CHAPTER 135

COASTAL ARMORING: EFFECTS, PRINCIPLES AND MITIGATION

by

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ABSTRACT

An attempt is made to conduct a rational assessment of the potential adverse effects of coastal armoring on adjacent shorelines and to propose methodology for mitigation, where appropriate. Specific attention is directed toward claims that armoring causes: profile steepening, increased longshore sediment transport, intensified local scour, transport of sand to substantial offshore distances, etc. The assessment presented here is based on a combination of sound principles and the availability or lack of laboratory and field data to either support or refute the claims. Although it is found that data relating to coastal armoring effects are sparse, conclusions can be drawn. There seems to be no factual data to support the contentions that armoring causes profile steepening, increased longshore transport, transport of sand to a substantial distance offshore, or significantly delayed profile recovery following a severe erosion event. Armoring does have the potential to cause intensified local scour both in front of and at the ends of an armored segment. Reasons for these effects, based on knowledge of response of a natural profile, are presented. Additionally, armoring which projects into the active surf zone can act as a partial barrier to the net longshore sediment transport, thereby causing downdrift erosion.

Methodology is presented for quantifying the appropriate mitigation for a particular armoring situation. The proposed mitigation is the annual placement of sand in the vicinity of the armoring to offset its potential adverse effects. The two potential adverse effects addressed in the methodology include the reduction of sediment supplied to the system as a result of the armoring and the blockage of longshore sediment transport by a protruding armoring installation.

INTRODUCTION

Coastal armoring in the form of seawalls or revetments is usually designed to be located along sandy shorelines which are either experiencing an erosional trend or which are subject to substantial seasonal

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swings and/or storm-induced fluctuations that could conceivably endanger upland structures.

Coastal armoring, once regarded as a relatively desirable means of achieving shoreline stabilization, has recently been the focus of much attention including various concerns over possible adverse effects to the adjacent beach system, see for example Kana and Svetlichny (1982). An analysis of the available literature demonstrates that definitive laboratory or field data are sparse, thereby providing a fertile ground for conjecture and misinformation. Placed along a shoreline with an erosional trend, armoring can perform its intended function of upland stabilization while the adjacent shoreline segments continue to erode. The resulting offset between stabilized and unstabilized segments may be interpreted incorrectly that the armoring has caused the adjacent erosion. Coastal armoring does have the potential of causing adverse effects to the adjacent shoreline. In situations where coastal armoring is contemplated, it is important to recognize, and where possible to quantify and perhaps mitigate for these adverse effects. Specific alleged adverse effects of coastal armoring include: (1) offshore profile steepening, (2) intensified local scour, (3) transport of sand to a substantial distance offshore, (4) adverse downdrift erosion, and (5) delayed post-storm recovery. The coastal engineering profession has a responsibility to develop an improved understanding of the interaction of coastal armoring with the nearshore sand transport system in order to allow jeopardized structures to be protected where warranted without causing adverse effects to adjacent shorelines.

ASSESSMENT

The two possibile bases that can be used to assess the effects of coastal armoring include sound principles and data either from the laboratory or the field. A principle is present below followed by a discussion of processes and available data relevant to various possible armoring effects.

Principle

The strongest principle that can be applied in any discussion of coastal processes is that of sediment conservation. Clearly, coastal armoring neither adds to nor removes sand from the sediment system, but may be responsible for the redistribution of sand and may prevent sand from entering the system. As an obvious and immediate application of this principle, if as has been contended, coastal armoring causes profile steepening through nearshore erosion, then that same volume of sand must be transported to and deposited elsewhere. It is important to keep the principle of sand conservation in mind in reviewing the interaction of coastal armoring with the adjacent shoreline and offshore profile.

