Protection against Wave-based Erosion

The guidelines below address the elements of shore structure design common to nearly all erosion control structures subject to direct wave action and run-up.

1. Minimize the extent waterward.

Erosion control structures should be designed with the smallest waterward footprint possible. This minimizes the occupation of the lake bottom, limits habitat loss and usually results in a lower cost to construct the project.

In the case of stone revetments, the crest width should be only as wide as necessary for a stable structure. In general, the revetment should follow the cross-section of the bluff or dune and be located as close to the bluff or dune as possible.

For seawalls, the distance that the structure extends waterward of the upland must be minimized. If the seawall height is appropriately designed to prevent the majority of overtopping, there is no engineering rationale based only on erosion control which justifies extending a seawall out into the water.

2. Minimize the impacts to adjacent properties.

The design of the structure must consider the potential for damaging adjacent property.

Projects designed to extend waterward of the shore will affect the movement of littoral material, reducing the overall beach forming process which in turn may cause accelerated erosion on adjacent or down-drift properties with less protective beaches.

Seawalls, (and to a lesser extent, stone revetments) change the direction (wave reflection) and intensity of wave energy along the shore. Wave reflection can cause an increase in the total energy at the seawall or revetment interface with the water, allowing sand and gravel to remain suspended in the water, which will usually prevent formation of a beach directly fronting the structure. This effect may impact the adjacent downdrift properties by either reducing beach formation (immediately adjacent) or potentially increasing beach formation (further downdrift). In extreme conditions, wave reflection may allow littoral material to be transported off shore rather than along the shore, which would potentially remove that material from the littoral system and starve downdrift beaches.

3. Structural Stability.

The design must include the applicable calculations to demonstrate that the proposed structure will have long-term stability.

For stone revetments, the stability of the structure depends on the unit weight of the armor stone, the slope and the design wave height. The most common calculation used is Hudson's Equation, which relates the design wave height and design slope of the revetment to the weight (and size) of the stone needed to resist uplift (and displacement) from wave energy. This calculation is below in the Revetment Design section.

The stability of a seawall depends on its total weight in cross-section, location waterward of the shoreline, cap elevation, underlying geology, and the degree to which it is used to retain the upland bluff or bank. A seawall is a shore-parallel structure with a nominally vertical face. Typical seawall designs include stacked pre-cast concrete block, cast-in-place concrete walls and stone-filled cribs.

The design should include details and specifications that show how blocks or cribs are to be connected and sufficient reinforcing detail that shows how cast-in-place concrete walls and caps will be connected. How the seawall is to be anchored into the underlying strata must also be detailed.

4. Materials of Construction.

The specifications for all materials to be used as part of the erosion control structure must be included in the design drawings. Particular attention should be paid to the specifications of fill materials that may be used under armor stone or behind seawalls. Demolition debris, concrete rubble and common clean fill (dirt) are not acceptable materials for structures potentially exposed to the wave action (either during construction or post-construction).

5. End Effects / Flanking.

The design should avoid abrupt, shore-perpendicular ends at property boundaries. In general, both revetments and seawalls should be "rounded" off at the ends and/or meet the existing bluff or bank slope contours. This will reduce the potential for erosion at the adjacent property working its way back behind the structure and causing upland slope failure and possible failure of the end of the revetment or seawall. If existing structures are present at adjacent properties, the proposed design should transition to these as smoothly as possible.

6. Design of Toe Protection.

Adequate toe protection should be included in the design to prevent sliding failures, scour and undermining at the base of a seawall. Both revetments and seawalls should also be adequately set into the underlying strata.

For armor stone revetments it is common practice to specify that stone at the upper end of the armor stone size range be placed at the toe, or toe stone 1 to 2 tons or greater than the design median armor stone size.

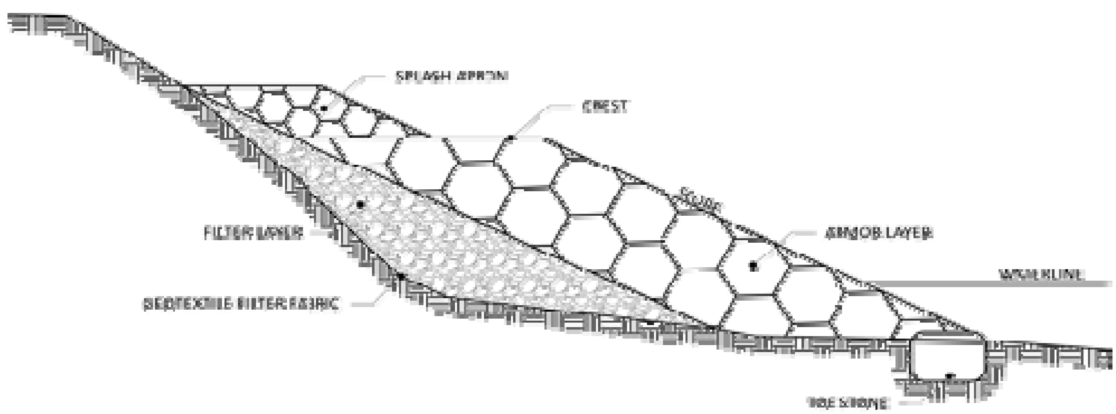
Many seawalls are used for recreational or watercraft access. The use of armor stone as toe protection in the design of a seawall may interfere with this function. Nevertheless, toe protection at the seawall base is recommended as a means of preventing the scouring and undermining of the structure and increasing its expected life.

