Critical review of geosystems in hydraulic and coastal engineering applications

K.W. Pilarczyk
Rijkswaterstaat, Road and Hydraulic Engineering Division (DWW), Delft, the Netherlands

Keywords: Geotextiles, Geosystems, Design, Coastal works, Limitations

ABSTRACT: Geosystems, as geomattress, geotubes, geocontainers, geocurtains, etc., are relatively new construction systems in civil (hydraulic/coastal) engineering applications. Till recently, these systems were designed based mainly on the experience from the previous (usually small) projects. Information provided to the potential users is usually restricted to general folders. Actually, Pilarczyk (1999) has reviewed most of the systems available on the international geosynthetic market. His conclusions on the use of geosystems and some recommendations for future use and/or improvements are presented in the paper.

1 INTRODUCTION

In recent years traditional forms of river and coastal works/structures have become very expensive to build and maintain. Various structures/systems can be of use in hydraulic and coastal engineering, from traditional rubble and/or concrete systems to more novel materials and systems such as geotextiles/geosynthetics, natural (geo)textiles, gabions, waste materials, etc.

Geotextile systems utilize a high strength synthetic fabric as a form for casting large units by filling them with air, water, sand or mortar, as a screen for guiding flow or a curtain for collecting sand, etc. Structures made of flexible, high-tensile strength geosynthetics have the advantage of simple manufacturing, lightweight transportation and usually an easy construction process; strength and durability can be chosen according to the purpose. A large number of ideas has been born on the use of geosynthetics in civil engineering. Pilarczyk (1999) has listed a number of actual and/or potential applications.

The aims of this paper are to review the pros and cons for the use of geotextiles/geosynthetics in various geosystems with applications in hydraulic and coastal engineering, to present relevant data gained from various studies, and to record data from projects where geotextiles and geosystems were installed. To achieve these aims various existing literature has been reviewed, information from the suppliers of the products has been collected, and the author's own supplementary research for selected applications has been carried out and the results have been included (Pilarczyk, 1999).

The following geosystems will be reviewed in more detail: geotextiles in revetment structures, geomattresses, geotubes, geocontainers, and geocurtains. The main points of the comment concern: availability of (proper) design criteria of the systems, functional design and durability, execution aspects, and limitations in application.

2 REVETMENTS AND GEOMATTRESSES

2.1 *Functional design*

The function of a revetment is to protect the slope against hydraulic (and other) loadings, such as waves and currents. To evaluate the stability, information is required about the hydraulic design conditions, the structural properties and the possible failure mechanisms. It is stressed that, when designing revetments, the designer should bear in mind that *the geotextile is only one of the components involved*, and that the revetment is only a part of the total project. Geotextiles primarily contribute to criteria on filtration and retention, but also to criteria on stability of revetment, and must also satisfy the other criteria resulting from functional requirements. The fulfilling of all theses criteria can even be conflicting.

The geotextile can serve three functions, of which only the first two will be considered here:
- separation; prevention of erosion of the subsoil through the structure,
- filtration (permeability),
- reinforcement of the subsoil against sliding.

In principle, the geotextile must always remain more permeable than the base soil and must have pore sizes small enough to prevent the migration of the larger particles of the base soil. Moreover, concerning the permeability, not only the opening size but also the number of openings per unit area (Percent Open Area) is of importance. However, it has to be stressed that geotextiles cannot always replace the granular filter completely. A granular layer can often be needed to reduce (damp) the hydraulic loadings (internal gradients) to an acceptable level at the soil interface. After that, a geotextile can be applied to fulfill the filtration function. In respect to the filters for erosion control (granular or geotextile) the distinction can be made between (see Figure 1):

- geometrically tight filters
- geometrically open filters, and
- transport filters (when a limited settlement is allowed).

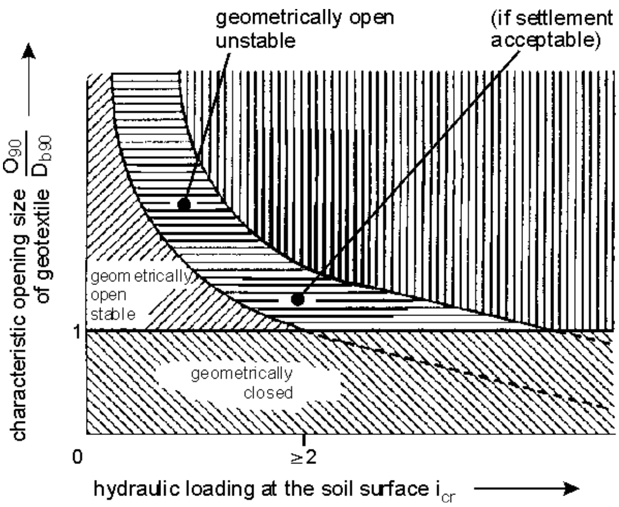

Figure 1 Principles of filters

The main performance benefits of geotextiles are:
- reduction in the number of layers and volume of granular filter materials,
- providing consistent quality filtration characteristics properties,
- effective filters for fine silty soils subject to turbulent variable flow conditions,
- reduction of maintenance of erosion control systems and cost,
- maintaining and enhancing stability of protection structures,
- providing easier installation than conventional filter layers, particularly for underwater installation.

The important properties of geotextiles and criteria in respect to the functional requirements are:
- suitable filtration qualities and high permeability,
- stable fibre network,
- resistance to damage during construction,
- installation flexibility,
- soil - geotextile friction angle, and
- ultraviolet light resistance.

2.2 Availability of (proper) design criteria for geotextiles in revetment applications

The soil tightness of the initial situation and permeability requirements can be checked by means of the well-known criteria for geometrically tight (geotextile) filters. However, the large number of this criteria and often unclear limits of their application are very confusing for designers. Especially, the definition of permeabilities, treatment of unstable soils and proper interpretation of index tests vs. performance tests are still a problem for designers.

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). 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 (Pilarczyk, 1998). Also, the requirement that the permeability of the cover layer should be larger than that of the underlayers 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 the case of a geotextile 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 outflowing 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, represented in the leakage length, is found to be the most important structural parameter, determining the uplift pressure (Pilarczyk, 1998, 1999). In general, all low-permeable top layers (block revetments and geomattresses) should be design based on definition of their leakage length which provides a kind of optimization between all design requirements, and which leads automatically to application of the concept of geometrically open geotextiles.

2.3 Geomattresses

The permeability of the mattress is one of the factors that determine the 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 susceptability 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 on proper information on the total permeability of the mattresses, the indicative permeabilities of mattresses can be calculated based on the knowledge of placed block revetments and the collected information from the literature and company informations. By introducing the concept of leakage length the indication of stability for various geomattresses can be given as shown in Figure 2 (DELFT HYDRAULICS/DELFT GEOTECHNICS, 1998, Annex 6, Pilarczyk, 1998, 1999). To obtain more accurate results it is recommended to perform (by manufacturers) permeability tests for mattresses as a hole (as a system) and some model/prototype tests for verification of stability.

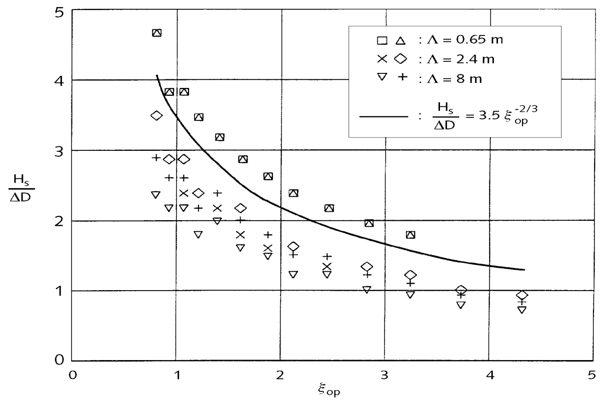

Figure 2 Calculation results for concrete mattresses

Hydraulic performance of geomattresses. About 20 years of experience with concrete mattresses all over the world provides an evidence that these systems, if properly designed and taking into account all possible failur modes, may function as originally designed and with a minimum or no maintenance. Documented measurements exist for application of these systems on slopes equal or milder than 1 on 1.5 with wave heights up to 1.5 m and current velocities up to 7 m/s. Application of concrete mattresse placed directly on sand is usually limited to a wave height of about 1.0 m due to the possible geotechnical instabilty of subsoil when exceeding this value. Often, other failure modes can be decesive for the damage of structure, therefore, especially in case of a severe wave attack, it is important to put due attention to design of the filter, the flanks, the crown (crest) and the toe of the mattress.

Durability .Ultraviolet (UV) strength degradation of geosynthetics is always a concern to prospective users. The fabric for geomattresses is usually manufactured with nylon and polyethylene yarns which are, on short term (a few years), 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 effect the stability of the system.

Where appearance is an important consideration, the upper surface may be spray coated with dilute colored acrylic emulsion, at about 5 year intervals, which provides also the additional protection of the fabric against ultraviolet degradation.