Laboratory and/or Field Data Relating to Various Possible Effects

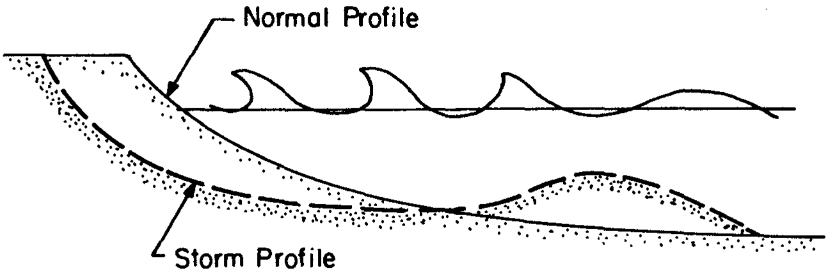
Offshore Profile Steepening - Some have claimed that steeply sloping revetments, vertical seawalls and even steep dunes cause an associated increased wave reflection and sand to be eroded and transported and deposited so far offshore that it is effectively "lost" to the littoral system. Increased wave reflection can clearly occur as a result of coastal armoring; however, there does not appear to be a mechanism for an associated offshore transport to significant depths nor is there evidence to support such transport.

While wave reflection can cause shore parallel bars in the laboratory, primarily for monochromatic waves, the existence of reflection bars in nature does not appear to be well-documented or at least highly prevalent. Moreover, the hydrodynamics associated with wave reflection does not offer an obvious explanation for offshore sediment transport. It appears that the behavior of a beach in nature is dependent primarily on the amount of sand in the nearshore system as compared to that for the equilibrium profile. Under normal conditions, the profile fronting seawalls and natural beaches will be the same up to the location of the seawall. If waves were completely reflected, it is acknowledged that the onshore and offshore forces on a sediment particle must be completely balanced and for this limiting condition, no tendency for onshore or offshore motion could exist. The equilibrium profile in this case could only be the superposition of barred topography on an otherwise horizontal bottom.

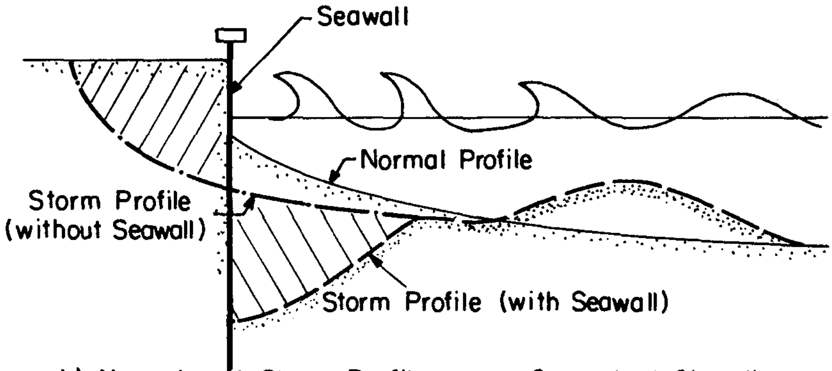
Storm-Induced Intensified Local Scour - Local scour under normal wave conditions has been addressed in the preceding section. During conditions of elevated water levels and high storm waves, the equilibrium profile requires sand to be transported seaward, both along natural and armored shorelines. Some of this material will be deposited as an offshore bar. Consider first a two-dimensional case as would occur in a wave tank. Because the armoring "denies" upland material for bar formation, this material is obtained from as near a location to the natural source as possible, i.e. immediately adjacent to the base of the seawall. This explanation is illustrated in Figure 1. Thus, during storms, it is expected that increased scour would occur at the toe of the vertical seawall. This is consistent with data presented by Kriebel, et.al. (1986) for post-Hurricane Elena profiles in which, relative to natural profiles, accentuated toe scour occurred at the base of seawalls, see Figure 2.

Extending to three dimensions, the above discussion of shoreline response during storms, since immediately in front of armoring there is insufficient sand to satisfy the "demand" of the offshore bar, the shore parallel downward slope to the area immediately seaward of the unarmored segment, combined with the mobilizing effects of breaking waves causes sediment to flow from the region offshore of the natural shoreline to that offshore of the armored segment. The effect of this interaction is to cause an additional "erosional stress" adjacent to the armoring with the magnitude of this stress increasing with the length of the armoring. This interaction is illustrated in Figure 3 and is consistent with post-Hurricane Eloise measurements as reported by Walton and Sensabaugh (1979), see Figure 4.

