BANGLADESH WATER DEVELOPMENT BOARD

Design Guidelines for River Bank Protection Work

Office of the Chief Engineer, Design, BWDB,
Pani Bhaban, Dhaka

April'2021

প্রধান প্রকৌশলীর দপ্তর
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Memo no- 1043 -CE, D Date: 11-04-2021

Design Guidelines for River Bank Protection Work

Bangladesh is a country of river. Morphology of all river are not similar. Moreover, morphology of all reaches of a same river is also not similar. As a result, queries are arises about the variation of size of protection material, dumping volume, distribution of dumping volume etc. Under this circumstance, an attempt was made to prepare a Design Guideline with an intention to have a unified approach or concept for the design of river bank protection work.

Different Text Book, Manual, Guideline, Journal, Model Test Report and experience from different projects of BWDB are discussed and considered. After a series of discussion meeting among the Design Engineers of BWDB, this Design Guideline was finalized. List of Design Engineers of BWDB who contributed to prepare this Design Guideline are enclosed herewith.

Different Text Book, Manual, Guideline, Model Test Report etc. shall also be studied in addition to this Guideline during design.

(Md. Harun ur Rasheed)
Chief Engineer, Design
BWDB, Dhaka

Memo no- 1043 /CE, D Date : 11-04-2021

Copy forwarded with a copy of Design Guideline for favour of kind information and necessary action to: -

1. ADG, Planning/East/West, BWDB, Dhaka.
2. Chief Engineer, Planning, BWDB, Dhaka.
3. Superintending Engineer, Design circle 1/2/4/5/6/7/8/9, BWDB, Dhaka. He is requested to circulate it among all EE, SDE & AE under his circle.
4. Superintending Engineer, Planning 1/2/3, BWDB, Dhaka.
5. CSO to DG, BWDB, Dhaka.

(Md. Harun ur Rasheed)
Chief Engineer, Design
BWDB, Dhaka.

Design Guidelines for River Bank Protection Work

1. Study DPP provision and guideline.
2. Study Feasibility Study or Technical Committee Report provision.
3. Identify the alignment and length on Google Map. Check it with field Data.
   Length : A Sustainable Length shall be selected.
   a. Braided River : Minimum Length shall be extended up to which erosion is ceased.
   b. Meandering River : Length shall be extended up to that point where Thalweg shifted to other bank.

   Length shall be selected in a holistic approach following the concept of Delta Plan 2100. If the length submitted by Field office are insufficient, then give a 'Note' in the design by mentioning that "for sustainable bank protection, minimum …….m protection is needed. Requested to send the rest data for design and included it in DPP".

4. Design Data
   a. Discharge : Yearly Maximum
      i. Major River 1:100 or 1:50 years
      ii. Medium River 1:20 years
      iii. Minor River 1:20 years or Bankfull Discharge
      iv. In case of no Discharge Data : survey the cross-section, measure the velocity. Q = A V
      v. Velocity may be measure by float method, if current meter is not available.
      vi. If it is not possible to measure the Velocity, then 2.00-3.00m/s may be assumed.
      vii. In Coastal Area, data may be collected from the Model output.

   b. High Water level : Yearly Maximum
      i. Major River 1:100 or 1:50 years
      ii. Medium River 1:20 years
      iii. Minor River 1:20 years or Bankfull Level
      iv. In case of no Water level Data : May be collected site survey & asking local people.
      v. Data May be collected from BIWTA.

   c. Low Water level
      i. Average water level in the dry months i,e average water level from December to April.

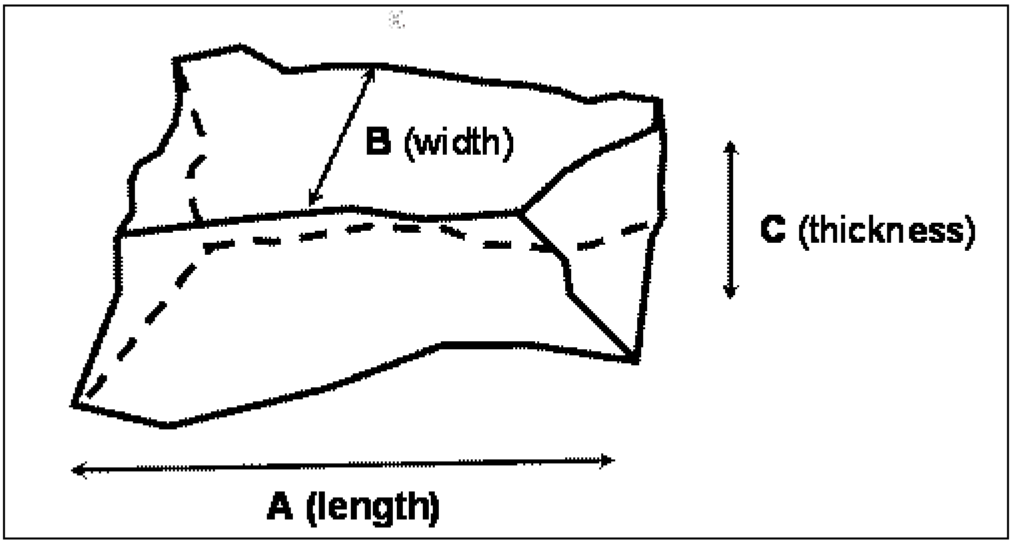
   d. <u>Frequency Analysis</u>
      i. Gumbel's Distribution
      ii. Log Normal Distribution
      iii. Log-Pearson Type III (LP3) Distribution

   e. Normally for Frequency Analysis Gumbel's Distribution is used.

f. Velocity, Wind Speed, Wind Duration, Wave period, Wave Height, Fetch Length etc.
g. D_{50} of river bed material
h. Cross Section of river
i. Index map, Site Plan
j. Soil Bore log
   i. Two Bore log in a section, one on the bank, other in river bed
   ii. Determine Depth of Bore log from Scour Depth.

