Designed Reefs for Reef and Coastal Restoration and Erosion Potential Applications for the City of Herzlia, Israel

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Abstract

This paper presents technologies using custom designed (sometime referred to as artificial) reefs for reef ecosystem restoration and coastal erosion protection, with the added amenities of environmental enhancement and recreation. These projects include post-tsunami and post-hurricane reef restoration with coral rescue and propagation techniques, and designed reef submerged breakwaters for beach restoration and stabilization. Project sites include Florida, Thailand, and the Caribbean, where recreational and ecotourism amenities are essential design elements.

Wide crested submerged breakwaters can provide shoreline stabilization by mimicking the functionality of natural reefs. Recent submerged breakwater projects constructed using designed reefs in shallow water reduce wave energy reaching the shore, while also providing the environmental and recreational benefits associated with natural reefs. These benefits and applications include providing marine habitat, mitigation of damages, and enhancing recreational benefits such as swimming, snorkeling, diving, fishing and surfing.

Introduction

Although beach nourishment often is considered as the most effective methodology for shoreline stabilization, especially in the United States and Florida in particular, it is not economically or environmentally suitable for some sites. Even successful beach nourishment projects such as Miami Beach, Florida have required coastal structures to assist in stabilizing the beach at “hot spots” that erode at higher rates than adjacent areas.

The projects presented in this paper include submerged breakwaters designed to assist with shoreline stabilization. Coastal engineering applications include nearshore sills for perched beaches, offshore breakwaters for wave refraction and attenuation, and other coastal structures associated with stabilizing shorelines, including assisting with beach nourishment projects. These structures may be constructed of rock, concrete, steel and other traditional “hard” materials; or “soft” materials such as geosynthetics used as filter cloth foundations and/or sand-filled container systems. Submerged sand-filled container systems have been referred to as artificial reefs, but also could be referred to as artificial sandbars.

Shoreline Stabilization by Submerged Breakwaters

There are many examples in nature where natural reefs act as submerged offshore breakwaters, contributing to the stability of the beaches in their lee. Submerged breakwaters can assist with shoreline stabilization, while minimizing adverse impacts on adjacent beaches. There are two mechanisms by which submerged breakwaters can assist with stabilizing shorelines: (1) wave attenuation and (2) wave refraction, which are discussed in the following paragraphs.

As the name "breakwater" implies, the submerged breakwater can be designed so that the larger waves are forced to break on the structure, reducing the wave energy that reaches the shore. This wave attenuation is quantified by the wave transmission coefficient, which is the ratio of the transmitted wave height to the incident wave height. Due to the complexities in wave breaking, physical and numerical model tests are performed to determine the wave transmission coefficients for various breakwater configurations and materials (Harris and Friebel, in press).

Unlike traditional emergent breakwaters (also known as subaerial breakwaters), for which the wave attenuation decreases with increasing wave height, for submerged breakwaters the wave attenuation generally increases with increasing wave height. During periods of smaller waves, little or no wave attenuation occurs, with the waves passing unaffected over the submerged structure. This allows the normal coastal processes to occur in the lee of the reef without disruption, thereby minimizing any adverse effects on adjacent beaches. During periods of larger waves, the submerged breakwater forces the waves to break, reducing the wave energy reaching the shore, and reducing the erosion of the beaches.

Even if the waves do not break on the submerged breakwaters, they can still assist with shoreline stabilization due to wave refraction effects. When waves break at an angle to the shoreline, a longshore current is generated that can transport sand down the coast. The greater the angle of the waves to the shoreline, the greater the magnitudes of the longshore current and littoral transport of sand. As waves enter shallower water, they refract and bend to become more nearly parallel to the shoreline. For waves traveling across sufficiently wide and shallow submerged breakwaters, this wave refraction or "wave rotation" can reduce the magnitude of the longshore current and sand transport, hence reducing sand losses from an area (Mead and Black, 2002).