Projection of Armoring into the Active Surf Zone - If an isolated armored segment is constructed on an eroding shoreline where a substantial longshore sediment transport exists, the armoring will in time project into the surf zone and will act as a groin to block the



a) Normal and Storm Profiles on a Natural Shoreline



b) Normal and Storm Profiles on a Seawalled Shoreline and Comparison with Profiles on a Natural Shoreline

Figure 1. Additional Scour Immediately in Front of a Seawall Due to Storms.

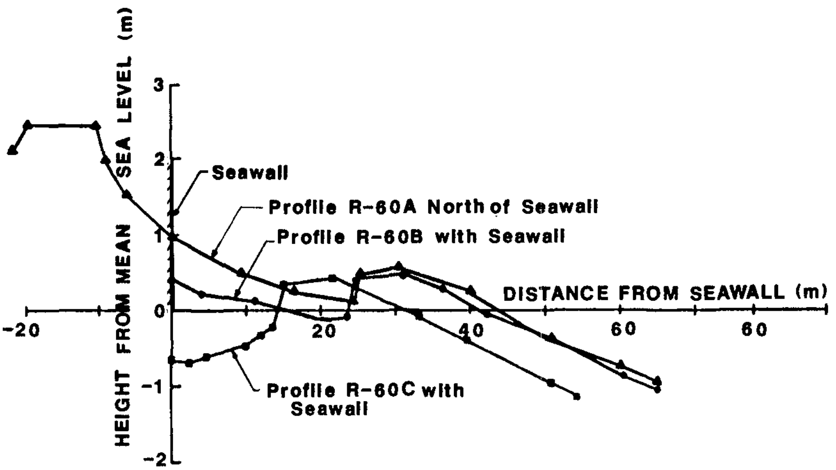
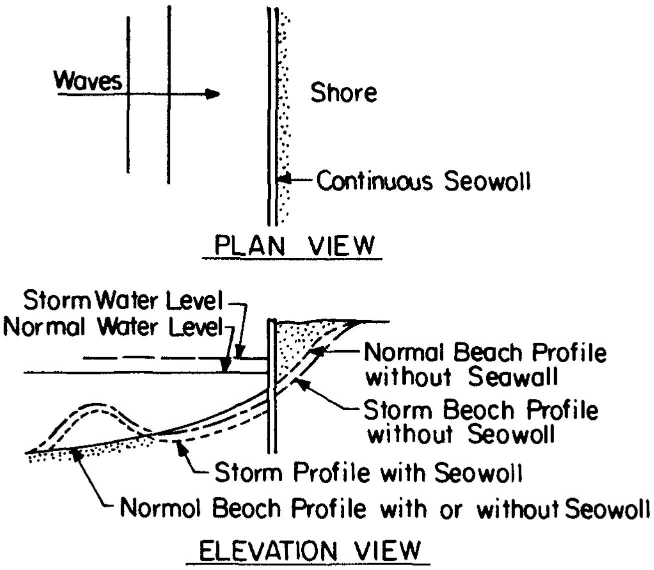


Figure 2. Comparison of Response of Natural and Seawalled Profiles to Hurricane Elena, September, 1985. (From Kriebel, et.al., 1986).

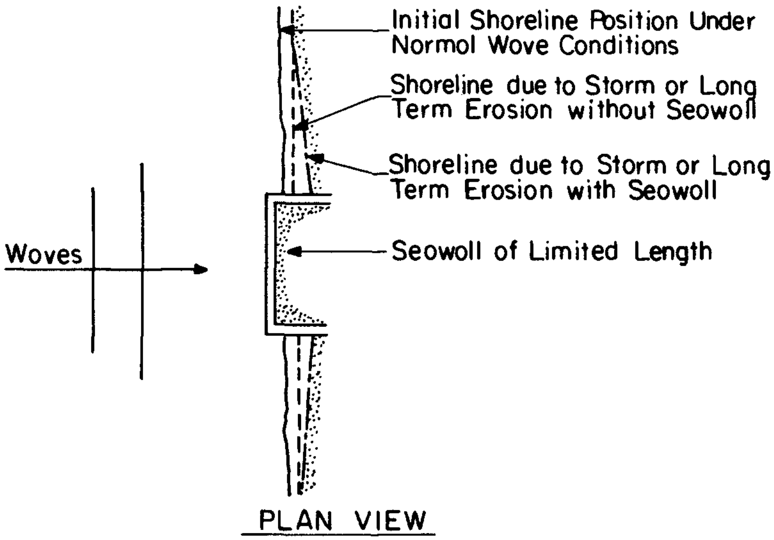
net longshore sediment transport. The annual deficit of sediment downdrift of the armoring will be the sum of that blocked by the projecting armoring and that not yielded by the upland protected by the armoring. The downdrift annual deficit will thus increase with (a) the length of the armoring, and (b) time as a result of increasing projection into the surf zone thereby blocking a greater and greater fraction of the longshore sediment transport. A simple method will be presented later to quantify approximately the downdrift deficit.