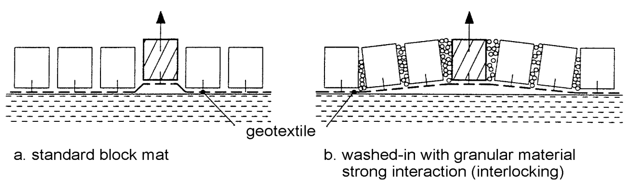

Figure 3 Example of functioning of a block mat attached to the geotextile

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 (Figure 3); 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.

The system illustrated in Figure 3 is based on a geotextile to which the blocks are attached. Since the geotextile allows blocks to be displaced slightly a considerable interactive force can be mobilized which may induce the movement of the filter material. The system only works properly if washed-in material is applied. If the system does not satisfy the above specifications the cover layer should be designed as loose blocks.

Additional cabling. 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. In addition the cable pass through the grout ducts rise in every block and through the edge narrow section interconnecting the blocks. When filling the fabric with the grout slurry the grout ducts rise to the approximate center line of the blocks. Therefore, the cables are nominally located in the center of the blocks. The cables become embedded in the concrete-filled compartments (blocks) to enable the mattress to resist tension.

Recommendations

For the future study on the design guidelines for the concrete mattresses the following items can be recommended:

- There is still a need for a proper testing and specification of permeability for various geomattresses, and for verification of calculation method on the effective permeability of systems.
- It is still necessary to determine more precise values of internal friction between the mattresses and various subgrades (including geotextiles) both, in dry conditions as well, in wet conditions (under water).
- It is necessary to investigate/collect information concerning the real contact (cavities) between the mattress and the subsoil for various types of mattresses, and various quality of execution. This is important in respect to the possible soil migration along the slope leading to the deformation of subsoil surface, and also in respect to the uplift forces on the mattress. This aspect likes the most uncertain point in the design procedure, and may affect the quality of design.
- The existing stability criteria for the wave attack should be verified on large scale, especially, for applications with wave height larger than 1 m;
- More attantion should be paid to the stability of the edges of the mattress to avoid overturning by current action.
- When using concrete mattresses for pipeline protection, especially in the surf zone, some additional studies are needed on their stability under the combined action of currents and breaking waves.
- Due to the fact that the mattresses, on the long term, must function as block mats the number and strength of binders should be carefully examined for this purpose.
- 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. These informations can be used for further improvement and/or extension of the range of application of these systems.

2.4 Execution aspects

Filter or revetment constructions with geotextiles for riverbank and shore protection, bottom protection, and other applications are vulnerable during installation. Especially, the risk of damage caused to the geotextiles by falling stones should not be underestimated. The following factors should be taken into consideration:

- weight and shape of stones;
- the fall height;
- type and strength of geotextile;
- type, compaction grade and saturation level of the subsoil.

The following situations can be distinguished:

- the tensile strength of a geotextile is exceeded due to the falling stone. It can happen because of the stone penetrating the geotextile or by punching when the stone laying on the geotextile is hit by another stone;
- the tensile strength of a geotextile between the stones is exceeded due to the tensile forces exerted by stones, resulting in the geotextile tearing.

Although the existing damage criteria are not yet fully examined they are usually adequate for practice if followed. Therefore the proper supervision during execution is of great importance.

3 GEOTUBES

Geotubes and Geocontainers, systems developed and patented by Nicolon, have recently been successfully applied in hydraulic and coastal engineering such as shore protection and breakwaters (Pilarczyk, 1999). Geotubes can be used as alternatives to the Longard system.

3.1 Functional design

A geotube is a tube made of permeable but soiltight geotextile and filled with sand or dredged material. Its diameter and length are specific for each project and are limited by installation possibilities and site conditions only. The geotube is delivered at the site, rolled up on a steel pipe. Inlets and outlets are regularly spaced along the length of the tube. The tube is filled with dredged material, which is pumped as a water-soil mixture (commonly a slurry of 1 part of solid on 4 parts of water) using a suction dredge delivery line.

The choice of geotextile mainly depends on the characteristic properties of the fill material. The major design considerations include sufficient geotextile and seam strength in order to resist pressures during filling and during impact on the bottom, and compatibility between fabric and soil. Long-term UV-resistance, resistance to abrasion, tearing and puncturing (including vandalism), and tube flattening resulting from the consolidation of sediments within the tube are additional design considerations. Thus, the geotextile fabric used to construct the tubes is designed to:

* contain sufficient permeability to relieve excess water pressure,
* retained the fill-material,
* resist the pressures of filling and the active loads without seams or fabric rapture,
* resist erosive forces during filling operations,
* resist puncture and tearing, and
* resist ultraviolet light.

The structural strength of a sandtube is provided by a geotextile envelope. This geotextile is a woven fabric, which is UV-stabilized and has great resistance to oil and chemicals, which are likely to occur in coastal and river environments. The sandtubes are available in standard diameters up to 4 metres, and unlimited lengths. The sandtubes can be filled with any cohesionless sandy material, capable of being transported hydraulically. Naturally occurring beach or river sand is the usual choice of fill. However, other fill material should be considered if this sand is not available in the local area.

Usually, the nominal dimensions of sandtubes are given as the diameter of the equivalent cylinder having the same diameter or circumference as the woven envelope. In practice, the crosssectional shape of a filled sandtube is approximated by a circle with a flat top. Field experience has demonstrated that it is possible to fill the sandtubes to 95 percent of their theoretical maximum capacity, however, in such case, the required tensile strength must be very high and the tube is less stable due to the circular shape. Usually, the average height (thickness) of a tube (d) is in order of 2/3 of the theoretical diameter. Achieving a relatively high unit weight and thickness for a filled tube is essential for stability under severe hydraulic conditions, where drag, lift and inertia effects can reduce the tube stability. In order to assess the stability of the sandtube structure, current and wave forces have to be estimated.

3.2 *Availability of proper design criteria of the systems*

For the selection of the strength of the geotextile and calculation of a required number of tubes for a given height of structure, knowledge of the real shape of a tube after filling and placing is necessary. The change of the cross-section of the tube depends on the static head of the (sand)slurry.

The design of the shape of the geotube and the choice of geotextile strength is an iterative process. To obtain a proper stability of the geotube and to fulfill the functional requirements (i.e. required reduction of incoming waves/proper transmission coefficient, the width and the height of the tube (= a certain crest level) must be calculated. If the obtained shape of geotube does not fulfill these requirements a new (larger) size of a geotube must be taken into account or a double-line of tubes can be used.

The strength of geotextile can be determined by using Leshchinsky's model (Leshchinsky et al., 1995, 1996, Pilarczyk, 1999). As an example, the shapes of the geotube (with the theoretical diameter of 3.25m) for the height of 1.8 m, 2.0 m and 2.1m are shown in Figure 4 (based on Leshchinsky's method). The maximum width is b = 4.15 m (d = 1.8 m and 2.0 m) to 4.0 m (d = 2.1m), and the cross-section area is A = 6.41, 6.88, and 7.06 m^2 respectively. The width of base of the tube (= contact width with foundation layer) is about 3.10, 2.90, and 2.60 m respectively. The required minimum pumping pressure is about 0.2 psi = 1.5 kPa = 0.15 m of a water column for d = 1.8 to 2.0 m. In case of d = 2.1 m the minimum pumping pressure is 0.4 psi = 3.0 kPa = 0.30 of a water column. The required tensile strength of geotextile is about 80kN/m (including safety factor).

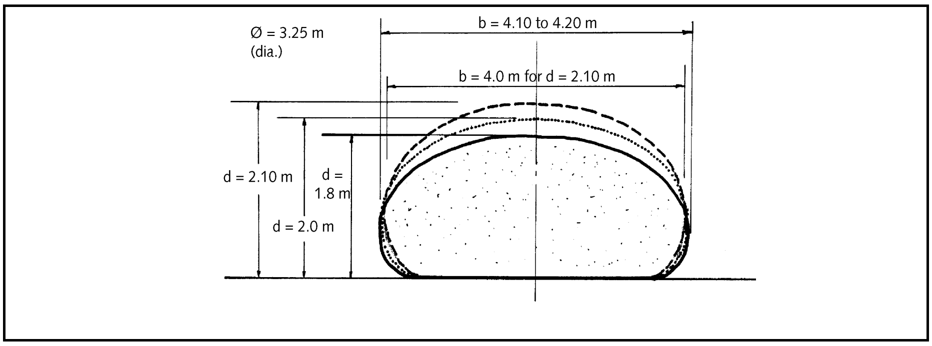

Figure 4 Examples of shape of geotube with 3.25m diameter

3.3 *Execution aspects*

Durability/UV-protection. There is no problem with durability of the geosystems when they are submerged or covered by armour layers. However, in case of exposed geosystems the UV radiation and vandalism are the factors which must be considered during the design. All synthetics are vulnerable to UV. The speed of UV degradation, resulting in the loss of strength, depends on the polymer used and type of additives. Polyesters (PET) are by nature more light stable than, for example, polyamide (PA) and polypropylene (PP).

