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The Use of Submerged Narrow-Crested Breakwaters for Shoreline Erosion Control

Donald K. Stauble† and Jeffery R. Tabar‡

†U.S. Army Engineer Research and Development Center
Coastal and Hydraulics Laboratory
3909 Halls Ferry Road
Vicksburg, MS 39180, USA

‡PBS&J
Coastal Engineering Division
5300 West Cypress Street, Suite 300
Tampa, FL 33607, USA

ABSTRACT

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The performance of six installations of modular narrow-crested submerged breakwaters constructed of prefabricated concrete has been reviewed as a possible lower cost shoreline erosion prevention device. Two types of breakwaters that have been deployed since 1988, are reviewed here. Three Prefabricated Erosion Prevention (P.E.P.) Reefs™ have been constructed and monitored to assess performance at three sites on the lower central east coast of Florida, two in Palm Beach County and one in Indian River County. Three Beachsaver Reefs™ have been installed along the New Jersey Coast, two in Cape May County and one in Monmouth County. Both types of reef breakwaters have similar dimensions and are triangular in cross-section. The objective of these relatively low cost reef structures were to reduce wave heights, maintain a stable shoreline position, retain the existing volume of sand on the beach and protect the beach from storm waves. All six projects have been monitored for at least two years after installation. The monitoring evaluated the change in the position of a project defined shoreline, the volume of sand gained or lost behind the breakwater as well as control areas adjacent to the reef installation, settlement of the structure, scour around the base of the units and the amount of wave attenuation afforded by the structure. The installation configurations differ along with coastal morphology, underlying geology, coastal processes and placement relative to other shore protection structures. All of the installations measured scour at the landward side of the reef. This scour along with turbulence induced by waves interacting with the return flow deflected upward by the reef shape resulted in settlement of the reef over a two to six month period after installation. The settlement was mitigated by the use of a geotextile mattress and filter cloth on two of the projects. With and without settlement of the reef, the wave transmission was around 10% for all of the installations. The three Florida projects placed the P.E.P. Reef some distance off the beach in a shore parallel configuration. Two of the projects had a single solid reef line resulting in structure induced scour and erosion of the beach. The third placement was modified to a staggered inshore and offshore placement with gaps between the segments. All of the projects measured erosion or less accretion behind the reef relative to the control areas. The three New Jersey projects placed the Beachsaver Reef adjacent to groins, with one project semi-enclosed adjacent to an inlet terminal groin and the other two completely across the seaward end of groin compartments, forming a perched beach. Beach fills were also placed as part of the initial installation on two of the projects. The two locations that were completely enclosed in groin compartments retained the most sand.

ADDITIONAL INDEX WORDS: *Prefabricated concrete breakwaters, narrow-crested submerged breakwaters, shoreline change, beach sand volume change, scour at structures, wave attenuation, settlement of structures, breakwater performance evaluation.*

INTRODUCTION

With increasing erosion pressures and limited resources, alternative methods of shore protection are needed to protect upland property and provide recreational and environmental habitat at a lower cost than conventional techniques. One such alternative method that has been tried in recent years has been the submerged prefabricated modular breakwater or artificial reef unit. The purpose of this type of structure is to attenuate waves and provide shoreline stabilization. Six such deployments have been monitored over the past decade to assess their usefulness as an erosion prevention tool. This paper will review their performance.

The most common type of detached breakwater in use today is the shore-parallel rubble mound structure. These types of structures were usually emergent, constructed out of some type of natural rock material or concrete units, and placed some distance seaward of the shoreline. Some deployments are a single structure and some are segmented with gaps between the structures. Design guidance is available on this type of shore protection structure (CHASTEN *et al.,* 1993). Project design and performance data are available in DALLY and POPE (1986), POPE and DEAN (1986), KRAFFT and HERBICH (1989), CHASTEN *et al.* (1994) and BASCO (2001).

A modification to this traditional concept is a submerged breakwater. These so-called reef breakwaters are usually shallow, narrow-crested rubble mounds, with a crest height below the still water level, and without a traditional multilayer cross section (AHRENS, 1987). They are applied to provide partial attenuation of waves to protect a beach. Since they are below still water, they are not visible from the beach. As waves encounter the structure, they shoal and break dissipating some of their energy as they pass over the crest. Theses structures can also be less costly to build than other shore protection options. Performance characteristics of wave transmission, wave reflection and energy dissipation have been determined by laboratory model tests (AHRENS, 1987; AHRENS and FULFORD, 1988). These tests showed that the submerged breakwater caused premature breaking of waves, therefore dissipating wave energy more than a natural sloping beach. Submerged breakwaters dissipated between 17 and 56 percent of the wave energy in tank tests (AHRENS and FULFORD, 1988). Reefs with small cross-sections had less influence on larger waves.

Several factors control the effectiveness of any submerged breakwater configuration including: breakwater dimensions, depth of water and placement distance offshore of the beach, the incident wave climate and the nearshore profile (DEAN *et al.,* 1994b; WAMSLEY *et al.,* 2002). The parameters of relative crest width and relative depth of submergence of the crest below the water surface were identified as significant parameters by DATTATRI *et al.* (1978). HARRIS (1996) has identified three types of low crested breakwaters (1) rubble mound with a trapezoidal cross section of rock or concrete, (2) prefabricated modular units constructed of concrete, timber or other materials and (3) flexible-membrane units constructed of concrete-, sand- or water-filled containers. Little is written on the design or performance of prefabricated modules or flexible membrane units (HARRIS, 1996).

Several different designs have emerged for the prefabricated narrow-crested concrete breakwater or artificial reef. These breakwaters consist of various configurations of modular units placed in the nearshore. GOLDSMITH *et al.* (1992) evaluated deployments of theses types of units in the 1970's and 1980's. They list 29 installations along the Atlantic, Great Lakes, Gulf of Mexico and Hawaii coasts of the United States.

Six projects have been monitored to some extent in the past decade using two types of prefabricated concrete breakwater configurations. The first type of unit is called P.E.P. Reef™ short for Prefabricated Erosion Prevention concrete breakwater (AMERICAN COASTAL ENGINEERING, 1993), which was installed in two separate experimental projects in Palm Beach County, FL at the Dupont property and at Midtown Palm Beach from 1988 through 1995. The third installation was in Indian River County, FL at Vero Beach in 1996. The first configuration of the P.E.P. Reef used at the Dupont property was constructed of reinforced concrete units that were 1.52 m (5 ft) high, 7.32 m (24 ft) long and 3.66 m (12 ft) wide (MITCHELL, 1994). Units used in the second Palm Beach and Vero Beach installation were modified to 1.83 m (6 ft) high, 3.66 m (12 ft) long and 4.57 m (15 ft) wide at the base with a 0.31 m (1.0 ft) crest width and weights of approximately 22.7 metric tons (25 tons). The units are made of reinforced concrete and cast offsite in a mold. They are then transported by barge and placed by crane in the nearshore adjacent to the beach in the Atlantic Ocean (Figure 1). The individual units were locked together, and placed parallel to shore in segments of various lengths and configurations, depending on the project location. The general triangular shape units have three openings just below the crest, and the flatter sloping face was oriented seaward. The design purpose of the P.E.P. Reef was to a) reduce wave height, b) stabilize the shoreline position, c) limit sediment volume changes in the vicinity of the breakwater, and d) lower wave energy landward of the breakwater during storms (AMERICAN COASTAL ENGINEERING, 1993).

A second design, called the Beachsaver™ breakwater unit was designed by Breakwaters International (CRETER *et al.,* 1994) and was installed in three project locations in New Jersey to test different configurations and site conditions. The first installation of this type of breakwater was in Long Island Sound at Oakwood, New York, in 1984. A shifting problem resulted in a redesign of the units. The initial open ocean deployment of these units was at Sea Isle City, New Jersey, in 1989. Two 61 m (200 ft) long breakwaters were placed in the Atlantic Ocean 76 m (250 ft) from shore and were monitored for 9 months by Lehigh and Drexel University researchers (HERRINGTON, 1988). The shoreline moved seaward some 21 m (69 ft) at the structure but uneven settlement of the individual units caused the removal of this installation. The State of New Jersey sponsored a pilot project to evaluate the Beachsaver Reef at Avalon, New Jersey adjacent to Townsends Inlet in July 1993. A second deployment was constructed at Cape May Point, New Jersey, in May 1994 in an area influenced with strong tidal currents at the entrance to Delaware Bay. The third placement was at Belmar/Spring Lake, New Jersey, in August 1994 along an open coast with high wave activity. All of theses projects placed Beachsaver units in shore-parallel locations adjacent to the beach in the Atlantic Ocean. Theses reinforced prefabricated concrete units have similar dimensions to the P.E.P. Reef and were 1.83 m (6 ft) high, 3.05 m (10 ft) long and 4.57 m (15 ft) wide, with a crest width of around 0.46 m (1.5 ft) and weigh around 19.1 metric tons (21 tons) (HERRINGTON and BRUNO, 1998). These individual units also interlock together to form longer reef structures. These units are also triangular and have a raised crest area with openings designed to allow water and sediment to pass through (Figure 2).

Both of theses prefabricated concrete breakwaters are considered narrow-crested due to their triangular shape with a smallest dimension at the crest width. Both types of units are placed with the longer flatter slopping face in the seaward direction and the steeper shorter sloping face toward the beach. The raised crest area on both types is designed to trip the waves as they pass over the units. The steeper slope of the shoreward face cause return flow under the breaker to be forced upward to enhance the wave tripping mechanism and any sand placed in suspension should be transported back toward the beach. Sand is then supposed to be trapped on the shoreward face preventing it from flowing offshore.

This paper is produced as part of a US Army Corps of Engineers Research and Development program authorized under Section 227 of the Water Resources and Development Act of 1996 called the National Shoreline Erosion Control Development and Demonstration Program. The focus of Section

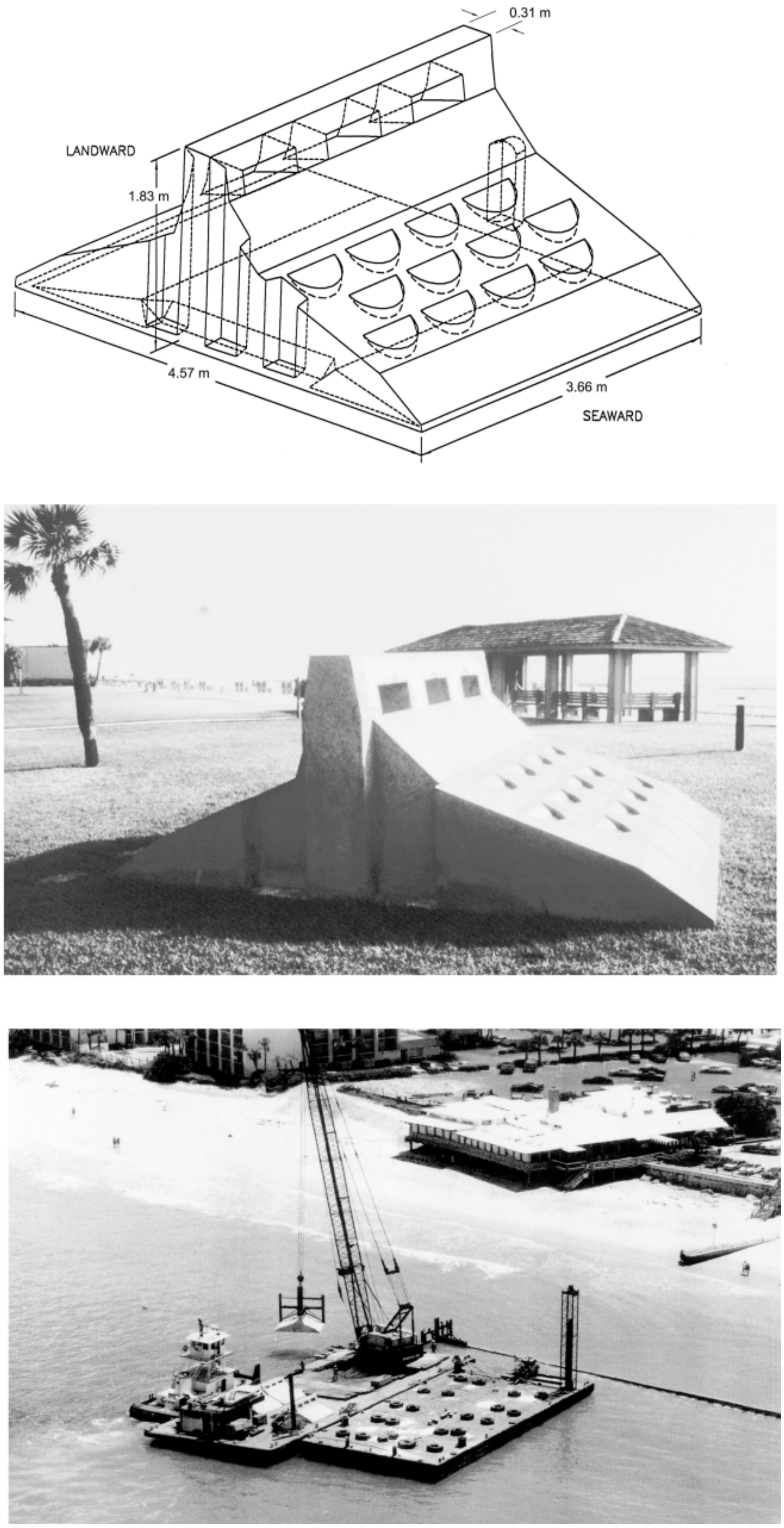

Figure 1. (a) Diagram of P.E.P. Reef unit, (b) photo of unit, and (c) placement of units at Vero Beach, FL (Stauble, 2002).

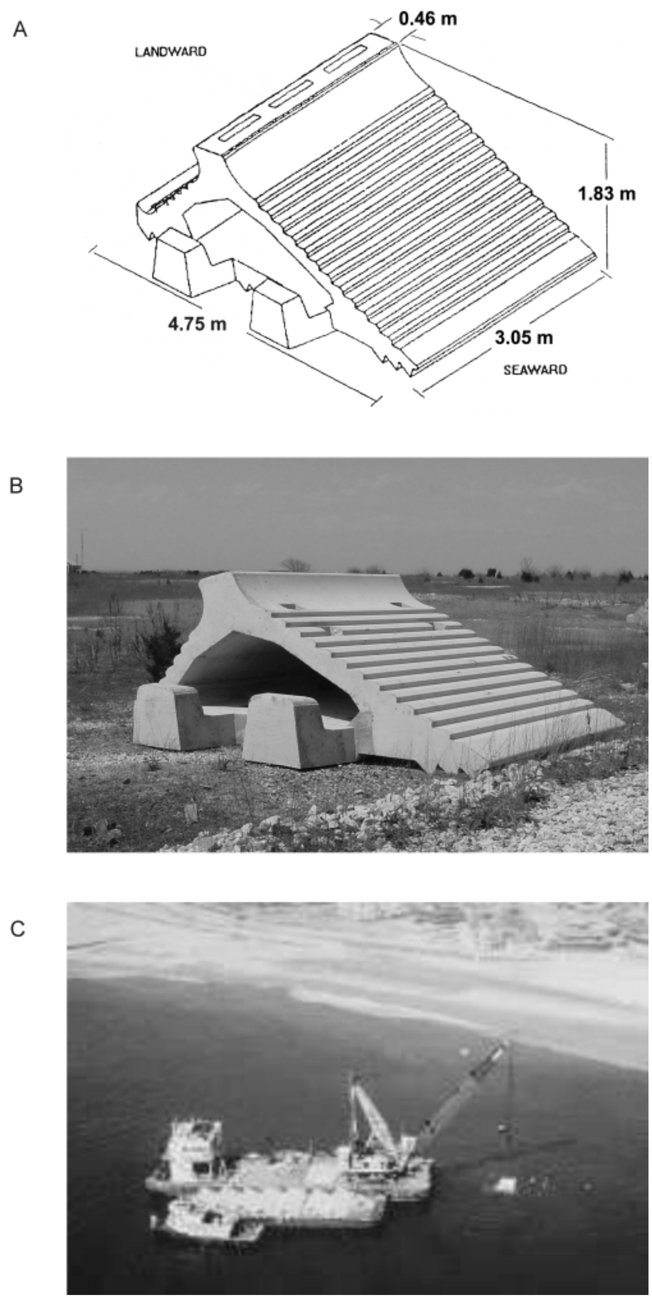

Figure 2. (a) Diagram of Beachsaver Reef unit (after Herrington and Bruno, 1998), (b) photo of unit, and (c) placement of unit at Avalon, New Jersey.

227 is the demonstration of prototype-scale "innovative" or "non-traditional" methods of shoreline erosion control. Studies under this program are investigating recent approaches in shoreline erosion control technologies. This review of the use of concrete prefabricated breakwater units is being investigated as one of these technologies.

The following section provides a detailed account of the six submerged breakwater projects and the findings. A brief introduction to each project is given describing the area of placement and configuration. Second, an overview of the monitoring program is presented identifying the areas and timeframe data was collected. Each program varied slightly, however, data was gathered through measurements of beach profile surveys, settlement of the units, scour at the base, and wave height reduction and structure induced currents to some degree for all projects. Monitoring results are presented in terms of shoreline response, sediment volume change, settlement, scour, wave attenuation, and current measurements. Lastly, a discussion of the performance is provided that characterizes the validity and outcome of each project.

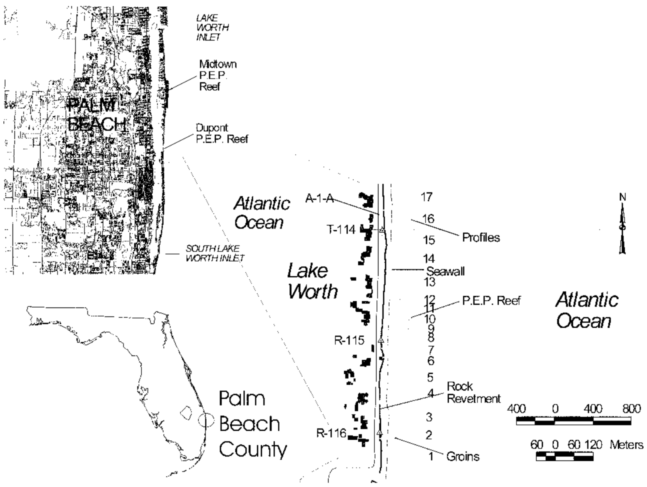

Figure 3. Location of the P.E.P. Reef installations at the Dupont property, Palm Beach County, Florida.

PALM BEACH, FL—DUPONT PROPERTY PROJECT

The first installation of the P.E.P. Reef was in May 1988. A 23-unit breakwater was placed in a continuous 168 m (552 ft) long line, located 53 m (175 ft) offshore of the mean high water line in about −2.4 m (−8 ft) NGVD of water at the Dupont property on the Atlantic Ocean in Palm Beach County, Florida (MITCHELL, 1994). This property had suffered shoreline erosion in the Thanksgiving Storm of 1984. Florida's Department of Environmental Protection (DEP) has established a beach profile network statewide with R-monuments approximately every 304.8 m (1,000 ft) along most of the state's Atlantic and Gulf of Mexico shoreline. The project was located near DEP monument R-115 in Palm Beach County (Figure 3) and covered an area 128 m (420 ft) north and 54.9 m (180 ft) south of the monument. This initial installation of the P.E.P. Reef was of the larger units. Several existing shore protection structures were already present, including a series of short T-head groins; a low, vertical concrete seawall; and a rock revetment, which created an irregular shoreline prior to P.E.P. Reef installation (LEADON, 1991). The P.E.P. Reef installation was seaward of all of these existing shore protection structures. Natural hardbottom is located seaward of the breakwater, but the reef was placed on a sand bottom and the effects of the hardbottom were not discussed.

Monitoring Program

This project had a limited monitoring program, consisting of profile surveys covering a two-year period from pre-installation in March 1988 through March 1990 (LEADON, 1991). A series of 17 project specific beach and nearshore profile locations were established approximately 61.0 m (200 ft) apart for 305 m (1,000 ft) north and south of the reef units and 30.5 m (100 ft) apart in the vicinity of the reef (Figure 3). Surveys were conducted on a 3-month interval (Table 1). The profiles did not survey the landward 30.5 m (100 ft) of the profile, which originated at the project-established baseline.

Table 1. *Monitoring for P.E.P. Reef at Dupont property, Palm Beach, FL.*

Year	Month	Profile Survey	Events
1988	March	Pre-Survey	
	May		P.E.P. Installation
		Post-Survey	
	August	Survey	
	December	Survey	
1989	February	Survey	
	March		*Northeaster*
	April	Survey	
	July	Survey	
	November	Survey	
1990	March	Survey	

Monitoring Results

Shoreline Response

The shoreline, defined as the mean high water line (MHWL), was determined from beach profiles. The pre-project shoreline was irregular and no consistent pattern was found in the response of the shoreline over the project-monitoring period (LEADON, 1991). A general seasonal signal was found with gain in sand and seaward movement of the shoreline during calm wave periods (usually in the summer) particularly near the groins. Figure 4 shows the irregular change in MHW shoreline position from the pre-installation (March 1988), the post storm (April 1989) and the final two-year monitoring (March 1990). The general trend was for shoreline retreat from the pre-installation survey to the post-storm survey, with a larger retreat in the northern control area just to the north of the reef location. In the lee of the reef structure, the shoreline position was the same as after the storm except for one survey line between two groins that was just seaward of the pre-installation position. The area south of the reef, showed a seaward movement after the storm at one groin location but for the most part, the shoreline in March 1990 was landward of the March 1988 location. LEADON (1991)

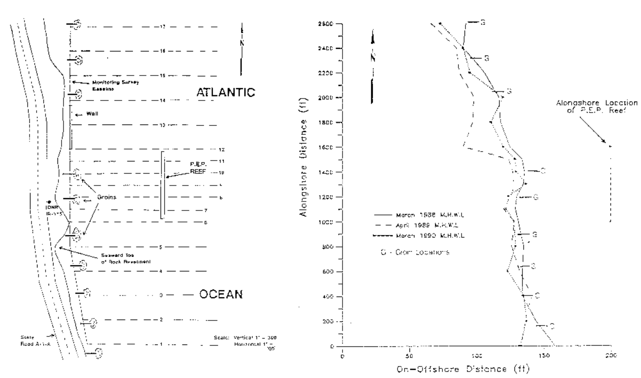

Figure 4. Comparison of the annual shoreline changes at Dupont property, Palm Beach County, Florida (after Leadon, 1991).

