CHAPTER 158

DEVELOPMENT OF DESIGN CRITERIA FOR SEGMENTED BREAKWATERS

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ABSTRACT

This paper will discuss experience and approaches to the use of segmented breakwaters for beach erosion control in the United States. Several prototype cases are examined and generalizations drawn concerning the resultant beach response. This experience is further evaluated in order to develop a preliminary approach for developing design criteria.

INTRODUCTION

A shore parallel breakwater separated into segments is a viable and proven approach for protecting the shore. Such segmented breakwater projects have been constructed in various areas of the world (Bishop, 1982; Silvester and Ho, 1972; Toyoshima, 1972; Lesnick, 1979). Beach erosion control breakwaters have been designed and constructed as both single and segmented structures. In both cases the breakwater is built approximately parallel to shore with the intent of causing beach accretion. Breakwaters can range from structures that are very close to shore with sufficent elevation to prohibit overtopping, resulting in artifical headlands or tombolos, to those which are offshore submerged structures which cause bulges in the shoreline.

Whereas a single breakwater is usually built to protect a short, local section of beach, a segmented breakwater system has gaps in between and functions as a system to protect large portions of the shore. The purpose of this paper is to discuss the more complex, segmented system. A segmented breakwater system may promote the beach to accrete to the structure resulting in the formation of tombolos. In other situations, a series of sinuous bulges develop in the beach planform, called "salients." A particular system may form both salients and tombolos or evolve back and forth from one form to the other as local wave and water level conditions vary.

BEACH EROSION CONTROL IN THE UNITED STATES

United States shores include eroding sandy beaches, shores which may be innundated by coastal storms, heavily structured shores, eroding cohesive bluffs, and migrating beach forms such as barrier islands. Each beach which has erosion or flooding problems may be worthy of a

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different solution. Segmented breakwaters are not applicable in all situations. Beach erosion control plans or devices which work well in one place may not work elsewhere. The design intent of a segmented breakwater system may vary. For example, the purpose of the breakwater and the resultant beach response may be to preserve a recreational beach, halt erosion of the backbeach, or reduce storm surge induced flood damages.

Much of the United States shore is developed for recreational, residential, or commerical use. Public interest and shoreline use often dictate the need to design the erosion control solution to minimize downdrift impacts. Expected benefits to the shore to be protected have to be weighed against potential damages to neighboring shores. Beach fill placement is an important means of mitigating these damages, but its behavior is difficult to predict. When designing segmented breakwaters an accurate prediction of the beach response is necessary in selecting the structure configuration. A review of previously constructed segmented breakwater projects provides insite into developing this ability.

SEGMENTED BREAKWATER PROJECTS IN THE UNITED STATES

Experience in the United States with segmented breakwaters has been limited to littoral sediment-poor shores which are characterized by a local fetch-dominated wave climate. Thus these projects typically experience short period, steep waves which tend to approach the shore with only limited refraction, and therefore tend break at a steep angle to the shore. These projects also tend to be in areas which are prone to storm surges and erratic water level fluctuations, particularly the Great Lakes projects.

Table 1 is a summary of the seven breakwater projects in the United States which were assessed in this study. Figure 1 displays the geographic location of each of these projects. Four of these projects are on Lake Erie in the Great Lakes. This does not necessarily mean that these projects are located in "protected waters," as both Presque Isle and Lakeview Park have experienced significant storms accompanied by storm surges in excess of 1 meter. The two projects in the Atlantic coastal area are in relatively protected areas. Only the Holly Beach project can be considered as on the "open" ocean coast.

Most of these projects have been monitored and reported on elsewhere in the literature (Pope and Rowen, 1983; Pope, 1985; Gorecki, 1985; Bender, 1985; Dean, Pope, and Fulford, 1986; Nakashima, et al., 1987). Only the East Harbor and Winthrop Beach projects have not been monitored. The typical monitoring program consists of the acquisition of beach response and some process information for a period of 2 to 5 or more years after initial construction. Full evaluation of the monitoring data is still continuing for most of these projects. However, in all cases, including those projects which have not been subjected to a formal monitoring program, the development of a characteristic equilibrium beach planform and the general impact on the littoral regime can be determined. The brief review which follows on each project will describe the project parameters and beach response.