5. Shape Factor of Protection Material

The shape of a stone can be generally described by designating three axes of measurement: Major, intermediate, and minor, also known as the "A, B, and C" axes, as shown in Figure.



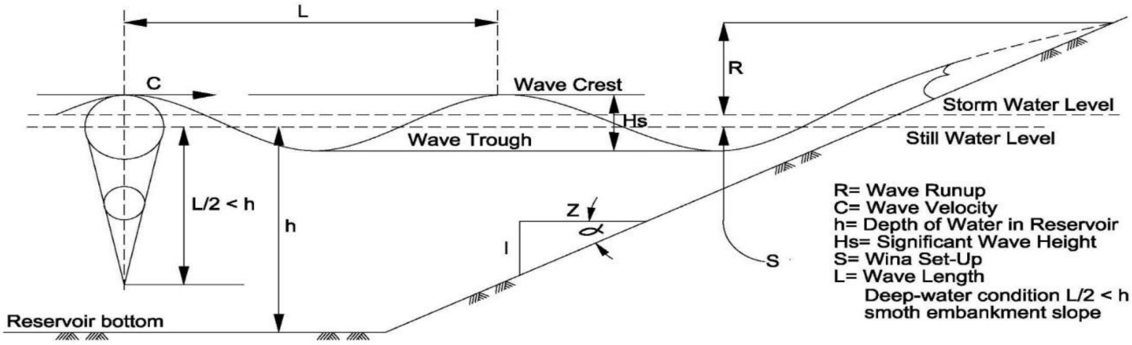
Riprap stones should not be thin and platy, nor should they be long and needle-like. Therefore, specifying a maximum allowable value for the ratio A/C, also known as the shape factor, provides a suitable measure of particle shape, since the B axis is intermediate between the two extremes of length A and thickness C. A maximum allowable value of 3.0 is recommended.

$$\frac{A}{C} \leq 3.0$$

The theory or formula of Boulder are adopted for cubical shape CC Block as it has resemblance with Boulder. The shape factor shall be taken into consideration for design of protection material.

6. Wave

The primary variables used in describing waves are wavelength L (the horizontal distance between wave crests), height H (the vertical difference between the wave crest and adjacent trough) and period T (the time between successive crests). The wave speed, or celerity, is the wave length divided by the period (= L/T). Another factor that affects wave height is the still-water depth D, which is the depth of water if there were no waves.



Waves are classified as deep, transitional and shallow water waves. For deep water waves, the wave height is virtually unaffected by the depth and the wave celerity is unaffected by the bottom. For transitional water waves the bottom has some effect on the wave height and celerity. For shallow water waves the celerity is only a function of depth. If the water depth is greater than 0.5 times the wave length, it is considered a deep water wave. If the water depth is less than 0.04 times the wave length, it is a shallow water wave. Transitional water waves are in the range between 0.04 and 0.5 times the water depth.

Waves that are produced by wind are affected by the wind speed, wind duration and fetch. Fetch is the distance that an unobstructed and constant wind, both in terms of speed and direction, acts over a body of water. Land is an absolute limit to fetch but changes in water depth and wind direction can also limit fetch. For very large bodies of water, the change in wind directions due to the circular wind field of a hurricane can limit fetch.

Breaking Wave : A breaking wave is one whose base can no longer support its top, causing it to collapse. A wave breaks when it runs into shallow water, or when two wave systems oppose and combine forces. When the slope, or steepness ratio, of a wave is too great, breaking is inevitable.

Individual waves in deep water break when the wave steepness—the ratio of the wave height H to the wavelength λ—exceeds about 0.17, so for $H > 0.17\,\lambda$. In shallow water, with the water depth small compared to the wavelength, the individual waves break when their wave height H is larger than 0.8 times the water depth h, that is $H > 0.8\,h$. Waves can also break if the wind grows strong enough to blow the crest off the base of the wave.

In shallow water the base of the wave is decelerated by drag on the seabed. As a result, the upper parts will propagate at a higher velocity than the base and the leading face of the crest will become steeper and the trailing face flatter. This may be exaggerated to the extent that the leading face forms a barrel profile, with the crest falling forward and down as it extends over the air ahead of the wave.

Significant Wave Height : Hs = $H_{1/3}$, defined as the average of the highest one third of the waves during the peak of the storm usually 1 – 3 hours long. Hs corresponds closely to the visual estimate of wave height in a sea state.

The ***Coastal Engineering Manual*** provides a simplified wave prediction method which is suitable for most riprap sizing applications. The method is described as follows:

Step 1: Estimate the wind speed, fetch length, and still water depth (USACE Coastal Engineering Manual).

Step 2: Calculate the drag coefficient (C_d) :

$$C_d = 0.001 \times (1.1 + K_u V_{wind})$$

where:

C_d = Coefficient of drag, dimensionless

V_{wind} = Sustained design wind velocity measured at 10 m height, ft/s (m/s)

K_u = Coefficient equal to 0.0107 for wind velocity in ft/s, and 0.035 for wind velocity in m/s

Step 3: Calculate the friction velocity (u_*):

$$u_* = V_{wind} \sqrt{C_d}$$

where:

u_* = Friction velocity, ft/s (m/s)

Step 4: Calculate dimensionless fetch length ($\hat{X}$) :

$$\hat{X} = \frac{gX}{u_*^2}$$

where:

$\hat{X}$ = Dimensionless fetch length

g = Gravity constant, 32.2 ft/s^2 (9.81 m/s^2)

X = Actual fetch length, ft (m)

Step 5: Calculate dimensionless wave height ($\hat{H}$) :

$$\hat{H} = 0.0413(\hat{X}^{0.5})$$

where:

$\hat{H}$ = Dimensionless wave height

$\hat{X}$ = Dimensionless fetch length

Step 6: Calculate the significant wave height (H_s) :

$$H_s = \frac{\hat{H}(u_*^2)}{g}$$

where:

$\mathbf{H_s}$ = Significant wave height, ft (m)

$\hat{H}$ = Dimensionless wave height

Step 7: Calculate the dimensionless wave period ($\hat{T}_p$):

$$\hat{T}_p = 0.751(\hat{X}^{0.33})$$

where:

$\hat{T}_p$ = Dimensionless wave period

$\hat{X}$ = Dimensionless fetch length

Step 8: Calculate the wave period (T) :

$$T = \frac{\hat{T}_p (u_*)}{g}$$

where:

T = Wave period, sec

$\hat{T}_p$ = Dimensionless wave period

Step 9: Check the calculated wave height vs. still water depth:

If H_s is greater than 0.8 times the still water depth (d), use H_s = 0.8d.

