CHAPTER 179

Performance of a Submerged Breakwater for Shore Protection

Albert E. Browder[1], A. Member, ASCE; Robert G. Dean[2], Member, ASCE; and Renjie Chen[3]

Abstract

A summary is presented of the results from a 3-year monitoring study of a submerged breakwater placed alongshore for shore protection. The experimental breakwater project, located in Palm Beach, Florida, USA, was concluded in August, 1995. The monitoring program was instituted to determine changes in wave climate and bathymetry, and to assess the shoreline response relative to pre-project conditions. The Palm Beach breakwater consisted of 330 interlocking concrete units, each 1.8 meters in height, 3.7 m long, and 4.6 m wide, which formed a 1,260 m-long shore parallel barrier. The breakwater, termed the Prefabricated Erosion Prevention (P.E.P.) Reef was placed in approximately 3 m of water roughly 73 m from the shoreline. The project was intended to increase shore protection against storm waves and to create a wider beach in the lee of the Reef. Wave transmission measurements indicated a 5 to 15% reduction in incident wave heights due to the Reef. The results of the monitoring program at the end of two years indicated erosion throughout the project area, primarily in the lee of the Reef, where the annual volumetric erosion rate was measured to be 2.3 times higher than the pre-project rate. The submerged breakwater is interpreted to have increased the longshore currents via ponding of water trapped behind the breakwater, which was then diverted alongshore. Laboratory experiments were conducted to investigate this ponding phenomenon and to test the performance of various segmented and repositioned breakwater arrangements. Shoreline erosion in the lee of the Reef was sufficiently severe to warrant removal of the structure in August, 1995.

---

[1]Coastal Engineer, Olsen Associates, Inc., 4438 Herschel St., Jacksonville, FL, 32210 USA, 904-387-6114.

[2]Chairman & Graduate Research Professor, Coastal & Oceanographic Engineering Dept., University of Florida, Gainesville, FL 32611, USA.

[3]Graduate Research Assistant, Coastal & Oceanographic Engr. Dept., U. of Florida.

Introduction

The Town of Palm Beach lies on the southeast coast of Florida, U.S.A. The project site is 7.2 km south of the Port of Palm Beach Entrance (see Figure 1). This tidal entrance was created artificially in 1918, followed by the construction of jetties on either side of the inlet in 1925. The excavation of the inlet resulted in the rapid recession of the shoreline to the south along Palm Beach Island. The erosion problems experienced alongshore prompted the Town of Palm Beach to take action in three ways:

- The construction of seawalls alongshore,
- The use of beach nourishment, beginning in 1944,
- The construction and operation of a sand bypassing plant at the Port entrance, which was built in 1958. The plant operated until 1990, when it was damaged by storms. The plant re-opened in 1996.

The latter two actions resulted in the placement of over 5.86 million m^3 of sand along the shoreline south of the Port entrance between 1944 and 1990. As a result, the average shoreline position in 1990, from the Port entrance southward 11 km, lies some 18 m seaward of its 1944 location, despite a persistent background erosion rate attributed mainly to the Port Entrance. This background erosion rate was estimated to be about 9.3 m^3/m/yr by the U.S. Army Corps of Engineers (1987).

