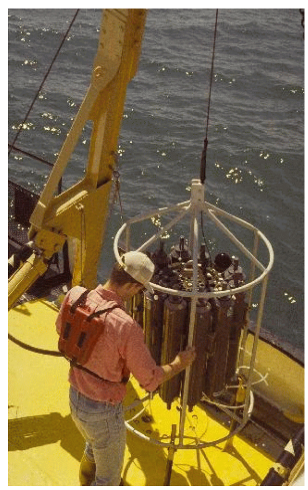
GUIDANCE FOR IN-SITU SUBAQUEOUS CAPPING OF CONTAMINATED SEDIMENTS:

Appendix A: Armor Layer Design

by
Steve Maynord
U.S. Army Engineer Waterways Experiment Station
Vicksburg, Mississippi

Prepared for
U.S. Environmental Protection Agency
Great Lakes National Program Office
Assessment and Remediation
of Contaminated Sediment Program
Chicago, Illinois 60604



Monitored by
U.S. Army Engineer Division
North Central
Chicago, Illinois 60605-1592

Appendix A: Armor Layer Design

If an evaluation of cap erosion indicates that the capping material will not be sufficiently resistant to erosion, an armor layer can be considered. Such an armor layer would be incorporated into the cap design and would replace any previously determined cap sediment thickness component for erosion.

A design of capping armor layers has been developed as a part of the EPA ARCS program and is presented in this Appendix. This section provides guidance for the design of armoring to ensure the long term stability or integrity of the cap. Caps might be subjected to a variety of physical stresses such as river or tidal currents, wind wave generated currents, ice and debris scour, or propeller wash in navigation channels. Preliminary technical guidance is provided on the hydraulic design of in-situ capping/armoring of contaminated sediments with riprap. Factors pertinent to flood flows, navigation effects, and wind wave induced currents are presented and then formulas and sample calculations are provided. Less predictable forces on ISC such as scouring from ice and debris, flow from velocities generated by channel blockages such as ice dams, or massive bank failure are not evaluated by this analysis. Designers of ISC should consider the significance of these forces and potential effects in the evaluation of the feasibility of ISC.

Filter Design

Filters provide an interface between the riprap layer and the protected material and are an essential element for protecting contaminated sediments, particularly poorly consolidated sediments. Filters prevent turbulence and groundwater from moving sediments through the revetment. Filters serve as foundations or load distributors for the riprap for poorly consolidated material which is typical of many contaminated sediments. Filters can be either geotextile, granular, or a combination of the two. Granular filters are generally more expensive but have been shown to provide long term performance. Geotextile filters are less expensive but have not been around long enough to completely evaluate the potential for clogging of the geotextile over long time periods. Problems can occur with geotextiles if the permeability factor is too low. Gas and advective ground water may displace a cap that has too low a permeability. Uncertainty in design should err on the side of providing too large a permeability. A sand layer on top of fine-grained sediments may be required prior to placement of either a granular or geotextile filter. A bedding layer of granular material (sand or gravel) may be placed on top of the geotextile to prevent damage during

placement of the riprap. Guidance on design of geotextile filters can be found in Pilarczyk (1984) and PIANC (1987). In determining the stability of intermediate granular layers subjected to velocity forces, the Worman (1989) equation is

$$\frac{V^2}{gS} = C \frac{d_{85}}{D_{15}} \tag{1}$$

Where V is the mean flow velocity above the granular layer, g is gravity, S is the granular layer thickness, C is a coefficient that varies with the uniformity of the granular layer, d_{85} is the 85 percent passing size of the base material, and D_{15} is the 15 percent passing size of the granular material. Based on experimental work by Manamperi (1952), the coefficient for uniform riprap having D_{85}/D_{15} = 1.3 is C = 24 and for Manamperi's graded riprap having D_{85}/D_{15} = 6.7, C = 10. D_{85} is the 85 percent passing size of the riprap. For relatively uniform riprap having D_{85}/D_{15} = 1.3, V = 7 ft/sec, S = 1.0 ft, and D_{15} = 5 in., the required d_{85} of the intermediate granular layer is 0.32" or 8.1 mm. Additional guidance on design of granular filters can be found in Pilarczyk (1984), EM 1110-2-1901 (USACE 1986), and EM 1110-2-2300 (USACE 1982).

