

STABILITY CONSIDERATIONS AND CASE STUDIES OF SUBMERGED STRUCTURES CONSTRUCTED FROM LARGE, SAND FILLED, GEOTEXTILE CONTAINERS

Jose C. Borrero¹, Shaw T. Mead¹ and Andrew Moores¹

The use of large, sand filled geotextile containers for the construction of offshore structures is gaining acceptance as a cost effective method of submerged breakwater or reef construction. This method of construction is particularly well suited for multipurpose structures where the intent is to provide breakwater-like wave attenuation and shore protection while at the same time providing recreational amenities such as ecological enhancement or surfing. Because the materials and methods used in these structures is relatively new, design guidance is lacking. This paper discusses the general stability considerations for submerged structures constructed from sand filled geotextile containers (SFC's) and describes a method of assessing container stability through the use of numerical models and empirically derived stability formulae. The paper also describes lessons learned from case studies of four very different examples of this type of construction.

Keywords: submerged breakwater, geotextile, artificial reef, stability, low-crested breakwater

INTRODUCTION

The use of large, sand filled geotextile containers (SFC or GSC) for the construction of offshore structures is gaining acceptance as a cost effective method of submerged breakwater construction. However, design guidance for such structures is often lacking. Individual armour unit stability for rubble mound structures is normally determined through the use established design formulas which give the weight of an armour unit required to ensure the stability of the armour layer. These equations are not directly applicable to the situation where large containers filled with sand are used as the primary construction element in a structure. Furthermore, the geotextile structures are subject to additional stability issues such as the strength of the geotextile material used to fabricate the containers, the strength of the sewn seams, the settlement or readjustment of the fill material inside the containers as well as the potential for large scale scour and settlement of the structure itself.

STABILITY OF INDIVIDUAL UNITS

It is important to recognize the scale of the so called 'sand bags;' used in multipurpose reef and breakwater construction. While a range of physical scale model tests have been conducted to assess geotextile container stability, the studies generally depict situations where individual bag units are $1/4^{\text{th}}$ to $1/10^{\text{th}}$ of the water depth. In practice however, the height of the bag units is more on the order of one-third of the water depth for multi-layer structures. On single layer structures, container heights approximate the water depth. These container sizes are compared graphically in Figure 1.

Individual unit stability for rock is normally determined through the use established design formulas which give a necessary rock diameter or weight of an armour unit required to ensure stability of the armour layer subject to an acceptable level of damage. These equations are not directly applicable to the situation where large geobags filled with sand are used as the primary construction element in a structure.

Taveira-Pinto (2005) compared formulas for stability of armour stone in the construction of submerged breakwaters. He noted that for a typical submerged, shore parallel breakwaters with steep slopes under large wave conditions (5-7 m) with either a 10 or 15 second period, the recommended armour unit weight is between 6 and 20 tons. When compared to a typical SFC which has a mass on the order of 100 to 500 tons, the SFC units would appear be sufficiently stable.

¹ ASR Limited, Marine Consulting and Research, 1 Wainui Road, Raglan 3297 New Zealand

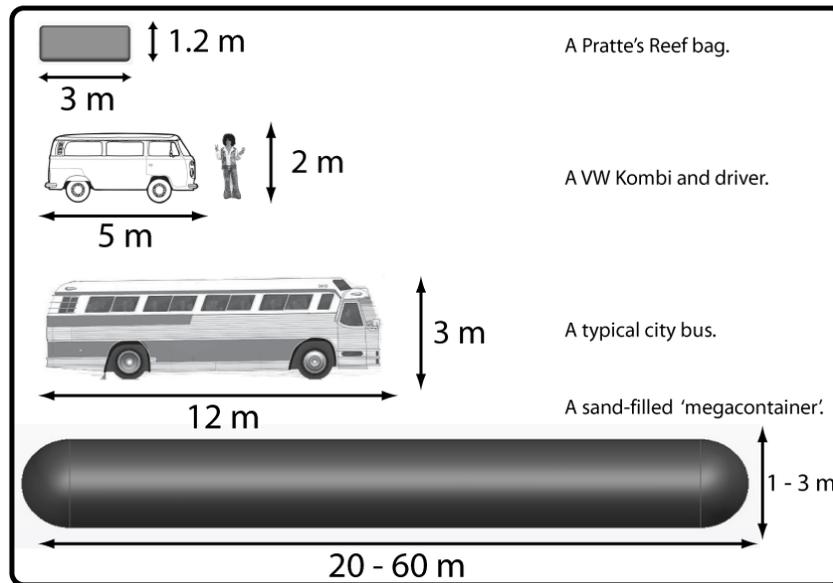


Figure 1. Size comparison between sand filled geotextile containers (SFC's)

Hudson and Cox (2001)

Laboratory tests performed by Hudson and Cox, 2001 assessed the stability of sand filled geocontainers. They defined three types container motion related to stability; skin movement where the geotextile fabric is moved by the action of waves or currents, initial movement where an entire unit moves by rocking or pulsing and bag displacement where an entire bag was moved by half a bag dimension.

