facilities.

4.8.7 *Contaminated sediments*

The discharge of effluent waste from industrial plants into water courses is a common pollution problem. Many of these pollutants are non-soluble in water and settle into, and contaminate, the sediments of lakes, ponds, streams and rivers. Examples include organic compounds, e.g. polychlorinated biphenyls (PCB's), pentachlorophenols (PCP's), polycyclic aromatic hydrocarbons (PAH's), pesticides and dioxins; heavy metals, e.g. mercury, cadmium, lead, copper, zinc and arsenic; and may also include raw sewage in less-developed regions. These contaminants are harmful to humans, animals and aquatic life.

Environmental dredging is the most common form of contaminated sediment remediation. Here, the sediment is dredged and pumped to storage impoundments, or treated at on-shore facilities before disposal either on-site or off-site. On-shore treatment normally involves dewatering to reduce the volume and to render the sediment in a solid form that can be transported. Examples of geotextile tube dewatering of contaminated sediments are given by Duke et al. (2000), Mori et al. (2002a), Mori et al. (2002b) and section 4.9 of this paper.

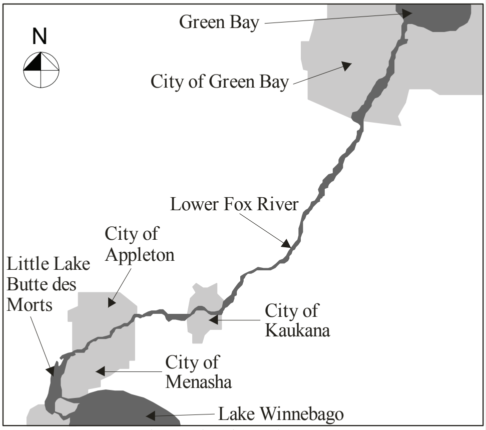
4.9 *Geotextile tubes for dewatering contaminated sediments, Fox River, Little Lake Butte des Morts, Wisconsin, USA*

The Lower Fox River flows Northeast approximately 65 km from Lake Winnebago (in the Southwest) to Green Bay (in the Northeast) and then into Lake Michigan, fig: 27a. During the late 19th, early and mid 20th centuries many pulp and paper companies were attracted to the area to establish plants along the Lower Fox River because of its constant supply of fresh water and its close proximity to timber sources. By the mid 1950's this area had the highest concentration of pulp and paper operations in the world.

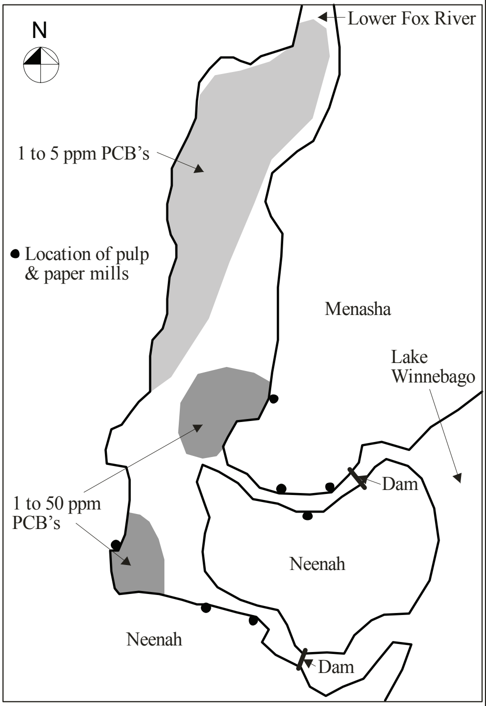
In 1954 the paper mills along the Lower Fox River began producing carbonless copy paper using PCB (polychlorinated biphenyl) coated emulsions. Between 1954 and 1971, when the use of PCB's ceased, it is estimated that some 350 tonnes had been discharged into the Lower Fox River. A portion of these PCB's settled into the river sediments and was ingested by fish and (then) birds. While the use of PCB's ceased in 1971, recycling of PCB coated paper after that time also generated discharges of PCB's into the river.

To reduce the local concentrations of PCB's and to prevent their continual migration into Green Bay it was decided to remediate the Lower Fox River. This remediation is under the auspices of the US EPA Superfund and is funded by the relevant pulp and paper companies in the area. The overall remediation project has divided the Lower Fox River into a number of regions with Little Lake Butte des Morts, lying at the upper reaches of the river (see fig: 27a), being the first to undergo remediation.