Note : ***If Significant Wave Height and Wave Period are not available from field, then above formula may be used. If data from field are supplied, then above formula may be used for cross check.***

7. Two issues in Design of Protective Work
   a. Hydraulic Issues
   b. Geotechnical Issues

8. Stability of Protection Material

   Besides other, Force acting on Protection Material

   a. Wave attack
   b. Current attack

   All these forces are encountered by self-weight of Protection Material.

9. Size of Protection Material : above LWL

   a. Stability Under Wave attack
   b. Stability Under Current attack

<u>Protection Material :</u>

Boulder/ Hard rock : Shall be used in Gradation. Gradation may be as below :

22-30cm	30%	or	30-45 cm	40%
30-45 cm	30%		45 above	60%
45 above	40%			

CC Block : Normally use, 1 size.
2 size may be used to create roughness against wave and velocity.

Geobag : Use for temporary slope protection only or to prevent Bank Line shifting before pitching work by CC Block or Boulder or Hard Rock.
1 size shall use.
Use either 1 layer with 15% overlapping or 1 layer with Geotextile filter. More layer may be used, if designer opted for higher safety or sustainability.

10. Size of Protection Material : below LWL

    a. Stability Under Current attack

<u>Protection Material</u>

Boulder/ Hard rock : Shall be used in Gradation. Gradation may be as below :

22-30cm	30%	or	30-45 cm	40%
30-45 cm	30%		45 above	60%
45 above	40%			

CC Block : Normally use, 2 size.
Minimum difference between 2 size shall be 100mm.
Minimum size of CC Block is 30 x 30 x 30 cm
If 30 x 30 x 30 cm Block are used, then it shall be used in lower layer.

Geobag : 1 size shall use.

11. Stability Under Wave attack

a. Pilarczyk (1990)

$$D_n \geq \frac{H_s \cdot \xi_z^b}{\Delta_m \cdot \Psi_u \cdot \phi_{sw} \cdot \cos\alpha}$$

Where

Dn	[m]	characteristic size of the revetment cover layer (single unit size for loose elements, thickness for mattress systems)
Hs	[m]	significant wave height
Δ_m	[-]	relative density of submerged material = $(\rho_s-\rho_w)/\rho_w$
g	(m/s^2)	acceleration due to gravity (= 9.81)
$\varnothing_{sw}$	[-]	stability factor for wave loads
Ψ_u	[-]	system specific stability upgrading factor
α	[°]	bank normal slope angle
ξz	[-]	wave breaker similarity parameter= $\tan\alpha \cdot \frac{1.25 \cdot T_m}{\sqrt{H_s}}$
T_m	[s]	mean wave period
b	[-]	wave structure interaction coefficient, dependent on roughness and porosity of protective material

The formula is restricted to values ξz <3 and cotα ≥ 2, i.e. to plunging breakers, which generate high local pressure heads. Otherwise overestimation of the unit size is likely, because dynamics of the breaking process are diminishing.

Wave Type after Pilarczyk			
	ξ z <	0.5	Spilling
0.5	< ξ z <	2.5	Plunging
2.5	< ξ z <	3.5	Collapsing
	ξ z >=	3.5	Surging

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In the formula 'b' is the exponent related to the interaction between waves and revetments (0.5 ≤ b ≤ 1.0). For rough and permeable revetments, b = 0.5, for smooth and less permeable placed-block revetments it is close to unity. For other systems b = 0.67 may be applied. Ψ_u is the system specific stability upgrading factor.

Table : Coefficients for design of various cover materials against wave attack

Revetment type	Stability factor for incipient motion φ[-]	Stability upgrading factor, Ψ_u [-]	Interaction coefficient, b [-]
Randomly placed, broken riprap and boulders	2.25-3.00	1.00-1.33	0.50
CC blocks, cubical shape, randomly placed in multi-layer	2.25-3.00	1.33-1.50	0.50
CC blocks, cubical shape, hand placed ,single layer (geotextile filter)	2.25	2.00	0.67 - 1.00
CC blocks, cubical shape, hand placed in single layer, chess pattern (geotextile on sand)	2.25	1.50	0.67 - 1.00

CC blocks cable connected	2.25	1.80	0.67
Wire mesh mattress	2.25	2.50	0.50
Gabions/mattress filling by stone	2.25	2.50	0.50

(2) Hudson

$$W = \frac{H_s^{\,3} \cdot \rho \cdot \tan\alpha}{k \cdot \Delta_m^{\,3}}$$

(3) Iribarren

$$W = \frac{f \cdot H_s^{\,3} \cdot \rho}{\Delta_m^{\,3}(\cos\alpha - \sin\alpha)^3}$$

Where

W	(kg)	weight of revetment material
H_s	(m)	significant wave height
α	(°)	bank slope angle
f	(-)	coefficient related to the amplitude of the wave and slope angle
Δ_m	(-)	relative density of submerged material = $(\rho_s - \rho_w)/\rho_w$
ρ_s	(kg/m^3)	density of protection material
ρ_w	(kg/m^3)	density of water
k	(-)	coefficient varying from 3.2 for smooth quarry stone to 10 for tetrapods

