The Evolution of Multi-Celled Sand-Filled Geosynthetic Systems for Coastal Protection and Surfing Enhancement

Lee E. Harris¹ and Jay W. Sample²

¹Associate Professor of Ocean Engineering
Department of Marine and Environmental Systems
Florida Institute of Technology Melbourne, Florida 32901
lharris@fit.edu

²President, Advanced Coastal Technology, Inc.
3335 Camp Branch Road, Topton, NC 28781
act@dnet.net

ABSTRACT

This paper reviews the development of sand and water-filled geosynthetic container systems for coastal erosion control, storm protection, and artificial reefs. The use of sand-filled containers in the design and construction of coastal protective structures has increased significantly in recent years due to the improvements in geosynthetic materials, development of engineered systems, and the desire for “softer” and more “user-friendly” forms of shore protective structures. The use of sand-filled geosynthetic containers on sandy recreational beaches has proven to be more “user friendly” than the more traditional “hard structures” such as vertical seawalls and sloped revetments constructed of rock and concrete, which can impede recreational uses of these areas. These improved geosynthetic systems have resulted in the development and implementation of sand-filled container systems which provide significant levels of storm and coastal erosion protection, as evidenced by the performance during the four major hurricanes impacting Florida in 2004. In addition to the historical developments and coastal engineering applications of these systems, unique container shapes, materials, and designs are being developed for constructing submerged artificial reefs for both shoreline stabilization and recreational amenities including surfing enhancement.

ADDITIONAL INDEX WORDS: Geosynthetics, geotextiles, sand-filled containers, geotubes, geosystems, geocontainers, submerged breakwaters, sills, artificial surfing reefs.

INTRODUCTION

The concept of employing sand filled containers of various sizes and shapes for erosion control has been in existence for centuries (KOERNER, 1998). The initial evolution of sand-filled containers for coastal erosion control has occurred over the past four hundred years, since the Dutch first employed small sand-filled containers to shore up their dike and dam structures in the 17th century. The myriad of enormous dikes surrounding Holland provide continuous protection to a nation which is sited largely below sea level.

The earliest fabrics employed in the containment of sand for the construction of dikes and levees were degradable natural materials which suffered from severe limitations, but the development of synthetic fibers has provided stronger and more durable materials. The problems with sand-filled container systems have been and continue to be related to
inadequacies of the fabric materials and seams containing the sand fill, insufficient size and mass of the containers to withstand larger wave forces, and inappropriate container shapes which reflect rather than attenuate wave energy.

Recent improvements in geosynthetic materials and fabrication techniques have resulted in increased strengths and durability, allowing improved designs and performance of sand-filled container systems. State-of-the-art geosynthetic fabrics today combine high strengths and resistance to abrasion, puncture, tear, and ultraviolet deterioration, as well as site specific characteristics such as the ability to be colored to match the beach sand at a project area.

Sandbags and geotextile containers have also been used to construct harder, more rigid structures by filling them with grout or concrete. In these applications, the primary function of the container material is to provide a temporary form within which the concrete can harden. If the concrete-filled fabric units are joined together utilizing steel or other connecting/reinforcing elements, the engineering design and performance of these concrete-filled container structures is similar to that of articulated mats or other concrete structures. If no connecting elements are employed, the design and performance of the individual units is similar to other rock or concrete unit rubble-mound structures. Only water and sand filled containers are covered in this paper.

**TYPES OF MATERIALS AND CONTAINER DESIGNS**

Geosynthetic materials are fabrics which have been specifically created for use in, on, under and around the earth. Specialized materials have been developed in order to withstand the harsh marine conditions including exposure to waves, water-born debris, storm surge, sand abrasion, and sunlight. These geosynthetic materials include both geotextile (porous) and geomembrane (non-porous) materials that are fabricated into very large containers that can be filled with sand and used for many applications, including systems for shoreline stabilization (TRANIER, et al., 1997).

The term “sand-filled container” (SFC) is used to differentiate between the smaller “sandbags” whose small sizes limit slope stabilization applications to inland waterways, and the larger “sand-filled containers” with increased sizes allowing them to be utilized on the open ocean coast. Terms used to refer to these containers have included bags, sandbags, geobags, sausages, tubes, geotubes, geocontainers, geosystems, etc., some of which are being used as registered trade names. The standard small sand-bags are filled with approximately 0.03 cubic meters (1.0 cubic foot) of sand, and weigh approximately 40 kilograms (90 pounds) each (HARRIS, 1987). This allows filling of the small sand-bags first, with subsequent transportation and placement at another location. However, the small sizes and weights of these sandbags limit their use and effectiveness. For open ocean exposure sites, extremely large sand-filled containers are now available in lengths of over 100 meters (328 feet) and in widths or diameters of over 5 meters (16.4 feet).