Little Lake Butte des Morts is a shallow, slow flowing waterway approximately 5 km in length and 1 km in width located immediately downstream of Lake Winnebago, fig: 27b. A number of pulp and paper mills are located at the upstream end of this lake. Fig: 27b also shows the locations where PCB concentration levels are greater than 1 mg PCB to 1 kg sediment (1 ppm) in the lake. The highest concentration areas (1 to 50 ppm) lie in the vicinity, or immediately downstream, of existing pulp and paper mills in the South and Southeast of the lake. Another large area in the central North of the lake has PCB concentrations from 1 to 5 ppm due to movement of PCB's from the highest concentration areas before entering the Lower Fox River.



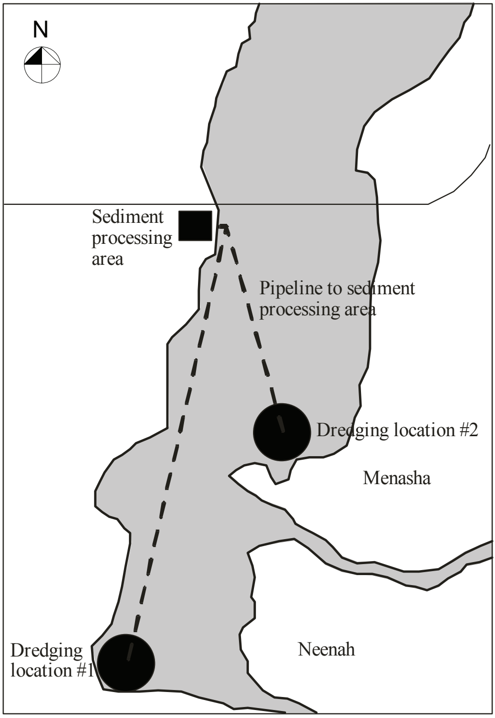
a) Lower Fox River site location map



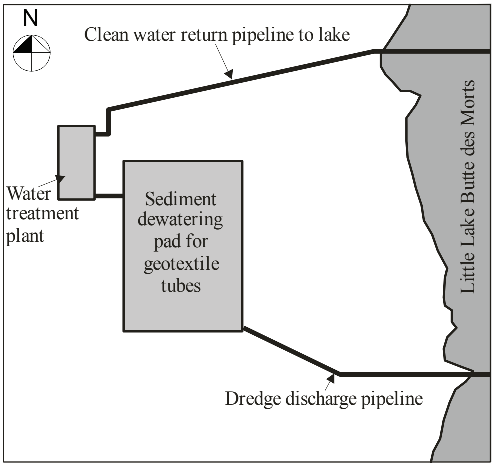
b) Little Lake Butte des Morts along with sediment PCB concentrations

Figure 27. Lower Fox River location and PCB concentration levels in Little Lake Butte des Morts.

Several remediation options were investigated for Little Lake Butte des Morts. It was concluded that dredging of the contaminated sediment along with off-site disposal provided the best solution. A target of 1 mg PCB to 1 kg sediment (1 ppm) was



a) Little Lake Butte des Morts cleanup map



b) Layout of sediment processing area

Figure 28. Details of the remedial dredging and sediment treatment operation in Little Lake Butte des Morts.

established as the required cleanup level as this gave the optimum solution between long term safety to humans and wildlife and overall project cost. 98% of the PCB concentration lies in the upper metre of the sediment layer. This requires the dredging of approximately 600,000 m^3 of contaminated sediments (approximately 1,700 kg of PCB's) in the lake, and is to be carried out over a 6 year seasonal period, beginning in 2004. Subsequently, a long term monitoring programme will be put in place to track the concentration of PCB's in various media.

The remediation process involves several steps: First, sediment is dredged from the lake bed by a hydraulic dredge and is pumped through a floating pipeline to the staging area and into geotextile tubes, where it dewaters. Next, the water is collected from the lined gravel drainage area beneath the geotextile tubes and pumped into a treatment plant, where it is cleaned with sand and activated carbon treatments to remove contaminants. The clean water is then returned through another pipeline to the lake. Finally, when the contaminated sediment is dry enough, it is removed from the geotextile tubes and loaded into lined, covered trucks for transport to a disposal site. The disposal site is fully licensed for the disposal of sediment containing PCB's.

An extensive evaluation programme was employed to determine the appropriate geotextile tube dewatering performance parameters. A large number of hanging bag tests were performed to determine the appropriate accelerant type and dosage rates, the likely rates of dewatering and the resulting effluent quality. Calculations were then performed to determine the required quantities, sizes and safe filling heights of the tubes.

