The Effect of Hard Stabilization on the Sediment Transport System along the Shoreline of Puerto Rico

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ABSTRACT

This study examines the effect of shore-parallel hard stabilization on the beaches of Puerto Rico. During the summer of 1988, forty-eight sites around the island were studied. The examination of each site involved beach profiling, measurement of structures and description of the setting.

Shore-parallel structures are found oceanward of private property, coastal cities, ports and major roads. Most structures are small, privately-funded revetments or seawalls, often in disrepair. These small structures are usually constructed without regard to other adjacent structures or to adjacent beach effects.

The effect of hard stabilization in Puerto Rico is beach degradation. The dry beach is narrower on stabilized shores than on unstabilized shores. When structures extend seaward of the wet-dry line, groining of sediment updrift may result in the formation of downdrift offsets. Beach slope updrift of the structure is steeper than downdrift, most likely the result of updrift groining. Seaward of the structure, the landward end of the profile is sheared off, leaving only the gentler seaward portion of the profile.

INTRODUCTION

The ocean is encroaching on the shores of Puerto Rico. Relative sea level is presently rising at a rate of 3 millimeters per year on the north coast and 2 millimeters per year on the south coast (Webb, 1989). The greenhouse effect is expected to increase the rate of sea level rise. By the year 2100, sea level is predicted to rise by 56 to 345 centimeters (Hoffman, et al., 1986). In Puerto Rico, the increase in sea level rise will certainly further the retreat of the shoreline, presenting a major problem for shoreline development.

Figure 1. location map Puerto Rico

Society has three basic management alternatives to a retreating shoreline: hard stabilization, soft stabilization and retreat. Hard stabilization involves a combination of shore parallel armoring, groins and jetties. It fixes the position of the shoreline. Soft stabilization replenishes the beach and extends it seaward. Retreat is a relatively passive response by which man retreats with the shore.

This study describes shore parallel armoring and its effect on the beaches of Puerto Rico, the easternmost island of the Greater Antilles (Figure 1). Puerto Rico was chosen as an ideal location because hard stabilization could be examined in a variety of settings, differing shoreline types and wave energies.

The study had a twofold purpose. First, it examined the present effect of hard stabilization on the beaches. Dry beach widths, beach slopes and end-around effects are discussed. The findings should provide further insight into the controversial problem regarding the role of hard stabilization. Secondly, it provides a data base for future studies. The stabilization itself and the beaches in front of and adjacent to the stabilization are described. The study's findings may have significant implications for the future management of the Puerto Rican shoreline,

REGIONAL GEOLOGY

The Caribbean plate is believed to have originated as a section of the East Pacific plate that was wedged into the opening formed when the North and South American plates diverged during the Middle Mesozoic. The original relative direction of movement of the "Pacific-Caribbean" plate was to the north and was initially subducted below the North American plate along the present Puerto Rican Trench. The subduction zone gave rise to a volcanic arc, the proto-Greater Antilles. The direction of subduction reversed in the early Cretaceous and the North American plate was thrust below the "Pacific-Caribbean" plate. During the Eocene, the Caribbean plate decoupled from the East Pacific plate and altered direction to the present relative eastward motion (Figure 2) (Edgar, et al., 1971; Malfait and Dink Leman, 1972; Mattson and Pessagno, 1979).

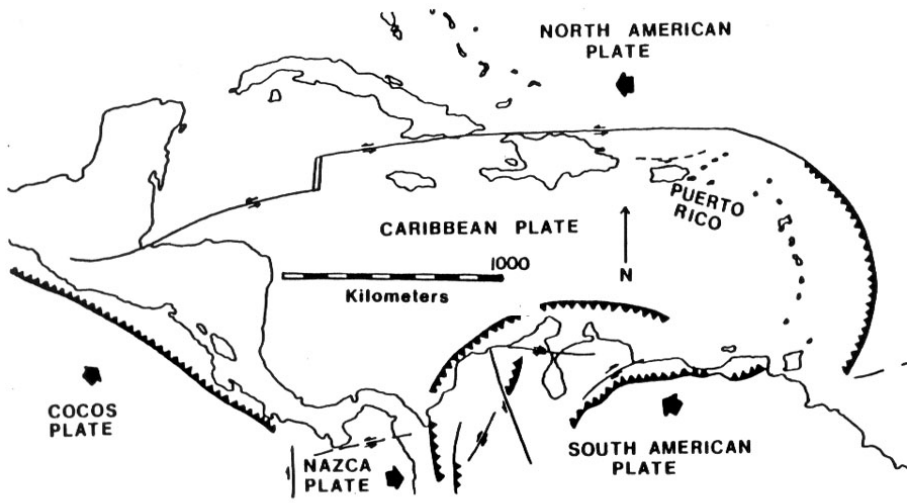


Figure 2. Plate tectonics map of the Caribbean

Puerto Rico is the easternmost of the four major islands of the Greater Antilles. The island can be divided into three principal geologic regions: the central mountain core of volcanic, plutonic and sedimentary rocks; flanking elevated sedimentary rocks, primarily limestones; and Quaternary surficial deposits (Figure 3).

The east-west trending Central Cordillera is composed of igneous and highly folded metasedimentary rocks. Exposed rocks include Cretaceous and Early Tertiary marine lava and ash deposits, sandstones and conglomerates derived from reworked pyroclastic rocks, and limestones resulting from reefs forming on the early volcanic arc platform.

Associated with the volcanic rocks are Late Cretaceous and Early Tertiary intrusives composed of granodiorites and quartz diorite. The largest two intrusives are the Utado stock in the central portion of the island and the San Lorenzo batholith in the eastern portion of the island. The Laramide intrusives are thought to have originated as the North American plate underthrust the "Pacific-Caribbean" plate (Mattson and Pessagno, 1979).

Exposed on the southwestern section of the island, the Late Jurassic to Early Cretaceous Bermeja complex forms the basement rock of the central mountain core. The Bermeja complex is composed of metathoelitic rocks, pillow lavas, serpentinized peridotites and deep sea cherts and is interpreted as an ophiolite resulting from the initial subduction of the "Pacific-Caribbean" plate beneath the North American plate (Mattson and Pessagno, 1979).

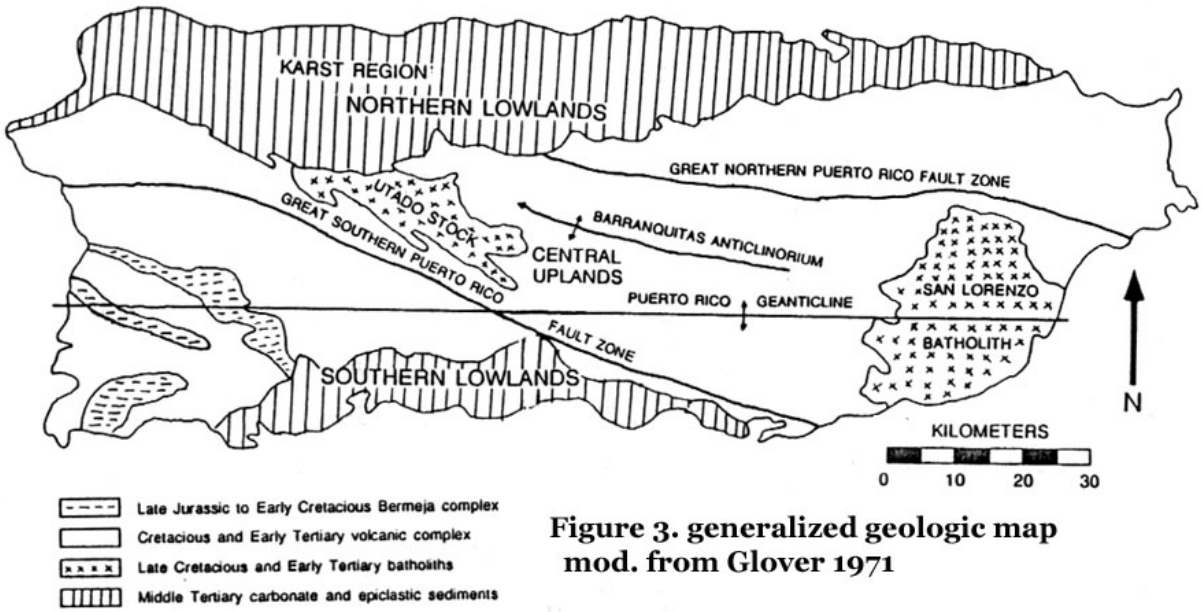


Figure 3. generalized geologic map mod. from Glover 1971

During the Middle Tertiary, the Central Cordillera was folded into a geanticline (GIover, 1971). The limbs of the fold dip to the north and the south. The Central Cordillera is cut by hundreds of faults, with the largest being left lateral transcurrent faults trending northwest (Monroe, 1973).

Forming an angular unconformity with the underlying rocks, Middle to Late Tertiary sediments up to 1700 meters thick are deposited on the limbs of the geanticline (Monroe, 1973). The basal deposits are mainly conglomerates, sands and clays weathered from the igneous core. The thick overlying sediments are primarily limestone. The limestones on the northern flank are relatively undisturbed and dip gently northward at an angle of 1 to 5 degrees. Karst topography is typical of these limestones. The southward flank dips at an angle of 10 to 30 degrees and is highly faulted, with offsets up to hundreds of meters.

Unconformably overlying the Tertiary limestones, the Quaternary deposits are located in the river valleys and in intermittent swaths along the coast. The only consolidated sediments form eolinate ridges, found chiefly along the north coast.

SETTING

Puerto Rico is the smallest of the chain of islands that form the Greater Antilles. The rectangular-shaped island covers 8,497 square kilometers, with a length of about 160 kilometers from east to west and a width of about 50 kilometers from north to south. The east-west trending mountain range in the center of the island reaches a maximum elevation of 1338 meters above sea level (Figure 4).

Located at about 18 degrees north latitude, the island of Puerto Rico is strongly influenced by the northeast trade winds. The trade winds provide a light but consistent breeze to the west.

Sea level is thought to have risen at a rate of 2 millimeters per year for the last 8,000 years in the San Juan area (Rodriguez, 1987). Relative sea level is presently rising at a rate of 3 millimeters per year on the north coast and 2 millimeters per year on the south coast (Webb, 1989).

The waves are primarily driven by the westerly trade winds. Due to the large fetch of the Atlantic Ocean and the narrow shelf, the north coast is subjected to large waves from the east, with an annual mean wave height of 1.25 meters (Webb, 1989). During storms, the north coast is buffeted by waves from the north to northwest, with wave heights of 3 meters and larger. The east, south and west coasts are subjected to much lower wave energy. Local influences, which include islands, reefs and drowned beach rock, have a great impact on wave energy.

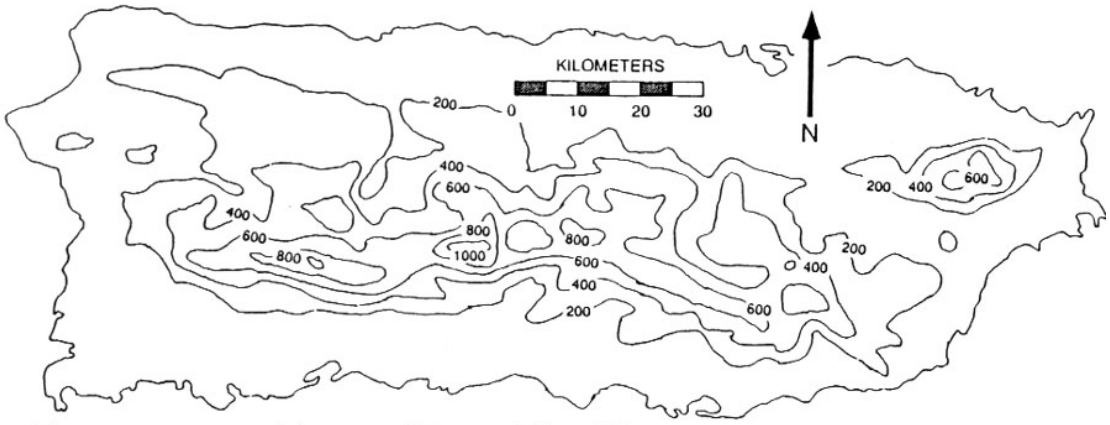


Figure 4. topographic map of Puerto Rico. CI = 200 m

Wave action is the dominant process affecting sediment transport on Puerto Rico's microtidal coastline. The mean tidal range is 0.48 meters at Bahia de Fajardo on the east coast, 0.24 meters at Playa de Ponce on the south coast, 0.48 meters at Mayaguez on the west coast and 0.48 meters at San Juan on the north coast (NOAA, 1989). The tides are normally semidiurnal except on the south coast where the tides are diurnal.

The constancy of the winds has a strong effect on coastal currents and littoral drift (Figure 5). Using morphological drift indication (such as spits and natural groins), Kaye (1959) reported that nearshore currents move east to west on the north and south coasts. He speculated that current reversals may occur on the north coast as a result of coastal configuration. Kaye also suggested that nearshore currents move to the north on the east and west coasts. In a more recent study, Morelock, et al. (1985), confirmed that the nearshore currents and littoral drift is generally to the west on the north coast and that eastern driven currents are occasionally set up by north and northwest wave trains. In a more complete study of the littoral transport along the west coast, Morelock (1987) found that transport is strongly north to south.

