Geotextile containers for coastal and hydraulic engineering structures made of specially designed nonwoven geotextiles

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ABSTRACT: For decades geotextile containers and tubes are used in hydraulic, coastal and later also offshore engineering as construction elements for erosion control, bottom scour protection, groynes, seawalls, breakwater, dune protection and also artificial reefs. Geotextile containers and tubes offer environmentally friendly "soft" solutions at sandy beaches instead of "hard" solutions with steel or concrete. The paper presents the special development and experience with needle-punched staple fiber nonwoven geotextiles for sand containers and sand-filled tubes. Product requirements out of the decades of experience and technical recommendations for design and layout of the geotextile container / tube manufactured of Needle-Punched Staple Fiber NonWoven GeoTeXtiles (NP SF NW GTX) are given. Based on large-scale wave flume tests developed design criteria for the wave stability of sand containers are presented for onshore and offshore application. Some case studies are dealing with various options of filling, handling and installation of geotextile sand containers / tubes. Separate technical requirements for sand container / tube solutions based on woven or NP SF NP GTX are strongly recommended.

1 INTRODUCTION

In the beginning of the seventies of the last century a big failure at a scour protection system of an important coastal defense structure was reported in Germany. There was a suspicion that a "new" material – a woven geotextile – being installed in the scour protection system was part of the problem (Heerten 1981). After this failure extensiv investigations have been carried out at the Germany North Sea Coast in order to safeguard and expand the knowledge on long-term resistance of geotextiles applied in coastal protection structures like dike revetments, groynes, sea walls or storm surge barriers. This early investigation program dealt with geotextiles – woven and nowoven – being installed from 5 to 21 years at 13 different locations of the North Sea Coast at the German Bight. This program was carried out by the author and the results have been published in Heerten (1981) and Heerten (1980). The key experience out of this research program was that the long-term stability of geotextiles with state-of-the-art resin and product stabilization is not a problem at all, but that damage during installation and possible further abrasion attack are the main risks for geotextiles with a big difference between woven and needle-punched nonwoven fabrics. Much more woven fabrics showed puncture after stone dumping than needle-punched nonwoven geotextiles, indicating that tensile strength is not the appropriate material parameter for installation robustness.

Already in these early days the German Federal Waterways Engineering and Research Institute (BAW), Karlsruhe, established laboratory tests for testing puncture and abrasion resistance for geotextiles. The tests will be described later. The robustness criteria established by the BAW paved the way for needle-punched staple fibre nonwoven geotextiles being dominantly used in hydraulic and coastal engineering applications in Germany still today. Also when sandbags, sand containers and sand filled tubes in the beginning have been made of woven fabrics because of high strength requirements following the wrong idea that higher strength is a better suitable product, nowadays this application in hydraulic and coastal engineering is dominated by the use of needle-punched staple fibre nonwoven geotextiles in Germany, but also some other countries like Australia (Saathoff et al. 2007), Bangladesh, South Africa (Maastrecht 2009), Malaysia, Indonesia, Brunei or Sri Lanka, especially for sandbags and sand containers up to 5 t of weight. This paper will mainly deal with the author's experience in designing, filling and placing of sandbags, sand containers, but also sand-filled tubes made of NP SF NW GTX (Needle-Punched Staple Fiber NonWoven GeoTeXtiles). Recently achieved results of the wave stability of NP SF NW GTX sand containers based on physical and numerical model tests are presented also (Oumeraci 2002, Recio 2007).

Encapsulating or wrapping sand into geotextile units provides a variety of flexible, economical and ecological coastal applications. Especially at indifferent dynamic sandy beaches where the use of rocks, steel and concrete as "hard coastal structures" is contrary to the soft and environmentally friendly coastal protection philosophy, geotexile sand containers made of needle-punched staple fiber nonwovens offer more advantages as "soft rock structures". As flexible construction elements geotextile containers behave advantageously with regard to cyclical hydrodynamic loads and morphological sea bed changes. In recent years, geotextile container and tube technology – made of special woven fabrics (Lawson 2008) or NP SF NW GTX - has experienced great success at highly visible projects. Nowadays, geotextile sand containers find their application as construction elements for erosion control, scour protection, reefs, groynes, dams, breakwaters and dune revetments. But when dealing with a technical solution by using geotextile container or tube technology for a project, it should be considered that the geotextile solution can **not** be specified by one and the same or even a mixed specification of geotextile parameters of woven fabrics or NP SF NW GTX with regard to the stress/strain or filtration parameters. The client should decide if he wants a woven sand container / tube solution or a solution based on NP SF NW GTX, because there are normally good arguments to prefer the woven or the nonwoven solution in a special case.

2 FIELD INVESTIGATIONS AND LONG-TERM FIELD EXPERIENCE

The main reason for the carried out field investigations on coastal structures was the examination of the long-term behaviour of the installed geotextile products under service conditions after the already mentioned big failure. In the framework of the investigations carried out multi-filament fabrics, tape fabrics and needle-punched nonwovens made of different polymers (PET, PA, PP, PP/PE) were examined. At 13 locations on the North Sea coast of the German Bight sampling operations were carried out. Altogether 39 samples were taken. 16 samples were dug out from revetments of sea dikes and 23 samples were taken from sandbags and sand filled tubes. Fig. 1 gives an impression of the challenging and complex sampling operation at the sea dike revetment.

Figure 1: Digging out a filter fabric beneath the riprap of a sea dike revetment in 1979, 5 to 9 years after construction

The picture in Fig. 2 gives an example of the application of sand filled tubes. It shows a small dam in land reclamation fields in the tidal flats in front of the sea dikes. From the sandbags and sand filled tubes two different samples were taken, one of the weathered upper side and one of the protected bottom side. Thus it is possible to calculate the influence of weathering on the long-term resistance of the fabrics.

Figure 2. Sand-filled tube in a land reclamation field, 10 years after construction in 1969

One exciting and at that time (1979) unexpected result was the extensive increasing of the weight of the NP SF NW GTX by a multiple of the virgin fabric weight due to the incorporation of a huge amount of soil particles in the three-dimensional fiber labyrinth of the geotextile – it's forming a real geo-textile. Figure 3 gives an example of a nonwoven fabric with a filling rate of about 9,000 g/m² by a fabric weight of about 1,000 g/m² and a thickness of 6 mm.

Even with this soil filling rate the needle-punched nonwoven geotextiles showed a good permeability, still far above the permeability of the embankment soil (Heerten 1980). The 90 % pores of the fiber labyrinth are only partly filled and enough pore space for good permeability is still available. The trapped soil in the "geo-textile" will always be placed inside of the fiber labyrinth with a far lower density than the embankment soil density itself. This is the reason for the good hydraulic performance of the needle-punched nonwoven geotextiles in the long term. The only laboratory filtration test simulating this fiber labyrinth–soil interaction based on the knowledge and experience of the author is the "turbulence test" of the German Federal Waterways Engineering and Research Institute (BAW), Karlsruhe. The test set-up is shown in Figure 4. Samples taken out of this test are showing a comparable filling range of the fiber labyrinth with soil particles as estimated in the dug up needle-punched nonwoven geotextiles with a multiple of the virgin fabric area weight being trapped as soil mass in the fiber labyrinth, thus forming a fiber reinforced soil layer. The "turbulence test" is also described in prEN ISO 10772 (CEN WI 00189146) "Test method for the determination of the filtration behaviour of geotextiles under turbulent flow conditions".

