Geosynthetics in hydraulic and coastal engineering: Filters, revetments and sand filled structures

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ABSTRACT: The paper deals with 2 applications of geotextiles in coastal and hydraulic engineering: Geotextiles in filters and revetments; and geotextiles in sand filled structures. Geotextiles are often replacing granular filters. However, they have different properties than a granular filter. For the application of geotextiles in revetments, the consequences of the different properties will be shown: how permeability is influenced by a geotextile and what can be the consequences of the weight differences between granular and geotextile filters. In the other application, the filter properties of geotextiles are only secondary. In geotextile tubes and containers the geotextile is used as 'wrapping material' to create large units that will not erode during wave attack. The structures with geotextile tubes and containers serve as an alternative for rock based structures. The first of these structures were more or less constructed by trial and error, but research on the shape of the structures, the stability under wave attack and the durability of the used material has given the possibility to use design tools for these structures. Recently also the morphological aspects of these structures have been investigated. This is of importance because regularly structures with geotextile tubes fail due to insufficient toe protection against the scour hole that develops in front of the structure, leading to undermining of the structure. Recent research in the Delta Flume of Deltares and the Large Wave Flume in Hannover has led to better understanding what mechanisms determine the stability under wave attack. It is shown that also the degree of filling is of importance and the position of the water level with respect to the tube has a large influence.

1 INTRODUCTION

Geotextiles are widely used in coastal and hydraulic engineering. Some of the largest hydraulic structures ever built, the Eastern Scheldt Storm Surge Barrier and the Moses Flood Barrier in Venice are founded using geotextiles.

A quite common application in coastal and hydraulic engineering is that a geotextile replaces (partly) a granular filter. The construction of granular filters, especially below the water line is rather costly because several layers has to be made with granular material going from fine to coarser to avoid that the fines are washed out. The Deltaworks in the South-Western part of the Netherlands and the Moses flood barrier in Venice show the development of the use of geotextiles.

No geotextiles were used in the 60's of last century, during the construction of the Haringvliet-dam. A polder was made and the filter construction was made in a dry environment. In the 70-ties during the construction of the Eastern Scheldt Storm Surge barrier, still granular filters were used, but these were applied in mattresses where geotextiles were the separation layers, see Figure 1.

The life time of the geotexiles could be relatively short, because after placement there is always the granular filter. By using this method the construction of the temporarily polder could be avoided. During the construction of the Moses Flood Barrier, last decade, the knowledge of the durability of geotextiles has advanced so far that the geotextiles were now designed as an integral part of the filter structure (see Figure 2 and Figure 3) again saving money, because the mattresses could be made thinner and with fewer layers.

Geosynthetic filters are nowadays often used in revetments where they also replace granular filters. This contribution will deal with criteria for these filters. It will be shown that more than just the filter criteria have to be taken into account.

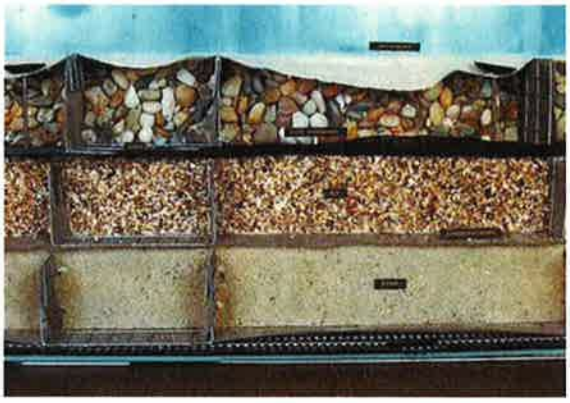


Figure 1. Filter mattress Eastern Scheldt storm surge barrier. 3 granular layers

Figure 2. Filter mattress Mose, Venice. 1 granular layer

The sand filled tubes and containers are quite different applications. The idea to use sand filled bags to prevent erosion of sand is rather old, but due to the limited strength of the traditional bags, made from jute, only bags of limited dimensions could be used. The development of geotextiles makes much larger bags possible. This allows for the development of new erosive resistant structures. The first application of large sand filled bags is already more than 50 years ago. Yet it is still a 'nice market'. In this contribution reasons for that will be discussed.

This paper will first deal with the application of geotextiles as a filter; will discuss the filter rules, the permeability and the importance of weight of the various layers to reach stability in case of revetments. The second part (Sections 5 and 6) will deal with sand filled geotextiles, the applications, design aspects, possibilities and limitations.

Other applications of geosynthetics and geosystems can be found in Pilarczyk (2000), Fowler et al. (2002), Heerten et al. (2010), Lawson (2010) and Homsey et al. (2002).

2 FILTER CRITERIA

2.1 *Different criteria*

A filter prevents that fine material is washed out. Filters can be geometrically stable or hydraulically stable. The first criterion is fulfilled when the fines in the filter cannot pass through the pores of the larger material. Such a filter is stable for all gradients, because it is impossible that the fines of the subsoil are transported though the larger stones of the filter layer. The only way that failure can occur is when the coarse layer of the filter becomes unstable. In a hydraulically stable filter, it is possible that the fines are transported through the pores of the coarser material but a certain hydraulic gradient is necessary for such a transport. If it can be proven that such a gradient will not be reached, then the filter is also stable. In coastal engineering the maximum possible hydraulic gradient can normally reach quite high values, so that there is little to gain by using a hydraulically stable filter (Grauw et al., 1983). Therefore this paper deals with geometrically stable filters only

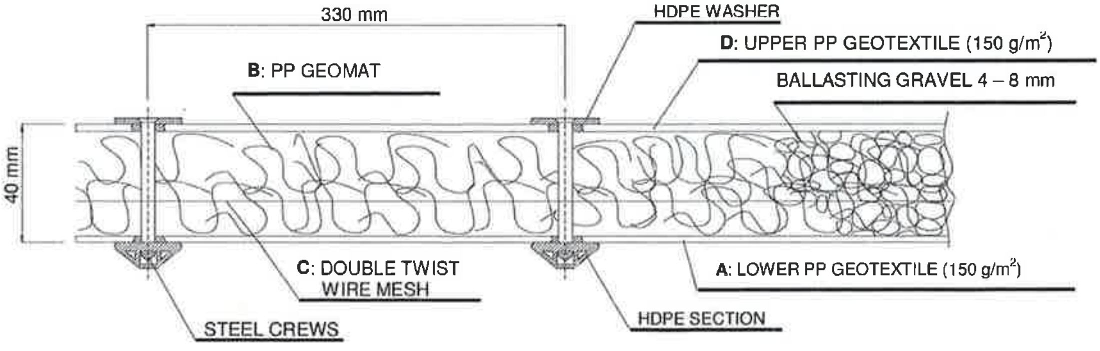


Figure 3. Filter mattress Eastern Scheldt Storm surge barrier. 3 granular layers

2.2 *Grain size distribution*

In a granular filter, the coarse layer, the filter layer, will be applied during construction. Normally this layer has a rather uniform grain size distribution. The same is valid for the opening size of woven geotextiles. The subsoil is normally natural material and therefore this can be in all gradations. Important is that the subsoil is internally stable. As for hydraulic filters, this is not an absolute criterion. It is possible that some fines migrate from the subsoil and that this migration creates a natural filter. Close to the filter layer, the permeability will then be a bit higher because fines will be washed out. However, it is also possible that the fines are collected at the boundary between the subsoil and the filter, creating an impermeable boundary. This mechanism is called 'blinding'. It is difficult to say what will happen beforehand and therefore it is advised to perform some gradient ratio tests (ASTM D 5101) at the expected gradients (static or cyclic) with the designed geotextile filter when the subsoil is not internally stable or (partly) replace the subsoil by more uniform material

Whether or not subsoil is internally stable is given by Kenney and Lau (1985). Their method is shown graphically in Figure 4 in a particle size distribution (PSD) curve. The essence of their method is to compare the fraction with the particle size (D) with the fraction with the particle size (4D) as explained in the figure.