Dredging of the contaminated sediments began in 2004 in the area of highest PCB concentrations to the South and Southeast of the lake, fig: 28a. The dredges used were special, small-scale cutter-suction dredges that created minimal sediment disturbance during operation. The accurate positioning of the dredges was via GPS with an accuracy of 1 m. The depth of dredging varied according to contaminant concentration between 0.3 m and 1 m. The accuracy of the depth of dredging could be controlled to within 0.1 m.

The dredged contaminated sediment was pumped hydraulically through two floating pipelines to the on-shore sediment processing area located on the central Western shore of Little Lake Butte des Morts, fig: 28a. The sediment processing area consisted of a sediment dewatering pad that supported the geotextile tube dewatering and a water treatment plant that removed the contaminants from the effluent water, fig: 28b. These two processing units were connected by pipelines from the dredges, and from the sediment dewatering pad to the water treatment plant. Once treated the clean water was returned to the lake by pipeline.

a) Lined drainage blanket beneath geotextile tubes

b) Sediment dewatering within geotextile tubes

c) Removal of dewatered sediment from geotextile tubes

Figure 29. Various dewatering components and stages of the dewatering process using geotextile tubes.

The dewatering pad consists of a clay underlayer with a geomembrane liner. On top of this a geotextile protection layer has been placed prior to the placement of the gravel drainage blanket, fig: 29a.

The geotextile tubes are laid out on the gravel drainage blanket and connected by a pipe network to the incoming dredged sediment. The pipe network enables the filling and re-filling of the geotextile tubes (following each dewatering cycle) 5 times before the final dewatering and consolidation stage is reached. The incoming dredged sediment is dosed and mixed with the appropriate amount of chemical dewatering accelerant in order to maximise the rate of dewatering within the geotextile tubes. The size of the geotextile tubes, their filling heights, and the number employed at any point in time had to match the volume of incoming dredged sediment, which ranged between 4.5 m^3/min and 5.5 m^3/min. Because of space limitations at the dewatering pad the geotextile tubes were stacked several high during the dewatering process, fig: 29b.

The effluent water drains out of the geotextile tubes, down through the gravel drainage blanket, and then down to a sump located at the lowest point of the pad. When the sump fills up, pumps automatically switch on and pump the effluent water into the treatment plant. The treatment plant utilises dissolved air floatation combined with sand and activated carbon filtration to clean the water. The clean water is then returned to the lake by means of an outlet pipeline.

After dewatering, the contained sediments ranged in solids concentration between 35% and 80%. This variation was due to the variation in the amount of granular particles in the geotextile tubes and the time over which the geotextile tubes were allowed to consolidate (the bottom layer was allowed more time than the upper layer). This increase in solids concentration results in a reduction in contained volume of 60% and 85% respectively. After 6 months the dewatered sediment was removed from the geotextile tubes by excavators and transported to a licensed off-site landfill disposal facility, fig: 29c. The sediment is transported using lined trucks to prevent loss of the contaminated soil.

5 GEOTEXTILE CONTAINMENT FOR OFFSHORE DISPOSAL OF CONTAMINATED SEDIMENTS

In many countries industrial development has occurred historically around the coastline as this gave convenient access to imports and exports, and enabled access to the hinterland via rivers, etc. In Asia, for example, much of the industrial development lies within, or near, seaports and coastal cities. With industrial development has come industrial effluent, which over the years has been deposited, along with river and marine sediments, within ports and river and coastal areas. Much of this industrial effluent has consisted of non-soluble organic compounds (e.g. polychlorinated biphenyls (PCB's), polycyclic aromatic hydrocarbons (PAH's), pesticides and dioxins) and heavy metals (e.g. mercury, cadmium, lead, copper, zinc and arsenic) while raw sewage has also been deposited (in undeveloped areas). Today, these sediments contaminated with non-soluble organic compounds, heavy metals and raw sewage present a major problem when it comes to their safe disposal from marine construction sites and land reclamation schemes. These contaminated sediments may vary from over-consolidated clays to very soft clays.

Due to a shortage of available land in Asia the on-shore disposal of contaminated sediments is virtually impossible. Furthermore, the treatment of contaminated sediments is very expensive and can be very difficult. Consequently, controlled offshore disposal sites are employed. These offshore disposal sites are normally located in an area that has been pre-dredged, or are contained within submarine dykes, and are founded at considerable water depth (normally > 20 m).