Several types of materials and container systems have been developed specifically for the design of coastal erosion protection systems (PILARCZYK, 1996) and for beneficial uses of dredged material (HARRIS, 1994). Sand-filled containers have been utilized to construct a variety of traditional coastal erosion control structures, including both shore-perpendicular and shore-parallel structures. These systems have included jetties, groins, vertical seawalls, sloped revetments, breakwaters and sill structures with varying degrees of success (U.S. ARMY CORPS OF ENGINEERS, 1981; and ZADIKOFF, et al., 1998). Due to the lower
costs and less need for heavy equipment, sand-filled containers have been used in developing countries (HARRIS and ZADIKOFF, 1999).

Due to the large sizes and weights, the larger sand-filled containers must be filled in-situ – the container is positioned in its final design position first while empty, with subsequent filling. The exception to in-situ filling is the use of a split hull barge, in which the geosynthetic fabric is laid in the barge, the sand placed on top, the material wrapped around the sand and seamed, and final offshore placement made by dropping the containers through the bottom of the barge (see e.g. TRANIER, et al., 1997 and BEZUIJEN, et al., 2000). The disadvantages of the split-hull barge method of installation are (HARRIS, et al., 2004):

1. the difficulty in constructing a smooth overall design profile,
2. the difficulty in precise placement of the containers,
3. the inability to construct the top of the structure any higher than the draft of the barge,
4. the requirement that the seams be made in the barge after the sand is placed, rather than in the controlled environment of a factory.

In-situ filling of the containers is done by pumping a sand-water slurry into the pre-fabricated container. For a geotextile material, the water flows out through the permeable fabric leaving the sand behind, and for an impermeable geomembrane material, exit ports are temporarily installed to allow the water to exit. An advantage in using an impermeable geomembrane material for the container is that the container can be filled rapidly first with only water, so that the container takes on its full shape, and then the water can subsequently be displaced with sand. Figure 1 shows the in-situ filling of a sand-filled geomembrane container using fill and exit ports.

![Figure 1](image-url)

Figure 1. In-situ filling of one multi-celled geomembrane container above water (left) and in-situ filling of single-celled geotextile container underwater (right).

**Sand-filled Container Shapes**

For purposes of engineering design, sand-filled containers can be classified into two basic shapes:

1. Two-dimensional “pillow-shaped” or single-celled (as shown in Figure 2), and
2. Three-dimensional or “multi-celled” (as shown in Figure 1).
The simplest container or tube can be fabricated from a single piece of fabric folded over with sewn seams to connect the edges, similar to a pillow case. When empty this container is a 2-D flat shape, and when filled with sand this container will take on an approximate elliptical shape, as shown in the photographs in Figure 2. Multi-cell containers use internal web and end panels, so that they will take a precise shape when filled with sand, as shown in Figure 1.

Figure 2. Two-dimensional sand-filled container installation at Fort Pierce, Florida.

A comparison between the single-celled pillow-shaped container and multi-cell container cross-sections for equal structure heights and widths is shown in Figure 3 (both units have a toe tube). Note that the multi-cell container requires less sand volume. More important is the comparison of the seaward structure slopes (seaward is to the right). As long as the sand level seaward of either of the containers is up to the level of 50% or more of the total container height, the exposed cross-section has a sloped front for both container cross-sections. For the multi-cell container, no matter what the sand level is on the seaward side of the multi-cell container, a gentle seaward slope will always be exposed to the waves. However, as the sand level seaward of the single-cell pillow-shaped container falls to 50% or less of the container height, the seaward slope of the container becomes vertical, resulting in increased wave reflection and toe scour seaward of the container. This increased wave reflection and toe scour seaward of the container can undermine the container and allow it to roll seaward, with increased stresses in the material causing failure, as shown in Figure 4. In order to reduce the wave reflection and toe scour, a gentle sloping seaward front must be maintained. Also note that less sand cover will be required over the sloped cross-section to maintain sand thickness on top of the container.