Reef Ball™ Reef Units

One of the designed reef units that have been used to construct submerged breakwaters is the Reef Ball™ reef unit, shown in Figure 1, with data on available sizes and weights in Table 1. Variations of this reef unit include the "Layer Cake" reef unit, also shown in Figure 1. Originally designed as reef units for habitat enhancement in deeper water depths, Reef Ball units have several advantages over traditional breakwater materials, including:

1. easy and economical on-site fabrication using a patented mold system, as shown in Figure 2,
2. easy and economical deployment of the units by floating them using lift bags (not requiring barges and cranes, see Figure 3),
3. ability to anchor the units to the bottom (covered later), and
4. units can be custom designed as habitat for selected benthic and pelagic species, including aquaculture applications and transplanting and propagation of corals.

Figure 1. Traditional Reef Ball™ Unit (L) and "Layer Cake" Reef Ball Unit (R)

Table 1. Available Reef Ball Unit Sizes (smaller sizes are also available)

Style	***Width***	***Height***	***Weight***	***Concrete Volume***	***# Holes***
Goliath Ball	6 feet (1.83m)	5 feet (1.52m)	4,000-6,000 lbs (1800-2700 kg)	1.3 yard (1.0 m3)	25-40
Super Ball	6 feet (1.83m)	4.5 feet (1.37m)	4,000-6,000 lbs (1800-2700 kg)	1.3 yard (1.0 m3)	22-34
Ultra Ball	5.5 feet (1.83m)	4.3 feet (1.31m)	3,500-4,500 lbs (1600-2000 kg)	0.9 yard (0.7m3)	22-34
Reef Ball	6 feet (1.83m)	3.8 feet (1.22m)	3000-4200 lbs (1350-1900 kg)	0.75 yard (0.6m3)	22-34
Pallet Ball	4 feet (1.22m)	2.9 feet (0.9m)	1500-2200 lbs (700-1000 kg)	0.33 yard (0.25m3)	17-24
Bay Ball	3 feet (0.9m)	2 feet (0.61m)	375-750 lbs (170-340 kg)	0.10 yard (0.08m3)	11-16
Mini-Bay Ball	2.5 feet (0.76m)	1.75 feet (0.53m)	150-200 lbs (70-90 kg)	less than four 50 lb bags	8-12
Lo-Pro Ball	2 feet (0.61m)	1.5 feet (0.46m)	80-130 lbs (35-60 kg)	less than two 50 lb bags	6-10
Oyster Ball	1.5 feet (0.46m)	1 foot (0.30m)	30-45 lbs (15-20 kg)	less than one 50 lb bag	6-8

Custom designed reef units such as the Reef Ball™ have been designed to attract and provide habitat for fish, lobster, and other marine life. Each Reef Ball module on average produces about 180 kilograms (400 lbs) of biomass annually. A special concrete mix using special additives was developed that allows the Reef Ball modules to be deployed within 24 to 48 hours of being fabricated, and with special formulations that reduce the concrete pH to match that of natural seawater. The pH balancing and unique textured surface of the Reef Ball modules ensures that coral larvae and other marine life can easily attach to the modules to develop into a natural biological reef.

Figure 2. Traditional Reef Ball Unit Mold Fabrication

Concrete is poured into the top of the assembled mold, as shown on the left, with an inflated buoy located in the center to form the hollow interior, and smaller balls fastened to the mold pieces for external holes. After hardening, the buoy is deflated and removed, and the mold is removed, leaving the completed Reef Ball as shown in the photograph on the right.

Figure 3. Deployment by Floating Reef Ball Units from Beach

Fabricated units awaiting deployment can be seen in the background.

Reef Ball Submerged Breakwaters

A new application for Reef Balls was developed for shoreline stabilization, using Reef Ball reef units to construct submerged breakwaters. Physical model tests have been performed to evaluate the stability of the individual units, and to test the wave attenuation of various configurations and numbers of rows of units deployed as submerged breakwaters.

The first submerged breakwater project constructed using Reef Ball™ reef units was along the southern Caribbean shore of the Dominican Republic during the summer 1998. Figure 4 shows the three-row Reef Ball submerged breakwater. Approximately 450 Reef Ball™ reef units were installed to form a submerged breakwater for shoreline stabilization, environmental enhancement and eco-tourism. The individual units used for the breakwater were 1.2m high Reef Ball units and 1.3m high Ultra Ball units, with base diameters of 1.5 and 1.6 meters, respectively, and masses of 1600 to 2000 kilograms. The breakwater was installed in water depths of 1.6m to 2.0m, so that the units were 0.3m to 0.8m below the mean water level (the tide range in the project area is approximately 0.4m).