Gradation and layer thickness considerations

Both riprap gradation and layer thickness play a significant role in defining the stability of the armor layer. The gradation of rock produced by quarries across the country varies widely and standardized gradations have not been widely adopted in the U.S. The gradations shown in Table A1 are taken from EM 1110-2-1601 and give a maximum or upper limit and a minimum or lower limit at the 100, 50, and 15 percent sizes. Any gradation falling between the maximum and minimum limits is acceptable.

Minimum layer thickness requirements vary depending on the type of attack on the revetment. For flood flows, the minimum layer thickness is $1D_{100}$(max) or $1.5D_{50}$(max), whichever is greater. D_{100} is the riprap size of which 100 percent is smaller, i.e. the largest riprap size. The (max) refers to the upper or maximum limit curve. For propeller wash where turbulence is much greater than flood flows, the minimum layer thickness is $1.5D_{100}$(max) or $2D_{50}$(max), whichever is greater.

Placement and Limits of Coverage

Placement of riprap and filters in dry conditions generally presents no problems and the minimum layer thickness given above is applicable. Underwater placement presents uncertainties with even coverage of stone and a 50 percent increase in granular filter and riprap volume is required. Placement of geotextiles in shallow depths and low velocity can be accomplished as described in the Appendix C case studies, by the method shown in the main body of this report or by attaching the fabric to a framework and lowering the framework into position prior to stone placement. Underwater placement in moderate to high velocity (> 2 ft/sec) would present significant problems with geotextile placement. With a granular filter, a diver may be required to insure adequate coverage in deep placement conditions.

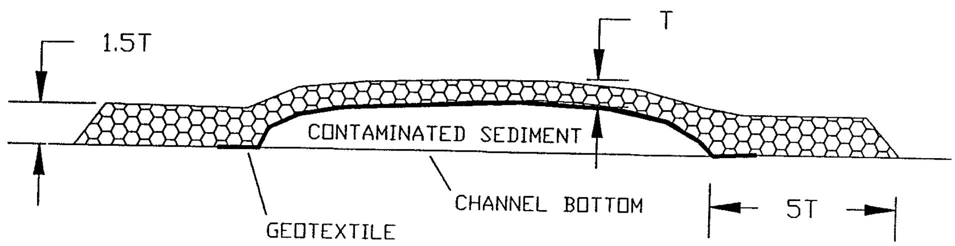


Figure A-1. Cross section of riprap and edge protection.

Table A1. Gradations For Specific Stone Weight of 165 LB/FT^{3},[a] From USACE (1994)

D_{100}	Limits of Stone Weight (lb) for Percentage Lighter by Weight[b]						D_{50}
(Max)	100		50		15		(Min)
(in)	Max	Min	Max	Min	Max	Min	(ft)
9	36	15	11	7	5	2	0.43
12	86	35	26	17	13	5	0.58
15	169	67	50	34	25	11	0.73
18	292	117	86	58	43	18	0.88
21	463	185	137	93	69	29	1.02
24	691	276	205	135	102	43	1.07

[a] 1 lb/ft^{3} = 16.018kg/m^{3}

[b] Stone weight limit data from USACE (1994). Relationship between diameter and weight is based on shape of a sphere.

The limits of protection and a typical cross-section are shown in Figure A1. Riprap protection should extend 5 times the thickness of the riprap protection beyond the edge of the contaminated material. The thickness of the edge extension should be 1.5 times the riprap thickness to allow for scour along the edges of the protection. On the outer bank of channel bendways, significant scour can be expected at the toe of the bank during flood flows. For contaminated sites on the outer bank of bendways, refer to EM 1110-2-1601 (USACE 1994) for design of toe scour protection. If contaminated sediments on the bed are adjacent to the toe of the bank, protection should not only cover the bed sediments, but should also extend partially up the side slope.