Figure 3. Comparison between the single-cell pillow-shaped (elliptical shape) and the multi-cell (shaded) container cross-sections, with seaward direction to the right.
OVERALL DESIGN CROSS-SECTIONS

Custom designed cross-sections are necessary to achieve specific design goals and performance of sand-filled container systems. In order to create a cross-section other than an elliptical shape, two methods can be used:

1. a system using several sand-filled containers in a design cross-section, or
2. a multi-celled container that will form to a designed shape when filled.

Examples of these methods applied to coastal engineering applications are presented in this section.

Stacked Container Cross-sections

A cross-section comprised of stacked containers will be stable either due to (a) the weight and interlocking of the units (as in a rubble mound structure design) or (b) by the use restraints such as straps to hold the containers in place. Figure 5 shows the submerged breakwater and surfing enhancement reef offshore at Surfers Paradise in the Gold Coast region of Australia, which was constructed in 1999 by dropping sand-filled geotextile containers from a split-hull barge (HEERTEN et al., 2000). This is a stacked sand-filled container system, which relies on individual container weights and interlocking for stability. The two large shore perpendicular lobes were designed to reduce the wave energy reaching the beach, plus enhance the surfability of the wave breaking.
Strap Restraint Systems

Strap restraint systems have been developed to assist in maintaining the overall structural integrity of the sand-filled container structures. The purpose of the straps is to tie the individual containers together to increase the stability of the overall structure, and to prevent individual containers from being displaced. Several different strap restraint systems have been employed with varying degrees of success (HARRIS, 1989). The systems covered in this paper include (in the order of their development):

1. circumferential straps around the entire structure cross-section,
2. circumferential straps around each individual container and strapped together, and
3. internal strap systems.

To increase the vertical dimension above one container height, two rows of containers on the bottom with a third row on top has been used. This design has been referred to as a “mound” structure, and is also the basic configuration employed in the cross-sectional design of sand-filled container groins or jetty structures. In this pyramid stacking method, the required number of containers increases exponentially with increases in structure height (HARRIS, 1988).

The first strap system developed employed a single strap tied completely around the cross-section of the multiple containers. This circumferential strap system was typically used at 1.5 meter (5 feet) intervals along the length of the structure. Due to the ability of the individual containers to flex throughout their length, this strap system provided only a minor increase in structural stability. This strap restraint system is shown under construction and after damaged by storms in Figure 6.
The next attempt at the design of a strap restraint system consisted of a strap that went completed around each individual container, crossing between containers as it also completely encircled the cross-section of the structure, as shown in Figure 7. This strap system, referred to as a triple-loop strap when used around three containers, held the individual containers more securely. However, over time and with multiple storm events, the containerized sand can return to a saturated semi-liquid state during long duration, heavy wave attack. This phenomenon allows the sand to move around inside the containers, moving away from the strap encircled areas, thereby loosening the straps and allowing individual containers to be displaced, as shown in Figure 7.

More recent developments in strap restraint systems utilize an internal strap system, with PVC pipes placed inside and running along the upper length of each container. The straps are laid under the containers, and are tied directly to the internal PVC pipes, rather than around the outside of the sand-filled containers. The PVC pipe inside each container is connected by internal straps within each row of the entire structure, and serves as a flexible “spine.” The entire strap system is attached to a crest anchor tube that is buried landward of the structure, similar to the dead-man anchors used in seawalls and bulkheads. This strap restraint system is shown in Figure 8.
A unique advantage of this internal strap restraint system is that when completed, all of the straps are underneath the containers, preventing them from being damaged by waterborne debris or vandalism. This strap restraint system requires the use of specially designed containers which are specifically fabricated to employ the PVC pipes inside the containers. Both the PVC pipes and the containers are filled with sand after being placed in position. This strap restraint system is employed in the “Subsurface Dune Restoration System” or SDRS (SAMPLE, 1990, Patent #4,919,567), which is a sloped sand-filled container design incorporating multiple rows of containers. Figure 9 shows the 14-row SDRS under construction in Vero Beach, Florida in 1989, and in the fall 1996 after northeast storm uncovered a few rows near the center of the cross-section. Figure 10 shows the system immediately before and after successfully withstanding back-to-back blows from major Hurricanes Frances and Jeanne in the fall of 2004.
Figure 10. 14-row SDRS before (left photo) and after (right photo) back-to-back strikes from major Hurricanes Frances and Jeanne in fall of 2004. Unlike the adjacent properties that suffered upland erosion of 50 to over 100 feet, the SDRS prevented loss of upland property.