Non-soluble organic compounds, heavy metals and raw sewage remain motionless and non-dissolvable within a stationary soil mass. However, when the contaminated sediments are disposed of in an uncontrolled manner at an off-shore disposal site, as shown in fig: 30a, they can dissipate into the surrounding marine environment by the action of tidal and marine currents. Normally, on reaching the bottom of the offshore disposal site further dissipation does not occur provided the bed of the disposal site is free from marine currents. Thus, the critical contaminant dissipation phase occurs during the actual dumping of the contaminated sediments.

Geotextile containers have been used to ensure the dumping of contaminated sediments is carried out in a controlled manner. The basic technique is shown in fig: 30b where the geotextile container has been filled with the contaminated sediment and is dumped within the offshore disposal site. The geotextile container prevents the contaminated sediment fill from dissipating into the surrounding marine environment and also encapsulates the contaminated sediments on the bed of the disposal site. This technique was first used in USA, e.g. Fowler et al. (1995b), Fowler & Trainer (1998), and has since been used elsewhere.

The integrity of the geotextile containers during filling, dropping and after placement is crucial for the safe, controlled disposal of contaminated sediments. Section 3.2.3 discusses in detail the tensions generated in geotextile containers during installation for hydraulic and marine structures. For contaminated sediment disposal the generated tensions can be greater due to the following. First, the size of the containers is relatively large (c.f. those used for marine structures) and they are dropped in considerable water depth. Second, the fill material is over-consolidated or soft clays that provide little-to-negligible internal shear resistance during dumping. Third, to ensure no loss of the contaminated sediment during dumping a combination geotextile skin consisting of a woven, outer layer (for strength) with a nonwoven, inner lining (for complete soil retention) is normally

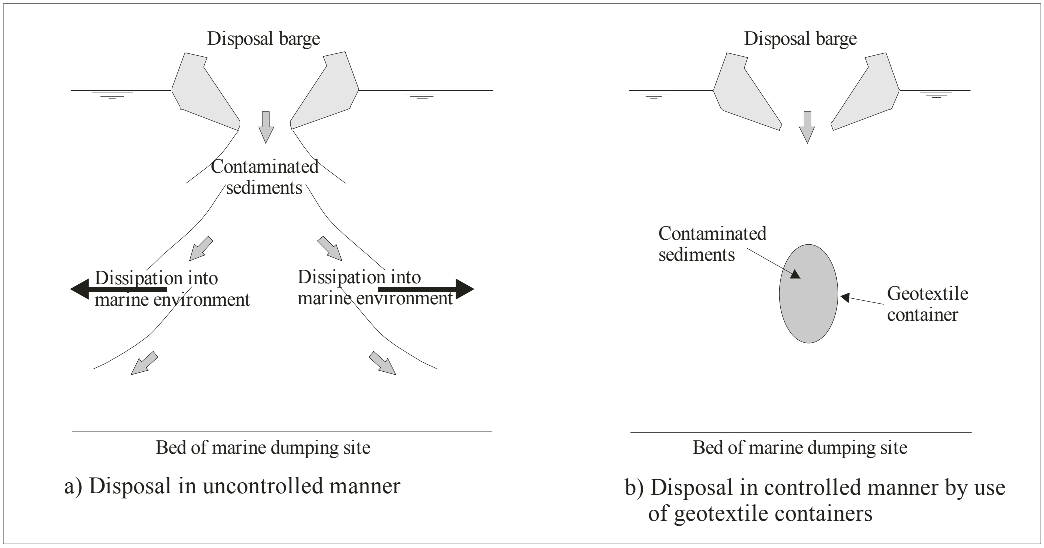


Figure 30. Use of geotextile containers for the controlled off-shore disposal of contaminated sediments.