Stone Sizing for Flood Flows

Waterways that do not experience significant navigation may require protection for the maximum flood flow or storm velocities near the capped sediments for the required life of the project. At sites without

navigation having flow velocities typically found in flood control channels, the riprap protection requirements should follow the guidance provided in Chapter 3 of the EM 1110-2-1601 entitled "Hydraulic Design of Flood Control Channels" (USACE 1994). The procedures for riprap protection in EM 1110-2-1601 should be used for design guidance and revised as deemed necessary to provide an adequate but practical protection for specific project conditions. Both the guidance presented herein and EM 1110-2-1601 will be useful in evaluating design specifications of riprap protection for capping projects.

Stone Size Equations

Velocity and flow depth are the two basic factors used in design of riprap protection. The method of determining the stone size in EM 1110-2-1601 uses depth-averaged local velocity. Stone size computations should be conducted for flow conditions that produce the maximum velocities at the riprap boundary.

The following equation, modified from EM 1110-2-1601, relates velocity to stone size and is applicable to any location in the channel. The changes from the EM include the use of the gradation factor and basing stone size on D_{50} instead of D_{30}. This was done to use the same characteristic riprap size as in the navigation sizing presented subsequently.

$$D_{50} = S_f C_s C_v C_T C_G d \left[\left(\frac{\tilde{a}_w}{\tilde{a}_s - \tilde{a}_w} \right)^{1/2} \frac{V}{\sqrt{K_1 g d}} \right]^{2.5} \qquad (2)$$

Where,

D_{50} = characteristic riprap size of which 50 percent is finer by weight.
S_f = safety factor, minimum = 1.1
C_s = stability coefficient for incipient failure,
thickness = $1D_{100}$(max) or $1.5D_{50}$(max), whichever is greater,
D_{85}/D_{15} = 1.7 to 5.2
= 0.30 for angular rock
= 0.375 for rounded rock
D_{85}/D_{15} = gradation uniformity coefficient(typical range= 1.8 to 3.5)
CV = velocity distribution coefficient
= 1.0 for straight channels, inside of bends
= 1.283-.2log(R/W) for outside of bends (1 for R/W > 26)
= 1.25 downstream of concrete channels
= 1.25 at end of dikes
R = centerline radius of bend
W = water surface width at upstream end of bend
C_T = blanket thickness coefficient(typically 1.0 for flood flows)
C_G = gradation coefficient = $(D_{85}/D_{15})^{1/3}$
K_1 = side slope correction factor(see EM 1110-2-1601 for other slopes
d = local depth, use depth at 20 percent upslope from toe for side slopes
V = local depth averaged velocity, use velocity at 20 percent upslope from toe for side slope riprap
ã$_w$ = unit weight of water
ã$_s$ = unit weight of stone (typical value of 165 lb/ft^3)
g = gravitational constant

A key element in any riprap design problem is the estimation of local depth-averaged velocity at the protection location. The EM primarily addresses velocity estimation in areas where erosion is expected which is normally the outer bank of channel bendways. Plate B-33 in the EM (Figure A2) provides an estimate of the maximum velocity that will occur in a bend on the outer bank. For sites where flow velocities are the predominate force, contaminated sediments needing protection may be located on either the bed or bank at any position along the length of the channel. Bernard and Schneider (1992) have developed a PC based depth-averaged numerical model that includes secondary current effects that occur in channel bends. This model has been shown to give good results in trapezoidal channels. This model will provide a velocity estimate at any position across the channel and along the bend.

Normally the minimum safety factor for riprap design is 1.1; however, if the consequences of failure are extremely hazardous, the designer should increase the safety factor accordingly. A computer program incorporating the EM 1110-2-1601 procedures is available from the Hydraulics Laboratory of the Waterways Experiment Station.

Examples of Design for Flood Flows

Consider the Sheboygan River which has contaminated sites along the upper non-navigable reach. The two-year average discharge is 3140 cfs, the five-year is 5000 cfs, and the ten-year is 6150 cfs. For the purpose of this example design, assume design average channel velocity of 6 ft/sec, the channel plan view in Figure 3, and design depths shown in the following table.