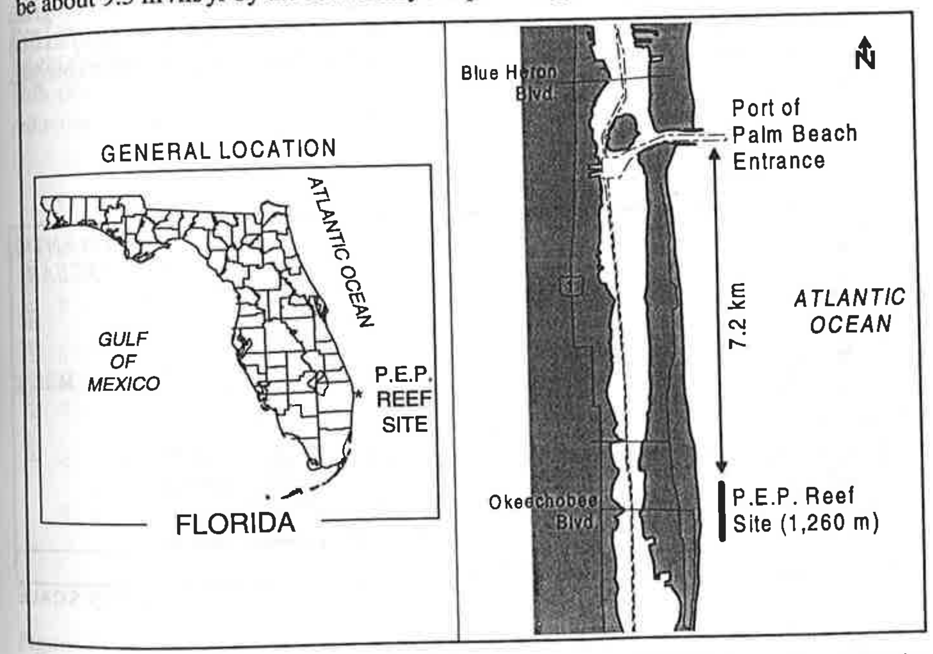

Figure 1 Location of P.E.P. Reef Site in the Town of Palm Beach, FL. The site lies approximately 7.2 km south of the Port of Palm Beach Entrance.

In an effort to provide a long-term "hard" solution to the erosion problem, the Town of Palm Beach investigated the use of a narrow-crested submerged nearshore breakwater, which was intended to increase shore protection against storm waves and to create a wider beach in the lee of the Reef.

The project involved the installation of 330 pre-cast concrete P.E.P. Reef units, each of which weighed 23 metric tons. The units were 1.8 m in height, 4.6 m in cross-shore width, and 3.7 m in length alongshore. When assembled the units extended 1,260 m alongshore. The units were placed in approximately 3 m water depth, about 73 m from the existing seawall along the heavily armored shoreline (see Figure 2).

Construction of the project began in July, 1992, with the placement of 57 units. Hurricane Andrew passed through southeast Florida in August, 1992, after which significant settling of the placed units was observed. The settlement of the units suspended construction of the project until the following summer. The remaining 273 units were placed between May and August, 1993. All 330 units were placed directly on the sandy bottom with no underlayment or foundation bedding.

To gauge the performance of the installation against its pre-project expectations, a monitoring program was conducted by the University of Florida Coastal and Oceanographic Engineering Department beginning in August, 1993. The program included quarterly topographic and hydrographic surveys of the site, wave transmission and unit settlement measurements, and an analysis of the background erosion processes and rates.

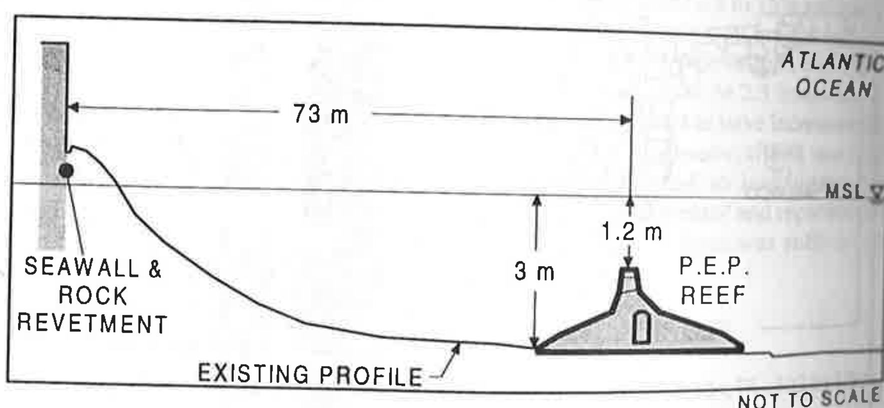

Figure 2 Schematic profile illustrating the relative location of the P.E.P. Reef structure to the shoreline.

Wave Transmission

To measure the effects of the Reef on the incident wave climate, two bottom mounted pressure-velocity gages were installed approximately 25 m on either side of the Reef just south of the centerline of the structure. The offshore and inshore gages were deployed in 4 and 2 m water depths, respectively. These gages collected data on an hourly basis, taking average pressure and bi-directional current measurements. Wave measurements were collected beginning in October, 1993, and continuing to the end of the monitoring period in June, 1995. Transmission coefficients were computed from each hourly measurement by calculating the ratio of the measured nearshore wave height to the wave height measured offshore, after shoaling the offshore wave height to the depth of the nearshore gage via linear wave theory. Figure 3 illustrates a schematic of the wave measurement arrangement and the summarized results.

