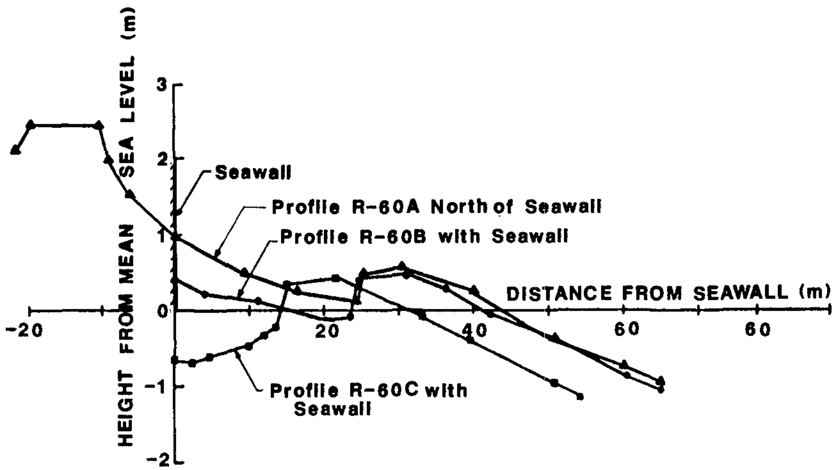
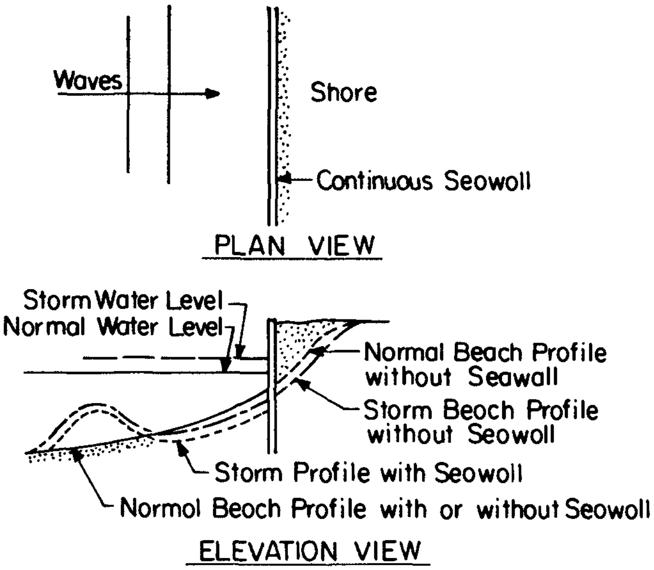


Figure 2. Comparison of Response of Natural and Seawalled Profiles to Hurricane Elena, September, 1985. (From Kriebel, et.al., 1986).

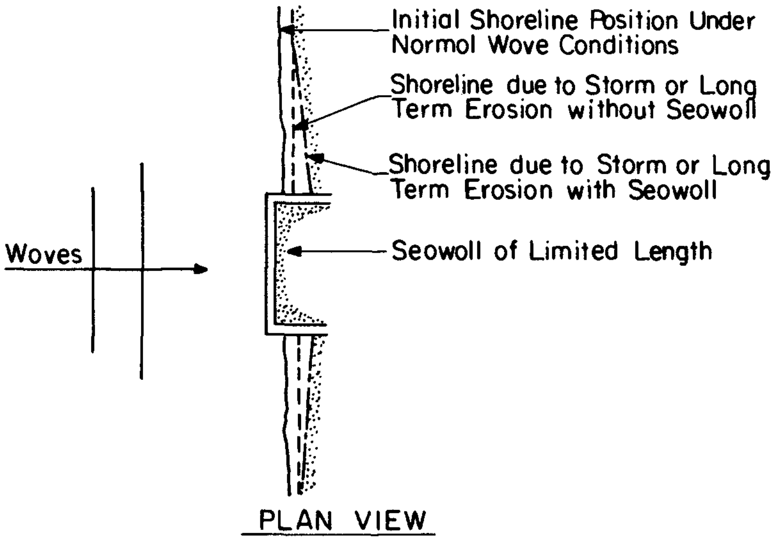
net longshore sediment transport. The annual deficit of sediment downdrift of the armoring will be the sum of that blocked by the projecting armoring and that not yielded by the upland protected by the armoring. The downdrift annual deficit will thus increase with (a) the length of the armoring, and (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.