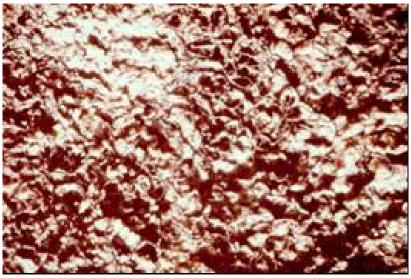

Figure 3. Nonwoven fabric filled with sand and mud particles, 9 years after construction in 1970

Figure 4. BAW filtration test (hydrodynamic soil retention test)

This soil / needle-punched nonwoven GTX interaction is a very important issue also for sand container / sand-filled tube technology. The advantages out of this soil particle / fiber labyrinth interaction is

- a higher overall robustness to all kind of loads <u>after</u> installation in a short period of service including abrasion loads by sand movement induced by waves and currents,
- a higher local stability with much reduced risks for flapping under wave and current action, giving higher surviveability under high dynamic loads.

The fiber labyrinth of a thick NP SF NW GTX with a very high amount of pores (85 – 90 % pore volume, 10 – 15 % fiber mass) has also the advantage of the highest gas permeability compared to other geotextiles. Therefore, trapped air in the sand containers can easily be released during dumping operations without the risks of bursting caused by the explosion like release of trapped air! Based on own experience, this also leads to a more accurate placing of the sand containers made of NP SF NW GTX because of less drifting due to less problems with trapped air.

When sand containers or sand-filled tubes at large coastal engineering structures need to be stapled on top of each other, NP SF NW GTX show the highest friction value between the textile layers, and the stability can be further improved by introducing double-sided Velcro strips in the connection area.

Another important aspect is that the open fiber structure of NP SF NW GTX is forming an attractive, well accepted settling ground for algae growth and soft corals forming the food source for a variety of marine life at the sandcontainer structures as shown in Fig. 5 and 6, as it has been reported from the mega-sandcontainer strucutre at Narrowneck Reef, Goldcoast, Queensland, Australia (Heerten & Werth 2005, Jackson et al 2004).

Figure 5. Algae growth on NP SF NW GTX at sand-containers at Narrowneck Reef, Goldcoast, Queensland, Australia

Figure 6. Soft corals growth on NP SF NW GTX at sand containers at Narrowneck Reef, Goldcoast, Queensland, Australia

Early experiences in coastal engineering application have also shown that needle-punched nonwoven geotextiles produced of continuous filaments are endangered to lose the comparatively light needle-punch bonding under wave action. This problem is topically confirmed by Heibaum et al. (2008). To make use of the mentioned advantages, Needle-Punched Staple Fiber NonWoven GeoTeXtiles are the options to be preferred.

The main technical parameters of superior importance for sand container / tube application are summarized in Fig. 7.

Figure 7. The most important requirements for geotextiles used for sand containers / tubes

Out of the field investigations it can be concluded additionally that the results determined on samples of the salt-water region could be influenced by a lot of parameters like suspended load of the seawater, duration of tidal overflow, covering of the fabrics by mud, seaweed, micro-organism or rubble and their temporary variation, giving additional protection against the main enemy "UV radiation". Type of resin, type and amount of stabilizer, fiber fineness and area weight of the fabric are also important parameters for UV resistance. But the damage of fabrics could also be caused by wave-action, drifting-wood or ice, shipping or tourists.

Most of the parameters are only influencing the sections with unprotected weathering like the upper sides of the sand filled tubes. Geotextile filter fabrics in revetments protected by several cover-layers are less endangered but attention must be paid so that no damage of the fabrics occurs during construction time. Finally it has to be considered with regard to the research program that the fabrics have been produced with the technical knowledge of their production time in the time frame 1955 to 1975, 5 to 24 years before the research programme was carried out. Currently produced and sufficiently stabilized geotextiles will perform even better based on the positive technical development in the meantime.

Ageing by biological and chemical damages is of much lower importance and could not be identified. Serious attention – even repeated here again - has to be paid that no damage of fabrics already occurs during the construction. This demand is very much supported by the results of investigations carried out on the woven geotextile filter fabric used as a construction element of protection against scouring at the mentioned coastal engineering structure with the big failure. The protection against souring was damaged, but the first assumption that the damage was caused by insufficient long-term resistance of the woven fabric could not be confirmed. The damage (puncturing) already occurred during installation - by installing the first gravel layer (10 cm, Ø 15 to 30 mm) - because of the low fabric weight of only 200 g/m^2 compared to NP SF NW GTX with an area weight ≥ 600 g/m^2, successfully tested with the BAW puncture and abrasion test, which is toaday's current coastal and hydraulic engineering practice in Germany and some other parts of the world.

3 NEEDLE-PUNCHED STAPLE FIBER NONWOVEN GTX REQUIREMENTS AND CONSIDERATIONS

NP SF NW geotextiles used for sand-filled containers and tubes are subjected to significantly different forces than geotextiles used in the conventional drainage, filtration and separation applications. These differences must be taken into account when designing these structures. The sections below describe the issues which should be considered when designing a sand-filled geotextile container with NP SF NW geotextiles.

Experience has shown that although large tube structures or very large sand containers are cost effective in the short term, they do not provide the best long-term engineering solution as localized damage or vandalism can cause large sections of the structure to fail. The individual sand containers should be as large as necessary, but as small as possible to avoid potential large damage in any case. Fig. 8 shows the flexibility of small sand containers to bridge a gap when one container has failed without endangering the integrity of the coastal defense structure.

Figure 8. Advantage of "as small as possible" sand containers for the safety of coastal defense structures

But sandcontainer technology has developed, so that today the client can choose the best container type for a range of applications in coastline protection and marine structures (reefs, scour protection). But the following requirements should be considered.

3.1 *Damage and abrasion resistance*

For the harsh environment of coastal and offshore engineering we need geotextiles of very high robustness. To try to save money by reducing the area weight of the geotextiles is trying to save money at the wrong end! Vandalism and incidental damage from drifting wood or ice etc. to sand-filled containers or tubes is unavoidable. The geotextile must therefore have high elongation and puncture resistance to limit damage from these impacts.

Surviving the "stone dumping test" of BAW as shown in Figure 9 is a very good minimum criterion for the harsh environment of coastal and offshore engineering combined with a minimum area weight of 600 g/m² of the NP SF NW GTX – don't try to save money on the wrong side!

As an example, Figure 10 is showing the resistance of the individual Terrafix® product range of needle-punched staple fiber nonwoven geotextiles as function of mass per unit area, stone weight and max. drop height.

The containers and tubes will be exposed to constant abrasion due to water born sands and gravel carried by currents and waves, this abrasion can be extreme in areas where sand, coral and shell fragments are present. It is well-known that even steel structures are suffering very much by sand abrasion and are completely destroyed in a period of some years. The geotextile must therefore have the highest possible abrasion resistance.

Figure 9. Test set-up for simulating stone dumping (BAW)

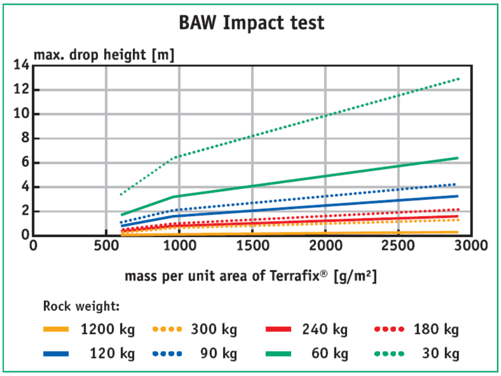

Figure 10. Impact resistance against stone dumping

As an early abrasion test, the "sliding block method" for geotextiles was developed (ASTM Test Method D 4833 – 88: Abrasion Resistance of Geotextiles (Sand Paper / Sliding Block Method)). Unfortunately this test takes into account only a loading that simulates the sliding of a solid mass over carpets or seat covers etc. The contact of soil and geotextile is different! Soil is not a solid surface that slides as a block over a geotextile specimen. The soil grains do not behave like a rigid surface, but roll, tumble, rock or draw off. Therefore interaction of soil and geotextile is not represented by such a test. Additionally, concerning the use of geotextiles in hydraulic applications, most of these tests are not adequate since they are performed in dry conditions.