Multi-cell Container Cross-sections

The use of one or more multi-cell containers is another method of constructing a specific design cross-section. Figure 11 shows a 2-meter high 8-meter wide ProTecTube™ multi-cell sand-filled container cross-section designed to be used in a “Subsurface Dune Protection System” (USACE, 1993 and SAMPLE, 1990b, U.S. Patent #4,966,491). This design has three cells separated by vertical “webs” and an additional toe tube at the seaward end that is designed to flex downward if needed to protect against toe scour. This multi-cell design with vertical webs creates the desired design structure shape when filled with sand, and the multi-cell design also offers protection against total structural failure in the event one of the cells is ruptured. Figure 12 shows a ProTecTube installation at Cape San Blas, located in the Florida panhandle, and Figure 13 shows this project before and after being impacted by major Hurricane Ivan in 2004. These photographs show that the system survived the storm and did provide reduced erosion and protection to the upland development. Unfortunately, even though originally designed, the landward return was not constructed on the west end of this project due to the last minute withdrawal of a property owner from the project, so that the system was flanked with more damages occurring at that end.

Figure 11. ProTecTube™ multi-cell sand-filled container cross-sectional design (SAMPLE, 1990b, U.S. Patent #4,966,491).
Figure 12. ProTecTube™ multi-cell sand-filled container Subsurface Dune Protection System with the initial erosion problem (left), installation of sand-filled container (center), and completed project (right).

Figure 13. ProTecTube™ Subsurface Dune Protection System one year after installation and prior to Hurricane Ivan (left), and after being impacted by major Hurricane Ivan in 2004 (right).

SUBMERGED BREAKWATERS AND ARTIFICIAL REEFS
Sand-filled containers also can be used as offshore breakwaters. Single-cell sand-filled containers have been used as submerged and emergent breakwaters, as in the examples from the Caribbean shown in Figure 14. A submerged breakwater for shoreline stabilization and surfing enhancement located near Ventura, California is part of the U.S. Army Corps of Engineers Section 227 National Shoreline Erosion Control Development and Demonstration Program (USACE, 2004). The preliminary design for this project is shown in Figure 15, which will be the first multi-celled wedge-shaped sand-filled artificial reef structure in the United States. This ProTecReef™ structure will be manufactured in the factory, with the multiple modular components each comprised of 11 internal cells. Each multi-celled modular component will typically measure 40 meters (130 feet) across the base, 15m (50 feet) in width, and approximately 5m (16 feet) in height at the highest point of the reef, where the crest will be within 0.5m (1.6 feet) of the mean low tide level. Installation and sand-filling will be in-situ underwater; and the overall reef will measure approximately 200m (660 feet) in length (shore parallel). The reef structure is designed to reduce the beach erosion in its lee, and provide surfing enhancement amenities for the benefit of the local communities.
Construction techniques for deployment and underwater filling of the submerged sand-filled container systems have been successfully developed for the Caribbean installations, using limited equipment. For deployment of larger containers in deeper water depths, such as the
one planned for Ventura California, barges and tugboats will be required. The Rapidly Installed Breakwater (R.I.B.) project, which is an experimental water-filled geomembrane container floating breakwater system designed for deployment within 48 hours and tested by the U.S. Army Corps of Engineers offshore Florida’s central east coast in recent years (USACE, 2003), provides additional techniques that can be extended to deployments of other large offshore water and sand-filled container systems.

Figure 16 shows the empty R.I.B. container accordion-folded on the barge prior to deployment, and one 60m (200 feet) long by 9m (30-feet) diameter R.I.B. segment offshore in 14m (45 feet) water depth, following its deployment and offshore in-situ filling of the container with water. The deployment methodology for the Ventura, California ProTecReef™ segments is planned to be similar to that used for the R.I.B. deployment, with the deployment of the empty containers from barges, using embedment anchors in the sea bottom and straps to hold the containers in place while they are filled in-situ underwater.