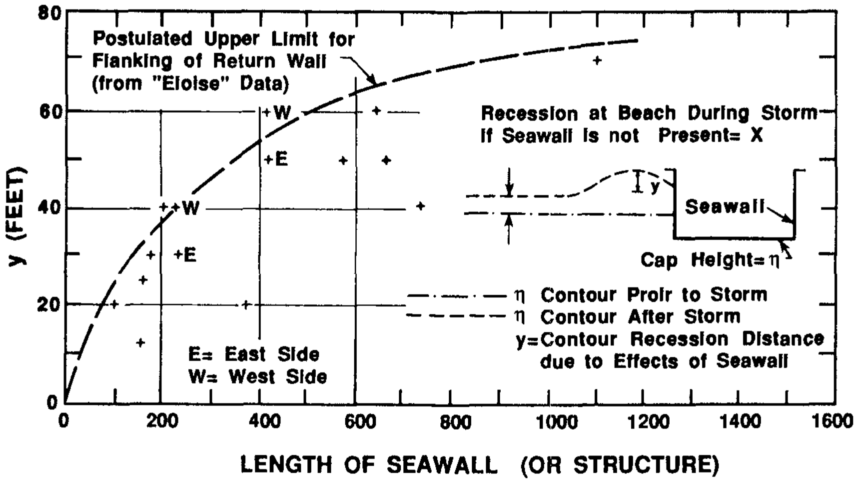


Figure 4. Additional Bluff Recession Due to Seawalls. Based on Post-Hurricane Eloise Field Observations by Walton and Sensabaugh.

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.

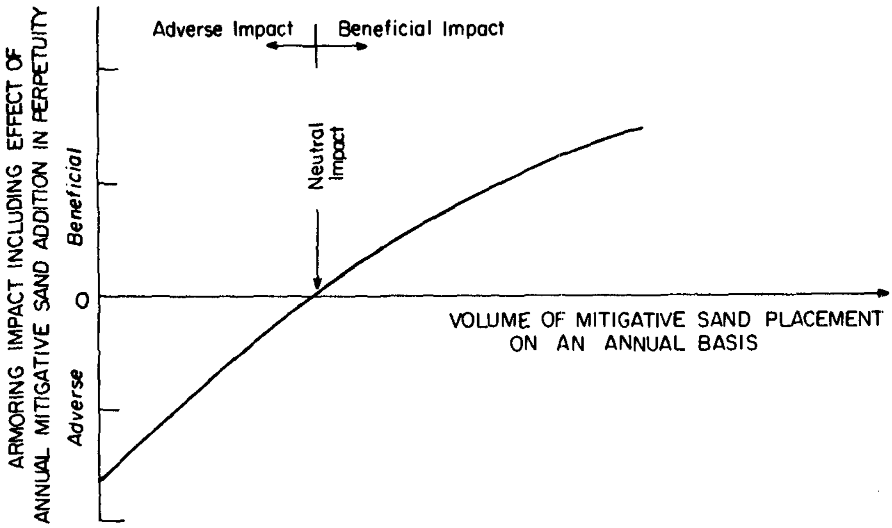


Figure 6. Effect of Annual Mitigative Sand Placement in Reducing the Adverse Impact of a Coastal Armoring Project.

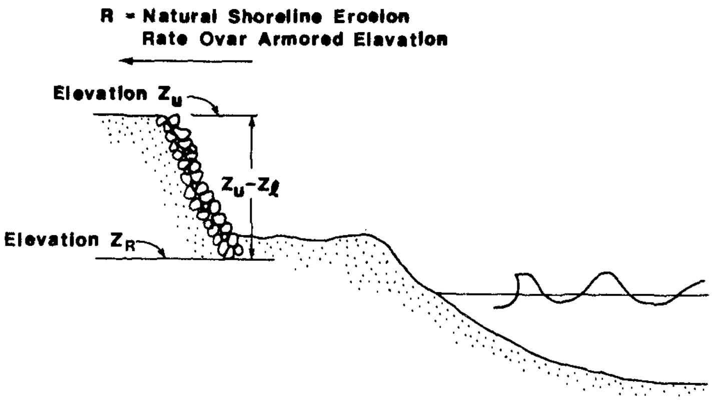


Figure 7. Definition Sketch. Describing Basis for Armoring Mitigation Due to Prevention of Upland Supply by Erosion.