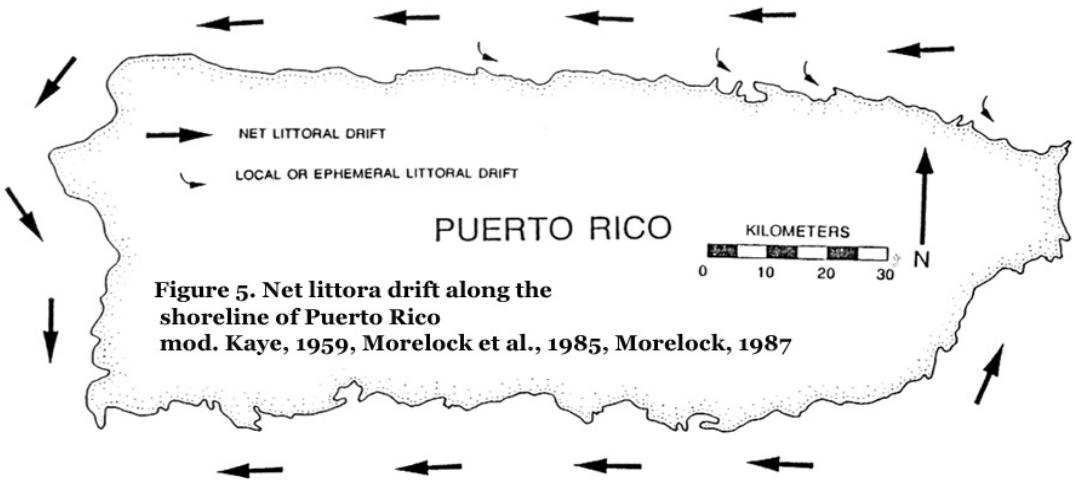


Figure 5. Net littora drift along the shoreline of Puerto Rico mod. Kaye, 1959, Morelock et al., 1985, Morelock, 1987

The rainfall on the island is orographically controlled. The warm trade winds become moisture-laden over the ocean and then rise up over the central highlands, cooling and condensing. The rain subsequently formed mainly falls on the north coast (Figure 6). In Sierra Luquillo, as much as 4000 mm is reported for the year (Monroe, 1976). Since most of the rain water drains to the north, a large supply of terrigenous material is provided to the north coast. In the lee of the Cordillero, a rain shadow is formed with arid conditions prevailing in the south. Less than 1000 mm of annual rainfall is reported on the southwest coast

(Monroe, 1976). Rainfall occurs throughout the year but is generally heaviest during the summer months. Most showers tend to be sudden and may cause severe flooding.

Hurricane season extends from August to mid-October. Due to the island's east-west elongation, hurricanes generally pass to the north and the south of the island. Hurricanes that pass near the island are usually from the east or the southeast. From 1893 to 1985, 30 hurricanes have passed near Puerto Rico and only 12 have reached landfall. Prior to this investigation, the last two hurricanes to pass over Puerto Rico were Frederick in 1979 and Betsy in 1956.

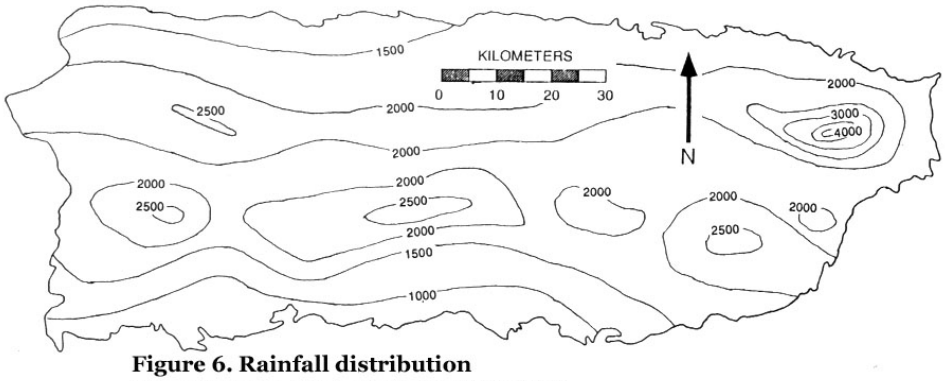


Figure 6. Rainfall distribution
CI = 500 mm. mod. from Monroe,1980

COASTLINE

The highly compartmentalized Puerto Rican coastline shows great variability in shoreline types and wave energies. Even neighboring compartments may be widely different. Shorelines of Puerto Rico may be grouped into three broad categories: beach, rocky headlands and swamps. Beaches may be further subdivided into quartz sand beaches, carbonate sand beaches, heavy mineral sand beaches or gravel beaches. Following the classification of Wright and Short (1983), beach types range from reflective beaches, often observed on the east coast, to dissipative beaches, mainly found on the north coast. Kaye's study (1959) remains the most complete description of the Puerto Rican shoreline. The following summary of the coast draws primarily on this early work.

The east coast extends from Cabezas de San Juan to Cabo Mala Pascua (Figure 7). In the northeast, the long spurs of the Sierra Luquillo form a highly indented coast of rocky headlands with fringing reefs and small islands offshore. Because of the low wave action, little reworking of the coast has occurred except for a few low cut wave cliffs and some alluviation between headlands. South of Naguabo, the coast becomes less crenulated with broad alluvial valleys between large rocky headlands. Waves become more important in shaping the coast as wave eroded cliffs may extend up to 30 meters. The headlands in this area drop steeply into deeper water.

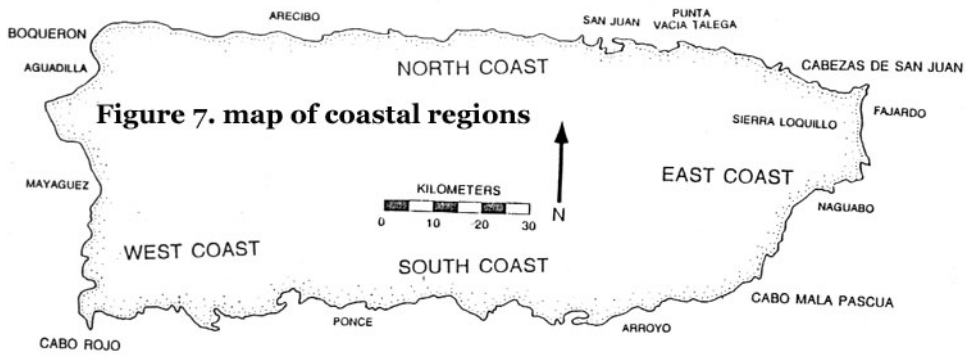


Figure 7. map of coastal regions

Stretching from Punta Maunabo to Cabo Rojo, the south coast is composed of alternating narrow sand beaches and mangrove swamps. To the east, dark colored sands dominate the beach with gravels or cobbles often found in the swash zone. To the west, carbonate sands form the beach. The rounded capes of the south coast result from large alluvial fans being drowned by the sea. Offshore, a few fringing reefs can be found. The reefs, along with the broad insular shelf, keep the nearshore wave energy low. At the

southwest corner of the island, the unique feature of a double tombolo has formed around two limestone knobs.

The west coast, extending from Cabo Rojo to Punta Boqueron, is typified by broad valleys defined by mountain chains. The southern end is protected by a relatively broad insular shelf and by a few fringing reefs that can be found as far north as Mayagüez. Due to the low wave energy, mangrove swamps are common. Carbonate sands are the major beach constituent. Around Mayagüez, however, heavy minerals and rock fragments become the dominant beach material. To the north, wave energy increases and 45 to 60 meter high limestone cliffs line the coast. Cemented dunes form rocky headlands seaward of the cliffs.

Beach rock is consistently found along the beaches of the north coast, which stretches from Punta Boqueron to Cabezas de San Juan. To the west, the limestone cliffs which occur on the west coast continue. This section of the coast also contains the only large sand dunes found on the island. In the central portion of the north coast, between Arecibo and Punta Vacia Talega, a series of semi-parallel cemented dune ridges constitutes the most extensive single type of coastline found on the north coast. Formed when the outer ridge is breached, small embayments with pocket beaches dot the coastline. Any of the major types of beach sands may be the principal constituent of the pocket beaches. The central section also is the site of the highest wave energies found anywhere around the island. The coast east of Punta Vacia Talega contains the island's widest beaches along with areas of extensive mangrove swamps. Fringing reefs are quite common.

PREVIOUS WORK

In an early study of the coast of Puerto Rico, Kaye (1959) wrote what is considered the classic description of the coastal morphology. In his study, Kaye related direction of sediment transport to beach morphology. He used drift indicators (e.g., spits and natural groins) to suggest current direction.

In more recent studies, Morelock (1985; 1987) has measured sediment transport on the north and west coasts. He used beach sediment samples, river input data, and coastal erosion data to determine net direction of transport.

Few studies of the hard stabilization in Puerto Rico have been conducted. The areas of stabilization have only been described in a general manner (Bush, 1989). Quantitative studies of the effect of hard stabilization on the seaward beach have considered only isolated, individual locations. Morelock's examination (Morelock, 1984) of coastal erosion at eleven locations around the island included seven locations containing coastal structures. A few studies for US Army Corps of Engineers' permits to build coastal structures have also been made (USACE, 1987; USACE, 1986). However, no comprehensive field studies of the effect of armoring on the beach have yet been completed.

The effect of stabilization on the seaward beach is presently garnering significant attention. For example, the Journal of Coastal Research devoted Special Publication #4 (1988) to the topic. Yet, according to a literature review by Kraus (1987), contradictory claims are common. Work on the subject continues to center on theoretical studies of the interaction between the structure and frontal shore processes and field studies (in particular, post-storm recovery studies) of the beach seaward of a single structure. Whether structures alter or degrade beaches is a question needing further examination.

Narrowing of the beach oceanward of the structure is one effect of walls that has been noted in the literature. Wright and Pilkey (1989) related dry beach width to the density of stabilizing structures in New Jersey, North Carolina and South Carolina. They found that dry beach width decreases with increasing density of hard stabilization. MacDonald and Patterson (1985) examined a 30 kilometer strip of shoreline along Gold Coast, Australia. Using data from beach surveys conducted since 1964, the study reported that at the two stabilized locations on receding shorelines, "the receding beach has effectively placed the seawall progressively further and further seaward on the beach profile until no beach exists at all in front of the wall." Reynolds (1987) examined the effect of hard stabilization along the shoreline of Marco Island

using aerial photographs from 1926 to 1981. He notes that prior to construction along the coast, the beach was accretionary, but after construction began in 1966, beaches seaward of coastal structures disappeared.

Erosion at the end of structures is another possible effect of hard stabilization. Suggested mechanisms for such erosion include: loss of sediment to the littoral system due to trapping of sediment landward of the structure, groining caused by trapping of sediment updrift of the structure, and flanking. While many papers provide qualitative observations about end-around effects (e.g., Escoffier, 1951; MacDonald and Patterson, 1985; Dette and Gartner, 1987), few quantitative studies have been conducted. In one of the few field studies, Birkemeier (1980) used aerial photographs to examine shoreline and bluff erosion along five 1.6 kilometer reaches of the Lake Michigan shoreline in Berrigen County, Michigan. The study was conducted between 1970 and 1974, during which time a 579-meter-long seawall was built on one of the reaches. The downdrift cut which formed following completion of the wall in 1971 was measured. The results of the study suggest a correlation between the amount of sediment trapped behind the seawall and the amount of sediment eroded from the adjacent downdrift shore. In another study, McDougal, et al. (1987) performed wave tank experiments to measure flanking effects of seawalls. The experimental results suggest that the magnitude of end-around effects are directly proportional to wall size.

Hard structures may also permanently alter the profile of the seaward beach. Kraus, et al. (1986) examined profiles for the years 1953, 1963, 1985 and 1986, along a twelve mile stretch of the New Jersey coastline. Their results suggest that profiles on a seawall-backed beach will tend to steepen as a result of coarsening of the beach sediment in front of the seawall. However, in a paper summarizing present ideas about seawalls, Dean (1986) proposes that "under normal conditions, profiles fronting seawalls and natural beaches will be the same up to the location of the seawall."

Many studies state that structures do not affect the beach or the ability of the beach to recover from storms (e.g. Baba and Thomas (1987); Berrigan (1985); Davis and Adronaco (1987)). In a survey of beach width, Basco (1987) studied a twenty mile section of the southern Virginia coastline using wave, bathymetry and shoreline change data. He concluded that offshore bathymetry and wave conditions, not the seawall, were responsible for decreased beach width. While he demonstrates the importance of considering offshore conditions, many of his findings on the effects of seawalls are based on insufficient evidence. Based upon beach profiles collected from 1979 to 1983 along a seawall on the Trivandrum coast of southwest India, Baba and Thomas (1987) also suggest that seawalls do not alter the oceanward profiles.

The present prevailing opinion suggests that seawalls do not adversely affect the beach if sediment supply is sufficient to maintain the beach. Seawalls on sediment-deficient beaches or retreating shorelines are considered to cause narrowing of the oceanward beach. Any structure may impact adjacent beaches either by flanking or by groining effects if the structure becomes projected into the surf zone. Quantitative field studies are needed to resolve the contradictory and untested claims that continue to be made in the literature.

METHODS

Field Work

The field work for this study was conducted between July 15 and September 4, 1988. Preliminary selection of possible stabilized sites for examination was initially made by observing a recent aerial video tape of the shoreline of Puerto Rico (Duke/USGS, 1988). Large harbors, located at such port cities as San Juan, Fajardo, Ponce, and Mayaguez, were excluded as the depth of water was too deep to study the upper nearshore. The metropolitan areas of San Juan and Ponce and the coast immediately north of Joyuda were also excluded because the lengthy uninterrupted coastal armoring in these areas lack natural beaches for comparison. With the exception of the above mentioned urban stabilization, nearly all of the hard stabilization along the coast of Puerto Rico was examined. Field visits were made to each selected location in a series of short trips around the island (Figure 8).