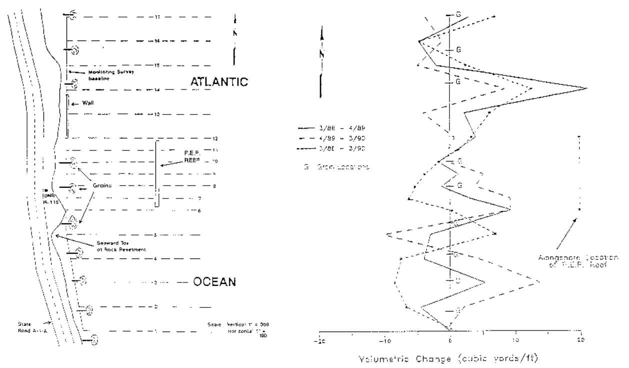

Figure 5. Comparison of the annual volumetric changes at Dupont property, Palm Beach County, Florida (after Leadon, 1991).

concluded that there was no net benefit in shoreline position stability between the pre-installation and two-year surveys leeward of the reef.

Sediment Volume Response

Volume change analysis compared the change in profile volume between each survey period. The volume change pattern was reported as very irregular due to the existing shore protection structures in the study area (Leadon, 1991). Figure 5 shows a comparison of the annual volumetric changes for the first year (March 1988 to April 1989), the second year (April 1989 to March 1990) and a total pre-installation to final monitoring period (March 1988 to March 1990). A gain in volume was found during the first year of monitoring in the north control area, a loss in the lee of the north half of the P.E.P. Reef area and a gain in the southern half of the P.E.P. Reef based on the profile survey after the storm in March 1989. A loss was also measured just south of the reef, with a gain further to the south in the control area. The second year showed a similar pattern but the north control area volume gain was less than the first year and the gain and loss in the south area was more pronounced. The overall change in volume showed a variable pattern with gain in the north control, loss behind the P.E.P. Reef increasing to the south, and a gain just to the south of the reef but loss further to the south. The net drift is to the south in this area.

Analysis of contours and surface maps also showed a similar pattern. It was noted that any surface change that occurred, was found on both the landward and seaward sides of the reef and appeared to not be the result of the reef Leadon (1991). No recognizable benefits could be identified from this monitoring data.

Structural Stability

The northeast storm in 1989 caused some of the units to move seaward (Mitchell, 1994). The reef units were realigned after the storm and the monitoring was continued Leadon (1991). No further movement was measured during the second year of monitoring.

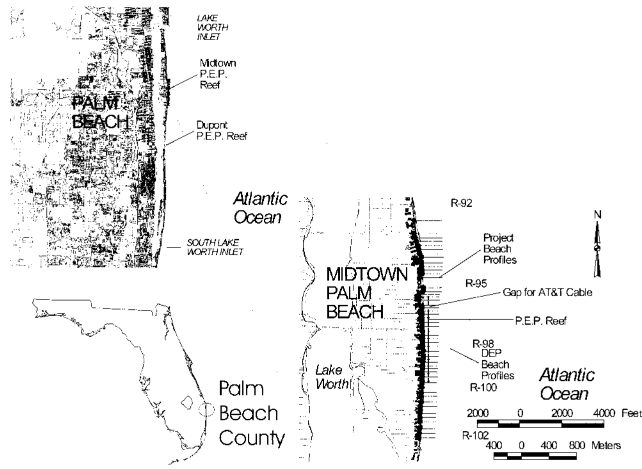

Figure 6. Location of the P.E.P. Reef installations at Midtown Palm Beach, Florida.

Project Performance

At the end of the two year monitoring, the mean high water shoreline had moved landward of the pre-project position. Seasonal changes in profile response were also measured. The existing structures (seawalls and groins) had an effect on both the shoreline and volume change patterns that were difficult to separate from the P.E.P. Reef presence. Volume change indicated a variable pattern, with some gain and some loss in sand volume, but the changes could not be directly attributed to the P.E.P. Reef (Leadon, 1991). The units were dislodged and scattered by the strong northeaster, and required realignment. Woodruff (1994) reported that the project had little beneficial effect on the beach and was ordered removed. The units were eventually left in place as an artificial reef and are providing habitat for marine organisms.

MIDTOWN PALM BEACH, FL PROJECT

A second project, the Midtown Palm Beach project, was constructed to mitigate for coastal erosion on the Atlantic Ocean shoreline of the Town of Palm Beach, FL. The units were placed in −2.87 m (−9.4 ft) NGVD of water around 76.2 m (250 ft) from the shoreline on the Atlantic Ocean in the Town of Palm Beach Florida some 7.2 km (4.5 miles) south of Lake Worth Inlet (Figure 6). Net drift in that region is to the south with the prevailing wave approach direction from the northeast to east (Stauble, 1993). Previous erosion has resulted in armoring of most of the shorefront with seawalls and revetments. A natural hardbottom composed of coquina (a semi-cemented shell and quartz sand) beach rock outcrops around 304.8 m (1,000 ft) offshore and has a crest elevation of −2.44 m (−8 ft) NGVD. The project was installed in two phases, with the first 52 P.E.P. Reef units placed in July–August 1992. Hurricane Andrew impacted the area as the reef was under construction. Post-hurricane surveys indicated that the reef units had settled further than settlement

Table 2. *Monitoring for P.E.P. Reef at Midtown Palm Beach, Florida.*

Year	Month	Profile Survey	Wave Data	Scour Studies	Events/Other Monitoring
1992	July	Pre-Survey			
	July/August				Initial Instillation–57 units in south area
	August				*Hurricane Andrew*
1993	April	Survey			
	July/August				Complete Installation–237 units north and south of initial units
	August	Post-Survey		Scour	
	September		Wave Gages		
	December	Survey		Scour	
1994	March	Survey		Scour	
	June			Scour	
	July	Survey			
	September			Scour	
	October				
	November	Survey			
					Hurricane Gordon
	December	Survey			
1995	January		Wave Gages		
	March	Survey			
	April				Video Camera
	June	Survey		Scour	

expectations (MARTIN and SMITH, 1997). Further installation was postponed while performance and settlement criteria were evaluated over the winter months on the existing units. Little further settlement was measured four-months after the initial placement so the remaining 273 units were placed in July and August 1993 (DEAN *et al.,* 1994a). The total submerged breakwater consisted of 330 units placed in a continuous line parallel with the shore with one gap of 65.8 m (216 ft) spanning offshore communication cables.

Monitoring Program

A comprehensive monitoring of the 1,273 m (4,176 ft) long project (including the gap) was done by the Coastal and Ocean Engineering Department of the University of Florida (details can be found in BROWDER et al., 1994; BROWDER, 1995; DEAN and CHEN, 1995a; DEAN and CHEN, 1995b and DEAN and CHEN 1995c). This monitoring program included wave data from two directional wave gages located landward and seaward of the breakwater to measure wave changes as they pass over the units (DEAN *et al.,* 1994a). The wave gages were approximately 15.2 m (50 ft) on either side of the breakwater, with the landward gage in 1.9 m (6.1 ft) water depth and the offshore gage in 4.1 m (13.5 ft) water depth. Seventy-five beach profile lines were used to monitor the change in sand elevation. Supplemental project specific benchmarks were established between the DEP lines for this project monitoring (Figure 6). Eleven survey locations were within the boundary of the P.E.P. Reef starting on the north near DEP monument R-95. The rest were control survey locations, established both north and south of the project to assess updrift and downdrift effects as well as native profile changes. The north control area covered 610 m (2,000 ft) north of the northernmost reef unit and the south control extended 610 m (2,000 ft) south of the southernmost reef unit. Most of the lines were surveyed on a quarterly basis, from the benchmark to wading depth by standard rod and level techniques, and in the nearshore by boat mounted fathometer. The quarterly surveys extended offshore to around 366 m (1,200 ft). The annual surveys were extended to 1,067 m (3,500 ft) offshore. DEP lines were only surveyed annually and extended 1,981 m (6,500 ft) seaward. Profile data provided information on shoreline position change and volume change along the profiles. Settlement of the units was monitored by direct measurement of the elevation of the north, middle and south crest of each reef unit. Scour at the base of the P.E.P. Reef units was measured by installing 28 scour rods at the north, central and south ends of the breakwater and on both the seaward and landward sides. These rods were surveyed in and the sand elevation change was measured by a disk that could move along each rod by divers. Scour rods were also placed in a north and south control area. Sand samples were also collected annually in the vicinity of the breakwater (DEAN *et al.,* 1994a). Table 2 provides an overview of the survey periods and reef installation dates.

Monitoring Results

Shoreline Response

Shoreline response was measured from the profile surveys. The shoreline was defined using the change in the position of the mean high water (MHW) line position. The study was divided into three zones with a 610 m (2,000 ft) north control area, a roughly 1,219 m (4,000 ft) P.E.P. Reef area and a 610 m (2,000) southern control area. Shoreline change in the north control area was mixed alternating between ±15.2 m (±50 ft), with a net average recession of 2.84 m (9.31 ft) over the entire study period (Figure 7). Within the P.E.P. Reef zone, the overall shoreline change measured from the pre-installation survey in July 1993 to the final survey in June 1995 measured an average of 7.86 m (25.8 ft) of shoreline

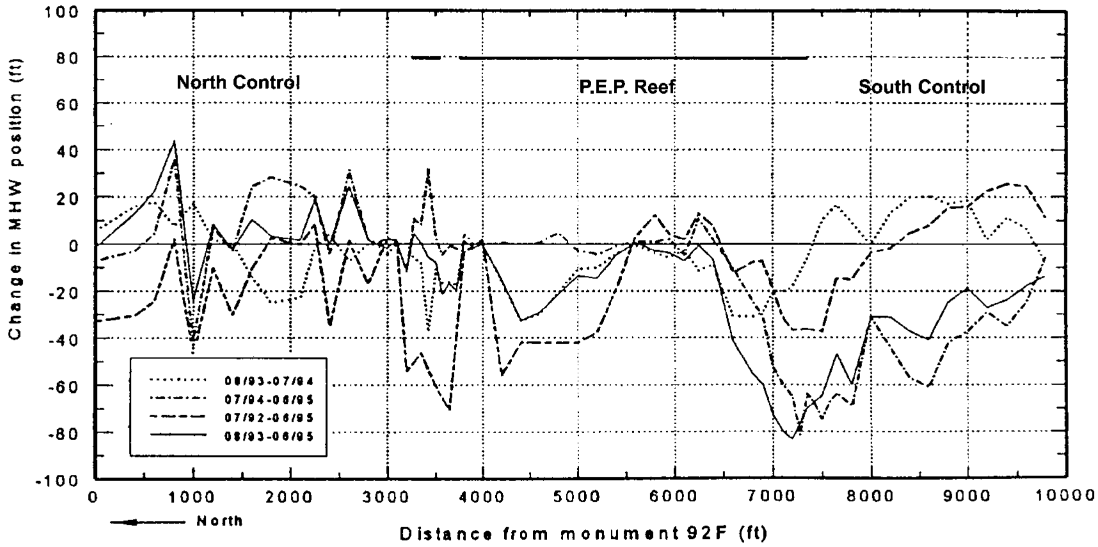

Figure 7. Comparison of the annual shoreline changes at Midtown Palm Beach, Florida (after Dean and Chen, 1996).

recession (DEAN and CHEN, 1995c). Since this area was backed by seawalls or rock revetments over 80% of the shoreline length, the landward movement was stopped when the shoreline retreated to the shore protection structures. The largest recession was measured in the area at the south end of the P.E.P. Reef and the northern south control area. This area showed an average net recession of 18.7 m (61.2 ft). There was initial shoreline advancement in this south area up until March 1994, but since that time the shoreline has receded. The overall average shoreline change in the south control area was a slight seaward movement of 0.20 m (0.66 ft). Within the zones, the highest long-term shoreline retreat was measured in the P.E.P. Reef area.

Sediment Volume Response

The volume change was measured as the difference between beach profile surveys at each profile line. The volume change results were similar to the shoreline change. The north control area experienced both erosion and accretion over the monitoring period. Erosion has been measured in the lee of the P.E.P. Reef and just to the south of the reef zone. DEAN and CHEN (1995c) reported that from August 1993 (after the installation of the entire reef) to June 1995 erosion was measured as 141.6 cu m/m (56.4 cu yd/ft) between the seawalls and the P.E.P. Reef (Figure 8). Seaward of the reef structure, volume changes were mixed over the monitoring period but were of much less magnitude than landward of the reef.

Cumulative changes in volume by zone over the monitoring period showed that the north control zone exhibited only a minimal loss in sand. The area behind the reef structure had a trend for loss, which totaled 81,736 cu m (106,900 cu yd) from pre-installation survey of July 1992 to final survey of June 1995 (DEAN and CHEN, 1995c). The south control zone experienced accretion until July 1994, and then showed a loss in sand volume (Figure 9). In plan view, this cumulative change is illustrated in Figure 10, with the greatest loss in the lee of the reef structure over the thirty-five month monitoring. Up to 1.52 m (5.0 ft) of sand was removed with a shoreline recession of around 7.9 m (26 ft) behind the reef and to the south of the reef. The only areas of gain in sand of greater than 0.31 m (1.0 ft) were measured on the beach and in the offshore of the north control zone and in the nearshore south control zone. DEAN and CHEN (1995c) provided representative profiles to show the volume changes in each zone. A representative profile from the north control (R-94D) shown on Figure 10 as A-A′, is located approximately 457 m (1,500 ft) north of the P.E.P. Reef and is backed by a seawall. Figure 11a shows that there was a slight gain in sand over time at that location. Profile R-96F (shown on Figure 10 as line B-B′), located approximately 304.8 m (1000 ft) south of the north end of the P.E.P. Reef shows the representative sand elevation losses of around 72.5 cu m/m (28.9 cu yd/ft) experienced behind the P.E.P. Reef (Figure 11b). Most of the loss was between the seawall base and the P.E.P. Reef unit. Changes in the south control zone are represented by profile line R-100B (shown as line C-C′ on Figure 10), which is approximately 304.8 m (1,000 ft) south of the P.E.P. Reef. This area, also backed by a seawall, gained sand from July 1992 to August 1993 and continued till July 1994 (DEAN and CHEN, 1995c), but experienced erosion form July 1994 to June 1995 (Figure 11c) with a net loss of about 76.8 cu m/m (30.6 cu yd/ft) relative to the pre-installation July 1992 survey.

Settlement

The 57 units installed in August 1992 have settled an average of 0.84 m (2.74 ft) over the 34 months of monitoring in June 1995. The 273 units placed in August 1993 have settled on average 0.60 m (1.98 ft) over 22 months of monitoring

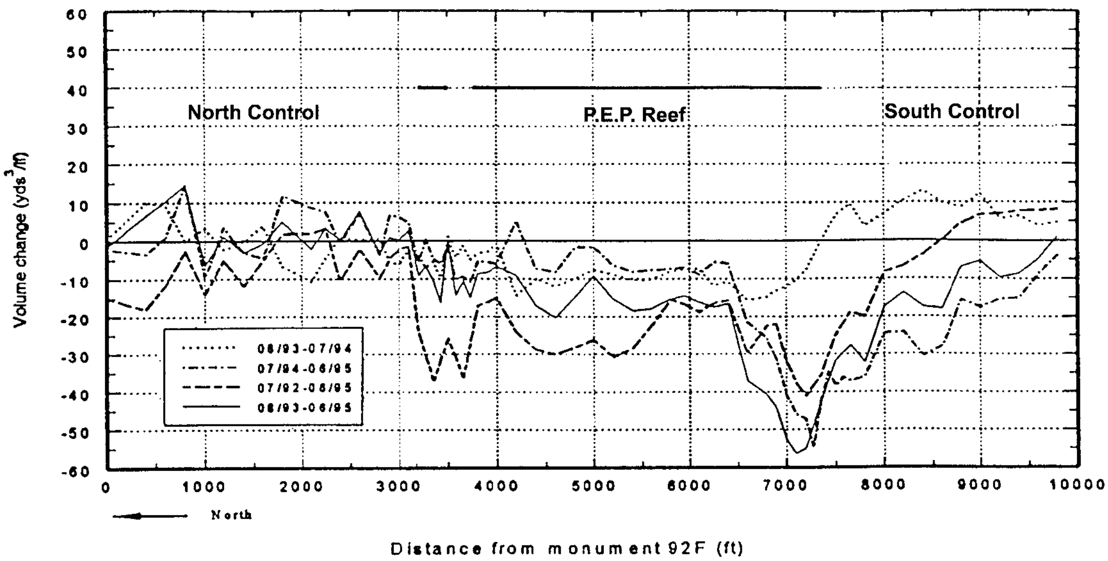

Figure 8. Comparison of the annual volumetric changes at Midtown Palm Beach, Florida (after Dean and Chen, 1996).

(DEAN and CHEN, 1995c). The units installed in 1992 reached an equilibrium depth within the first 5 to 6 months after placement, responding to the effects of Hurricane Andrew (Figure 12). The units placed in 1993 took around 18 months to reach a constant depth. The rate of settlement was most rapid within the first three months after placement. All of the units were placed on a sandy substrate although there is hardbottom consisting of coquina beach rock under the sand in this area.

Scour

Measurements were made on the 28 scour rods placed in various locations around the reef on six different periods from 29 July 1993 to 24 June 1995. Scour ranged from 38 to 99 cm (15 to 39 inches) over the last monitoring period from September 1994 to June 1995 (DEAN and CHEN, 1995c). An average rate of scour was given as 0.13 m/month (0.43 ft/month) at scour rods 14 to 19 at the north end of the south breakwater and in the gap between the two reefs. Less scour was measured in the center of the longer reef section than at the ends. The southern control scour rods showed about the same magnitude of scour as the ends of the reef sections, but the north control had less scour than the reef area. While there was a large scattering of the scour data, scour was measured at all of the rod positions.

Wave Attenuation

To determine the effectiveness of the P.E.P. Reef in reducing wave height, wave data was analyzed from the two wave gages on the landward and seaward sides of the reef structure. Wave transmission coefficients were given as:

$$K_T = \frac{H_{s\ nearshore}}{H_{s\ offhsore\ shoaled}} \quad (1)$$

where, K_T is the transmission coefficient, $H_{s\ nearshore}$ is the nearshore significant wave height, and $H_{s\ offshore\ shoaled}$ is the offshore significant wave height shoaled in accordance with linear wave theory to the location of the nearshore gage (DEAN and CHEN, 1995c). There was much scatter in the data due to differences in daily tide levels, resulting in more transmission during high water periods. Additionally, larger offshore wave heights caused less transmission, and loss of beach landward of the reef structure caused greater reflection from seawalls and revetments at the landward end of the beach profiles. For the period between December 1993 and July 1995, the wave transmission coefficients ranged from 0.62 to 1.17 (DEAN and CHEN, 1995c). Periods when there were higher waves, the transmission coefficients averaged around 0.76 and during periods of lower waves the coefficients were around 0.87. Two control wave gages were also in operation for a short 15 day period at a location 152 m (500 ft) south of the reef installation and measured wave attenuation over the natural bottom. From a comparison of the wave attenuation of the control gages, there was an energy loss between 5 and 15% over the natural bottom (DEAN and CHEN, 1996). It was determined that the P.E.P. Reef associated transmission coefficients ranged from 85 to 95% (DEAN and CHEN, 1995c).

Project Performance

The trend exhibited in the Midtown Palm Beach application of the P.E.P. Reef showed that the area south of the reef and in the lee of the reef experienced erosion. The shoreline also retreated in theses areas. The project monitoring documented that the area behind the reef lost large amounts of sand within the first four months of the full project installation, while both north and south control zones gained sand (DEAN *et al.,* 1994a). The trend continued during the entire

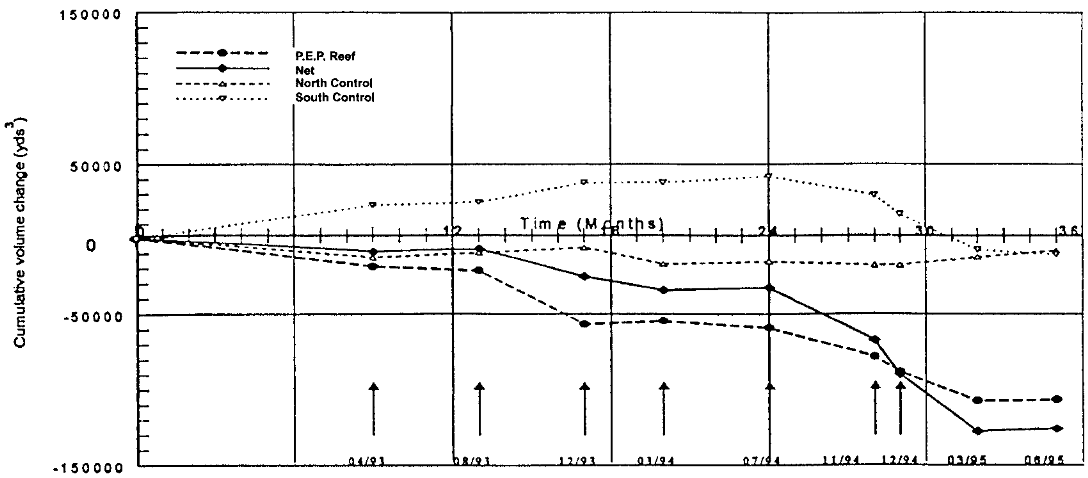

Figure 9. Cumulative change in volume by zone at Midtown Palm Beach, Florida (after Dean and Chen, 1996).

monitoring period with the addition of erosion immediately to the south of the reef (DEAN and CHEN, 1995c). BROWDER (1995) suggested that the large amounts of sand movement indicated that the reef structure was modifying the natural current patterns in the area. DEAN *et al.* (1994a) suggested that the structure caused a pumping mechanism. Water and possibly suspended sand are transported landward over the reef and due to the presence of the reef in the water column, the natural return flow of the wave induced circulation is interrupted. Some of the water is trapped on the landward side of the reef and flows alongshore until it reaches the end of the reef, where it is allowed to flow offshore. This induces flow, and along with the natural longshore current, causes sand to be transported to the end of the reef and redeposited in a downdrift location away from the reef structure. Laboratory experiments with dye flow and drogue trajectories around the elongated P.E.P. Reef structure indicate a structure-induced circulation that moves water and sand along the landward side to the ends of the structure (DEAN *et al.*, 1994b).