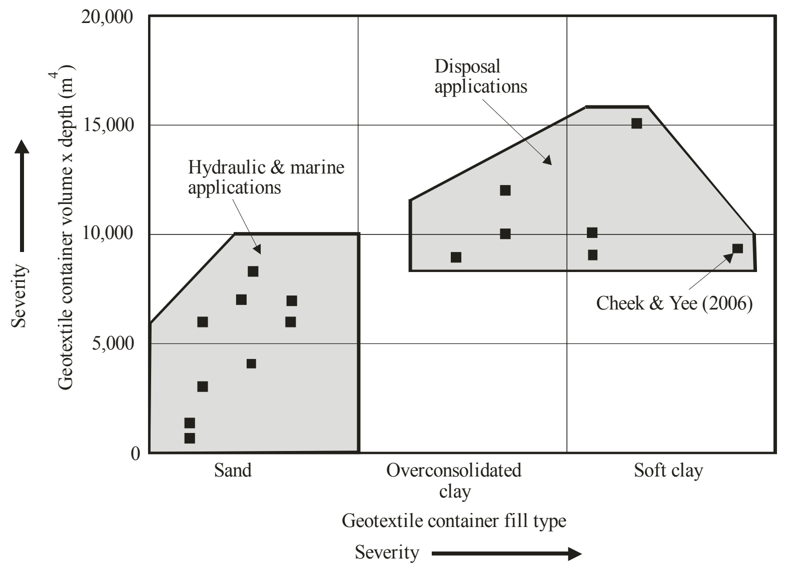


Figure 31. Geotextile container operating spectrum according to type of application.

required. Further, high capacity seams have to be used throughout the geotextile container to ensure its mechanical integrity.

Fig: 31 plots data obtained from a number of geotextile container installation sites. The vertical axis represents the geotextile container volume (in m^3) multiplied by the water depth of installation (in m). The maximum value of 20,000 m^4 shown on the vertical axis can equate to a 1,000 m^3 geotextile container installed in 20 m water depth (which is an extreme instance). The higher the value on the vertical axis, the more severe the application in terms of larger container volumes and/or greater water depths. The horizontal axis represents the type of fill placed inside the geotextile container. Basically, three fill types have been used ranging from sand to overconsolidated clay to soft clay. In moving to the right along the horizontal axis the severity increases because the geocontainer fill has less internal shear resistance (and therefore less absorption of energy). This has a significant effect on the tensions generated in the geotextile container when it impacts the seabed (see section 3.2.3.4).

The data in fig: 31 can be divided into two distinct regions according to the type of geotextile container application. The lower left region is where geotextile containers are used as structural elements in hydraulic and marine applications (see section 3.2). Here, the disposal conditions are less severe, as the geotextile containers are relatively small in volume in order meet specific installed geometric requirements and are normally placed in relatively shallow water depths. Furthermore, the fill in these geotextile containers is sand, or a high percentage of sand, for its structural and volume stability.

The upper right region in fig: 31 is where geotextile containers are used to dispose of contaminated sediments. Here, the disposal conditions are more severe, as the geotextile containers are relatively large in volume in order to conform to dredging and reclamation capacities and are normally placed in relatively deep offshore disposal sites. Further, the contaminated fill in these geotextile containers is either overconsolidated clays or soft clays. Recently, the work of Cheek & Yee (2006) has extended the boundary of this region further to the right (more severe) by disposing of very soft sediments in large containers from a reclamation site in Hong Kong.

While the conditions are more severe for disposal applications, the geotextile containers must maintain mechanical integrity during installation to ensure the contaminated sediments do not dissipate into the surrounding marine environment. The tensile strengths required of geotextile containers increase as the application moves from the lower left in fig: 31 to the upper right. This applies to both the tensile strength requirements of the geotextile itself as well as that of the seams in the geotextile container. For disposal applications high strength geotextiles using high capacity seams and other special joining techniques are required.

6 CONCLUSIONS

Geotextile containment presents very interesting opportunities in the areas of hydraulic and marine engineering, and environmental engineering. The three basic containment units – tubes, containers and bags – can be applied to many applications.

By containing sand and other similar materials geotextile tubes, containers and bags act as mass-gravity structures in hydraulic and marine applications. Sand, or like fill, is used for these applications because it does not undergo consolidation once installed and the units can maintain their existing shape and height.

When installed in hydraulic and marine environments care is required especially if the geotextile containment structures are continually exposed over long periods of time. In these situations, aspects such as UV resistance, abrasion resistance and liquefaction of the sand fill need to be taken into account.

Geotextile tubes and geotextile bags provide an efficient medium for the dewatering of waste streams and contaminated sediments. Their high contact surface area and good filtration characteristics, in addition to their simplicity, make them readily suited for this technique. The addition of chemical dewatering accelerants can enhance the rate of dewatering significantly and can trap contaminants within the dewatering waste. Other dewatering accelerant techniques, such as EKG, offer interesting prospects in the future. To ensure success, the geotextile tube dewatering system needs to be designed hydraulically to ensure all components meet the capacity requirements. Also, the strengths and filling heights of the geotextile tubes must be closely controlled.