Table 1. Summary of United States Segmented Breakwater Projects

Table 1

SUMMARY OF U.S. BREAKWATER PROJECTS

Project	Location	Coast	Date of Construction	Number of Segments	Project Length (Lp)	Segment Length (Ls)	Gap Length (Lg)	Distance Offshore Preproject	Distance Offshore Effective ($\bar{X}$)	Water* Depth (ds)	Fill Placed	Beach** Response
Winthrop Beach (Low Tide)	Massachussetts	Atlantic	1935	5	625m	91m	30m	unknown	80m	3.0m (mlw)	No	1
Winthrop Beach (High Tide)	Massachussetts	Atlantic	1935	1	625	625	0	305	205	5.7 (mhw)	No	3
Lakeview Park	Ohio	Lake Erie	1977	3	403	62	49	137	85	3.8	Yes	4
Presque Isle (Low Water)	Pennsylvania	Lake Erie	1978	3	440	38	60,91	46	20	1.2	Yes	2-3
Presque Isle (High Water)	Pennsylvania	Lake Erie	1978	3	440	38	60,91	46	30	1.7	Yes	3
Colonial Beach (Central Beach)	Virginia	Atlantic	1982	4	427	61	45	64	20	1.7	Yes	2
Colonial Beach (Castlewood Park)	Virginia	Atlantic	1982	3	335	61,93	26,40	46	20	1.1	Yes	1
Lakeshore Park	Ohio	Lake Erie	1982	3	244	38	60	120	100	2.2	Yes	5
East Harbor	Ohio	Lake Erie	1983	4	550	46	90,105,120	170	170	2.3	No	5
Holly Beach	Louisiana	Gulf of Mexico	1985	6	555	47,53	93,89	64	61	2.5	No	4

* Datum used is local average water depth at structure location during the period of post-construction monitoring (unless otherwise stated).

** Beach response is coded as follows:
1 - permanent tombolos
2 - periodic tombolos
3 - well developed salients
4 - subdued salients
5 - no sinuosity

Local conditions make each project unique and the design nontransferable to another site. However, by reviewing the structure configuation and planform response, a pattern of project effectiveness has been identified which can be used to develop some general design guidance. A more detailed summary of most of these projects appears in Dally and Pope, 1986.