Values of Stability Coefficient K_D	K_D	
Rock : Breaking Wave	2.00	
Non Breaking Wave	4.00	
Cube : Breaking / non breaking wave	6.50	7.50
Tetrapods :	7.00	8.00
Dolosse :	15.80	31.80
JMREMP Manual	3.20	10.00

(4) California State Highways: (in FPS unit)

$$W = \frac{2.31 \times 10^{-3} \cdot S_s \cdot Hs^3}{(S_s - 1)^3 \cdot \sin^3(70 - \alpha)}$$

12. Stability Under Current attack

(1) Pilarczyk

$$D_n \geq \frac{0.035 \cdot \overline{u}^2}{\Delta_m \cdot 2g} \cdot \frac{\phi_{sc} K_\tau K_h}{K_s \cdot \Psi_{cr}}$$

Where,

D_n	(m)	Equivalent diameter (cover layer)
Δ_m	(-)	$(\rho_s - \rho_w)/\rho_w$ = relative density of submerged material
ρ_s	(kg/m^3)	density of protection material

ρ_w	(kg/m^3)	density of water
$\bar{u}$	(m/s)	depth averaged mean flow velocity;
g	(m/s^2)	acceleration due to gravity
φ_{sc}	(-)	stability factor for current
K_τ	(-)	turbulence factor
K_h	(-)	depth factor, dependent on the assumed velocity profile and water depth (h) to equivalent roughness height ratio.
K_s	(-)	Slope parameter
Ψ_{cr}	(-)	critical Shield`s parameter,
α	(°)	slope angle of bank or structure
θ	(°)	angle of repose considering the material specific internal friction

The stability of revetment elements also depends on the slope gradient under which the revetment is applied in relations to the angle of internal friction of the revetment. This effect on the stability is taken into account with the slope parameter K_s, which is defined as

$$K_s = \sqrt{1-\left(\frac{\sin\alpha}{\sin\theta}\right)^2} \quad \text{where } \theta > \alpha$$

or, $K_s = \cos \alpha_b$

α_b = slope angle of the river bottom (parallel to the flow)

Type of Protection Material used	Shields parameter	Angle of repose (°)		Bed roughness factor, Kr
	ψ_{cr}	Geotextile filter	Granular filter	
CC Block, hand place,single layer	0.05	20	25	0.1
CC Block, multi layer	0.035	30	35	1
Stone Boulders/Rock	0.035	40	40	2
Geobag (filled with dry sand)	0.05	35	35	1
CC Block, Cable connected	0.06	20	25	
Gabion / Mattress filled with stones	0.09	45	45	
Wire Mesh Mattress filled with brick	0.07	20	25	

Table : Values of stability factor (Pilarczyk 1998)

Revetment Type	Stability factor φ_{sc}	
Cover layer	Continuous protection [-]	Exposed edges transitions [-]
Randomly placed, broken riprap and boulders	0.75	1.5
CC blocks, cubical shape, randomly placed in multi layer	0.80	1.50
CC blocks, cubical shape hand placed in single layer chess pattern	0.65	1.25
Riprap and placed blocks; Sand fill units	1.0	1.50
Block mats, gabions, washed-in blocks, geo-bags, concrete filled geo-bags and geo-mattresses, wire-mesh mattress	0.5	1.00
Gabions/ mattress filling by stones	0.75	1.5

Table : Turbulence Intensity Factor K_τ (current) (FAP 21/22)

Turbulence Intensity	K_τ (-) Gabions, Mattresses	K_τ (-) Others
Normal turbulence in rivers	1.0	1.0
Non-uniform flow with increased turbulence, mild outer bends	1.0	1.5
High turbulence, local disturbances, sharp outer bends	1.0	2.0
Jet impact, screw race velocity, hydraulic jump	3.0 - 4.0	3.0 - 4.0

With the depth parameter K_h, the water depth is taken into account, which is necessary to translate the depth averaged flow velocity into the flow velocity just above the revetment. The depth parameter also depends on the measure of development of the flow profile and the roughness of the revetment. Logarithmic velocity profiles exist for long stretches with constant bed roughness. For most engineering works as bottom protection or slope protection, the non developed velocity profile is usually present. K_h is the coefficient due to conversion from the local mean bottom velocity to mean velocity ū.

The following formulas for K_h are recommended (Pilarczyk 2008):

Fully developed profile: $K_h = 2 \cdot \left[\log\left(1 + \frac{12h}{k_s}\right) \right]^{-2}$

Non-developed profile: $K_h = \left(1 + \frac{h}{k_s}\right)^{-0.2}$

Very rough flow ($h/k_s < 5$): $K_h = 1$

Where, h is the water depth (m), in the case of dimensioning the revetments on a slope, the water level at the toe of the slope must be used for h.

k_s is the bed roughness (m) given approximately by:
$k_s = 0.1D$ for smooth units (i.e. pitched concrete blocks),
$k_s = D$ for block mats, and
$k_s = (1 \text{ to } 3)D_n$ (rough units, i.e. rock).

For riprap, k_s is equal usually to twice the nominal diameter of the stones ($k_s \approx 2D_n$),
for bags it is usually equal to the thickness (d),
for mattresses it depends on the type of mattress:
k_s of about 0.05 m for smooth types and about the height of the rib for articulating mats.

Note: usually $12h/k_s$ is applied, however, by using $(1+12h/k_s)$ the discontinuity at small values of h can be avoided; the same adjustment is also applied for other velocity distributions. The effect of this additional (imaginary) depth practically vanishes for $h/k_s>2$ (after Pilarczyk 2008).