To avoid the problem with light degradation the fabrics must be properly selected (i.e. polyester) and UV stabilized. As the period in which the fabric is exposed is short (in terms of months), no serious problems are to be expected. In case of more or less permanent applications under exposed conditions the fabric must be protected against direct sunlight. There is a number of methods of surface protection for geosystems. To provide additional UV and abrasion protection to the exposed sections of tubes, a coating of elastomeric polyurethane is often used. This coating, however, has a tendency to peel after about a number of months and therefore, has to be reapplied. Lamberton (1983a) describes a positive experience with UV-protection by using the "acrylic spray coat".

The permanent surface protection by riprap or blockmats is a rather expensive solution and it will normally be applied only when it is dictated by necessity due to a high wave loading or danger of vandalism or other mechanical damage ie. boating, anchoring, etc. In other cases it will be probably a cheaper solution to apply a temporary protection of geotextile tubes by an additional layer of a strong geotextile provided with special UV-protection layer. This geotextile layer might provide a protection for at least 10 years. Every 10-years (probably more) a new geotextile surface-layer must be added, however, it can be that the life-time of this layer is much longer. There is always a possibility to pass on to a permanent protection if necessary. In case of this solution a maintenance program is necessary to quarantee the maintenance budget at a proper time. To avoid lifting up, this protective layer must be prepared by using a strong, heat-stabilized geotextile (i.e. polyester, 100kN/m), but relatively open ($O_{90.} \sim 0.5$ mm).

3.4 *Other design considerations*

The lay-out and overall dimensions of cross-section of coastal protection structure are determined by the functional requirements and hydraulic interactions. However, the actual dimensions follow often from structure-specific construction method. Morever, geosystems are usually only a part of the total project. Execution includes a number of factors affecting the design. Therefore, the construction aspects (materials, site accessibility, execution method, equipment, etc.) should be taken under consideration already during the design process. The availability of materials, access to the construction site, the height of the structure, the preparation of foundation, and the chosen construction method may strongly affect the total costs and thus, the feasibility of the project. Also, the external conditions are of importance for workability (waterdepth both for access and construction, wave- and wind conditions and their seasonal variations, daily tides and currents, temperature, visibility).

Because each structure has its specific conditions a tailor made construction method has to be selected. Other factors affecting the construction (and partly also the design) include:

- environmental restrictions for construction (preventing water and air pollution, taking care of ecological aspects, noise limitations, traffic restrictions);
- availability of equipment and labour;
- local experience with comparable construction works;
- infrastructural facilities (accommodation, roads, railways, ports, water and power supply, communication means, etc.);
- facilities for future maintenance.

The dos and don'ts geotubes

When installing geotubes special care should be taken in order to ensure an optimal quality of work. During the installation on a number of sites the following observations/recommendations were developed:

- *Site preparation and positioning*
Any kind of hard object which may constitute a potential danger or damaging the fabric should be removed or covered. Common objects are stones, shells and debris.

During filling, the tubes are extremely unstable, above as well as under water. Minor forces can move the tube out of position. One should bear in mind that if a partly filled tube is displaced, it is hardly possible to move it back onto position. When still empty, the tube should be stabilized against wind during placing. This can be done by dead weights or by securing the tube with ropes to guiding posts. However, during filling, ropes may cause inacceptable point loads on the fabric.

If possible, it is preferred to place the tubes in temporary trench. A trench can be constructed between two bunds. They should then be lined with a plastic sheet as a precaution against erosion caused by filling water. Negligence may lead to a breach of the bund, and consequently to the deformation of the tube.

If none of the above precautions can be taken, the foundation of the geotubes shall at least be level, measured perpendicular to the tube axis.

When filling the tube (partly) under water, it can be stabilized against current action by placing temporary guides on both sides of the tube. Alignment can be improved by attaching the tubes with ropes o the guides.

- *Filling material and filling process*
The properties of the filling material must comply with the specifications of the fabric. Besides, if the material is too fine, it will hardly settle in the tube. Furthermore, obstacles in the filling material, such as debris (fishing gear), marine growth or very course material, may jeopardise the filling operation.

Inlet/outlet ports are commonly closed off with a rope. This method is somewhat old-fashioned and certainly not in line with the state of the art of applied geotextile techniques. Manufacturers of tube products are challenged to develope a device that stands for durability, reliability and convenence.

The filling process is usually carried out by visual monitoring. Therefore it is important that the fill master has adequate sight on the process. In close connection with this he must be able to communicate directly with the pump operator. Besides, the pumping process must have an as short as possible response time in order to avoid mishaps.

Tubes are commonly filled by hydraulically pumping a mixture of sand and water. The pressure of this process can easily cause excessive forces on the tube wall. This phenomenon will occur if filling water cannot escape sufficiently from the tube and may lead to the collapse of the tube. Therefore the outlet ports should be of an appropriate aperture and should be controlled during filling. On the other hand, pressure is required to achieve the optimal shape of the tube. Obviously a tight balance must be sought and adhered to.

When filling reaches the allowable height, a natural transport channel will develop in the top of the tube. This is a critical phase, because if the velocity of the sand/water mixture drops, the sand may settle and consequently the transport channel will be blocked. In this state it is virtually impossible to get tha filling process started again.

- *Restrictions*
During construction and lifetime, geotextile tubes (and containers) are vulnerable to all sorts of environmental influences, such as mechanical and chemical impact, vandalism etc. Engineers should pay attention to these facts and realize that even geotubes have limitations in their application.

It should be stated that execution methods cannot be learned from the book. Experience should be obtained on the work site itself. Gathering the art of work management in all its aspects requires numerous projects and guidance of experienced senior personnel. However, as a good introduction the Manual on Rock in Hydraulic Engineering (CUR/RWS, 1995) and Offshore Breakwaters (Pilarczyk & Zeidler, 1996) can be recommended.

3.5 *Conclusions and recommendations*

The geosystems as bags, mattresses and tubes can be a good and mostly cheaper alternative for more traditional materials and protection systems. These new systems deserve to be applied on a larger scale. However, there are still many uncertainties in the existing design methods. The objective of this literature search and additional analysis is to uncover, as far as possible, the technical information on these systems and make it available to the potential users. It will help to make proper choices for specific problems/projects and it will stimulate developments in this field.

Geosystems, and specifically geotubes, can be considered for alternative structure designs at several different applications (Davis and Landin, 1997, 1998). Many of these uses severely challenge designers because of the limitations of geosystems. They can be punctured and abraded easily by vandals, debris, and ice; their life expectancy after prolonged exposure to UV light is unknown; and they are difficult to construct to precise alignment and crest elevations. Yet, used as temporary structures, as hidden components of structures, in shallow water with low wave energy and tidal regimes, on projects where is no risk to life or property in the event of failure, on projects where inspections and maintanance will be established, and/or on projects where sand is being dredged, geotextile tubes and bags can be very effective.

Wetlands restoration projects developed on dredged material placed to intertidal elevations satisfy many criteria necessary for successful geotube application (Davis and Landin, 1997, 1998). The relatively low costs of geotubes makes them an attractive alternative for erosion protection and dredged material containment.

Pilarczyk (1999) notes that many worthwhile applications for geosystems exist, but they should not be considered for general coastal engineering applications without further investigation, experiments and practical experience at various climatic conditions.

The criteria identified at the national US-workshop ((Davis and Landin, 1997, 1998), though not all-encompassing, may serve as a reasonable guide because they avoid or minimize the effects of geotextile limitations. While the construction of geosystems is conceptually easy to understand, it should be remembered that these are often massive structures. Therefore, to have a successful project, foundation, scour, overtopping, and flanking protection must be given great consideration in design.

4 GEOCONTAINERS

4.1 *Functional design*

Geocontainers are relatively new engineering systems (Figure 5). Nicolon B.V. has developed this system and copyrighted the name for GeoContainers. Geocontainers hydraulically and/or mechanically filled with (dredged) granular materials have been successfully applied in hydraulic and coastal engineering in recent years (shore protection, breakwaters, etc.). They can also be used to store and isolate contaminated materials obtained from harbour dredging, and/or as bunds for reclamation works.

A geocontainer is a mechanically-filled geotextile and a "box" or "pillow" shaped unit made of a soil-tight geotextile. The containers are partially prefabricated by sewing mill widths of the appropriate length together and also at the ends to form an elongated "box". The "box" is then closed in the field, after filling, using a sewing machine and specially designed seams. Barge placement of the site-fabricated containers is accomplished using a specially configured barge-mounted crane or by bottom dump hopper scows, or split barges. Subsequently, containers are filled on a split barge and placed when the barge is securely moored in the desired position (Figure 5). Positioning of such a barge for consistent placement - a critical element of constructing "stacked" underwater structures - is accomplished with the assistance of modern surveying technology. The volume of actually used geocontainers varies from 100 to 10000 m^3.