2.3 *Filter criteria*

For a geosynthetic filter to act well, it has to fulfil different criteria. A criterion for the subsoil was already mentioned above. Furthermore, the opening size of the filter has to be limited to prevent subsoil transport, There have to be enough openings to prevent 'blocking' and also the permeability has to be high enough, so that the geotextile attributes only limited to the flow resistance. Literature presents quite a number of filter criteria (Heibaum, 2004, Heibaum et al. 2006), which mostly agree for rather uniform subsoil, but differ when it comes to subsoils with are less uniform (have a larger value for the coefficient of uniformity, d_{60}/d_{10}).

The results of the various criteria, based on Dutch research and uniform subsoil sands with thus a low ratio d_{60}/d_{10}, are summarized graphically in CUR 174 (2009), based on the work of Mlynarek (1994) and shown in Figure 5 and Figure 6. The filter criteria for wovens present an unlikely result suggesting that even if the openings are small enough, in case the permeability of the geotextile is 100 times larger than the permeability of the sand, it is still possible that there is washing out of the sand. As mentioned this is an unlikely result, because when the openings are small enough the sand cannot pass. It is more likely that such a high permeability ratio k_g/k_b (permeability geotextile/permeability subsoil) cannot be reached with woven geotextiles that have small enough openings. It is also possible that this mistake is made by translation from the original publication.

Apart from this unlikely result these graphs are an elegant way to present the various criteria that have to be used. Only in the white area in the middle it is possible to make a stable filter with a limited pressure drop over the geotextile. The results presented are, as mentioned only for steep graded subsoils, for other situations it is advised to use the relations presented by Heibaum et al. (2006). The permeability criterion presented by Mlynarek in the graphs of Figure 5 and Figure 6, is a nice way to show the influence of the permeability, but it will be shown below that the permeability of a geotextile, perpendicular to the plane is not easy to determine and possibly even not a very useful parameter, so these results should be used with great caution.

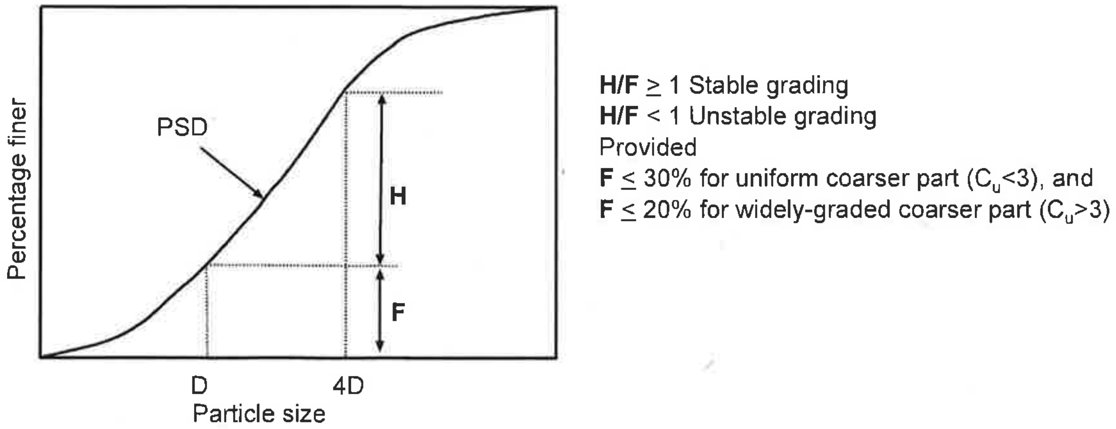


Figure 4. Grafical presentation of the procedure from Kenney and Lau (1985) for internal stability assessment (mofified from Indraratne and Raut, 2006)

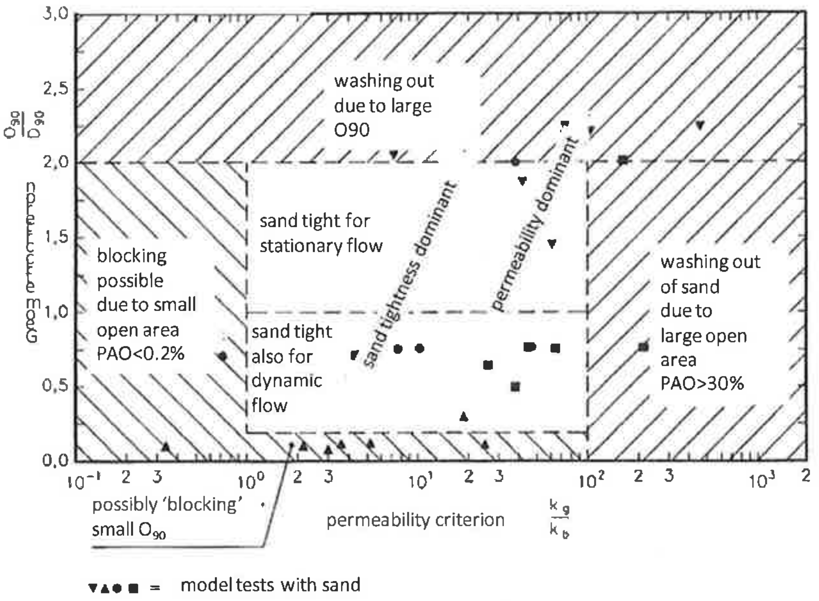


Figure 5. Filter criteria for woven geotextiles according to Mlynarek (1994), taken from CUR 174 (2009), modified

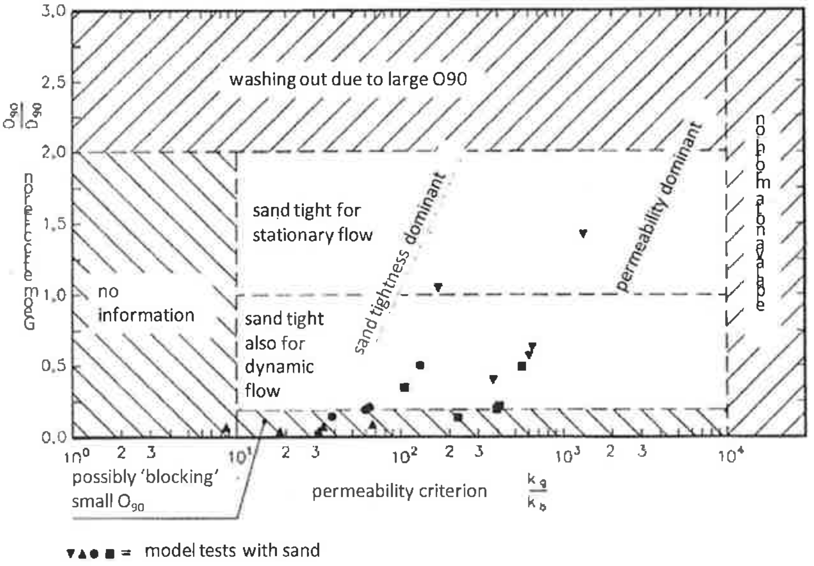


Figure 6. Filter criteria for non-woven geotextiles according to Mlynarek (1994), taken from CUR 174 (2009), modified

2.4 *Use of a filter in a revetment*

A layer of granular material that acts as a filter can have more functions than just a filter function. In a revetment, the weight of a granular layer is often used to prevent instability of the slope, see Bezuijen & Köhler, 1996. During run-down of a wave the water pressure in front of the revetment will be lower than the pore pressure inside the slope of the revetment, resulting in an outward directed gradient that will jeopardize the slope stability unless the weight of the filter layers and armour layer is sufficient to keep the slope stable. By replacing the granular filter layers with a geotextile, that has the same filter function, the filter function is assured, but the weight of the combination of filter layers and armour layer has decreased. Therefore, it is necessary to control again whether or not the slope of the structure is sufficiently stable against the design wave attack.