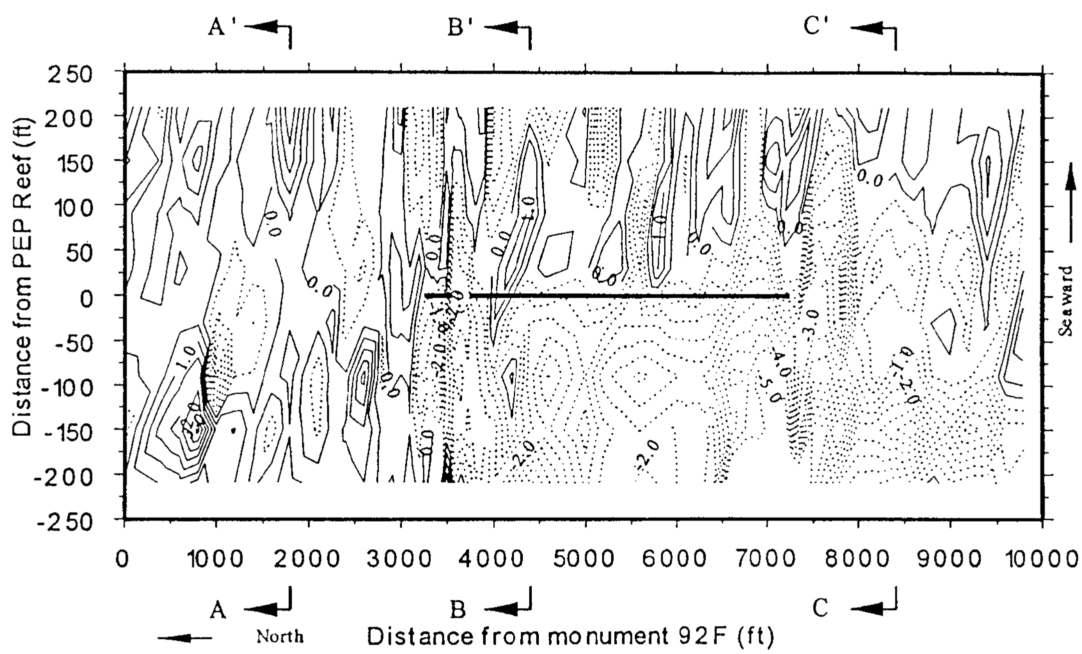

Figure 10. Plan view of cumulative change in 36-month monitoring of nearshore volume between August 1993 and June 1995 (after Dean and Chen, 1996).

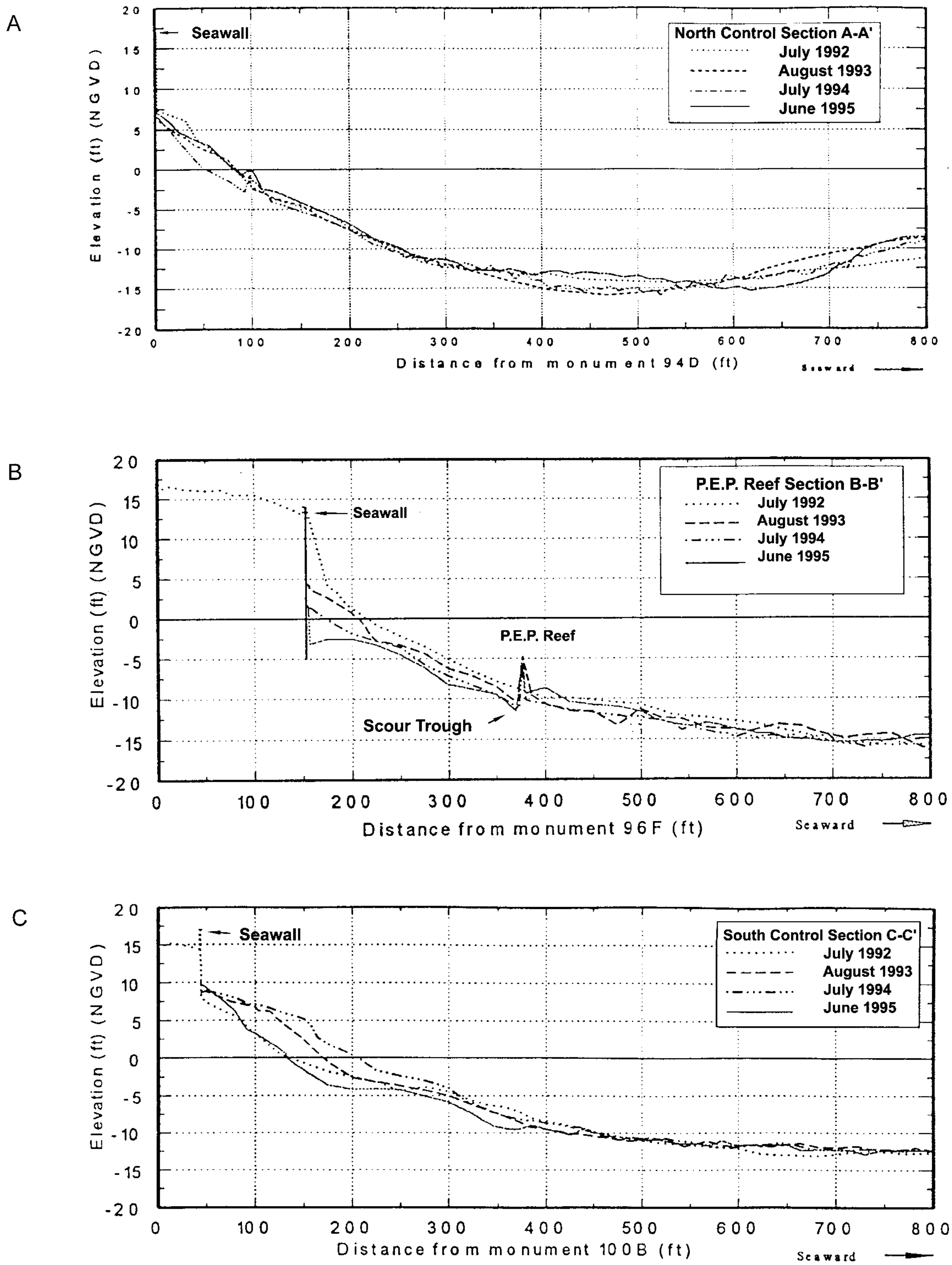

Figure 11. Representative profiles from (a) R-94D north control, (b) R-96F P.E.P. Reef, and (c) R-100B south control (from Dean and Chen, 1996).

The wave transmission coefficients measured at the reef indicated a range of 0.70 to 0.90 and over the natural bottom at 0.79 to 0.97 (Browder, 1994), which suggests that the P.E.P. Reef was not reducing the wave energy as predicted. The settlement of the units has reduced it effectiveness. Dean and Chen (1995c) concluded that the P.E.P. Reef structure was responsible for about two-thirds of the erosion measured landward of the reef. One third was attributed to the

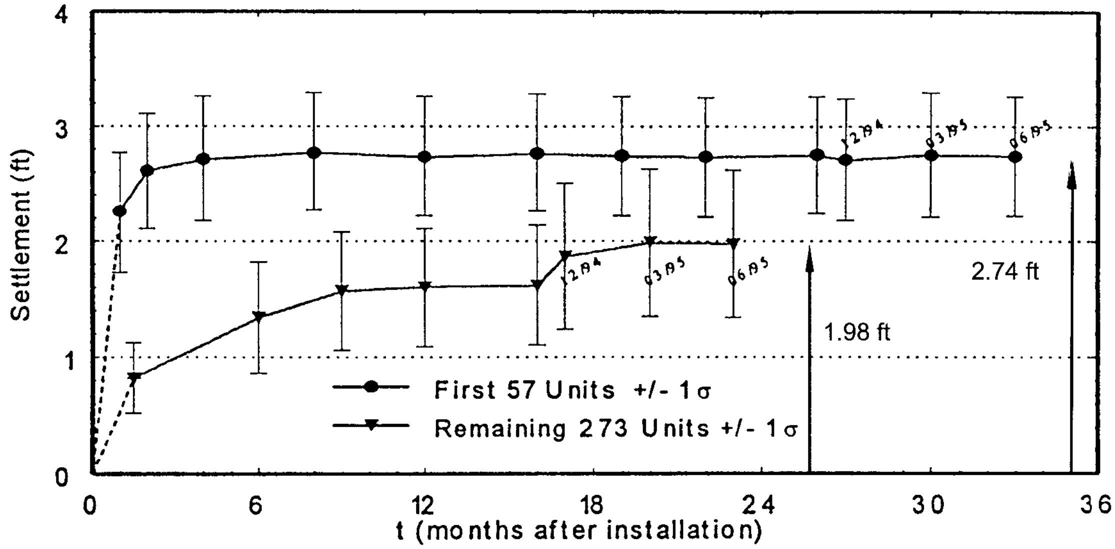

Figure 12. Average settlement after 33 months for the first 57 units and after 20 months for the remaining 273 units at the P.E.P. Reef installation at Midtown Palm Beach (after Dean and Chen, 1996).

general sediment deficiency in the area. The remaining loss of sediment in the lee and downdrift to the south was a result of the trapping of water behind the reef with flow along the landward side of the reef to both the north and south directions with a predominant flow to the south. The measured sediment volume change patterns and shoreline response support this hypothesis.

This installation was removed in 1995, as it was deemed ineffective in reducing wave energy or retaining sand on the beach. The ongoing erosion was mitigated by placement of around 611,680 cu m (800,000 cu yd) of beach fill between DEP monuments R-95a and R-100a, which was stabilized with 11 modular adjustable groins placed perpendicular to the shore. The groins used the P.E.P. Reef units as a core covered with rock (ATM, 1996).

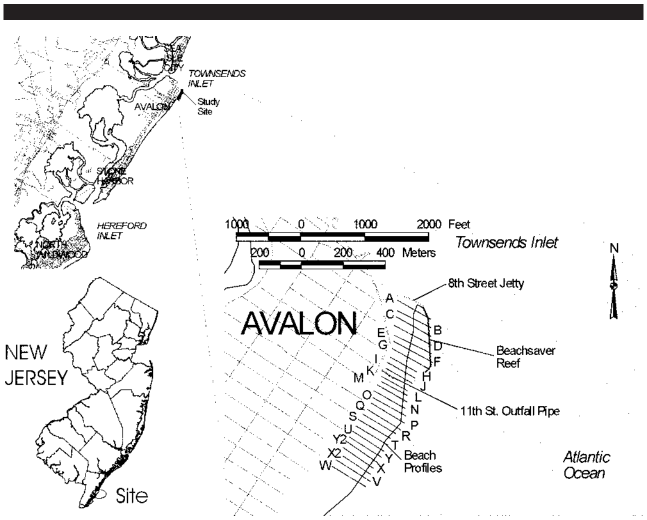

Figure 13. Location of the Beachsaver Reef installation at Avalon, New Jersey.

AVALON, NEW JERSEY, PROJECT

A Beachsaver Reef was constructed in the Atlantic Ocean at Avalon, NJ in July 1993, as part of the State of New Jersey Pilot Reef Project (BRUNO *et al.*, 1996a). The submerged concrete artificial breakwater was connected to the end of the 8th Street jetty, which is the south jetty for Townsends Inlet. The Borough of Avalon occupies the northern half of Seven Mile Island, a barrier island along the southern New Jersey Atlantic coast approximately 35 km (22 miles) south of Atlantic City (Figure 13). Townsends Inlet is a downdrift offset inlet separating Ludlam Island to the north and Seven Mile Island to the south. The inlet is unstructured on the north, but has an inlet shore-parallel timber bulkhead with a toe rock revetment and three shore normal short rock groins to stabilize the shoreline on south side of the inlet throat. The inlet throat revetment extends seaward from the shore as a small jetty (more apply called a terminal groin) located at the seaward end of 8th Street on the north end of Avalon to stabilize the highly dynamic shoreline adjacent to the inlet. This area has long had a history of erosion, with the loss of between six and seven blocks of land area due to waves and tidal currents since the community was established in 1892 (FARREL, 1995). Although the predominant drift is to the south along this section of the New Jersey coast, a localized northward drift is also active at the north end of Avalon, associated with wave refraction around the ebb shoal complex of the inlet (HERRINGTON and BRUNO, 1998).

The inlet channel has historically migrated downdrift to the south, eroding the north end of Avalon. A beach nourishment project on Sea Isle City, to the north on Ludlam Island

Table 3. *Monitoring of Beachsaver Reef at Avalon, New Jersey.*

Year	Month	Profile Survey	Wave Data	Settlement	Events/Other Monitoring
1978					*Beach Fill #1*
1990					*Beach Fill #2*
1992					*Beach Fill #3*
1993	May	Pre-Survey			
	May–Sept				*Beach fill #4*
	June				Beachsaver Installation
	September	Post-Survey	Wave Gages		
	November	Survey		Settlement	Dye Study
1994	January	Survey		Settlement	
	March	Survey		Settlement	
	May	Survey		Settlement	
	September	Survey		Settlement	
	November	Survey		Settlement	
1995	February	Survey		Settlement	
	May	Survey	Wave Gages	Settlement	Currents
	June				*Beach Fill #5*
	July	Survey			
	September	Survey			
	December	Survey			

in 1978 used the inlet ebb shoal as a borrow source. The ebb channel at Townsends Inlet was realigned from its natural southward trending orientation to a channel that cut straight across the middle of the ebb shoal. The Sea Isle City beach was renourished in 1984 using the same ebb shoal borrow area. As this channel realigned, the north end of Avalon's shoreline eroded (FARREL, 1995). Due to this severe loss of beach sand, four beach nourishment projects were completed on the north end of Avalon, starting in 1987, with 997,803 cu m (1.305 million cu yd) of fill placed between 8th and 28th Streets. In 1990, an additional 308,898 cu m (404,000 cu yd) of fill was placed from 9th to 16th Streets and from 21st to 27th Streets. By 1992, an additional 313,486 cu m (410,000 cu yd) of fill was placed between 9th and 16th Streets. Finally, in 1993, 182,739 cu m (239,000 cu yd) of sand was added between 8th and 15th Streets and along the inlet shore (FARREL, 1995). Along with this last fill, geo-tubes were placed along the inlet shoreline to help retain the fill and protect the bulkhead. The Beachsaver Reef was installed off the 8th Street jetty to help hold the sand fill at the north end of the island, adjacent to the inlet. At the end of the Beachsaver monitoring period in June 1995, an additional beach fill placed 305,840 cu m (400,000 cu yd) along the north end of the beach (BRUNO *et al.,* 1996b). This new fill buried the submerged reef. Monitoring of the fill continued through December 1995.

The 305 m (1,000 ft) long, submerged breakwater, composed of 100 Beachsaver units, was attached at its north end to the terminal end of the 8th Street jetty (HERRINGTON and BRUNO, 1998). It extends to the southwest in a more or less shore-parallel direction some 100 to 150 m (328 to 492 ft) seaward of the shoreline, with its south end open to the ocean. The installation was done from barges in the water. Steel H-piles were driven into pre-cast openings in the center of the concrete reef structure at all end or transition units to provide more stability (BRUNO *et al.,* 1996b). This site was strongly influenced by tidal currents and the ebb shoal features of Townsends Inlet. The inlet has been highly dynamic, with large movements of the ebb shoal sand bodies in the vicinity of the north end of Avalon (FARREL, 1995). The top of the reef structure was placed between −0.4 and −2.0 m (−1.3 and −6.6 ft) MLW in a water depth of 2.2 to 3.8 m (7.2 to 12.5 ft) MLW. A geotextile fabric was placed under the Beachaver units for scour protection. Halfway through the monitoring period a polyethylene geomattress filled with stone was placed along the southern 73 m (240 ft) of the landward side of the base to mitigate for scour (BRUNO *et al.,* 1996a). Additional structures in the study area include a timber bulkhead that runs parallel with the beach and delineates the landward extent of the sand beach. A pile-supported storm water outfall pipe is located to the south at 11th Street and extends approximately 61 m (250 ft) seaward perpendicular to the shoreline (BRUNO *et al.,* 1996b).

Monitoring Program

Project monitoring included establishment of a project baseline and 27 beach profile lines perpendicular to the shore parallel baseline, beginning with Profile A next to the 8th Street Jetty and extending south to Profile W (Figure 13). Profiles were approximately 30.4 m (100 ft) apart and the total shoreline covered was around 823 m (2,700 ft) south from the 8th Street jetty (BRUNO *et al.,* 1996b). Profiles were measured with a total station and prism on land and a fathometer on a boat in the offshore to a depth of −2.44 m (−8 ft) MLW. One pre-installation survey was done in May 1993 and post-installation surveys were collected in September 1993 soon after placement, November 1993, January, March, May, September and November 1994 and February and May 1995 (Table 3). The two 1995 surveys were limited to the area landward of the reef due to a sand transfer operation after sever erosion in January 1995, which included profile lines A through G (BRUNO *et al.,* 1996a). Settlement measurements were initially estimated from visual observations. High rates of settlement resulted in surveys of the top elevation of the reef starting in November 1993 and extending to May 1995

(Bruno *et al.,* 1996b). Scour was examined by divers as well as from profile data. Waves were measured by two Inter-Ocean S4 electromagnetic current meters fitted with high-resolution pressure sensors mounted 1 m (3.28 ft) above the bed. Wave data were recorded over two time periods during the monitoring. The first was a three-day period between 12 and 15 September 1993 (Bruno *et al.,* 1996b). The inshore gage was placed 6.3 m (20.7 ft) landward of the reef in around −3.9 m (−12.8 ft) MLW. The offshore gage was placed 20 m (65.6 ft) seaward of the structure in around −3.6 m (−11.8 ft) MLW. Both meters were about 180 m (591 ft) south of the 8th Street jetty. A second deployment occurred over a five-day period between 20 and 25 May 1995. During this second deployment one meter was placed 6.0 m (19.7 ft) inshore of the reef structure in −3.9 m (−12.8 ft) MLW depth. The other wave gage was placed 15 m (49.2 ft) to the ocean side of the structure, in a depth of −3.3 m (−10.8 ft) MLW. The gages were further north along the reef at 123 m (404 ft) south of the 8th Street jetty (Bruno *et al.,* 1996b). Currents were evaluated in the May 1995 deployment. An additional study of circulation around the reef was done with the deployment of Rhodamine dye in November 1993. Dye was released landward of the reef around 180 m (591 ft) south of the 8th Street jetty and in a control area 585 m (1,919 ft) south of the reef structure.

Monitoring Results

Shoreline Response

Beach fill was placed between the May 1993 and September 1993 surveys. The reef was also installed at that time. The seaward movement of the shoreline is in response to the fill. Subsequent shorelines surveys showed a retreat as the fill adjusted to the waves and tidal currents in November 1993, January 1994 and March 1994 (Bruno *et al.,* 1996b). By May 1994, the beaches south of the submerged breakwater had retreated back to the pre-fill location, but the shoreline behind the reef was still seaward of the pre-fill shoreline. A seasonal accretion occurred between May 1994 and September 1994 during the calm summer months. Little change was measured through November 1994, with additional accretion in the north. Between November 1994 and February 1995, several winter storms eroded much of the beach fill material. Sand was transferred mechanically from the northern end of the project to the southern area (Bruno *et al.,* 1996a). With the limited surveys in 1995, profiles behind the Beachsaver Reef (A–C) showed more stability than the profiles to the southern open end of the reef (F–G) (Bruno *et al.,* 1996b). The northern profiles were approximately 15.2 m (50 ft) wider than the pre-fill beach, while the southern beaches returned to a pre-fill width (Figure 14).

Sediment Volume Response

Volume data were not presented, but elevation change data were presented between the September 1993 post-installation/fill survey and the last full survey in November 1994. Erosion was measured in the nearshore area. Several northeaster storms were reported during this time (Bruno *et al.,* 1996b). Scour was measured to the south of the Beachsaver Reef during the November 1993 and March 1994 surveys. The outfall structure and the bulkhead may have contributed to the erosion, as well as changes offshore to the southern ebb shoal features. Erosion rates were calculated for the area between the bulkhead and the seaward extent of the reef. The average rate of erosion was around 30.6 cu m/m (40 cu yd/ft) for the northern 183 m (600 ft) of the reef structure and around 47.4 cu m/m (62 cu yd/ft) for the southern end of the reef (Figure 15). South of the reef structure, the profile measured an average of between 35.9 to 71.1 cu m/m (47 to 93 cu yd/ft) with the highest rates in front of the vertical faced timber bulkhead (Bruno *et al.,* 1996b).

Settlement

Evaluation of the top of reef surveys showed that the settlement was highly variable. The settlement measurements covered a 21-month period from November 1993 to May 1995 (Bruno *et al.,* 1996b). Settlement was measured at around 0.37 m (1.2 ft) at the northern end to around 1.52 m (5 ft) on the southern end (Figure 16). Most of the settlement was measured during the first 9 months after installation. Even with the settlement, the reef units remained interlocked together. The reef units were placed on top of a 2 m (6.6 ft) thick layer of medium sand. A thin veneer of cohesive sediment was located 0.91 m (3 ft) below the sand bed and may be the reason for the settlement. The settlement stopped once the fine material was eroded beneath the structure (Bruno *et al.,* 1996b).

Scour

A scour zone was identified on the landward side of the Beachsaver units. This narrow zone is adjacent to the landward base of the concrete units. After the new beach fill placement in June 1995, monitoring continued around the southern end of the reef. Scour was measured inshore of the southern end of the reef in the post-fill survey of July 1995. The fill had buried the reef, but the crest quickly became exposed, with a scour to the south of the end unit (Bruno *et al.,* 1996b). This scour zone inshore of the southern end of the reef continued to grow to a depth of −0.91 m (−3 ft) as of September 1995 and extended some 12.19 m (40 ft) landward of the structure. By December 1995, the scour zone deepened to −1.22 m (−4 ft) below the crest of the reef.