The German rotating drum test method (BAW abrasion test as shown in Fig. 11) best replicates the abrasive near shore surf environment, which these structures will be exposed to.

Figure 11. BAW rotating drum test for abrasion testing

In-situ sediment and bedload transport applies just such a load on the geotextile. Recovered samples that have undergone severe sediment and bedload transport show a nearly identical damage like fabric that was tested in the BAW abrasion tester (Heibaum et al. 2008).

In this test, a mixture of stone chippings and water passes over geotextile samples installed in a rotating drum. The standard test comprises two abrasion phases of 40,000 revolutions each. The drum speed is set at 16 rpm and the direction of rotation is reversed every 5,000 revolutions. The samples are visually checked after the first 40,000 revolutions. If the samples are not degraded new stone chippings are filled in and the second phase is carried out. If the samples have not been destroyed after 80,000 revolutions, samples are taken from the centres of the abraded surfaces and their tensile strength is testes.

The tensile strength after abrasion is tested in the direction of abrasion load, id.e. in the longitudinal direction of the sample (200 x 300 mm). Due to the sample size, testing according to EN ISO 10319 is not possible (only an area of 170 x 280 mm is loaded, the margins are protected). Therefore tensile strength is tested according to RPG (1994) (DIN 53857: specimen size 100 mm width x 200 mm length, deformation rate 200 mm/min). For reason of comparison, the sample has to be tested the same way before the abrasion test as after the test. The tensile strength according to RPG (1994) is in most cases equal to the tensile strength according to EN ISO 10319, even though the test procedure is somehow different. (Heibaum et al. 2008).

Eight samples undergo simultaneously the abrasion test in the rotating drum. Four are loaded in machine direction and four in cross-machine direction. A geotextile is considered resistant to abrasion loads if 75 % of the required layer thickness and of the required tensile strengths are still left after execution of abrasion test. The remaining tensile strength should be given in strength units, not in percent, since often fabric is offered that shows higher virgin tensile strength than required whereas it experiences a larger loss than 25 %, but still meeting the absolute threshold value of 75% of the required tensile strength.

The values required in specifications for this test are minimum values, so every sample has to fulfill these requirements. Therefore the definition of a mean value and standard deviation is not decisive, which allows the testing of only a reduced number of samples.

It is a fact that after an abrasion test some fabric still shows significant tensile strength even though there is no filter function due to holes in the fabric. Therefore it is considered not sufficient to test the remaining tensile strength after the abrasion test as requested by RPG (1994). It must also be guaranteed that the opening size and thus the filtration capacity has not changed in an unacceptable manner. The opening size should not increase the opening size required in the filter design more than 0.01 mm to guarantee sufficient filtration function also after a certain amount of abrasions (Heibaum et al. 2008).

The geotextile should also allow the ingress of sand into the fiber labyrinth structure as it is best achieved with NP SF NW GTX to limit damage by e.g. knife cut. A composite NP SF NW GTX with an additional coarse fiber layer has been developed which traps about 3 kg/m^2 of sand within the geotextile (Saathoff et al 2007). Two alternative cross sections of such composite products are shown in Fig. 12. These products have significantly improved the resilience and durability of individual containers.

Also the stability under wave action by reduced risk of "flapping" is improved and a reduced potential of internal sand movement is achieved.

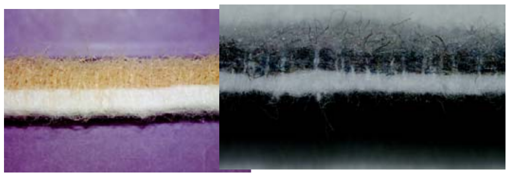

Figure 12. Composite NP SF NW GTX to improve damage and abrasion resistance

3.2 *Elongation*

A high elongation geotextile allows the containers to mould itself in with the existing feature and also allows a certain degreee of self-healing of the structure as already shown in Fig. 8.

An ultimate elongation (wide strip) of greater than 50% is recommended to limit installation damage and allow flexibility of the structure.

This high elongation requirement will allow deformation of the NP SF NW GTX product forming the container or tube and will avoid high stress concentrations with possible tearing and rupture during all phases of filling, handling, installation and service.

3.3 *UV resistance*

The need for either short- or long-term resistance to weathering depends on the site conditions. In most cases containers are exposed to UV light for only a limited time during storage, transport and installation and are subsequently protected lateron due to soil or installation under water. Furthermore the containers are protected against UV degradation from soil or biological natural cover at the surface of the container.

Ageing of exposed containers is mainly initiated by the ultraviolet (UV) component of solar radiation, heat and oxygen, with contributions from other climatic factors. This is a general property of polymers and is not restricted to geosynthetics. Chemical Additives used at the production of the fibres in the polymer increases the resistance to ultraviolet radiation.

It is therefore recommended that all containers should be tested for their resistance to weathering, using an accelerated test which provides a high level of radiation coupled with cycles of temperature and moisture, such as ASTM D 4355 "Standard Test Method for Deterioration of Geotextiles by Exposure to Light, Moisture and Heat in a Xenon Arc Type Apparatus" and EN 12224 "Geotextiles and geotextile-related products - Determination of the resistance to weathering".

Extended artificial weathering tests using methods similar to those in EN 12224 are required for materials which are to be exposed for longer durations. If the radiation is increased too much, the temperature of the geosynthetic rises to a point where the accelerated test is no longer representative of the performance in service. This limits the degree of acceleration to about a factor of three, with the result that many years' testing may be required to simulate the service life of a geosynthetic exposed permanently to light.

In Portugal special free weathering tests with severe UV attack conditions have been carried out (Recker et al. 2010). The test conditions have been established in a way that prevents the geosynthetic from soil or biological natural cover at the samples surface. Under these severe conditions a NP SF NW GTX being used for sand container production showed a retained strength and elongation of more than 50 % after 5 years of completely unprotected free weathering. The geotextile was produced of white coloured PP staple fibers with good selected chemical additive as stabilizer in a unit weight of 600 g/m². With a higher mass per unit area this very good UV resistance can further be improved.

3.4 *Soil retention*

The containers will be exposed to wave action and dynamic flow conditions and it is critical the geotextile selected retain sufficient fill material to ensure the container does not deflate and remains stable.

The BAW turbulence test as shown in Figure 4 and also described in CEN EN ISO 10772 (draft) is the recommended test for testing soil retention.

As mentioned, there is also no better test set-up available to give an estimate of the ingress of soil particles into the fiber labyrinth of the nonwoven geotextile.

3.5 *Permeability*

The containers are likely to be exposed to cyclic wetting and drying, e.g. due to tidal variation, the geotextile through flow will control the period for which the sand fill remains saturated after being submerged, stability of the structure is dependant of the water release capacity of the geotextile, i.e. the faster the water is drained from the container the more stable the structure. The geotextiles should be dimensioned as filter or alternatively have a minimum permeability of 10 higher comparing the fill material. The turbulence test is used to test the mechanical filtration stability of geotextiles for use with very fine-grained soils (d_{20} < 0.06 mm) on exposure to turbulent external flow conditions. The test results show whether the rate [%] at which soil passes through the geotextile has stabilized as required. A permeability test afterwards is an indication for sufficient long-term permeability k [m/s], if $k_{geotextile}$ is higher or equal in comparison to k_{soil}.

3.6 *Interface friction*

This angle is of importance when assessing the stability of the structure, particularly when containers are placed on top of each other. Again the greatest friction angle is desirable. A large 300 mm x 300 mm shear box should be used for this test to limit edge effects. For the described NP SF NW GTX, friction test results show contact friction angles of about 20° to 26° between both geotextiles under wet conditions (Recio 2008).

