DEFENSE OF SHORELINES
BY
STRUCTURAL APPROACHES
by
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1. INTRODUCTION

Structural approaches can be employed to stabilize shorelines against erosion, to provide sheltered areas for swimming or for a myriad of other benefits. In this section, the emphasis will be on shoreline stabilization although much of the information and discussions presented would be equally applicable to accomplish other objectives. Three general types of structures are discussed in this treatment of defense of shorelines: (1) detached breakwaters, (2) groins, and (3) armoring. Artificial headlands and perched beaches will be considered herein as a subclass of detached breakwaters. It should be noted that each of these structure types can be employed for stabilization purposes in conjunction with beach nourishment. The sections below discuss each of the types.

2. DETACHED BREAKWATERS

Although not completely descriptive, detached breakwaters as discussed here will include those which due to their length and proximity to the shoreline become attached to the shoreline, thereby forming a "tombolo". This type of structure has been of substantial interest to many investigators due in part to their wide usage and the opportunities provided to "architect" the shoreline and to retain sand placed in conjunction with beach nourishment. There are reportedly some 2500 detached breakwaters in Japan.

Figure 1 illustrates a detached breakwater. These structures can be emergent or submerged. Their primary purpose is to provide wave sheltering of the beach, thereby reducing the sand transporting capacity of the waves and causing a wider beach than would otherwise be present. Several aspects of detached breakwaters are discussed in the following sections.

2.1 Critical Conditions for Attachment

The critical conditions governing attachment of a breakwater to a shoreline have not been established definitively. Certainly the closer the breakwater to the shoreline relative to its length, $l$, the more likely the occurrence of attachment. Considering the diffracted wave fronts to be represented by quarter circle
Figure 1. Schematic of a Single Detached Breakwater

Figure 2. Non-Dimensional Salient Value versus Non-Dimensional Breakwater Length. From Hsu and Silvester (1990).
segments, one can easily develop the following simple criterion for attachment

\[
\frac{s}{l} \leq 0.5
\]  

(1)

This relationship may be considered as a first approximation; however, the actual conditions also depend on beach profile and wave height and direction characteristics and several other factors.

Hansen and Kraus (1990) employed a numerical model (GENESIS) to evaluate conditions which would result in various depositional types in the lee of a single detached breakwater. The results were found to compare favorably with field data. It is stated that there are at least 14 parameters controlling the depositional form. Of particular interest is the inclusion of wave transmission as could occur over a submerged breakwater or wave penetration through a permeable breakwater. The conditions for a tombolo to form were determined to be

\[
\frac{l}{L} \leq 11(1-K_r) \frac{H_o}{h_s}
\]  

(2)

in which \( L \) is the "local" wave length presumably evaluated at the breakwater, \( H_o \) is the deep water wave height, \( h_s \) is the water depth at the breakwater, and \( K_r \) is the transmission coefficient past the breakwater. It is surprising that this result is independent of the breakwater separation distance, \( s \), from the shoreline.

2.2 Single Detached Breakwaters

Hsu and Silvester (1990) have analyzed laboratory and field data representing a single detached breakwater and have developed empirical relationships between the non-dimensional separation distance, \((S-X)/\ell\), and the non-dimensional breakwater length, \(\ell/s\), as shown in Figure 2. Although the fit between these variables appears good, it is not clear that the prediction of tombolo attachment is an improvement over other approaches. Two empirical fits were made to the data in Figure 2. One of these fits resulted in no tombolo formation and the other predicted tombolo formation when \( s/\ell \approx 0.2 \), much smaller than normally considered.
2.3 Multiple Detached Breakwaters

Pope and Dean (1986) assembled data from ten segmented breakwater projects in the United States and proposed a classification scheme which ranged from tombolos to salients to no sinuosity as shown in Figure 3. The dominant controlling parameters were found to be the ratio of effective distance offshore to water depth at the breakwater, \( s/h \), and the ratio of segment length to gap length, \( l_s/l_g \). Although there is some uncertainty as to the boundaries of the three regions, the general effects of the identified parameters are evident in Figure 3.

![Figure 3. Classification For Various Shoreline Forms Behind a Detached Breakwater. From Pope and Dean (1986)](image)

Suh and Dalrymple (1987) carried out model tests in a spiral wave basin to investigate shoreline response to multiple breakwaters. The resulting data were combined with other lab and field data to predict the salient projection, \( X \), and the volume deposited, \( V_d \), as a result of the breakwater. The following results were developed results were
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\[
X = 14.8 s \left( \frac{t_s^2}{K_s^2} \right)^{-2.83} \left( \frac{t_s}{K_s} \right)^{5.5}
\]

and

\[
V_d = \frac{am^2X^2}{4}
\]

in which \(a\) is a factor found to be approximately 2.0 and \(m\) is a representative beach slope.