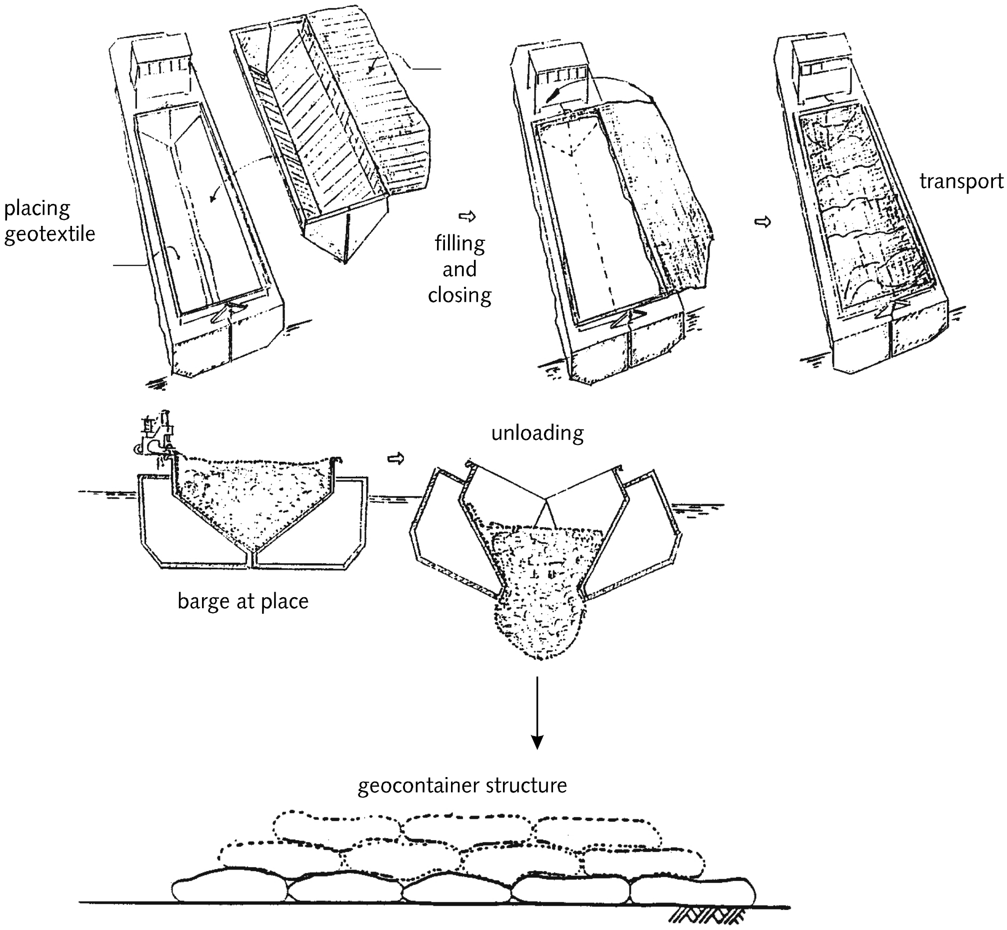

Figure 5 Procedure of filling and placing geocontainers

The advantage of these large barge-placed containers include:

- Containers can be filled with locally available soil which may be available from simultaneous dredging activities.
- Containers can be placed relatively accurately regardless of weather conditions, current velocities, tides and water depths.
- Contained material is not subject to erosion during/after placement.
- Containers can provide a relatively quick system build-up.
- Containers are cost competitive, especially for larger projects.

4.2 *Availability of (proper) design criteria of the systems*

Geocontainers are manufactured from top quality polyester and/or polypropylene geotextiles. This geotextile is a woven fabric, which is UV-stabilized and has great resistance to oil and chemicals, which are likely to occur in coastal and river environments. This means that they can be designed for the correct durability for a number of applications. Geocontainers utilize a high-strength synthetic fabric as an envelope to make large units by filling with sand, clays, industrial waste materials or dredged materials.

The major design considerations include sufficient geotextile and seam strength in order to resist pressures during filling and release, impact of the geocontainer on the bottom and compatibility between fabric and soil. Long-term UV resistance, resistance to abrasion, tearing and puncturing (including that caused by vandalism), and container flattening resulting from the consolidation of sediments within the container are additional design considerations (Pilarczyk, 1999).

Normally the seam strength is the weakest link in the design and, depending on the seaming technique specified, this value may be only 50 to 70 percent of the fabric's ultimate strength. Therefore, the strength of the seams should be used as a reference strength in the design in respect to possible exerted forces.

The various phases in the placing of geocontainers, with a qualitative sketch of the resulting forces on the geotextile, are shown in Figure 6.

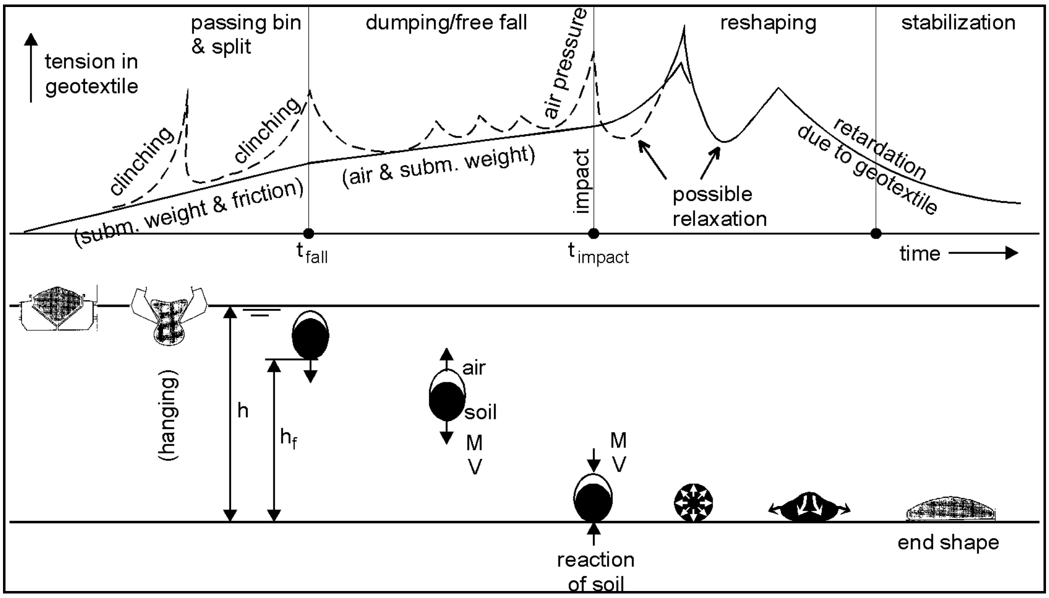

Figure 6 Development of forces during the dumping process of containers

When applying geotubes or geocontainers the major design considerations are related to the integrity of the units during release and impact, the accuracy of placement on the bottom and the stability under current and wave attack. The following design aspects are of importance:

a) Forces during the release of the geocontainer from the bin;
b) Changes in the shape of the units as a function of the perimeter of a unit, fill-grade, and opening of a split barge;
c) Dumping process and impact forces;
d) Dump velocity/equilibrium velocity, velocity at impact on the bottom;

e) Stresses in the geotextile during impact and reshaping;
f) Hydraulic stability of the structure;
g) Resulting structural and operational requirements.

Commonly, the filter geotextile (against scour) and a flat tube are fully deployed by floating and holding them in position prior to starting the filling operation. Geotubes are often used as a bottom protection for geocontainers. A sheet of geotextile is furnished with small geotubes at the edges. When these geotubes are filled with sand, they will keep the filter apron in place. This apron must also extend sideways of the geocontainer units, commonly 1-2 times the height of the entire structure.

The first applications were based on past experience with similar systems. Recently, new preliminary design rules supported by model and prototype tests, and some analytical calculations have been developed in the Netherlands and the USA. A number of preliminary calculation approaches are discussed in Pilarczyk (1999). These approaches should often be treatead more as a contribution to discussion than as the final solutions. Much research is still needed to arrive at the final solutions. However, it is hoped that these preliminary approaches will encourage further research in this field.

4.3 *Execution aspects*

When applying this technology, the manufacturer's specifications should be followed. Installation requires split barges and an experienced contractor. In Pilarczyk (1999), for each design aspect the main attention points related to execution are mentioned (preparation, installation and filling conditions, transport and releasing/dumping geocontainers, etc.).

4.5 *Conclusions and recommendations*

From the recent studies (Bezuijen, 1999) discussed in this chapter the following conclusions can be formulated:

1. When using geotextile containers, i.e. mechanically-filled/field-closed units, for underwater constructions, the major problems are related to the integrity of the containers during release and impact (impact resistance, geotextile durability, abrasion, tear, burst, seam strength, etc.), the accuracy of placement on the bottom and in the mound cross-section, and the stability of the mounds under various hydraulic conditions.