3 PERMEABILITY OF THE GEOTEXTILE PERPENDICULAR TO THE PLANE

3.1 *Permeability reduction due to granular material*

As mentioned, a geotextile filter, as a granular filter, has to be able to block the fine granular material, but must allow for sufficient water flow through the geotextile. The water flow through a geotextile as a function of the hydraulic head is measured in the index test: EN ISO 11058. However, the actual permeability normal to the plane of a geotextile in sand or granular material is much lower than measured in the EN ISO index test. Bezuijen & Köhler (1996) have measured that a geotextile surrounded by two layers of granular material has a flow capacity normal to the plane (permittivity see further this section), that is 5 times lower than the permeability of the geotextile alone. Their explanation is that the geotextile openings of the woven used where partly blocked by the granular material, see Figure 7.

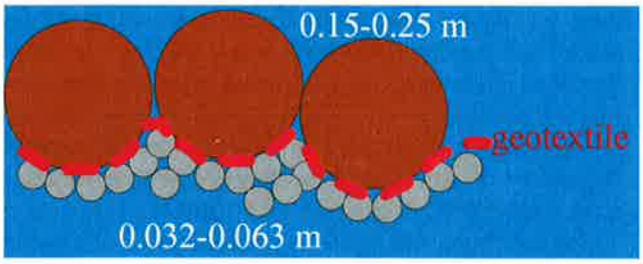


Figure 7. Partly blocking of geotextile openings by larger and smaller grains

This decrease in permeability made the difference between a geotextile that was sufficient permeably not to influence the stability of the structure (as was assumed in the original design calculations), or a geotextile that resulted in such a decrease in permeability on the filter boundary that there was a significant decrease the stability (as was found in the field).

Permeability tests by van Beek and Schenkeveld (2011) showed that the permeability of a non-woven geotextile (Colbond PF 150, O_{90}=90 μm) that was covered on one side with medium fine sand (Baskarp, d_{50}=135 μm, d_{60}/d_{10}= 1.6) and on the other site with a stainless steel plate that has an openings ratio of 35% resulted in a permittivity of the geotextile plate system that is closely related to the permeability of the sand. A lower permeability of the sand (achieved by densification of the sand to a lower porosity) resulted in a lower permittivity, see Figure 8a. Furthermore, the permittivity of the geotextile with sand is 5.5 to 35 (!) times lower than the permeability measured in an index test without soil, see Figure 8b.

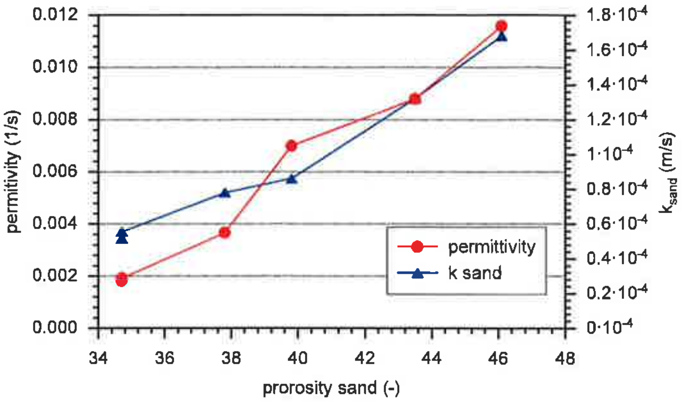


Figure 8a. Permittivity of geotextile supported by stainless steel plate with 35% openings, influenced by the permeability of the sand on top, results of measured permittivity (dots) compared with the measured permeability of the sand (triangles

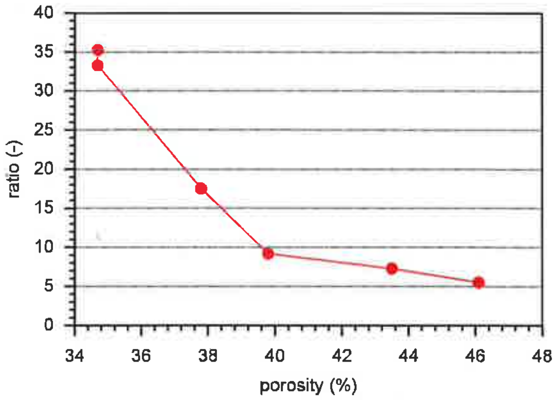


Figure 8b. Ratio permittiviy geotextile meared without sand (as in an index test) and permeability of the same geotextile measured with on one side Baskarp sand, d_{50}=135 mm, as a function of the prososity of the sand.

These findings make the permeability of a geotextile a rather arbitrary parameter. The EN ISO 11058 test can be used to compare different geotextiles, but it is even not sure that the geotextile that resulted in the highest permeability in the index test also gives the highest permeability when placed in soil. There seems to be quite a complicated soil structure interaction, which resulted in this case in a flow resistance at the boundary between the geotextile and the sand that is equal to a few centimetres of sand. The effect is a bit exaggerated because the stainless steel plate had an openings percentage of only 35%, but still it is remarkable that applying a permeable geotextile with a thickness of approximately 0.1 cm leads to an extra flow resistance comparable from 1 to more than 2.5 centimetres of sand (that is less permeable than the geotextile), depending on the porosity. When critical, the actual permeability of a geotextile in a filter construction can best be determined in a gradient ratio test (ASTM D 5101). In such a test it is possible to investigate whether or not there is a large pressure drop over the geotextile at a certain flow. This pressure drop is of importance to judge whether or not the geotextile is well or not sufficient permeable.

3.2 *Permeability versus permittivity*

The familiar term permeability is used in the part above. However, the last section showed that this is not the most useful parameter to determine how permeable a geotextile is. According to Darcy, the permeability (k) presents the ratio between the filter velocity (v) and the hydraulic gradient (i) :

$$v = k . i \qquad (1)$$

But the hydraulic gradient is not really of interest. What is of interest is whether or not there is a drop in piezometric head over the geotextile ($\Delta\phi$), thus the relation of interest is:

$$v = \psi . \Delta\phi \qquad (2)$$

where ψ is the permittivity (1/s).