(2) Isbash

$$W = \frac{4.1 \times 10^{-5} \cdot S_s . V^5}{(S_s - 1)^3 \cdot \cos^3 \alpha}$$

(3) California State Highways:

$$W = \frac{2 \times 10^{-5} \cdot S_s \cdot V^6}{(S_s - 1)^3 \cdot \sin^3(70 - \alpha)}$$

(4) PIANC

$$D_n = \frac{0.70\,V^2}{g\,(S_s - 1)\cdot \cos\alpha\left[1-\left(\tan^2\alpha/\tan^2\theta\right)\right]^{0.5}}$$

(5) JMBA

$$D_n = \frac{0.7V^2}{2\cdot(S_s - 1)\cdot g}\cdot\frac{2}{\log(6h/D)^2}\cdot\frac{1}{\left[1-(\sin\alpha/\sin\theta)^2\right]^{0.5}}$$

(fps or metric unit) (the equation has been developed for cc blocks)

In these equations:

W	(kg or lb)	weight of Individual stone
D	(ft or m)	diameter of stone
Dn	(ft or m)	dimension of cube
V	(ft/s or m/s)	mean velocity at the adjacent channel
h	(ft or m)	depth of water
S_s	(-)	specific gravity of stone
α	(°)	slope of bank
θ	(°)	angle of repose of revetment material
Ψ	(-)	Shield's parameter
g	(m/s^2 or ft/s^2)	gravitational acceleration

Note : PIANC gives excessive large size. Not recommended.

13. Thickness of Riprap for Pitching Work above LWL

Opinion of different authorities and professionals regarding the thickness of slope pitching are given below.

a) U.S. Army Corps of Engineers (1991), recommends that thickness of protection should not be less than the spherical diameter of the upper limit W_{100} (percent finer by weight) stone or less than 1.5 times the spherical diameter of the upper limit W_{50} stone, whichever results in greater thickness.

Used to determined thickness US Army Corps				
	From Table 10.3, Page 208, Neil			
Velocity	W_{100} %		W_{50} %	
m/s	mm	kg	mm	kg
upto 3.05	0.450	136.08	0.300	36.29
upto 3.96	0.750	680.40	0.500	181.44
upto 4.57	1.200	2268.00	0.750	680.40
1 lb = 0.4536 kg				

b) California Highway Division (1991) recommended that there should be at least two layers of overlapping stones so that slight loss of materials does not cause massive failure.

c) ESCAP (1973) recommends that thickness of protection should be at least 1.5D, where D is the diameter of the normal size rock specified.

d) Inglis (1949) recommended following formula to compute thickness of protection required on the slope of revetment,

$$t = 0.06\ Q^{1/3}$$

Where,

t	(m)	thickness of stone riprap
Q	(m^3/s)	discharge

The Inglis formula apparently gives excessive thickness for higher discharge.

e) The thickness of stone pitching and soling for permanent slopes required at head, body and tail of guide bank for river flowing in alluvial plains as recommended by Gales (1938).

River	Rivers with discharge 0.25 to 0.75 million cusec		Rivers with discharge 0.75 to 1.50 million cusec		Rivers with discharge 1.50 to 2.50 million cusec	
Parts of guide bundh	Head	Body and Tail	Head	Body and Tail	Head	Body and Tail
Pitching stone	3′-6″	3′-6″	3′-6″	3′-6″	3′-6″	3′-6″
	1.07 m	1.07 m	1.07 m	1.07 m	1.07 m	1.07 m
Thickness of soling ballast	7″	7″	8″	8″	9″	9″
Total thickness	4′-1″	4′-1″	4′-2″	4′-2″	4′-3″	4′-3″

Thickness suggested by Gales is 1.07m. This Thickness suggested by Gales is valid for discharge from 7086 cumec to 70860 cumec.

f) Thickness of Stones on Slope as per Spring

River bed materials as classified by Springs	Thickness in inches for river slopes in inches per mile					Remarks
	3	9	12	18	24	
Very Coarse Coarse Medium Fine Very Fine	16 22 28 34 40	19 25 31 37 43	22 28 34 40 46	25 31 37 43 49	28 34 40 46 52	The stone pitch prevents sand underneath from being sucked out by high velocity. More rationally stone pitch thickness should be based on velocities.

(Thickness suggested by Spring varies from 0.40m to 1.30m)

Note: The thickness suggested above, should be increased by 50% when the riprap is placed under water to provide for uncertainties associated with the type of placement (US Army Corps of Engineers).

g) NCHRP Report 568 :

- Layer thickness should not be less than the spherical diameter of the D_{100} stone nor less than 1.5 times the spherical diameter of the D_{50} stone, whichever results in the greater thickness.
- Layer thickness should not be less than 1 ft (0.30 m) for practical placement.
- Layer thickness determined either by criterion 1 or 2 should be increased by 50% when the riprap is placed underwater to compensate for uncertainties associated with this placement condition.

14. Thickness for CC Block

- The above recommendations are for boulder. Due to resemblance of cubical shape CC Block with boulder, the above recommendations are adopted for CC Block.

- USACE, ESCAP, California Highway Division, NCHRP recommended thickness equal to larger Size, 1.5 layer & 2 layers for boulder etc.

- For Pitching work above LWL, BWDB adopted 1 layer of CC Block. Size of CC Block is determined in such a way that it is not washed out by wave & current attack. 3 layers of filter are used so that soil beneath the Pitching Block are not comes out.

- BWDB adopted minimum 2-layer thickness for CC Block below LWL.