Results from the initial wave measurements indicated a wave height reduction of as much as 15 to 25% (Dean and Chen, 1995). The range in wave height attenuation reflects the variable water levels and wave heights in the project area. The structure would have a greater effect (i.e., more wave height reduction) on larger waves and/or at lower water levels. The wave measurements indicated wave height reductions somewhat greater than anticipated by published literature (e.g., 0 to 10%, Ahrens, 1987). Additional wave measurements were taken at similar cross-shore locations south of the Reef structure. Analysis of the resulting data indicated a partial reduction in wave height due to natural effects such as wave breaking and bottom friction of approximately 10% (Browder, 1994). Thus, for an overall wave height reduction of 15 to 25%, the reduction due to the Reef was estimated to be 5 to 15%.

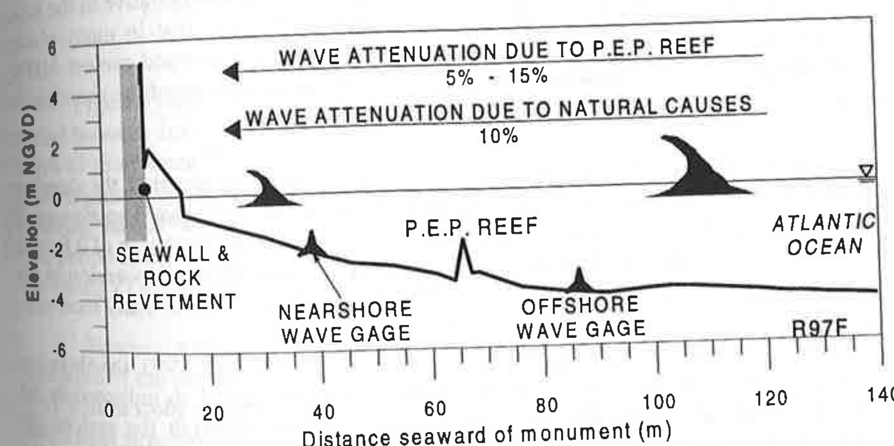

Figure 3 Schematic illustrating the cross-shore location of the wave gages and the P.E.P. Reef. The Reef was found to reduce incident wave heights by 5 to 15%, with another 10% reduction attributed to natural causes.

Littoral Performance

The littoral performance of the P.E.P. Reef project was measured via extensive hydrographic surveys, conducted on a quarterly basis during the project. The performance of the project was gaged against the historical shoreline behavior in the area. Ten surveys were conducted during the monitoring program, beginning in July, 1992, with the pre-construction survey. Each survey included 75 profile lines based from the Florida Department of Environmental Protection (FDEP) "R" monuments, which are spaced approximately 300 m apart alongshore. Additional profiles were surveyed between R-monuments at spacings of between 23 and 122 m.

The beach profiles were surveyed using standard land surveying techniques (swimming surveys with a rod and level) and boat/fathometer surveys. The swimming portion of the surveys extended at least 15 m seaward of the Reef to provide adequate overlap with the boat surveys. Each profile extended at least 365 m offshore. On annual surveys, the profiles were surveyed out to 1,070 m offshore. Profiles surveyed from R-monuments extended offshore 1,980 m. The hydrographic surveys were conducted on the following dates: July, 1992; April, August, and December, 1993; March, July, November, and December, 1994; and March and June, 1995. The November and December, 1994, surveys represent pre- and post-storm surveys of the area due to the passage of Tropical Storm Gordon.

Figure 4 shows the change in location of the Mean High Water Line (MHWL, approximately +0.6 m above the National Geodetic Vertical Datum, NGVD, which is approximately Mean Sea Level of 1929) measured alongshore over the course of the monitoring period. In the figure, the MHW shorelines are plotted relative to the July, 1992, *pre-project* shoreline location. It is important to note that in many places alongshore, the pre-project MHWL as well as the various surveyed project MHW shorelines fall on the seawall, thus limiting the landward recession of the shoreline in these areas.