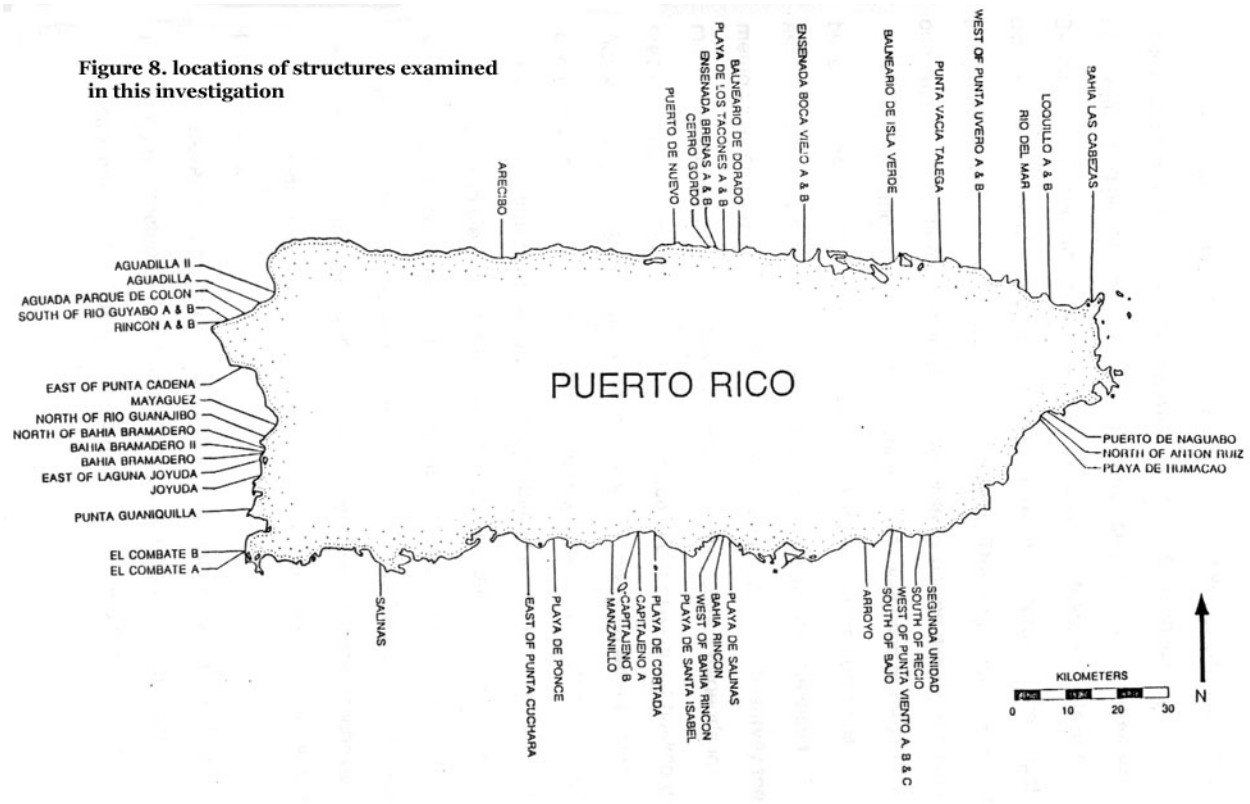


Figure 8. locations of structures examined in this investigation

For each site, the overall setting was described in terms of the shape of the coastline, the dominant beach material, the wave height and the angle of wave approach relative to the shoreline. The shape of the coastline was categorized as a small embayment (e.g., Puerto De Nuevo; less than 1.5 kilometers at the widest point), medium embayment (e.g., Bahia Las Cabezas; 1.5 to 3 kilometers at the widest point), or large embayment (e.g., Ensenada Boca Viejo; greater than 3 kilometers at the widest point) or as a straight coastline (e.g., El Combate). The dominant beach material was categorized as quartz sand, carbonate sand, heavy-mineral sand or gravel. Classification was based on visual field examination. Wave conditions at the time of site visit were estimated.

For each site, a map of the coastal armoring was sketched (Appendix). Each map shows the types (e.g., seawalls, revetments or gabions) of stabilization and position of each type that compose the structures present. Definitions of stabilization types are listed in Table 1. Measurements of the dimensions of each of the constituent types were also recorded. The height and angle of the oceanward face were estimated. The length was measured by odometer if longer than 0.3 kilometers, otherwise by pacing along the beach.

Table 1. Types of Shore Parallel Stabilization

Sea Wall:
Any vertical or stepped structure, any cement structure, or any needy vertically cemented structure that protects the shore.

Cement Sea Wall**:** A free standing vertical sea wall made of cement.

Building Wall: A sea wall formed by a building (business, home, etc.) wall.

Revetment:
Any shore protection structure composed of loose, piled material.
Boulder Revetment: A revetment composed of boulders. Similiar to rip-rap.
Trash Revetment: A revetment composed of rubble, construction debds, or trash.

Gabion:
Any shore protection structure composed of cobbles held together by wire.

Breakwater:
Any shore protection structure either completely unattached from the shore or attached to the shore only along one end of the structure. The structure is designed to reduce the wave energy along the landward shore.

The "stake and horizon" method (Emery, 1961) was used to measure beach profiles at each of the study sites. Sighting on the horizon is assumed to produce a level for measuring relative changes in elevation. This method was chosen because it provides a quick and easy way to survey the many beaches studied. With this simplicity, however, comes tradeoffs in precision and accuracy. The most likely source of error lies in not holding the rods vertical, particularly when measuring in strong breaking waves. Not following a transect normal to the shoreline is another source of error. A further disadvantage is that errors may be compounded at each measurement along a profile. For example, each measurement may overestimate the change in elevation by one centimeter. If twenty measurements are made, the overall change in elevation will be twenty centimeters too low. Regardless of these possible sources of error, the Emery method remains a standard technique for measuring beach profiles as the errors in precision and accuracy are assumed to be negligible.

Wherever possible, profiles at each site were taken at adjacent beaches apparently unaffected by the structure, at adjacent beaches apparently affected by the structure (profiles taken within 5 meters of the structure), and in front (i.e., immediately seaward) of the structure (Figure 9). For long structures or those affecting beaches for long distances, additional profiles may have been taken.

Profiles were measured to chest-deep water. As each profile was surveyed, the wet-dry line and mean water line were noted. The mean water line was considered to be at the midpoint between high and low swash at the moment of profiling or if in deeper water, at the average midpoint between crest and trough of several waves. At most measurements along a profile, the median size of a hand-grabbed, surface sediment sample was visually estimated by comparison with a classification card of known sizes based on the Wentworth Scale (Wentworth, 1922).

End around effects were also measured. Offsets were measured by pacing the distance from the wet-dry line on the adjacent beach to the farthest seaward point of the structure. The maximum height of any scarps possibly related to the structure were measured and the length of the scarp was paced.

Whenever possible, either the property owner or a nearby property owner was interviewed to determine the history of hard stabilization on the beach. Interview questions covered the following topics: original beach width; history of changes in beach geometry; original position on the coast where hard stabilization was constructed; time since initial hard stabilization was constructed; amount of maintenance performed on the present structure; effect of the structure on people's use of the beach; and personal solutions to the erosion problem.

Data Manipulation

The wet-dry line was used as the datum point for the profiles. Elevation of the wet-dry line was set to zero (z = 0). For profiles beginning below the wet-dry line, the elevation of the mean water line was calculated (Figure 10). To calculate this elevation, the difference in elevation between the wet-dry line (zwd) and the mean water line (zmw) of the other profiles at the site was averaged (avg. $\Delta z = \Sigma(zwd - zmw)/\#$ of profiles). This average difference (avg. Δz) was subtracted from the mean water line of the original profile (initially set to 0) to determine the calculated elevation (zmw actual = zmw original - (avg. Δz)).

The estimate of the mean water line elevation is another possible source of error. The estimate is based on an average calculated from profiles at the location. This average may be skewed by atypical profiles experiencing local or unusual conditions. Changes in wave energies caused by local topography in an embayment may cause such atypical profiles.

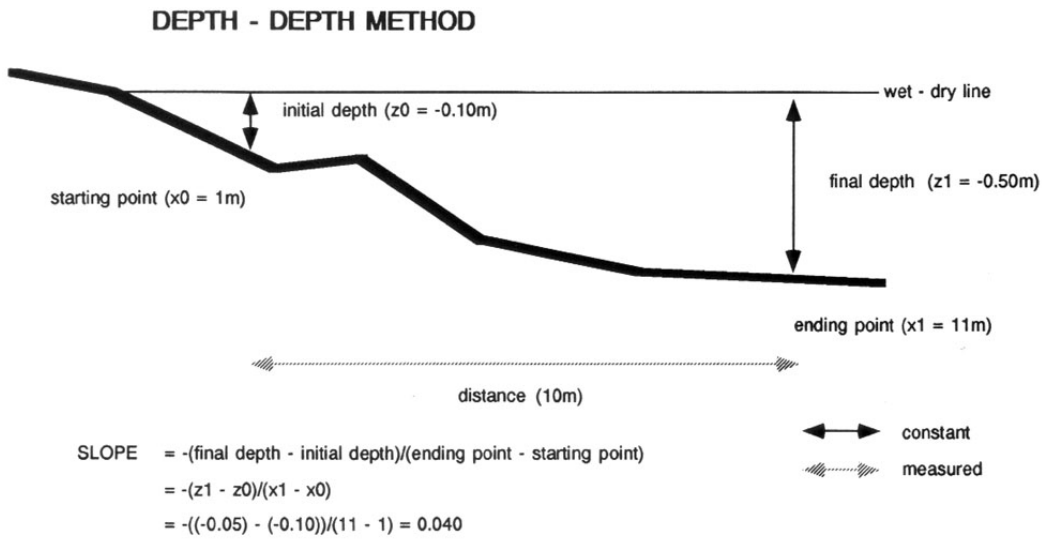


Figure 11. the "depth-depth" method for calculating slopes

Slopes were calculated by one of two methods: "depth-depth" or "depth-distance". The "depth-depth" method (Figure 11) uses a constant initial (z0) and final (zl) depth, which define the endpoints of the profile. The starting point (x0) is the first point seaward of the wet-dry line at the selected initial depth. The ending point (xl) is the first point seaward of the starting point at the selected final depth. Distance between the starting and ending points is measured and the slope is determined by dividing the change in elevation between the starting and ending points by the distance between the two points (slope = -(zl - z0)/(xl - x0)).

The "depth-distance" method (Figure 12) uses a constant initial depth (z0) as the start of the profile and from that point measures some constant distance seaward to define the ending point (xl). The starting point (x0) is again the first point seaward of the wet-dry line at the selected initial depth. The final depth (zl) is measured and the slope is again determined by dividing the change in elevation between the starting and ending points by the distance between the two points (slope = -(zl - z0)/(xl - x0)).

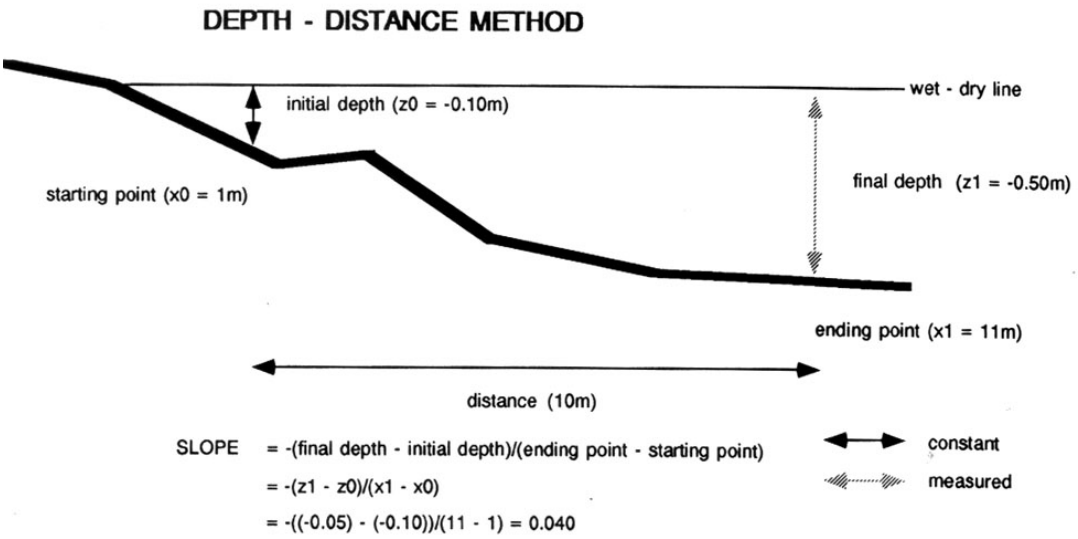


Figure 12. the "depth-distance" method for calculating slopes

DESCRIPTION OF HARD STABILIZATION

Along the shores of Puerto Rico, hard stabilization is a popular response to a retreating shoreline (Table 2). Small structures (defined as structures less than 75 meters in length) are the most common form of hard stabilization. Privately funded, the structures are often constructed independently of other structures on the beach and are in need of upkeep. Revetments are prevalent on all the coasts while seawalls are typically found in small embayments formed between rocky points. These walls often armor the entire shoreline of the embayment. When the density of small revetments and seawalls increases in coastal towns, a single irregular structure is formed. These irregular structures were observed at Salinas and Playa de Cortada on the south coast and along much of the central portion of the west coast.

Table 2. Stabilized Shoreline Study Sites

East Coast:

1. **Puerto de Naguabo** (P Naguabo)
Sea Wall, Revetment

Almost the entire shoreline of the embayment is stabilized. A vertical cement sea wall protects Rte. 3 along the southern end of the embayment. A collection of poorly upkept revetments and sea walls protect the central and northern end of the embayment.

2. **North of the Rio Anton Ruiz** (N Rio Anton)
Boulder Revetment

The 579 meter long boulder revetment protects Rte 3. The revetment itseft is in good condition. Erosion continues to undercut Rte. 3 to the south (downdrift) of the revetment. An 0.30 meter deep toe scour trough is located at the southern end of the stabilization.

3. **Playa de Humacao** (P Humacao)
Gabion, Revetment

The 83 meter long stepped gabion, which is in excellent condition, protects houses. The gabion may have cost more than the houses it protects. To the south of the gabion is a small revetment.