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, $\rlap{-}V_1$, to achieve a neutral effect is

$$\rlap{-}V_1 = (Z_u - Z_\ell)(R)(\ell) \tag{2}$$

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

$$\rlap{-}V_1 = (5-0)(1)(100) = 500 \text{ m}^3/\text{yr}.$$

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 long-shore 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 long-shore 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, $\rlap{-}V_{2_a}$, can be shown to be

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

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, $\rlap{-}V_{2_b}$, is

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

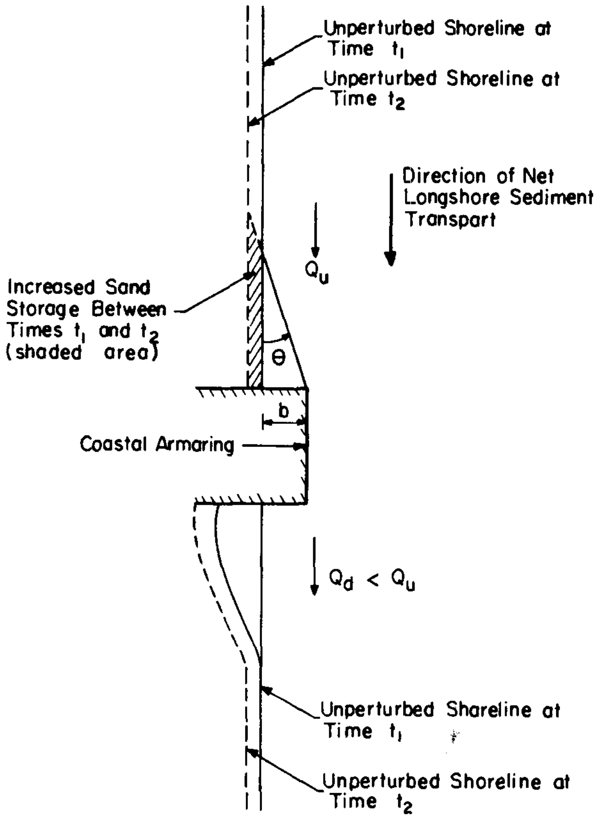


Figure 8. Illustration of Sand Storage by Coastal Armoring Projecting Beyond the Unperturbed Shoreline.

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 $\mathcal{V}_2$ are too large and too small respectively, it is recommended that an average of the two be used, i.e.

$$\mathcal{V}_2 = \frac{1}{2}\left(\mathcal{V}_{2_a} + \mathcal{V}_{2_b}\right) = \frac{Rb}{\tan\theta}\left[B + \frac{h_* + \frac{3}{5}h'}{2}\right] \qquad (5)$$

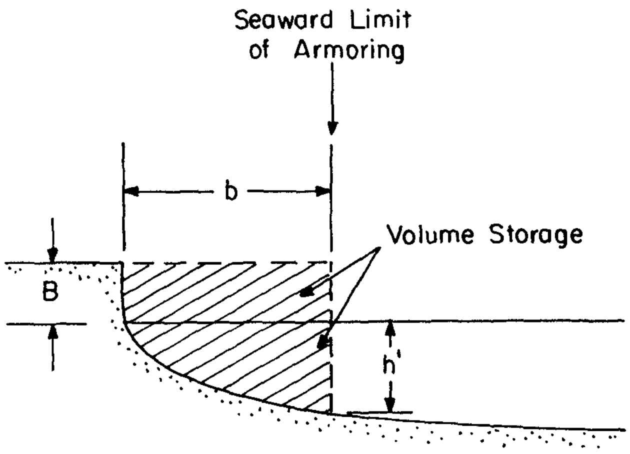


Figure 9. Profile Considerations in Method B.

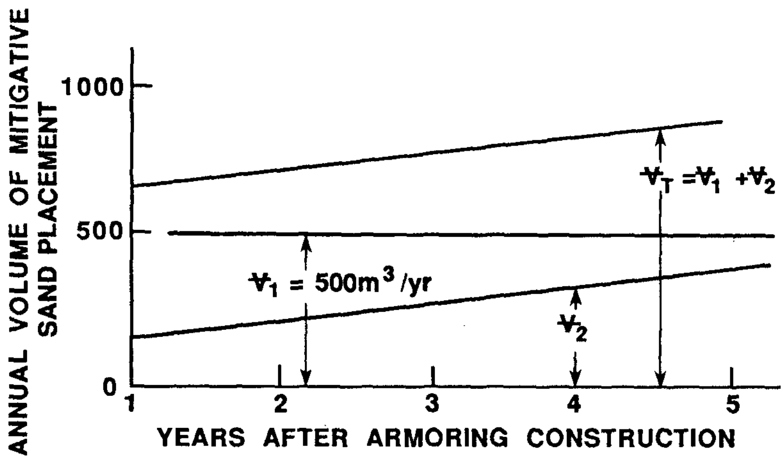


Figure 10. Illustration of Annual Volume of Mitigative Sand Placement for Example Presented in Text.