3.7 *Seams for closure of containers / tubes*

Geotextile sand containers will be subjected to extreme pressure during the filling and placement operation and as such high strength seams are a requirement. They should have single, double or triple stitching depending on the size, method of installation and risk of damage to the container. For a fill volume of 1 m^3 a double seam is required. The yarn used for the stitching must be high strength, abrasion resistant and UV stabilised. The yarn should also be flexible and provide permeable stitches to leave out air bubbles. The sand container should have minimum closure seam strength of 80% in relation to the geotextile material. The closure of prefabricated (factory seams with high quality standards) containers is mainly done on site. Geotextile tubes are delivered to construction site advantageously completely prefabricated despite of inlet and outlet devices, which have to be closed after the hydraulic fill process, e.g. by use of cable ties.

3.8 *Technical data of NP SF NW GTX sand containers*

For specification of NP SF NW GTX to produce sand containers the technical data given in Table 1 can be recommended based on the author's decades of application experience in hydraulic, coastal and offshore engineering.

Table 1. Technical specifications for NP SF NW GTX for sand container applications

Property	Test method	Unit	Size	
			1 – 2 m³	150 m³
Raw Material	-	-	PP / PES	
Mass per unit area	EN ISO 9864	g /m²	600	1200
Thickness	EN ISO 9863-1	mm	5.0	7.5
Max. Tensile strength md/cmd	EN ISO 10319	kN/m	25.5/25.5	45 /78
Elongation at max. tensile strength md/cmd	EN ISO 10319	%	50 /30	
Characteristic opening size	EN ISO 12956	mm	0.08	
Water permeability VI_{H50}-Index	EN ISO 11058	m/s	$3\cdot10^{-2}$	$1.2\cdot10^{-2}$

For sand container sizes smaller than 1 m³ (2 t) the mass per unit area should not be reduced, but taken as minimum value of 600 g/m² for sufficient damage and abrasion resistance, too. For sand containers of 10 m³ (20 t) or above a mass per unit area of 1200 g/m² is recommended. Other sizes may be interpolated.

For very small sand containers (> 0.1 m³ / 0.2 t) a mass per unit area of 400 g/m² has shown to be the lowest limit also with regard to damage and abrasion resistance as reported by Heibaum et al (2008) based on application experience with millions of very small sand containers being used for permanent bank protection in the Jamuna Meghna River Erosion Mitigation Project in Bangladesh.

4 WAVE STABILITY OF SAND CONTAINERS

In the light of growing acceptance of sand containers for dune protection, but also offshore scour protection at wind farms during the last years several hydraulic model tests involving coastal structures made with geotextile sand containers (NP SF NW GTX) were performed at Leichtweiß Institute for Hydrodynamics and Coastal Engineering (LWI) of the Technical University Braunschweig, Germany (Oumeraci 2002, Recio 2008).

These wave flume model tests showed the dislodgment and pull-out of the slope containers by wave action, being strongly affected by the deformation of the sand containers (Fig. 13).

Simple stability formulae like those proposed by Oumeraci et al. 2002 are shown as graph "Hinz and Oumeraci (2002)" in Fig. 14 for slope containers. These test results did not include the mentioned deformation effects (Oumeraci 2002). Therefore further comprehensive model tests have been done by LWI for determination of stability criteria and formulae with consideration on deformation effects (Recio 2008) as also shown in Fig. 14 as graph "Recio and Oumeraci (2007)".

The referred stability formulae according to Fig. 14 are given in Fig. 15.

Hydraulic model tests were also performed in the wave flumes at LWI to study comparatively the hydraulic performance and the stability of traditional and GeoCore rubble mound breakwaters under wave attack (Oumeraci et al. 2008). GeoCore rubble mound breakwater includes a core of geotextile containers instead of rip-raps.

Figure 13. Large-scale model tests with geotextile containers (Oumeraci et al., 2002)

Based on the experimental results, a better understanding of the processes which affect the hydraulic stability of the geotextile sand container structure (GSC) has been achieved by Recio (2008), including the effect of the deformations of the sand containers and their mutual interaction. In Recio (2008) it is summarized, that

- The most critical location on the seaward slope with respect to the hydraulic stability is for the containers placed just below the still water level.
- The deformations of the containers strongly affect the stability of GSC-structures. Deforma-

tions reduce the resisting contact areas between the containers and thus, the resisting forces on the containers

- The internal movement of sand inside the container induces deformation of the container and therefore substantially affects the stability of the GSC-structure. Internal movement of sand depends on the sand fill ratio of the container which should thus, be strictly controlled to ensure the stability of any GSC-structure. The sand fill ratio of GSCs should be optimal (equal or higher than 80%, depending on the elongation properties of the geotextile used for the containers).
- Breaking waves are not as critical as originally expected for the hydraulic stability of GSC-structures. This is probably due to the flexibility and damping properties of the GSCs which contribute to attenuate the propagation of pressure inside the GSC-structure.

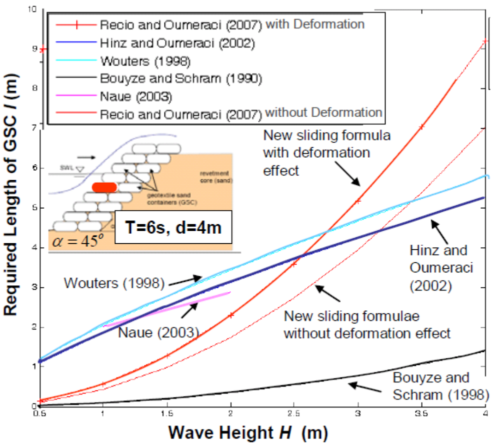

Figure 14. Comparison between stability formulae with and without deformation effects including further available formulae – valid for slope containers (Recio 2008)

Based on own current experience for most applications the wave stability of NP SF NW GTX sand containers can be calculated as "slope" containers using the Recio (2008) design graph (new sliding formulae with deformation effect) shown in Fig. 14 and the corresponding design formulae in Fig. 15. The sand container dimensions (weight and length with corresponding size at 80 % fill ratio) received with the design approach are corresponding well with practical application experience at groynes and seawalls when checking the sand container size of structures in service with this design tool (see e.g. chapter 5.3).

Sliding Formulae with Deformation Effect	$l_c \geq u^2 \dfrac{[0.5KS_{CD}C_D + 2.5KS_{CL}C_L\mu]}{\left[\mu KS_R \Delta g - KS_{CM}C_M \dfrac{\partial u}{\partial t}\right]}$	$C_D = 9 \quad C_M = 0.30 \quad C_M = 1.0$ $KS_{CD} = 1.4 \quad KS_{CM} = 1.0 \quad KS_{CL} = 0.94 \quad KS_R = 1.6$
Hinz and Oumeraci (2002)	$\dfrac{H_S}{\left(\dfrac{\rho_E}{\rho_W} - 1\right) \cdot D} = \dfrac{2.75}{\sqrt{\xi_0}}$	$\xi_o = \dfrac{\tan\alpha}{\sqrt{H_s / L_o}}$ $D = l_c \sin\alpha$ $\rho_E = (1-n)\cdot\rho_s + \rho_w$
Wouters (1998)	$\dfrac{H_S}{\left(\dfrac{\rho_E}{\rho_W} - 1\right) \cdot D} = \dfrac{2.5}{\sqrt{\xi_0}}$	$\xi_o = \dfrac{\tan\alpha}{\sqrt{H_s / L_o}}$ $D = l_c \sin\alpha$ $\rho_E = (1-n)\cdot\rho_s + \rho_w$
Bouyze and Schram (1998)	$\dfrac{u_{cr}}{(g\Delta D)^{0.5}} = 1.0$	$D = l_c$
Naue (2003)	Based on existing projects	
Sliding formulae without deformation effect	$l_c \geq u^2 \dfrac{[0.5C_D + 2.5C_L\mu]}{\left[1.6\mu\Delta g - C_M \dfrac{\partial u}{\partial t}\right]}$	$C_D = 9 \quad C_M = 0.30 \quad C_M = 1.0$

Figure 15. Different stability formulae according to Fig. 14 for slope containers (Recio 2008)

For sand containers in a "crest" position where the still water level is in the level of the crest container and breakwater waves have to be considered then the container size has to increase and can be calculated with corresponding "crest" container design curve and formulae also given by Recio (2008).