The permeability relation suggests that a 2 times thicker geotextile would lead to a 2 times higher drop in piezometric head (as is the case in sand where Darcy is valid and this is correct). However, the examples of measurements shown before show that how permeable a geotextile will be in a structure is not determined by its thickness, but by the interaction between the geotextile and the granular material. Changing the thickness of the geotextile in a structure is likely to have only a limited to no influence on how permeable it is. Consequently the permittivity represents better the real behaviour of the geotextile in a filter construction.

3.3 *Consequences*

As a consequence of what is written above, it is not possible to say the permeability of the geotextile has to be x times higher than the permeability of the soil. To check whether or not a geotextile is suitable for his task in a filter construction Giroud (2010) in his Prestigious Lecture, "Development of criteria for geotextile and granular filters" at the 9th ICG derived a criterion from the granular mechanics and concluded that for wovens to be used in filters the openings must be more than 10% of the total area and for non-woven geotextiles the porosity has to be larger than 55%. In our opinion these are not absolute criteria. In the Netherlands a lot of wovens are used in filters that do not fulfil the woven criterion, but these criteria can be a starting point. For the non-wovens the situation is easier. It will be hard to find a product that does not fulfil the non-woven criterion mentioned by Giroud, even when subjected to compressive stresses.

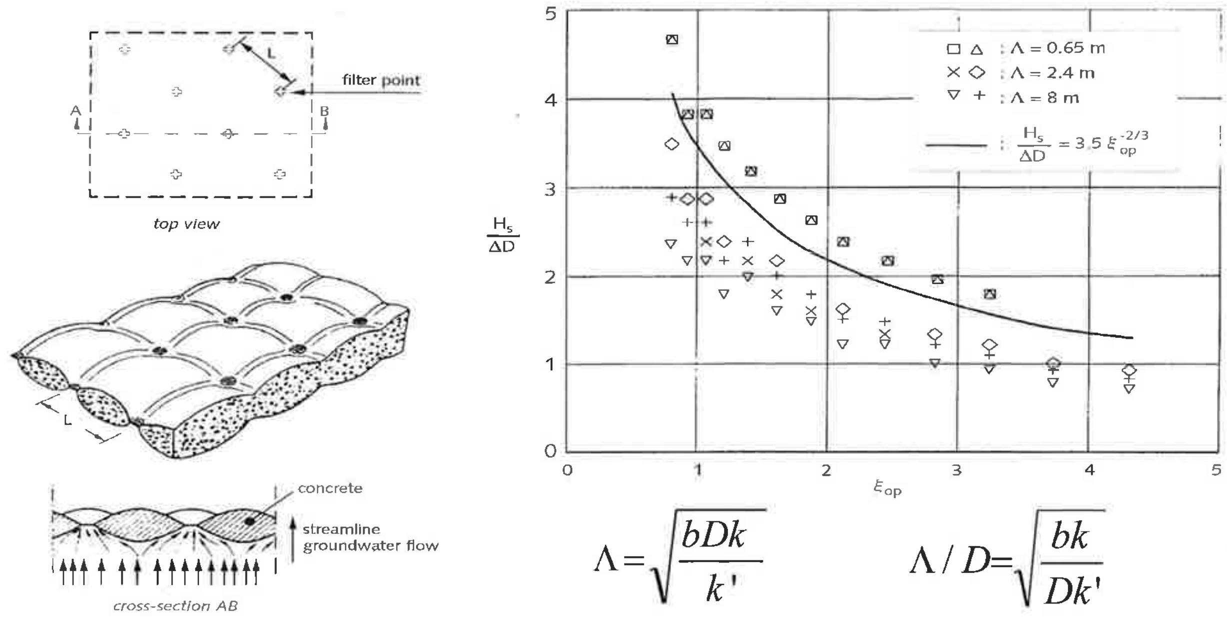
4. DESIGN OF BLOCK REVETMENTS AND GEOMATTRESSES

4.1 *Placed black revetments*

In revetment structures geotextiles are mostly used to protect the subsoil from washing away by the hydraulic loads, such as waves and currents. Here the geotextile replaces a granular filter. Unfortunately, the mere replacing of a granular filter by a geotextile can endanger the stability of other components in the bank protection structure (i.e. internal stability of the subsoil at the interface with a geotextile), see Section 2.4. Therefore, an additional criterion concerning the necessary total thickness (or unit weight) of revetment (top layer plus sublayer) to avoid internal instability of soil should be defined (Klein Breteler et al.1994, 1998, Pilarczyk, 2000, 2002).

Furthermore, the usual requirement in a rip-rap revetment that the permeability of the cover layer should be larger than that of the under layers cannot be met in the case of a closed block revetment. The cover layer is less permeable, which introduces uplift pressures during wave attack.

In case a geotextile is situated directly under the cover layer, the permeability of the cover layer decreases drastically. Since the geotextile is pressed against the cover layer by the out flowing water, it should be treated as a part of the cover layer. In this case the permeability ratio of the cover layer and the base or filter layer and its thickness, represented in the leakage length (Λ), is found to be the most important structural parameter, determining the uplift pressure, see Figure 9; (Klein Breteler et al., 1998, Pilarczyk, 2000, 2002, www.tawinfo.nl). In general, all low-permeable top layers (block revetments and geo-mattresses) should be designed based on definition of their leakage length which provides a kind of optimization between all design requirements (Klein Breteler et al., 1994,1998, CUR, 1995). This part is kept short because the extensive description on design of revetments incorporating geotextiles can be found in references and also is available online.



$$\Lambda = \sqrt{\frac{bDk}{k'}} \qquad \Lambda / D = \sqrt{\frac{bk}{Dk'}}$$

(Λ=leakage length [m], D = thickness of top layer b = thickness of the filter layer (m), k = permeability of the filter layer or subsoil (m/s), and k′ = permeability of the top (cover)layer (m/s))

Figure 9a. Calculation results for stability of concrete mattresses

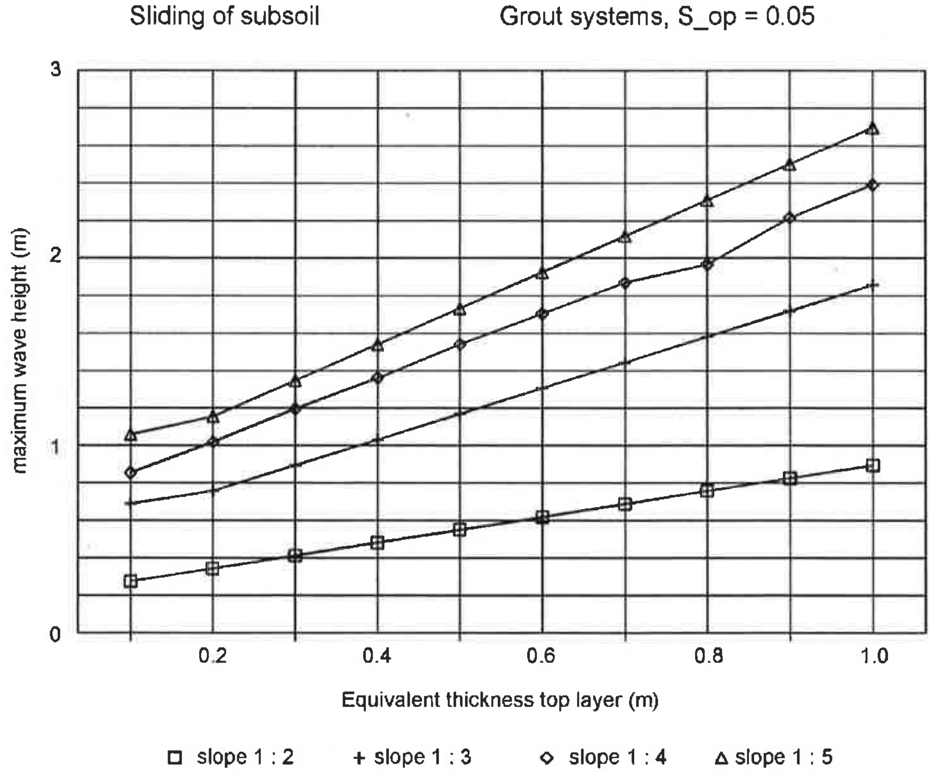


Figure 9b. Geotechnical stability; design diagram for mattresses and wave steepness H_s/L_{op} = 0.05