Wave Attenuation

Inshore and offshore directional wave data were collected to determine the wave attenuation by the Beachsaver units for a 3-day period in September 1993 and a 5-day period in May 1995. This wave data was supplemented with 1) a National Weather Service surface wind speed and direction meter deployed at Atlantic City some 40 km (25 miles) north of the site; 2) a deepwater NOAA directional wave buoy located some 72 km (45 miles) to the SSE of the site; and 3) in 1993, a U.S. Army Corps of Engineers directional wave gage deployed 3.2 km (2 miles) south of the site as part of the beach fill monitoring (Bruno *et al.,* 1996b). With the close prox-

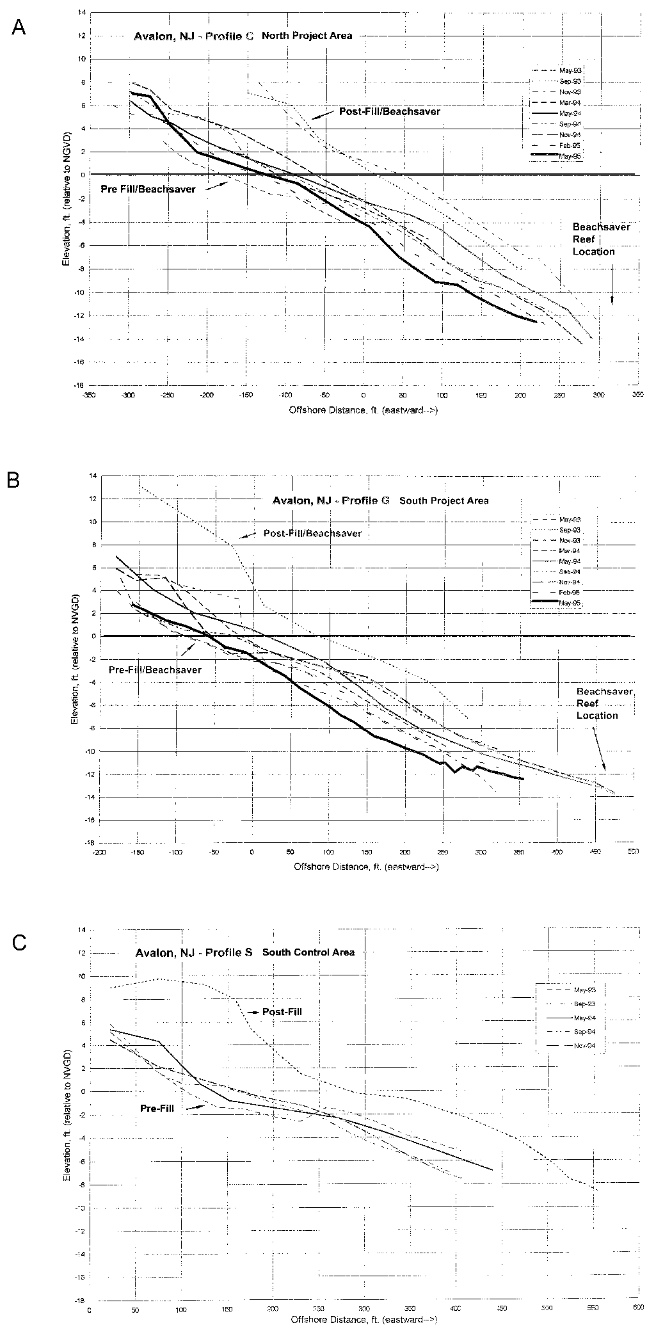

Figure 14. Representative profile monitoring of the Avalon, New Jersey, Beachsaver site. (a) Profile C on northern end of the Beachsaver reef, (b) Profile G at southern end of reef, and (c) south control profile S (after Bruno *et al.*, 1996b).

imity of this reef to Townsends Inlet, the currents had a strong tidal flow component flowing northward into the inlet on flood and south on ebb. The first deployment in September 1993 indicated that the offshore wave height was similar to the inshore wave height but the inshore gage only recorded every six hours due to limited memory. The second deployment in 1995 increased the sampling interval to one hour on both gages for better resolution. During small wave events, the inshore gage measured a slight reduction in wave height relative to the offshore gage on the order of 5 cm (1.7 inches). During larger wave events, the inshore gage measured waves up to 10 cm (3.4 inches) smaller (Bruno *et al.*, 1996b). The reported maximum wave reduction was measured at 20% during the study. Wave transmission was calculated using a spectra-based significant wave height from the inshore and offshore gages using Eq. (1). When the negative freeboard

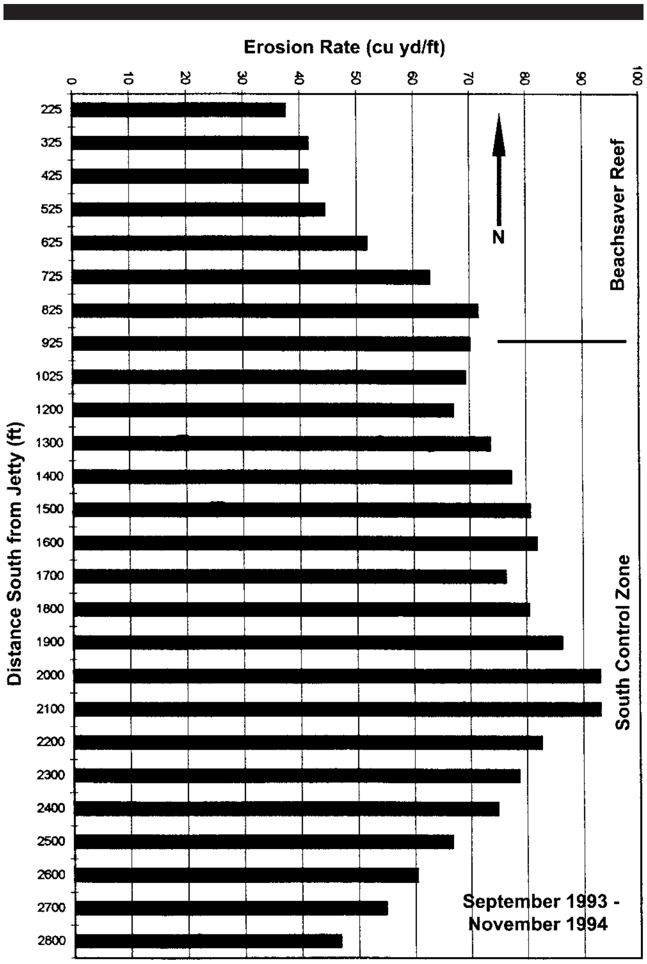

Figure 15. Average erosion rates at Avalon, New Jersey, Beachsaver site (after Bruno *et al.*, 1996b).

exceeded 0.8 times the water depth or 6.5 times the offshore significant wave height there was total wave transmission.

Dye and Current Studies

The dye study in November 1993 compared the release of dye behind the reef with an area south of the reef. The study was conducted on a calm day with little wind. The tidal currents seemed to control the flow dispersion, with the first readings taken at the beginning of a ebb tide. The dye behind the reef indicated a dominant offshore inlet-directed flow while the control area to the south showed a dominate southward wave induced longshore current (Bruno *et al.,* 1996b). A further study of currents measured with the electromagnetic current meters on 23 May 1995 indicated that the inlet tidal currents were the dominant feature in the circulation near the reef structure.

Project Performance

Profile analysis indicated that the Avalon shoreline returned to a pre-project position by May 1995. The area of the beach fill south of the Beachsaver Reef and ocean outfall lost an average of 181 cu m/m (72 cu yd/ft) between September 1993 and November 1994. The beach near the southern end of the Beachsaver Reef experienced erosion of 156 cu m/m (62 cu yd/ft) and the northern end of the reef measured an average of 100 cu m/m (40 cu yd/ft). This northern end was closed by the jetty and it may have provided protection to this beach from the inlet wave and tidal current interactions (Bruno *et al.,* 1996a). Farrell (1995) reported that the reef trapped sand along its seaward face along the entire length of the structure. Some sand was possibly moved seaward in a narrow gap in between the 8th Street jetty and the northern end of the Beachsaver Reef. These reef units have settled from 0.61 m (2 ft) on the northern end to 1.22 m (4 ft) on the southern end (Bruno *et al.,* 1996a). Scour was also found along the landward side of the reef structure (Farrell, 1995). A pronounced scour zone developed within 12.19 m (40 ft) of the inshore face of the reef, with a depth of scour reaching 1.22 m (4 ft) (Bruno *et al.,* 1996b). Sand loss was also reported at times south of the southern end of the reef structure. The location of the installation was strongly influenced by inlet processes with strong flood-dominated tidal currents flowing parallel to the reef structure. The Beachsaver Reef at this location was reported to be only partially successful in that it reduced beach erosion only on the enclosed north end, but since no negative impacts were measured, it was recommended to leave the structure in place (Bruno *et al.,* 1996b).

CAPE MAY POINT, NEW JERSEY, PROJECT

In May 1994, a 305 m (1,000 ft) long Beachsaver Reef was installed at Cape May Point, NJ as a continuation of the State of New Jersey Pilot Reef Project. This location is around 96 km (60 miles) south of Atlantic City. Cape May Point is the southernmost beach in New Jersey. The beach fronts on the Atlantic Ocean at the entrance to Delaware Bay. Strong tidal currents flowing around the point in the Cape May Channel just offshore have scoured the shoreline requiring the construction of nine timber and stone groins perpendicular to the shore around 122 m (400 ft) in length to help stabilize the beach (Herrington and Bruno, 1998). Net drift direction is from east to west toward Delaware Bay. Chronic erosion to the east at Cape May Meadows and the State Park has limited updrift sediment input to the groin system. There is little sand transport between the eight approximately 152 to 183 m (500 to 600ft) wide groin compartments, with most of the sand transport in the offshore direction by wave and tidal induced currents (Herrington *et al.,* 1997). In an effort to mitigate for the offshore sand loss, the Beachsaver Reef was installed between the Lehigh Avenue groin, Whilldin Avenue groin and the Coral Avenue groin in groin compartments 2 and 3 (Figure 17). The structure was constructed in two segments of 50 Beachsaver units each, around 137.2 m (450 ft) long to connect the seaward end of all three groins. A jack-up barge was used to place the individual concrete reef units. Capstone was used to connect the ends of the breakwater with the groins. The objective was to provide protection for the two pocket beaches between the

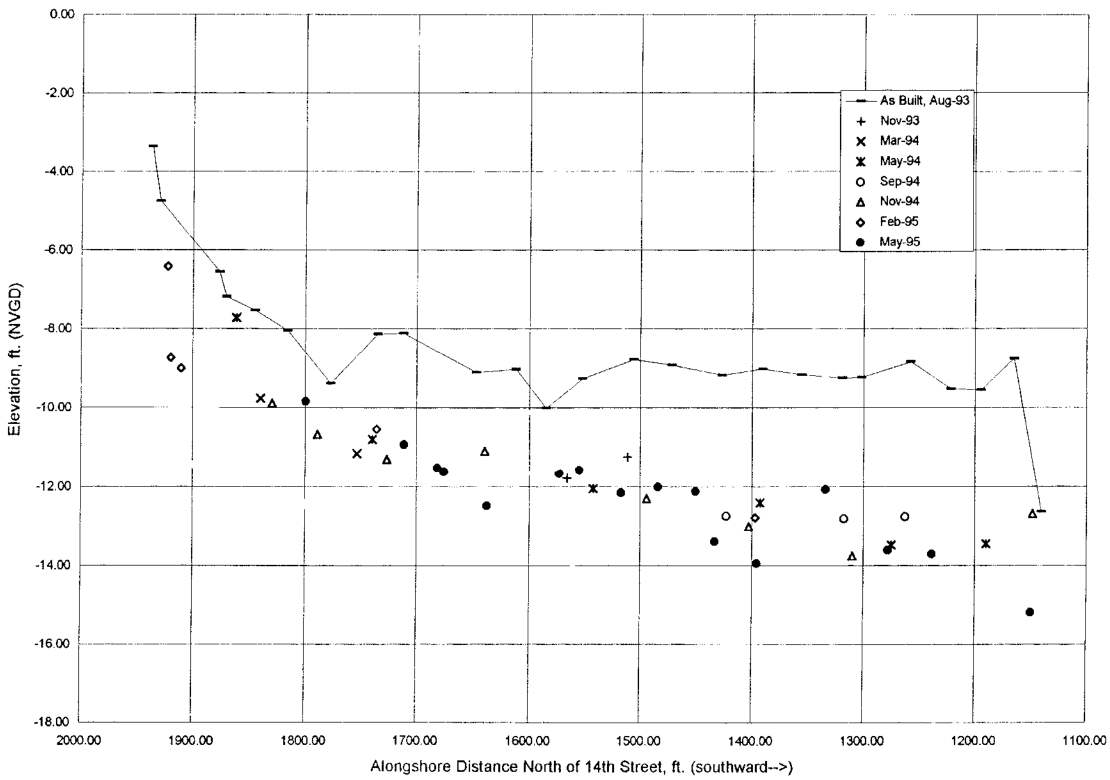

Figure 16. Settlement at Avalon, New Jersey, Beachsaver site (Bruno *et al.*, 1996b).

three groins from scour by the strong tidal eddies (HERRINGTON *et al.,* 1997).

The reef structure was placed in more shallow water than the Avalon reef between −2.1 and −2.4 m (−7 and −8 ft) MLW, with a crest elevation of between 0.15 and −0.61 m (0.5 and −2.0 ft) MLW (BRUNO *et al.,* 1996a). This shallow crest elevation close to MLW makes this installation different from the others in this report. A geotextile fabric was also placed under the reef units on this installation for scour protection, but the thickness was doubled as compared with the Avalon project. A 1.3 m (4.3 ft) wide polyethylene geomattress filled with 6.1 to 10.2 cm (2.4 to 4 inch) stone was placed along both the landward and seaward side of the base to mitigate for scour based on the experience with the Avalon monitoring. To further stabilize the reef steel H-piles were driven to a maximum depth of 3.05 m (10 ft) below the bed at all end and transition units (BRUNO *et al.,* 1996a).

Monitoring Program

Project monitoring included the creation of a 457 m (1500 ft) long baseline covering the two pocket beaches where the Beachsaver Reef was constructed and a control area to the west in the next groin compartment. A total of 12 profile lines were established, with 5 in the first groin compartment, 5 in the second compartment and two in the third. Two of the lines were removed after November 1994 giving an alongshore spacing of around 45.7 m (150 ft) between profiles (HERRINGTON *et al.,* 1997). The seaward extent of the profiles was at the Beachsaver Reef. A total station with prism rod was used in the collection of the beach profiles out to the reef crest and a fathometer was used for the offshore bathymetry. A pre-installation profile data set was collected in May 1994 and a post-installation survey was collected in September 1994 (Table 4). Additional beach profile surveys were collected in November 1994, February, May, July, September, December 1995 and April and August 1996 (HERRINGTON *et al.,* 1997). Offshore bathymetry surveys were collected in May, September and November 1996, May, July, September and December 1995.

Settlement measurements were made by measuring the tops of the reef units with the total station and prism. Settlement surveys were made in September and November 1994, February, May, July and September 1995, and April and August 1996. Two InterOcean System S4 electromagnetic current meters were installed inshore and offshore of the reef to obtain wave and current data for one day on 25 July 1995 (HERRINGTON *et al.,* 1997). The inshore meter was 3 m (9.84 ft) landward of the reef in a water depth of 2 m (6.56 ft) MLW. The offshore meter was placed 5 m (16.4 ft) seaward of the structure in a water depth of 4 m (13.12 ft) MLW. The meters recorded for 18 minutes every hour for six hours from 09:00 to 14:00 at a depth of 1m (3.28 ft) above the bed. A dye study was performed on 27 September 1994 to examine any reef influence on water circulation in the vicinity of the reef.

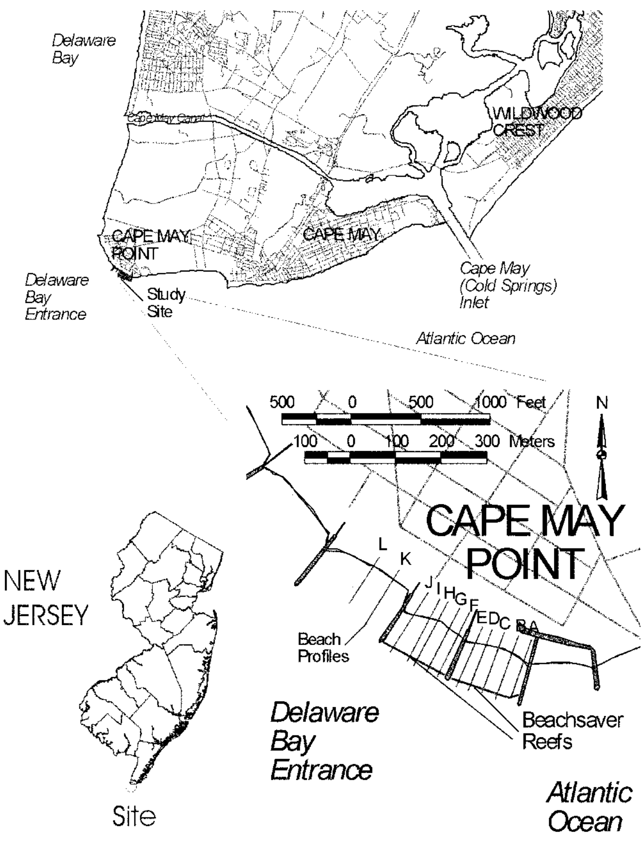

Figure 17. Location of the Beachsaver Reef installation at Cape May Point, New Jersey.

A ½ gallon volume of Rhodamine dye was released on the inside of the reef between the Lehigh Avenue and Whilldin Avenue groins and on the west side of the Coral Avenue groin in the control area to compare the rate of dispersal between the reef area and the non-reef area. Measurements were made at three times over a tidal cycle. The dye was released on a flooding tide and was measured 10 minutes after release, approximately 1.5 hours after high tide, and on an ebbing tide.

Monitoring Results

Shoreline Response

Shoreline response was measured by the movement of the MLW contour line from the beach profiles collected at the various survey intervals. The analysis was divided into three cells related to the two groin compartments and the control area on the west (HERRINGTON *et al.,* 1997). The shoreline in the eastern-most compartment (Cell 2) between the Lehigh Avenue and Whilldin Avenue groins moved seaward on average 13.4 m (44 ft) between May 1994 and April 1996 as illustrated by Profile C (Figure 18a). The compartment between the Whilldin Avenue and Coral Avenue groins (Cell 3) had a shoreline seaward movement on average of 4.6 m (15.13 ft) as seen in representative Profile G (Figure 18b). The shoreline in control cell west of the Coral Avenue groin migrated landward an average of 4.6 m (15.13 ft) as shown in Profile L (Figure 18c). A trend of increased landward movement to the west was evident in this study (HERRINGTON *et al.,* 1997).

Sediment Volume Response

The total volume change in each cell was measured by calculating the average unit volume change between profiles collected at two time periods and multiplying it the distance between adjacent profiles, then summing over the entire cell alongshore distance (HERRINGTON *et al.,* 1997). For the eastern Cell 2 between the Leigh and Whilldin Avenue groins there was a gain in sand volume of 2,761 cu m (3,611 cu yd) for the period between May 1994 and May 1995. From May 1995 to April 1996, a loss of sand volume was measured at 650 cu m (850 cu yd). Over the two-year study, there was a net gain of 2,111 cu m (2,761 cu yd) of sand in the cell, with the most pronounced accretion on the eastern side of the cell (Figure 19). The most gain was found in the nearshore and foreshore portion of the profile around 122 m (400 ft) landward of the reef.

A gain in sand volume in Cell 3 between the Willdin and Coral Avenue groins was reported as 868 cu m (1,135 cu yd) between May 1994 and May 1995. A loss of 488 cu m (638 cu yd) was measured for the second year between May 1995 and April 1996 (HERRINGTON *et al.,* 1997). A net gain of over the two-year period was 380 cu m (497 cu yd). Again, the most

Table 4. *Monitoring of Beachsaver Reef at Cape May Point, New Jersey.*

Year	Month	Profile Survey	Wave Data	Settlement	Events/Other Monitoring
1994	May	Pre-Survey			
	June				Beachsaver Installation
	September	Post-Survey		Settlement	Dye Study
	November	Survey		Settlement	
1995	February	Survey		Settlement	
	May	Survey		Settlement	
	July	Survey	Wave Gages	Settlement	
	September	Survey		Settlement	
	December	Survey		Settlement	
1996	April	Survey		Settlement	
	August	Survey		Settlement	

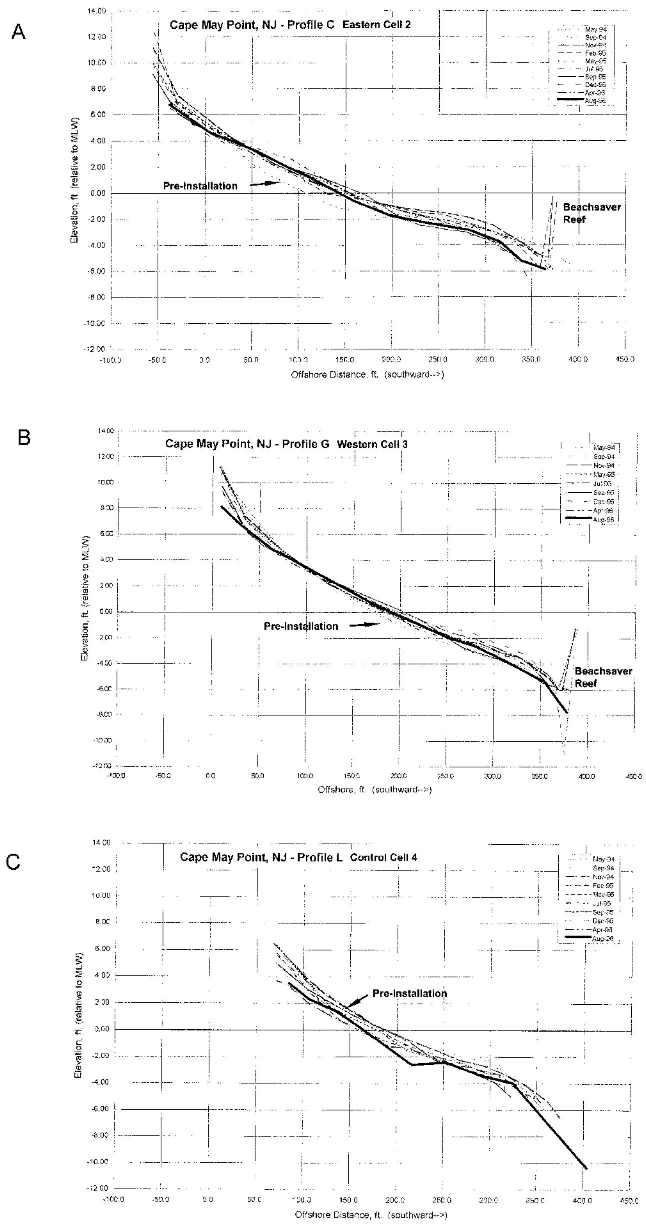

Figure 18. Representative profile monitoring of the Cape May Point, New Jersey, Beachsaver site. (a) Profile B in Cell 2, Profile G in Cell 3, and Control Cell 4 Profile L (after Herrington *et al.*, 1997).

gain was measured on the eastern side of the groin compartment. Since the volume gain was less than the west cell the main sand accretion was found in the nearshore over an area 76.2 m (250 ft) landward of the reef.