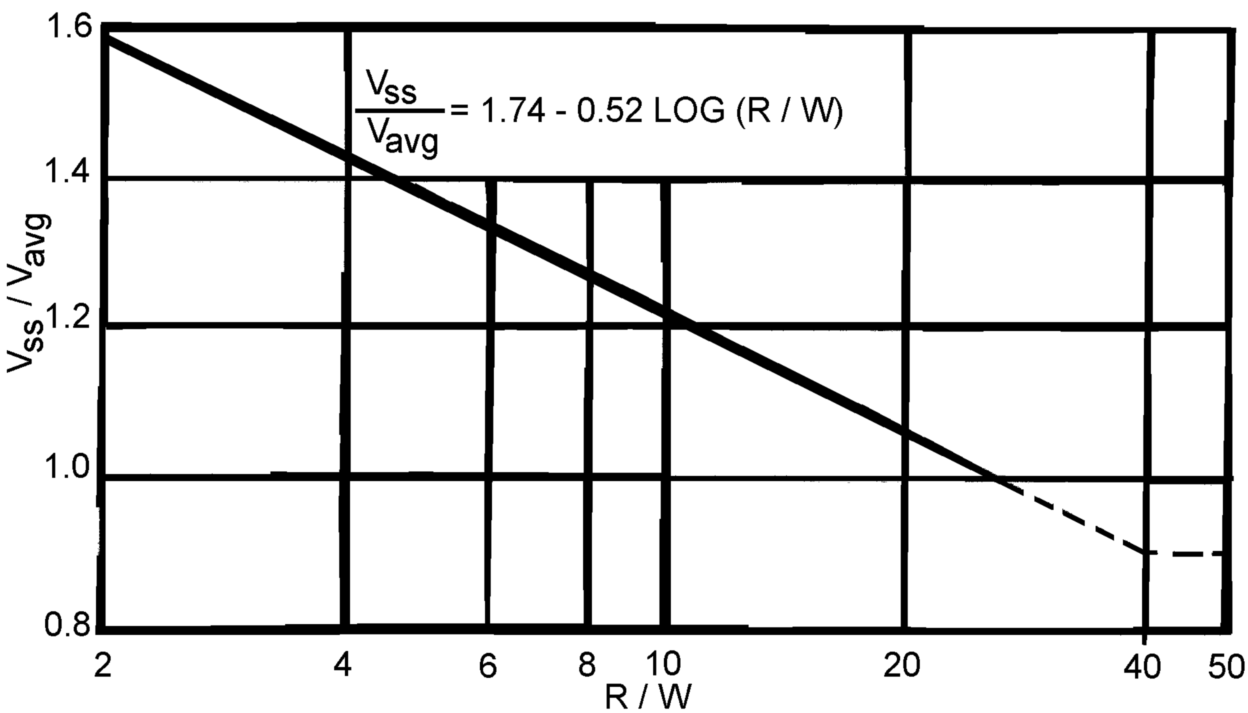
AREA	DEPTH
1,5	9 Ft
8,10,11	6 Ft

The following analysis uses a unit stone weight of 165 #/ft^3, minimum S_f = 1.1, angular rock (Cs = 0.30), blanket thickness = 1 D_{100} (C_T = 1.0), 1V:2H side slope (K_1 = 0.88) for all areas, and a gradation having D_{85}/D_{15} of 2.0.

Areas 1 and 5 in Figure 3 are on the outside of bendways where velocities are the highest. From Figure 2, an assumed R/W = 3 gives a ratio between the outer bank velocity and the average channel velocity of about 1.5, so the local velocity is 1.5(6) =9.0 ft/sec. Using equation (2) results in D_{50} = 0.57 ft. From Table A1, a gradation having D_{50}(min) greater than or equal to the computed value would have a D_{100}(max) of 12 in. and if placed in the dry, a thickness of 12 in.