Figure 4. Gran Dominicus 3-Row Reef Ball Submerged Breakwater (Harris, 2003)

In the fall of 1998 shortly after the installation of the breakwater system, a direct hit by Hurricane Georges (Category 3) and large waves from Hurricane Mitch (Category 5) impacted the project area, but not a single Reef Ball™ unit was displaced or damaged. The beach profile shown in Figure 5 shows that the Reef Ball™ breakwater has been very effective in stabilizing the beach, with a significant increase in beach width and elevation along the project shoreline.

Shoreline and sand volume calculations are shown in Table 1. As shown in Figure 6, the beach and shoreline in the lee of the submerged breakwater system has been stabilized and has accreted sand, and there have been no adverse impacts on adjacent beaches. In addition, the use of designed reef units for the breakwater provides habitat enhancement for the marine life, which can be enjoyed by divers and snorkelers.

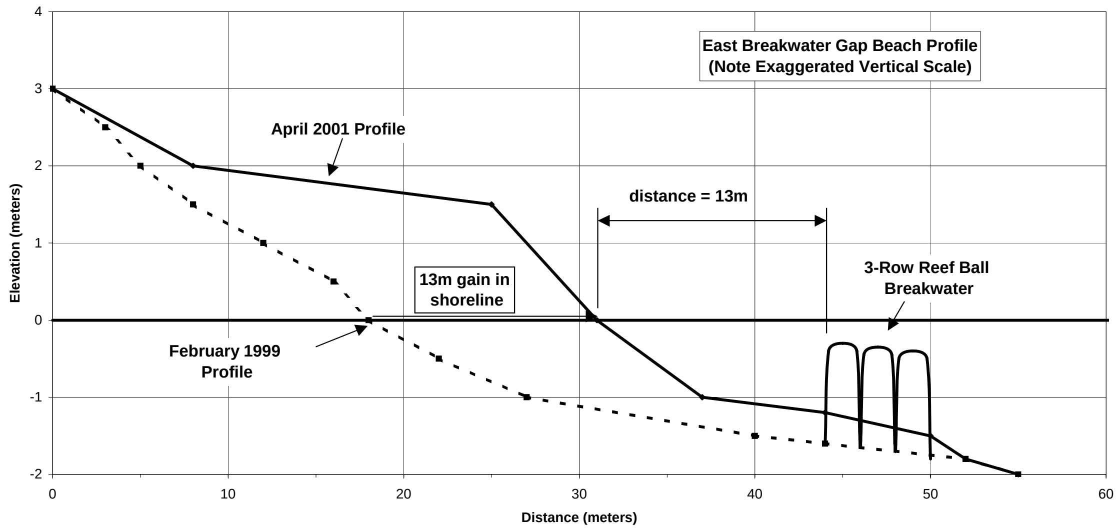

Figure 5. Beach Profile across Breakwater at Gran Dominicus (Harris, 2003)

Table 2. Changes in Shoreline and Sand Volume Calculations 1998 to 2001

Profile Line	Shoreline Change (meters)	Sand Volume Change (m^3/m)
West	+10 m	+25.65 m^3/m
East	+13 m	+44.25 m^3/m
Control	0 m	+2.0 m^3/m

Figure 6. Increased Beach Width at Gran Dominicus– 1998 (Left) to 2001 (Right)

Other Reef Ball submerged breakwaters have been constructed in other parts of the Caribbean including the Cayman Islands. This 5-row submerged Reef Ball breakwater, shown in Figure 7, was constructed in 2002, and is located offshore of the Marriott Beach Resort at the south end of Seven Mile Beach on Grand Cayman Island. The before and after photographs shown in Figures 8 and 9 show the successful beach stabilization, even with Hurricane Ivan impacting the area in 2005 and other wave impacts from more distant storms.