Effect of Wave Reflection on Longshore Sediment Transport - It has been argued that wave reflection from a seawall causes greater longshore sediment transport in front of the seawall and thus a local steepening of the profile. As presented in the discussion on "Principle" if this were the case, one would expect this effect to contribute to an equivalent deposition downdrift of the armoring, since greater quantities of sediment would be transported in the longshore direction in front of the armoring, but the transporting capacity of the waves would not be increased downdrift of the armoring. Contrary to the hypothesis that wave reflection causes increased longshore sediment transport, a rational argument can be advanced that the effect of wave reflection is to reduce the longshore sediment transport. Clearly, for an idealized shoreline with straight and parallel bottom contours, the total net longshore thrust, F_L, can be determined from momentum flux considerations as

$$F_L = \frac{\gamma H_o^2}{32} (1 - \kappa_r^2) \sin 2\alpha_o \qquad (1)$$



a) Qualitative Effects of Continuous Seawall on Storm Beach Profile.



b) Effect of Seawall of Limited Length on Storm or Long-Term Beach Planform.

Figure 3. Two- and Three-Dimensional Effects of a Seawall on Beach System during Storms.

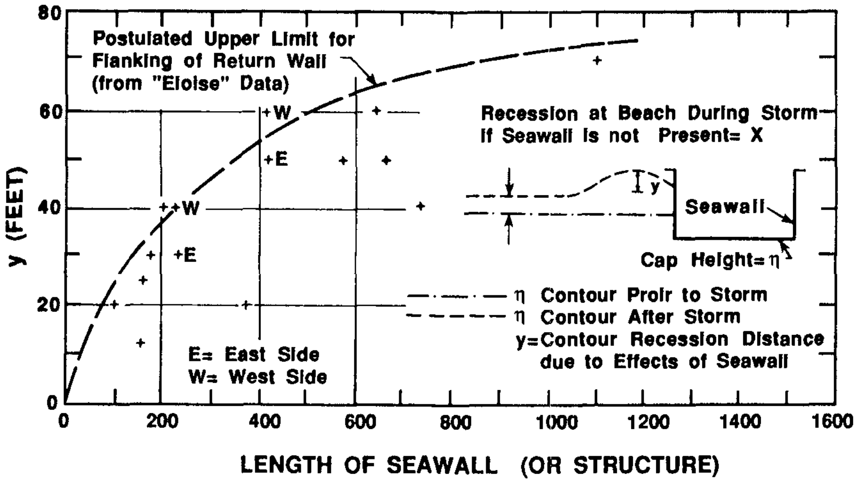


Figure 4. Additional Bluff Recession Due to Seawalls. Based on Post-Hurricane Eloise Field Observations by Walton and Sensabaugh.

in which κ_r represents the reflection coefficient as measured seaward of the surf zone, γ is the specific weight of sea water, and α_0 is the deep water wave direction relative to a normal to the bottom contours. Thus for larger reflection coefficients, the total longshore thrust is reduced. Counter arguments are that there is an increase in the longshore current because the very shallow water portion of the profile provides much of the retarding force and that even with a reduced total longshore thrust, the currents and associated sediment transport can be increased. Clearly, this is a complex problem and deserves careful consideration prior to reaching a conclusion.