4.2 *Geo-mattresses*

The permeability of the mattress is one of the factors that determine its stability. It is found that the permeability given by the suppliers is often the permeability of the geotextile, or of the so-called filter points. In both cases, the permeability of the whole mattress is much smaller. A high permeability of the mattress ensures that any possible pressure build-up under the mattress can flow away, as a result of which the differential pressures across the mattress remain smaller. The stability is therefore the largest with a large mattress permeability. In the long term, however, pollution of the filter points or the clogging of the geotextile can cause a decrease in the permeability. The susceptibility for blocking can be reduced by increasing the gradation of the subsoil. To reduce the susceptibility for clogging it is recommended to reduce the sludge content of the subsoil. Due to the lack of proper information on the total permeability of the mattresses, the indicative permeability of mattresses can be calculated based on the knowledge of placed block revetments and the collected information from the literature and company information. By introducing the concept of leakage length the indication of stability for various geo-mattresses can be given as shown in Figure 9 (Klein Breteler et al., 1998, Pilarczyk, 2000, 2002). To obtain more accurate results it is recommended to perform permeability tests for mattresses as a whole (as a system) and some model/prototype tests for verification of stability; see also website for details http://www.deltares.nl/en/knowledge-and-innovation The design method with regard to geotechnical (in) stability is presented in the form of design diagrams. An example is given in Figure 9b (for more details and diagrams for other systems: see CUR 1995, Pilarczyk 2000). The maximum wave height is a function of equivalent thickness equal to the sum of the cover layer (ΔD) and filter thickness (b_f).

4.2.1 *Durability geo-mattresses.*

Ultraviolet (UV) strength degradation of geosynthetics is always a concern to prospective users. The fabric for geo-mattresses is usually manufactured with polypropylene and polyethylene yarns, which are, on short term (a few years, depending on the amount of anti-oxidant that is used), quite UV resistant. Often, silt which is accumulated in textured surface will provide the additional protection. However, the top layer of fabric forming the concrete units will gradually loose its strength. The bottom fabric is not subject to UV degradation and therefore does not suffer loss of strength. The geotextile is principally treated as a fabric form for the containment of concrete; the reduction of strength in the top fabric does not necessarily affect the stability of the system. Where appearance is an important consideration, the upper surface may be spray coated with dilute coloured acrylic emulsion, at about 5 year intervals, which provides also the additional protection of the fabric against ultraviolet degradation.

On long term, especially when no UV-protection for geotextile is applied, the surface-geotextile will deteriorate and the concrete filled-mat will function as a block mat with concrete units connected to the lower sheet of geotextile by existing binders, which normally are used as spacers to provide a required thickness. These binders should have a proper strength to compensate the weight of the concrete element. That also means that for structures with a long lifespan the stability of the mattress should be controlled for this situation. Where severe wave action is anticipated possibly with danger of severe scour, or where soil cannot be properly compacted and extensive settlement is expected (i.e. soft soils), concrete mattresses may be constructed (strengthened) with cabling. Nylon or polyester cables (ropes) are usually used instead of steel cables to avoid any possibility of damage by corrosion. Cables are inserted between the two layers of fabric prior to concrete injection. Synthetic cables are lighter than the grout slurry that is utilized to fill the mats and therefore semi floats within the grout mass. The already existing constructions and the future applications should be systematically documented and evaluated in respect to their performance under various soil and hydraulic conditions.

5. SAND FILLED GEOSYNTHETIC TUBES AND CONTAINERS

5.1 *Introduction*

Apart from sand filled geotextile tubes and containers, the subject of this section, there also exist slurry fillled geotextile tubes and containers. These can be used to dewater the slurry (tubes) or to have some containment around the slurry. These structures have different design aspects and will not be dealt in this paper. Example of such applications can be found in Lawson (2010). In principle sand filled synthetic tubes and sand filled geosynthetic containers are quite comparable. Geotextile is wrapped around sand or slurry to make a large structure that is stable in current and wave attack. Tubes are used on shore or in shallow water. A large geotextile tube is filled with sand by means of hydraulic fill. Dimensions can be up to 4 m high. Figure 10 and Figure 11 show a moment during construction of a geosynthetic tube and the final result of dams constructed with a sand filled geosynthetic tubes (as a core) respectively. It can be seen from the first picture that the geosynthetic tube is kept in the desired position by fixing it with piles. No geotextile is visible in the final result, because it is covered with gravel.

Figure 10. Moment in the construction of secondary dam

Figure 11. Secondary dam constructed with geosynthetic tubes as a core

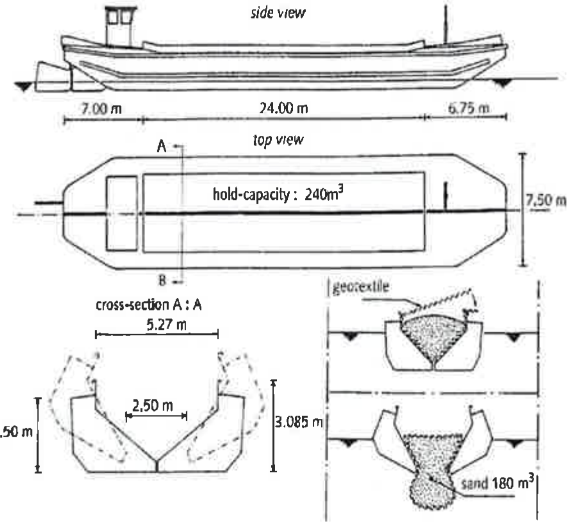


Figure 12. Construction of a geosynthetic container in a barge and dumping

Geosynthetic containers are used in deeper water. They are constructed in a split barge and sailed to the desired position. There, the split barge opened and the geosynthetic container is dumped in position. With respect to the water depth sand filled geosynthetic tubes and geosynthetic containers are complementary. Tubes need rather shallow water or construction on shore. Containers need deeper water, because the split barge must be able to sail over the dumping location. Both systems can be used in the construction of a dam: geosynthetic containers for the deeper parts and geosynthetic tubes for the more shallow parts. The geosynthetic container in a split barge is sketched in Figure 12. An artist impression of the actual dumping is presented in Figure 13.

Figure 13. Artist impression dumping of a geosynthetic container

Geosynthetic tubes are mostly used for coast or shore protection (Fowler et al. 2002 and Hornsey et al., 2011). Geosynthetic containers are used to make steep slopes on a sand dike, hanging beaches and also to dump polluted slurry in a way that it does not pollute large areas of the seabed.