15. Scour Depth:

Lacey's regime formula is used to find out scour depth. This empirical regime formula is:

$$R = 0.47\,(Q/f)^{1/3}$$
$$D_s = XR - h$$

Where, D_s (m) Scour depth at design discharge
Q (m^3/s) Design discharge
f (-) Lacey's silt factor = $1.76\,(d_{50})^{1/2}$
d_{50} (mm) Median diameter of sediment particle
X (-) Multiplying factor for design scour depth
h (m) Depth of flow, may be calculated as (HFL-LWL)

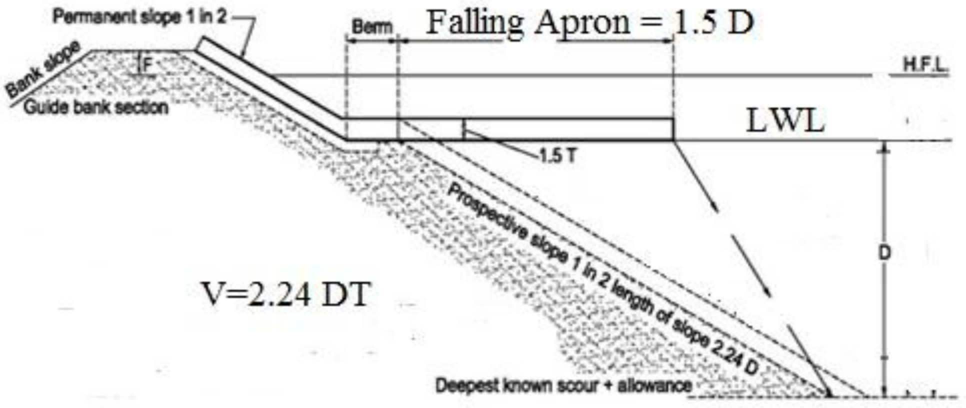
Table : Multiplying Factors for Maximum Scour Depth by Lacey's approach and Size of bed material.

Nature of location	Factor (X)
Straight reach of channel	1.25
Moderate bend	1.50
Severe bend	1.75
Right angle abrupt turn	2.00
Noses of piers	2.00
Alongside cliffs and walls	2.25
Noses of guide banks	2.75

Oblique Flow : Multiplying factor for design scour depth, X =2.00

Size of bed material	
Silt factor, f	D_{50} (mm)
0.4	0.052
0.5	0.081
0.6	0.116
0.7	0.158
0.8	0.207
1.0	0.323

16. Dumping Volume



D = Scour Depth
T = Thickness of Prospective protection

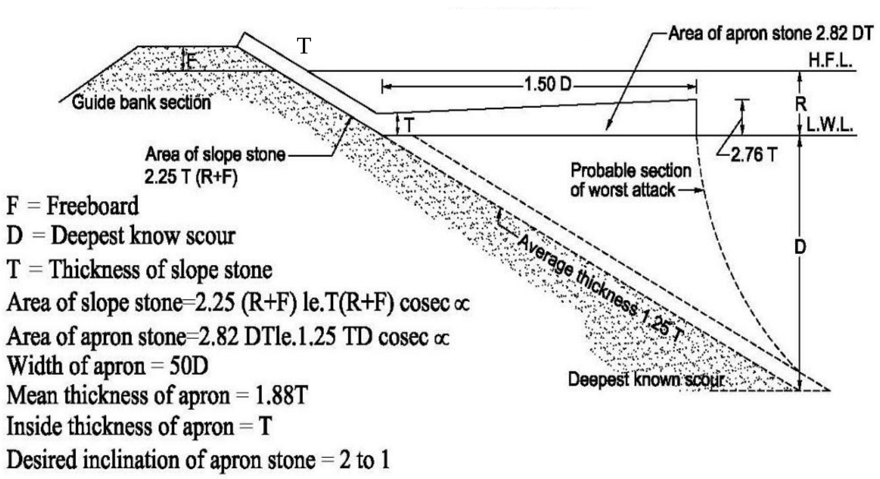
Length of Falling Apron = 1.5 D
Thickness of Falling Apron = 1.5 T

Dumping Volume, V = 2.24 DT, assuming that material will be launch in 2:1 slope.

Among the various methods, launching apron or falling apron has been considered to be most economic and common method of toe protection of revetment. Falling aprons are generally laid horizontally on flood plain/river bed at the foot of the revetment, so that when scour occurs, the material will launch and will cover the surface of the scour hole in a natural slope.

17. Distribution of Dumping Material

a. Shape of apron suggested by Spring (1903)

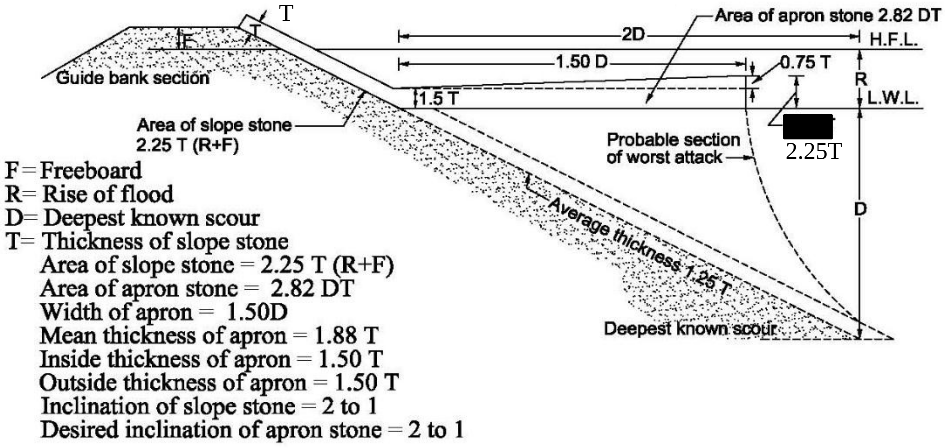


Spring recommended a minimum thickness of underwater protection equal to 1.25 times the thickness of stone riprap of the slope of revetment.

If the thickness of slope protection is T, then thickness of protection after launching will be 1.25T.