The results of their experiments produced a relationship between the modified spectral stability number (N_s') and the level of submergence (y/B_h) where y is the depth of water above the structure crest and B_h is the height of the SFC. N_s' is defined by the following equation:

$$N_s' = (H_c^{2/3} + L_p^{1/3}) / (\Delta B_h) \quad (1)$$

Where, H_c is the critical deep water wave height, L_p is the Airy deep water wavelength and Δ is the submerged density equal to $(\rho_b - \rho_w) / \rho_w$. This formulation is taken from Van de Meer (1991) however modified by using the bag height (B_h) as a surrogate for the nominal size of the rock armour units.

Using these relationships, the required bag height (B_h) for a submerged density of 0.4, deep water waves of 6 m at 12 s and a reef crest at 1 m submergence is either 1.6 m or 2 m depending whether the recommended or conservative relationship is used.

By assuming a more extreme scenario where $y = 0.1$ m, the resulting B_h is 1.8 m to 2.2 m. If however the submerged density is increased to 0.8 (a more typical value for multipurpose reef deployments) then the stable bag height decreases to 0.7 and 0.85 m for the first case ($y = 1$ m) and 0.9 and 1.1 m for the second case ($y = 0.1$ m).

It should be noted that Hudson and Cox state that their tests were only conducted for y/B_h values between 1 and 4, i.e. where the depth above the reef is at least as high as the reef unit itself. However, in many cases for artificial reefs, this ratio could be quite small, i.e. 0.5 m of water over a 3 m diameter SFC, implying a y/B_h ratio of 0.17. Even so, in an example provided by the authors, they calculate a stable bag height of 1.6 m for a submerged depth of 1 m, or a y/B_h ratio of 0.625, which is also out of the range of their physical model study.

Recio and Oumeraci (2009)

Multiple aspects of SFC stability were investigated by Recio (2007) and Recio and Oumeraci (2009). These works summarised laboratory experiments investigating the stability of geotextile containers arranged in a variety of configurations over a wide range of wave conditions. The analysis has led to the first set of design formulae specific to sand filled containers. Their method uses a force balance approach, relating mobilising forces caused by waves to resisting forces caused by friction between containers and the weight of the containers themselves. Using experimental data, the stability formula for sliding are described in terms of the bag length (l_c) and overall weight (W_{SFC}) required to keep the container from moving.

Using their approach, an SFC is stable against sliding when the resisting forces are greater than or equal to the mobilising forces, i.e.:

$$\mu[W_{SFC}-F_L] > F_D + F_M \quad (2)$$

Where W_{SFC} is the net weight of the structure acting downwards, F_L and F_D are the lift and drag forces generated as wave driven currents flow past the container, μ is the coefficient of friction between two SFC's or between an SFC and the seabed, and F_M is the inertial force acting on the container.

The individual terms in (2) can be expressed as:

$$W_{SFC} = \rho_s Vg - \rho_w Vg \quad (3)$$

$$F_L = 0.5 C_L \rho_w A_T u^2 \quad (4)$$

$$F_D = 0.5 C_D \rho_w A_s u^2 \quad (5)$$

$$F_M = 0.5 C_M \rho_w V (du/dt) \quad (6)$$

Where: g is the acceleration due to gravity, ρ_s and ρ_w are the densities of sand and water, C_L , C_D , and C_M are experimentally derived coefficients of lift, drag and inertia, u and du/dt are the wave driven water velocity and acceleration at the container center of mass, A_s and A_T are the horizontal and vertical projections of the container area and V is the container volume.

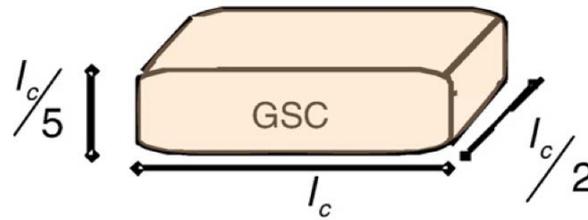


Figure 2. Relationship between SFC dimensions (from Recio 2007).