Areas 8, 10, and 11 in Figure 3 are in a relatively straight reach of channel not strongly affected by upstream channel curvature. In these areas the right part of the natural channel curve (Figure 2) is applicable and bank velocity/average channel velocity = 1.0. This leads to a bank velocity of 1.0 (6.0) = 6.0 ft/sec and equation (2) yields a D_{50} = 0.19 ft.

In these examples, rock from a nearby source having D_{50} greater than the computed D_{50} would have to be specified. In practice the largest rock size required is often specified for both areas due to economics. It is assumed that the risk to human health and the environment is greater for a failure of a contaminated sediment cap than for a failure of a bank erosion control riprap layer. Therefore, additional margins of safety in stone sizing may be warranted for a ISC to protect the cap from localized very high velocities resulting .



NOTE: V ss IS DEPTH-AVERAGED VELOCITY AT 20 PERCENT OF SLOPE LENGTH UP FROM TOE

Figure A-2. Riprap design velocities.

Stone sizing for navigation effects

Navigation can generally be divided into two categories, underway and maneuvering. For large commercial vessels underway in relatively small channels, the vessel creates a variety of erosion producing forces that are primarily water-level drawdown, return velocity acting opposite to the direction of travel, transverse stern waves, and a limited attack of the propeller jet. For underway vessels, these forces tend to increase with increasing speed and with decreasing channel size. In harbor areas, typical underway speeds tend to be low and erosion producing forces will also be low.

The second category of navigation, maneuvering vessels, produces erosion generating forces that are primarily caused by the propeller jet and can be large. Rock sizing guidance that follows will address the protection requirements for the propeller jet of maneuvering vessels.

Propeller Jet Stone Sizing Equations

The basic equations used in the analysis of riprap size are presented in Blaauw and van de Kaa (1978). The equation for the maximum bottom velocities in the propeller wash of a maneuvering vessel is

$$V_b(\max) = C_1 U_o D_p / H_p \tag{3}$$

where

$V_b(\max)$ = maximum bottom velocity
C_1 = 0.22 for non-ducted propeller
= 0.30 for ducted propeller
U_o = jet velocity exiting propeller
D_p = propeller diameter
H_p = distance from propeller shaft to channel bottom

The ratio D_p/H_p is a measure of the clearance of the propeller above the channel bottom. High values indicate the propeller is close to the channel bottom. Values of $D_p/H_p > 1.2$ are outside the range of data used in developing Equation 3 and should be used with caution.

The jet velocity exiting a propeller is given by Blaauw and van de Kaa (1978) as

$$U_o = C_2 \left(\frac{P_d}{D_p^{\,2}} \right)^{1/3} \qquad (4)$$

where
U_0 = jet velocity exiting propeller in ft/sec
P_d = applied engine power/propeller in Hp
D_p = Propeller diameter in ft
C_2 = 9.72 for non-ducted propellers
= 7.68 for ducted propellers

The applied engine power used in equation 4 is the most difficult question to answer and one of the most important parameters in determining stone size. Blaauw et al (1984) gives the following equation for rock size

$$V_b(\mathrm{max}) = C_3 * (g * \text{Ä} * D_{50})^{1/2} \qquad (5)$$

where
C_3 = coefficient
Ä = ($\tilde{a}_s$ - $\tilde{a}_w$)/$\tilde{a}_w$

Blaauw et al. (1984) found C_3=0.55 for no movement and C_3=0.70 for small transport. Data from Maynord (1984) using equations 3-5 show that C_3 = 0.55 provides good agreement with experimental results for no transport and should be used in harbor areas where repeated attack can be expected and no movement can be allowed. For channel protection where infrequent attack can be expected, C_3 = 0.6-0.7 should be used in design.