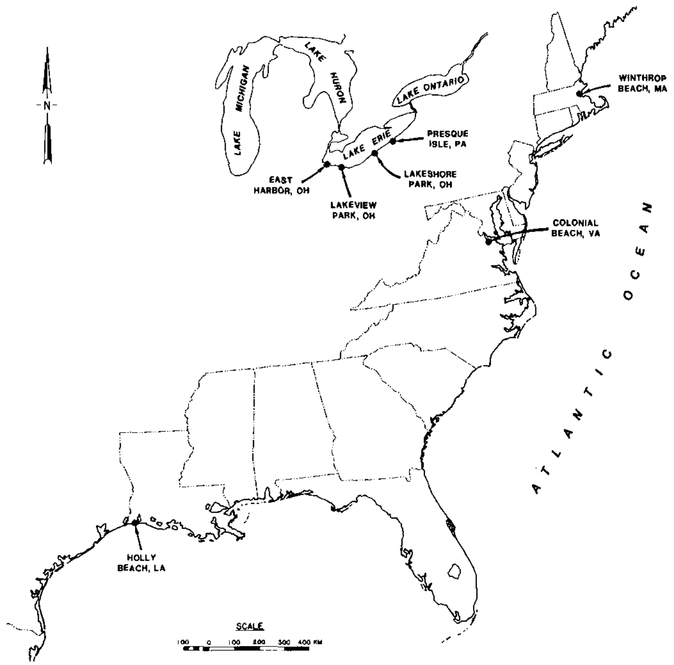

Figure 1. Location Map for United States Segmented Breakwater Projects

Winthrop Beach

The Winthrop Beach project was built in 1935. It consists of five breakwater segments separated by very small gaps. It was built 305 m off of the backbeach seawall and is in an area which experiences an approximately 2.7-m tide range. No beach fill was placed (Magoon, 1976). During high tide the five segments behave as one breakwater, resulting in a single, well developed salient. However, during low tide, individual tombolos are exposed behind several of the segments resulting in low tide headlands (Dally and Pope, 1986). This project has effectively trapped material out of the littoral regime resulting in a stable salient and tombolos along a shore which otherwise lacks a subaerial beach.

Lakeview Park

The Lakeview Park project consists of three breakwater segments, two terminal groins, and a placed beach fill (Walker, Clark, and Pope, 1981). It was constructed in 1977 and formally monitored for 5 years. The monitoring program consisted of semi-annual bathymetric and topographic surveys, three sets of aerial photography each year, annual sediment sampling, Littoral Environment Observations (LEO) made daily by a local volunteer to document the nearshore wave and current conditions, periodic project inspections, and a limited current measurement study and wave gage data collection. The structures have successfully established a stable beach headland along an otherwise sandless coast (Pope and Rowen, 1983). Once the project had established an equilibrium beach planform in response to the structure configuration, the range of wave and water level conditions only caused minor variations in the shoreline. The beach planform at Lakeview Park remained fairly stable within a limited envelope (Figure 2). There is some minor response to seasonal conditions. In particular, during the low water of the fall, the beach tends to exhibit three discernable, although subdued salients. During the high water of the spring, the beach typically will have only two subdued salients and a slight "hip" behind the western-most breakwater. As there is a strong asymmetry to the local wave climate with most of the wave energy out of the west, the west end of the beach retreated. Active transport of the native littoral material continues from west to east, through the project. However, the overall quantity of sand in the lee of the breakwaters has gradually increased through time. Over the five years of monitoring, the project gained approximately 3000 cubic meters of material per year (Pope and Rowen, 1983).

Presque Isle

The Presque Isle segmented breakwater project was built in 1978 as a prototype experiment to determine if breakwaters could be used to retard the erosion of a very large (approximately 10-km long) recurved sand spit which has been the target of various attempts at beach erosion control for over 150 years (Pope and Gorecki, 1978). Three segments were constructed and beach fill was placed. The beach exhibits some seasonal variablity resulting in two characteristic planforms, primarily responding to changes in the water level and the resultant degree of structure overtopping during storm events. During low water levels and low wave energy conditions, a tombolo sometimes forms behind the western-most (updrift) segment with two downdrift salients behind the other segments. However, during high water levels or after significant storms the tombolo is severed from the segment, resulting in three distinctive salients (Figure 3). The amount of sediment behind the breakwaters has remained fairly stable, despite an evolutionary trend toward offshore deepening (Gorecki, 1985).

Colonial Beach

Two segmented breakwater projects were built at Colonial Beach, Virginia on the Potomac River estuary in an attempt to build recreational beaches and protect a public highway which had frequently been