Geotextile containers have demonstrated their ability to safely dispose of contaminated sediments in off-shore disposal facilities. This application is more severe on the geotextile container than the more conventional hydraulic and marine application because of the relative size of containers used, their dropping depth and the normally poor shear resistance of the contaminated fill. Ensuring the integrity of the geotextile container during installation requires the use of high strength geotextiles with high capacity seams, along with relatively small pore sizes to ensure negligible loss of fill.

REFERENCES

Austin, T. 1995. A second life for dredged material. *Civil Engineering*, November: 60-63.

Artières, O., Dunand, M. & Durand, F. 2005. Coastal protection with filter tube breakwater “Amelie” beach case. *Proc. EuroGeo 3*, Munich, Germany: 367-370.

Bezuijen, A., Schriver, R.R., Klein Breteler, M., Berendsen, E. & Pilarczyk, K.W. 2002a. Field tests on geocontainers. *Proc. 7th Int. Conf. on Geosynthetics*, Vol. 3, Nice, France: 997-1000.

Bezuijen, A., Oung, O., Klein Breteler, M., Berendsen, E. & Pilarczyk, K.W. 2002b. Model tests on geocontainers, placing accuracy and geotechnical aspects. *Proc. 7th Int. Conf. on Geosynthetics*, Vol. 3, Nice, France: 1001-1006.

Bezuijen, A., de Groot, M.B., Klein Breteler, M. & Berendsen, E. 2005. Placing accuracy and stability of geocontainers. *Proc. EuroGeo 3*, Munich, Germany: 123-128.

Bjerrum, L., Moum, J. & Eide, O. 1967. Application of electro-osmosis to a foundation problem in Norwegian quick clay, *Geotechnique*, 17, Thomas Telford: 214-235.

Black, K. 1998. Design of a multi-purpose reef for surf riding, sheltered swimming and coastal stability: Gold Coast, Australia. *Proc. 2nd Int. Artificial Surfing Reef Symposium*, San Diego, USA.

Borrero, J.C. & Nelson, C. 2002. Results of a comprehensive monitoring program at Pratte’s Reef. Department of Civil Engineering, University of Southern California, USA.

Buckley, J. & Hornsey, W. 2006. Woorin beach protection – sand filled tubes vs sand filled containers. *Proc. 8th Int. Conf. on Geosynthetics,* Yokohama, Japan: (in press).

Cantré, S. 2002. Geotextile tubes – analytical design aspects, *Geotextiles and Geomembranes*, 20, Elsevier: 305-319.

Cheek, P.M. & Yee, T.W. 2006. The use of geosynthetic containers for disposal of dredged sediments – a case history, *Proc. 8th Int. Conf. on Geosynthetics,* Yokohama, Japan: (in press).

das Neves, L., Gomes, F.V., Silvano, R. & Lopes, M.L. 2005. Sand filled containers in dune erosion control, a case study from the NW coast of Portugal. *Proc. EuroGeo 3*, Munich, Germany: 129-134.

de Bruin, P. & Loos, C. 1995. The use of Geotubes as an essential part of an 8.8 m high North Sea dyke and embankment, Leybucht, Geomany, *Geosynthetics World*, April: 7-10.

Duke, M.L., Fowler, J. & Schmidt, M.L. 2000. Dredging and dewatering of hazardous impoundment sediment using the dry dredge and geotubes, U.S Corp of Engineers, Vicksburg, USA.

Fourie, A.B., Pavlakis, J. & Jones, C.J.F.P. 2002. Stabilisation of mine tailings deposits using electro-kinetic geotextiles, *Proc. 7th Int. Conf. on Geosynthetics*, Vol. 3, Nice, France: 1031-1034.

Fourie, A.B., Johns, D. & Jones, C.J.F.P. 2004. In-situ dewatering of mine tailings using electro-kinetic geosynthetics, *Proc. 11th Int. Conf. on Tailings and Mine Waste*, Colorado, USA: 341-345.

Fowler, J., Toups, D., Duarte, F. & Gilbert, P. 1995a. Geotextile contained dredged material, Red Eye Crossing, Baton Rouge, LA. *Proc. 16th Technical Conference of Western Dredging Association*, Minneapolis, USA: 257-262.

Fowler, J., Toups, D. & Gilbert, P. 1995b. Geotextile contained contaminated dredged material, Marina Del Rey, Los Angeles and Port of Oakland, California, *Proc. 14th World Dredging Congress*, Amsterdam, The Netherlands.