If the containers are represented as parallelepipeds with fixed relationships between the container length, width and height (Figure 2) the container volume can be expressed as a function of its length (l_c). Then, substituting Equations (3-6) in to (2) yields:

$$l_c \geq u^2 \frac{[0.5C_D + 2.5C_L\mu]}{[\mu\Delta g - C_M \frac{\partial u}{\partial t}]} \quad (7)$$

and:

$$W_{SFC} \geq \left(\rho_s \left(u^2 \frac{[0.5C_D + 2.5C_L\mu]}{[\mu\Delta g - C_M \frac{\partial u}{\partial t}]} \right) \right)^3 / 10 \quad (8)$$

Where $\Delta = \rho_s/\rho_w - 1$.

Expressions (7) and (8) relate the required container length (l_c) and weight (W_{SFC}) for the container to remain stable against sliding under the prescribed wave conditions. Note however that these expressions are only valid for containers where the height is 1/5th of the container length and the width is 1/2 of the container length. For other geometries, the expressions must be re-derived.

It should be noted that wave induced velocities are periodic, varying from 0 to u_{max} as a wave crest passes over the container. The worst case scenario which maximises the lift and drag forces is the case when the

structure crest is just under a continuous layer of water and a maximum design wave breaks directly on the leading edge of the container. Once the structure is exposed to air, the lift force disappears since there is no flow above the structure to contribute to the lift. Additionally, under linear theory, wave driven velocities are at a maximum when acceleration is at a minimum and vice versa. Because the drag force governs, the maximum velocity is used in conjunction with $1/10^{\text{th}}$ of the maximum acceleration to approximate typical accelerations observed under non-linear wave conditions (Recio 2007).

More details on the derivation of these relationships and the determination of the appropriate force coefficients as well as the effect of container deformations is found in Recio (2007) and Recio and Oumeraci (2009)

Additional Stability Considerations

Unlike rock or concrete armour, the stability of an SFC does not depend only on the size or shape of the construction unit. Of primary importance to the stability of SFC's is the strength of the material used to fabricate the container and the strength of the sewn seams. SFC's can be damaged before or during installation as a result of inappropriate handling that causes excessive stress to the material or seams. This can include hoisting the container without using proper lifting straps and using excessive pump pressures during filling operations. Once a container has been filled, the filling ports must be securely closed to ensure that the fill material is not able to leak from the container causing partial deflation. An example of a properly secured filling port is shown in Figure 3. There have been instances where inappropriate container closures have led to the deflation and eventual failure of an SFC.



Figure 3. A properly closed and secure filling port on an SFC.

Once in place, SFCs are susceptible to mechanical damage by boats making direct impact or anchoring over the structure. Sharp and/or heavy anchors are capable of puncturing certain grades of geotextile. Additionally, if an anchor becomes wedged in a container, the vessel operator may try to extract the anchor using the force of the boat engines causing even greater damage. Vandalism is also a concern for some SFC structures. Sharp knives can be used to rip holes into SFC's.

Once a container has been compromised, the fill material will begin to leak out under the action of waves until the container is completely deflated and fails. This 'all or nothing' type of failure is a concern for any structure that proposes to use SFC's as a construction element. For this reason, SFC's should be sized to be as small as possible for construction, but as large as necessary for stability to ensure that one container failure does not compromise the stability of the structure.

CASE STUDIES

The following case studies of submerged structures constructed from large SFC's will be explored:

- Narrowneck Reef, Gold Coast, Queensland, Australia (Jackson et al., 2007)
- Pratte's Reef, El Segundo, California USA (Borrero and Nelsen, 2003)

- The Mount Reef, Mount Maunganui, New Zealand (Black and Mead, 2007)
- The Boscombe Reef, Boscombe, England (Mead et al., 2010).

The Narrowneck Reef, Gold Coast, Australia: Numerical Stability Analysis

Built between 1999 and 2000, the Narrowneck Reef is a submerged structure made from sand filled geotextile containers. The primary purpose of the Narrowneck Reef is to provide a coastal control point to stabilize nourished beaches along the Gold Coast. The reef was also designed to enhance recreational amenities including surfing, swimming, diving and fishing while providing aquatic habitat. By most accounts the reef was successful in its primary goal and partially successful as a surf break (Jackson et al, 2007, Turner, 2009).

The reef was constructed from ~400 SFC units ranging from 3 to 4.5m diameter by 20m long. Each container was hydraulically filled with sand in a split-hull hopper dredge and dropped onto the seabed (Jackson et al, 2007). Due to the construction method, a highly accurate, tightly spaced placement of the containers was not possible (Figure 4a,b). Furthermore, the final constructed reef volume was much smaller (~60,000 m³) than the intended design volume of (140,000 m³).