So, here Dumping Volume, V = 2.24 * D * (1.25T) = 2.82 DT

b. Shape of apron suggested by Rao (1946)



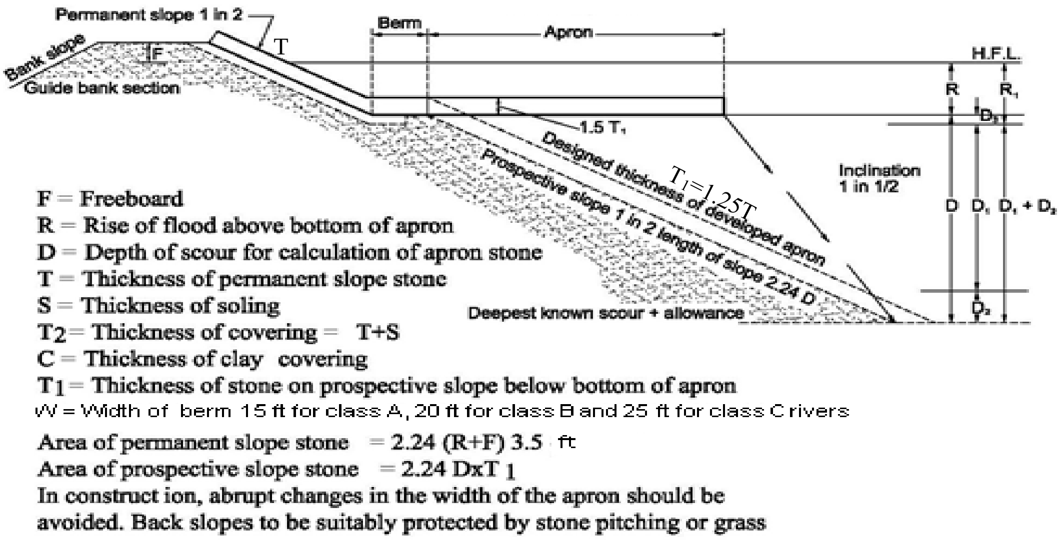
Since Apron stone has to be dumped under water and cannot be hand placed, thickness of apron at junction should be 1.5 times thickness of slope protection T.

Thickness of pitching work is T

Dumping Volume, $V = ½ (1.5 + 2.25) T * (1.5D) = 2.82 DT$

Thickness of protection after launching is 1.25 T.

c. Shape of apron suggested by Gales (1938)



Thickness of Pitching Stone = T

Thickness of Stone on Prospective Slope, $T_1 = 1.25 T$

Width of Falling Apron = 1.5 D

So, Dumping Volume, $V = 2.25DT_1 = 2.25 D *(1.25T) = 2.82 DT$

18. Prospective Thickness and volume for Dumping Material (Boulder & CC Block)
    a. Spring, Rao & Gales recommends Prospective Thickness for under water slope protection is 1.25 times the thickness of Pitching Stone.
    b. Dumping Volume is same in all the three distribution.

Thickness of Pitching work = T
Thickness on Prospective Slope after launching, $T_1 = 1.25$ T
Thickness of Falling Apron = 1.5 T_1
Width of Falling Apron = 1.5 D
Dumping Volume : $V = 2.25DT_1 = 2.25D * (1.25T) = 2.82$ DT
Or, $V = (1.5D) * (1.5T_1) = 2.25DT_1$
$= 2.25D * (1.25T) = 2.82$ DT

19. Thickness for Geobag coverage (from JMREMP Guidelines) :
    a. Systematic coverage of the bank slope by minimum three layers of geobag from the deepest part to the Low Water Line may provide a dependable protection;
    b. To ensure minimum two-layer coverage at least four layers of geobags need to be placed systematically.
    c. A 15 m wide falling apron at the end of Arial Coverage (average 45 m wide) towards the deeper section of the river shall be built to attain a sustainable protection. The thickness of falling apron shall be at least 0.50 m or 3 layers of geobag.

20. Thickness of Geobag in Areal Coverage

a) From the Recommendation of JMREMP Guidelines

3 layer Geobag provides a dependable protection.

To attain 3-layer coverage, 5-layer Geobag shall be dumped systematically, considering different uncertainties such as velocity, depth of water, direction of flow, position of geobag after dumping etc.

Thickness of 5-layer Geobag = 5*0.167 = 0.835m.

b) *If we combine* JMREMP Guidelines and *US Army Corps of Engineers*

3-layer coverage (dependable protection) + 50% increase for uncertainties, then Thickness for Geobag = 3 * 1.5 = 4.5 layer,
say 5-layer Geobag = 5*0.167 = 0.835m

21. Thickness of Geobag for Falling Apron

From the Recommendation of JMREMP Guidelines

3 layer Geobag provides a dependable protection i,e thickness of prospective slope coverage, T = 3 layer.

Thickness of Falling Apron = 1.5 T = 1.5 * 3 = 4.5 layer, say 5 layer
Thickness of 5-layer Geobag = 5*0.167 = 0.835m.

Width of Falling Apron = 1.5 D
Dumping Volume, V = (1.5D) * (***5-layer***) = (1.5D) * (***0.835***)

22. Thickness for Mixed Material

When CC Block and Geobag are mixed for under water protection, then ratio of mixture shall be 50:50 by volume. This ratio was fixed according to Model Test in RRI. In this situation minimum thickness for protection shall be 1.00m.

Advantage : In the first year, it became difficult to manufacture large quantity of CC block. In this situation, Geobag provide the initial coverage.
Geobag act as a filter layer.
Geobag prevent the bed material to comes out.

CC block provides a protection for Geobag and act as a cover layer to some extent.

Areal Coverage:

When Thickness of Protection, t = 1.00m

0.50m CC Block, 0.50m Geobag

CC Block					Remark
t = 0.50 m, Volume = 0.50 cum/sqm/m					
Size of Block	Calculated	Provided			
	nos./sqm	nos./sqm	Volume	Total Volume	
0.40 m 0.30 m	4.69 7.41	4.5 7.5	0.288 0.203	0.491	Roughly creates 2 layer coverage
0.45 m 0.35 m	3.29 4.66	3.5 4.5	0.319 0.193	0.512	
0.50 m 0.40 m	2.40 3.13	2.5 3	0.313 0.192	0.505	

Geobag : t = 0.5m, Volume = 0.50 cum/sqm/m					
250kg (nos./sqm)		175kg (nos./sqm)		125kg (nos./sqm)	
Calculated	Provided	Calculated	Provided	Calculated	Provided
3.00	3	4.30	4.3	5.95	6