Fowler, J., Bagby, R.M. & Trainer, E. 1996. Dewatering sewage sludge with geotextile tubes. *Proc. 49th Canadian Geotechnical Conf.,* St John’s, Canada: pp.31.

Fowler, J. 1997. Geotextile tubes and flood control. *Geotechnical Fabrics Report*, July: 28-37.

Fowler, J. & Trainer, E. 1998. Overview of geocontainer projects in the United States. *Proc. Western Dredging Conf.*, USA.

Fowler, J., Duke, M., Schmidt, M.L., Crabtree, B., Bagby, R.M. & Trainer, E. 2002. Dewatering sewage sludge and hazardous sludge with geotextile tubes, *Proc. 7th Int. Conf. on Geosynthetics*, Vol. 3, Nice, France: 1007-1012.

Fowler, J., Ortiz, C., Ruiz, N. & Martinez, E. 2002. Use of geotubes in Columbia, South America. *Proc. 7th Int. Conf. on Geosynthetics*, Vol. 3, Nice, France: 1129-1132.

Gaffney, D.A., Martin, S.M., Maher, M.H. & Bennert, T.A. 1999. Dewatering contaminated, fine-grained material using geotextiles. *Proc. Geosynthetics '99*, Vol. 2, Boston, USA: 1017-1032.

Gadd, P.E. 1988. Sand bag slope protection: design, construction and performance. Arctic Coastal Processes and Slope Protection Design, ASCE, USA: 145-165.

Giroud, J.P. 1996. Granular filters and geotextile filters, *Proc. Geofilters 96*, Montreal, Canada: 565-680.

Glendinning, S., Jones, C.J.F.P., Huntley, D.T. & Lamont-Black, J. 2006. Dewatering of sewage sludge using Electrokinetic Geosynthetics, *Proc. 8th Int. Conf. on Geosynthetics,* Yokohama, Japan: (in press).

GRI GT12 : 2004. Hanging bag test for field assessment of fabrics used for geotextile tubes and containers, Geosynthetics Research Institute, Folsom, USA.

Heibaum, M. 1999. Coastal scour stabilisation using granular filter in geosynthetic nonwoven containers. *Geotextiles and Geomembranes,* 17, Elsevier: 341-352.

Jackson, L.A. 1987. Evaluation of sand filled geotextile groynes constructed on the Gold Coast, Australia. *Proc. 8th Australian Conf. on Coastal and Ocean Engineering*, Launceston, Australia: 235-238.

Jagt, H.J. 1988. Bed protection, Old Meuse, by means of geocontainers. Internal report, Rijkswaterstaat, The Netherlands, April.

Jones, C.J.F.P. 1996. *Earth reinforcement and soil structures*, Thomas Telford, London.

Jones, C.J.F.P., Glendinning, S., Huntley, D.T. & Lamont-Black, J. 2006. Case history: in-situ dewatering of lagooned sewage sludge using electrokinetic geosynthetics (EKG), *Proc. 8th Int. Conf. on Geosynthetics,* Yokohama, Japan: (in press).

Kazimierowicz, K. 1994. Simple analysis of deformation of sand-sausages, *Proc. 5th Int. Conf. on Geosynthetics,* Vol. 2, Singapore: 775-778.

Koerner, G. & Koerner, R.M. 2006. Geotextile tube assessment using a hanging bag test, *Geotextiles and Geomembranes*, 24, Elsevier: 129-137.

Lawson, C.R. 2003. Geotextile containment – international perspectives. *Proc. 17th GRI Conference*, Geosynthetic Institute, Philadelphia, USA: 198-221.

Leschinsky, D., Leschinsky, O., Ling, H.I. & Gilbert, P.A. 1996. Geosynthetic tubes for confining pressurized slurry: some design aspects, *Journal of the Geotechnical Engineering Division*, American Society of Civil Engineers, Vol. 122, No. 8: 682-690.

Liu, G.S. 1981. Design criteria of sand sausages for beach defences, *Proc. 19th Congr. of the Int. Assn. for Hydraulic Research,* New Delhi, India: 123-131.

McClarty, A., Cross, J., Gilbert, L. & James, G.M. 2006. Design and construction of a coastal erosion protection groyne using geocontainers, Langebaan, South Africa. *Proc. 8th Int. Conf. on Geosynthetics,* Yokohama, Japan: (in press).