In terms of container stability, the Narrowneck reef has performed quite well. The reef has weathered intense waves ($H_{max} > 10\text{m}$) with very few documented instances of container failures. It can be suggested that the failure of the containers in the Narrowneck Reef have been caused by one or more of the following reasons:

- 1) Containers not placed as accurately as in the design specifications
- 2) Containers not properly filled, thus allowing for large deformations which reduced stability, or 'fatigue' failure due to material flapping under wave activity
- 3) Small holes caused by boat anchors or vandals which allowed fill material to escape until complete deflation.



Figure 4. A typical geotextile container used on the Narrowneck reef (left) and an aerial photograph of the completed reef (right), note the large gaps between the SFC units. The black line represents the approximate location of the cross section used in the stability analysis.

To assess the stability of the geotextile containers used in the Narrowneck Reef, a modified version of the COBRAS numerical model (Liu et al., 1997, Recio, 2007) was employed. This model solves the full Navier-Stokes equations using a volume of fluid approach. The model domain was run over on a 2-D cross section through the as-built profile of the reef (Figure 4b). The cross section was simplified to reduce computational time by merging containers located in non-critical areas. Individual containers were resolved in the model profile along the reef crest and the leading edge of the middle layer (Figure 5).

Inputs to the model were extreme and operational deep water wave conditions. For input to the model, wave heights affecting the reef were reduced to their depth limited value, approximately 0.6 time the water depth, at the offshore toe of the reef (approx. 5 m depth). As such the operational wave conditions were simulated as 2 m at 5 seconds while extreme conditions were simulated as 3 m @ 8 seconds due to the depth limited breaking.

To assess container stability wave-induced pressures along the perimeter of each geotextile sand container were computed by the model and integrated to assess the resultant horizontal and vertical forces acting on each container at each timestep. Based on this, each container is analyzed for stability for two scenarios:

Uplift displacement: If wave induced vertical forces exceed the weight of the container (including any overlying containers) it is unstable. This scenario is common for smaller containers but is not expected for the large containers used on the Narrowneck Reef. The stability is expressed as:

$$F_L \leq (\rho_s - \rho_w) gV \quad (9)$$

where F_L is the wave induced vertical (lift) force, ρ_s and ρ_w are the densities of the fill sand (dry) and water, g is gravity and V the volume of the container.

Sliding displacement: Sliding occurs when wave-induced horizontal forces exceed the resisting forces, i.e. the weight of the container minus vertical force at the analyzed time step multiplied by the friction factor. Therefore, container is stable against sliding if:

$$F_D \leq [(\rho_s - \rho_w)gV - F_L]\mu \quad (10)$$

where F_D is the wave induced horizontal force and μ is the friction factor between geotextiles (or geotextile and sand).

It should be noted that pure sliding displacement can only occur when the incident wavelength is at least twice the length of the container. This ensures that at one point in time, the container will be acted upon by upward forces along its entire length. With shorter wavelengths, a portion of the container will have downward directed force concurrent with upward directed forces.

The results for individual containers are depicted in Figure 6. The seaward container in the middle layer was determined to be the most critical in terms of stability. Although the container is predicted to be stable, it is only by a small margin, with a horizontal mobilizing force of 5.1 kN resisted by 6.7 kN. For the seaward container on the upper layer of the reef, the numerical simulations show that the critical scenario is when a wave breaks directly on the container, however, the container remains stable under those conditions. With larger waves, breaking occurs further offshore, resulting in lower forces at the container itself.

Regarding the relative magnitudes of the wave induced forces, the vertical forces are created through lift, while the horizontal forces are created through drag. Because the lift force is determined by integration over the area of the container projected in the vertical direction, it is generally greater than the horizontal force caused by drag. Although the horizontal force generated during impact are much higher than the lift pressures acting on the container, the uplift forces are integrated over a larger area than the horizontal forces, thus resulting in a larger total force in the vertical direction.

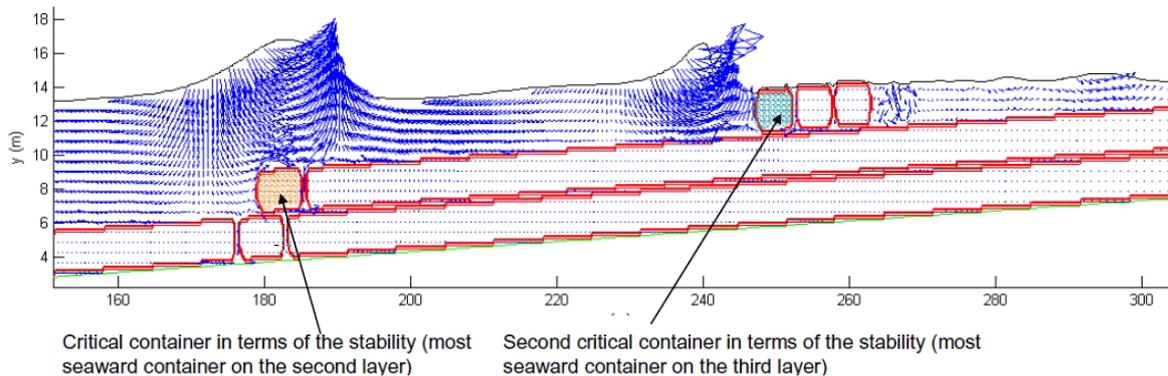


Figure 5. Cross section of the Narrowneck Reef used in the numerical stability analysis and numerical results of the forces acting on the seaward crest containers in the second and third layers.