Figure 4 indicates that during the first 13-month monitoring period, the shoreline south of R-98, in the vicinity of the original 57 units, advanced seaward an average of over 11 m. Along the remaining project shoreline north of R-98, recession of 2.8 m on average was measured, with some areas experiencing over 10 m of recession at the MHWL. Once again the presence of the seawall limited recession at many locations.

Following complete installation of all 330 units in August, 1993, the shoreline in the lee of the reef began to recede landward toward the seawall, as indicated by the July, 1994, surveyed MHWL. This recession continued through the end of the monitoring program, at which time (June, 1995) the shoreline along the majority of the 1,260-m project length had retreated to the seawall (with the exception of the shoreline at R-96 (Clarke Avenue), where there is no seawall; whereat the shoreline receded almost 23 m over 35 months).

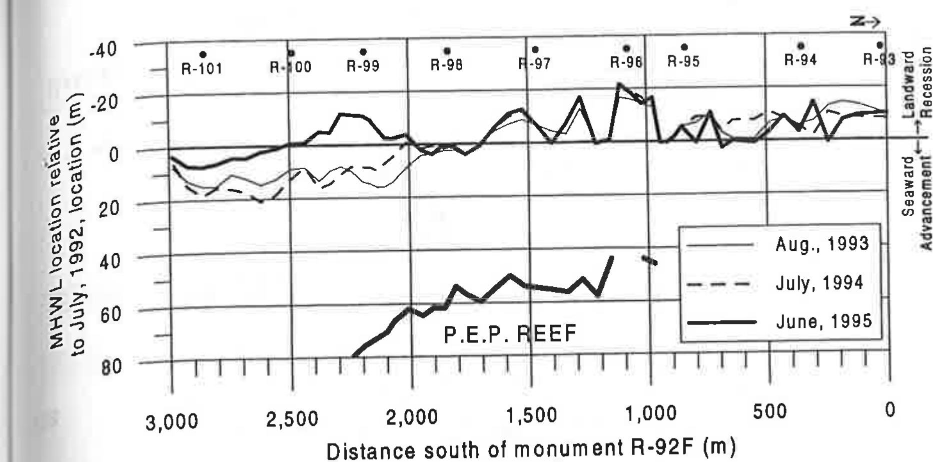

Figure 4 Location of the Mean High Water Line (MHWL) relative to the July, 1992, *pre-project* shoreline. The figure indicates the recession of the shoreline along the southern portion of the project, while the central and northern portions remain mostly unchanged. This is due to the presence of the seawall alongshore. Most of the central and northern MHWL was located at the seawall prior to the project, and no seaward advancement of the MHWL occurred at these locations.

Figure 5 illustrates the changes in one beach profile measured over the 35-month period between July, 1992, and June, 1995, at monument R-98J, approximately 23 m north of monument R-99, at the southern end of the Reef. Inspection of the three profiles plotted in the figure indicates that between July, 1992, and August, 1993, the shoreline had advanced seaward roughly 15 m (measured at Mean High Water). This time period spans the time in which the first 57 Reef units were already in place and the remaining 273 units were installed.

Between August, 1993, and June, 1995, however, the profile at R-98J retreated landward of the pre-project, July, 1992, position, to the seawall. The profile lowered over 2 m in front of the seawall in the 22-month period following completion of the entire Reef structure. Over the entire area in the lee of the 1,260-m long structure, i.e., between the Reef and the seawall, the seabed lowered an average of 0.7 m between August, 1993, and June, 1995.