2.4 Effect on Longshore Sediment Transport

The question of the effect of detached breakwaters on the longshore sediment transport system is relevant to the stability of the adjacent beaches. Considering the idealized case of waves approaching at a constant oblique direction and the formation of a protuberance or "bulge" in the shoreline, leads to the following conclusion. The breakwater will cause the updrift shoreline to continue to accrete and the downdrift shoreline will continue to erode at the same volumetric rate as the updrift accretion. This is based on the Pelnard Considere (1956) solution for the case of a single shore perpendicular structure for constant wave direction in which regardless of the structure length, the updrift and downdrift shorelines continue indefinitely to accumulate and lose sand respectively, albeit at a decreasing rate as time progresses. In fact it is surprising that according to the Pelnard Considere theory, the amount of sand stored on the updrift shoreline approaches infinity as time approaches infinity! Counter arguments have been advanced that a detached breakwater will cause a longshore current which will result in the updrift volume impoundment reaching an equilibrium; however, this result does not appear to be documented.

Considering the more realistic case of variable wave direction, the net effect on longshore sediment transport is not so evident. Two subcases could be considered, one in which the waves arrive from a range of directions which all contribute to the same transport direction and the second in which the wave directions produce varying transport directions, but with a finite net transport. In the first case the transfer around the breakwater would occur in a more variable fashion than without a changing wave direction. Perhaps this problem could be addressed through a careful application of numerical modelling. Although this question must still be regarded open, this author believes that the correct answer for each subcase is a variation of that obtained by Pelnard Considere for constant wave direction; that is, the updrift volume deposited would approach infinity with time.
2.5 Artificial Headlands

Artificial headlands are structures which anchor the shoreline usually in a sediment deficient area and, through interaction of the incoming wave field, can result in a variety of planforms. The planforms have been given several names including: crenulate bays, spiral bays, half-heart bays and others. As is the case with other types of coastal structures, this type has natural analogues which probably have contributed to their interest. An idealization of an artificial headland with a predominant oblique wave direction is presented in Figure 4.

Artificial headlands have been studied by Yasso (1965), Silvester (1970), Silvester and Ho (1972), and Rea and Komar (1975), among others. To the first approximation, the associated beach planforms may be considered as parallel to the wave fronts as affected by diffraction and refraction. Segmented breakwaters, each with a tombolo connection to shore are artificial headlands. Depending on the wave direction, magnitude of sediment transport and the headland geometry, a range of planforms can ensue as can be imagined by considering the shapes of the modified wave fronts.

Silvester and Ho (1972) have combined data from the laboratory and field for the ratio of indentation to gap between headlands as shown in Figure 4. Considering the ambient longshore sediment transport to be zero, and a simple wave pattern in which the diffracted crests in the "shadow zone" are circular arcs and are unaffected in the "illuminated zone", the ratio a/b is given by

\[ \frac{a}{b} = \sin \beta \]  

which has been added to Figure 4 and is seen to yield a/b values larger than measured. One partial explanation is that, as seen in Figure 5, that qualitatively, the indentation ratio is a function of the ratio of actual to potential sediment transport, \( \frac{Q}{Q_o} \). The potential sediment transport \( Q_o \) is the amount of transport that would occur if an ample amount were available to be transported.

Artificial headlands and their associated beaches may be considered (in a similar manner as will be discussed for groins) as compartmenting and reorienting the shoreline such that the waves approach dominantly directly shore-normal. Thus a shoreline can be maintained, perhaps in a more advanced position, than would otherwise be the case. Silvester and Ho (1972) have reported on a land reclamation project in Singapore where artificial headlands were used to stabilize the placed material. It is clear that the viability of such a project is absolutely dependent on the maintenance of the connection between the headland and the shore.
Figure 4. A Crenulate Bay Formed by Oblique Waves Approaching Headlands at an Angle, $\beta$. Indentation Ratio, $a/b$ versus $\beta$. From Silvester and Ho (1972).

Figure 5. Qualitative Variation of Indentation Ratio, $a/b$ With Ratio of Actual to Potential Sediment Transport, $Q_*/Q_o$. 
One approach is to construct a rubble mound or sheet pile stem from the headland to shore, thereby contributing to the integrity of this connection.

2.6 Perched Beaches

The concept of a perched beach in its most simple form is two-dimensional in which an underwater structure, hereafter termed a sill is placed offshore to "perch" sand placed to widen the beach, see Figure 6. The primary advantage of this type structure is the potential substantial reduction in required sand volumes to achieve a desired additional beach width, especially if the sand is fine and therefore of a naturally mild slope. In application, there is need to consider sand losses at the ends of the installation and therefore it may be desirable to connect the ends of the sill to the shoreline with "return" structures.