Interference with Post-Storm Recovery - Wave reflection from coastal armoring could be the cause of a delayed post-storm recovery. Although this hypotheses has been proposed, it is again helpful to look to nature to attempt to address this question. First if the presence of coastal armoring were responsible for a delayed post-storm recovery, there should be ample evidence in the form of deposits remaining seaward of armoring and armored shorelines in front of which the contours are displaced landward relative to the adjacent shorelines. Data presented by Kriebel, et.al. (1986) from Hurricane Elena supports an equally rapid or nearly equally rapid recovery adjacent to coastal armoring. Moreover, observations by Mr. Ralph Clark immediately after Hurricane Elena (September, 1985) and approximately eight months later (May, 1986) indicate that recovery had occurred to at least the pre-storm condition. Figure 5 presents a somewhat representative pair of photographs taken immediately after Elena and eight months later; inspection of these photographs supports natural beach recovery even in front of vertical seawalls.

a) September 9, 1985, within One Week after Hurricane Elena.

b) May 16, 1986, Approximately Eight Months after Hurricane Elena.

Figure 5. Beach Recovery in Front of a Vertical Seawall. Comparison of Photographs Showing Eroded Shoreline after Occurrence of Hurricane Elena and Naturally Recovered Shoreline Eight Months Later (Courtesy of R. R. Clark).

Summary Assessment Based on Principles and Available Data

Based in part on the discussion above, Table I presents a summary assessment and evaluation of some common perceptions concerning the effects of coastal armoring.

PROPOSED APPROXIMATE PRINCIPLES

Based on the foregoing discussion and observations of cases of armoring in nature, the following two approximate principles are proposed:

1. In a two-dimensional situation in nature with wave and sediment conditions not conducive to formation of an offshore bar, the beach profile seaward of an armored segment does not depend on the presence of the armoring, but depends almost entirely on the equilibrium beach profile vis-a-vis the amount of sand available to form this profile.

2. In a two-dimensional situation in nature with wave and sediment conditions conducive to formation of a longshore bar, the additional volumetric scour immediately fronting the armoring will be less than or equal to that volume of material that would have been provided through erosion by that portion of the profile upland of the armoring if the armoring were not present.

MITIGATION

It has been noted that coastal armoring can cause adverse effects to adjacent shorelines, primarily through: (1) depriving the littoral system of material that would have been provided if erosion of the upland had not been prevented by the armoring, (2) blockage of the longshore sediment transport by armoring projecting into the active littoral zone, and (3) during storms due to sediment being drawn from adjacent profiles to replace that prevented from being eroded by the armoring.

In principle, it would appear desirable to assess the potential adverse effects of each armoring considered and to condition the construction on appropriate mitigation to offset these adverse effects. The mitigation would be the annual addition of sand to volumetrically compensate for that denied the adjacent shorelines by the armoring. This concept is illustrated by Figure 6, where installation of armoring without any mitigative sand placement will result in adverse effects to the shoreline, but with increasing annual volumes of sand added, the combination of armoring placed plus mitigative sand added become a benefit. The focus of this section is to recommend methodology for identifying the "neutral" point where the annual mitigative sand placement just offsets any adverse effects of the armoring. Two effects will be considered: (1) the reduction in sand supply through prevention of erosion, and (2) the blockage of sediment transport by a projecting revetment.

Reduction of Upland Sediment Supply by Armoring - Consider the situation presented in Figure 7 in which the erosional trend is, R, in

Table I. ASSESSMENT OF SOME COMMONLY EXPRESSED CONCERNS RELATING TO COASTAL ARMORING

Concern	Assessment	
Coastal armoring placed in an area of existing erosional stress causes increased erosional stress on the beaches adjacent to the armoring.	TRUE	By preventing the upland from eroding, the beaches adjacent to the armoring share a greater portion of the same total erosional stress.
Coastal armoring placed in an area of existing erosional stress will cause the beaches fronting the armoring to diminish.	TRUE	Coastal armoring is designed to protect the upland, but does not prevent erosion of the beach profile waterward of the armoring. Thus an eroding beach will continue to erode. If the armoring had not been placed, the width of the beach would have remained approximately the same, but with increasing time, would have been located progressively landward.
Coastal armoring causes an acceleration of beach erosion seaward of the armoring.	PROBABLY FALSE	No known data or physical arguments support this concern.
An isolated coastal armoring can accelerate downdrift erosion.	TRUE	If an isolated structure is armored on an eroding beach, the structure will eventually protrude into the active beach zone and will act to some degree as a groin, interrupting longshore sediment transport and thereby causing downdrift erosion.
Coastal armoring results in a greatly delayed post-storm recovery.	PROBABLY FALSE	No known data or physical arguments support this concern.
Coastal armoring causes the beach profile to steepen dramatically.	PROBABLY FALSE	No known data or physical arguments support this concern.
Coastal armoring placed well-back from a stable beach is detrimental to the beach and serves no useful purpose.	FALSE	In order to have any substantial effects to the beaches, the armoring must be acted upon by the waves and beaches. Moreover, armoring set well-back from the normally active active shore zone can provide "insurance" for upland structures against severe storms.