Figure 7. Five-Row Reef Ball Submerged Breakwater offshore of the Grand Cayman Marriott Beach Resort

Figure 8. Marriott Beach before Reef Ball Breakwater Installation (on the left, Fall 2002) and after the Reef Ball Breakwater Installation (on the right, February 2003)

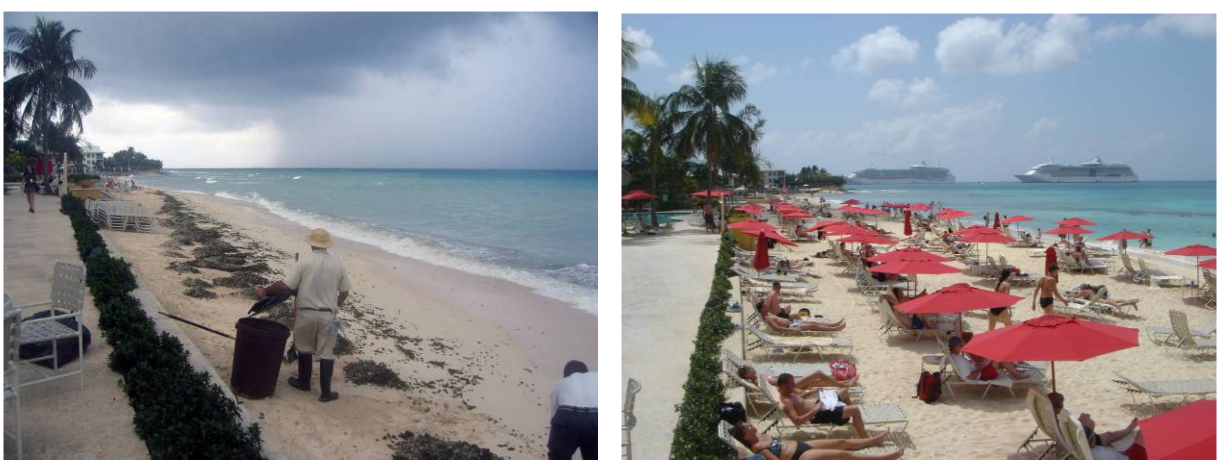

Figure 9. Grand Cayman Marriott - November 2006 (L) and February 2007 (R)

The breakwater reef units have remained stable during waves from major hurricanes, including the direct hit by Category 5 Hurricane Ivan in 2005 (Figure 10 shows breakwater and beach with no damages, but damages to upland buildings which forced its demolition) and large waves from

Category 5 Hurricane Wilma (as shown in Figure10). An overall comparison of before and after breakwater conditions is shown in Figure 11 below.

Figure 10. 2005 Photos: Hurricane Ivan Damaged Upland Buildings but not the Reef Ball Breakwater or Beach (L), Waves from Hurricane Wilma striking the Marriott Seawall (R)

Figure 11. Marriott Beach before Reef Ball Breakwater Installation (on the left, Fall 2002) and after the Reef Ball Breakwater Installation (on the right, February 2007)

Environmental and Recreational Enhancements

Depending on the materials used to construct submerged breakwaters, they may act as natural reefs, providing habitat for benthic and pelagic flora and fauna. Designed reefs are also used for mitigation of damages caused by burial and sedimentation on natural reefs due to dredging or beach nourishment projects, and can be used for aquaculture and eco-tourism.

In addition to the natural marine growth, hard and soft corals can be transplanted and propagated on designed reef units. The reef units provide stable bases upon which coral can be attached, as shown in Figure 12. Corals can be moved from areas that have been or will be damaged from ship groundings, storms, dredging or other natural or man-made activities. Figure 13 shows Staghorn coral growth on Reef Ball reef units in Curacao, and Figure 14 shows the rapid growth of *Acropora* corals propagated on the Reef Ball breakwater units in Antigua (both sites in the Caribbean). Natural coral growth on a Reef Ball unit in Indonesia after five years is shown in Figure 15. Designed reefs can be used for aquaculture applications, including fish and lobsters.

Figure 12. Coral Transplants and Propagation

Figure 13. Staghorn Coral Propagation Growth in Curacao (Reef Ball Foundation)

Figure 14. Coral Propagation Growth on Reef Ball Breakwater (Reef Ball Foundation)
Coral plug growth from November 2003 to June 2004 in Antigua.

Figure 15. Coral Growth on Reef Ball after 5 Years in Indonesia (Reef Ball Foundation)

For recreational enhancement, designed reef units can be designed as snorkel and diving trails. Figure 16 shows a 5-row submerged breakwater being completed in Antigua, which has gaps and special areas designed for use by swimmers, snorkelers and divers.