![Figure 16. The experimental Rapidly Installed Breakwater (R.I.B.) water-filled container floating breakwater system, empty and folded on barge (left) and deployed in the Atlantic Ocean (right).](image)

**ENGINEERING DESIGN RECOMMENDATIONS**

Historically, sand-filled geosynthetic container systems have been used to provide low cost solutions in low wave climate environments, and have been considered as temporary structures, with a design life of five years or less due to the lack of strength and durability of the materials used to fabricate the containers. Degradation due to ultraviolet light from the sun, abrasion by sand, and puncture by water-borne debris or vandalism are commonly cited as the principal concerns in material failures. However, due to the continued development of improved materials and designs, and as recently demonstrated by the performance of these systems during the four major hurricanes striking Florida in 2004, these systems can be considered for greater design storm levels and longer term applications.

In addition to increased strengths in the materials used to retain the sand, an extra outer protective layer of high-strength and abrasion-resistant armor material can be used to protect the inner sand-retaining material. This dual layer approach significantly increases resistance to abrasion, puncture, tearing and ultraviolet deterioration and provides better traction for pedestrian traffic across the containers during exposed periods between storm wave attack and the post storm recovery cycle. Gentle slopes used in the design cross-section also reduce the tendency of sand to be able to leave the containers through holes or tears, as compared to
vertical faces. Failure of the seams of the containers has been another problem that can be addressed in the fabrication process.

The engineering design considerations for sand-filled container systems are similar to those for traditional coastal structures: they can be designed with crest elevations to resist or minimize wave run-up, overtopping, and wave transmission; with adequate toe penetration (base elevation) to resist undercutting and toe scour; and with adequate returns at the ends of the project to avoid flanking. Due to the smaller specific weight of sand compared to rocks, as well as the flexibility of an individual sand-filled container, a more gentle slope is recommended for the overall sand-filled container structures. The 3 or 4 horizontal to 1 vertical slope has functioned well in sand-filled container systems constructed in Florida, compared to the steeper 1.5 or 2 H to 1 V slopes commonly used for rock structures (HARRIS, 2003).

Analysis of the stability of sand-filled container structures is more difficult than with rigid units such as rock or concrete, as the sand within the individual containers is free to migrate within the container under sustained wave attack. Due to the smaller specific weight of sand compared to rocks, very large containers are often used, but if these are not multi-cell containers, there is an increased risk in catastrophic failure if punctured or torn, and greater potential movement of the sand within the container. The use of impermeable geosynthetic materials to contain the sand fill reduces the potential for re-suspension of the sand particles within the container, but the sand can still be moved by external forces. The use of strap restraint systems to structurally link the containers together can be used to increase the stability, especially when the straps are linked to an upland crest anchor tube or other substantial anchoring such as helixes into the sea bottom.

Sand-filled containers have several potential uses in conjunction with beach nourishment projects. Terminal groins and/or groin fields may be necessary to retain the beach fill, and may provide ways to lower the required frequency of renourishment. Another potential for sand-filled container structures for assisting in increasing the lifespan of beach nourishment projects is the use of offshore breakwaters, designed to reduce wave action and longshore current, and to help stabilize the beach fill as a “perched beach” landward of the sill. In addition to reducing the frequency of renourishment, these applications can provide environmental enhancement by providing marine habitat and by minimizing adverse affects on natural resources such as reefs, rock outcroppings, and vegetation that can be buried by offshore movement of the fill (HARRIS, 2003).

**SUMMARY AND CONCLUSIONS**

Sand-filled containers can be successfully used in engineering designs for coastal erosion control. Improvements in the geosynthetic materials, fabrication methods, and designs of these systems have increased the applications and longevity of these structures. These improvements include better material properties, the use of a protective armor layer, multi-cell containers, improved seam design and fabrication, and gentle seaward sloping container system surfaces.

As demonstrated by the recent major hurricanes in Florida, the sand-filled container systems can be used in the design of a full revetment structure, with adequate crest elevation to resist overtopping, and adequate toe penetration to prevent undercutting by the beach erosion accompanying the design storm. The gentle seaward sloping sand-filled container structures
also can be employed in the designs of backshore sills for dune restoration and toe scour protection, and in the designs of offshore breakwaters including surfing enhancement.

Sand-filled containers are “softer” and more “user-friendly” than structures constructed of rock, concrete and steel, making them more desirable and benign in areas of natural sandy beaches. Advances in sand-filled container systems engineering, and developments in composite geosynthetic materials technology will continue to increase the strengths, extend the lifespan, and expand the applications and capabilities of these unique materials.

**LITERATURE CITED**