The control area west of the Coral Avenue groin, without the Beachsaver Reef, had a volume loss of around 343 cu m (448 cu yd) between May 1994 and May 1995. The loss trend continued the next year with a loss of 310 cu m (405 cu yd) of sand. The two-year total volume change in this cell was a loss of 660 cu m (863 cu yd), with most of the loss on the western side of the cell and between the dune base and 61 m (200 ft) offshore (Herrington *et al.,* 1997).

Settlement

Crest elevations of the Beachsaver units remained relatively constant with average settlement of around 15.2 cm (6 inches) over the two-year monitoring (Herrington *et al.,* 1997). Both lateral and vertical stability appear to be maintained over the study. A layer of medium to fine sand was on top of a layer of fine sand and mud. The use of a filter cloth and geotextile mattress appeared to limit settling. The units in Cell 2 were initially placed at MLW and settled less that the units in Cell 3, which were placed around −0.5 m (−1.5 ft) MLW (Figure 20).

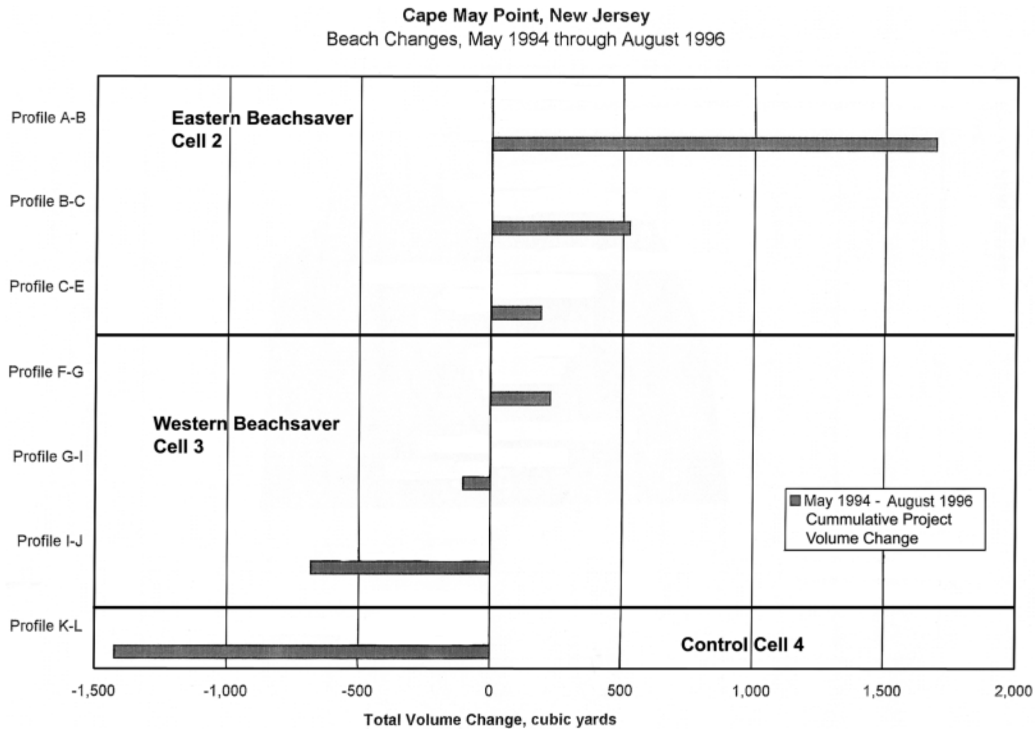

Figure 19. Volume change between profiles at Cape May Point, New Jersey (after Herrington *et al.*, 1997).

Scour

Scour of up to 0.6 m (2 ft) was observed just landward of the reef in the form of a reef-parallel trench in the western Cell 3. The eastern Cell 2 had a well-defined trench at the landward base of the reef structure up until September 1995. The trench has filled in since then on the eastern end but is still present on the western profiles (B thru E). Surveys taken in March 2002 indicate that a scour trench is still present along the landward side of the Beachsaver Reef in both cells with a depth of from −2.7 to −4.6 m (−9 to −15 ft).

Wave Attenuation

With only a one-day deployment, the wave attenuation portion of the study was limited. The study was done on 25 July 1995 during the summer months with low wave heights, but they increased as the day progressed from an offshore H_s of 0.28 to 0.31 m (0.92 to 1.02 ft). Wave attenuation coefficients between 0.86 and 0.96 were measured over the last three hours of the study (Herrington *et al.,* 1997). A wave height reduction was thus estimated at around 10 percent for the Cape May Point installation.

Dye and Current Studies

Under the influence of the incoming tide, the first measure of dye on 27 September 1994 remained close to where it was first placed both behind the reef units in the east cell and in the control area to the west. As the tide reversed, the dye was quickly dispersed to the east on the ebbing tide. Herrington *et al.* (1997) concluded that the reef structure did not adversely impact the circulation in the east cell.

Project Performance

With the gain in sand on the landward side of the Beachsaver Reef, particularly on the east cell the reef has stabilized the beach between the three groins at Cape May Point (Herrington *et al.,* 1997). Profile monitoring indicated that the beach lost sand from the dune base and backshore but gained sand in the foreshore and nearshore out to the reef position and responded to the typical seasonal cycle of the area. The MLW shoreline moved seaward within the two groin compartments with the reef on average 13.4 m (44 ft) for the east cell and on average of 4.6 m (15.13 ft) for the west cell. The control groin compartment shoreline retreated landward on average 4.6 m (15.13 ft), while the profile showed erosion and no seasonal signal. After monitoring the project for two years, the cumulative volume in the two cells protected by the Beachsaver Reef gained sand volume, with the east cell gaining a net 2,111 cu m (2,761 cu yd) and the west cell gaining a net 380 cu m (497 cu yd). Over the same period the control cell in the next groin compartment lost a net 660 cu m (863 cu yd) (Herrington *et al.,* 1997). Settlement of the units was prevented by the use of a thick filter cloth placed under the units. Measurements of the unit tops showed that the settlement was negligible over the two- year monitoring (Herrington *et al.,* 1997). Scour was measured on the landward side of the Beachsaver Reef with the formation of a trench of 0.61 m (2 ft) deep located at the landward side of the reef.

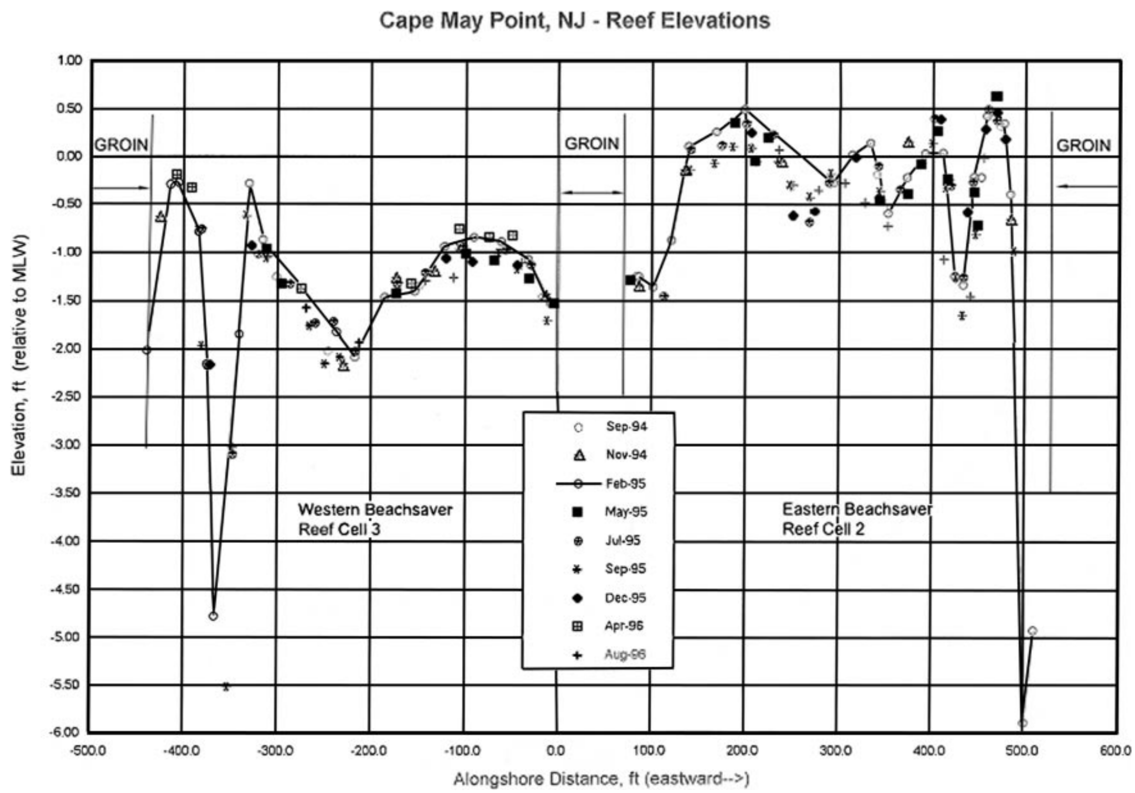

Figure 20. Settlement at Cape May Point Beachsaver Reef (after Herrington *et al.*, 1997).

HERRINGTON *et al.* (1997) speculated that the trench was formed due to the bottom return flow being deflected by the base of the reef. This installation was unique in that the reef structure was placed high in the water column. It was estimated that wave heights were reduced by 10 percent for the fair weather waves measured. HERRINGTON *et al.* (1997) suggest that wave heights would decrease even more for larger storm waves. Dye studies indicated that water exchange occurred in concentrated currents along the edge of each groin. The project remains in place, with plans to construct another Beachsaver Reef in an adjoining jetty compartment, with its crest at MLW. This new Section 227 monitoring project will compare if a shallower placement will change the performance.

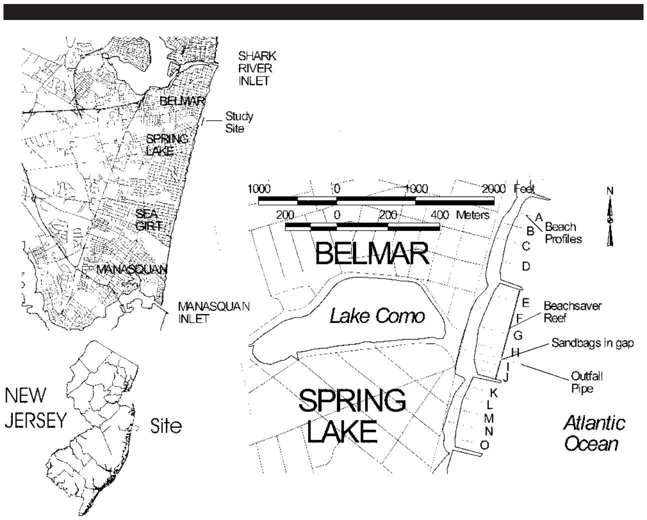

Figure 21. Location of the Beachsaver Reef installation at Belmar/Spring Lake, New Jersey.

BELMAR/SPRING LAKE, NEW JERSEY, PROJECT

A third installation of the State of New Jersey sponsored Pilot Reef Project was completed in August 1994 on the border between the boroughs of Belmar and Spring Lake, NJ. This area is along the northern New Jersey coast is approximately 32 km (20 miles) south of Sandy Hook (Figure 21). This area is characterized as a headland coast and is located between Shark River Inlet and Manasquan Inlet. The net drift direction is from south to north along this stretch of coast. Beach erosion has been a constant problem and almost the entire shoreline is armored by seawalls to protect Ocean Avenue. Several stone groins around 168 m (550 ft) in length have been constructed perpendicular to the shoreline to trap the limited amount of sand available in the littoral system. The beaches are narrow, with a steep offshore slope. Of the three sites in New Jersey, this site has the most energetic wave climate and is about halfway between the two inlets so there is no strong inlet tidal flow influence as was present at Avalon and Cape May Point. A truck haul beach fill was also placed in this groin compartment along with the Beachsaver Reef (BRUNO *et al.,* 1996a).

To test the effectiveness of reducing incident wave energy, a 100-unit, 335 m (1,100 ft)-long Beachsaver Reef was constructed between the Pitney Avenue groin in Spring Lake on the south and the 19th St. Groin in Belmar on the north (CRETER *et al.,* 1994). The reef was attached to the two groins about 128 m (420 ft) seaward of MLW, in water depths of 2.3 to 2.4 m (7.5 to 8 ft) MLW (HERRINGTON and BRUNO, 1998). A 6.1 m (20 ft) gap was left to enable a 0.91 m (3 ft) diameter ocean outfall pipe buried 0.91 m (3 ft) below the bottom to extend offshore, perpendicular to the shoreline. The gap was filled with a stacked geomattress configuration up to the crest elevation of the Beachsaver Reef. Reef crest elevations of between −0.7 to −1.16 m (−2.3 to −3.8 ft) MLW were measured after placement at this site. The same double thickness geotextile fabric underlayment as was used at Cape May Point, was used on this installation for scour protection. The polyethylene geomattress filled with stone was placed along both the landward and seaward sides of the base to also mitigate for scour. To further stabilize the reef, steel H-piles were driven to a maximum depth of 3.05 m (10 ft) below the bed at all end and transition units (BRUNO *et al.,* 1996a). The ends of the reef were connected to the groins with capstone.

Monitoring Program

The monitoring program at Belmar/Spring Lake was initiated after the Beachsaver Reef was installed. A beach profile baseline was established along 945 m (3,100 ft) of the shoreline in September 1994, with 15 beach profile lines. The survey plan included a north control section with four profiles in the next groin compartment north of the 19th St. groin in Belmar (Figure 21). Six profiles were established in the Beachsaver Reef compartment, with four profiles north and two south of the ocean outfall location. A south control was established in the next groin compartment south of Pitney Avenue groin, with five profile lines (BRUNO *et al.,* 1996a). These profiles were spaced approximately 30.5 to 61 m (100 to 250 ft) apart. Additional surveys were collected in November 1994, and in March, May, September and December 1995 (Table 5). Surveys were collected with a total station and prism rod out to just past the Beachsaver Reef and offshore surveys were collected with a boat mounted fathometer.

Settlement measurements consisted of surveys of the top of the reef structure. They were collected in September and November 1994 and March and May 1995 (BRUNO *et al.,* 1996a). No wave measurements or dye studies were done at the Belmar/Spring Lake site.

Monitoring Results

Shoreline Response

Fill material placed in the Beachsaver Reef compartment on the upper beach by truck was removed from the upper beach during the 1994/95-winter storm season. This sand was moved to the nearshore landward of the reef (BRUNO *et al.,* 1996a). Minor recovery was measured during the spring of 1995. An active hurricane season in the summer and fall of 1995 with several storms moving up the east coast offshore resulted in berm erosion and bar formation in the September and December profile surveys (Figure 22a). The 0 NGVD elevation shoreline moved landward approximately 15.2 m (50 ft) over the monitoring period based on profile plots (BRUNO *et al.,* 1996a; HERRINGTON and BRUNO, 1988). Profile B in the control area (which did not receive any fill) located in the next groin compartment to the north (downdrift) indicated that the shoreline remained relatively stable with a seaward movement of approximately +6.1 m (+20 ft) over the same monitoring period from September 1994 to December 1995 (Figure 22b).

Sediment Volume Response

Measurements of volume within the profile from the berm to the Beachsaver Reef indicated that the material placed in August 1994 was retained within the profile, but was redistributed from the berm to the nearshore bar inside of the reef structure (BRUNO *et al.,* 1996a). As of July 1996, the net volume change within the groin cell was a loss of 3.3 cu m/m (1.3 cu yd/ft) of sand (HERRINGTON and BRUNO, 1998).

Settlement

Settlement of around 1 m (3.3 ft) was observed at the Belmar site. A 1 m (3.3 ft) layer of medium sand was over a 1 m (3.3 ft) thick clay layer. The settlement stopped once the reef units reached the clay layer (HERRINGTON and BRUNO, 1998). The settlement ranged from 0.12 m (0.4 ft) at the southern end of the reef to around 1.95 m (6.4 ft) at the center of the structure. Most of the settlement was measured in the first 6 months from September 1994 to March 1995. BRUNO *et al.* (1996a) concluded that the settlement was related to the bottom material. Less settlement was measured at the Belmar/Spring Lake site, possibly because the filter fabric used was thicker than the Avalon installation, as well as addition of the rock filled geotextile mattress at the base of the reef structure. There was also no open end since the reef was tied into the groin on either end. More scour was observed in areas where the geotexitile mattress was more than 0.6 m (2 ft) landward of the structure. This distance allowed the sand to be undermined and the reef units settled due to the landward scour trench.

Table 5. *Monitoring of Beachsaver Reef at Belmar/Spring Lake, New Jersey.*

Year	Month	Profile Survey	Settlement	Events
1994	August			Beachsaver Installation
	September	Post-Survey	Settlement	
	November	Survey	Settlement	
1995	March	Survey	Settlement	
	May	Survey	Settlement	
	September	Survey		
	Oct–Nov			*Several Storms*
	December	Survey		

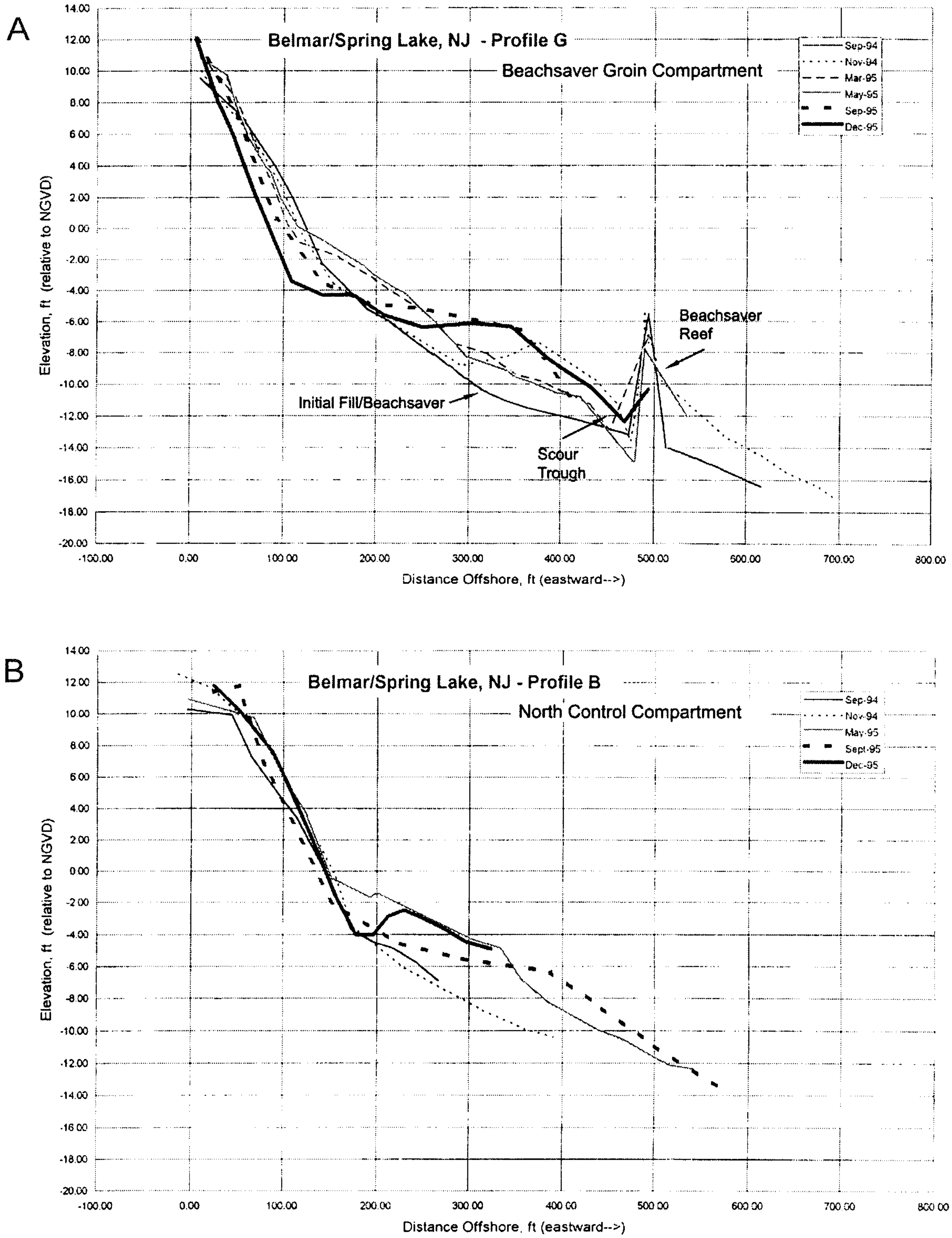

Figure 22. Representative profile monitoring of the Belmar/Spring Lake, New Jersey, Beachsaver site. (a) Profile G in beachsaver groin compartment and (b) Profile B in north control groin compartment (after Bruno *et al.*, 1996a).

Scour

Scour was measured at the landward base of the reef structure. The scour was limited to a zone of 15 to 18 m (49 to 59 ft) landward of the reef with a depth varying between 1.2 m (4 ft) in November 1994 to 2.1 m (6.9 ft) in July 1996 (HERRINGTON and BRUNO, 1998).

Wave Attenuation

Wave attenuation was not measured at the Belmar/Spring Lake site.

Project Performance

No final report was available on the Belmar/Spring Lake site. From the preliminary reports BRUNO *et al.* (1996a) and HERRINGTON and BRUNO (1998), the shoreline was qualitatively reported as moving landward as the trucked beach fill moved from the upper berm to form a bar in the nearshore area landward of the reef structure, while the unfilled control area groin compartment to the north remained relatively stable. The net volume of the profiles within the groin compartment was basically conserved as the profile was reshaped. With the use of a thick filter fabric as a base along with a stone filled geotextile mattress, the settlement was reduced with most of the settlement measured in the center of the groin compartment. A scour trench did develop on the landward side of the reef structure in spite of the geotextile mattress. The seaward side did not show any scour trench development. The design of this installation placed the Beachsaver Reef across the entire groin compartment with attachment to the groins on either side with caprock. The reef crest was at an intermediate depth relative to the other two New Jersey installations. To date this reef structure remains in place.

VERO BEACH, FLORIDA, PROJECT

The final installation of the P.E.P. Reef was in August 1996 at Vero Beach, Florida. Indian River County is located on the central Florida Atlantic coast, approximately 97 km (60 miles) south of Cape Canaveral. The City of Vero Beach, occupies 6.3 km (3.9 miles) of beach along a 35-km (22-mile) long barrier island coast some 24 km (15 miles) south of Sebastian Inlet and 21 km (13 miles) north of Ft. Pierce inlet (Figure 23). A naturally occurring, discontinuous, nearshore reef system composed of coquina beachrock (containing mostly broken shell fragments and quartz sand grains cemented together) is found in the nearshore. This reef is part of the Anastasia Formation (a long, narrow linear rock formation) which extends south from Anastasia Island (St. Augustine) some 322 km (200 miles) to Palm Beach (STAUBLE and MCNEILL, 1985). The nearshore reef formation is around 305 to 610 m (1000 to 2000 ft) wide, parallels the shoreline and is found in the surf zone along almost the entire length of Indian River County. The rock may be covered with sand at some times of the year and outcrops as bare rock at other times. The rock reef structure starts just south of Sebastian Inlet and becomes exposed at low tide at Riomar Point.