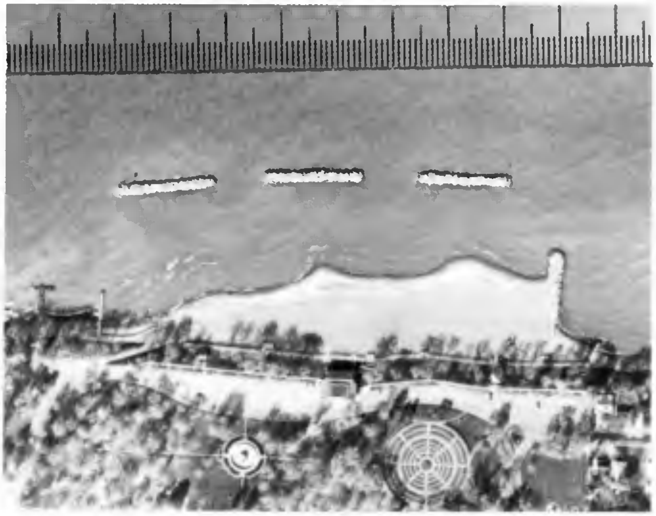

Figure 2 . Aerial Photograph of Subdued Salients at Lakeview Park, Lorain, Ohio

Figure 3. Aerial Photograph of Well-Developed Salients at Presqu Isle, Erie, Pennsylvania During Higher Water Levels

damaged by erosion (Dean, Pope, and Fulford, 1986). Central Beach consists of four segments and Castlewood Park consists of three segments plus a downdrift terminal groin. Beach fill was placed at both locations. The breakwaters in both projects were built fairly close to shore with small gap to segment length ratios (Table 1). Thus the breakwaters functioned as efficient traps which gained material from the littoral system (approximately 2000 cubic meter per year per project). The beach at Castlewood Park has been relatively inactive. Tombolos quickly formed and have remained as stable features. Central Beach is slightly more dynamic with an apparently stable tombolo behind the second segment from the updrift end and well-developed salients behind the other three segments (Figure 4). Between the salients and the breakwater segments there are very narrow channels of open water. The breakwater crest elevation is low enough that moderate storms will cause overtopping of the structure. Dye studies conducted at Central Beach suggest that even this very narrow section of open water behind the segments is important in allowing alongshore transport within the project and in releasing any hydraulic head which may otherwise be created within the compartment during a storm surge.

Lakeshore Park

The Lakeshore Park project is a three-segment structure built in 1982 at Ashtabula, Ohio on Lake Erie (Bender, 1985). Within a very short period of time after construction the placed beach fill shoreline began to retreat. The beach has continued to erode as material is lost alongshore. There is very little suggestion of sinuosity in the beach planform (Figure 5). The tendency for erosion may be partially due to the fine grain size of the beach fill, but the lack of morphological response in the shoreline suggests that the structures are too far offshore to significantly reduce the inshore wave climate and prevent erosion.

East Harbor

Four segments were constructed at East Harbor, Ohio in 1983 to protect and restore a recreational beach. No beach fill was placed and, as this is an area of low sediment supply, the project will mature slowly. High lake levels, poor sediment supply, and a structure location approximately 180 m offshore, have combined to result in the beach planform which is fairly unresponsive to the structures.

Holly Beach

In late 1985, a six-segment breakwater system was built along the erosion and hurricane prone Louisiana coast of the Gulf of Mexico to protect a highway which has frequently been damaged. One segment is rubblemound and the other five segments are built out of various geometries of timber-pile rows with tires stacked over the piles (Nakashima et al., 1987). The tire-and-pile breakwaters tend to have a higher coefficient of wave transmission than the rubblemound structures which have been used at the other project sites reviewed during this study. Salient formation occurred rapidly even though no fill

Figure 4. Aerial Photograph of Periodic Tombolo Formation at Central Beach Colonial Beach, Virginia

Figure 5. Oblique Photograph of Non-sinuous Beach response at Lakeshore Park, Ashtabula, Ohio

had been placed. Initial salient formation occurred at the two ends of the project as sediment was driven into the protected section of shore from either direction. The rubblemound breakwater has created a low-tide tombolo but the tire-and-pile breakwaters exhibit various salient morphologies in response to the wave transmission characteristics of each segment. The higher transmission segments tend to cause more subdued and blunted salients. The lower transmission segments (including the rubblemound) are backed by better defined, more peaked salients.