4.1 *Stability of sand containers as scour protection for offshore monopiles*

By developing the use of alternative/renewable energies, also the construction of offshore wind energy plants is being promoted. All over the North Sea offshore wind farms are being constructed in water depths of 30 to 40 m outside the shipping routes. The installation of wind energy plants which are subjected to very high dynamic loads caused by waves, tide currents and wind is a big challenge, especially if in case of a sandy seabed possible scour may occur at the foundation element.

An innovative solution for scour protection is the use of geotextile sand containers. Geotextile sand containers have many advantages compared to traditional scour protection with rubble and filter layers beneath. The soft material reduces the danger of damage at the cable entry and at the corrosion protection of the foundation element itself. In addition, the costs are lower and it is comparatively easy to remove the sand containers at the end of the service life of the wind energy plant.

To check the stability of such scour protection solutions, a joint research project was initiated at the Coastal Research Centre (FZK) which is a joint institution of Leibniz University Hanover and Technical University Braunschweig, Germany.

The research project deals with "Offshore wind turbines – Large-scale investigations on scour protection for monopile foundations under sea state conditions".

To minimize the influence of scale effects, the tests were carried out in a large-scale physical model in the large wave flume (GWK) of the Coastal Research Centre (FZK) (Fig. 16.)

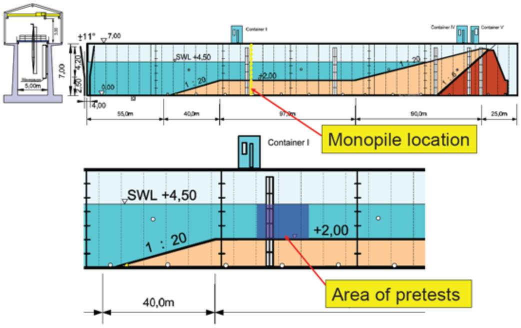

Figure 16. Longitudinal section of the large wave flume with the installed sand profile and the monopile foundation

The simulation of the wave induced hydrodynamic processes and especially the scaling of the fine sand which can be often found in the German Bight and the North Sea require a model setup in this dimension.

At first, extensive basic tests were carried out with geotextile sand containers on the stability of single containers and container groups. With the results of these experiments the scour protection systems for a monopile have been dimensioned for the tests in the large wave flume.

For the stability tests, altogether four test series were carried out with a complete scour protection at monopile foundation. The scour protection with a diameter of 24 m is designed for a monopile structure with a diameter of 5.5 in a water depth of 21 m. The height of the design wave for the scour protection is $H_{1/3}$ = 7.5 m. For the tests in the large wave flume a scale of 1:10 was used for these boundary conditions.

The parameters for the different test types are summarized in Table 2. In the first test the geotextile sand containers were placed regularly and installed without water in dry condition. In the other three tests the sand containers were placed in an irregular way: in dry and wet condition with water depths of 0.50 m and 2.10 m. Fig. 17 shows the unloaded scour protection in the large wave flume directly after installation, on the left side with regularly arranged sand containers and on the right side with an irregular arrangement.

Table 2. Test series with sand containers performed in GWK

Testseries 4.5 kg 85 % filling	Layers	Number of sand containers			Placing conditions	
		Lower layer	Upper layer	Total		Waterdepth [m]
I	2	87	66	153	regular	0 (dry)
II	2	97	92	189	irregular	0 (dry)
III	2	95	94	189	irregular	0.5
IV	2	100	96	196	irregular	2.1

Figure 17. 1:10 model for scour protection variants with geotextile sand containers in the large wave flume (left: regular placement, right: irregular placement)

After the first tests with wave heights which correspond to the designed wave height, four sand containers within the scour protection have changed their position. This can be interpreted as self-correcting displacement and thus as increased stability after installation that means the stability of the scour protection is not affected.

For the further tests the significant wave height and the peak period were increased step by step. Shiftings of more than 5 % of the total number of installed sand containers only occurred at a significant wave height > 1.00 m (increasing the design wave from $H_{1/3}$ = 7.5 m to $H_{1/3}$ = 10 m).

Fig. 18 shows two pictures with the corresponding displacements of the sand containers after different wave spectra with 2000 waves each.

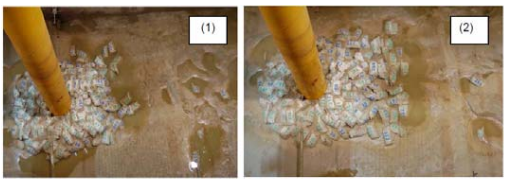

Figure 18. Pictures of scour protection after tests with different wave spectra, after 2000 waves each during test series II

The following concluding remarks and outlook can be given for scour protection at offshore wind turbines with geotextile sand containers:

- ➢ The stability is not only a function of the weight, but also for the filling percentage and the direction of the wave attack.
- ➢ For regularly placed sand containers the process of displacing continues faster in comparison to irregularly placed sand containers.
- ➢ For irregularly placed sand containers a self correcting placing occurs at the beginning of the wave attach.
- ➢ For the investigated windpark geotextile sand containers of about 3.0 to 3.5 tons (1900 kg/m³) with nearly 85 % filling should be a safe solution for the design wave of $H_{1/3} = 7.5$ m, a water depth of 21 m and a diameter of 5.5 m of the monopile foundation structure.

The investigations on scour protection at offshore structures are continued and further results can be expected in the future.

4.2 *Stability of breakwaters with core made of geotextile containers*

A systematic experimental study in the twin-wave flumes of Leichtweiss-Institute (LWI) was performed on a geocore breakwater and a conventional rubble mound breakwater in order to comparatively determine the hydraulic stability and the hydraulic performance, including wave reflection, wave transmission, wave run-up and wave overtopping.

The geocore breakwater consists of a core made of sand-filled geotextile containers covered by an armour made of rock (Fig. 19). The geocore is more than an order of magnitude less permeable than the quarry run core of a conventional breakwater. As expected, the core permeability strongly affects the armour stability on the seaside slope, the wave transmission and the wave overtopping performance. Surprisingly, however, wave reflection and hydraulic stability of the rear slope are less affected. Formulae for the stability and hydraulic performance of the geocore breakwater were proposed, including wave reflection, transmission, run-up and overtopping (Oumeraci et al. 2008).