Revetments:

Revetments are onshore structures with the principal function of protecting the shoreline from erosion. Revetment structures typically consist of a cladding of stone, concrete, or asphalt to armor sloping natural shoreline profiles.

Components of an armor stone revetment are:

1. The ***armor layer*** consists of sufficiently sized stone and a thickness designed to be stable under the design wave conditions and the design slope.
2. The ***filter layer*** consists of smaller stone or rubble that supports the larger armor stone and prevents erosion of the underlying bluff material. This layer may also be called a bedding layer. If this material is intended to be impermeable, it may be referred to as a "core". Geotextile fabric is included under the filter layer to further reduce the potential for erosion of underlying fine-grained bluff material.
3. The ***toe stone*** consists of heavier stone placed at the waterward edge of the revetment, and serves to prevent slipping failure of the upper revetment. In many cases the toe stone will also be placed in an excavated trench into the underlying natural material.



4. The ***crest*** is the upper elevation of armor stone.

In addition to its recreational and aesthetic features, the presence of a beach waterward of an armor stone revetment will aid in erosion protection.

5. When the crest is designed as a horizontal feature, it is nominally as wide as the armor stone layer thickness. The height of the crest above the design water level is determined by the calculated run-up elevation of the design wave.
6. The ***splash apron*** is located above the crest and usually consists of much smaller stone. It serves as a less costly means of dissipating the remaining wave run-up, splash and spray that can extend above the armor layer. *(see illustration)*

Revetment Design

Armor material:

Sandstone and limestone can be used for armor stone. Allowances for the lighter mass density of sandstone (specific gravity of 2.2 to 2.5 for sandstone versus 2.6 for limestone) must be included in the design calculations. Sandstone is more resistant to cracking than limestone but it is also a softer material and more easily eroded. The use of concrete block or specialty concrete forms as armor material is addressed in the Corps of Engineers’ Shore Protection Manual (SPM) found at http://publications.usace.army.mil/publications/eng-manuals/ Concrete typically has a specific gravity of 2.4, but it can be much lighter.

Concrete rubble should never be used as armor material due to its tendency to crack and break apart easily, reducing the unit weight of the block. It is also difficult to obtain concrete rubble of a sufficient weight per piece that would be needed to resist wave forces. Further, it is also difficult to control the size and shape of rubble since most rubble tends to be from slabs that are limited in one dimension (the slab thickness). This shape limitation tends to result in both breaks and the creation of large voids, neither of which favor a stable structure.

Slope:

The maximum recommended slope of a random-placed armor stone revetment is 1.5 horizontal to 1 vertical. Slopes greater than this will tend to be unstable. A 1.5H to 1V slope results in the smallest stable footprint along the shore. Where possible, revetment slopes should be selected to match the existing bluff/bank slope's stable angle of repose. In practice, revetment slopes range from 1.5 to 1 to 2.5 to 1. Slopes greater than 3 horizontal to 1 vertical are rarely specified mostly due to the higher cost of armor stone needed to construct what would be a wider revetment than might be necessary.

Armor layer:

The basis of the design for sizing the necessary weight and size of the armor stone units is the relationship between the force of the design wave (design wave height) and the slope of the structure. This relationship is expressed as follows:

Hudson's Equation

$$W_{50} = \frac{W_r H^3}{K_D (S_r - 1)^3 \cot\theta}$$

Where:

W_{50} is the 50th percentile (median) weight of the stone (lbs)
W_r is the unit mass of the stone (lb/ft^3) Limestone typically is 160-165 lb/ft^3
H is the design wave height (ft) at the toe of the structure
$S_r = W_r / W_w$; (W_w = 62.4 lb/ft^3)
K_D is an empirical value based on physical testing.
For randomly placed, angular stone K_D = 2.0
$\cot\theta$ is the design slope of the revetment. For a 2:1 slope, $\cot\theta = 2$

Hudson's equation addresses only the stability of armor stone with respect to wave forces at a given slope. The calculation relies on the risk assumed with a given design water level (the return period) and wave height, both of which may be exceeded during the life of the structure.

The other factors that can affect long term stability include the quality of the stone, the range of actual sizes supplied, the placement on the slope, fracturing of the stone over time and the effect of ice forces. These factors are independent of each other and can all add to the long-term risk of failure of the revetment.

Ice forces are very unpredictable and difficult to calculate for revetments. Ice may act laterally against the slope moving and displacing stone, large ice blocks may drag stone waterward as the ice recedes and ice can exert an uplift force on the stone as it forms along the shore and is thrust landward by wave action.

Armor stone is subject to fracturing over time and during transportation and placement. The stone will fracture due to ice, freeze and thaw and wave forces, losing its unit size/weight and thus its stability.