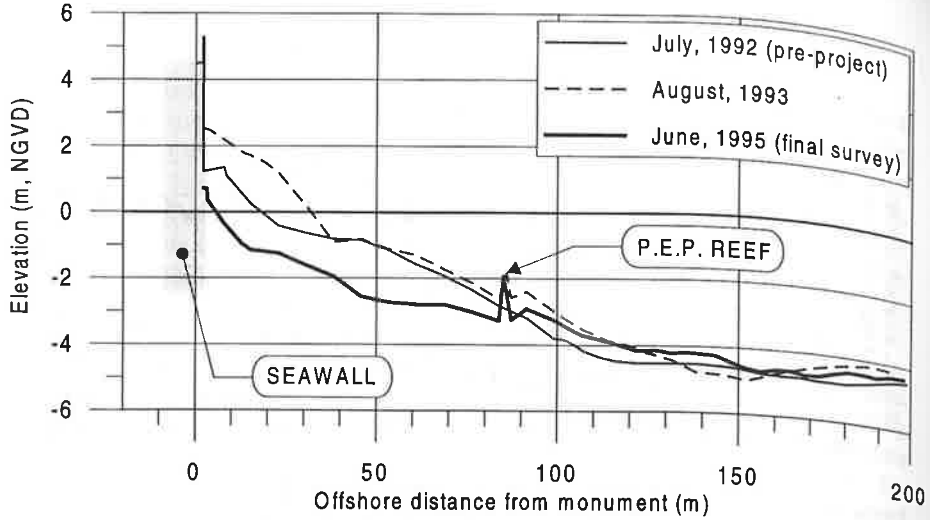

Figure 5 Profile changes measured at monument R-98J, near the southern terminus of the Reef. The plot indicates an initial seaward advance of the upper beach, followed by extreme erosion over the last 22 months of the monitoring program.

On a volumetric basis, analysis of the survey data indicates a net erosional signal in the area surrounding the installation. Figure 6 presents the measured volumetric changes in six zones surrounding the P.E.P. Reef installation. During the first year following complete installation (August, 1993, to August, 1994), the area in the lee of the Reef lost 28,600 m^3 of material while the area immediately to the south gained 13,500 m^3 (Dean & Chen, 1995) It is noted that of the 28,600 m^3 of erosion measured in the lee of the Reef, the majority (over 80%) of the erosion occurred in the first four months following complete installation of the Reef. Figure 6 indicates that in the remaining 4 zones, very little volumetric change occurred during this 12-month period.

Over the last year of monitoring, from July, 1994 to June, 1995, the area in the lee of the Reef continued to erode at roughly the same rate, losing 36,500 m^3 while the area immediately to the south lost 40,500 m^3 of material. Volumetric changes to the north of the project and offshore of the Reef again were relatively small (Figure 7).

Overall, during the full 35-month monitoring period, the area between the Reef and the seawall lost some 81,700 m^3 of sand (Figure 8). This loss translates to an average lowering of the seabed of 0.9 meters. Cumulative measurements of scour in the vicinity of the Reef's northern end indicate that the seabed immediately adjacent to the Reef had lowered between 0.5 and 1.05 m during the monitoring study.

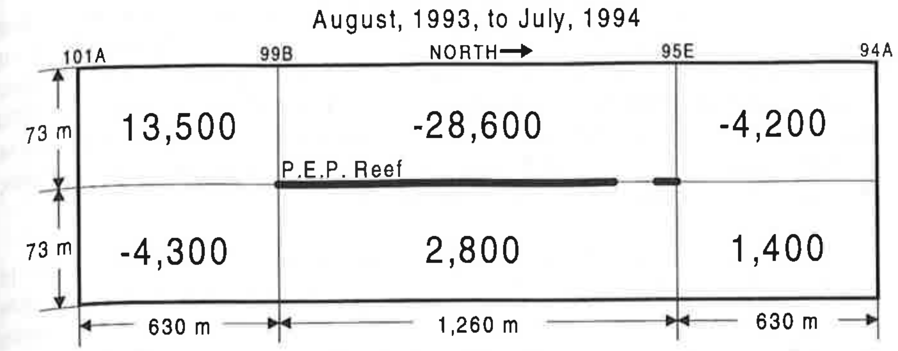

Figure 6 Volumetric changes (m^3) measured in six zones surrounding the P.E.P. Reef Installation between August, 1993, and August, 1994.

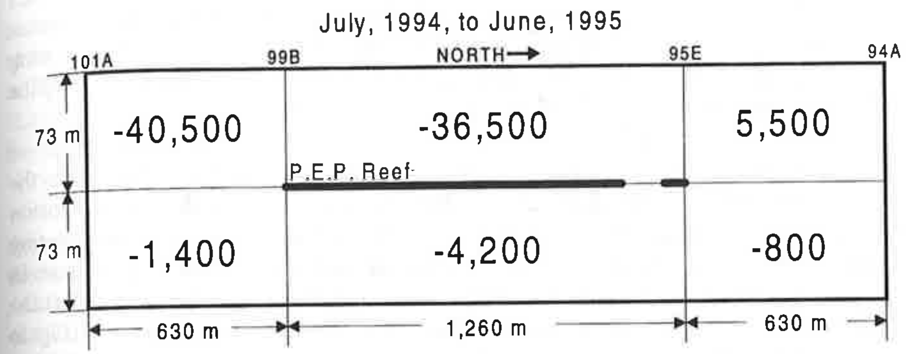

Figure 7 Volumetric changes (m^3) measured in six zones surrounding the P.E.P. Reef Installation between July, 1994, and June, 1995.