2. The results from field measurements seem to indicate that the process of opening the barge represents the critical loading for a geocontainer filled with sand, and the impact on the subsoil represents the critical loading for a geocontainer filled with slurry. However, the number of measurements is not yet sufficient to derive definitive conclusions. Furthermore, due to the position of the strain gauges in the experiments, it is likely that it is not the maximum strain that is measured along the geocontainer.

N.B. for large projects it could be efficient to construct a special designed split barge allowing complete barge opening equal to the barge width; in this way the release forces can be minimized.

3. Leshchinsky's method is useful for calculation of the shape of a geocontainer filled with slurry. It calculates the stationary situation after dumping, therefore the calculated loading will not be the maximum loading, but only a fraction of that. The shape of a geocontainer filled with sand is determined by the impact and therefore deviates from the result obtained by the Leshchinsky method. Assuming a pressure distribution at impact, the actual shape of a geocontainer filled with sand, when it hits the bottom, can be approximated. With some modifications the calculation method can also be used to simulate the shape of the free-hanging part of the container between the two parts of the split barge before dumping.

4. The methods proposed in literature to estimate the loading during the opening of the barge and during dumping appear to be insufficient. Since both loading stages have aspects that are rather uncommon in geomechanics, some detailed measurements are needed. These measurements also have to include dumping under a certain angle.

5. The fall velocity was measured, and calculated with a distinct element method and calculated with an analytical method as derived by Den Adel. There are some differences. These differences are caused by the uncertainty of the height of fall (at which moment the geocontainer is released), the degree of saturation of the material in the container (which is essential for the weight), the drag coefficient (C_D), and area of the container in the horizontal plane (A_s). Since the fall velocity determines the impact and the impact is proportional to the square of the velocity, it is essential to have a good estimation of the fall velocity in order to calculate the impact forces.

6. Some deformation in the geocontainer is necessary for dumping and to overcome the impact. This means that the container cannot be filled completely. This also means that, after dumping, some deformation is possible.

7. At the moment, the theoretical base is too small to arrive at an accurate design model. A "worst case design" is possible but leads to a rather conservative approach.

The recommendations are:

a. To perform model tests with a geocontainer. In these tests, stresses and strain in the geotextile have to be measured during the opening of the split barge and at impact. The final shape of the container has to be measured as well. This chapter contains information on where to install strain gauges. Position and velocity have to be measured accurately to be able to compare the results with existing models.

b. Simulation of the experiments with the distinct element model of Palmerton. This model presents information about velocities and stresses during impact and possible failure mechanisms.

c. By combining the results of measurements and numerical calculations, the dominant failure mechanisms can be derived, if the results of both are in agreement. Using these mechanisms a reliable design method can be derived.

d. Experimental work, a physical model and numerical calculations will calibrate a design method.

e. Practical design methods can be derived from the results of the former step.

General conclusions

Based on the actual developments and experience the following general conclusions can be drawn:

- The technologies uncovered in the literature search and presented in this chapter offer the potential for the construction of low-cost structures out of readily available materials and systems. This technology offers the versatility to be virtually any size or shape simply by stacking additional tubes/containers. The following areas are potential applications of dredged-soil containment systems using tubes or containers:

  1. Remote dike and levee constructions for disposal islands, beach nourishment, wetlands reclamation, and emergency closing of dike breaches.
  2. Lateral erosion control structures such as groins, jetties and breakwaters.
  3. Containment, placement and long-term confinement of contaminated materials.
  4.Underwater capping of contaminated materials and pipelines protection.
  5. Accelerated dewatering of fine-grained dredged material.

- Sand-filled containers can also be used in engineering designs for coastal erosion control. Developments in the designs of these structures have increased the insight in applicability and stability of these structures. Sand- or clay-filled containers can be used for strengthening of dunes and dikes, or as bunds for construction of dikes and dams. However, the most efficient (technical and economic) application of geocontainers seems to be in the design of nearshore sill structures for detached or offshore breakwaters, and as a core of harbour jetties and breakwaters. This system can be used in the design of a full structure, with adequate crest elevation to resist overtopping by the design storm, and adequate toe protection to prevent undercutting by the beach erosion accompanying the design storm. If necessary, an additional surface protection can be applied. The advances in the technology of composite materials, including the geotextile materials used for geocontainers, has and will continue to extend the strengths and applications of these materials and systems.

- Geocontainers (and geotubes) can be a reasonable disposal alternative for contaminated dredged material and municipal and industrial waste (including sewage sludge, water treatment sediments, fly ash, etc.). Tests with nonwoven liners have shown that no particules escape from the geocontainers. Containment of clean and contaminated materials in geocontainers for sea disposal and/or for land reclamation with capping by a clean sand layer is proving to be an environmentally, technically and economically feasible alternative to other disposal techniques. This technology is very competitive with construction of upland confined disposal facilities and dredged material containment islands.

- Geocontainers offer the advantages of simplicity in placement and construction, cost effectiveness, and minimal impact on the environment.

- When applying geocontainers, the major design considerations/problems are related to the integrity of the units during release and impact, the accuracy of placement on the bottom (especially at large depths), and the hydraulic stability.

- A number of weak points of geocontainers can be omitted when the actual knowledge/experience is applied in the design and technological improvement of these systems, which includes such aspects as fabric choice, fabric liners, filling method, installation techniques, stability criteria, and lifespan.

- When applying this technology, the manufacturer's specifications should be followed. Installation requires an experienced contractor.

- Theoretical models to calculate the dump velocity and the impact forces of a geocontainer on the subsoil have been developed and calibrated with the test results. However, the theoretical model to simulate the impact forces has, until now, provided indicative results only.

- The technologies related to geocontainers have been utilized extensively in Europe, Northern America, Japan, Malaysia and Taiwan, producing often successful installations and providing new technical design details and experience. The intention of this literature search is to uncover, as far as possible, the technical information on these systems and make it available for the potential users. It will help to make a proper choice for specific problems/projects and it will stimulate further developments in this field.

- Technically the methodologies have shown to be feasible, but there are still many uncertainties regarding design and consruction that must be addressed. Therefore, further improvement of design methods and more practical experience with various fill-materials and at different loading conditions is still needed.

It is hoped that the results of this search will be used as a basis of learning in the planning, design, and operational considerations for the containerization of dredged sediments and their use as alternative construction systems in hydraulic and coastal engineering.

5 REMARKS ON OTHER SYSTEMS

5.1 *Geocurtains*

There are a large variety of types and potential applications of geosynthetic screens and curtains. An example of that is the BEROSIN curtain described briefly below.

A very promissing alternative for the tackling of coastal erosion problems are BEROSIN curtain systems. BEROSIN stands for '*better erosion inhibitor*'. It has also been a registered trade mark (patents applied for) since 1977. The BEROSIN curtain is a flexible structure made of various woven geotextiles which, after being placed near the shore and anchored to the bed, catches the sand transported by currents and waves, thus providing accretion on a shore and preventing erosion. The proper choice of permeability of a geotextile creates the proper conditions for the sedimentation of suspended sediment in front of or under the curtain and at the same time allows the water to flow out without creating forces that are too high on the curtain and, thus, on the anchors. The quick sedimentation process will help to minimize the forces on the lower edges of the curtain. Special open pockets on the surface at the lower edge of a curtain are filled with sand already at the beginning of the sedimentation process and function as anchors. To allow the process of catching sediment, the upper edges are equipped with a floating capacity adapted to the specific flow conditions and the depth. The curtains must be prepared and installed strictly to the specifications prescribed and under the professional supervision of the BEROSIN office. The BEROSIN curtains can be provided in lengths of 10 to 40 metres (or even more) and heights of 0.5 to 5.0 metres (or more). The length of a curtain measured along the shore is practically unlimited. There are BEROSIN systems in various configurations (vertical and horizontal). The principle of these systems is illustrated in Figure 7.