CLASSIFICATION SCHEME FOR BREAKWATER PROJECTS

In order to develop design criteria for segmented breakwaters, the desired beach response must first be identified (Dally and Pope, 1986). There are specific implications to beach use, degree of protection and effect on the littoral regime associated with tombolo formation. Salient formation may result in a more aesthetic and naturally behaving recreation beach with fewer adverse impacts on the littoral regime, but salients are usually not as stable and therefore tend to be less effective in providing permanent, reliable protection to the backbeach. The amplitude of the salient sinuosity (i.e., well-developed verses subdued) has important implications on the shoreline retreat behind the gaps. In general, the more sinuous the shoreline, the more stable it will be during times of increased wave action.

Beach response characteristics which need to be considered in developing the design are: the resultant beach width and planform (the presence of tombolos or salients); the amount and rate of sediment trapping from the littoral regime including regional impacts; the sinuosity of the beach planform; the beach profile slope and uniformity along the length of the project beach; and stability of the beach despite seasonal changes in wave activity, water level, and storms.

Beach response is a direct result of the amount of wave energy reaching the lee of the breakwater segments. A classification scheme has been developed based on the beach planforms which have been observed in the described projects (Figure 6). The subject projects are ranked relative to a classification scheme where the lowest wave energy in the lee of a breakwater projects results in tombolo formation. Projects in which high wave energy reachs the shore tend to have little or no sinuosity. The five beach response planforms used in this classification scheme follow:

(a) PERMANENT TOMBOLOS - In this case, very little wave energy reaches the shore and the protected beach is stable. There is very little transport along the shore. Littoral transport maybe displaced into deeper water, seaward of the structures. Castlewood Park at Colonial Beach exhibits this planform.

(b) PERIODIC TOMBOLOS - One or more segments are periodically backed by tombolos. This is primarily due to variablity in the wave energy reaching the lee of the individual segments. In the classification scheme developed here, periodic tombolos may be either unstable or stable through time, or the planform maybe variable through the

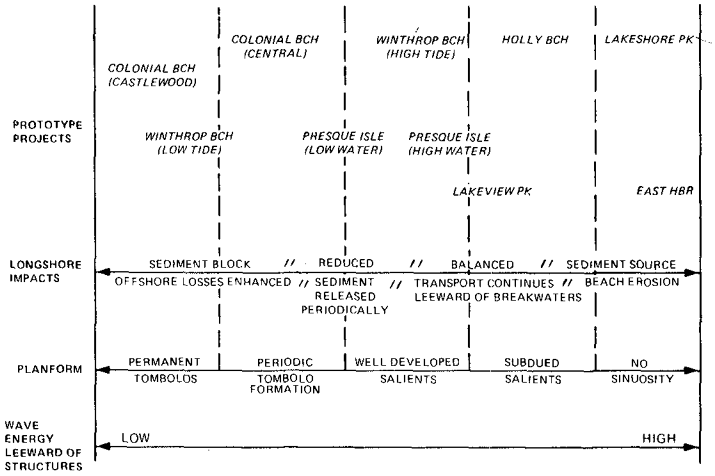

Figure 6. Proposed Classification Scheme for Segmented Breakwaters Based on Beach Response

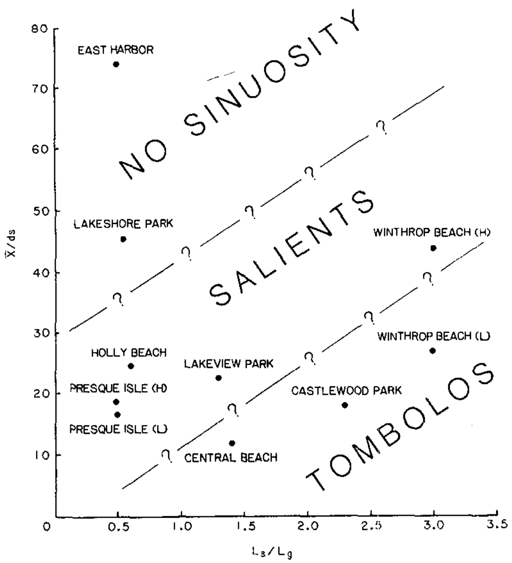

Figure 7. Dimensionless Plot of United States Segmented Breakwater Projects Relative to Structure Configuration.