South Coast:

4. **Segunda Unidad** (Seg Unidad)
Building Wall

Two houses located on the eastern side of a small embayment. The base of an older sea wall can be seen oceanward of the eastern house. Stairs in front of the wall have been destroyed. The length of the structure is 135 meters. Former beach rock can be seen underwater extending across most of the embayment.

5. **South of Recio** (S Reccio)
Cement Sea Wall

A cement sea wall below the wet-dry line protects a house. Sea grass grows out in the embayment.

6. **West of Punta Viento** A & B & C (W Pta Viento)
Cement Sea Wall, Revetment

A: Cement sea walls protect houses. The total length of the structure is 105 meters.

B: A cement sea wall and trash revetment protect buildings. The revetment is built around a small point. The total length is 73 meters.

C: A 109 meter, over 2 meters tall cement sea wall protects Rte. 3. Slight undercutting from behind occurs on the west end. The structure holds back a bluff.

7. **South of Bajo** (S Bajo)
Sea Wall

Two cement walls seperated by a log picket wall protect houses on the west side of the embayment. The 56 meter long stabilization is tied into the rocky point to the west. These walls are behind the wet-dry line.

8. **Arroyo** (Arroyo)
Trash Revetment

A trash revetment with a boulder breakwater attached to the west. The breakwater protects a marina. The total length of the structure is 260 metem. Extension of the breakwater along with construction of another breakwater to the west has been proposed to correct the problem of sediment filling the marina.

9. **Playa de Salinas** (P Salinas)
Sea Wall, Revetment

A largely stabilized shoreline consiting of a combination of building walls, sea walls, revetments and short stretches of unstabilized shoreline. The structures mainly protect expendable housing.

10. **Bahia Rincon** (B Rincon)
Boulder Revetment

A 563 meter long boulder revetment, in good condition, protects Rte. 1. The west end of the revetment is tied into the shoreline. The rubble of two smaller, previous cement sea walls can be seen.

11. **West of Bahia Rincon** (W B Rincon)
Revetment

A small (15 meters long) revetment protecting nothing.

12. **Playa de Santa Isabel** (P Santa Isabel)

Building Wall

A business establishment in the water. To the west of the wall, a large bulkhead with a boat ramp is being built.

13. **Playa de Cortada** (P Cortada)
Sea Wall, Revetment

A largely stabilized shoreline consiting of a combination of building walls, sea walls, revetments and short streches of unstabilized shoreline. The structures mainly protects expendable housing.

14. **Capitajeno A** (Capitajeno A)
Trash Revetment

Failed housing pushed onto the beach to form a trash revetment. The 17 meter long revetment protects nothing.

15. **Capitajeno B** (Capitajeno B)
Trash Revetment

Failed housing pushed onto the beach to form a trash revetment. The 49 meter long revetment protects nothing.

16. **Manzanillo** (Manzanillo)
Boulder Revetment

A 370 meter long boulder revetment protects a road built on backfill. After only 4 months, the revetment is falling apart and the road is being undercut. The structure and backfill appear to be more expensive than the cheap housing they protect. The beach has been lost from in front of the structure.

17. **Playa de Ponce** (P Ponce)
Trash Revetment

The beach has been completely lost from in front of the mounded, trash revetment. The 402 meter long revetment protects cheap housing. On the eastern end of the structure a fishing dock extends 25 meters seaward. Also on the east end, a sand sheet extends over 50 meters from the shore. This sand could have resulted from dredging in the nearby port of Ponce.

18. **East of Punta Cuchara** (E Pta Cuchara)
Boulder Revetment

A boulder revetment protecting Rte 2

19. **Salinas** (Salinas)
Sea Wall

A cement sea wall built on the eastern side of a small embayment. The wall exhibits slumping on the front due to undercutting by fresh water runoff from behind. The eastern side of embayment is very shallow and the bottom is vegetated by sea grass. A heavily used recreational beach is on the western side of the embayment.

West Coast:

20. **El Combate A** (El Combate A)
Revetment

A 62 meter long revetment protects a business. The northern (updrift) beach is offset by 5.4 meters while the southern (downdrift) beach is offset by 19.4 meters. The bottom is "clayey" in the lee of the revetment. Heavily used recreational beaches border on either side of the structure.

21. **El Combate B** (El Combate B)
Building Wall

A house below the wet dry line. The length of the house is 15 meters. The foundation of a porch can be seen in front of the house. Heavily used recreational beaches border on either side of the structure.

22. **Punta Guaniquilla** (Pta Guan)
Building Wall

House walls in the water. The total length of the structure is 78 meters. Some parts of the walls have experienced severe undercutting. Heavily used recreational beach borders the structure to the north.

23. **Joyuda** (Joyuda)
Sea Wall, Revetments

A largely stabilized shoreline consiting of building walls, sea walls, and revetments. Some owners of houses have added armoring to the base of their walls. Some revetments form "artificial" headlands. Former beach rock and reefs can be seen protecting sections.

24. **East of Laguna Joyuda** (E Lag Joyuda)
Building Wall, Gabion

The 32 meter long structure is composed of a rusty gabion to the south of a house wall. The house wall has been armored at the base to stop further undercutting. The base of a former sea wall can be seen on the beach to the south. The northern (updrift) beach is offset 10.6 meters while the sourthem (downdrift) beach is offset 17.2 meters.

25. **Bahia Bramadero** (B Btam)
Sea Wall

House walls and cement sea walls stabilize most of this small embayed shoreline. In the center of the embayment, no beach exists. Basal armoring has been added to some of the houses to prevent undercutting. Attached boat ramps exhibit slumping. Total length of the structure is 402 meters.

26. **Bahia Bramadero II** (B Bram II)
Building Wall

Two house walls located in the water. Total length of the walls is 53 meters. Basal armoring of boulders has been added to the southern end to stop further undercutting.

27. **North of Bahia Bramadero** (N B Bram)
Trash Revetment

A 32 meter long trash revetment, in need of upkeep, protects a house. No beach exists in front of the revetment. The northern (updrift) beach is offset 4.5 meters while the southern (dowdrift) beach is offset 15 meters.

28. **North of Rio Guanajibo** (N Rio Guan)
Revetment, Cement Sea Wall

Protecting houses, the 236 meter long structure is composed of trash revetments along with one sea wall. A small break of unstabilized beach occurs toward the northern end of the structure. Unlike most other structures on the west coast, the northern beach (3.26 meter offset) is offset more than the southern beach (2.6 meter offset).

29. **Mayaguez** (Mayaguez)
Revetment

The southern end consists of boulder revetments protecting Rte 102. The northern end consists of trash revetments protecting houses. At one spot in the northern section, reinforced concrete from a house plowed down to the beach was observed. The structure is interrupted at 2 points by rivers. The total length of the structure is 2460 meters.

30. **East of Pta. Cadena** (E Pta Cadena)
Building Wall

House walls and severally undercut cement porches form this structure. The stabilization countinues around a point to the west. A sand sheet lies in front of the houses. To the east, the shoreline is set back 11.9 meters from the front of the structure. Cobbles are found piled to the east in the lee of the structure.

31. **Rincon A & B** (Rincon)
Cement Sea Wall

Two cement sea walls stabilize most of the small embayments shoreline. The sea walls are seperated only by a short stretch of unstabilized beach. The walls provide support for the bluff behind.

32. **South of Rio Guayabo A & B** (S Rio Guay)
Revetment, Sea Wall, Gabion

The Rio Guayabo located to the north supplies tremendous amounts of heavy mineral rich sand to the beach in front of these two structures.

A: A revetment protects houses along the southern end of the embayment.

B: A small gabion, a sea wall and a large boulder revetment form a single structure farther to north of the structure A. Total length of the structure is 178 meters.

33. **Aguada Parque de Colon** (Colon Parque)
Gabion

A 499 meter long sloped gabion stabilizes the northern and central portions of the embayment. The gabion itself is in good condition but the boat ramps attached to the gabion have collapsed. The structure provides access problems for the local fishermen.

34. **Aguadilla** (Aguadilla)
Boulder Revetment

A boulder revetment protects one of Aguadilla's main roads. To the south of the revetment a jetty traps sediments forming a wide beach. This wide beach is an active recreational beach. The structure continues to the north.

35. **Aguadilla II** (Aguadilla II)
Building Wall

An abandoned parking garage in water serves as a sea wall. The length of the garage along the beach is 58 meters. Two 10 meter piers on pilings are attached to the structure. The northern (upddft) beach is offset 4.3 meters from the front of the wall while the southern (downdift) beach is offset 10 meters. A 0.16 meter deep toe scour trough can be readily observed on the southern side of the wall. A large pier for a marina has been proposed to be built along the shore at this location.

North Coast:

36. **Arecibo** (Arecibo)
Revetment, Cement Sea Wall

Long streches of revetments and a few cement sea walls form this structure along the Arecibo shoreline. With no dry beach in front of it, the structure provides protection for a road. The stabilization rests on a rocky cliff. Former beach rock can be seen underwater in front of sections of the structure. The structure measured from the west end is 2860 meters long.

37. **Puerto de Nuevo** (P Nuevo)
Sea Wall

The entire shoreline of the small embayment is unstabilized. A cement wall on the central and eastern section of the embayment protect a road. In front of the wall is a heavily used recreational beach. House walls and sea walls form the western end of stabilization. Undercutting of some of the homes can be seen. Former beach rock protects the western side of the embayment.

38. **Cerro Gordo** (Cerro Gordo)
Sea Wall

Sea walls armor most of the western and central sections of the embayments shoreline. Former beach rock can be observed underwater in front of the houses. A heavily used recreational beach is oceanward of the houses and also to the east of the houses.

39. **Ensenada Brenas A & B** (E Brenas)
Sea Wall

A & B: Two large sea walls protect houses on the west and east sides of this very small embayment. A small drainage nver runs between the walls. The western seawall is 35 meters long while the eastern seawall is 64 meters long.

40. **Playa de los Tacones A & B** (P L Tocones)
Revetment, Sea Wall

An overlapping breakwater protects the small embayment.
A: Sea walls protect houses on the western end of the embayment. The total length of the structure is 94 meters. A new sea wall was observed being added to the stabilization at this location.
B: A 227 meter long revetment lines part of the central and eastern shoreline of the embayment.

41. Balneario de Dorado (B Dorado)
Sea Wall

A 268 meter long, less than a meter tall wall which merges with a building wall marks the backside of a heavily used recreational beach. The wall is very irregular in map view.

42. **Ensenada Boca Viejo A & B** (Boca Viejo)
Boulder Revetment

A: A long boulder revetment protects a Rte. 868 and a smaller road on the eastern side of the ernbayment. No beach exists in front of the revetment.
B: A long boulder revetment protects Rte. 165, a smaller road and buildings on the west side of the embayment. No beach exists in front of the embayment. The slope in front of the structure is very steep.

43. **Balneario de Isla Verde** (B Isla Verde)
Boulder Revetment, Gabion
A 186 meter long boulder revetment protect',~, a Rte. 187. The revetment is just west of a pair of jetties. A small gabion has been added to prevent further undercutting of the road to the west due to the severe erosion occudng downdrift of the structure. To the west of the wall is a heavily used recreational beach.

44. **Punta Vacia Talega** (Vacia Talega)
Revetment

A revetment protects a pull off spot along a road.

45. **West of Punta Uvero A & B** (W Pta Uvero)
Trash Revetment

A: A 40 meter long boulder revetment protect houses on the eastern end of an embayment. Eorming an "artificial" headland, the revetment is in need of upkeep. The eastern (updrift) beach is offset 7.8 meters from the front of the revetment while the western beach (downdrift) is offset 20.7 meters.
B: A 22 meter long boulder revetment protect houses farther east than structure A. Forming an "artificial" headland, the revetment is in need of upkeep.

46. **Rio del Mar** (Rio Del Mar)
Revetment

A 77 meter long revetment in the central section of a small embayment. The boulder revetment protects a golf course. Local replishment has been clone on the beach within the embayment. Unlike most other structures on the north coast, the eastern beach (5.4 meter offset) is more offset than the western beach (0 meters offset, but a scarp is formed in the sandy beach).

47. **Luquillo A & B** (Luquillo)
Cement Sea Wall, Revetment

The central portion of the embayment is unstabilized and undercutting of a road can be observed. Former beach rock can be seen offshore on the eastern side of the embayment.

A: An 86 meter long rock revetment on the eastern side of the embayment protects a road.

B: A 230 meter long cement sea wall on the western and central portions of the embayment protects a road and a hotel. The wall is tied into a rocky point.

48. **Bahia las Cabezas** (B L Cabezas)
Building Wall

Foundation of an abandoned building in the water forms this wall. The total length of the structure is 122 meters. The depth at the toe of the center of the wall was too deep to be measured. Beach rock armors the beach to the east and west of the wall.

Continuous armoring formed from many types and sizes of structures is generally constructed along the shores of the major coastal cities. Often docks form much of the hard stabilization. Major coastal cities include: Fajardo on the east coast; Ponce on the south coast; Mayagüez and Aguadilla on the west coast; and Arecibo and San Juan on the north coast. Also armoring the coast are smaller marinas typified by Playa Sardinera on the east coast and Arroyo, Salinas and Santa Isabel on the south coast. Oil companies and the US military maintain isolated ports and revetments.

Many large structures (greater than 75 meters in length) serve to protect highways and roads from the encroaching sea. Large rock revetments built within the last ten years protect Route 3 north of the Rio Anton Ruiz on the east coast, and Route 1 near Bahia Rincon and Route 2 east of Punta Cuchara on the south coast. Major roads are also protected by coastal structures at Parque de Colon, Mayagüez, and Aguadilla on the west coast and at Arecibo and Balneario Isla Verde on the north coast.

A few isolated large structures have been built to protect rows of low cost housing. The structures appear to be more costly than the property they protect. They include the gabion at Playa de Humacao on the east coast and the revetments at Manzanillo and Playa de Ponce on the south coast.