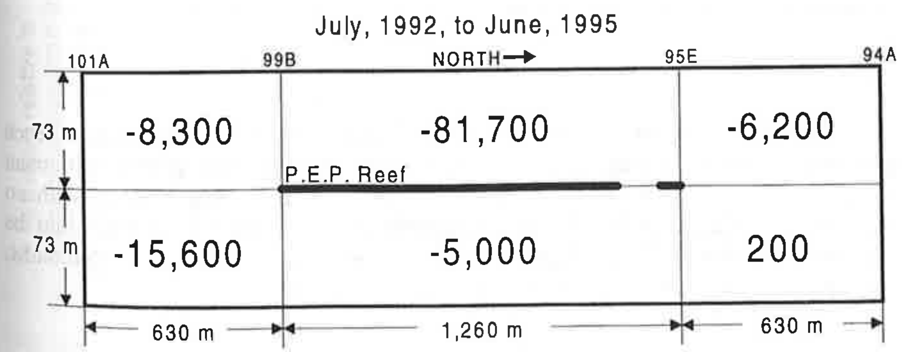

Figure 8 Volumetric changes (m^3) measured in six zones surrounding the P.E.P. Reef Installation between July, 1992, and June, 1995.

While the area to the south of the Reef had indicated accretion during the first two years of the study, erosion in the last year (40,500 m^3, Figure 7) resulted in a net erosional signal south of the Reef over the 35-month monitoring period. Referring back to Figure 4, by June, 1995, only the southernmost 500 meters of the shoreline (some 300 meters south of the southern terminus of the Reef) were significantly seaward of the July, 1992, pre-project shoreline at the end of the study. Over the entire monitored area, 116,600 m^3 of sand eroded during the 35-month period.

Pre-project data indicate that the project area is sediment-starved, due at least in part to the presence of the Port of Palm Beach Entrance. To compare the erosion rates measured during the monitoring program to the background erosion rates, two separate comparisons are investigated. Inspection of Figure 8 reveals that over 35 months, the erosion rate immediately in the lee of the Reef was 5.6 times higher than the rate along a combined equivalent shoreline distance north and south of the Reef. During the 23 months that the entire 330 Reef units were in place, the erosion rate was 2.5 times higher in the lee of the Reef than the adjacent shorelines (Figures 6 & 7). By reference to approximately 50 years of historical shoreline data, the overall erosion rate during the project was found to be 2.3 times higher than the pre-project rate estimated by the U.S. Army Corps of Engineers (1987)[4].

The degree of erosion immediately landward of the Reef as compared to the areas to the north and south suggests the following mechanism for the overall erosion patterns. The monitoring data suggest that waves 'pump' water over the Reef, creating a ponding situation in which the ponded water is prevented from returning offshore in the normal return flow fashion and is instead redirected alongshore. This augments the natural longshore current and increases sediment transport in the lee of the Reef (Figure 9). With very little sediment supplying the area in pre-project conditions, the addition of the Reef (which did not introduce additional sand) caused a 'pumping out' of sediment from behind the Reef. This sediment was transported predominantly south to the adjacent shoreline, where it was temporarily deposited until the natural littoral transport carried it farther southward, resulting in an overall erosive condition.

Unit Settlement

In addition to the beach profiles, measurements of the top elevations of each units were conducted during each quarterly survey to document the vertical settlement of the 330 units. The units were placed directly on the sandy bottom, with no foundation bedding or underlayment. The analysis of the settlement is divided into the average settlement of the original 57 units, which were in place a total of 35 months, and the remaining 273 units, which were in place 23 months.

4 USACE (1987) estimates the erosion rate to be 9.3 m^3/yr/m alongshore. Along the 1,260 m shoreline in the lee of the Reef, this translates to 11,720 m^3/yr of erosion.