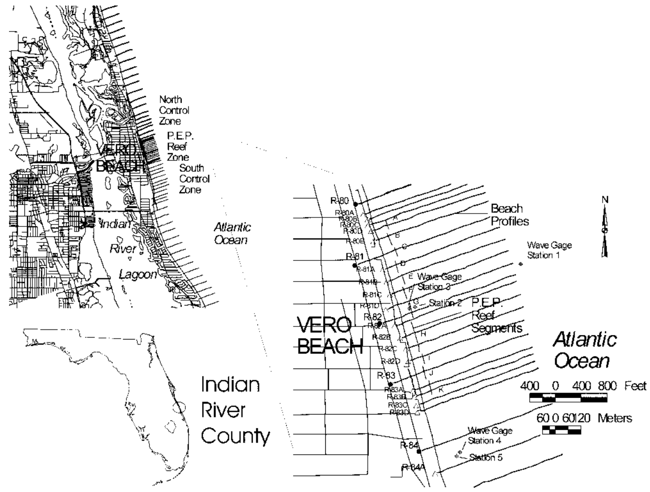

Figure 23. Location of the P.E.P. Reef installation at Vero Beach, Florida.

Indian River County has experienced erosion along most of its coastline in the past. Erosion of concern occurs particularly along the shorefront of the City of Vero Beach. The coastline of Indian River County has few erosion control structures. There are currently 34 structures, totaling 1,741 m (5,711 ft) of shoreline (about 5% of the county's shoreline) armored with seawalls. The main concentration of seawalls fronts the commercial district within the City of Vero Beach. The rest of Indian River County's shoreline is backed by a coastal dune with a crest height around 4.6 m (15 ft). These seawalls, constructed of various designs and materials ranging from vertical concrete to metal sheet pile were built over the years to protect upland property from wave damage during storms. Between Florida Department of Environmental Protection (DEP) Range monuments R-80 and R-83, approximately 95% of the shoreline is backed by coastal armoring structures. This is the area of P.E.P. Reef installation.

To mitigate erosion, a 914 m (3,000 ft)-long submerged P.E.P. Reef was placed by Indian River County, along the shoreline of the City of Vero Beach between 20 July and 15 August 1996. A total of 217 interlocking P.E.P. Reef units were placed in an alternating onshore/offshore configuration with gaps between each segment. This alternating placement design is approximately 61 to 76 m (200 to 250 ft) seaward of the beach, and extends from DEP monument R-80C to R-83B. This modified project placement configuration with gaps between shorter segments was determined by wave tank studies and the experience gained with the measurement of inshore face scour on the single line configuration of the Midtown Palm Beach project (DEAN *et al.,* 1994b). The breakwater consists of eleven segments (A–K) ranging in length from 51 to 93 m (168 to 304 ft), placed in a configuration as shown in Figure 23. Design bottom elevations were −2.1 m (−7 ft) for inshore units and −2.7 m (−9 ft) for offshore units. This placement would provide design water depths above the inshore unit crests of 0.3 m (1 ft) NGVD and above the offshore units of 0.9 m (3 ft) NGVD.

Monitoring Program

A four-year monitoring program funded by Indian River County was conducted by the US Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory (CHL) to provide an independent evaluation of the effectiveness of the P.E.P. Reef system (Stauble, 2002). This monitoring program, which began with a pre-installation survey in May 1996, included: quarterly beach profile surveys to assess shoreline and sand volume change; multiple wave gage deployments (year 1 and 2) to measure wave transmission; breakwater settlement monitoring (year 1) to determine settlement of concrete units on sand and hardbottom substrate; and scour rod measurements (year 1 and 2) to assess scour adjacent to P.E.P. Reef segments, as well as an analysis of pre-project historical shoreline change conditions. Due to high tropical storm activity in the summer and fall of 1999 and the rapid post-storm beach sand recovery (in the third year), an anomalous condition was created for the final scheduled survey conducted in December 1999. A newly designated final survey was taken in June 2000, at which time it was thought that the beach would return to a more typical configuration. The purpose of the program is to evaluate the effect of the P.E.P. Reef on profile and area volumetric changes, wave attenuation, structure stability and shoreline response. Beach profiles were collected by Morgan and Eklund, Inc., and scour and wave attenuation studies were provided by the Florida Institute of Technology, Division of Marine and Environmental Systems.

A total of 40 profile lines were established using DEP Monuments R-75 to R-89 plus supplemental profile locations between the DEP monuments (Figure 23). DEP monuments are spaced around 305 m (1,000 ft) apart, so supplemental monuments were spaced 61 m (200 ft) between lines within the limits of the P.E.P. Reef to provide coverage of each reef unit. Control profiles were established up to 1,524 m (5,000 ft) north and south of the breakwater terminus, with a 152 m (500 ft) spacing of supplemental profiles outside of the P.E.P. Reef limits. Surveys extended out to between 457 m (1,500 ft) and 1,067 m (3,500 ft) seaward of the baseline on all profiles. This was well seaward of the P.E.P. Reef position. The wading portion of the profile was collected with the standard rod and tape method. The nearshore survey was collected by boat with a fathometer. An overlapping area in the nearshore was collected by both methods to calibrate the fathometer survey and provide a match for continuous cross-shore profile coverage. All profile surveys extended seaward of the natural hardbottom reef, onto a natural sand bottom. The surveys show little to no change in the bed elevation in this offshore area over the entire monitoring period. A potential error estimate in determining sediment volume changes at hardbottom locations is estimated to be ± 1.1 cu m/m^2 (± 0.13 cu yds/ft^2) (length of shoreline/cross-shore distance). This value was determined by comparing the volume differences at hardbottom locations between several profiles over the study period (Stauble, 2002).

A total of 36 scour rods were placed and maintained at strategic locations to measure scour at different segments and at the gaps between segments from 1996 to 1998 (Table 6). Placement and measurement of the scour rods was done by divers. Elevation data was also collected at -2.1 and -2.7 m (-7 and -9 ft) NGVD contours derived from profile survey data in the north and south control areas to compare with elevation changes at P.E.P. Reef locations. Four scour rods were placed in the vicinity of the north end of P.E.P. Reef Segment A. Six rods were deployed around the south end of Segment A, along Segment B and at the north end of Segment C. Another set of 10 rods was placed in the center of the project between Segment F, G and H (near station 2 and 3 wave gages) to monitor the center of the project. The final 5 scour rods were placed at the south end of the project, around unit J and 4 scour rods were placed at the south end of unit K (the southernmost unit in the project). No scour rod measurements were scheduled during 1999 or in June 2000, but profile surveys were used to measure a pronounced scour trough that was always present on the landward side of each P.E.P. Reef segment. A scour trough was also measured on the seaward side of the reef segments, but the seaward side scour trough was prominent on some surveys and was filled in on other surveys (Stauble, 2002).

P.E.P. Reef unit crest elevations were measured in conjunction with the as-built beach profile survey directly following unit placement on 16 August, 1996. Settlement was measured by placing a survey rod on the top of the reef unit. This structure measurement was made again in December 1996 thru February 1998 to assess changes in each reef unit's crest elevation during the first year (Table 6). Biofouling was prevalent on the reef segments and this growth was scraped off before settlement measurements were made so that the rod was placed directly on the top of the concrete of each unit. This procedure gave an accurate measure of settlement of each unit. No structure measurements were scheduled for 1998 and 1999. Settlement measurements were not taken in conjunction with the final June 2000 survey. However, elevation measurements of the fouled top of the P.E.P. Reef were measured as part of the beach profile survey. This method is not as accurate for measuring settlement, as it did not measure the top of concrete. The survey rod was simply placed on top of the marine growth on the P.E.P. Reef crest. Comparison was made between the elevation of the clean P.E.P. Reef units taken during the August 1996 profile survey and the June 2000 survey (which included biologic growth) to give an approximate measure of the elevation change of the unit top between immediate post-installation and the final 46-month survey. Settlement of each individual unit depended on unit placement relative to the natural hardbottom. Where the hardbottom was near the surface on initial installation, scour resulted in the unit settling to the top of the rock. Some units became perched on the natural rock ledge and some units ended up on an angle over the edge of the rock ledge. Other units settled into a sand substrate, where hardbottom was not near the surface (Stauble, 2002).

Aerial photography was taken for the entire project length in 1993 (used as a pre-project base map) and annually between 1996 and 1999 (Table 6). No photography was flown in 2000, but an additional set was flow in 2001 after the official monitoring ended. Color photography in 9″ × 9″ (22.8 × 22.8 cm) format was flown to show the shoreline and nat-

Table 6. *Monitoring of P.E.P. Reef at Vero Beach, Florida.*

Year	Month	Profile Survey	Wave Data[1]	Settlement	Events/Other Monitoring
1996	May	Pre-Survey			
	August				P.E.P. Installation
		Post-Survey	Waves (3)	Settlement	Scour/Air Photos
	September				Scour
	October				
	November				Scour
	December	Survey	Waves (3)	Settlement	
1997	January				Scour
	February				
	March	Survey	Waves (c)	Settlement	Scour
	April		Waves (3)		
	May				Scour
	June	Survey		Settlement	Scour
	July		Waves (c)		Scour/Air Photos
	August		Waves (3)		Scour
	September	Survey		Settlement	
	December				Scour
1998	February	Survey		Settlement	
	May	Survey	Waves (5)		Scour
	June				Scour/Air Photos
	July				Scour
	August				Scour
	September	Survey			
1999	February	Survey			
	June	Survey			
	July				Air Photos
	Aug–Nov				*Several Storms*
	December	Survey			
2000	June	Survey			
2001	June				Air Photos

[1] Notes: (c) = operating wave gage Stations 4 and 5 (control) only; (3) = operating wave gage Stations 1 (offshore), 2 and 3 (at P.E.P. Reef) only; (5) = operating wave gage Stations 1, 2, 3, 4, and 5.

ural reef positions. Morphologic features such as the MHW line (identified as the visible wet/dry line which is slightly different from the shoreline derived from a datum elevation off the profiles), seawalls and dune locations were determined from the photographs and compared with previous photographs. The P.E.P. Reef positions in relation to the landward beach and natural hardbottom reef were visible on most of the photographic sets. Construction of photo mosaics allowed for an overview of the regional coastal morphology at Vero Beach and to see details of the highly variable natural hardbottom locations and extent. Minimal change was observed in the natural reef pattern, but the shoreline position and beach width changed over the study.

Five self-recording directional pressure (P*uv*) wave gages were installed in the vicinity of the P.E.P. Reef at various times over the first two years of the study. This wave gage monitoring was ended around September 1998 and no wave gages were deployed after that time. The outer gage, referred to as Station 1, was located in −7.3 m (−24 ft) NGVD water depth and characterized the offshore wave climate. Two gages were placed on the seaward (Station 2) and landward (Station 3) sides of Reef Segment G near profile line R-82 to record wave transmission effects (Figure 23). Using a Differential Global Positioning System (GPS), Station 2 was located approximately 23 m (75 ft) seaward of Segment G in −3.5 m (−11.5 ft) of water, and Station 3 was located 6.1 m (20 ft) landward of Segment G at around −2.7 m (−9 ft) depth. Station 3 was placed close to the structure due to the shallow water depth landward of the P.E.P. Reef. Two additional control wave gages were installed 183 m (600 ft) to the south of the southern P.E.P. Reef terminus at similar cross-shore locations and depths as the primary wave gage pair. The purpose of these control wave gages were to measure waves at locations unaffected by the P.E.P. Reef so that wave transmission effects due to the natural reef could be compared with the P.E.P. Reef. The seaward control gage (Station 4) was located in −3.5 m (−11.5 ft) water depth and the landward control gage (Station 5) was located in −2.7 m (−9 ft) water depth near profile transect R-84A. All four of these wave gages (2 thru 5) were located landward of the natural reef outcrop (STAUBLE, 2002).

Monitoring Results

Shoreline Response

During the August 1996 to June 1999 period, the change in shoreline position (defined as the mean high water line, measured as the +0.58 m (+1.91 ft) NGVD elevation datum from the beach profiles), averaged a large 10.5 m (34.4 ft) of seaward movement in the north control. The P.E.P. Reef zone averaged −2.8 m (−9.28 ft) of landward movement and the south control averaged a landward movement of −1.7 m (−5.6 ft). Figure 24 shows this relative pattern of seaward movement in the north control, a landward movement in the

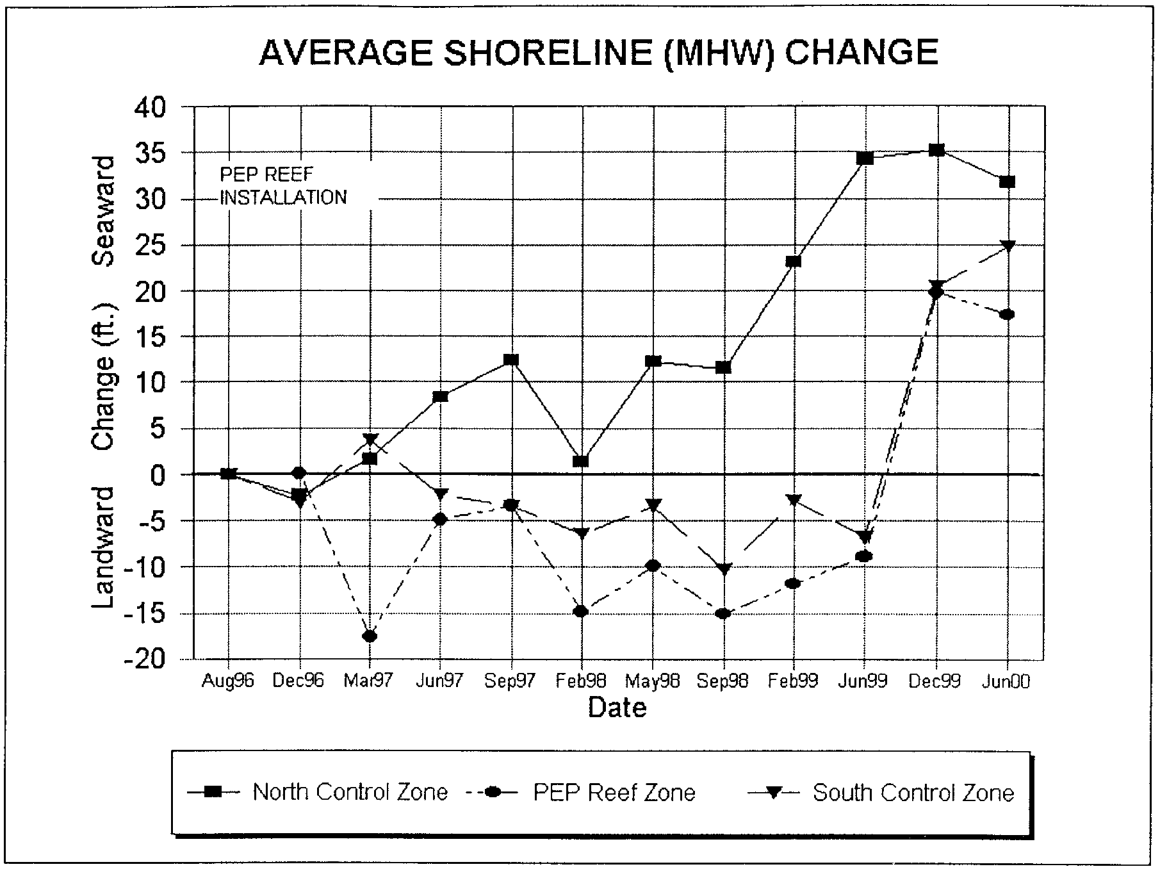

Figure 24. Cumulative shoreline change at Vero Beach P.E.P. Reef installation (Stauble, 2002).

P.E.P. Reef zone and a mixed sometimes landward and sometimes seaward movement in the south control zone persisted from installation to June 1999 (STAUBLE 2002).

Reflecting a large post-storm gain in sand on the subaerial beach, the shoreline over the entire project length moved seaward as of the December 1999 survey. Over the cumulative August 1996 to December 1999 (forty-month) period, the average seaward movement of the MHW shoreline reflected a gain in sand on the berm at all profile locations. The cumulative shoreline position landward of the P.E.P. Reef moved seaward an average of 6.0 m (19.8 ft), showing the first seaward movement in the shoreline since installation. The shoreline in the north control zone also averaged a large 10.7 m (35.1 ft) seaward movement and south control zone averaged a relatively large move of 6.2 m (20.4 ft) seaward.

Due to lack of storm activity between December 1999 and June 2000 (over the winter and spring), the shoreline continued to average an overall seaward movement trend for the entire project length. Most of the seaward movement this time was in the south control zone. An average cumulative seaward shoreline change of 7.6 m (24.9 ft) was measured over the entire study period from August 1996 to June 2000 in the south control zone. Within the P.E.P. Reef zone, the average overall project cumulative movement of 5.3 m (17.4 ft) was also in the seaward direction, due to the large accretion in the last measuring period. The north control zone showed a slight landward movement from December 1999 to June 2000. However, the cumulative overall project average (August 1996 to June 2000) was still the largest seaward movement, measuring 9.7 m (31.7 ft). This cumulative shoreline movement is due to the almost constant seaward movement of the shoreline in this zone for the other periods.

Sediment Volume Response

Cumulative volume change over the August 1996 to June 1999 period (characterized the general project response) for the north control zone experienced accretion averaging 45.98 cu m/m (18.32 cu yd/ft). In the vicinity of the P.E.P. Reef, volume change showed erosion averaging −7.81 cu m/m (−3.11 cu yd/ft) length of beach. The south control averaged a loss of −5.95 cu m/m (−2.37 cu yd/ft).

The volume change analysis comparing the baseline August 1996 survey to the post-storm December 1999 survey showed the same trends in sand accretion as was measured in the shoreline seaward movement (Figure 25). In the P.E.P. Reef zone, the beach volume change experienced accretion of 11.70 cu m/m (4.66 cu yd/ft). The south control experienced a

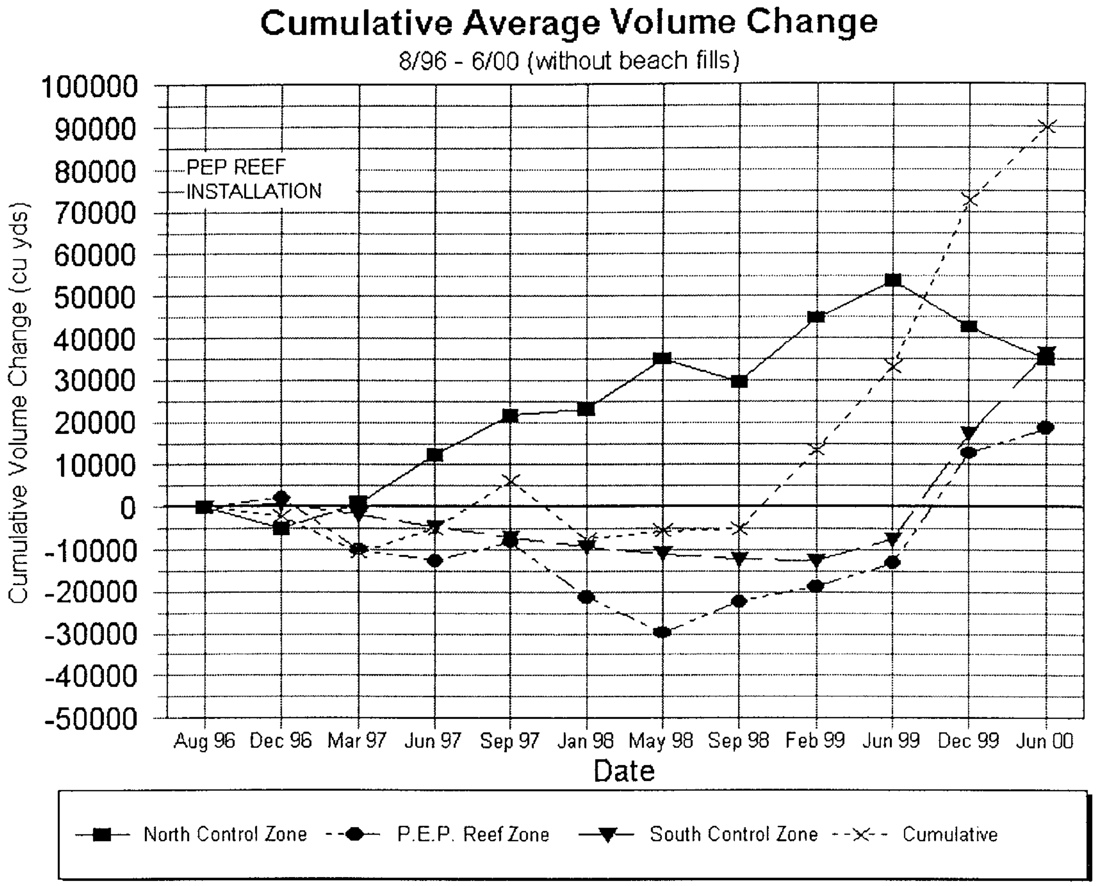

Figure 25. Cumulative volume change at Vero Beach P.E.P. Reef installation (Stauble, 2002).

slightly larger gain of 15.31 cu m/m (6.10 cu yd/ft). The north control area showed the largest gain in sand volume of 31.88 cu m/m (12.70 cu yd/ft). The majority of the volumetric gain in all three zones occurred on the berm area of the profile. This gain in sand on the berm in December 1999 reflects the rapid recovery of sand to the beach by a period of fair weather waves in November and December after the storms, which ended in October.

A similar trend in sediment volume was observed over the winter months between December 1999 and June 2000 with a slight gain averaging 7.3 cu m/m (2.9 cu yd/ft) in the P.E.P. Reef zone, mostly on the upper beach adjacent to the seawalls. A larger gain of 14.8 cu m/m (5.91 cu yd/ft) was measured on the beaches in the south control zone, again mostly on the foreshore and berm (Figure 26). The north control zone experienced a slight loss in volume averaging −3.3 cu m/m (−1.31 cu ft/yd), which was mostly confined to the nearshore area of the profile between 0 NGVD and the first hardbottom outcrop. The berm and foreshore also gained sand volume in this zone. The long-term project monitoring measured during the August 1996 to June 2000 period, showed that the area to the north of the P.E.P. Reef experienced an average accretional volume of 28.6 cu m/m (11.39 cu yd/ft). Volume change in the vicinity of the P.E.P. Reef averaged a gain of 18.9 cu m/m (7.54 cu yd/ft) length of beach and in the south control zone gain an average 30.1 cu m/m (12.01 cu yd/ft).