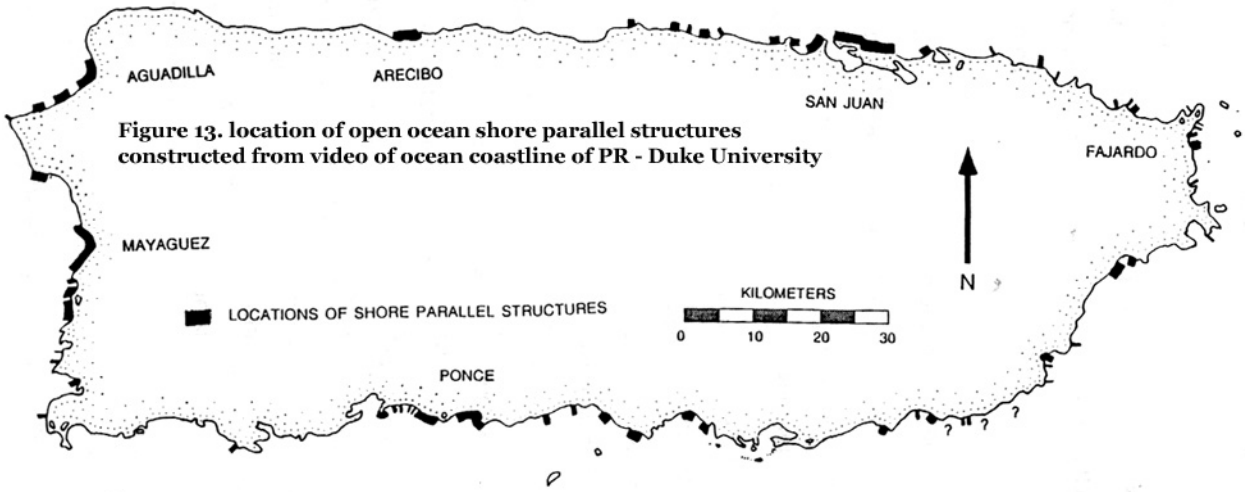


Figure 13. location of open ocean shore parallel structures constructed from video of ocean coastline of PR - Duke University

Figure 13 depicts the degree of stabilization along the shores of Puerto Rico. Dominated by a rocky coast, the east coast has few beaches and a scattered population. Only a few large structures have been constructed. The eastern portion of the south coast is dotted by small, isolated structures. West of Arroyo, population centers increase. Single large structures and structures composed of united small structures are more common. Individually funded projects are poorly built and in need of upkeep. East of Salinas, hard stabilization is absent. The southern end of the west coast has few structures located only at Combate and Boqueron. From Joyuda to Mayagüez, small structures form a continuous line of stabilization. North of

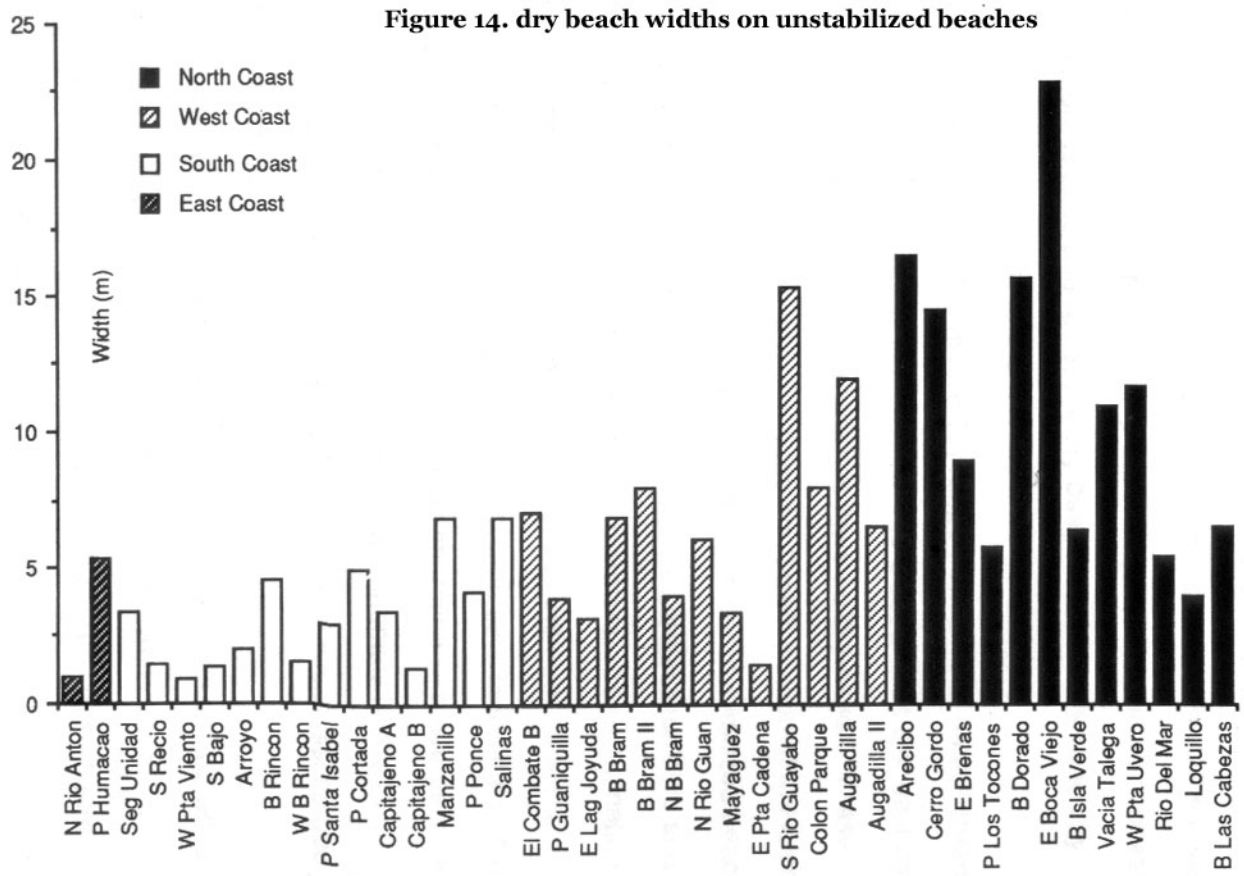
Mayagüez, the coast turns rocky and large structures located at population centers are present. Due to the rough wave conditions, rocky coasts and low population density, the western end of the north coast lacks any structures. East of Arecibo, the coast is dotted with structures armoring all or portions of small embayments. The exception is the metropolitan San Juan area, which contains a nearly continuous line of armoring. This area has some of the oldest structures on the island.

BEACH EFFECTS

Dry Beach Width

Wright and Pilkey (1989) suggest using dry beach width, which extends from the wet-dry line to the vegetation line, if present, otherwise to the toe of the structure, as a measure of the effects of hard stabilization on the beach. This method has several clear advantages. It is easy to measure regardless of tidal stage. It is also a clear representation of the recreational beach available to the public at high tide. A major disadvantage is the temporal variability in the measurement of dry beach width. Storms or spring tides may temporarily reduce the dry beach width to zero on both stabilized and unstabilized shores. Other factors that may influence dry beach width are the position of the structure relative to the shoreline at the time of construction, the time since initial hard stabilization was constructed, and sediment supply.

The dry beach widths in Puerto Rico were measured during the summer of 1988, a season of low storm activity. The landward edge of the dry beach was defined in order of preference as the natural vegetation line, an estimated vegetation line sighted from nearby vegetation or the toe of the structure.



The dry beach width of unstabilized beaches (Figure 14) range from just under one meter west of Punta Viento on the south coast to over twenty meters at Ensenada Boca Viejo on the north coast. The north coast has the greatest average dry beach width, averaging over ten meters. The relatively wide dry

beach there is interpreted as reflecting the large sediment supply brought to the north coast by rivers and the groin effect of high headlands which trap sediment in pocket beaches. The north coast is also affected by large storm waves which maintain a wide dry beach by preventing the seaward advance of vegetation. The most narrow dry beaches are generally found on the lower energy south coast. Located in the rain shadow of the central uplands, the small rivers on the south coast do not provide as much sediment to the coast as do the rivers on the north shore. Due to protection (i.e., dampening of ocean swells) by offshore islands and reefs, the dry beach is further narrowed by vegetation able to grow almost to the wet-dry line.

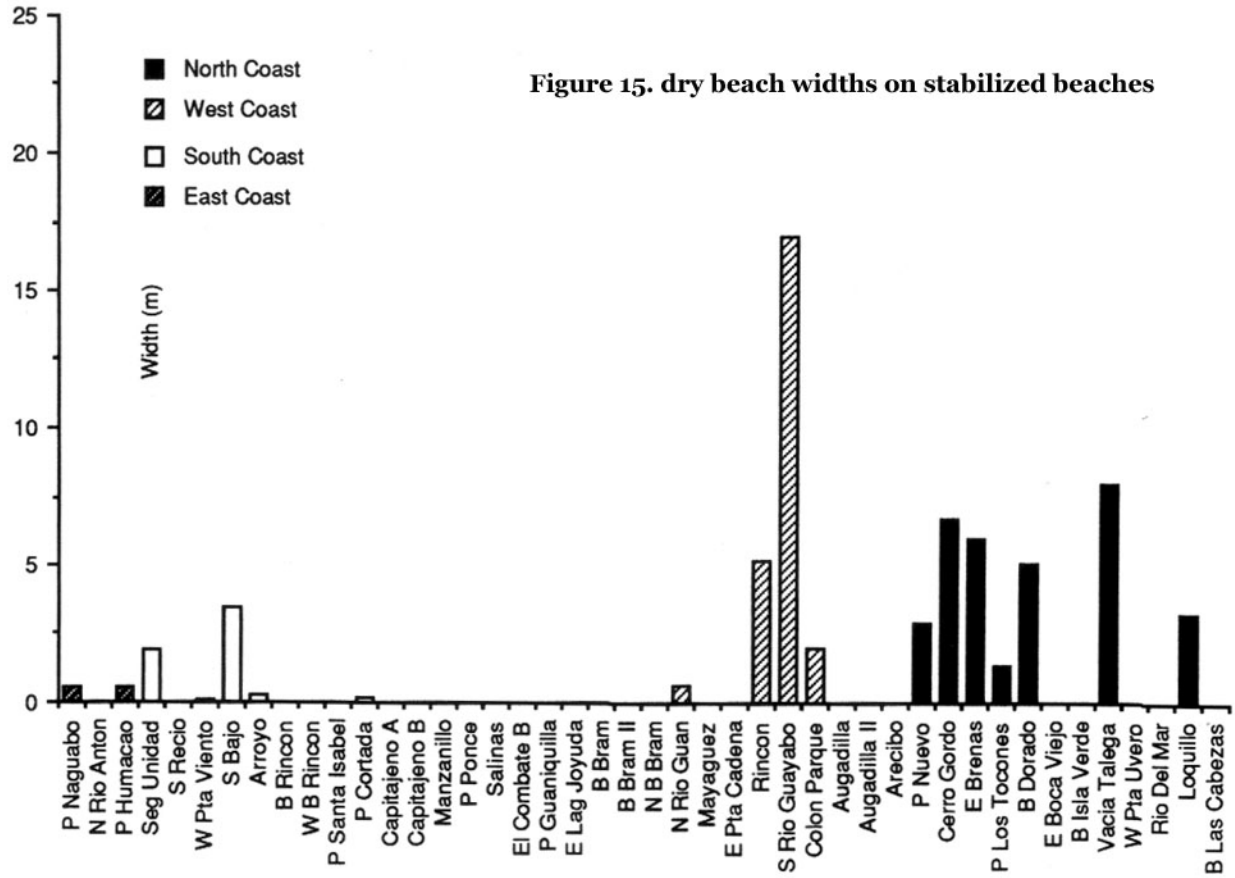


Figure 15. dry beach widths on stabilized beaches

Stabilized dry beach widths (Figure 15) range from zero at many locations to over fifteen meters at the study site south of Rio Guayabo on the west coast. Sixty-four percent of all the stabilized beaches have no dry beach. These "beachless" sites are located mainly along the southwest portion of the island. The north coast is the only area with a significant number of stabilized beaches with a dry beach; fifty percent have dry beach widths greater than zero and several beaches have a width of greater than five meters. The explanation for the width of the dry beach on unstabilized sections of the north coast is probably the same for the north coast's relatively wide stabilized beaches (i.e., abundant sediment supply). The only stabilized shoreline with over ten meters of dry beach is the site south of Rio Guayabo. This anomaly is due to the large amount of sediment supplied from the Rio Guayabo River which discharges just updrift of the structure.

A decrease in dry beach width on stabilized beaches as compared to unstabilized beaches is observed at all study sites but two, south of Rio Guayabo on the west coast and south of Bajo on the south coast (Figure 16). As mentioned above, the exception at the site south of Rio Guayabo is most likely due to the large sediment supply from the nearby river while the wider stabilized dry beach at the site south of Bajo appears to be due to a natural groining effect. The seawalls at the site south of Bajo are located on the

western end of a small embayment and are anchored into the rocky point to the west. The rocky point traps sediment carried by the westward moving longshore current.