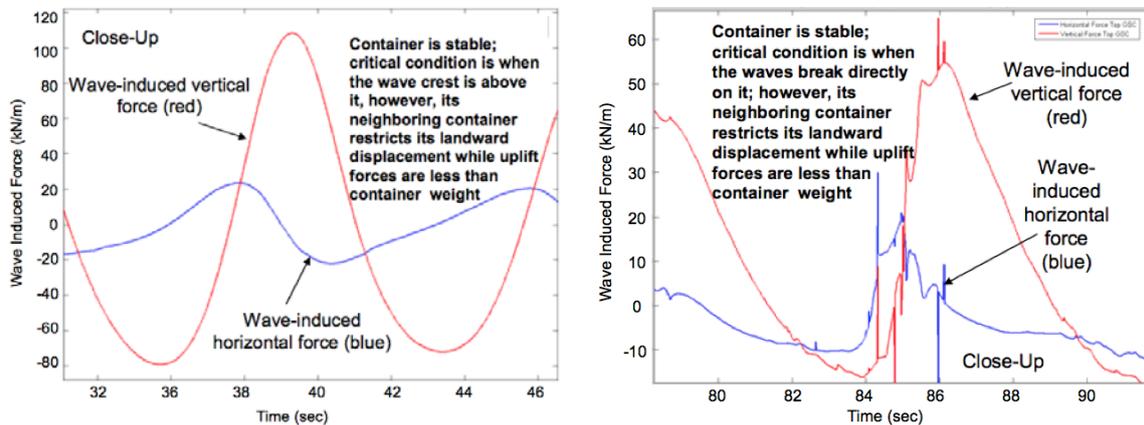


Figure 6. Numerical results of the forces acting on the seaward containers of the middle and top layers.

Pratte's Reef, California, USA: Deficient Design and SFC Failures

Pratte's Reef was a multipurpose reef project built in El Segundo, California. The structure was envisioned as a surfing reef to mitigate for lost surfing opportunities after construction of a groyne and associated beach nourishment resulted in the degradation of several well known surfing locations. The reef was designed as a small, submerged breakwater composed of 110 sand filled geotextile containers, each containing a maximum volume of 7.9 m^3 – (see Figure 1). Each bag was filled to between 80 and 90% capacity due to restrictions imposed by the equipment used to fill and close the bags.

Initial construction of Pratte's Reef took place in September, 2000. The SFC's were dry-filled and transported by a barge to the reef site. A barge-mounted crane was used to individually place the containers into position. After the initial installation, the depth at the outermost point of the reef was approximately 1.8 m below MLLW. A second set of SFC's was added in April 2001. Ninety new bags were installed increasing the reef volume by 80%. The crest of the reef was widened and made shallower, to within 1 m of MLLW. The new bags were placed directly over the phase 1 bags, which had been largely covered in sand that had moved offshore during the winter.

After construction, a comprehensive monitoring program (Borrero and Nelsen, 2003) was conducted to assess the reef performance. The monitoring program included beach profiles, offshore bathymetric surveys, surf observations and underwater dive surveys. During various dive surveys, evidence of deterioration and degradation of the sand bags was noted. A survey in August 2002 revealed that several reef bag units were ripped and were losing their fill material as shown in Figure 7.

Two types of SFC's were used in the construction of Pratte's Reef. Of the two, the woven polypropylene (black) containers were more prone to failure as the weave pattern was such that small tears would loosen adjacent fibres and the allow the rip to propagate across the bag, releasing the material inside. Containers using a different weave patterns did not fail in such a manner. Unfortunately detailed information on these containers is not available.

In addition to the material, the failure of the containers can be related to, the size of the containers, the filling method and manner of installation. The containers used for Pratte's Reef were small, only 7.9 m^3 in volume, and were not tightly filled. Thus, sections of the geotextile would move under wave activity leading to tears and eventual failure. Furthermore, by using a crane to place the SFC's, the weight of each container caused small rips to form where the lifting straps were sewn on. These rips gradually increased under wave activity until the container failed. It should be noted that no formal stability calculations were undertaken as part of the reef design. This resulted in the use of significantly undersized containers. The low weight and small and footprint of the containers allowed for movement under wave action leading to scour and self-burial. Pratte's reef never met its intended goals due primarily to the deficient design process and incredibly small budget for such a project. The mostly buried remnants of Pratte's Reef were removed in late 2008 (Liedersdorf et al., 2008).