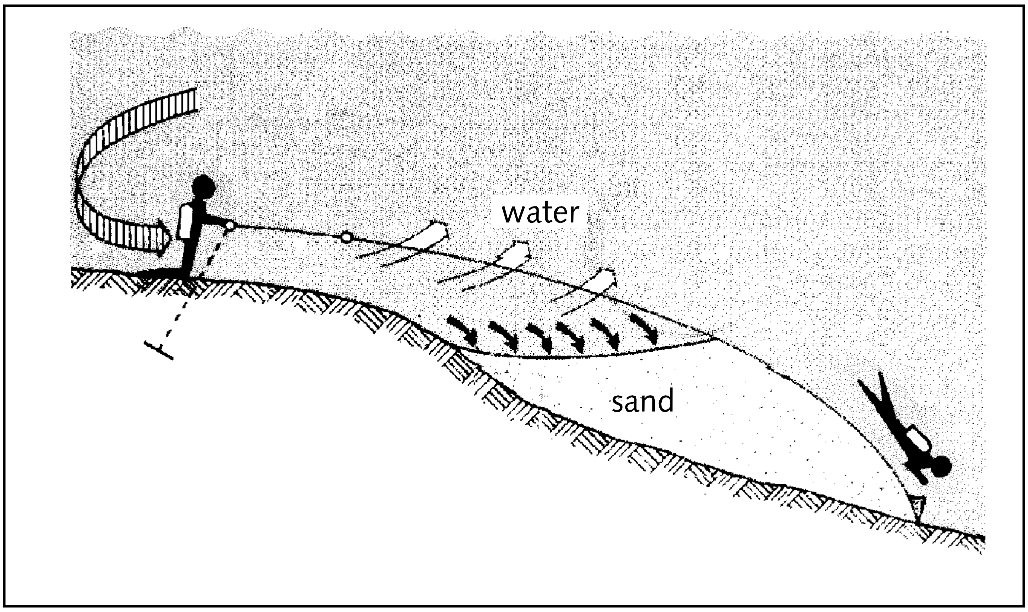

Figure 7 BEROSIN underwater curtain; principles of the horizontal system

In general, the sections on calculation methods in (Pilarczyk, 1999, Chapter 8) have shown that much knowledge has been developed in recent years on the design of various screens (curtains). However, experience with the past pilot projects carried out to test various screens show that the practical application is often accompanied by some unexpected problems. A common experience is that in all field tests some damages occurred to a screen or the screen did not function as expected. In most cases the size of the damages could probably have been reduced if the application had been developed in smaller steps and proper design calculations had been used. A longer development process would often have resulted in better screen designs for the local conditions. This shows that the development of a new application of a synthetic screen as a bottom screen should be planned carefully.

Some suggestions for a phased development process are the following:

- An inventory of all the forces exerted on a screen by means of field measurements, and a literature survey;
- A conceptual design of a screen;
- Determination of failure mechanisms;
- Determination of the design conditions by means of following a probabilistic approach, with the results of:
    - physical model investigations,
    - mathematical model simulations of flow and wave paterns, and calculation methods to extrapolate the field measurements to design conditions,
    - knowledge on the behaviour of synthetic material (aging, fatigue) in the field is often insufficient and intensive cooperation with the company that produces the selected synthetic material is necessary;
- Often, samples of the material and of the joints should be tested at the location of the future bottom screen;
- A small-scale field test with only a few sections of the prposed screen structure should be used to verify the results of physical model investigations and mathematical model simulations. The planning should be flexible to repeat this small-scale test with a modified design;
- A detailed monitoring programme should be set up to monitor these few screen sections. The results should be analyzed in cooperation with the producer of the selected synthetic material(s);
- Final design of a complete screen structure;
- After installation of the screen a monitoring programme should be started to provide field data for an evaluation of the behaviour of a screen.

Such development processes require cooperation between many participants: manufacturers of synthetic materials, water-management authorities, field-survey companies, consulting engineers, universities and institutes for applied research. Preferably, these development processes should be part of research and development programmes on a national or an international level.

All these steps will result in relatively high development costs, but the costs of the construction and operation of well-designed screen structures of synthetic material will be low compared with traditional solutions. Low-budget development projects can result in disappointments and they can delay the introduction of new applications of these innovative systems.

5.2 *Inflatable dams*

A special group of geosystems are flexible geo-dams, which are made of a synthetic membrane or geotextile secured to the channel bed. There are a variety of flexible dams (see Figure 8). Parachute dams (open type), in which the upper end of the membrane is fixed to a floating boom and restrained by guys, are similar to the bottom screens.

Inflatable dams are made of a synthetic membrane (or impregnated fabric) and filled with air or water. Both types of flexible dams (open and closed types) are usually used as both temporary and permanent structures for river regulation, flood protection, irrigation and increase of reservoir capacity. They can also be used as submerged breakwaters near harbour entrances. Most often, inflatable dams are used for water regulation as part of a water management scheme or an irrigation project. In a few cases these dams function as flood protection.

The main part of an inflatable dam is an inflatable synthetic membrane which is connected with a foundation and a side wall. The principle of an inflatable dam is a cylindrical tube filled with water, air or a combination of both. This cylindrical tube, which is made of a synthetic membrane, is connected to the foundation over the whole length of this cylinder. The impounding height can be varied by increasing or decreasing the internal pressure by means of pumps. After use, the deflated membrane can be stored in the foundation of the dam and the river discharge can pass the dam without backwater effects and navigation can also pass without hindrance. Water is used most often to inflate the dam, but in some cases air or partly water and partly air have been used. The width of the foundation is determined by the required space for the pipes needed to fill and to empty the dam and the minimum required width for the stability of the foundation. The width between the upstream and the downstream anchorage is a design parameter.

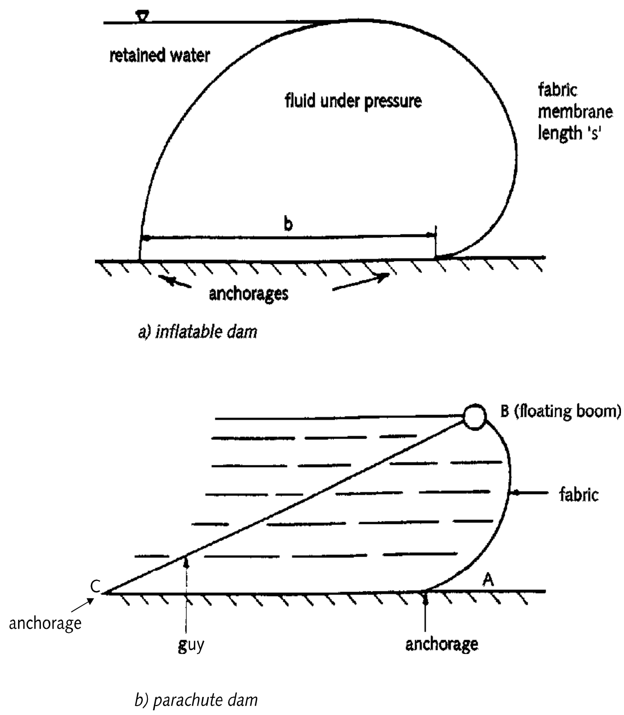

Figure 8 Principle schemes of flexible dams

Design parameters are the tensile force in the membrane, T (N), and the impounding height h_u - h_d which is the difference between the high water level and the lower water level. The relevant properties of the membrane are its thickness, density or weight per square meter, elasticity, strength, and elongation at failure.

Simulations with mathematical models or testing in physical models are standard tools for the design of an inflatable dam. Two- and three-dimensional mathematical models are under development; these models are often used for a preliminary design. Two-dimensional models often consider a cross-section of the tube. To design the connection of the tube to a sloping bank, a three-dimensional model might be necessary. For a final design the following aspects are often investigated in a physical model:

- the dynamic response of the tube to irregular wave loading,
- the storage of the tube in the foundation while deflating the tube, and
- the vibrational forces in the tube by overflowing water.

The elastic properties of the synthetic material of the tube have to be reproduced in the scale model. The design process might include field testing of samples of different synthetic materials and testing of end sections on prototype scale (1:5 to 1:1).

With the advent of the stronger fabrics, more ambitious applications have been planned and executed. An increasingly common use is the intake dam or diversion weir for small hydropower plants. Another application is the tidal barrier where the inflatable dam is used either to stop tidal surges or to prevent contamination of agricultural areas by saline intrusion.

Inflatable dams can be constructed along a river-front in place of levees and can remain deflated and out of the way when not needed. They can be installed around critical facilities and, inflated only when flooding is imminent (Plaut et al., 1998).

The scale-increase of application of inflatable systems has stimulated developments in design techniques. Various numerical models have been developed for a hydrostatically loaded dam inflated with water, for example by Pover (1993), Leshchinsky et al (1996), and Dorreman (1997). Dorreman (1997) made a spreadsheet model for a dam loaded by hydrostatic forces only. The model was based on the formulas publicized by Van den Burg (1961), Parbery (1976, 1978) and Harrison (1970). The calculation starts in an anchorage point and proceeds along the segments of the membrane. At the end of the calculation it is checked if the end point is in the position of the other anchorage point. If not, the calculation has to be repeated with adjusted segments. This model calculates the shape of the membrane and the forces in the membrane. These results have been confirmed by the results of physical model investigations.

However, in practice, inflatable dams are often als loaded by waves or by a combination of flow and waves. The dynamic response of the dam to wave loading during the filling stage and the operational stage often determines the design. The numercal model developed by Pover can be extended to also include the dynamic response due to wave loading. A model to estimate the dynamic response of an inflatable dam to wave loading has been prepared by Delft Hydraulics (van Meerendonk, 1996). This model is based on a strong schematization of the relevant phenomena. If a dam is used as a weir, then oscillations of the membrane can be caused by instabilities in the overflow and in the downstream recirculation (Hitch, 1984).

There are numerous potential applications of anchored and unanchored filled-in or inflatable structures in providing flood protection (Plaut et al., 1998). Some alternative applications of geosystems for flood protection, as patented by Van Driel (1995), are shown in figure 9.