Miller, S., Murphy, A., Veal, C. & Young, M. 1998. Improved filtration of sewage sludges using electrodewatering, Report No. ET/IR140, CSIRO, Australia, November.

Moo-Young, H., Gaffney, D.A. & Mo, X.H. 2002. Testing procedures to assess the viability of dewatering with geotextile tubes, *Geotextiles and Geomembranes*, 20, Elsevier: 289-303.

Mori, H., Miki, H. & Tsuneoka, N. 2002a. The geo-tube method for dioxin-contaminated soil, *Geotextiles and Geomembranes*, 20, Elsevier: 281-288.

Mori, H., Miki, H. & Tsuneoka, N. 2002b. The use of geo-tube method to retard the migration of contaminants in dredged soil, *Proc. 7th Int. Conf. on Geosynthetics*, Vol. 3, Nice, France: 1017-1020.

Newman, P., Hodgson, M. & Rosselot, E. 2003. The disposal of tailings and minewater sludge using geotextile dewatering techniques, *Proc. Processing and Disposal of Minerals Industry Wastes*, Falmouth, UK: pp.10.

Nickels, H. & Heerten, G. 1996. Building elements made of geosynthetics and sand resist the North Sea surf, *Proc. EuroGeo 1*, Maastricht, The Netherlands: 907-910.

Nor Hisham, M.G., Kam, S. & Yee, T.W. 2006. Geotextile tubes for protection of mangrove coast at Tanjung Piai Johor National Park, Malaysia. *Proc. 8th Int. Conf. on Geosynthetics,* Yokohama, Japan: (in press).

Oh, Y.I., Shin, E.C. & Das, B.M. 2006. Application of submerged geotextile tubes for erosion prevention in East coast of Korea. *Proc. 8th Int. Conf. on Geosynthetics,* Yokohama, Japan: (in press).

Palmerton, J.B. 2002. Distinct element modelling of geosynthetic fabric containers. *Proc. 7th Int. Conf. on Geosynthetics*, Vol. 3, Nice, France: 1021-1024.

Perrier, H. 1986. Use of soil-filled synthetic pillows for erosion protection. *Proc. 3rd Int. Conf. on Geosynthetics*, Vol. 4, Vienna, Austria: 1115-1119.

Pilarczyk, K.W. 2000. *Geosynthetics and Geosystems in Hydraulic and Coastal Engineering*, Balkema, Rotterdam.

Poirier, M.R. 2001. Improving the filtration of sludge/monosodium titanate slurries by the addition of flocculants, Report WSRC-TR-2001-00175, US Department of Energy, Oak Ridge, USA.

Restall, S.J., Jackson, L.A., Heerten, G. and Hornsey, W.P. 2002. Case studies showing the growth and development of geotextile sand containers: an Australian perspective, *Geotextiles and Geomembranes*, 20, Elsevier: 321-342.

Restall, S.J., Hornsey, W., Oumeraci, H., Hinz, M., Saathoff, F. & Werth, K. 2005. Australian and German experiences with geotextile containers for coastal protection. *Proc. EuroGeo 3*, Munich, Germany: 141-146.

Seay, P.A. 1998. Finite element analysis of geotextile tubes. Department of Civil Engineering, Virginia Polytechnical Institute, USA.

Spelt, K. 2001. Geotubes as the core of guide dams for Naviduct at Enkhuisen, The Netherlands, *Terra et Aqua*, 83: 21-25.

Tonks, D.M., Parry, D., Howells, R. & Smith, D.M. 2005. River Mersey closure embankments applications of geobags and geosynthetics. *Proc. EuroGeo 3*, Munich, Germany: 147-152.

Townsend, M. 2005. Semaphore Park offshore breakwater: a trial. *Proc. 17th Australasian Coastal and Ocean Engineering Conference*, Australia: 691-696.

Wei, J., Chua, K.C., Ho, K.Q., Ho, W.H., Cheng, S.K., Seng, M.K., Yee, T.W. and Cheah, R.S.C. 2001. The use of geocontainers for the Southern Islands Reclamation Project, *Proc. Int. Conf. on Engineering for Ocean and Offshore Structures*, Singapore: 146-156.

Worley, J.W., Bass, T.M. & Vendrell, P.F. 2004. Field test of geotextile tube for dewatering dairy lagoon sludge, *Proc. ASAE/CSAE Annual International Meeting*, Ottawa, Canada: pp.12.

Worley, J.W., Bass, T.M. & Vendrell, P.F. 2005. Performance of geotextile tubes with and without chemical amendments.