project length. During high wave energy, tombolo(s) may be severed from the structure resulting in a salients. During low wave energy periods sediment accretes and the tombolo returns. The longshore effect of this type of planform may be periodic trapping of littoral material followed by a release of a "slug" of sediment. Even in a relatively stable project, only some segments may be backed by tombolos, due to alongshore variablity in the amount of energy behind the breakwater system. Presque Isle, during low water, provides an example of periodic tombolos which are unstable. Central Beach at Colonial Beach is an example of periodic tombolos which are stable (Figure 4).

(c) WELL-DEVELOPED SALIENTS - The well-developed salient beach planform occurs when higher wave energy reaches the lee of the structure and is characterized by a balanced sediment budget. Well-developed salients are not apparent until sufficient time has passed for the project shore to stablize relative to the structure configuration. Longshore moving material enters and leaves the project at approximately the same rate. In addition, rip current development within the gaps is unusual and very little material is lost into the offshore. Presque Isle, during high water, exhibits the characteristics of this planform (Figure 3).

(d) SUBDUED SALIENTS - In this case, the shoreline sinuosity is not as obvious, and amplitude of the salient is of lower relief. The project beach may periodically store and release sediment. Although the quantity of material retained in the project may remain generally balanced through time, there will be periods of increased loss or gain and the uniformity of the beach planform is not as assured. Holly Beach and Lakeview Park are examples of this classification (Figure 2).

(e) NO SINUOSITY - If high wave energy reaches the beach, including the area directly behind the segments, the beach planform may not mirror the presence of the segments. Placed beach fill may actually serve as a source of material for downdrift beaches. Although there may be some minor trapping of material from neighboring shores, the characteristic shoreline morphology is missing. Lakeshore Park is an example of a nourished beach and East Harbor is an example of an unnourished beach which illustrate this classification (Figure 5).

PARAMETERS EFFECTING BEACH RESPONSE

The forementioned classification scheme subdivides the observed beach responses into a morphological hierarchy which reflects the level of wave energy which reaches the lee of the structure. The wave energy reaching the lee of the structure (E) may be considered to be a function of the incident wave energy at the structure (W*), the structure configuration or planform (S*), and the wave transmission characteristics of the structure cross section (T*) or;

$$E = f\ (W^*,\ S^*,\ T^*).$$

Incident wave energy, is the wave climate at the structure and the result of transformation of the deepwater wave climate (height, period, and angle) over the nearshore bathymetry. Variability of the wave climate will have a significant effect on stablity of the beach planform. As most segmented breakwater projects are built in shallow water, incident wave energy is frequently directly controlled by the local water depth (ds) and its variablity. The wave climate which drives the characteristic condition of the beach is the "average" wave condition rather than the extreme. A severe storm may erase the beach planform but a structure configuration which is designed for this event will probably not display the desired beach planform on a daily basis.

Structure configuration is the density of protection provided by the structure plan and is defined through several parameters: the segment length (Ls), gap length (Lg), project length (Lp), number of segments, and the distance offshore. The offshore distance is a parameter for which there are several possible definitions. The distance offshore may be described either as the distance off the original pre-project shore or as the distance between the placed beach fill shore and the structures. Neither definition is really a true indicator of the amount of open water over which the transmitted wave energy must be distributed within the lee of the structures. The averaged distance of the structure from the effective shoreline ($\overline{X}$) may be somewhat different due to the artificial advance of the shore by the addition of groins or beachfill.

Transmitted wave characteristics are a result of the amount of incident wave energy which is transmitted into the project lee either through or over the structure crossection. The structure crest elevation controls the amount of overtopping wave energy. The permeablity of the structure cross-section controls the efficiency of the structure in absorbing incident wave energy.