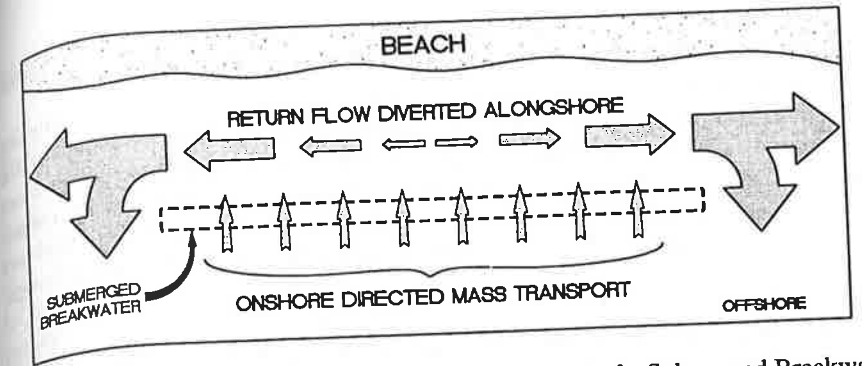

Figure 9 Schematic of Currents Generated Leeward of a Submerged Breakwater

Figure 10 illustrates the settlement of the units over time, relative to their estimated design depth. The original 57 units settled an average of 0.84 m, over 46% of the height of the Reef units (1.8 m). The remaining units settled an average of 0.60 m, 33% of the structure's height. While it is unclear exactly how much the passage of Hurricane Andrew in August,1992, affected the first 57 units, Figure 10 suggests that the hurricane may have contributed significantly to the settlement of these units.

The settlement of the units reduced the degree to which the units block the water column, which directly relates to the level of protection from wave attack afforded by the structure. At the same time, however, the lower structures may have prevented additional erosion caused by diverting more return flow water alongshore. Inspection of the bathymetric surveys and scour rod measurements conducted adjacent to the Reef suggests that the settlement was due primarily to the overall lowering of the sea floor in the vicinity of the Reef, rather than locally, structure-induced scour.

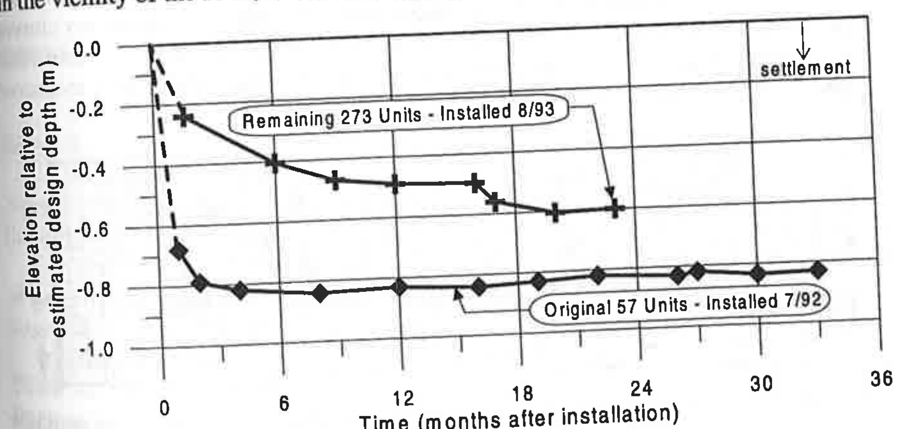

Figure 10 Average settlement of the first 57 units and the later 273 units.

Laboratory Findings

Laboratory experiments were conducted in conjunction with the monitoring program to investigate the ponding and associated phenomenon and to test the performance of various segmented and repositioned breakwater arrangements. Previous laboratory tests with two-dimensional tanks could not reveal the longshore current generation. Using the 3-d wave basin at the University of Florida Coastal and Oceanographic Engineering Laboratory, 1:16 scale models of the P.E.P. Reef units were tested on a fixed bed.

Laboratory measurements in this study included wave transmission and current velocities. Wave height measurements yielded transmission coefficients of approximately 95% for conditions simulating the Palm Beach P.E.P. Reef (i.e., continuous Reef structure with less than 50% of the vertical water column blocked by the Reef).