Design approaches are given in Oumeraci & Kortenhaus 2008. Following main model test results are concluded in Oumeraci & Kortenhaus 2008:

- The permeability of the geocore breakwater was found to be 14 times less permeable than that of the conventional breakwater with a quarry run core.
- No significant difference could be observed in terms of wave reflection performance. For both breakwaters, the surf similarity parameter surprisingly failed to describe the wave reflection.
- As expected, the difference in terms of wave transmission is essentially determined by the wave steepness and the relative freeboard. The full potential of the geocore breakwater will particularly emerge when used for the protection against long waves.
- For surf similarity parameter $\xi mo > 3$, which represents the values of interest for the design of rubble mound structures, the geocore breakwater is associated with a 20% higher run-up.
- The difference between the two breakwater types in terms of wave overtopping strongly depends on the relative freeboard. For common design freeboard ($Rc/Hm0 < 1.5$) the difference is less than expected.
- Regarding the difference in terms of the seaward armour stability, 50-70% larger armour units are required for the geocore breakwater with an allowable damage level $D = 5\%$. This is in the range of the published results on the effect of the core permeability. Very surprising, however, is that no significant difference in terms of the armour stability of the rear slope is observed, even for a relative freeboard larger than 1.5.
- Despite the case study character of the experimental investigations performed in this project, the results have shown that the geocore solution may indeed represent a feasible alternative with a wide application potential, especially in areas where rock is not available in large quantities and at low costs as well as in areas where the protection against long waves is a major issue. Moreover, the geocore concept should be extended for other classes of structures such as seawalls, artificial reefs, groins etc. The advantages of such a solution are expected to be particularly revealed in the case of reclaimed land protected by seawalls.

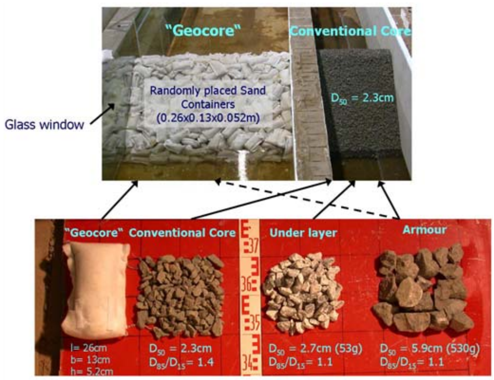

Figure 19. Construction materials used for both breakwater models

5 CASE STUDIES

The application of NP SF NW GTX sand containers or tubes has already a three decades history with a magnificent variability of different structures being constructed around the world in hydraulic, coastal and offshore engineering. The containers or tubes with very different dimensions have been dry or hydraulic filled and have been installed above and under water. In the following, some outstanding examples are dealing with the different filling and placing conditions.

5.1 *NP SF NW GTX sand container as scour protection at Eider Storm Surge Barrier, Germany (1993)*

The Eider Strom Surge Barrier (Eidersperrwerk), constructed during 1967 and 1973, protects the estuary of the Eider against storm tides, improves the discharge of the Eider and helps to maintain the shipping traffic on the Eider.

When the "Eidersperrwerk" was constructed, bottom scour protections were provided both on the sea and the landside. A minimum length of 150 m for a rigid bed stabilization in flow direction and with an inclination of 75:1, combined with flexible bordering transition areas with a minimum width of 30 m having the purpose to secure potential inner scour of the embankments and to avoid erosion towards the barrage were carried out.

As expected, scours developed next to the bed protection both on the inner and outer side. But the development of scours did not endanger the barrage as long as the flexible bed protection fulfills its purpose and thus prevents the scour from moving toward the rigid bed stabilization. After many year of service the flexible bed protection showed first damage. From 1981 to 1991, geotextile containers were installed in several intervals to stabilize the inner scour of the embankments on the sea and land side.

But special weir operation was needed during rehabilitation works creating severe hydrodynamic loads to different scour protection areas.

The flexible bed protection could no longer fulfill its purpose to flexibly adapt to the edges of the scour and to protect the rigid bed stabilization against undermining.

Since 1991, scour has developed particularly on the seaside, max. 25 m in depth. The inner scour embankments partly became very steep (approx. 1:1, partly precipices). Although the situation at the land side was slightly better, it was necessary to stabilise the inner embankments on the sea and land side by installing a filter layer on the existing scoured embankment, filling up the scours in order to, among others, flatten the scoured embankments (permissible inclination maximum 3:1) and stabilizing this filling with cover material. It was decided to stabilize the inner scoured embankments by using, apart from other measure, geotextile containers. Approx. 48,000 geotextile containers were installed (Fig. 20).

The geotextile container structure for the stabilization of the scour embankments at the Eidersperrwerk prevents that the bed material (sand) is washed out through the flexible bed protection. The mixed gravel filter material designed for this purpose consists of gravel, which was designed so that the material is filter stable in itself and tends to decompose during underwater installation, it cannot be dropped unfixed. Furthermore, the gravel would be washed out alreay during construction by currents. For this reason, the mixed gravel filter material was packed into geotextile container (1.35 m x 2.70 m in size).

The geotextile containers had to be regarded from the filter technical point of view. No filter technical problems appeared towards the gravel fill material. The filter technical dimensioning of the geotextile is rather based on the bed material in contact (sand).

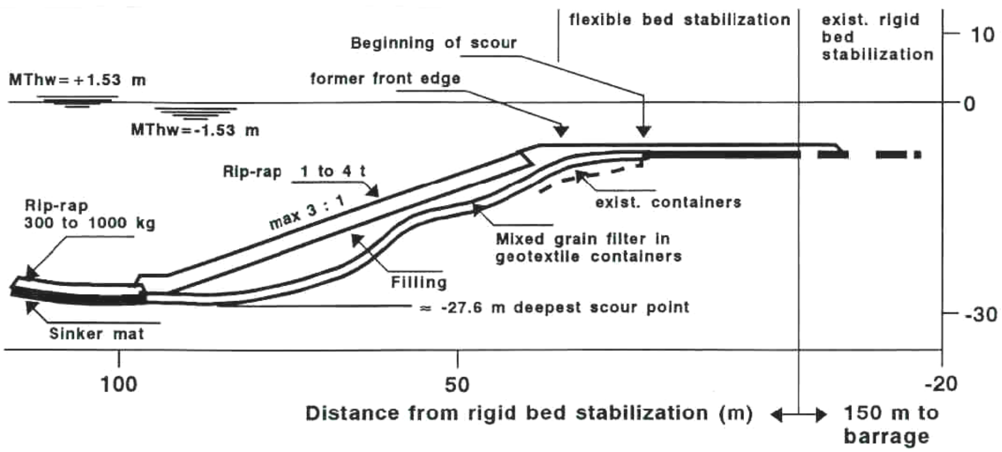

Figure 20. Realized cross-section profile at the outer embankment

Both the mixed gravel filter and the geotextile are thus filter stable towards the bed material (sand). The geotextile container for the installation of the mixed gravel filter provides a well designed geotextile filter with double safety. Because of the very high importance of the Eider storm surge barrier for flood protection this solution of belt and braces was carried out. Even if it is assumed that the mixed gravel filter might escape from the geotextile container, the filling of the scour with rip-raps Class II is filter stable toward the mixed gravel filter. Moreover, the filling is filter stable toward the upper layer consisting of rip-raps weighting between 1 and 4 tons. The properties of the geotextile containers according to the client's requirements are as follows:

- Containers made from NP SF NW GTX have to be used to achieve a higher roughness and thus a better interlocking. The maximal tensile strength according to DIN 53857 is $\sigma_z \geq 25$kN/m both for the container material and the seams. The characteristic opening size according to EN 12956 is: $0.10 \leq O_{90} \leq 0.25$mm.
- For the fill material a mixed gravel filter with grain sizes of 0.1 to 100 mm ($0.6 \leq d_{10} \leq 1.5$mm, $15 \leq d_{50} \leq 25$mm and $30 \leq d_{60} \leq 60$mm) which is filter stable toward the basis soil (the scoured embankments have soil particles from sand to clay; the prevailing fine sand has average grain size of approx. $d_{50}=0.15$mm) and the rip-raps Class III.
- The packing of the mixed gravel filter shall primarily prevent the decomposition of the material and losses resulting from installation. The degree of filling of containers is 80%. The containers are closed by a double chain stitch seam. The dictated fill quantity of 1 m³ per container may not be exceeded by mor than 10%. This shall ensure that the containers lie flat on the seabed and thus compensate irregularities and hollows.