An unusual application of geosynthetic containers was made at the Australian Gold coast (Heerten et al., 2000). A structure was made to increase the wave height for surfing and also to provide some shelter for the same surfers. The interesting part of this project is that the water is so clear that it was possible to see what structure was made. In more usual water conditions the positions of the containers has to be determined by sonar. Figure 14 shows a part of the realised structure.

Figure 14. Example of geosynthetic container application, Artificial reef, Gold Coast, Australia

When designing geosystems distinction must be made between the types of geotextile used. Usually woven and needle-punched nonwovens are applied. Woven geotextiles represent a large scale of tensile strength, low elongation but worse performance against impact. Nonwoven, needle-punched geotextiles are thicker (better filtration performance) but represent lower tensile strength, large elongation (shape deformation), and better performance against puncturing (impact forces). All of them must provide sufficient UV-protection. This kind of properties must be considered when selecting the most suitable material for specific project.

5.2 *History sand filled structures and position on the market*

Sand filled bags have been used as an emergency repair for dikes during a long time in the Netherlands. Figure 15 shows the first large scale application in the Netherlands, the closure of the Pluimpot, a small estuary in the Netherlands in 1957. Since then quite a number of applications has been realised (Lawson 2010, Heerten 2000, CUR 217, 2006). Although there is quite some experience, the sand filled structures are still present in the market of coastal structures. This has the following reasons:

Figure 15. The closure of the "Pluimpot", 1957

- At a number of locations sand filled structures have the same or a higher price level than traditional structures with gravel and rock (Das Neves, 2011^{a}).
- For a permanent solution it will normally be necessary to have a cover of granular material, or to have a strict maintenance programme with regular inspections.
- There are no well accepted design rules, as there are for traditional structures.

Consequently most of the applications of these structures fulfil one or more of the following:
- The structure is temporarily. The advantage is then that the structure can be easily removed.
- Gravel or rock cannot be used, because it will harm adjacent structures or people (the last in case of a surf reef or groins), or is not acceptable from an aesthetic point of view, for example at a beach.
- Gravel or rock is not readily available, or not desirable to use from an environmental point of view, or transporting large quantities of rock is dangerous.

5.3 *Shape of sand filled tubes and containers*

5.3.1 *Degree of filling*

The usual way to describe the degree of filling is to compare the cross-sectional area of a sand filled tube or container and compare that with the theoretically maximum cross-sectional area that is possible for given circumference of the geotextile. The theoretical maximum is when the cross-section of a tube or container (perpendicular to its longest axes) would be a perfect circle. So when the circumference (L) of the geotextile in a tube or container is given, and the cross-sectional area (A), the degree of filling (d_{fill}) is:

$$d_{fill} = 4\pi \frac{A}{L^2} \tag{3}$$

This definition will be used in the remaining part of this article. The difference between a sand filled container and a sand filled tube after placement is only a difference in degree of filling. A container has to be dumped with a barge and therefore it has to be 'squeezed' through the barge opening. This limits the degree of filling. Such restrictions do not apply for a tube. Normally the degree of filling for a sand filled container is 35 – 45% and for a tube 70 to 80%. Different definitions for the degree of filling are used. In the field the ratio of the actual height of a tube divided by the theoretically maximum height is used. This is done because this is easier to measure in the field. For geosynthetic containers the actual volume of the container divided by the volume of the split barge is sometimes used. These different definitions can be rather confusing and therefore one should be sure what definition is used when a degree of filling is mentioned. In this paper only the definition by Eq. (3) is used.

5.3.2 *Shape*

The shape of sand filled tubes of containers is of importance because this determines the height of the tube or container. The way to calculate the shape is the same for a tube and a container, only the degree of filling is different. Mechanically spoken a geotextile is a membrane. It can take tensile forces, but no bending forces. This means that the curvature of a part of the geotextile is determined by the ratio of tensile stress and the stress perpendicular to the geotextile or in formula for a 2-D situation:

$$\frac{T}{r} = p \tag{4}$$

With T the tensile force in the geotextile, r the curvature of the geotextile and p the pressure acting on the geotextile (Timoshenko & Woinowsky-Krieger, 1959). To calculate the shape of the container or tube, it is assumed that the tensile stress is constant over the part of the geotextile in contact with the fill and has no contact with the subsoil. This assumption is valid when the geosynthetic container is filled with slurry. It is not valid when the container is filled with sand, because a shear stress can develop between the sand and the geotextile. However, in general the shear stresses will be small because the sand is in a loose state and therefore the calculation method can also be used with a reasonable accuracy for a container filled with sand. With some coordinate transformations, described in Timoshenko & Woinowsky-Krieger 1959, it is possible to calculate the curvature of the geotextile as a function of height for a given tensile strength (T) and a starting pressure (p) of the fill at the top of the container or tube and assuming that the pressure increases hydrostatically with depth (which means that also the curvature will increase with depth). The result of such a calculation is shown in Figure 16.

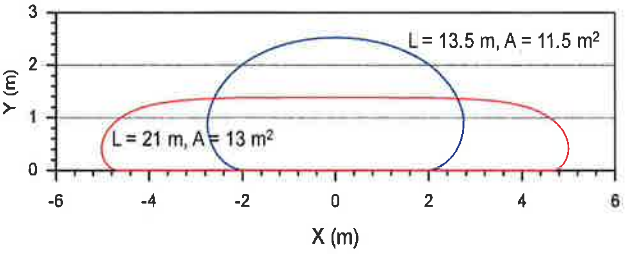


Figure 16. Shape of a geosynthetic container (L=21m, A=13m^2, d_{fill}=37%) and tube (L=13.5m, A=11.5m^2. d_{fill}=79%)

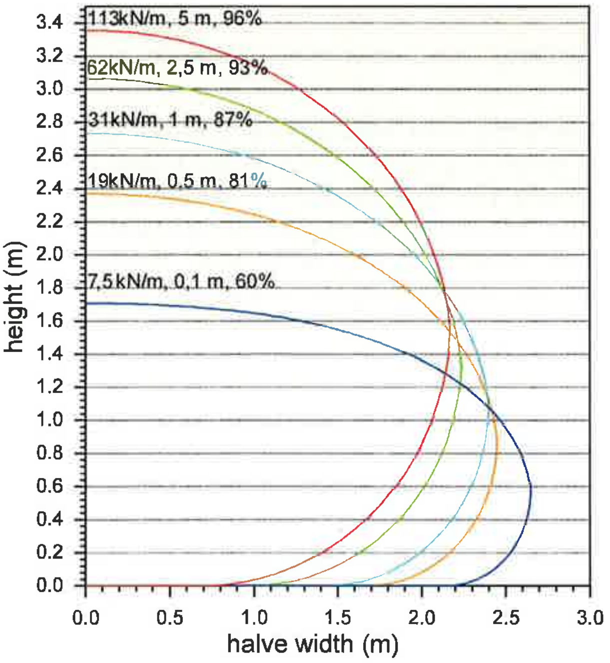


Figure 17. Relation between shape and tensile force (kPa), piezometric head above the tube (m) and decree of fill (%).

Figure 17 shows how the shape of the sand filled tube is related with the tensile force, filling pressure and the degree of filling. For the situation calculated, an extreme filling degree of 96% is only possible with a filling pressure that is the equivalent of 5 m water difference and will result in a tensile force of 113 kN/m. A more usual filling pressure the equivalent of 0.5 m water difference will lead to a degree of filling of 81%, which is also closer to the normally measured degrees of fill.