Figure 7. Remnants of a ripped SFC at Pratte's Reef in August 2002.

The Mount Reef, New Zealand: Settlement and Scour

The Mount Reef is located at Mount Maunganui on the Bay of Plenty coast of the North Island of New Zealand. The reef is an experimental project designed to enhance local surfing conditions. The reef was constructed from large sand filled geotextile containers (see Figure 1 for scale). The empty SFC's were loaded on to a barge, towed into position, anchored to the sea bed and pumped full of sand by a hydraulic dredge pump operated from a floating platform nearby. Construction of the reef was hampered by inexperienced contractors using inappropriate equipment. The construction process was further muddled by the inability of the construction team to rapidly mobilise to take advantage of fleeting construction windows. Eventually the construction budget was exhausted by the primary contractor with only 60% of the specified 5,000 m³ reef in place. Despite these setbacks, the reef has succeeded in producing high-quality surfing waves when the appropriate wave conditions are present (Figure 8).

This case study however focuses on the stability of the SFC units, specifically related to subsidence and scour. Throughout its history, the reef was regularly surveyed to assess changes in local bathymetry and crest levels of the reef. The data collected in 14 bathymetric surveys carried out between late 2005 and early 2009 has been used to establish the nature of local bathymetric changes around the reef and to assess any changes in the crest height of the reef over time.

Figure 9 details transects extracted from the three most recent bathymetry surveys. The transects are positioned over each reef arm and the offshore apex of the reef. The data suggests that over this time period the reef crest is relatively stable and no large scale settlement of the crest has occurred. Analysis of the complete set of transects however shows an over all reduction in the crest height that ranges from 0.22 to 0.69 m over the 3+ years of monitoring. This value is in accordance with the 0.5 m of assumed settlement that was factored into the design of this and other SFC multipurpose reef structures.

Figure 10 plots a shore perpendicular bathymetry transect passing through the apex of the reef structure (see Figure 9 for location). While the absolute crest height has remained relatively stable, the total crest height has subsided by approximately 0.5 m. The bathymetry transects also indicate the formation of a scour feature directly inshore of the reef. This scour feature has reached a state of dynamic equilibrium and is balanced by material accreting along the shoreline.



Figure 8. (Left, top and bottom) Construction of the Mount Reef, laying out the SFC's on land and deploying them off of a barge prior to filling. (Center) Reef design layout and location, inset is a current aerial photograph of the reef including additional containers added at the offshore apex. (Right, top and bottom) Waves breaking and being ridden on the Mount Reef.