Apart from concerns of the effects of this type project on adjacent beaches which could be greater if the returns were constructed, model tests by Chatham (1972) and Sorensen and Beil (1988) have shown that, especially if wave breaking occurs on the sill, the equilibrium depth on the landward side of the sill can be substantially deeper than the sill crest. This depth forms a boundary condition for the landward profile and the additional beach width associated with the equilibrium profile will be considerably less than expected if this scour landward of the sill is not taken into consideration. If the area landward of the sill is initially filled to the top of the sill, there can be a substantial amount of sand transported seaward over the sill from which it is unlikely to return landward of the sill as shown in Figure 6.

Figure 6. Laboratory Test Results of a Perched Beach. From Sorensen and Beil (1988)
2.7 Summary

Detached breakwaters can be effective in impounding sand from the longshore sediment transport system or in stabilizing sand placed to widen the beach. Applications may also include reduction of wave energy to improve recreational beach usage. It appears that detached breakwaters placed on a long beach characterized by a net longshore transport will exert a long-term effect by impounding sediment on the updrift side and causing an equivalent amount of volumetric erosion on the downdrift side. If the breakwaters are submerged or substantially overtopped, the mass transport of water to the lee side may cause undesirable longshore and/or rip currents.

3. GROINS

Groins are structures oriented normal or nearly normal to the shoreline. The purpose of groins is to interact with the longshore sediment transport to advance the shoreline seaward or to stabilize sand placed for the same purpose. The method by which groins function may be regarded as providing lateral support which resists the longshore stresses exerted by waves arriving at an angle. Through this process, the beach planform is locally reoriented into the incoming waves, thereby resulting in a local reduction of sediment transport. Figure 7 presents an example. Instead of transporting sand along the shoreline, the longshore force is resisted by the groins. A different way of viewing the interaction is that the groins cause the shoreline inside the groin compartment to reorient itself into the incoming waves such that locally there is no longshore shear stress.

![Figure 7. Shoreline Planforms For Various Values of the Ratio of Ambient to Potential Longshore Sediment Transport, Q* Q_o.](image_url)
The amount of additional shoreline resulting from a field of groins of a particular length and spacing is of design interest. The additional beach width, \( w \), can be expressed as

\[
w = f\left(\frac{H_b}{h_s}, s, \beta, m, Q_\ast/Q_c\right)
\]

in which \( h_s \) is the water depth at the end of the groin, \( s \) is the spacing between groins, \( \beta \) is the incident wave direction, \( m \) is the average slope of the beach profile over the groin length, \( Q_\ast \) is the ambient longshore sediment transport, and \( H_b \) is the breaking wave height. The qualitative manner in which some of these variables contribute to beach width will be discussed in the following paragraph.

The farther the groins extend offshore relative to the active zone of sediment transport, the greater the added beach width. Thus for a particular wave height and groin length, a mildly sloping beach will have a narrower beach than will a steeper beach. Obviously, waves arriving at a more oblique wave angle will result in a narrower average beach width than will waves with less obliquity. Considering the detailed transport fields within the groin compartments, it is seen that if the longshore sediment transport potential is large but the availability of sediment to be transported is significantly smaller, the width will be less as the forces which tend to remove sand from the compartment are related to the potential transport whereas addition of sand depends on the actual transport.

The effectiveness of groins can be influenced greatly by the tendency for large seasonal or storm related cross-shore sediment transport. Sand transported seaward from the groin compartment to form a bar will be available for longshore sediment transport and thus can move downdrift. If the volume of longshore transport on the bar is large relative to that available during the time that the bar is not present and thus the conditions are conducive for filling the compartment, then groins may be less effective.

Groins interact with the longshore sediment transport system in much the same manner as discussed previously for a detached breakwater. A single groin or a groin field extending beyond the shoreline will impound sand both updrift and in the case of multiple groins, within the compartments, first at a rapid rate, then at a decreasing rate as bypassing occurs. However, as noted previously, the theory of Pelnard Considere predicts that the groin will continue to trap sediment and that the total volume impounded will approach infinity as time approaches infinity.

A groin can fail functionally if it is flanked, that is if the shoreline recedes on one or both sides to the degree that water and sand flow landward of the groin. This constricted flow can cut a
fairly deep channel and render the groin ineffective. This will usually occur during a major storm or as a result of an erosional trend.