Measurements show that there is a good agreement between these theoretically determined shape and measurements, see Figure 18.

6. STABILITY SAND FILLED GEOSYNTHETIC TUBES AND CONTAINER UNDER WAVE ATTACK

6.1 *Introduction*

Evaluating the failure mechanisms of sand filled tubes and containers, it appears that the construction period is a critical period. Tubes can be damaged by too high pumping pressures; containers can be damaged during leaving the barge or during the impact on the bottom. In a design of a geosystem these failure mechanisms have to be taken into account. Information on these failure mechanisms can be found in Bezuijen et al. (2004). In this paper we focus on the failure mechanism of importance after construction, scour and stability against wave attack.

6.2 *Scour*

Quite often sand filled geotextile tubes are used at the beach as a coast protection, see Figure 19 for an example. For these structures scour is a major failure mode. When the lowest point of the tube is not located sufficiently deep in the sand, then sooner or later the structure will be undermined and fail. The possibility of scour is investigated by Das Neves (2011) in a number of small scale model tests. As usual with scour tests, there was quite some scatter in the results, but the results indicate that the scour depth of a geotextile structure is comparable to the scour depth of a rock and gravel structure (in theory the scour can be even more, because there is more wave run-up and run-down along the more impervious geotextile structure).

Consequently it can be mentioned that when the rule of thumb for a traditional breakwater is that the maximum scour depth will be less or equal to the incident unbroken wave height, this is certainly also the case for structures made of geotextile and sand and the toe protection should be built to cope with such scour depth.

6.3 *Stability under wave attack*

The stability of under wave attack of sand filled geotextile tubes and sand filled geotextile containers is recently tested in a series of physical model tests in the Netherlands. Tests details are reported by Van Steeg et al. (2011).

The results of the tests led to some adaption of the usual stability formulas for sand filled geotextile tubes, as will be described below. For the geotextile containers with a relative low degree of filling there appeared to be also a different failure mechanism possible, which was called the caterpillar effect. Both these mechanisms will be described in the following sections. Both test series were performed in the Delta flume of Deltares. This flume has a length of 235 m, a width of 5 m and a depth of 7 m. At one end of the flume irregular waves with a JONSWAP spectrum and a wave steepness, based on the peak wave period, of $s_{0,p} = 0.03$ was created, at the other end a structure made of geotextile elements was built. At all the test series a Geolon® PE180L geotextile was used, thus only woven geotextile containers were tested. The geotextiles had an opening size $O_{90} = 0.170$ mm. The experiments had a duration of around 1000 waves or until damage occurred.

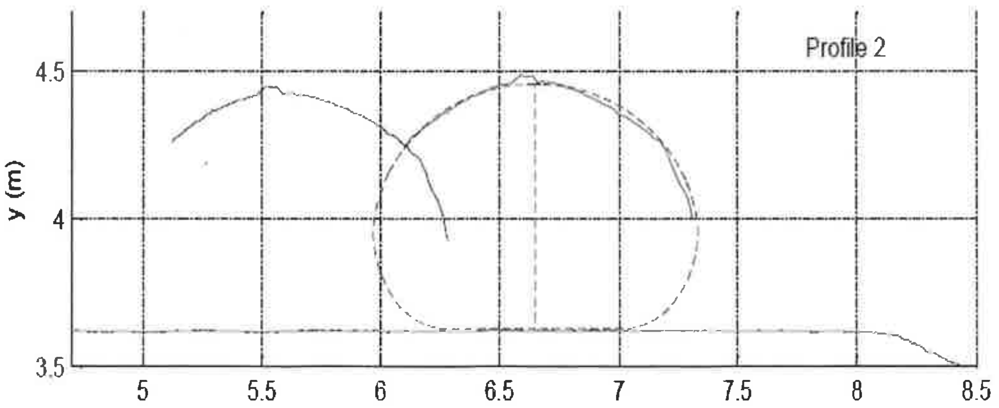


Figure 18. Measured shape in a model test in the Delta flume (drwan line) compared with the theoretical shape (dashed line). (model dimensions).

If no damage occurred during a test, a new test with a higher wave height was started.

Figure 19. Geotube on the beach

6.3.1 *Geosynthetic tubes*

Figure 20 shows a picture taken during the tests in the Delta Flume and Figure 21 shows the configurations tested. All layouts except the 2-1 stack were displaced due to sliding of an individual element. Significant deformation of the tubes did not take place except for the tube which was filled for 55%. This tube was significantly deformed. Tubes with a higher degree of filling deformed as a function of the degree of fill, see Figure 22. Failure of the 2-1 stack occurred due to a seaward sliding mechanism of the tube on top and the tube which was placed on the seaward side of the stack. The seaward sliding may be caused by a small wooden beam that was fixed at the landside of the tubes on the concrete substructure. This beam was used because the idea was that the concrete surface was too flat compared to a real situation where the tubes would be placed on sand or on top of other tubes. However, the seaward sliding does indicate that there can be also significant seaward forces in the 2-1 stack. The stability of one tube appeared comparable to the stability of 2 tubes. The water level has a large influence on the stability. Sand filled geosynthetic tubes are much more stable above the water line, compared to below the water line. The stability against sliding for a tube with its crest equal to the water line for wave higher than the height of the tube (D) can be given with the formula:

$$\frac{C\sqrt{H_s}}{\Delta\sqrt{B}(f\cos\alpha+\sin\alpha)} \leq 0.65 \qquad (5)$$

Where, C is a constant depending on the wave steepness varying between 0.5 and 0.65, H_s the significant wave height, Δ the relative density, B the width of the tube, f the friction coefficient between the geotextile and the concrete substructure in the tests and α the angle of the concrete substructure. For $C = 0.65$ and $\alpha = 0$ deg, this relation reduces until:

Figure 20. Wave impact on tubes during flume tests

$$\frac{H_s}{B} \leq (\Delta.f)^2 \qquad (6)$$

This relation is similar to the traditional stability equation for breakwaters that normally takes the form:

$$\frac{H_s}{\Delta D} \leq C_c \qquad (7)$$

Where D is the diameter of the blocks (average height of tube) and C_c a certain constant depending on various factors. The indicative value for the first approximation of stability of geotubes is $C_c = 1.5$. Although the equations (6) and (7) look similar, there is a remarkable difference. The influence of D (the height of the tube) is not available and the influence of Δ is much larger in equation (7), since Δ is taken to the square in the equation. This outcome would need further testing since in all tests Δ was close to 1 and then the difference is only small. The friction, however, was varied (by using the beam construction) and this relation was found. That B instead of D is found is understandable. A higher D will also give more exposed surface, while an increase of B results in more stability for the same exposed surface. The tests described here are performed with sand filled tubes with woven geotextiles. Recio and Oumeraci (2009) have performed tests for comparable structures, but made from non-woven materials. Their formulas can be used in case of non-woven material. They show that in some case also the deformation of the structure under wave attack is important, as is also the case with sand filled geosynthetic containers, see below.