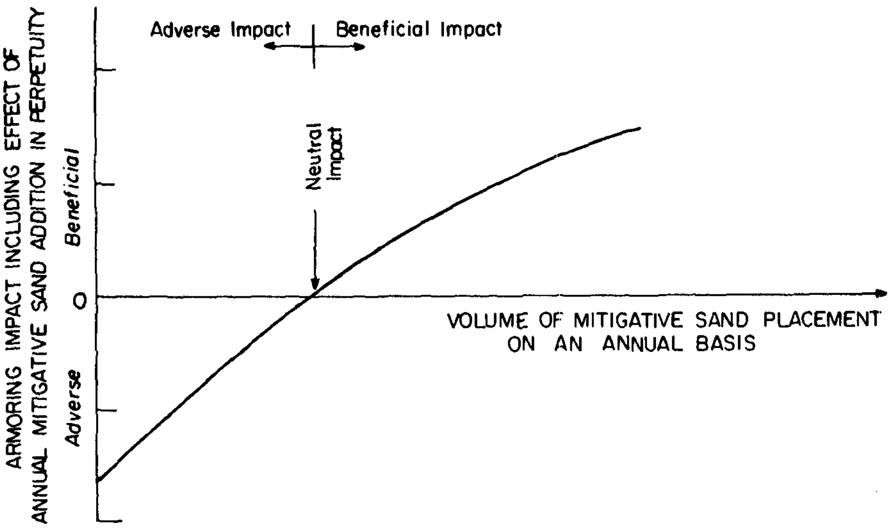


Figure 6. Effect of Annual Mitigative Sand Placement in Reducing the Adverse Impact of a Coastal Armoring Project.

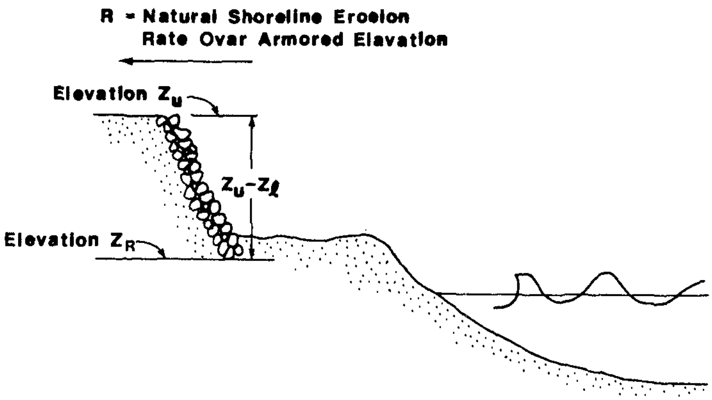


Figure 7. Definition Sketch. Describing Basis for Armoring Mitigation Due to Prevention of Upland Supply by Erosion.

m/yr and the armoring extends from a lower elevation, Z_ℓ, up to Z_u and the length of the armoring is ℓ. For this case, the required annual mitigative sand placement, $\forall_1$, to achieve a neutral effect is

$$\forall_1 = (Z_u - Z_\ell)(R)(\ell) \tag{2}$$

As an example, if the erosional trend rate is 1 m/yr, the length of the armoring is 100 m and the armoring extends from a lower elevation, Z_u, of 0 m to an upper elevation, Z_u, of 5 m, the annual volumetric mitigative requirement

$$\forall_1 = (5-0)(1)(100) = 500 \text{ m}^3/\text{yr}.$$

Interruption of Longshore Sediment Transport - A coastal armoring constructed on an eroding coastline will eventually protrude into the active surf zone where it will cause a partial blockage of the longshore sediment transport with the familiar pattern of deposition and erosion updrift and downdrift of the armoring, respectively. This problem is complicated as the rate of impoundment will increase annually with the ultimate potential of blocking the entire net longshore sediment transport.