An additional effect of groins is for the sand which bypasses a single or multiple groin installation to form a bar with an alignment trending shoreward and eventually attaching to the shore. The tendency for this attachment to occur at a greater distance downdrift is enhanced during conditions under which a bar would tend to form naturally. The effects of groin fields on adjacent shorelines will be reduced if the groin compartments are pre-filled and if the groin field is tapered. High groins can cause rip currents which carry both sand and water seaward. If the groin profile is configured as a slightly higher version of the desired beach profile, water can flow over the groins and rip currents will be less likely to form.

With the above mentioned effects on adjacent shorelines, the most appropriate locations for groin usage appear to be at the ends of littoral systems, such as immediately updrift of inlets, where, if the groins were not installed, the sand would be effectively lost to the nearshore system. Groins placed on a continuous beach should definitely be tapered in planform and pre-filled to minimize impact on adjacent beaches.

4. ARMORING

Coastal armoring as used here can encompass any type of shore parallel structure which, upon construction, has dry land behind it. Thus, such structures can include stone or other type revetments and seawalls. The purpose of armoring is to protect the land from the sea, either against a chronic erosional trend, an episodic event, or a combination of the two. There has been much discussion regarding the adverse effects of coastal armoring, however unless the structure projects into the active surf zone, the adverse effects are relatively limited. Two types of adverse effects of seawalls that are manifested during storms will be discussed below. The reader is referred to the series of eight articles on the interaction of seawalls and beaches in the volume edited by Kraus and Pilkey (1988).

During storms, on an unseawalled profile, sand is transported seaward from the beach and shallow water to form an offshore bar. If a seawall limits the supply of sand from the upper beach from which it would normally be taken, experience has shown that the waves will remove the sand from a region as close to that from which it would have otherwise originated, i.e. at the toe of the seawall. The amount of sand eroded from near the seawall toe has been determined through laboratory studies to be somewhat less than would have been removed from landward of the seawall location, Darnett and Wang, 1988. This effect is two-dimensional as would
occur in a wave tank, see Figure 8a. There is also a three-dimensional effect wherein during storms, there is an increased erosional pressure on the shorelines adjacent to an armored shoreline segment. The armored segment limits the seaward transfer of sediment during the storm and thus the supply of sediment available for construction of the offshore bar is diminished. Considering the offshore bar to have a certain level of "demand" for sand, a portion of this demand will be satisfied by sand flowing from the adjacent regions as shown in Figure 8b. Walton and Sensabaugh (1975) have documented this effect through field surveys after Hurricane Eloise in 1975 and have developed the results presented in Figure 9. The amount of additional shoreline recession at the ends of the armoring increases with seawall length.

Of course, if seawalls are constructed on an eroding shoreline, they will eventually protrude into the active surf zone and will cause the usual updrift accretion and downdrift erosion if a net longshore sediment transport is present.

In the United States, seawalls have been judged to have a wide range of adverse effects on beaches. Most of these claims do not have any basis in measurement or field data, and some of the more unrealistic suggest a net sand loss to the system or sand being carried out to deep water. An assessment by Dean (1986) on the effects of seawalls on the adjacent shorelines is presented in Table 1.

5. REFERENCES


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Figure 8: Two- and Three Dimensional Effects of a Seawall on a Beach System during Storms. From Dean (1986).
Table 1
Assessment of Some Commonly Expressed Concerns Related to Coastal Armoring. From Dean (1988)

<table>
<thead>
<tr>
<th>Concern</th>
<th>Assessment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coastal armoring placed in an area of existing erosional stress causes increased erosional stress on the beaches adjacent to the armoring.</td>
<td>TRUE</td>
</tr>
<tr>
<td>Coastal armoring placed in an area of existing erosional stress will cause the beaches frontal the armoring to diminish.</td>
<td>TRUE</td>
</tr>
<tr>
<td>Coastal armoring causes an acceleration of beach erosion seaward of the armoring.</td>
<td>PROBABLY FALSE</td>
</tr>
<tr>
<td>An isolated coastal armoring can accelerate downdrift erosion.</td>
<td>TRUE</td>
</tr>
<tr>
<td>Coastal armoring results in a greatly delayed post-storm recovery.</td>
<td>PROBABLY FALSE</td>
</tr>
<tr>
<td>Coastal armoring causes the beach profile to steepen dramatically.</td>
<td>PROBABLY FALSE</td>
</tr>
<tr>
<td>Coastal armoring placed well-back from a stable beach is detrimental to the beach and serves no useful purpose.</td>
<td>FALSE</td>
</tr>
</tbody>
</table>

Figure 9. Additional Bluff Recession During Storms Due to Proximity to Seawalls. Based on Post-Hurricane Eloise Observations by Walton and Sensabaugh (1976).