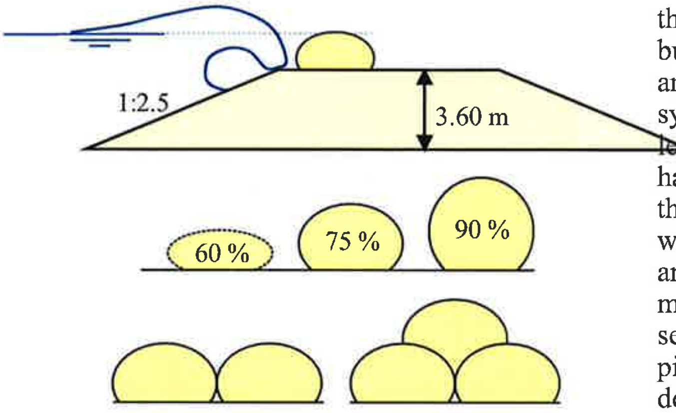


Figure 21. Configurations tested

Deformation tubes

The amount of deformation of the sand filled tube appeared to be a function of the filling percentage. The relative settlement is only small for well filled but increased significantly for lower degrees of fill.

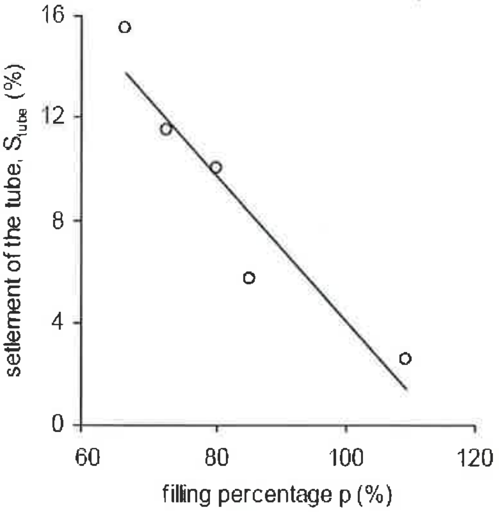


Figure 22. Settlement of tube during the test programme as a function of the filling percentage (Modified from Van Steeg et al., 2011).

This means that to minimize settlements after construction, a significant filling percentage of the tubes is needed and more than 80% percentage of fill is necessary. To reduce, at least in the model tests the settlement to 10% or less a filling percentage more than 80% is needed.

6.3.2 *Sand filled geosynthetic containers*

An additional failure mechanism appeared to result in failure at lower wave heights then expected for sand filled geosynthetic containers. In these tests there was not only sliding of the whole containers, but the sand migrated within the container. The example calculations in showed that sand filled geosynthetic elements with a degree of filling of 60% or less, the usual fill of a geosynthetic container will have only a very low tension force on the geosynthetic. Consequently this can start flapping under wave attack. This allows the sand grains to migrate and started what is called the 'catterpillar' failure mechanism. The whole geosynthethic container seems to move due to the migrating sand as a caterpillar from a bulldozer resulting in larger and larger deformation. This result was also found by Venis (1968) in larger scale tests on sand bags. It was not found in smaller scale tests and therefore Venis warned for the scale effects that can occur when tests are performed at only a small scale.

A consequence of this caterpillar mechanism is that sand filled geosynthetic containers will deform at significant wave heights higher than 0.8 m according the measurements in the flume. This limits the application of sand filled geosynthetic containers in situations with significant wave attack. This is, however, in most cases hardly a problem, since, as mentioned before, a minimum of 4 m water depth is necessary to dump the containers. Quite often this will be below the area where the largest wave attack can be expected. It should only be taken into account in areas with extreme tides.

Filter criteria

These tests also led to another result: quite some sand was found outside the containers. Unfortunately it could not be completely excluded that there was some bad seam in the container. However, the most plausible explanation is that it went through the geotextile although the geotextile with a d_{90} of 170 μm of should be sand tight for the sand used with a d_{50} of 194 μm.

It should however be realized that sand movement within the container allows also the movement of finer grains and that where without sand transport the fines will be trapped in the sand.

With sand transport, and 15% of the fines is smaller than the O_{90}, it is still possible that this 15% is washed out. Therefore allowing more sand movement into the structure requires stricter filter rules.

7 CONCLUSIONS

From the studies described in the paper the following conclusions are possible:

- Filter rules are derived for stable soil layers. They need to be stricter when soil can move around underneath a geotextile filter, as is the case when there is wave attack at a sand filled geosynthetic container.
- In coastal engineering applications the subsoil in a filter should fulfil the Kenny and Lau criteria (see section 2.2) to be sure that there is no development of impermeable layers in the subsoil.
- The sand – geotextile boundary is in itself a resistance for the water flow perpendicular to the geotextile. Such resistance is equivalent to a few centimetres more sand. The index test CEN/ISO 'water flow capacity normal to the plane' that is performed without sand can indicate a flow capacity at a given head difference that is up to more than an order of magnitude higher than the real flow capacity when the geotextile is placed in sand. This means that the flow test is just a poor indicator of real flow capacity.
- The shape of a sand filled geosynthetic tube or container can be calculated accurately by assuming that the geosynthetic is a membrane and that the sand applies a hydrostatic pressure on the membrane. The shape of the tube and container is then influenced only by the density of the fill with respect to the density of the volume outside the tube or container (this will normally be air or water) and the pressure of the fill material at the top of the tube and container.
- The stability of sand filled geosynthetic tubes under wave attack can be calculated using the formulas given in this paper or more in general by the formula presented by Van Steeg et al. (2011). For different configurations the formulas by Recio and Oumeraci, (2009) can be used.
- For the stability of sand filled geosynthetic containers there appears to be an additional failure mechanism. In these containers with a relative small percentage of fill (less than 50%), it appears possible that the sand migrates within the container leading to a caterpillar effect, resulting in deformation and failure at a lower wave height than when this failure mechanism is not present.

General remarks

- Geosynthetics and geosystems constitute potential alternatives for more conventional materials and systems. They deserve to be applied on a larger scale. However, doubts among specifying authorities and design engineers about the quality of the design criteria for some of the products, and the long-term performance, are still limiting factors in the increased use.
- The basic material for geosystems are geotextiles or, more generally, geosynthetics. Proper knowledge of these materials (technological properties, design specifications, test methods, etc.) is essential for a proper choice of material needed to fulfil the functional requirements of geosystems resulting from the specific requirements of a project under consideration. Information on these can be found in a number of publications, textbooks, manuals and design guidelines. Moreover, the designer should bear in mind that geotextiles and geosystems are only a part (or a component) of the total project and that they have to be treated and integrated in the total perspective of a given project.
- Systematic (international) monitoring of realized projects (including failure cases) and evaluation of the prototype and laboratory data may provide useful information for verification purposes and further improvement of prediction methods. It is also the role of the national and international organizations to identify this lack of information and to launch multi-client studies for extended monitoring and testing programmes, to provide users with an independent assessment of the long-term performance of geosynthetics and geosystems.
- There are still much uncertainties in the existing design methods. Therefore, further improvement of design methods and more practical experience under various loading conditions is still needed.
- There is an urgent need for internationally accepted guidelines for design and application of geosystems. The IGS in cooperation with other international organisations should undertake actions in this direction.

Finally, there is a rapid development in the field of geosynthetics and geosystems, and there is always a certain time gap between new developments (products and design criteria) and publishing them in manuals or specialistic books. Therefore, it is recommended to follow the professional literature on this subject (Journal of Coastal Engineering, Journal of Geotextiles and Geomembranes, Geosynthetics International, Geotechnical Fabric Report, and Proceedings of Geosynthetic Conferences) for updating the present knowledge and/or exchanging new ideas.

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