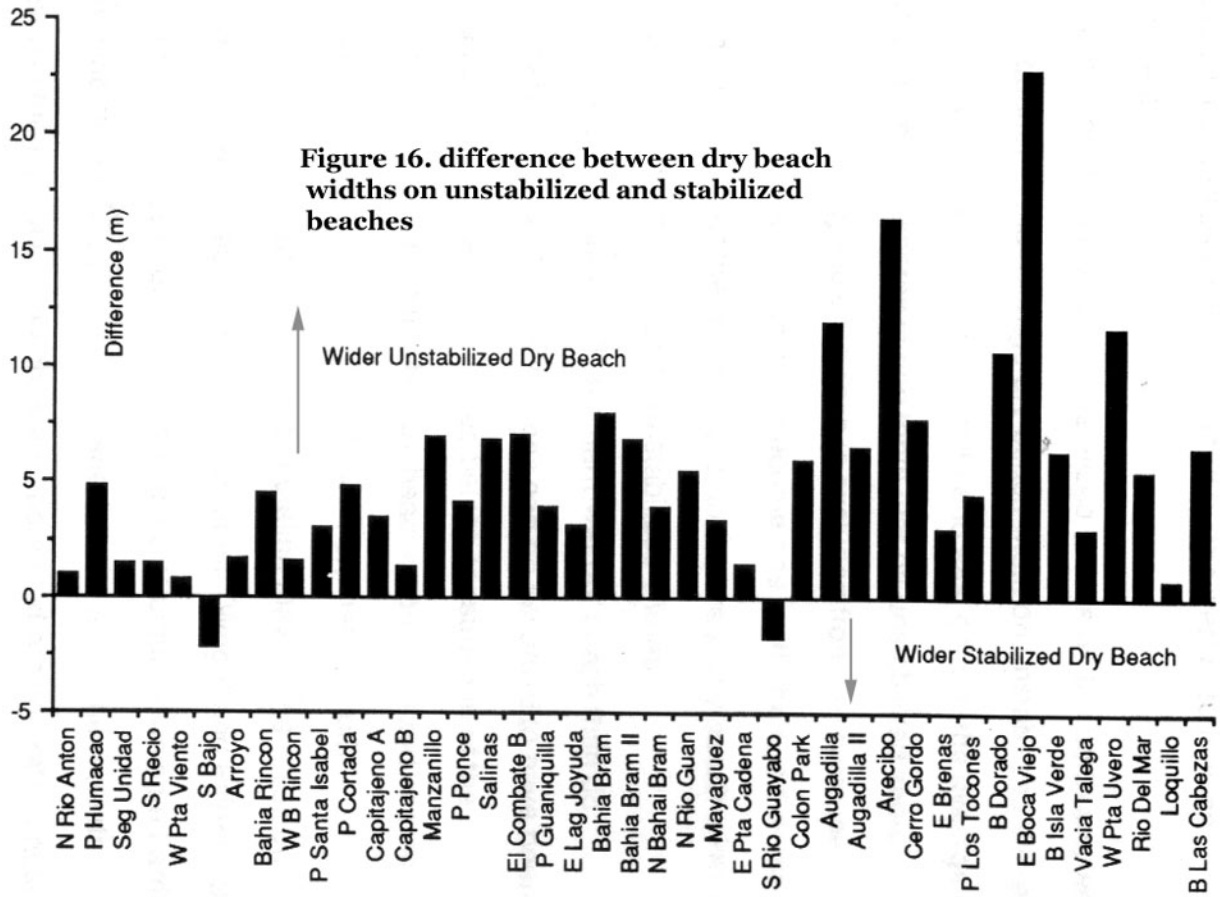


Figure 16. difference between dry beach widths on unstabilized and stabilized beaches

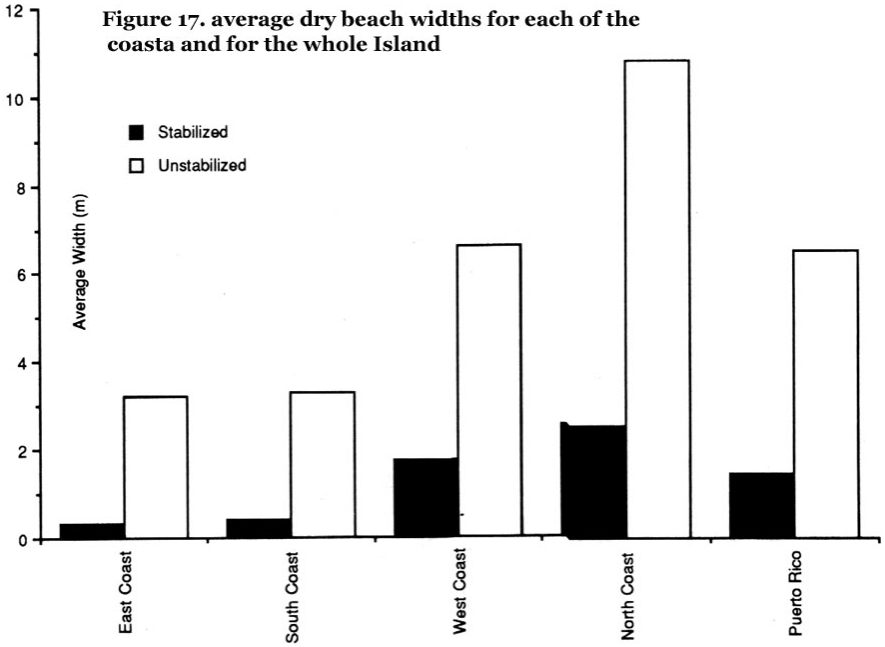


Figure 17. average dry beach widths for each of the coasta and for the whole Island

The average dry beach width for stabilized shores on the north and west coast are one quarter of the average dry beach width on unstabilized shores on those same coasts (Figure 17). On the south and east coasts, the average dry beach width on stabilized shores is one tenth that on unstabilized shores. If the exceptionally wide Rio Guayabo dry beach is excluded from the data, the stabilized shores on the west coast also become one tenth the width of the unstabilized dry beach. For the whole island, the average dry beach width of

stabilized shores is a quarter of that on unstabilized shores.

In general, stabilized shores have a narrower dry beach than do unstabilized shores. The stabilized beaches can be assumed to have been similar to the adjacent unstabilized shores before construction of the stabilization. The consistently narrower dry beaches on stabilized shores suggest that stabilization results in a decrease in dry beach width.

The loss of dry beach on a retreating shoreline may be the result of: passive erosion, active erosion or original placement (Wright and Pilkey, 1989). Passive erosion is the loss of dry beach due to the structure forming a barrier against shoreline retreat; the beach is drowned as the shoreline retreats. Active erosion is the loss of dry beach due to increased erosion rates caused directly by the structure. Placement refers to the loss of dry beach due to the structure being constructed seaward of the wet-dry line.

Lacking temporal data, this study is unable to discern which process is actually responsible for the observed narrowing of the stabilized beaches relative to their natural counterparts. Using the knowledge gained from observation and interviews, the process by which the dry beach narrows may be suggested for a few sites. At fourteen sites (such as Punta Guaniquilla and east of Punta Cadena), loss of dry beach appears to be the result of passive or active erosion; while at five sites (such as Manzanillo and Santa Isabel), loss appears to be due to placement. Regardless of the process, the loss of the recreational dry beach is a detrimental consequence of the hard stabilization in Puerto Rico.

Likewise, narrower dry beaches (as defined by comparisons of dry beach widths) on stabilized shorelines have been found for the New Jersey, North Carolina, and South Carolina coasts (Wright and Pilkey, 1989), for retreating shores along the city of Gold Coast, Australia (McDougal and Patterson, 1985), and for the coastline of Marco Island, Florida (Reynolds, 1987). The loss of dry beach oceanward of structures on retreating shorelines is a widespread problem.

Beach Slope

Beach slopes as measured from the wet-dry line to a point at one meter depth below the wet-dry line (zl = -1.00m) are generally steeper on unstabilized beaches than on stabilized beaches (Figure 18). The apparently steeper slopes on the unstabilized sections are actually artifacts of data manipulation; specifically, of the initial depth (z0) used in the calculation of the slopes by the "depth-depth" method. The initial depth (the profile starting point) on unstabilized beaches was defined as the wet-dry line (z0 = 0). The initial depth on stabilized beaches was defined as either the wet-dry line (z0 = 0) or the depth at the toe of the structure (z0 < 0) if the toe of the structure was below the wet-dry line. The toe of many of the structures in Puerto Rico are well below the wet-dry line. The gentler slopes found for the stabilized beaches can be accounted for by the tendency of profiles to flatten seaward from the wet-dry line to chest deep water. In other words, the transects seaward of structures are sampling only the flatter, offshore portion of the profiles (Figure 19).

To more accurately compare the slopes on stabilized and unstabilized sections of the beach, slopes were calculated by an alternative method, which defined the starting point (x0) as some depth that is constant for all the profiles at a given site. The "depth-distance" method was chosen because it increased the distance (x0 to xl) to be used in the calculation of the slope. Presumably, this increased distance will provide a more accurate slope by eliminating local fluctuations in bottom topography. Wherever possible, the initial depth was chosen to be the wet-dry line (z0 = 0). If the wet-dry line was not available on all profiles, the starting point for all profiles was chosen to be the maximum elevation which was included in all profiles (where z0 < 0). The ending point (xl) was the maximum distance offshore included in all profiles. The slopes measured in this manner showed no trend or pattern in the steepness of the slope on unstabilized versus stabilized shorelines (Figures 20 and 21). This result lends support to Dean's idea (Dean, 1986) that "profiles fronting seawalls and natural beaches will be the same oceanward of the structure."

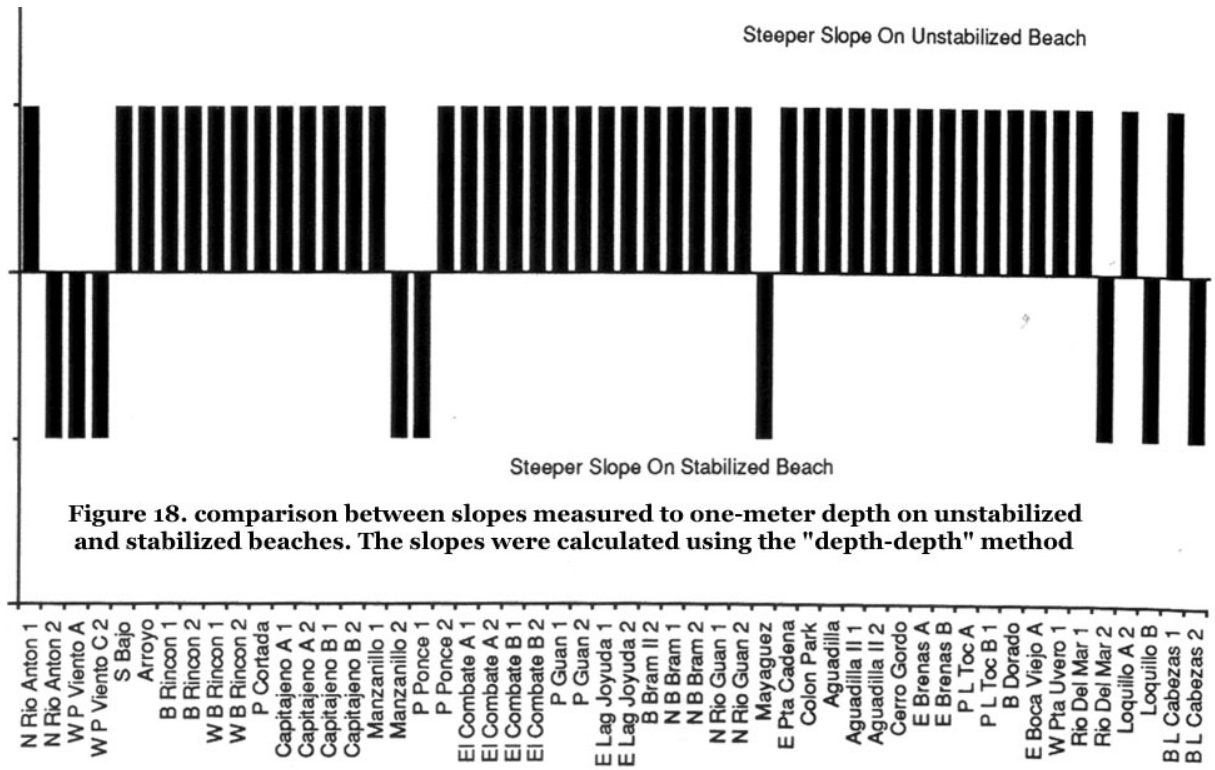
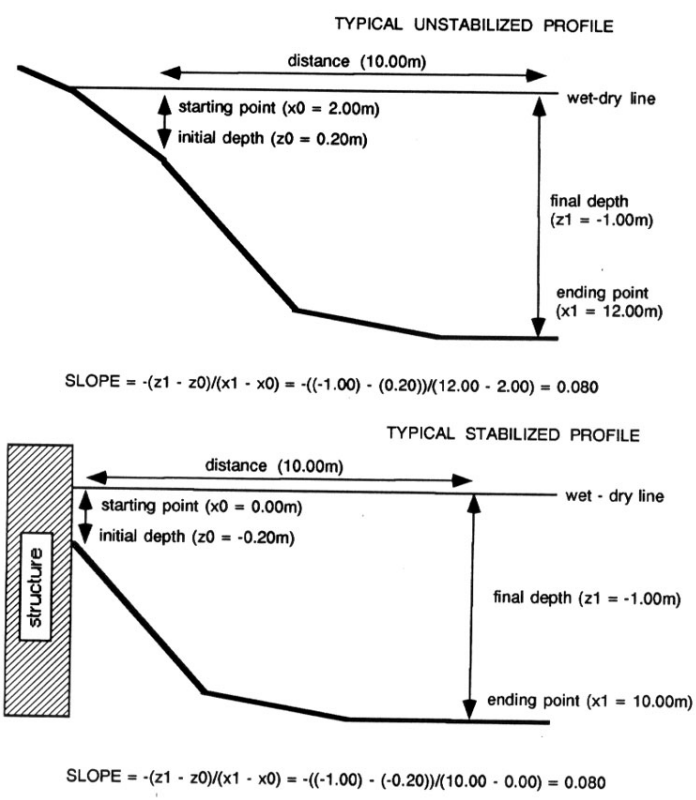


Figure 18. comparison between slopes measured to one-meter depth on unstabilized and stabilized beaches. The slopes were calculated using the "depth-depth" method

Profiles in front of structures undergo apparent "profile lowering" as the shoreface migrates landward (Figures 22 and 23). A structure forms a barrier against shoreline retreat. As shoreline retreat continues around the structure, the beach in front of the structure is essentially "pinched out" and becomes submerged. The profile seaward of the structure will reflect the gentler offshore slope of the natural shoreface, producing an apparent profile lowering.