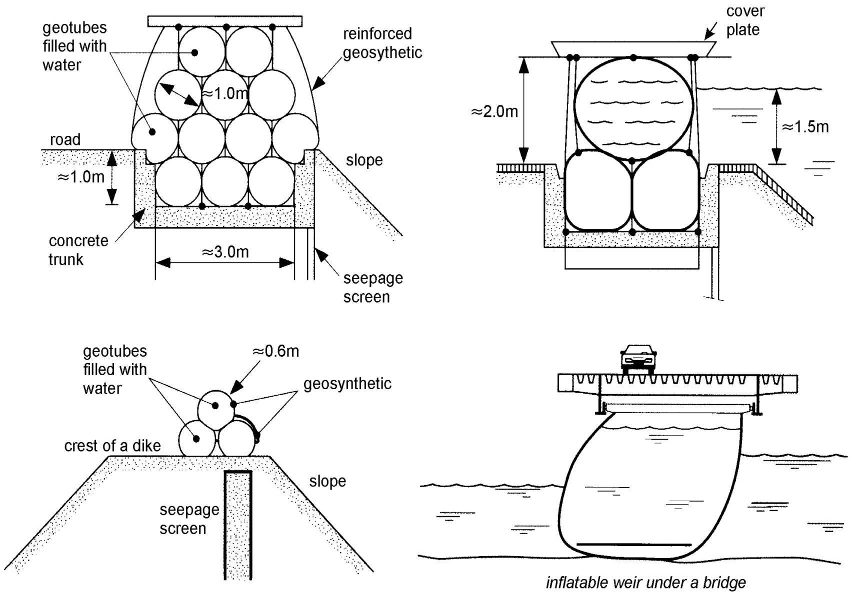

Figure 9 Alternative applications of geosystems for flood protection (Van Driel, 1995)

6 DURABILITY

When geosynthetic materials or products are applied in civil engineering, they are intended to perform particular functions for a minimum expected time, called the design life. Therefore, the most common (and reasonable) question when applying geosynthetics is 'what is the expected/quaranteed lifespan of these materials and products?'. There is no a straight answer to this question. Actually, it is still a matter of 'to believe or not to believe'. Both the experimental theory and practice cannot answer this question yet.

Experience with geotextiles in the Netherlands amounts to 30 years. The first evaluation of the prototype performance of geotextiles was carried out at the end of the 70s. The performance (hydraulic and mechanical properties) of about 30 various samples of woven geotextiles functioning under different conditions, the oldest of which was about 15 years, was still satisfactory (KNO, 1979). A similar conclusion has been drawn from the recent evaluation of the long-term performance of nonwoven geotextiles from five coastal and bank-protection projects (Mannsbart and Christopher, 1997). Actually, the Road and Hydraulic Engineering Division in the Netherlands has tested some samples of the polypropylene and polyamide geotextiles functioning for 30 years under block revetments on the Dutch sea dikes. The hydraulic functioning was still satisfactory and the tensile strength had decreased with less than 20 %. It is probably one of the oldest applications of geotextiles in the world and, therefore, for the time being, no more information can be expected from the prototype performance.

The technology of geosynthetics has improved considerably in the years. Therefore, one may expect that with all the modern additives and UV-stabilizers, the quality of geosynthetics is (or can be, on request) much higher than in the 60s. Therefore, for the 'unbelievers' among us, the answer about the quaranteed design life of geosynthetics can be: 50 years. For 'believers', one may assume about 100 years for buried or underwater applications.

These intriguing questions on the lifespan of geosynthetics are the subject of various studies and the development of various test methods over the world. Also, the international agencies related to normalization and standardization are very active in this field. The recent guide (European Standard) of the European Normalization Committee presents the actual 'normalized knowledge' on this subject (CEN, 1998). The object of this durability assessment is to provide the designing engineer with the necessary information (generally defined in terms of material reduction or partial safety factors) so that the expected design life can be achieved with confidence.

This CEN-report is not a real state-of-the-art report. One may imagine that for European normalization a certain compromise are a number of additional test methods in specialistic testing laboratories/institutes related to the durability which are often better than those recommended in European Standards, but too sophisticated to be recommended for standard testing procedure. However, in particular cases, these additional methods can be applied for more confidence of the designer or client.

The standard test procedure recommended by CEN should always be followed by designers in order for them to be safe from a legal point of view. However, it does not provide the absolute physical quarantee for the design life of geosynthetics (it is only a procedural quality assessment based on the actual knowledge). That also means that in cases of projects where the possible disfunctioning of the geosynthetics incorporated in the structures may have disastrous consequences, some alternative designs should be made. On the other side, designers or clients often formulate unnecessary high requirements for geosynthetics because of misconceptions with regard to the functioning of geosynthetics in various constructional and service stages of the project. For example, a high tensile strength is necessary when a geotextile functions as a bearing element for a block mat or when the stone is dumped on it from an uncontrolled height, but relatively low strength is needed in the case of placed blocks; for standard riprap bank protections, the geometrically-closed filter rules are often unnecessarily strict because a limited washing out of fines can often be allowed without negative consequences. The geometrically-closed rules for geotextiles on clay can practially not be fulfilled or will not function in the longterm because of clogging, whereas, as it has been proved, due to the protective function of geotextiles, high hydraulic gradients are allowed and thus a more open structure of the geotextile. In most civil engineering applications simple design rules are sufficient for a proper choice of geosynthetics. However, designers should be aware of situations where a more sophisticated approach is necessary, and be able to explain to the client that the difference in approach depends on the situation (type of application, loading conditions, and design life).

Practical or performance tests
In some cases it is desirable to perform practical tests. There is a special need for such tests when:

- great risks may arise as to the safety of man and environment when the geosynthetic is not successful in the construction;
- the project is of such a size that for an analysis of costs and profit a detailed specification of the geosynthetic in question is needed;
- special requirements are made which cannot be verified with tests or certificates;
- a reliable general calculation method is not yet available to determine the requirements of the geosynthetic to be applied.

Practical tests may have various forms. Local circumstances and loading situations have always to be imitated as much as possible to detect the collapsing behaviour. This can be realized by building a test track on the location of the future project or by executing a model experiment in a laboratory at a scale of 1:1. In a laboratory, special attention has to be paid to the imitation of the subsoil.

7 CLOSING REMARKS

Geosynthetics and geosystems constitute potential alternatives for more conventional materials and systems (Raymond and Giroud, 1993). 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. It is hoped that the results of this literature search will help to overcome some of these doubts and will be used as a basis for learning and promoting in the application of geosynthetics and geosystems.

The author hopes that his book will be of value to both practicing engineers and new generations of scientists. As to the former, he has in mind especially engineers in the field of hydraulic and coastal engineering, including those concerned with planning, design, and construction.

It is hoped that this book will be an inspiration for creating engineering alternatives utilizing the geosystems. However, a number of concepts discussed in this book still need further elaboration to achieve the level of design quality comparable with more conventional solutions and systems. Therefore, this book is also written for new generations of students and scientists.

A number of uncertainties in the design of geosystems can be solved in the scope of graduation work of students and doctoral dissertations. However, for a number of systems more practical experience is also still needed under various hydraulic conditions, for the verification of theoretical concepts. The realization of this need is only possible if manufacturers and clients cooperate closely. Usually, support from the governmental agencies related to research and development will be necessary. Problems regarding subsidies could readily be overcome if some research funds are diverted from traditional concepts that do not meet design requirements (but are artificially forced to do that).

The geosynthetic durability and the long-term behaviour of geosystems belong to the category of overall uncertainties and create a serious obstacle in the wider application of geosynthetics and geosystems and, therefore, are still matters of concern. Long-term durability, strength and functioning is more important today with regard to stronger and more ingenious geosynthetics and geosystems that offer solutions to geotechnical and hydraulic problems such as soil stabilization and reinforcement, containment of (dredged) materials, water defence, and others.

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 a multiclient studies for extended monitoring and testing programmes, to provide users with an independent assessement of the long-term performance of geosynthetics and geosystems.

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 Geotextiles and Geomembranes, Geosynthetics International, Geotechnical Fabric Report, and Proceedings of Geosynthetic Conferences) for updating the present knowledge and/or exchanging new ideas.

8 CONCLUSIONS AND RECOMMENDATIONS

The design of geotextile systems for various civil applications was in the past based more on rather vague experience than on generally valid calculation methods. However, the increased demand in recent years for new solutions and reliable design methods has led to new applications of geosynthetics and geosystems and to research concerning the design of these new systems.

In general it can be said that geosystems as well as all engineering systems and materials have (some) advantages and disadvantages which should be recognized before a choice is made. There is not one ideal system or material. Each material and system has a certain application at certain loading conditions and specific functional requirements for the specific problem and/or structural solution.