Thrusters

Bow and stern thrusters are often used in deep draft vessels to permit maneuvering in navigation channels. Thrusters are ducted propellers and, depending on the position of the vessel relative to the bank, the maximum attack may be on either the channel bottom or channel bank. Due to the uncertainty of the location of maximum attack, the general equation from which equation 3 was derived must be used to determine velocity along the bed and bank. The general form of equation 3 from Blaauw and van de Kaa(1978) provides the distribution of jet velocity and is

$$\frac{V_x}{U_o} = 2.78\frac{D_o}{x}\exp[-15.43(\frac{z}{x})^2] \tag{6}$$

where V_x = velocity at coordinates x,z
$D_o = 0.71D_p$ for non-ducted propeller
$= D_p$ for ducted propeller
x = horizontal distance from propeller
z = radial distance from axis of propeller

Thrusters generally operate at full power and a typical class 8 lake vessel has a bow thruster which is 6.8 ft in diameter and 850 hp. Typical stern thrusters are the same diameter and 1000 hp. Thruster centerlines are about 6.2 ft above the keel. Riprap sizing for thrusters would use equation 6 and solve for V_x at various point along the bottom and up the bank until the maximum V_x is found. This maximum V_x will be the V_b(max) to use in equation 5.

Example designs for navigation

Two examples are presented in this subsection, one based on commercial vessel traffic and another on recreational vessel traffic. On the Ashtabula River in Ohio, the possible areas for capping are located in the Federal Navigation Channel where depths in this area vary from 2 to 16 ft. Small recreational craft normally use this reach with an infrequent commercial vessel. Contacts with the U.S. Coast Guard led to the following findings regarding the largest commercial vessels using this reach:

Table A2. Largest Commercial Vessels on the Ashtabula River

		PROPELLER		**SHAFT**	
LENGTH	WIDTH	DIA-INCHES	DRAFT	BELOW W.S.	HP
FT	FT	INCHES	FT	FT	
42	12.5	40	6	4.5	300
72	22.5	60	9.4	6.5	1100
59	14.0	60	8	6.0	680

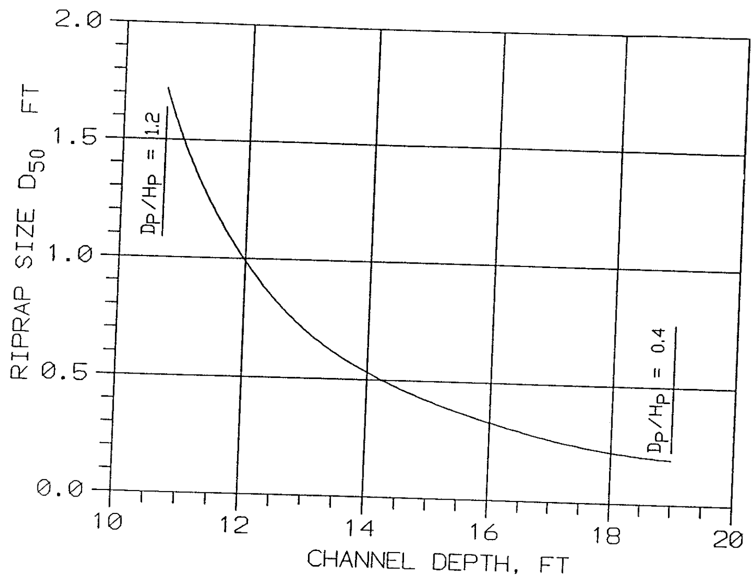


Figure A-4. Influence of channel depth on stone size, Astabula River, 1100 hp vessel, 25 percent power.

Using the 1100 hp vessel at 1/4 throttle which is typical of this vessel, the applied engine power is P_d = 1100(0.25) = 275 hp, and with the propeller diameter D_p = 5 ft, equation (4) results in U_O = 21.6 ft/sec for a non-ducted propeller. With a 16 ft depth, H_p = 9.5 ft and from Equation (3), V_b(max) = 0.22(21.6)5/9.5 = 2.50 ft/sec. From Equation (5) with C_3 = 0.60, D_{50} = 0.33 ft. A blanket thickness of 9 in. from Table A1 has a D_{50}(min) greater than or equal to 0.33 ft.

Two of the significant variables in the propeller jet stone sizing equations are the channel depth and the applied power. Figure 4 demonstrates the change in rock size D_{50} for changing channel depth with all other parameters as above for the 1100 hp vessel on the Ashtabula River. Rock size becomes large as the propeller approaches the bottom. Figure 5 demonstrates the change in rock size for changing percent of total power applied for a depth of 13 ft and all other parameters as above. Rock size becomes large for significant power increases.