Figure 19. slopes calculated by the "depth-depth" method are steeper on unstabilized beaches as compared to stabilized beaches due to the initial depths used in the calculation



End Around Effects

Coastal armoring also affects the beaches adjacent to structures. Once seaward of the natural wet-dry line, structures are able to influence the longshore sediment transport system. Sediment may be trapped by the structure on its updrift end, causing the beach downdrift to become sediment-starved. Lack of sediment will lead to erosion on the downdrift beach. An offset between the updrift and downdrift beaches and a new shoreline shape is the result. The difference between the updrift and downdrift offsets is dependent on the magnitude

of net drift and the length of time that stabilization at that site has been acting as a groin.

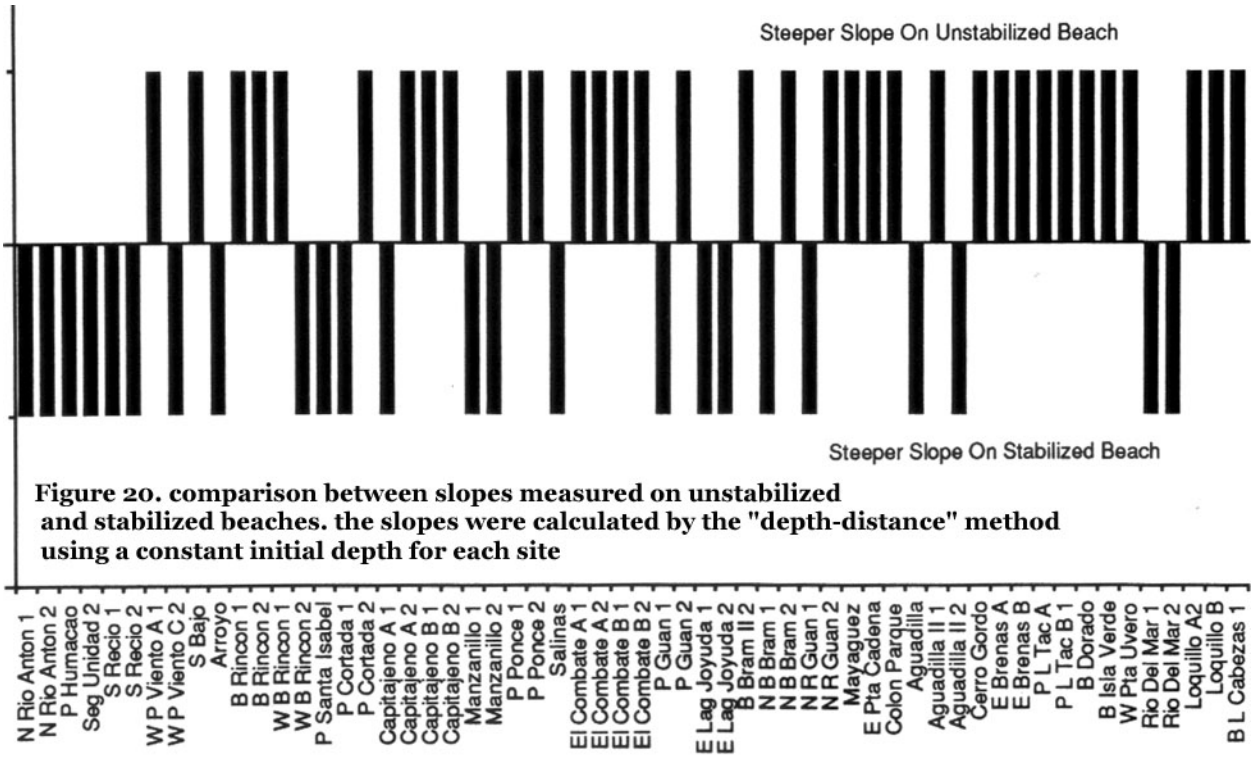
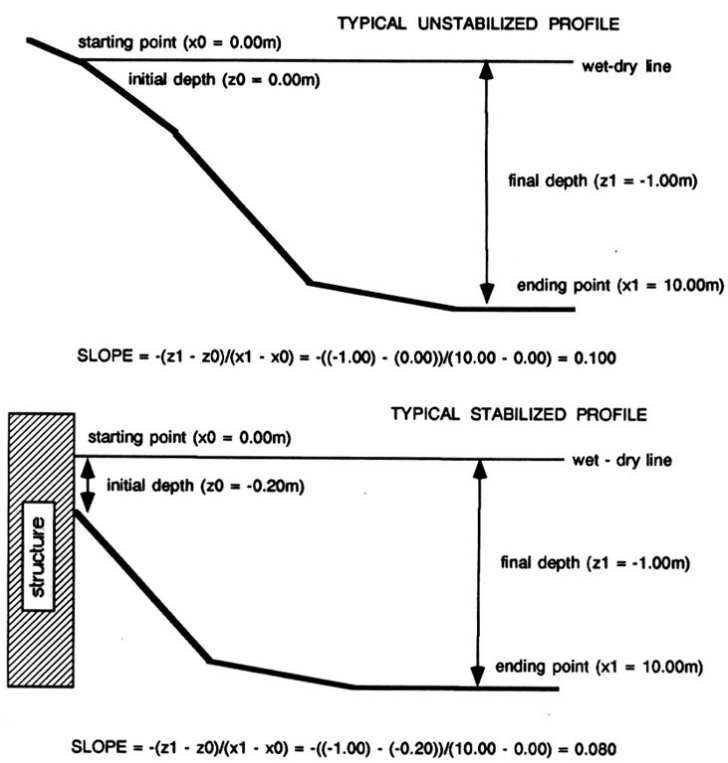


Figure 20. comparison between slopes measured on unstabilized and stabilized beaches. the slopes were calculated by the "depth-distance" method using a constant initial depth for each site

Figure 21. slopes calculated by the "depth-distance" method using a constant initial depth for each site



Offsets measured in Puerto Rico demonstrate that groining is occurring. The north, south and west coasts show similar trends of larger downdrift offsets (Figure 24). The lone noteworthy exception is at Rio Del Mar on the north coast, which may be the result of a local eastward current caused by the topography of the embayment. Groining is particularly prominent on the west coast, where locations at El Combate A, east of Laguna Joyuda, north of Bahia Bramadero and at Aguadilla II show differences between the updrift and downdrift offsets of over five meters. The great differences found on the west coast are most likely due to the strong transport of sand from north to south. The east coast has too few data points to be considered.

Figure 22. map view of the effect of a structure on beach topography

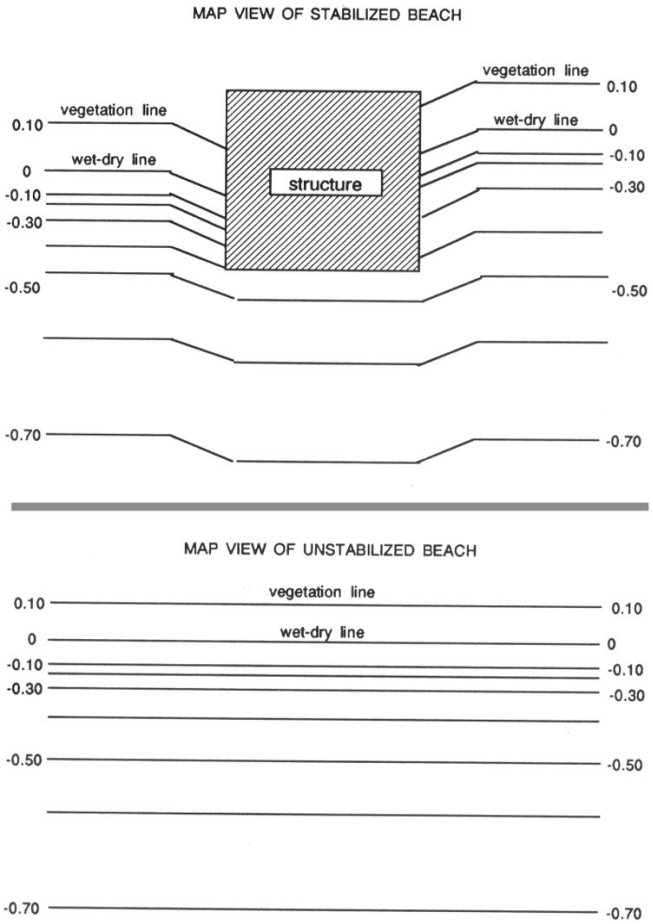


Figure 23. "Profile lowering" causes the landward end of the structure-backed profile to be sheared off as the shoreline retreats.

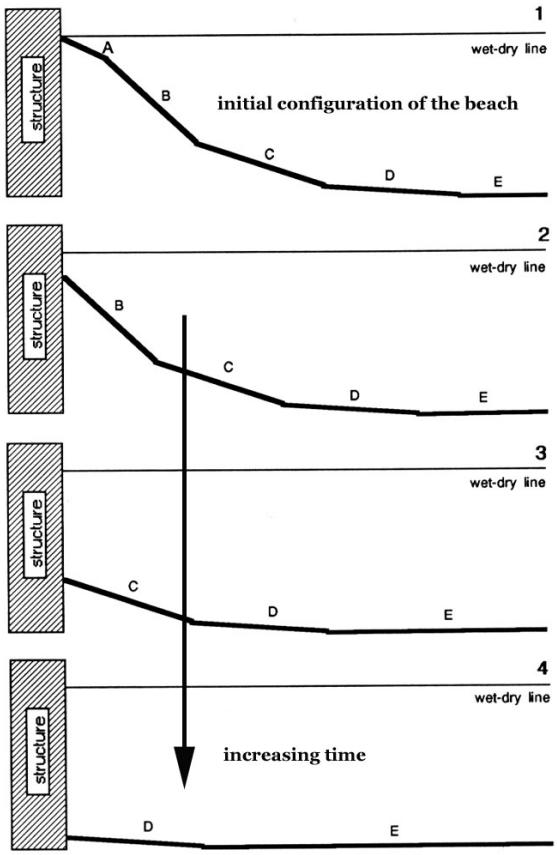
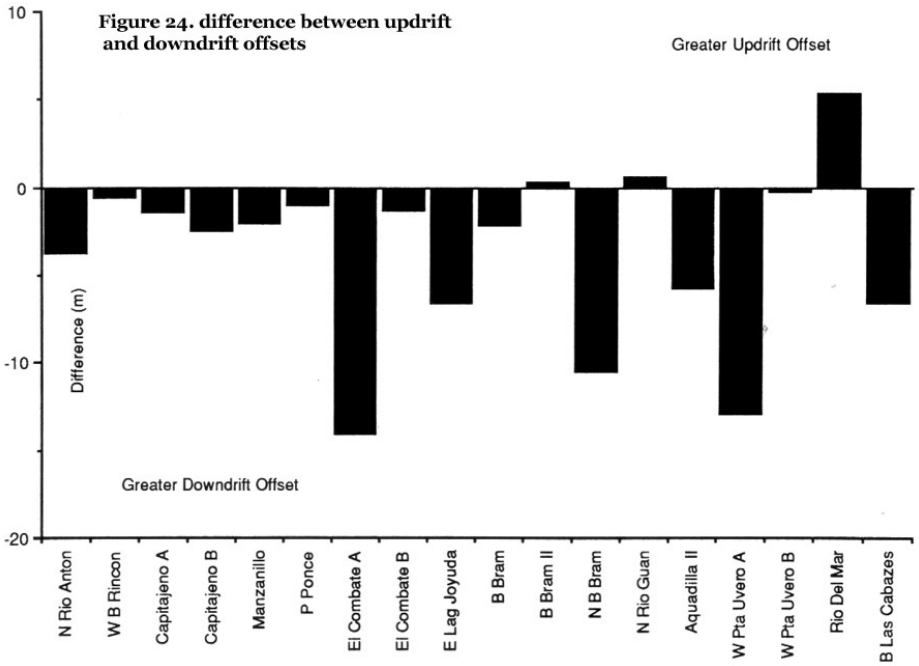