The lab tests, for all arrangements of the units, were able to reproduce the "pumping current" hypothesized from the littoral performance of the structure in the field (see Figure 9). Figure 11 illustrates the trajectories of bottom drogues documented in the laboratory report (Dean et al., 1994). Figure 11 indicates that for normally incident waves, in which there is no predominant wave or tidal generated longshore current, the presence of the submerged breakwater generates a longshore current that originates from the centerline of the structure in the lee of the Reef and flows toward the open ends, where the current is reduced through expansion.

While this longshore current was never directly measured in the field, the patterns of erosion measured in the lee of the Reef, relative to the volumetric changes along the adjacent shorelines, suggests that this "ponding and pumping" mechanism does in fact exist. It is believed that the pumping current existed as a secondary current to the longshore current, and was sufficient to increase the sediment transport rates along the seabed in the lee of the Reef, resulting in the substantial erosion measured between the Reef and the shoreline.

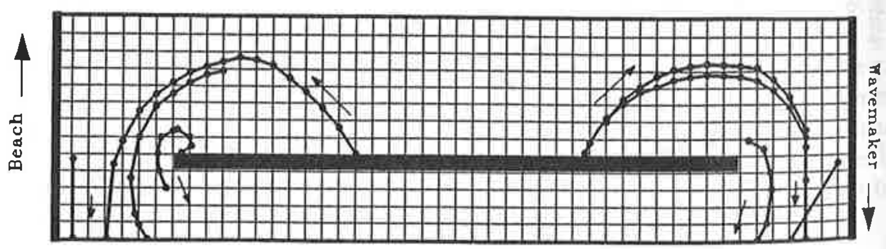

Figure 11 Typical circulation patterns witnessed in laboratory study using neutrally buoyant drogues. The patterns indicate that the Reef generates longshore currents in its lee that flow toward the ends of the Reef.

Summary

The results from a 3-year monitoring study of the Palm Beach, FL, Prefabricated Erosion Prevention Reef (P.E.P Reef), indicate that the reef modified both the incident wave climate and the nearshore current patterns. As defined by the State of Florida Department of Environmental Protection (FDEP), the project was intended to increase shore protection against storm waves and to create a wider beach in the lee of the Reef. Wave transmission measurements indicated a 5 to 15% reduction in incident wave heights due to the Reef. The results of the monitoring program at the end of two years indicated erosion throughout the project area, primarily in the lee of the Reef, where the annual volumetric erosion rate was measured to be 2.3 times higher than the pre-project rate. The submerged breakwater was found to have increased the longshore currents via ponding of water trapped behind the breakwater, which was then diverted alongshore. Laboratory experiments were conducted to investigate this ponding phenomenon and to test the performance of various segmented and repositioned breakwater arrangements.

Shoreline erosion in the lee of the Reef was sufficiently severe to warrant removal of the structure in August, 1995. Immediately following the dismantling the of the submerged breakwater, a large-scale beach nourishment project was constructed on the site. This project utilized some of the P.E.P. Reef units as the core material for shore-perpendicular groins within the beach-fill. The remaining units were moved into deeper water offshore to create artificial reef habitat

Acknowledgements

The authors would like to express their appreciation to FDEP and the Town of Palm Beach for supporting the project. Sea Systems, Inc., of Pompano Beach, FL, conducted the surveys in a professional and timely manner.

References

Ahrens, J.P., 1987, "Characteristics of Reef Breakwaters," Coastal Engineering Research Center, Technical Report CERC-87-17.

Browder, A.E., 1994, "Wave Transmission and Current Patterns Associated with Narrow-Crested Submerged Breakwaters," M.Eng. Thesis, Coastal and Oceanographic Engineering Department Rpt. No. UFL/COEL-94/022, University of Florida.

Dean, R.G., Browder, A.E., Goodrich, M.S., and Donaldson, D.G., "Model Tests of the Proposed P.E.P. Reef Installation at Vero Beach, FL," Coastal and Oceanographic Engineering Department Rpt. No. UFL/COEL-94/012, University of Florida.

Dean, R.G., and Chen, R., 1995, "Performance of the P.E.P. Reef Installation, Town of Palm Beach, Seventeen Months Results," Coastal and Oceanographic Engineering Department Rpt. No. UFL/COEL-95/004, University of Florida.

U.S. Army Corps of Engineers, 1987, "Beach Erosion Control Project, Palm Beach County, FL," Jacksonville District, FL.