The first mentioned requirement (use of needle-punched nonwoven fabrics) is also based on negative experiences gained with woven fabric containers with up to 25% failure rate during handling and installation. Nonwoven fabric material was therefore preferred to woven fabrics for the use as containers and filter material. The geotextile had to perform as a "filter" towards the fill material with varying grain sizes and it should filter the grains of the seabed.

The chosen geotextile containers with a capacity of 1 m³ and dimensions of 1.35 x 2.70 m had to fulfill special requirements:

- the geotextile must have a sufficient strength/robustness to withstand mechanical transport,
- the seams must have at least approx. 80% of the strength of the geotextile and
- only material with high UV resistance is suitable.

The geotextile containers have to be closed by sewing after they have been filled. The filled container should have a high static friction when they are piled up.

Containers of NP SF NW GTX with sufficient strength are the best to fulfill these requirements (Fig. 21). Moreover, they have, as compared to woven fabric containers, a higher flexibility and better friction properties (Saathoff et al. 2007)

From April to August 1993, about 48,000 geotextile containers were installed. Approx. 700 geotextile containers per day were filled on site (Fig. 22). This required the production and preparation of about 4,500 containers per week. The loading of the geotextile containers by means of a hydraulic crane with special grab took about 1.5 h per dumping barge (204 containers). Three to four layers of geotextile containers were loaded into each cargo hold (Fig. 23 and 24).

The sand container dumping barge was brought into position by means of a stern anchor, a ship's propeller in the bow (to maneuver the ship in transverse direction) and computer-aided navigation. The installation was done in intervals. Positioning and installation took about 1.5 h.

The implemented solution with geotextile containers is considered as unique worldwide and extremely successful. According to the supervisor, less than 10 of the 48,000 geotextile containers were damaged during the dumping process. The negative experience gained with the previously adopted woven fabric containers, which were also used in former projects, did not repeat with the nonwoven fabric containers. In future all persons concerned will surely prefer geotextile containers made from needle-punched staple fiber nonwoven fabrics. Further details of this project are given by Heibaum (1994, 2004).

Figure 21. Nonwoven sand containers are preferred due to high robustness and elongation behaviour

Figure 22. Overall view of the filling equipment (inclined con veyor belt with alternate filling of two chambers)

Figure 23. The loading process (stone dumper barge)

Figure 24. The Eider storm surge barrage in the background, sand container placement by positioning the barge

5.2 *Mega sand container as Narrowneck Reef, Queensland, Australia*

The Gold Coast area in Queensland, Australia, is regularly affected by cyclones which generate deep water waves in excess of 12 m (H_{max}) and severe short-term erosion of the beaches. While the extensive beachfront development is protected by boulder walls behind the dune system, the sediment budget currently available in the dune system is not adequate to withstand large storm events. In 1997 the "Northern Gold Coast Beach Protection Strategy" was initiated by the Gold Coast City Council to maintain and enhance the natural beach capacity by widening the beaches at Surfers Paradise (ICM International Coastal Management, 1997). Providing a long-term sustainable solution the strategy includes an initial 1.1 million m³ of beach nourishment with additional ongoing beach nourishment of approx. 80,000 m³ per year. In addition, the construction of a submerged artificial reef at Narrowneck is designed as coastal control point within the open sand system so as not to disturb the sediment balance (Jackson et al, 1997). As a world-wide pioneering feature two objectives have to be followed with this artificial geotextile "soft rock" reef constructed without any conventional hard elements like rip-rap, rocks and steel. Stabilizing and enhancing the natural beach capacity by beach widening and creating a world-class surf break. This pioneering geotextile "soft rock" coastal protection solution as an alternative to hard rock structures has the following decisive benefits:

- able to achieve design shape
- 50 % cost of rock (hard rock)
- surface reduces risk of injury to surfers
- no rock transport and no traffic on roads
- flexible to cope with seabed movements
- no works on beach or impact on beach users
- able to be easily topped up, modified or removed if necessary (important for approvals)

Constructed in 1999/2000, the Narrowneck Reef rates as one of the most innovative and complex geotextile sand container structures ever built (Fig. 25). The 200 m x 400 m submerged reef is an integral part of the Northern Gold Coast Beach Protection Strategy whose aim was to widen and protect the northern beaches as well as enhancing the surfing amenity. The reef provides a low profile, near shore control point to retain approx. 80,000 m³ of the 500,000 m³ of sand transported each year to the north along this shoreline.

Figure 25. Artifical reef with mega sand containers at Nar rowneck, Gold Coast, Queensland, Australia

The reef is made of about 400 nonwoven geotextile containers and more than 80,000 m³ encapsulated sand. It fits into a square of 600 m x 350 m, the cross-section profile ranges from about 1 m to 10 m below low tide sea level in distance of 150 m to the shoreline and it consists of two sides in V-shape with the northern part being the large than the southern part. The Northern part will form a right hand break, while the southern side will form left hand break on the Gold Coast. The reef is designed to be transparent for sediment movement and as a wave energy absorbing structure with a paddle channel in the centre. The shape of the reef jacks up the wave height by about 25 %.

Surfers were found to be key stakeholders and the choice of sand filled geotextile containers for the reef construction, made of heavy (1200 g/m²) needle-punched staple fiber nonwovens, was heavily influenced by the improved safety for surfers. One major international surfing competition on the Narrowneck reef will generate 2.2 million $ of benefits to the community.

More than 400 mega containers manufactured from heavy-duty polyester NP SF NW GTX (Fig. 26) have been installed. The containers varied from 3.0 m to 4.6 m in diameter, were placed using a split hulled, trailing suction hopper dredge fitted with computer interfaced DGPS (Fig. 27). The containers were accurately filled utilizing a calibrated flow density meter, ensuring repeatability and consistency of the construction. Containers were dropped in depths of water ranging from 3 m to 10 m, onto a sandy seabed. Because of the high elongation of the heavy (1200 g/m²) NP SF NW geotextile the containers have not been damaged – success by avoiding stress concentration by allowing deformation or deformation orientated design instead of stress orientated design!

Figure 26. Size of mega sand container for Narrowneck Artificial Reef

Figure 27. Split hulled, trailing suction hopper dredge "Faucon" from McQuade Dredging, Australia

The structure has proven to most successful in maintaining the widened beach profile (Turner, 2003). Based on the success of this first project the Gold Coast City Council will construct similar reefs at other erosion prone areas.

A feature not anticipated when considering the original design was the growth of algae and soft corals on the containers and how this food source has attracted marine life to the structure (Fig 28).

Figure 28. Spontaneous algae growth on sand containers; white = just dropped, black = algae covered after some days

The Australian National Marine Science Centre has carried out detailed research into the suitability of various geotextiles to promote growth of algae and provide habitat to small crustations (Edwards, 2003). Fig. 5 and 6 in chapter 2 show some examples of the growth and marine life found on the containers.

During the first design phases the main supplier Soil Filters Australia Ltd. has engaged BBG Bauberatung Geokunststoffe GmbH & Co. KG, Germany, for providing additional advice relating to technical geosynthetic questions.

5.3 *Dune Protection on a North Sea Island*

For the protection of the Wangerooge Island more than 3,000 sand containers in a size of 0.05 m³ were installed. They build a 260 m long seawall integrated in the natural form of the dune. After the installation the sandbags were covered with sand. The advantage of this method is the possibility of filling the sandbags with local material straight at the site. This helps to limit the influence on the environment.

The natural surface of the dune, with an inclination between 1:1 and 1:2, was first covered by a NP SF NW filtration geotextile up to 80 cm under the beach level. The first level of the sand container was installed about 1 m deeper as the dune foot.