Figure 24. difference between updrift and downdrift offsets



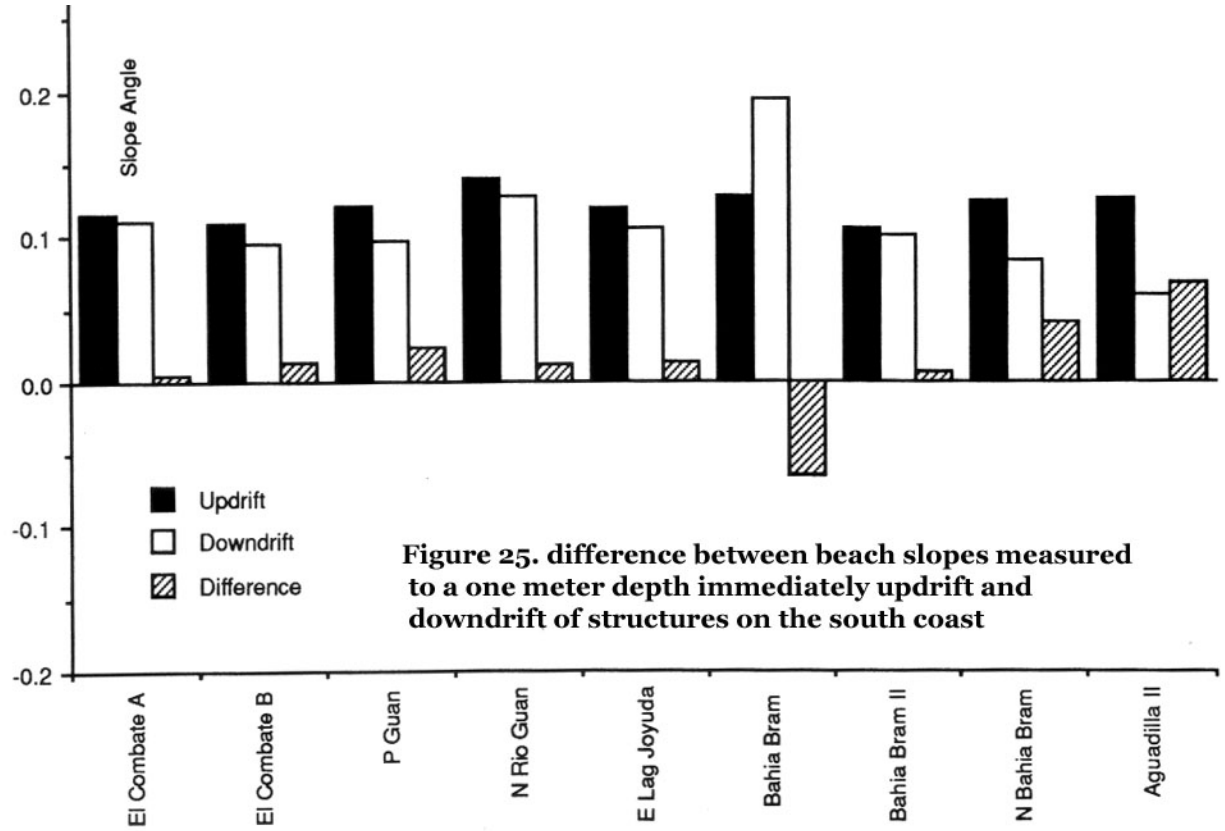


Figure 25. difference between beach slopes measured to a one meter depth immediately updrift and downdrift of structures on the south coast

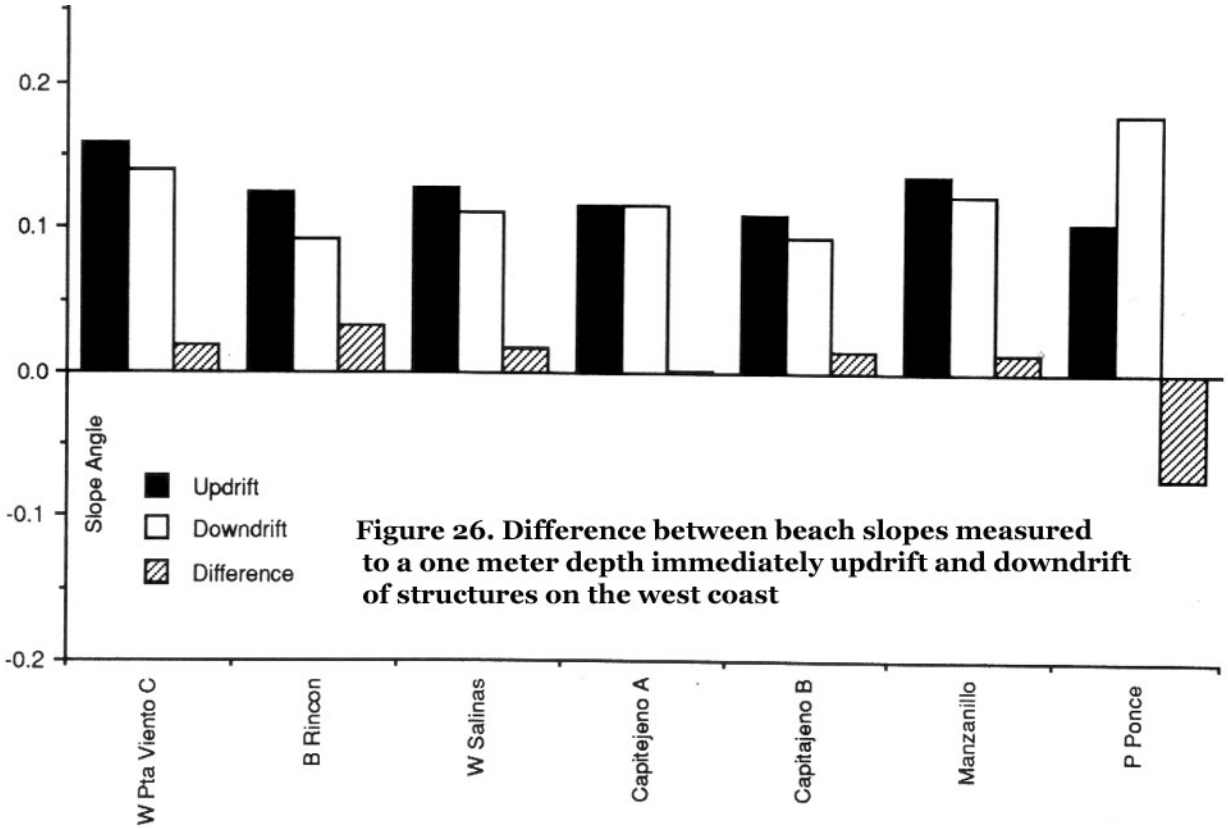
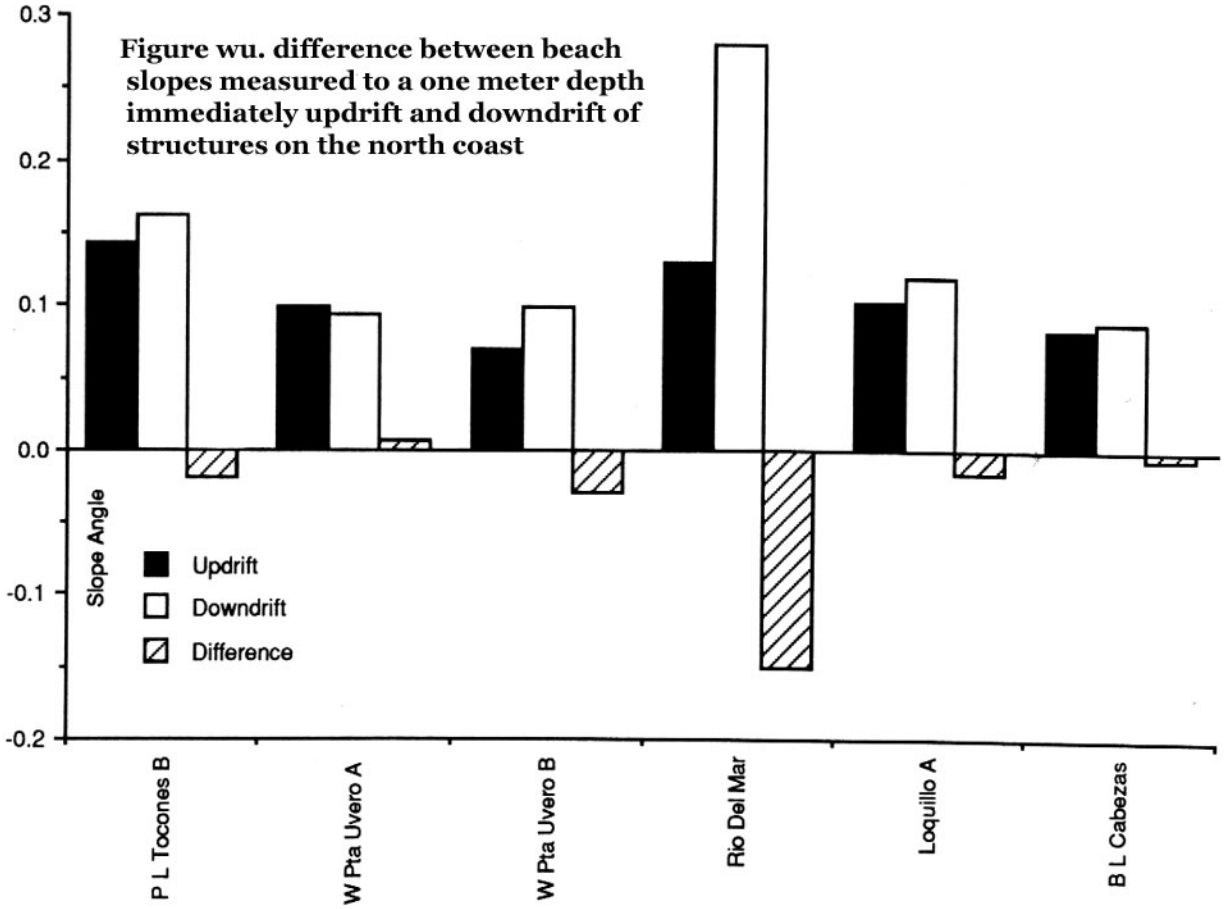


Figure 26. Difference between beach slopes measured to a one meter depth immediately updrift and downdrift of structures on the west coast

Slopes measured on the beaches near the ends of the walls show a consistent trend. The slopes on the south and west coasts tended to be steeper on the updrift side than on the downdrift side (Figures 25 and 26). This trend is most likely the result of groining. Groining causes an accumulation of sand updrift which steepens the profile. At the few locations measured along the north coast, an opposite trend is observed: the updrift slope is gentler than the downdrift slope (Figure 27). The slope at Rio Del Mar is consistent with the possible local eastward current suggested by the offset data. Located on the sides of small embayments, the other locations on the north coast may be affected by local topography and/or currents.



Toe Scour

Toe scour troughs in front of structures below the wet-dry line have often been observed (Sawargi and Kawaski, 1960; Kunz, 1987; Baba and Thomas, 1987). In Puerto Rico, noticeable toe scour troughs were found at only two locations. The toe scour trough was 0.30 meters deep at the site north of the Rio Anton Ruiz on the east coast and was 0.16 meters deep at the site at Aguadilla II on the west coast. At both locations, the toe scour trough was restricted to the downdrift end of the wall. A possible explanation is either the lack of sand downdrift due to a groining effect or the loss of normally available sand trapped behind the structure.

SOCIAL AND ECONOMIC ISSUES

The use of hard stabilization as the response to a retreating shoreline is a double-edged sword. It has the benefit of protecting the property landward of the structure; saving buildings constructed on the property (Many people interviewed favored construction of marinas as a form of hard stabilization as they would both protect property and be a savior for poor local economies. Of course the question is, how

many marinas can Puerto Rico support?). On the other hand, hard stabilization may degrade the beaches as well as incurring other adverse social and economic impacts.

Once hard stabilization is chosen as the response, it is difficult to switch to another alternative. The general public perceives the removal of a structure as expensive. In the long term, the effects on the shape of the shoreline, such as large offsets or complete loss of beach, may be impossible to remedy.

Hard stabilization tends to spawn continued lateral development. Additional structures are added to prevent offsets formed by a retreating beach. New structures of this type were observed under construction west of Punta Viento and at Playa De Los Tocones. Downdrift erosion caused by groining may also cause a "domino" effect with further armoring repeatedly added to prevent such erosion. The progressive, southerly advance of coastal armoring at Mayagüez is a classic example of the "domino" effect.

Hard stabilization degrades the recreational beach, a loss to the general public who use it. Degradation of the beach harms a key selling point for tourism, an important industry of the local coastal economy. The loss of the beach also forfeits a source of protection for the structure.

Hard stabilization provides access problems for recreational users, boaters and fisherman. The gabion at Aguada Parque De Colon is a good example. At this location, the boat ramps have failed. The steepness and height of the structure makes it difficult to go directly to the beach; the length of the structure makes it difficult to go around. The structure prevents fisherman from easily launching their boats and provides a barrier for their boats to be beached safely. The effect on fishermen is felt in the local coastal economy.

Hard stabilization must be maintained. Maintenance is costly and time consuming. Along the shores of Puerto Rico, structures in need of upkeep are a common sight. The stabilization at Punta Guaniquilla and east of Punta Cadena require repairs to prevent further undercutting.

Hard stabilization may be aesthetically unpleasing. The often used practice in Puerto Rico of constructing and maintaining structures with debris and garbage creates an eyesore. The reinforced concrete pushed to the shoreline of Mayagüez is certainly not attractive. The aesthetic value of the beach is a chief selling point for tourism.

Hard stabilization may cost more than the property it protects. The boulder revetment with backfill for a paved road at Manzanillo on the south coast and the stepped gabion of Playa De Humacao on the east coast both illustrate this point. At Manzanillo, the negative impacts are compounded because the structure is failing only six months after construction.

CONCLUSIONS

The conclusions of this study are the following:

- In Puerto Rico, the most common management response to the retreating shoreline is hard stabilization. Shore-parallel structures are found seaward of private property, coastal cities and major roads. Most structures are privately funded revetments and seawalls, often in disrepair. These small projects are usually constructed independently of adjacent structures.
- Along the coast of Puerto Rico, the effect of a shore-parallel structure is the degradation of the beach.
  - Dry beach width is narrower on stabilized shorelines than on unstabilized shorelines. The recreational beach is lost seaward of most structures.
- Where extending seaward of the wet-dry line, structures act as groins causing larger offsets downdrift than updrift. This difference is particularly true of the west coast.
- Beach slope at the updrift end of a structure is steeper than at the downdrift end due to the accretionary fillet at the updrift end.

· Profiles oceanward of the structure undergo "profile lowering." The landward end of the structure-backed profile is sheared off as the shoreline retreats. Seaward of the toe of the structure, stabilized and unstabilized profiles remain similar.

Advantages of shore-parallel structures along the coastline of Puerto Rico include:

· protection of property from daily waves if dry beach is absent.

· storm protection

Disadvantages of shore-parallel structures include:

· loss of the dry beach; important for both recreation and protection of the structure.

· increased erosion on adjacent beaches caused by groining or flanking; often necessitating further construction to remedy end around effects.

· permanent alteration of the shoreline shape.

· restricted access to the beach.

· costly and regular maintance.

· unpleasing aesthetics.

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