The majority of the volumetric changes in the P.E.P. Reef zone occurred landward of the breakwater axis and in both control zones landward of the natural hardbottom. Little change was detected in all of the profile volumes seaward of the P.E.P. Reef axis and over the natural hardbottom.

Settlement

Detailed survey measurements of reef settlement were limited to the first two years of the study. The tops of each unit were surveyed immediately after placement and during subsequent survey periods. Biofouling occurred very rapidly, and the growth of marine organisms had to be scraped off the tops of the units to measure the top of the concrete on each survey. The inner P.E.P. Reef segments settled approximately 1 m (3.4 ft) and the outer segments settled 0.9 m (2.8 ft) during the first four months (Figure 27). The units over hardbottom settled until the units rested on the hardbottom, which caused some shifting over the uneven bottom. The units over sand also settled during this adjustment period. After initial settlement, the units remained more-or-less stable over the rest of the monitoring period. During the final extended year

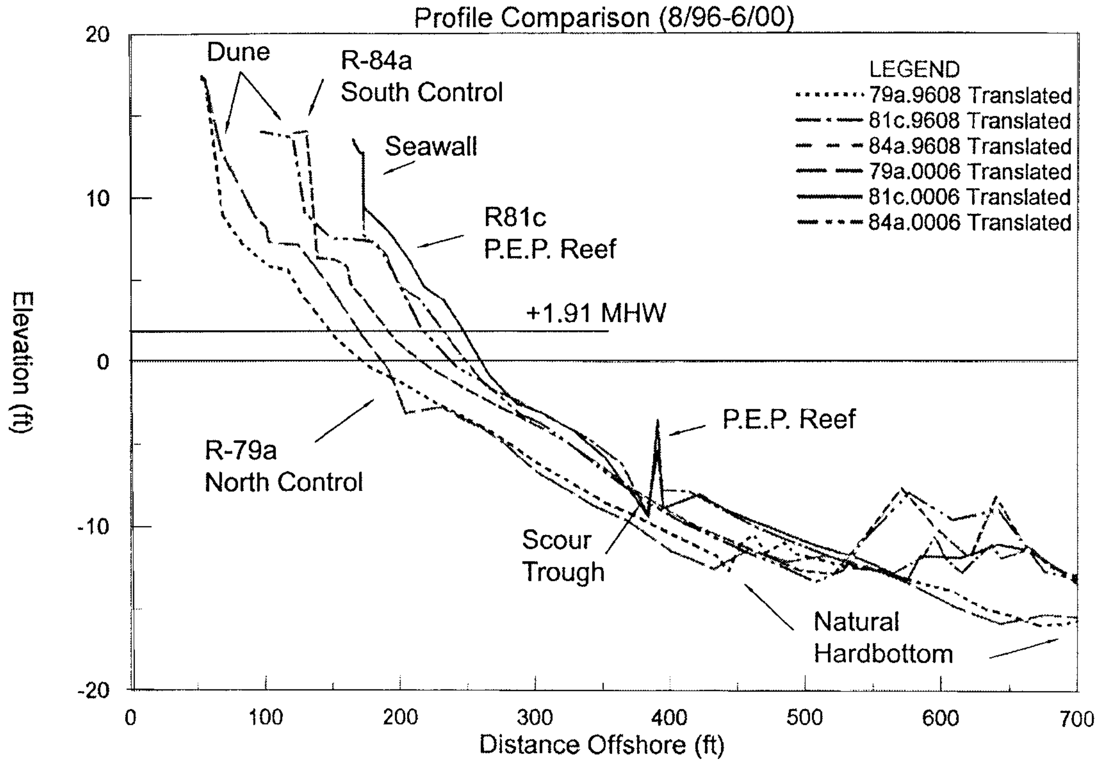

Figure 26. Representative profile monitoring of the P.E.P. Reef at Vero Beach site. (a) Profile R-79A in the north control, R-81C in the P.E.P. Reef, and R-84A in the south control zones (Stauble, 2002).

of monitoring, the tops of the P.E.P. Reef units were surveyed during the profile without scraping off the biofouling so exact measurements of the settlement could not be ascertained. Based on comparisons of the August 1997 and June 2000 surveys, all of the units have still shown a settlement from initial installation.

Scour

A scour trench persisted over the entire study period from August 1996 to June 2000 on both the landward and seaward side of the reef. The landward scour trench averaged 1.22 m (4 ft) deep and 6.4 m (20.9 ft) wide and was present along the landward side of the entire length of the P.E.P. Reef. The scour trench seaward of the P.E.P. Reef was not as persistent, and occurred mostly after storms. One was formed after the tropical storms, measured in the December 1999 survey, but had filled in by the June 2000 survey. A general pattern has emerged with the seaward scour trough present after storms and filled in after more of a fair weather period.

Formal monitoring of the scour trench was only scheduled to extend for the first two years of monitoring. As reported in the Second Annual Monitoring Report (Stauble and Smith, 1999), scour rods were placed at the north, center and south units of the P.E.P. Reef. The detailed measurements of the sand elevation at these rods at various times within the first two years indicated that a permanent scour trench was located landward of the breakwater. This trench is believed to be formed by wave/structure interaction-induced currents. The width varied between 3 and 9 m (10 and 30 ft), with a depth of 1.22 to 1.83 m (4 to 6 ft). Comparisons were made between scour at the north, central and southern units, seaward and landward of each unit, at inshore and offshore units, and at the P.E.P. Reef units versus natural profiles in the north and south control zones in the first two years. Measurements indicate the persistence of the landward scour trench over the entire study period. A seaward trench was present mostly after storm events, but would fill in during fair weather periods.

Wave Attenuation

Measurements from five *puv* wave gage stations made from 1996 to 1998 indicate that incident wave heights landward of the P.E.P. Reef were reduced by an average of 12% after initial installation. However, following the initial four-month settlement of the structure, wave height reduction averaged between 8 to 9%. A shorter monitoring data set from the control location south of the P.E.P. Reef indicated that, over the natural hardbottom the wave height difference ranged from an increase of 3% to an attenuation of up to 9%, based on the difference between the seaward control wave gage and the landward control wave gage. These data suggest that the P.E.P. Reef has minimal effect in attenuating wave energy, particularly after settlement of the reef structures.

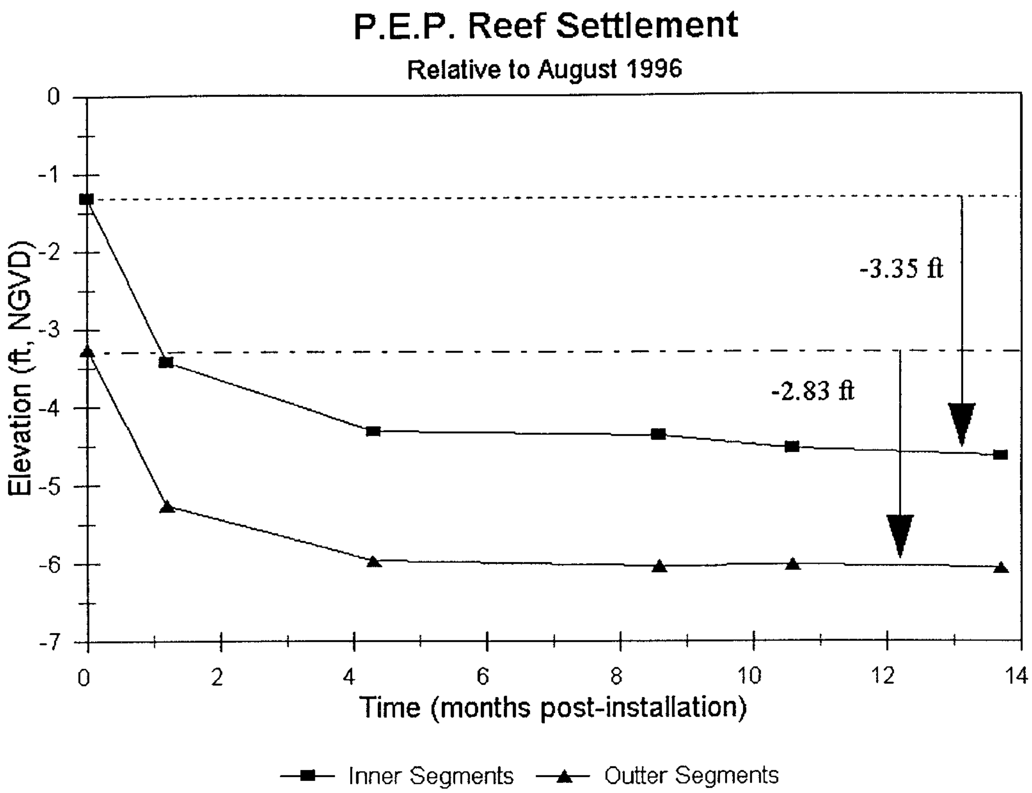

Figure 27. Average settlement after 14 months of the inner and outer P.E.P. Reef segments relative to initial installation in August 1998 at Vero Beach, Florida. (Stauble *et al.*, 2000.)

Project Performance

The trend of the shoreline and volume change for the initial 34-month period was for seaward movement of the shoreline and gain in volume for the north control area. Landward movement of the shoreline and loss in profile volume was measured in the P.E.P. Reef zone, and a slight seaward movement of the shoreline and a slight gain in volume was found in the south control area. The south control area showed the most fluctuation between landward and seaward shoreline movement, and gain and loss of profile volume of the three zones over time. There were no strong seasonal trends in either the shoreline or volume change. With the large accretion experienced in the December 1999 survey, the P.E.P. Reef shoreline moved seaward of the north control but was still landward of the south control. With the large accretion over almost the entire 45-month study period in the north control zone, the cumulative shoreline moved further seaward than the other zones. As of the December 1999 survey, the shorelines in the P.E.P. Reef and south control zone also moved seaward. Although accretionary between December 1999 to June 2000, the P.E.P. Reef zone, usually had the most landward shoreline position of the three zones. The south control shoreline position was stable, with minor seaward movement over the study duration.

The change in the beach profiles within the three zones is a result of several factors. The north control area is a wide beach backed by dunes. The nearshore natural hardbottom has a distinct two shore-parallel reefs separated by a sediment-filled trough. This zone was generally accretionary. The sand volume gain in this zone was mainly on the subaerial beach and foreshore area. Little change was measured in the nearshore. The north end of the P.E.P. Reef appeared to act as a groin trapping sand in the north control and restricting its movement to the south (direction of net drift). The P.E.P. Reef zone is characterized by narrow beaches backed by various types of seawalls that are irregularly aligned. The high water line is commonly at or past the base of most of the seawalls, so the beach is intertidal. Within this zone, the nearshore natural hardbottom morphology is characterized by three distinct natural reef structures extending out in a southeasterly direction from the shoreline. A single natural reef outcrop is offshore and parallel to the coast. Pockets of sand are found between two shore attached reef lines. The P.E.P. Reef segments were placed in this zone along two lines paralleling the shoreline in −2.13 and −2.74 m (−7 and −9 ft) of water. Some of the reef segments were placed on sand and some on outcropping hardbottom. Throughout the study, these beaches, were most erosive, especially in the north part of the P.E.P. Reef zone. The short profile and the interaction of waves directly on the vertical face of the seawalls, especially during periods of raised water levels, prevented sand from accumulating in large volumes. At the end of the study, the volume of sand was gained at the base of the seawalls. Locally, the nearshore profile was impacted by the placement of the P.E.P. Reef, as a landward trough developed at the base of all of the breakwater segments. A seaward trough also formed after storm waves. These troughs at the P.E.P. segments further reduced the volume of sand in this zone relative to pre-placement profiles. The south control profiles had an intermediate length profile mostly backed by low dunes and a few seawalls. The nearshore region was dominated by a shallow outcropping of the Riomar Reef, part of the natural hardbottom. This reef had the highest relief and was the closest to shore of hardbottom in the three zones. The beaches in this zone exhibited alternating erosion and accretion, with a large gain in sand at the end of the study on the upper beach and foreshore. Little change in volume was measured in the nearshore.

The relative importance of the breakwaters and the natural non-uniform outcropping of rocky hardbottom on the local coastal processes was evaluated. With natural hardbottom almost directly alining with the boundaries of the north control, P.E.P. Reef and south control areas, it was difficult to separate the impact of the P.E.P. Reef from that of the existing hardbottom. Comparison of long-term historical shorelines and more recent historical (1972, 1986, 1993) profile data from the Florida DEP with present day shoreline and volume changes after installation show a similarity in trends, with erosion in the P.E.P. Reef zone and accretion in the north and south control zones. The post-installation changes appear to be more exaggerated, but follow the long-term trends, indicating that the P.E.P. Reef has only a localized effect on the overall coastal processes.

The gain in sand on all three zones at the end of the study is problematic, with large sand gain measured on the upper portion of the beach after the passage of several tropical storms in the fall of 1999. This volume of sand remained throughout the winter and was only slightly redistributed in the alongshore direction. The large gain in sand in December 1999 is suspected to be the result of fair weather waves moving sand, originally moved into the nearshore by the storms, back onto the dry beach. A large volume of sand also moved downdrift from the north control through the P.E.P. Reef zone, to be deposited on the southern end of the P.E.P. Reef zone and northern portion of the south control zone. It is common to have a rapid recovery of sand back onto the dry beach after the passage of a tropical system, since most of these storms are followed by long periods of fair weather waves, that move sand back onto the beach. The volume of accretion measured after the storms, and the fact that it remained through the winter with little change in volume and only slight redistribution in both the cross-shore and longshore direction was surprising. The frequency of storms during the winter and spring of 1999/2000 was about average, however, the magnitude of the storms was lower than average. The post storm sand that accreted on the back beach was preserved and was only moved slightly in a southerly (downdrift) direction.

Wave transmission over the P.E.P. Reef was enhanced by the settlement of all of the segments within the first 14 months of the study. An average settlement of −1.01 m (−3.32 ft) on the inner segments and −0.86 m (−2.83 ft) on the outer segments resulted in only an 8% decrease in wave heights passing over the breakwater. Wave gage records indicate larger storm waves were reduced in height by around 12% after settlement. The crest width of 0.31 m (1 ft) of each P.E.P. Reef unit was too narrow to sufficiently reduce wave height. Wave and circulation modeling indicated that if the breakwater segments had not settled, they would have attenuated more wave energy and allowed for possible sediment accumulation up to 15 to 25 cm (0.5 to 0.7 ft) over a 30-day model test (ZARRILLO, 2002).

Based on current data collected along with the wage gage deployments, the breakwaters have limited influence on the currents. It is noted that, the current data was only collected for a short time and under low wave conditions. The P.E.P. Reef appears to be affecting the ability to transport sand in the longshore direction based on the shoreline and sand volume analysis. The north end of the reef appears to limit the movement of sand from the north control to the P.E.P. Reef zone. A large sand accumulation was measured on the south end of the north control zone. A bulge in the shoreline was observed to grow over the study from the aerial photographs just to the north of the first P.E.P. Reef segment (STAUBLE, 2002). The north part of the P.E.P. Reef zone had the most landward shoreline and smallest profile volumes throughout the study. For the first two years, the north end of the south control along with the last two segments of the P.E.P. Reef also seemed to be limited in sand volume and experienced landward movement of the shoreline. It was not until after the tropical storms in fall 1999, that this pattern of recession and accretion was changed resulting in sand moving alongshore through the system.

Early measurements of scour rods indicate that localized scour at the toe of the breakwater structure was directly related to settlement. Most of the segments are now resting on the natural hardbottom. Scour rods placed around the northern-most segments, the center segments and the southern-most segments documented a high degree of variability over time in sand elevation changes adjacent to these units. Scour started at the southern segments almost immediately after placement and has spread to all segments by the second year. Scour in the gap regions was more pronounced at the beginning of the study, with accretion measured in the last (May to June 1998) scour rod measurement period. Initially, more sand was scoured out from the offshore segments, but as the study progressed, scour was present around the inshore segments also.

At the time of this writing, the P.E.P. Reef has remained in place. There are no immediate plans for modifying or removal of the project.

CONCLUSIONS

Objectives

According to the vendors, there are three primary functional objectives of prefabricated submerged breakwaters along open ocean coasts (AMERICAN COASTAL ENGINEERING, 1993; CRETER *et al.,* 1994). The first is to reduce wave energy transmitted over the structure. The second is to stabilize the shoreline and allow increased volume of sediment to be retained shoreward of the structure. The third objective is to not increase erosion or adversely modify coastal processes. Of the six different deployments of this type of breakwater, three in Florida were constructed using the P.E.P. Reef units and three in New Jersey used the Beachsaver Reef units. The individual reef units of both products had a similar shape and dimensions. Each installation however, had localized differences in morphology, coastal processes and the influence of other shore protection structures to provide unique conditions at each site (Table 7).

Summary of Installations

The Dupont Property installation in the Atlantic Ocean at Palm Beach County, Florida was a 168 m (552 ft) long continuous line, located 53 m (175 ft) offshore of the mean high water line in about −2.4 m (−8 ft) NGVD of water or −2.14 m (−7.02 ft) MLW. The P.E.P. Reef, consisting of larger first generation concrete units, was seaward of several short T-groins and various seawalls and was placed on a sandy bottom landward of any hardbottom. This configuration was detached from any of the other shore protection structures.

The Midtown Palm Beach, Florida, installation in the Atlantic Ocean some 579 m (1,900 ft) north of the Dupont property was a larger structure, constructed in two phases with a total length of 1,273 m (4,176 ft) of smaller second generation P.E.P. Reef units. It was placed in a continuous line parallel with the shore with one gap of 65.8 m (216 ft) spanning offshore communication cables. The units were placed around 76.2 m (250 ft) from the shoreline in −2.9 m (−9.4 ft) NGVD of water or −2.6 m (−8.4 ft) MLW. The shoreline was also armored at this location with various seawalls landward of the submerged breakwater. A natural hardbottom beach rock outcropped around 229 m (750 ft) seaward of the reef.

The first Beachsaver Reef was installed at Avalon, New Jersey, in the Atlantic Ocean on the southern shore of Townsends Inlet. The 305 m (1,000 ft) long, submerged breakwater was attached at its north end to the inlet south jetty. It extended to the southwest in a more or less shore-parallel direction some 100 to 150 m (328 to 492 ft) seaward of the shoreline, with its south end open to the ocean in −2.2 to −3.8 m (−7.2 to −12.5 ft) MLW water depth. This installation used a thin geotextile fabric underlayment for scour protection. An additional polyethylene geomattress filled with stone was placed along the southern 73 m (240 ft) of the landward side of the base later in the monitoring period to mitigate for scour. A beach fill was also placed along this beach at the time of installation.

The Cape May Point, New Jersey, Beachsaver Reef installation was placed across the seaward end of two groin compartments between 91.4 and 122 m (300 to 400 ft) seaward of the MLW line in a high tidal current area at the entrance to Delaware Bay from the Atlantic Ocean. Both reef compartments were around 137.2 m (450 ft) long and were connect the seaward end of all three groins by capstone. The objective was to provide protection for the two pocket beaches between the three groins from scour by the strong tidal ed-

Table 7. *Dimensions and Installation Parameters of Short-Crested Prefabricated Concrete Breakwaters.*

Location	Reef Length (m)	Distance Offshore (m)	Water Depth (m, MLW)	Initial Freeboard Depth (m)	Notes
Dupont Property Palm Beach, FL	168	53	−2.14	−0.62	Seaward of short T-groins Various seawalls on backshore
Midtown Palm Beach, FL	1,273 includes gap	76.2	−2.6	−0.77	Placed landward of hardbottom outcrops on sand 1 gap 65.8 m wide toward north end Various seawalls on backshore Placed landward of hardbottom outcrops on sand
Avalon, N.J.	305	100 to 150	−2.2 to −3.8	−3.7 to −9.7	Attached at north end to Townsend Inlet south jetty Placed on thin geotextile mat Later added rock filled geo-mattress on land side
Cape May Point, N.J.	137.2	91.4 to 122	−2.1 to −2.4	0 to −0.61	Across seaward end of 2 groin compartments Attached to groins w/rock–no gaps Placed on thick geotextile mat Rock filled geo-mattress on land side
Belmar/Spring Lake, N.J.	335	128	−2.3 to −2.4	−0.7 to 1.16	Across seaward end of 1 groin compartment Attached to groins w/rock–1 gap filled with bags Placed on thick geotextile mat Rock filled geo-mattress on land side
Vero Beach, FL	914 total 51 to 93 per segment	61 inshore 76 offshore	−2.1 inshore −2.7 offshore	−0.31 to −0.91	11 segments alternating inshore and offshore w/gaps between segments Various seawalls on backshore Some segments placed on sand and some on hardbottom

dies. The reef structure was placed at between −2.1 and −2.4 m (−7 and −8 ft) MLW. A geotextile fabric underlayment was also used on this instillation for scour protection, but the thickness was doubled as compared with the Avalon project. A 1.3 m (4.3 ft) wide polyethylene geomattress filled with 6.1 to 10.2 cm (2.4 to 4 inch) stone was placed along both the landward and seaward side of the base to mitigate for scour based on the experience with the Avalon installation.

The Beachsaver Reef placed at Belmar/Spring Lake was also installed at the seaward end of a groin compartment with a width of around 335 m (1,100 ft). The reef was attached to the two groins about 128 m (420 ft) seaward of MLW, at −2.3 to −2.4 m (−7.5 to −8 ft) MLW depths. A 6.1 m (20 ft) gap was left to enable a 0.91 m (3 ft) diameter ocean outfall pipe buried 0.91 m (3 ft) below the bottom to extend offshore, perpendicular to the shoreline. The gap was filled with a stacked geomattress configuration up to the crest elevation of the Beachsaver Reef. Reef crest elevations of between −0.7 to −1.16 m (−2.3 to −3.8 ft) MLW were measured after placement at this site. The same double thickness geotextile fabric underlayment as was used at Cape May Point, was used on this instillation for scour protection. Again, the same polyethylene geomattress filled with stone was placed along both the landward and seaward sides of the base to also mitigate for scour. A truck haul beachfill was placed in the groin compartment after placement of the Reef.