Figure 16. Aerial Photograph of 5-Row Reef Ball Breakwater in Antigua
The breakwater also incorporates snorkel trails, swimming and diving areas.)

Reef Stability, Scour and Settlement

Stability, scour and settlement are much greater design problems for reef units deployed as submerged breakwaters in shallow water, and many experimental projects have undergone substantial settlement due to scour (Stauble, 2003). Submerged breakwaters must be designed to withstand the large forces due to breaking waves, wave induced currents, and scour that occurs in the surf zone. Both settlement and burial by sedimentation are important design considerations.

For reef units placed on hard bottom where settlement and scour cannot occur, the concerns are the strength of the units and resistance to movement by sliding or overturning. The weights of the individual units contribute to their resistance to movement, and the units can be pinned to the bottom for additional stability. When placed on sand in shallow water, reef units are very susceptible to scour and settlement (Smith, Harris, and Tabar, 1998). Two methods have been developed to increase the reef unit stability and resistance to movement, as well as minimizing problems due to scour and settlement of reef units:

1. rods or pilings driven or jetted through the reef units into the bottom (Figure 17) and
2. attaching the reef units to an articulated mat (Figure 18).

The pilings and rods go through the reef unit and into the bottom at an angle, so that the reef units will resist both movement and settlement.

Figure 17. Pilings (left) and Rods (right) into Sea Bottom through Reef Ball Units

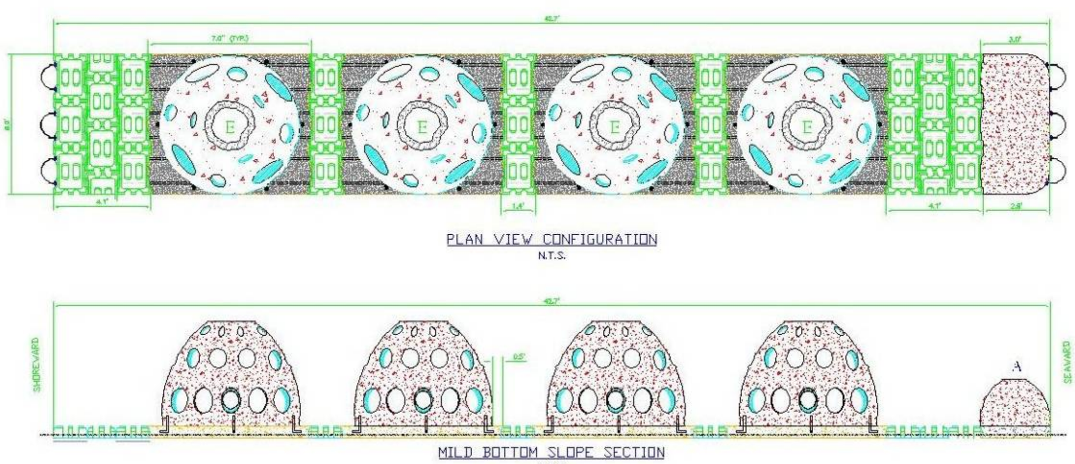

Figure 18. Reef Ball Units on Articulated Mat (Harris, Turk, & Mead, 2004))

Conclusions

Reefs and their ecosystems are some of the most productive and biologically rich on earth. Natural events such as storms and climate change in addition to human activities can damage and cause stresses on these fragile systems. Preservation and conservation efforts need to remain a top priority, as well as restoration of damaged reefs and the creation of new ecosystems to replace those that have been lost.

Designed reefs have been successfully used to construct submerged breakwaters for shoreline stabilization. These systems mimic natural reefs in reducing the wave energy that reaches the shore. Special design considerations are necessary to ensure that man-made reefs will be stable, durable, and provide the intended purposes. Anchoring of reef units may be necessary in shallow water or due to forces by large waves or strong currents. In addition to the coastal erosion protection, environmental, aquaculture, and recreational amenities can be provided by these systems. This includes environmental mitigation and enhancement, increased habitat for marine life, benthic and pelagic aquaculture applications, and recreational benefits including swimming, snorkeling, diving, fishing and surfing.

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