Although a basic assumption of this paper is that wave energy in the lee of the structure controls beach planform, sediment characteristics of the natural littoral regime and the placed fill are also significant in influencing the eventual beach response. The quantity of material available and grain size of the sediment is important in influencing the rate at which the project reaches maturity and the eventual profile slope. Theoretically there is also a relationship between the grain size of the littoral material and the stablity of that material when exposed to various levels of wave energy. However, stablity of various grain sizes under a particular longshore transport potential is here considered as a second-order design factor.

APPROACH FOR DEVELOPING DESIGN CRITERIA

Prototype experience with the described breakwater projects and the relationship between beach response and wave energy in the lee of the structures is used to develop an approach for designing segmented breakwaters. These criteria are based on both experience and an appraisal of coastal processes.

In order to relate the beach response classification scheme to a single measure of the project wave energy, E, each factor which controls E was explored. Although E is a function of three basic parameters, only structure configuration, S*, could be tested using prototype data. The number of prototype projects available to test any approach are very limited as was the data available on each project, particularly regarding incident wave energy, W*. However, a review of the projects suggested that although incident wave climate, W*, was different from project to project, all were located in low to moderate wave environments dominated by steep, local wind fetch generated waves. In each case, the wave transmission characteristics of the structure crossection, T*, did influence the variablity of the shoreline envelope around an average beach planform. However, only the pile-and-tire breakwaters of the Holly Beach project allowed enough wave transmission during non-storm periods, to modify the beach planform from segment to segment.

A number of dimensionless parameters were evaluated in order to test the influence of S* on the beach response characteristics. Figure 7 displays the relationship between all prototype projects relative to two dimensionless parameters. The ratio of segment length to gap length, Ls/Lg, was found to be an excellent parameter for defining the capability of the structure plan to block incident wave energy. The ratio of the average distance of the structures from the effective shoreline to the average water depth at the structures, $\overline{X}$/ds, represents the influence of the structure location in effecting shoaling and diffraction of the incident wave energy. Water depth at the structures, ds, limits the amount of wave energy which can enter through the gaps (i.e., controls the breaking wave height. The distance between the effective shoreline and the structures, $\overline{X}$, implies where the shoreline intersects the diffracted wave pattern.

The projects plotted in Figure 7 display a grouping which may illustrate fields of a predictable beach planform response for low to moderate wave climates. Figure 7 displays, in effect, the inverse of the average post-project slope relative to the segment-to-gap ratio. This is an exploratory effort which may be of interest to the coastal scientist who is selecting a breakwater plan. This is not, however, a final result and much testing of this premise is needed.

FUTURE WORK

Verification and testing of the classification scheme, the relationships discussed, and the fields suggested by Figure 7 are planned. Although additional prototype data will be sought, such data are difficult to attain and are often complicated by site specific parameters. A generalized shoreline response numerical simulation model (Hansen and Kraus, in preparation) will be used to extend the prototype data presently available. Individual prototype cases will be modelled. The dimensionless relationships suggested by Figure 7 and other parameters will be varied to explore the sensitivity of the beach planform to those parameters which affect wave energy in the lee of structures.

SUMMARY

A classification scheme was developed to summarize the stablized, or average, beach planform observed for eight segmented breakwater projects in the United States. Data and monitoring results are presented for each of these projects. An assessment of these projects suggests that beach response is directly related to the wave energy which reaches the lee of the structures. Wave energy in the lee of the structures is a function of the incident wave energy, the structure plan or configuration, and the wave transmission characteristics of the structure crossection. Prototype data is displayed relative to dimensionless parameters which suggest a correlation between the beach slope, segment plan, and beach planform.

This paper attempts to simplify the complexities associated with segmented breakwater design into some generalized design criteria. However, individual projects present a number of site specific limitations which restrict the application of generalized "rules of thumb." The summary presented here is an attempt to translate prototype experience into a form which may help in project planning. The use of physical and numerical models which have been adapted for the specific conditions of the project site are recommended for detailed design.

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