The volume of storage can be estimated by several different approaches. For purposes here, two different bases will be presented and it is recommended that an average of the two be used. For both, it is assumed that the updrift impoundment planform is linear and aligned with the incoming waves, see Figure 8.

The first method considers the profile in the storage area to be the same as that along the unperturbed beach. The additional annual volumetric storage rate, $\forall_{2_a}$, can be shown to be

$$\forall_{2_a} = \frac{(B + h_*)}{\tan\theta}\, b\, R \tag{3}$$

in which B = berm height, h_* = profile closure depth, R = long-term erosion rate, b = projection of armoring beyond unperturbed shoreline, and θ is angle of the wave crest approach relative to the unperturbed beach. Lacking specific information, a value of $\tan\theta = 0.1$ appears reasonable. It is noted that the projection distance b increases with time in accordance with $b = b_o + Rt$, in which b_o is the projection at the initial time and t is the number of years into the future.

The second method assumes that the profile modifications extend only out to the solid oblique line shown in Figure 8. Figure 9 shows profiles of the unaffected and assumed affected profiles for the second method. Clearly the second method represents an underestimate of the impounded volume whereas the first method is an overestimate. The equation for the annual rate of increased volume storage, $\forall_{2_b}$, is

$$\forall_{2_b} = \frac{1}{\tan\theta}\left(B + \frac{3}{5} h'\right) b\, R \tag{4}$$

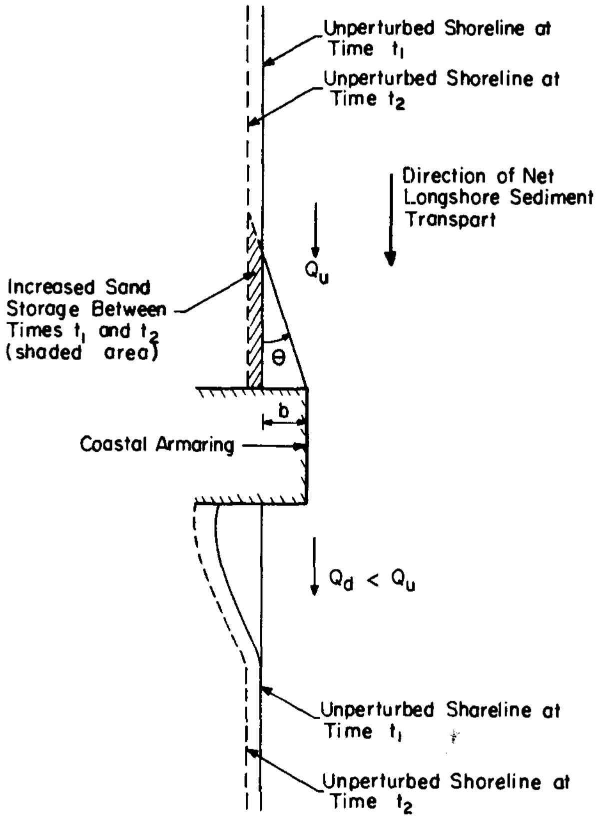


Figure 8. Illustration of Sand Storage by Coastal Armoring Projecting Beyond the Unperturbed Shoreline.

in which h' is the depth that would be present at the toe of the seawall if the seawall were not present. Eq. (4) incorporates the assumption of an equilibrium profile of the form $h = Ax^{2/3}$, in which h is the water depth at a distance x offshore and A is a scale parameter determined for the natural profile of interest. The parameter A has dimensions of $(\text{length})^{1/3}$ and for fine to medium sands is on the order of 0.1 $m^{1/3}$ (0.15 $ft^{1/3}$). Alternatively, h' can be estimated at a distance b along an unperturbed shoreline.