It is recommended that a safety factor be applied to the calculated unit stone weight as a measure of risk reduction against fracturing, ice forces, and variability in stone size and placement. The engineer should consider how these factors apply to each design and assign an appropriate safety factor that also incorporates the level of risk the property owner is willing to accept in return for the cost difference between larger or smaller armor units.

Armor Stone Weights and Dimensions (for Limestone)

Tons Stone Type	Pounds per Stone	Stone Diameter, (feet)	Two-unit layer thickness (feet)
8 - 9	17000	4.75 -5	9.5
7 - 8	15000	4.5 - 4.75	9
6 - 7	13000	4.25 - 4.5	8.5
5 - 6	11000	4 -4.25	8
4 - 5	9000	3.75 - 4	7.5
3 - 4	7000	3.5 - 3.75	7
2 - 3	5000	3 - 3.5	6
1 - 2	3000	2.5 - 3	5.5
	1250	2	4
	500	1.5	3
	160	1	2
	20	0.5	1

Notes

2. Stone size assumes rough cubic shape, quarry stone can be irregular.
3. The calculated two layer thickness is the approximate median value for the range based on the equations used by USACE. In-place thickness may be less.

It is common to specify a range of stone size, using the design weight from Hudson's equation as the lower value in the range. A range of stone size may also be a factor in the available supply of stone from a quarry. If a range of armor sizes is used, the design should specify that the larger stones be placed on the exposed layer directly receiving wave forces. This results in a conservative design that helps counter damage and poor placement of the stone during construction. USACE (in EM 1110-2-1614, "Design of Coastal Revetments, Bulkheads and Seawalls") recommends a range of armor stone between 0.75 x W50 and 1.25 x W50. USACE in the SPM notes that uniform sizing of armor units is more economical for design wave heights greater than 4.5 feet.

The thickness of the armor layer is determined by the dimensions of the stone size selected for stability. The most common, and perhaps most cost effective arrangement is to specify two layers of armor stone. The approximate diameters for armor stone weights and the calculated layer thickness for a two-layer armor design are included in the table on this page. The armor layer thickness will tend to be slightly less than those in the table if a larger range is specified due to closer packing of stones. The design armor layer thickness can be calculated using a formula from the SPM that requires one to assume the number of layers and the unit stone size.

A single layer of armor stone cannot be expected to have long-term stability or effectively prevent erosion. A single displaced stone could allow wash-out and erosion of the filter layer, and potentially the bluff/bank material, leading to failure of the revetment.

Crest elevation:

The crest elevation for an armor stone revetment is based on the wave run-up expected given the revetment slope, the design wave height, wave period and water level. The empirical formula shown below will generally result in a conservative run-up value.

Run-up = $$R = H\frac{a\xi}{1+b\xi}$$

R = run-up in feet
a = 1.022
H = design wave height in feet
b = 0.247
ξ = surf similarity parameter (Iribarren number)

The surf similarity parameter ξ

$$\xi = \frac{\tan\theta}{\sqrt{2\pi H / gT^2}}$$

tan θ= revetment slope (e.g. 2:1 slope = 0.5)
g = 32.2 ft/sec2
T = wave period in seconds

The calculated height of run-up is added to the DWL elevation to arrive at a conservative design elevation for the revetment crest.

Function of the filter layer:

The filter layer consists of graded rock or riprap and geotextile fabric. It acts as a transition between the underlying soil and the armor structure. It prevents the migration of fine soil particles through voids in the structure, distributes the weight of the armor material to provide more uniform settlement and permit relief of hydrostatic pressures within the soils. In the case of revetments which extend above the water level, filter layers also help prevent surface water from causing erosion beneath the armor material.

Filter layer design:

The long-term stability of the revetment armor layer rests, in part, on the design of the filter layer. The material(s) for the filter layer
should meet the following conditions:

The above photo shows typical concrete rubble of greatly varying size. The larger slabs may not be suitable as filter layer material.

1. The material should be resistant to erosion caused by run-up and water washing through the armor stone. Fine grained material or a mix of larger material with fines should not be specified.

A revetment is shown in the above photo.

2. The material should be capable of supporting the weight of the armor stone layer without significant displacement or creation of significant voids. Random pieces of concrete rubble are problematic as filter material due to the potential for large voids and uneven settlement.
3. The material should be capable of preventing erosion and loss of the underlying bluff material. Geotextile fabric placed between the filter layer material and the bluff material can prevent loss of the fine grained bluff material.

The filter layer should be designed to minimize the amount of fill needed. The slope of the filter layer will usually be the same as the slope of the armor layer. The thickness will be determined by the cross-section of the bluff and the type and size of material to be used. In general, the filter layer thickness is two to three times the average stone size used in the filter layer.

As a design guideline, the USACE recommends a filter layer stone size that is 10 percent of the size of the armor stone. The use of larger stone or rubble increases the potential for uneven settling and the creation of large voids. Smaller filter layer stone can be specified if it is underlain by impermeable bluff material and a geotextile fabric to reduce the loss of fine material from the bluff.

Neither the filter layer nor any underlying fill should ever be exposed to direct wave action or run-up.