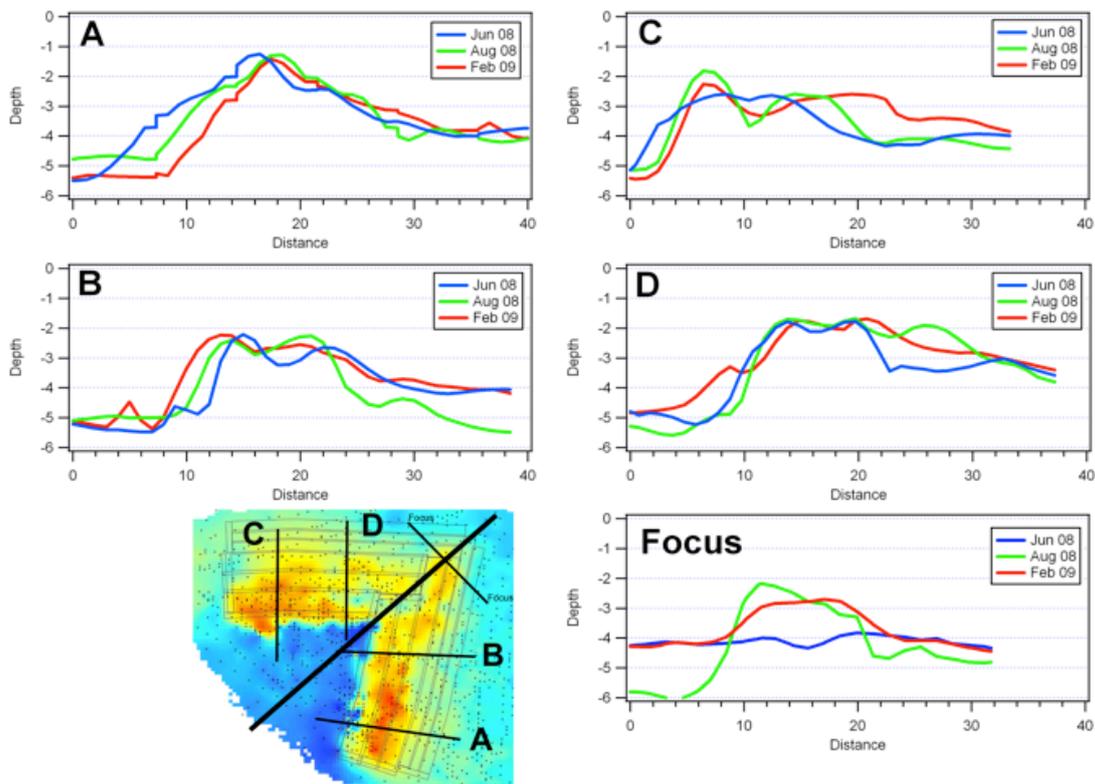


Figure 9. Transects extracted from surveys of the Mount Reef conducted in June 2009 (blue), August 2009 (green) and February 2010 (red). Transects A-D and the focus are shown in this figure while depths along the long diagonal transect are plotted in Figure 10.

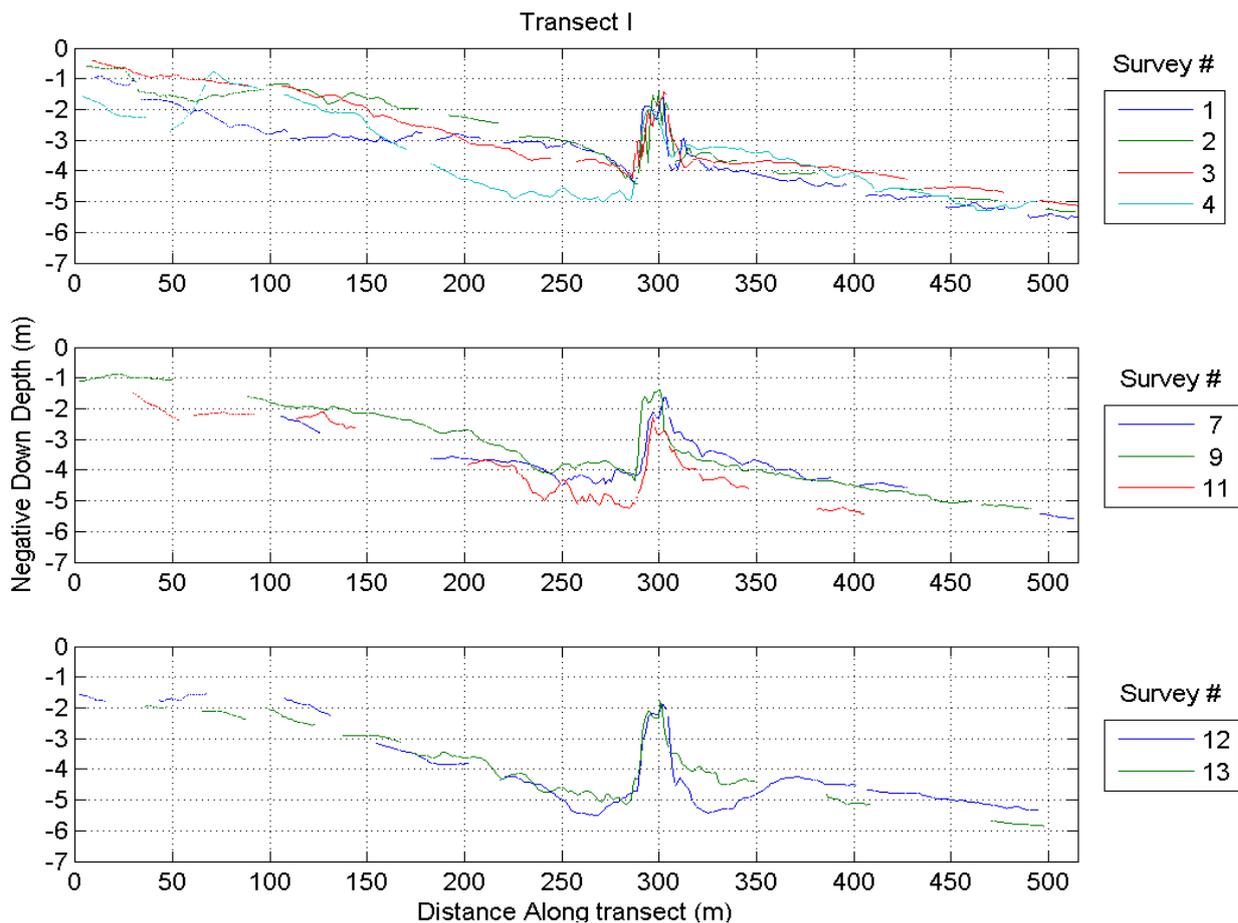


Figure 10. Transects extracted from surveys of the Mount Reef conducted in June 2009 (blue), August 2009 (green)