As noted before, recognizing that the first and second methods for estimating $\forall_2$ are too large and too small respectively, it is recommended that an average of the two be used, i.e.

$$\forall_2 = \frac{1}{2}\left(\forall_{2_a} + \forall_{2_b}\right) = \frac{Rb}{\tan\theta}\left[B + \frac{h_* + \frac{3}{5}h'}{2}\right] \qquad (5)$$

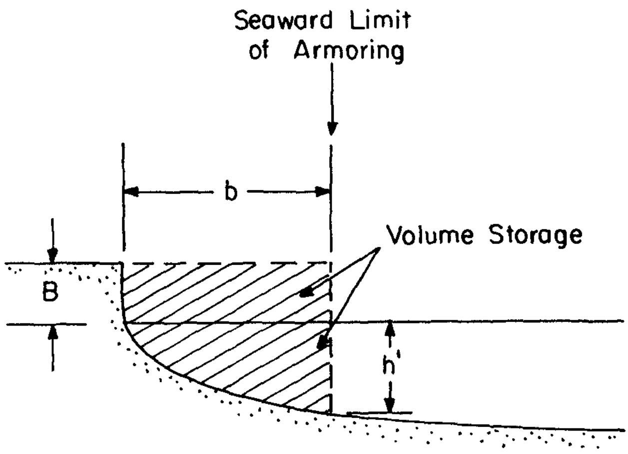


Figure 9. Profile Considerations in Method B.

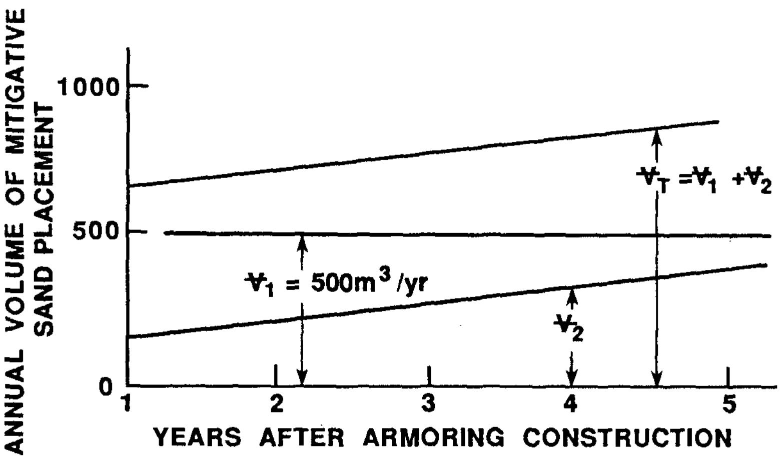


Figure 10. Illustration of Annual Volume of Mitigative Sand Placement for Example Presented in Text.

As an example, suppose that R = 1 m/yr, b_o = 2 m, $\tan\theta$ = 0.1, B = 2 m, h_* = 7 m and A = 0.1 $m^{1/3}$. The mitigative sand requirement increases with time as presented in Figure 10 where $\forall_1$, $\forall_2$ and the total annual mitigative sand requirement $\forall_T = \forall_1 + \forall_2$ are presented.

It should be noted that an upper limit to, $\forall_2$, should be the net longshore sediment transport and that bypassing around a projecting armoring could be considered as an alternate mitigative strategy.

SUMMARY AND CONCLUSIONS

Uncertainties resulting from a lack of definitive information has led to considerable speculation and claims regarding the adverse effects of coastal armoring on the adjacent shorelines. Employing sound principles and laboratory and field data, an attempt is made to evaluate the potential adverse effects of armoring. It is concluded that:

1. There are no factual data to support claims that armoring causes: profile steepening, increased longshore transport, transport of sand to a substantial distance offshore, or delayed post-storm recovery.

2. The interaction of an armored segment of shoreline with the littoral system is more of a "geometric" or "kinematic" interaction as contrasted to a "dynamic" interaction. The interaction depends on the amount of sand in the system vis-a-vis the equilibrium beach profile for the prevailing tide and wave conditions.

3. Armoring can cause localized additional storm scour, both in front of and at the ends of the armoring. A simple sediment supply-demand argument is proposed to explain the scour.

A methodology is presented to quantify the potential adverse effects of an armoring installation and appropriate periodic sand additions proposed as a means of mitigation to elevate the installation to one of neutral impact on the adjacent shoreline.

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