The geotextile was wrapped around the first container layer and finally the remaining containers were stapled in layers up to the final height (Fig. 29). After the installation all containers were covered by 1 m up to 3 m of sand. The following winter storms in the year 2001/2002 removed all the sand cover. The waves were higher than the sandbag barrier. This overtopping was a major danger of destroying the dune behind the artificial barrier.

Figure 29. Construction of the dune protection on the Island of Wangerooge, North Sea

In the year 2002 an additional investment was done to increase the height of the geosynthetic protection wall. The upper edge of the new construction was moved up to 3.90 m a.s.l. During the realization more than 6,000 Soft Rock sand containers were used again. To increase the installation speed special "easy filling" equipment was used (Fig. 30). The excavator bucket was rebuilt to allow the loading of sand, filling the container and final compacting in one work step. A clamp was used to fix the empty container. This change brought a saving of 50 % of the installation time and necessary personnel in comparison to the installation in the previous year. The construction time was reduced to only less than 2 months for the more than 6,000 sand containers.

At the end of October 2002 a strong storm hit the coast of the island with wind speed up to 150 km/h. This was the strongest storm within the last 10 years. The sand covering the artificial barrier was eroded by wave action. Due to the wind direction the storm tide was not critical at all and the structure survived nearly without damage (Fig. 31)

Figure 30. Easy filling of the sand containers

Figure 31. Wangerooge dune protection after the storm (28/29 October 2002)

During the following years with other storm surge events it became obvious that the 100 kg sand containers (0.05 m³) are too small. Caused by severe wave load the containers moved perpendicular out of the embankment structure as observed during a wave flume test, too (Recio 2008). If the sand containers are too small with regard to the given wave attack, they are creeping out of the structure in the area of the still water level (Fig. 32); the lower the friction between the sand containers, the quicker the creeping.

Figure 32. Singular sand containers moved out of the structure in the area of still water level

A trial confirmed that the "easy filling" was surprisingly also possible with 20 times heavier 1 m³ (2 t) sand containers. Fig. 33 is showing the difference in size of sand containers for Wangerooge Island dune protection.

Fig. 34 is showing the "easy" filling equipment and procedure for the 1 m³ (2 t) sand container as it has been carried out in summer 2006 to improve the Wangerooge Island dune protection.

Figure 33. Different size of Wangerooge sand containers

Figure 34. Easy filling of 1m³ (2 t) sand container for Wangerooge Island dune protection (2006)

Based on the now available wave stability design approach after Recio (2008) wave stability of a slope container was calculated with the following parameters:

- water depth in front of the structure d= 3 m
- significant wave height $H_{1/3} = 2$ m
- significant wave period $T_{1/3} = 4$ s
- wave length L = 19 m

The following results have been achieved:

- required length of container $L_c = 2.30$ m
- required volume of container $V_c = 1.0$ m³
- required weight of container $G_c = 2.3$ t

The results are showing good accordance with the experience-based choice of bigger sand containers with a volume of 1 m³! Fig. 35 is showing the Wangerooge Island dune protection structure in February 2007 after the next winter strom period. The bigger 1 m³ sand containers have been placed on top of the existing structure with the too small bags of 100 kg only. Up to now a good agreement between wave stability design and real conditions is given.

Figure 35. Wangerooge Island dune protection structure after winter storm period 2007

Beside this "easy filling" development for sand containers of 1 m³ (2 t) size other filling procedures have been developed for medium size sand containers of 2.5 m³ (5 t). The equipment and installation of 2.5 m³ (5 t) sand container at Australia's coasts are shonw in Fig. 36 and Fig. 37.

Figure 36. Filling equipment for 2.5 m³ (5 t) sand container (Saathoff et al. 2007)

Figure 37. Placing of 2.5 m³ (5 t) sand containers constructing a groyne in the surf zone

5.4 *Dune protection Figuera da Foz, Atlantic coast, Portugal*

Over a period of several years storms have constantly eroded the sandy beaches close to location Leirosa at the coastline of Figuera da Foz (Atlantic Coast) in Portugal.

Since 2005 two geotextile sand filled structures made of NP SF NW GTX have been realized along that coast combining each other in its dune protection function. The dune location is structurally weakened due to an existing pipeline outlet, which has to be protected additionally.

As first protection measurement a dune revetment as second line of defence has been executed using nonwoven sheets and beach sand in the manner of wrap-around method (Fig. 38).

With pre-defined and compacted sand layer thicknesses the terraced structure made of overlapping geotextile sheets has been constructed. As completion work the structure was covered with sand and protected with dune grass as surface erosion control. Only in case of storm tides with the loss of vegetation and sand cover an activation of the proposed barrier function is assumed.

As lesson learned after a storm surge, the geotextile overlapping lengths as well as the grade of compaction within each layer was not sufficient enough for withstanding high wave loads and water levels. As consequence the structure was not as stable as expected, but the dune protection against break through was given. Due to the convincing application the existing structure was optimized with geotextile sand filled tubes (by hydraulic filling) which have been placed along the first realized dune protection (Fig. 38). This measure can be seen as dune rehabilitation and was realized in 2007. The aim was to strengthen the dune toe area by to use of 20 m long geotextile tubes made of SF NP NW GTX with a mass per unit area of 1000 g/m^2. The diameter of the filled tubes is about 1.50 m (Fig. 39 and 40).

Figure 38. Former dune protection made of sand-filled wrap-around technique (2005) and preparation of geotextile tube installation in 2007, Figuera da Foz

Figure 39. Geotextile tube hydraulic fill process, Figuera da Foz (2007)

Figure 40. Installation of the 6th tube along the dune toe area of Figuera da Foz (2007)

6 CONCLUSION

Geotextile sand containers as "soft rock structures" for flexible coastal protection measure provide significant advantages over "hard coastal structures" made of concrete, steel and rocks. Geotextile "soft rock structures" are variable or even removable if necessary and they can easily be combined with conventional elements like rap-rap or rock revetment. Geosynthetics solutions may provide greater efficiency relating to costs, time and equipment if compared to conventional methods.

Special development and experience with needle-punched staple fiber nonwoven geotextiles (NP SF NW GTX) for sand containers and sand-filled tubes lead to the strong recommendation to separate technical requirements for woven or NP SF NW GTX when planning and designing a coastal structure with sand containers or tubes. The client should decide if he wants a woven sand container / tube solution or a solution based on NP SF NW GTX, because there are normally good arguments to prefer the woven or the nonwoven solution in a special case. It is impossible to cover both alternatives with only one specification especially with regard to stress / strain or filtration requirements.

Currently produced and sufficiently stabilized geotextiles will perform in the long term for several decades. Ageing by biological and chemical damages is not a concern. But the geotextiles have to be of high robustness to survive the filling, handling and installation operations of the sand containers / tubes, and highest abrasion resistance is required if exposed to wave action and water born sands, coral or shell fragments with extreme abrasion attack, where even sheet pile structures are destroyed on very short term.

Based on large-scale model tests in the Large Wave Flume of Hanvoer (GWK) a wave stability design for "slope" and "crest" sand containers is now possible and first answers are given for sand container stability being used as scour protection at the foundation of offshore wind turbines.

If properly designed and installed the NP SF NW GTX sand containers / tubes should maintain their functions over the desired design life of approx. 30 to 50 years.

For coastal engineers it should be a challenge to design coastal and hydraulic structures with geotextile sand containers or tubes balanced between the requirements of function, low-costs, flexibility and considerung the overall environmental impact. Since stresses and pressures are more or less important in the presence of flexible components on the one hand and, on the other hand, stress concentrations are often the cause of failure, for hydraulic, coastal and offshore engineering applications, as a governing principle, from the author's point of view coastal engineers should think in terms of elongation (strain) rather than in terms of strength which will prefer the NP SF NW GTX solution in many cases.

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