In the second example, the largest vessels in a contaminated reach adjacent to a towing basin are 300 HP recreational craft with maximum draft of 3.5 ft. These vessels are twin propeller boats with maximum propeller diameter of 1.44 ft with the centerline of the shaft 2 ft below the water level. The maximum throttle is about 25 percent. Water depth varies from 4-11 ft. Based upon the basic equations 3-5 and a water depth of 5 ft, the jet velocity for the maximum vessels would be based on 150 hp per propeller. The applied power is P_d = 0.25(150) = 37.5 hp. From Equation (4),U_o = 25.5 ft/sec. For a 5 ft depth, H_p = 3 ft. From Equation (3), V_b(max) = 2.7 ft/sec. From Equation (5), D_{50} = 0.38 ft and a blanket thickness of 9" from Table A1 (EM1110-2-1601) provides D_{50}(min) greater than or equal to 0.38 ft. If depth were 10 ft., Hp = 10-2 = 8 ft. From equation (3), V_b(max) = 1.0 ft/sec and Equation (5) gives D_{50} = 0.053 ft which would be equivalent to a large gravel covering.

Stone sizing for wave induced currents

Significant wind wave activity can create large bottom velocities that can erode an unprotected sand cap. To define the required armor layer size to prevent scour, Equation 5 should be used with with the maximum horizontal bottom velocity from the wave. For orbital velocities beneath waves, a C_3 = 1.7 is recommended.

Example Design for wave induced currents

Wave induced bottom velocities are calculated to be 7 fps for the design wave. Using equation 5 with C_3 = 1.7 results in D_{50} = 3.8" for unit stone weight of 165 lb/cf. A maximum/minimum stone size of about 2 is recommended to reduce attack of underlying layers and the resulting stone gradation is 2.5" to 5.0".

References

Bernard, R.S., and Schneider, M.L. 1992. "Depth-Averaged Numerical Modelling For Curved Channels," Technical Report HL-92-9, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Blaauw, H. G., and van de Kaa, E. J. 1978. "Erosion of Bottom and Banks Caused by the Screw Race of Maneuvering Ships," Publication No. 202, Delft Hydraulics Laboratory, Delft, The Netherlands, presented at the Seventh International Harbor Congress, Antwerp, May 22-26.

Blaauw, H. G., van der Knaap, F. C. M., de Groot, M. T., and Pilarcyk, K. W. 1984 "Design of Bank Protection of Inland Navigation Fairways," Publication No. 320, Delft Hydraulics Laboratory.

Headquarters, US Army Corps of Engineers. 1982. "Earth and Rockfill Dams," EM 1110-2-2300, US Government Printing Office, Washington, DC.

Headquarters, US Army Corps of Engineers. 1986. "Seepage Analysis and Control for Dams," EM 1110-2-1901, US Government Printing Office, Washington, DC.

Headquarters, US Army Corps of Engineers. 1994. "Hydraulic Design of Flood Control Channels," EM 1110-2-1601, US Government Printing Office, Washington, DC.

Maynord, S. T. 1984. "Riprap Protection on Navigable Waterways, "U.S. Army Engineer Waterways Experiment Station, Technical Report HL-84-3.

PIANC, 1987. "Guidelines for the Design and Construction of Flexible Revetments Incorporating Geotextiles for Inland Waterways," supplement to Bulletin No 57, Permanent International Association of Navigation Congresses.

Pilarczyk, K.W. 1984. "Filters," in Chapter 2, The Closure of Tidal Basins, edited by W. van Aalst, Delft University Press, Delft, The Netherlands.

Worman, A. (1989). "Riprap protection without filter layers," J. of Hydraulic Engineering, ASCE, 115,no. 12, Dec.

Manamperi, H.D.S. (1952). "Tests of graded riprap for protection of erosible material," Thesis submitted to Univ of Iowa.