Contrary to research on traditional materials and systems there was little systematic research on the design, stability and performance of geotextile systems. However, past and recent research in the Netherlands, some other European countries and in the USA on a number of selected geotextile products and applications has provided results which can be of use in for the preparation of a set of preliminary design guidelines (including stability criteria) for geotextile systems under current and wave attack. The results are presented in (Pilarczyk, 1999).

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 which 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.

The following general conclusions can be drawn based on the actual developments and experience:

- Geosystems offer the advantages of simplicity in placement and constructability, cost effectiveness, and minimum impact on the environment.
- When applying geosystems the major design considerations/problems are related to the integrity of the units during release and impact (impact resistance, seam strength, burst, abrasion, durability etc.), the accuracy of placement on the bottom (especially at large depths), and the stability.
- When applying this technology the manufacturer's specifications should be followed. The installation needs an experienced contractor or an experienced supervision.

 Analytical and/or experimental models to simulate the performance of geosystems have been developed and calibrated with test results. However, these models provide indicative results only.

Especially, the internal stability of the sand-filled systems and the geotechnical stability criteria in general, still need further improvement. In all cases, experience and sound engineering judgement play an important role in applying these design criteria, or else mathematical modelling or physical testing can provide an optimum solution.

 The material durability and the long term behaviour of geosystems are still the points of concern. Systematic 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 design criteria.

 There is a rapid development in the field of geotextiles and geotextile systems and there is always a certain time gap between new developments and publishing them in specialistic books. Therefore, it is recommended to follow the professional literature on this subject (Journal of Geotextiles and Geomembranes, Geotextiles Congresses, Coastal Engineering Congresses, etc.) and manufacturer's brochures for updating the present knowledge.

The final conclusion on the use of the fill-containing geosystems can be formulated as follows:

- 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. However, information presented by Pilarczyk (1999) on the design aspects, stability criteria and existing experience will be of help in preparing the preliminary alternative designs with geosystems.
- There is an urgent need for internationally accepted guidelines for design and application of geosystems. The IGS in cooperation with other internationl organisations (i.e., PIANC) should undertake actions in this direction.

REFERENCES

Adel, den, H., 1996, Alternative systems; geocon tainers (in Dutch), *Delft Geotechnics*, Report CO-365930.

Bezuijen, A., 1999, Geosystems, *DELFT GEOTECH NICS* (report prepared for Road and Hydraulic Engineering Division, RWS. NL.

Bubner, E., R. Koenen and K. Saxe, 1984, Structural mebrane elements in civil engineering hydraulics and shore protection (in German), *Nationales Symposium Geotextilen im Erd- und Grundbau*, Mainz, Germany.

CEN, 1998, Guide to durability of geotextiles and geotextile related products, *European Normalization Committee (CEN)*, CEN/TC189/WG5/N210, Paris.

Davis, J.E. and M. C. Landin, 1997, Proceedings of the national workshop on geotextile tube applications, *Technical Report WRP-RE-17, U.S. Army Engineer WES*, Vicksburg.

Davis, J.E. and M. C. Landin, 1998, Geotextile Tube Structures for Wetlands Restoration and Protection: An Overview of Information From the National Workshop on Geotextile Tube Applications, *CERCular, no.2, Dpt.Army Corps of Engineers*, Vicksburg.

De Groot, M., 1999, Designing with geocontainers (supplement to: Pilarczyk, 1999, Geosynthetics and Geosystems in ...), *GeoDelf.*

Den Adel, H., Hendrikse, C.H., and Pilarczyk, K.W., 1996, Design and application of geotubes and geocontainers, *Proceedings of the 1st European Geosynthetics Conference*, Maastricht.

DELFT HYDRAULICS/DELFT GEOTECHNICS, 1998, Alternatieve open taludbekledingen (Alternative open revetments), (in Dutch), *WL/Delft Hydraulics*, H 1930/AS.98.37.

Fowler, J. D. Toups, Ch. Mesa, and P. Gilbert, 1995, Geotextile contained contaminated dredged material, Marina del Ray, Los Angeles and Port of Oakland, California, *Proc. 14th World Dredging Congress (WODA)*, Amsterdam.

Giroud, J.P., 1987, Geotextiles and Related Products, in *Geotechnical Modelling and Applications*, Sayed M. Sayed editor, Gulf Publishing Company, Houston.

Harrison, H.B., 1970, The analysis and behaviour of inflatable membrane dams under static loading, Proceedings of the Institution of Civil Engineers, Vol. 45

Harrison, H.B., 1976, Interactive nonlinear structural analysis, Proc. ASCE, J. Structural Div., 102, ST7, pp. 1353-1364.

Hitch, N.M. and Narayanan, R., 1984, Pressure field over rigid model of an inflatable dam, Channels and channel control structures, Proc. 1st Int. Conf. Hydraulic Design in Water Resources Eng., University Southampton, Berlin, Springer-Verlag.

K&O, 1979, Shore and bank protection works in practice and theory; investigation of performance of geotextiles in practice (in Dutch), *25 years of Dutch Association for Coastal and Bank Protection Works (K&O),* Rotterdam.

Leshchinsky Dov and Ora Leshchinsky, 1995, Geosynthetic confined pressurized slurry (GeoCoPS); supplement Notes for Version 1.0, *US Army Corps of Engrs. and Nicolon Corporation.*

Leshchinsky, D., O. Leshchinsky, H.I. Ling, and P.A. Gilbert, 1996, Geosynthetic Tubes for Confining Pressurized Slurry: Some Design Aspects, *J. of Geotechnical Engineering,* ASCE, V. 122, No. 8.

Mannsbart, G. and B.R. Christopher, 1997, Long-term performance of nonwoven geotextile filters in five coastal and bank protection projects, *Geotextiles and Geomembranes,* Vol. 15, no. 4-6.

Meerendonk, E. van, 1996, Balgstuw Ramspol, Literatuuronderzoek en rekenkundig onderzoek, Delft Hydraulics, (in Dutch).

Otto F., M. Banz, E. Bubner, J. Goedert, and G. Papakostas, 1978, Membranes in Water; Dams, Flood Control, and Raising Dikes, *Mitteilungen des Instituts für Leichte Flächentragwerke, Stuttgart, Leichtbau und Energietechniek (IL 11)*.

Parbery, R.D., 1976, A continuous method of analysis for the inflatable dam, Proceedings of the Institution of Civil Engineers, Vol. 61, December, part 2.

Parbery, R.D., 1978, Factors affecting the membrane dam inflated by air pressure, Proceedings of the Institution of Civil Engineers, Vol. 65, September, part 2.

Pilarczyk, K.W., 1999, Geosynthetics and geosystems in hydraulic and coastal engineering,, A.A. Balkema Publisher, Rotterdam, balkema@balkema.nl.

Plaut, R.H. and S. Suherman, 1997, Two-dimensional analysis of geo-synthetic tubes, submitted to Journal of Geotechnical en Geo-environmental Engineering, ASCE.

Plaut, R.H, S.I. Liapis and D.P. Telionis, 1998, When the levee inflates, ASCE, *Civil Engineering*, January.

Plaut, R.H., S.I. Liapis and D.P.Telionis, 1998, When the levee inflates, ASCE, *Civil Engineering*, January.

Pover, J.P., 1993, Berekening Balgstuw Ramspol (in Dutch), Rijkswaterstaat.

Raymond, G.P and Giroud, J.P., eds., 1993, Geosynthetics Case Histories; thirty five years of experience, *International Society for Soil Mechanics and Foundation Engineering,* Bitech Publishers Ltd., Richmond, Canada.

Silvester, R., 1990, Flexible Membrane Units for Breakwaters, in '*Handbook of Coastal and Ocean Engineering*, John B. Herbich, editor, Vol. 1, pp. 921-938.

Sprague, C.J. and M.M. Koutsourais, 1992, Fabric formed concrete revetment systems, published in '*Geosynthetics in Filtration, Drainage and Erosion Control*, R.M. Koerner, ed., Elsevier Applied Science (reprinted from *Geotextiles and Geomembranes*, Vol. 11, Nos. 4-6).

Sprague, C.J., 1995, P.E.T. Geotextile Tubes and Containers for Beneficial Use of Dredged Material, *contract report for Bradley Industrial textiles, Inc., Valparaiso, FL, and Hoechst Celanese corporation, Spunbond Business Group, Spartanburg, SC.*

Van de Burg, H.J., 1961, De berekening van een stuw van rubber (calculation of a rubber dam), (in Dutch), De Ingenieur, December.

Van Driel, N.D., 1995, Autoband model voor waterkering (Car tire as a model for retaining structure), (in Dutch), *Land+Water*, No. 5, pp. 20-22.

Van Santvoort, G./Veldhuijzen van Zanten, R./, 1994, Geotextiles and Geomembranes in Civil Engineering: a handbook, A.A. Balkema Publ., Rotterdam.

Watson, R., 1985, A note on the shape of flexible dams, *Journal of Hydraulic Research*, Vol. 23, no. 2, pp. 179 - 194.