From the experience gained with the long single line Midtown Palm Beach installation of the P.E.P. Reef, the Vero Beach installation was modified to contain eleven segments ranging in length from 51 to 93 m (168 to 304 ft). They were placed in an alternating onshore/offshore configuration with gaps between each segment, covering a total alongshore length of 914 m (3,000 ft). This alternating placement was approximately 61 m (200 ft) from the beach for the inshore segments and 76 m (250 ft) for the offshore segments. Design bottom elevations were −2.1 m (−7 ft) for inshore units and −2.7 m (−9 ft) for offshore units. Reef crest elevations averaged between −1.37 m inshore to −1.83 m offshore (−4.5 to −6.0 ft) NGVD or −0.90 to −1.36 m (−2.95 to −4.45 ft) MLW after settlement. Some of the units were placed on a sandy bottom and some were placed on a thin sandy veneer over the natural hardbottom, which outcrops just seaward of the reef installation, which accounted for the differential settling. Various existing seawalls were on the backshore.

Performance Parameters

The monitoring of the six installations of the shallow-crested prefabricated breakwaters has allowed a cross comparison of performance parameters. Table 8 summarized the performance parameters of each breakwater installation. In attempting to meet the objectives, did the reef structures stabilize the shoreline? Was sediment retained behind these units? Did settlement of the units cause any change in their performance? Was there any scour caused by the placement or breakwater configuration? How much wave attenuation was afforded by the use of these types of structures as shore protection devices?

Shoreline Response

Shoreline response was measured in all six studies by measuring the change in lateral position of a datum elevation from beach profiles measured over the monitoring period from a fixed benchmark. The mean high water datum elevation crossing was used to represent the shoreline position along the profile at the P.E.P. Reef projects. The Beachsaver projects used the MLW datum at Cape May Point and 0 NGVD datum at Avalon and Belmar/Spring Lake crossing as a shoreline change indicator.

The Dupont Property P.E.P. Reef installation included a north (updrift) and south (downdrift) control area. Two years after placement of the P.E.P. Reef at the DuPont Property in Palm Beach County, the shoreline change was variable but essentially landward of the pre-project shoreline. The irregular shoreline was a function of the pre-existing groins and seawalls.

The Midtown Palm Beach site included two control areas north and south of the P.E.P. Reef. Over the 3 years of monitoring the updrift north control shoreline position was mixed with an net average recession. The highest long-term shoreline retreat was measured in the P.E.P. Reef area. The largest recession was measured in the area at the south end of the P.E.P. Reef and the northern part of the downdrift south control area. Overall, the south control area shoreline also retreated landward.

At Avalon, New Jersey, there was initial seaward movement of the shoreline in response to a beach fill placed at the same time as the Beachaver was installed. The monitoring area included the reef and southern control area. After two years, profiles behind the inlet jetty-attached northern end of the Beachsaver Reef showed more stability than the profiles to the southern open end of the reef and southern control area. The semi-enclosed northern profiles were approximately 15.2 m (50 ft) wider than the pre-fill beach, while the more open southern beaches returned to a pre-fill width.

At Cape May Point, New Jersey, the shoreline response was measured by the movement of the MLW contour line from the beach profiles. The analysis was divided into three cells, with Cells 2 and 3 related to the two groin compartments fully enclosed on the seaward end by the Beachsaver reefs and Cell 4, a open groin compartment, as a control area on the west. In the two-year monitoring period, the shoreline in the eastern-most compartment (Cell 2) moved seaward on average 13.4 m (44 ft), while Cell 3 had a shoreline seaward movement on average of 4.6 m (15.13 ft). The control Cell 4 to the west migrated landward an average of 4.6 m (15.13 ft). The trend was for more landward shoreline movement to the downdrift western direction.

The Belmar/Spring Lake placement was also completely across a groin compartment. Fill material was also placed on the upper beach of the Beachsaver reef compartment only. A north and south control area of one groin compartment on either side was also monitored. The 0 NGVD elevation shoreline moved landward approximately 15.2 m (50 ft) over the one year monitoring period. The north (downdrift) control area compartment (which did not receive any fill) shoreline

Table 8. *Summary of Performance Parameters of Short-Crested Submerged Prefabricated Concrete Breakwaters.*

Location	Type/ Monitoring Dates	Net Shoreline Change (m)	Net Volume Change (cu m/m)	Settlement (m) Per Time	Scour (m)	Wave Attenuation (K)	Placement Configurations
Dupont Property Palm Beach, FL	P.E.P. 3/88–3/90	Qualitative Only MHW line moved landward	+9.85 north control zone +5.65 P.E.P. Reef −3.06 south control zone	Not Mentioned	Not Measured	Not Measured	One segment Area backed by seawalls and short groins
Midtown Palm Beach, FL	P.E.P. 7/92–6/95	−2.84 north control zone −7.87 P.E.P. Reef +0.20 south control zone	−10.2 north control zone −67.1 P.E.P. Reef −13.7 south control zone	First 57 units −0.84 Final 273 units −0.60 4–18 months	−0.38 to −0.99	0.85–0.95	One long segment w/ small gap Area backed by seawalls
Avalon, N.J.	Beachsaver 8/93–12/95	−23.1 north reef[1] −20.9 south reef[1] −32.5 south control zone[1]	−100.4 north reef[1] −155.6 south reef[1] −180.7 south control zone[1]	−0.61 north reef −1.22 south reef 9 months on filter cloth	−1.22 Land side	0.80	One long segment attached to inlet jetty–open to south w/beach fill
Cape May Point, N.J.	Beachsaver 5/94–8/96	+13.4 E. compartment +5.8 W. compartment −3.5 control comp.	+20.81 East comp.[2] +3.04 West comp.[2] −11.72 control comp.[2]	0 on filter cloth	−0.6 Land side	0.86–0.96	Across 2 groin compartments Strong tidal currents
Belmar/Spring Lake, N.J.	Beachsaver 8/94–12/95	+6 north control compartment −15 compartment	−3.3 in compartment	−0.12 to −1.93 6 months on filter cloth	−1.2 to −2.1 Land side	Not Measured	Across 1 groin compartment w/truck fill
Vero Beach, FL	P.E.P. 8/96–6/00	+9.7 north control zone +5.3 P.E.P. Reef zone +7.6 south control zone	+28.6 north control zone +18.9 P.E.P. Reef zone +30.1 south control zone	−0.86 offshore segments −1.02 inshore segments 2 months	−1.22 to −1.83 on land side intermittent on sea side	0.88–0.90	11 staggered onshore and offshore segments w/gaps some segments on hardbottom Area backed by seawalls

[1] Shoreline positions and volume change at Avalon, N.J. calculated from post-beach fill 9/93–11/94.
[2] Volume change at Cape May Point, N.J. calculated from 5/94–4/96.

remained relatively stable with a seaward movement of approximately +6.1 m (+20 ft).

At Vero Beach, Florida, from the August 1996 to June 1999 period, the MHW shoreline, showed a relative pattern of seaward movement in the north control, a landward movement in the P.E.P. Reef zone and a mixed sometimes landward and sometimes seaward movement in the south control zone. As of the December 1999 survey, the shoreline over the entire project length moved seaward, reflecting large gains in sand from post-storm recovery. Over the winter and spring, the shoreline continued to average an overall seaward movement trend for the entire project length. Most of the seaward movement this time was in the south control zone, with a smaller but seaward movement also in the P.E.P. Reef zone. The north control zone showed a slight landward movement, but the cumulative overall project averaging was the largest seaward movement of the three zones. This shoreline change analysis may reflect a longshore movement of a sand wave from north to south through the project area in the last year of monitoring. The seaward movement of the shoreline in all three zones (with the least seaward movement in the P.E.P. Reef zone), indicate that the same processes were operating in all three zones, somewhat independent of the Reef structure.

Sediment Volume Response

Another way to assess the performance of these types of breakwaters, was to measure the change in volume of sand along the beach profiles. All projects measured the change in profile volume by comparison of temporal profiles. Shoreline position change gives an indication of gain or loss of sand at one point along the profile, and is a function of what "shoreline" indicator is chosen. The differences in volume between two dates, gives a measure of cut and fill along the entire measured profile, and documents the retention or loss of sand from behind the breakwater structure.

The overall change in volume at the Dupont property showed a variable pattern with gain in the north control, loss behind the P.E.P. Reef increasing to the south, and a gain just to the south of the reef but loss further to the south. At the Midtown Palm Beach site, the north control area experienced both erosion and accretion over the monitoring period with overall minimal change in sediment volume. Erosion has been measured in the lee of the P.E.P. Reef and just to the south of the reef zone. Seaward of the reef structure, volume changes were mixed over the monitoring period but were of much less magnitude than landward of the reef.

At the Avalon site, individual profile volume data was not presented, but three-dimensional elevation change data indicated that more erosion was found to the south of the Beachsaver reef units. The semi-enclosed jetty attached northern end of the reef had the lowest erosion rate, followed by the open southern end of the reef and the highest erosion rate was found in the southern control area. An outfall structure and the backshore parallel bulkhead in this southern area may have contributed to the erosion, as well as changes offshore to the southern ebb shoal features of Townsends Inlet.

The enclosed groin compartment configuration of the Cape May Point Beachsaver Reef installation, created more of a perched beach. A total volume change was given in each cell, rather than for individual profiles. Over the two-year study, the eastern Cell 2 between the Leigh and Whilldin Avenue groins had a net gain of sand, with the most pronounced accretion on the eastern side of the cell. The most gain was found in the nearshore and foreshore portion of the profile around 122 m (400 ft) landward of the reef. A smaller net gain in sand volume in Cell 3 between the Willdin and Coral Avenue groins was reported, with sand accretion found in the nearshore area. Again, the most gain was measured on the eastern side of the groin compartment. The downdrift west control Cell 4, measured a volume loss over the study, with most of the loss on the western side of the cell and between the dune base and 61 m (200 ft) offshore. A similar enclosed groin compartment deployment of the Beachsaver Reef at Belmar/Spring Lake also formed more of a perched beach, with an added volume from a truck fill on the backshore area. This material was retained in the compartment except for a slight loss of sediment as the fill moved from the berm to the nearshore portion of the profile landward of the reef structure.

The detached and staggered P.E.P. Reef at Vero Beach exhibited a gain in sand volume in the north control, loss in the P.E.P. Reef area and a mixed volume of gain and loss over time in the southern control zone for the first three years. With the gain is sand over the entire project area in the last year of the study, sand volume gain was measured in the backshore area of all three zones. The gain in sand volume was the least in the P.E.P. Reef area, with most of the grain in the two control zones. The majority of the volumetric changes in the P.E.P. Reef zone occurred landward of the breakwater axis and in both control zones landward of the natural hardbottom. Little change was detected in all of the profile volumes seaward of the P.E.P. Reef axis and over the natural hardbottom.

Settlement

Breakwater crest height is important in submerged breakwater design. One of the objectives of these narrow-crested breakwaters is to reduce wave height transmission. In order to be effective, the structure freeboard must be shallow enough to trip the incoming waves. Crest elevations on these units were placed within −1.22 m (−4 ft) of the surface on all of the installations. Settlement and movement of the units were monitored on some of the projects by measuring the change in elevation of the crest height over time.

No actual measurements were reported on settlement of the Dupont Property installation, but it was observed that some or the larger first generation P.E.P. Reef units moved seaward during a northeast storm. After realignment, no further movement was measured. Settlement occurred from 5 to 18 months after placement of the second-generation P.E.P. reef units at the Midtown Palm Beach installation. Placed on a sandy bottom, the settlement ranged from 0.6 to 0.8 m (2 to 2.6 ft).

Settlement of the Beachsaver Reef at Avalon was highly variable. Most of the settlement was measured during the first 9 months after installation and ranged between 0.4 m (1.3 ft) on the north end to 1.5 m (5 ft) at the south end. The underlying geology appeared to play a part in this settlement. These units were placed on a sandy bottom, but a clay layer some 0.91 m (3 ft) below the surface may have compressed over time causing the settlement (BRUNO *et al.,* 1996b). To mitigate for suspected settlement in the Cape May Point and Belmar/Spring Lake installations, a filter fabric blanket was placed as a foundation over the sand bed. At Cape May Point, the Beachsaver units have only settled a minimal amount around 15.2 cm (6 inches) or less over the two-year monitoring. The underlying geology consisted of medium to fine sand over a mud layer, but the filter cloth and geotextile mattress maintained lateral and vertical stability over the monitoring period. At the Belmar/Spring Lake site, a thicker geotextile mattress was put under the Beachaver units. The underlying geology indicated a layer of sand over a layer of clay, which may have accounted for the settlement (BRUNO *et al.,* 1996a). Average settlement of around 1 m (3.3 ft) was measured as the sand was eroded and the units ended up on the clay layer, which took about 6 months.

The staggered placement of the P.E.P. Reef at Vero Beach with an inshore and offshore alignment and the present of hardbottom just under the reef units resulted in differential settlement. All of the units were placed on sand, but the sand scoured out from under the units until the reef settled on to the rock surface, resulting in some shifting over the uneven bottom. Units on a sandy bottom settled further into the bottom. No filter cloth was used in this installation. The inner P.E.P. Reef segments settled averaged around 1 m (3.4 ft) and the outer segments settled 0.9 m (2.8 ft) with the most settlement occurred during the first four months.

Scour

A scour trough formed at all installations just to the landward side of both the P.E.P. and Beachsaver reef units. This scour trough appears to be the result of turbulence resulting from the return flow hitting the steeper face of the landward side of either brand of unit, creating an upward flow that interacts with the incoming waves. This flow interaction creates a vortex on the landward side resulting in scour at the unit base. A substantial trough formed along the entire length of both types of breakwaters resulting in undermining the base and enhanced settlement and slumping in some cases. Some of the projects reported a trough forming on the ocean side of the units, but this trough was not as deep as the landward side.

No mention of the scour trough was given in the Dupont Property P.E.P. Reef report. The Midtown Palm Beach project quickly formed a trough along the entire length of the project. Return flows were redirected along the breakwater to the ends of the project, causing scour and the measured erosion in the lee of the breakwater was more than twice the erosion in the control zones (DEAN and CHEN, 1996).

At Avalon, a scour zone was measured along the entire landward side of all of the Beachsaver units. Two years after placement of the reef a new beach fill was placed in June 1995. This new fill buried the reef, but the crest quickly became exposed, with a scour to the south of the end unit. By December 1995, the scour zone deepened to −1.22 m (−4 ft) below the crest of the reef and extended 12 m (40 ft) landward of the reef. A geomattress, filled with stone was placed along the landward side of the southern end of the reef to reduce the undermining and resulting settlement (HERRINGTON and BRUNO, 1998). At Cape May Point, a scour trough was present even with the filter cloth and geotextile mattress. The scour trough has reach a depth of between −2.7 to −4.6 m (−9 to −15 ft) and widths ranging from 2.7 to 30.5 m (9 to 100 ft) as of March 2002. The Belmar/Spring Lake site has a local scour zone of 15 to 18 m (49 to 59 ft) wide and a maximum depth of around 2.1 m (6.5 ft) (HERRINGTON and BRUNO, 1998). The geotextile mattress has settled in some places affected by the scour.

A scour trench was present along the landward side of all of the Vero Beach P.E.P. Reef segments, regardless of their position inshore or offshore. Some of the reef units became perched above rock outcrops. The landward scour trench averaging 1.22 m (4 ft) deep and 6.4 m (20.9 ft) wide. A scour trench was also found seaward of the reef segments on occasions. Generally, this seaward trench was present after storms and filled in during fair weather.

Wave Attenuation

The narrow-crested design of this class of prefabricated submerged breakwaters appears to have limited their effectiveness in wave attenuation. Settlement of the units has also reduced the freeboard depth and thus the ability to trip the incoming waves. BROWDER (1994) indicated that the freeboard was the most important variable in submerged breakwater design. The shallower the breakwater, the more wave attenuation is afforded. If the crest of the structure is close to the surface, it may also produce structure-induced currents. Wave energy reduction was found to be a function of the configuration and composition of the structure, negative freeboard (depth of water over the reef crest) and incident wave height and period. BRUNO *et al.* (1996b) observed higher wave energy reduction when the reef crest was closer to the water surface and the wave heights were larger. Broad-crested breakwaters dissipate wave energy by wave scattering as the wave travels over the shallow crest. In the case of the narrow-crested prefabricated concrete breakwaters with crest width of around 0.3 to 0.5 m (1.0 to 1.6 ft), the design is to induce strong vertical currents on the return flow as the wave passes over the unit (HERRINGTON *et al.,* 1997). This upward deflection of the current is expected to reduce the wave height.

Limited wave measurements are available from the Midtown Palm Beach, Avalon, Cape May Point and Vero Beach site monitoring, where wave gages were deployed for various lengths of time both seaward and landward of the breakwaters and wave attenuation was calculated. At the Midtown Palm Beach, Avalon and Vero Beach sites control wave gages were also deployed over the natural nearshore profile in one of the control zones to compare natural wave attenuation to that afforded by the breakwaters.

Wave data collected at the Midtown Palm Beach site, indicated a wide range of data over time from the offshore and inshore wave gages. This was due to differences in tide level, smaller wave transmissions with higher wave heights and greater reflection from existing seawalls and revetments on the back beach after loss of sand (DEAN and CHEN, 1995c). It was determined from a comparison of the wave attenuation between the concurrent control and reef gages, that the P.E.P. Reef associated transmission coefficients ranged from 0.85 to 0.95 at that site.

Comparing the deeper placement of the Beachsaver at the Avalon site with the shallow placement at Cape May Point, the wave measurements indicate that the wave attenuation was a strong function of the water depth over the reef crest and the incident wave heights. Wave transmission coefficients ranged from around 0.78 to 1.13 at the Avalon site (BRUNO *et al.,* 1996a) and around 0.9 at Cape May Point (HERRINGTON *et al.*, 1997). Wave heights were reduced over the breakwater for periods when the reef crests were near the water surface and for periods of large incident wave heights.

Initial wave measurements at the Vero Beach site indicate a wave transmission coefficient of around 0.88 soon after the initial placement before the P.E.P. Reef units settled. After the first four-month monitoring period when the most rapid settling took place, the coefficients averaged between 0.91 and 0.92. A control site south of the reef indicated that the wave height difference over the natural bed ranged from 0.91 to 1.03. The wave studies suggest that once the units had settled there was minimal reduction in the waves as they passed over the reef. Only the larger storm wave showed a significant reduction in wave height on the landward side of the reef.

Performance Criteria

This review of monitoring data of six different installations of prefabricated submerged, narrow-crested concrete breakwaters has allowed for evaluation of project performance, success or failure criteria and particulars of unique coastal environments of placement. The stated objectives of this type of breakwater were to a) reduce wave height, b) stabilize the shoreline position, c) limit sediment volume changes in the vicinity of the breakwater, and d) lower wave energy landward of the breakwater during storms.

Each placement site had some similarities and well as many differences in morphology, underlying geology, prevailing coastal and inlet processes and proximity to other shore protection structures. The P.E.P. Reef installations were all on open Atlantic Ocean shorelines along the lower central Florida coast away from the influence of inlets and shore perpendicular shore protection structures. The units were placed some distance from the beach in a shore-parallel configuration not in contact with any groins. All of the sites had various configurations of seawalls on the landward end of the profile. The Dupont property and Midtown Palm Beach sites were a single line of reef units landward of any hardbottom. The Vero Beach site was a staggered inshore and offshore placement of 11 segments placed at the edge of an extensive outcrop of hardbottom. The Beachsaver Reef placements were along the New Jersey Atlantic Ocean coast and were placed in close proximity to groins, with the Avalon site being adjacent of an inlet terminal groin but open on the downdrift end. The Cape May Point site at the entrance to Delaware Bay and Belmar/Spring Lake sites along a high wave energy coast, placed the reef as a solid barrier on the seaward end between groin compartments, creating a closed cell perched beach. Beach fills were placed concurrently with the Avalon and Belmar/Spring Lake projects.

The dimensions and triangular configuration were similar for both types of concrete structure. This narrow-crested design, with a steeper landward facing slope experienced scour on the landward base with minimal wave attenuating effect (around 10% at all projects). Filter cloth and a geotextile mattress used on two of the New Jersey sites appeared to minimize but not eliminate scour and settlement. The most successful projects as far as retaining sand on the beach profile and maintaining a stable shoreline were the two perched beach configurations at Cape May Point and Belmar/Spring Lake. Fill placed at Belmar/Spring Lake was retained within the groin compartment and the natural beach at Cape May Point was maintained with minimal loss using this closed cell design, which limits the seaward movement of sand within the compartment. In the more open coastal configurations, the reef was less successful in retaining sand on the beach and preventing landward movement of the shoreline. At Avalon, the northern end of the project was more successful in retaining beachfill sand in a semi-enclosed environment of the reef attached to the inlet terminal groin, than in the southern end of the project where the reef was detached and parallel to the shoreline. The three Florida projects were all placed parallel to the coast, detached from any other shore protection structures and are ineffective in retaining sand or stabilizing the shoreline behind the reef structures. Currents induced by the single long Midtown Palm Beach configuration seem to be responsible for scour along the reef and deposition beyond the ends of the structure. The staggered configuration of the Vero Beach project with gaps between the individual segments appeared to alleviate this reef-induced longshore current, but the northern most reef segments still limited an apparent sand wave from moving alongshore, resulting in initial higher erosion and later less accretion behind the reef, than in the two adjacent control areas. The natural hardbottom configuration and the presence of seawalls and narrower beach width behind the P.E.P. Reef also affected the retention of sand.

The most successful projects were when these narrow-crested prefabricated concrete submerged breakwaters were used to create a closed cell perched beach at the seaward end of groin compartments. While not dissipating much wave energy, the reef structure was able to prevent offshore transport of sand from within the compartment, as long as the reef was attached to the adjacent groin or jetty tips by rock. More open coast placement, where the breakwaters were detached from any shore normal structures, limited the sand trapping effectiveness by reef induced currents and limited wave attenuation due to scour and settlement.

Future placement of these types of submerged breakwaters should be limited to areas where they can form an enclosed cell and prevent offshore movement of sand off the beach profile. A new deployment of the Beachsaver Reef is planned in the fall of 2002 at Cape May Point. This new installation is in a groin compartment in an area where the tidal currents interact with the ocean wind waves and create an area of wave-current induced turbulence just seaward of the groins. The beach within this compartment has been eroded and the dune scarped by storm waves, threatening upland structures. This new reef will also be a perched beach type of installation enclosing the groins cell. An improved geotextile mattress and scour tube will be placed as underlayment, to mitigate for scour and settlement. The crest height is planned to be at MLW, so at low tide the breakwater structure will be exposed. It is expected that this shallower position will cause more wave breaking and less wave transmission than at the past sites.

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