The Boscombe Reef, England

The Boscombe Reef is a multipurpose reef constructed from large SFC's and located in Boscombe on England's southern Channel coast. Details of the reef design and construction are given in Mead et al. 2010 (this volume). Briefly, the reef was designed as a recreational structure to improve and enhance surfing and bodyboarding adjacent to the Boscombe Pier. The reef was conceived as part of a large scale redevelopment plan and was envisioned as a tourist attraction and leisure amenity that would differentiate the area from other seaside towns. The biggest design challenge however was the inconsistent and generally weak surfing wave climate which exists in the central English channel. This was taken in to account in the design of the reef which featured a broad shape designed to focus and maximise the limited wave energy at the site.

In response to the difficulties experienced during construction of the Mount Reef, a specialised construction team was formed to undertake the in-situ installation and filling of the large SFC's used in the Boscombe reef. The sectional approach used at the Mount Reef for deploying multiple, empty geotextile containers and anchoring them to the seabed prior to filling was abandoned during construction of the Boscombe reef in favor of a single container deployment method which allowed for greater placement accuracy and reduce the potential for damaged or lost containers if inclement weather set in before the containers could be filled. The containers were filled by a land based pumping system which delivered a sand slurry over 400 m out to the reef site (Figure 11).

In terms of stability, the Boscombe reef has not suffered from any container failures. The reef actively monitored and surveyed to look for container damage. Regular bathymetry surveys are conducted to monitor subsidence and excessive scour. So far, the monitoring results have failed to reveal anything unexpected or unusual.



Figure 11 The partially completed reef in the early summer of 2009. Note the tightly spaced and highly accurate placement of the geotextile containers.

A MODIFIED PROCEDURE FOR SFC STABILITY ANALYSIS

Because the analysis of Recio and Oumeraci (2009) is based on a force balance approach, the governing relationships can be adapted to reflect more accurately the geometry of the SFC's used in multipurpose reef applications. While their method assumes a rectangular block like geometry for the containers, in practice the units are long and slender with curved sides and a roughly elliptical cross sectional shape whose area is known *a priori* (Figure 12). Using the cross sectional area and the overall container length is a more conservative approach as it results in a smaller volume and lower computed resisting forces. With this approach, the fundamental relationships described in Equations (2 – 6) are solved directly. By implementing this calculation in a spreadsheet, different dimensions can be rapidly trialled as a first order assessment of the geocontainer stability.

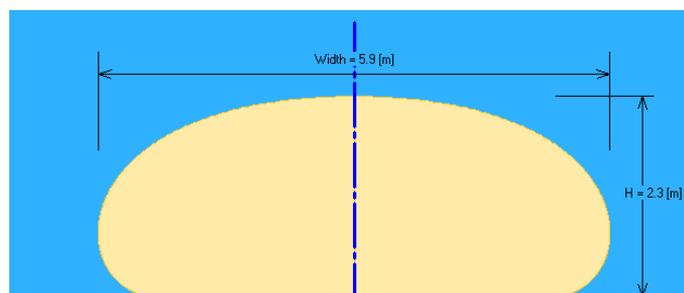


Figure 12 A cross section of a typical SFC, the cross sectional area is 11.4 m².

SUMMARY AND CONCLUSIONS

The stability of large, sand filled geotextile containers is an important consideration for their use in submerged or low crested coastal structures. While the very large mass of such containers makes them generally stable under typical wave loads, other factors are important for determining stability. These factors include the strength of the geotextile material itself, the strength of the seams sewn during container fabrication, settlement and readjustment of the fill material inside the container - as well as scour around the structure.

Case studies of structures built from large SFC's suggest that when properly designed and installed, SFC's can be highly stable even under extreme wave loads. The case studies also highlight the first order importance of the characteristics of the geotextile material, such as the type of weave, its tensile strength and resistance to

puncture and abrasion. Construction methods for SFC's also relate to the overall stability. Under-filled containers have sections of material that can move under wave action leading to failure, while over filling or over pressurizing the containers during filling can weaken the material or seams, making the SFC prone to future failure. The container filling ports must be properly closed to ensure that the fill material cannot escape.

Stability formulae for design guidance using SFC's does exist. The most recent set of stability formula are based on an extensive series of laboratory scale modeling. These formulas are based on a force balance approach and the governing relationships can be easily evaluated as a first order assessment of SFC stability.

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