Falling Apron :

When Thickness of Protection, t = 1.50m

0.75m CC Block, 0.75m Geobag

CC Block : t = 0.75 m, Volume = 0.75 cum/sqm/m					Remark
Size of Block	Calculated	Provided			
	nos./sqm	nos./sqm	Volume	Total Volume	
0.40 m 0.30 m	7.03 11.11	7 11	0.448 0.297	0.745	creates 2 layer coverage

0.45 m 0.35 m	4.94 7.00	5 7	0.456 0.300	0.756	
0.50 m 0.40 m	3.60 4.69	3.5 4.5	0.438 0.288	0.726	

Geobag					
t = 0.75 m, Volume = 0.75 cum/sqm/m					
250kg (nos./sqm)		175kg (nos./sqm)		125kg (nos./sqm)	
Calculated	Provided	Calculated	Provided	Calculated	Provided
4.51	4.5	6.44	6.5	8.93	9

23. Protection through Adaptive Approach

A) <u>FRERMIP Approach :</u>

Protection work is done in three stage. This approach was proposed in Jamuna & Padma at Kukuria (15km), Enyatpur (7km), Benotia (3.50km) & Horirampur (4km).

a) Initial Protection :

i) <u>Above LWL :</u>

Use slope protection by Geobag.

Either 1 layer with 15% overlapping or 1 layer with Geotextile filter. More layer may be used, if designer opted for higher safety or sustainability.

ii) <u>Below LWL :</u>

On the basis of Calculated scour depth, quantity or amount of Initial protection work are determined. Initial Protection are done by Geobag.

Keep 2-5 % stockpile (depending on the site condition) to address the emergency situation, in case of delay in adaptation work. Later, this stockpile will be adjusted with adaptation work.

b) Adaption Work : During design phase, on the basis of some assumption, quantity or amount of Adaption Work are determined. Adaption Work are done by Geobag.

From a study in JMREMP, it was found that the trends of scour of Jamuna are normally 10m in one year. Considering this phenomenon of 10m scour depth, an Adaptation plan was prepared for design Phase, for Jamuna. This approach may be followed for other rivers.

But actual Location, Quantity, Areal Coverage, Falling Apron will be finalized from field survey data when Adaptation will be needed. But it is a difficult job.

c) After completion of Adaption work

- 2 layer (or 0.50m) CC Block may be dumped, depending on site condition.
- Pitching work by CC block above LWL shall be done.

Example :

Calculated Scour Depth = 35m from LWL
Scour Depth = 32m from existing bed level
Assume Scour in 3 stage, i,e 12 + 10 + 10 =32m

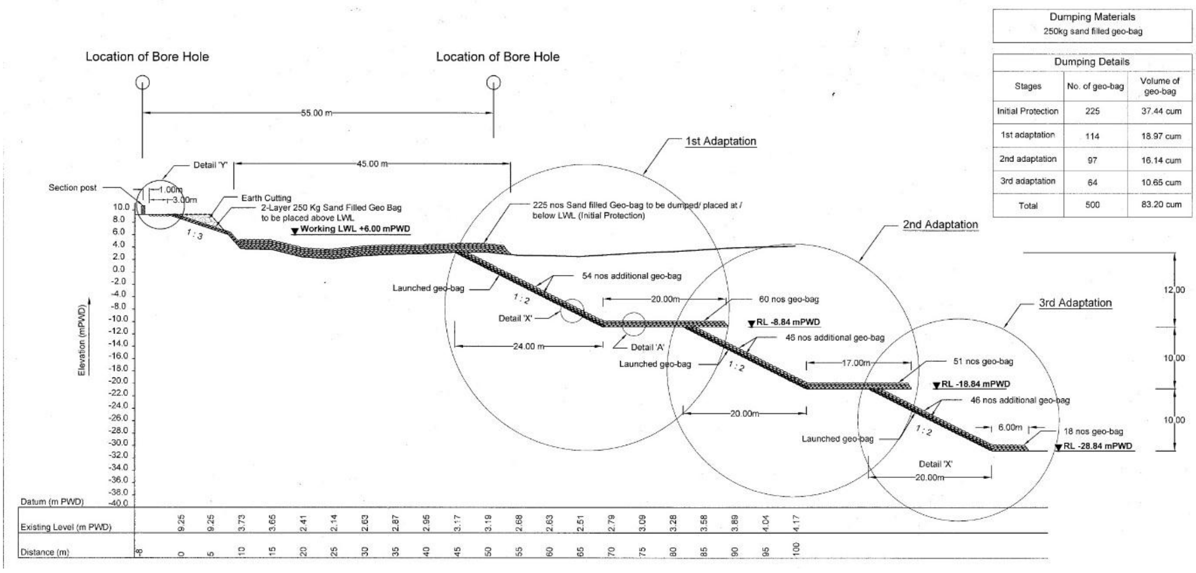
Stage 1 : Initial Protection :
D= Scour Depth from LWL
Width of Falling Apron = 1.5 D
T = Thickness, 5 layer Geobag
V = 1.5 D * (5 layer Geobag)

Stage 2 : 1st Adaptation :
D= 12m (assumed)
2-layer Areal Coverage over scoured slope = 2.24*12*(2 layer)
Assume Scour Depth for 2nd Adaption is 10m
Falling Apron = 1.5D = 15m + 2m (extra) =17m
Volume = 17*(3 layer).

Stage 3 : 2nd Adaptation :
D= 10m
Areal Coverage over scoured slope, 2 layer = 2.24*10*(2 layer)
Assume Scour Depth for 3rd Adaption =10m
Falling Apron = 1.5D = 15m+ 2m (extra) =17m
Volume = 17*(3 layer).

Stage 4 : 3rd Adaptation :
Assume, Calculated Scour Depth = 35m from LWL
Assume, Scour Depth = 32m from Present Bed Level

Depth needed to reach Final Scour Depth = 32 –(12+10) = 10m
Areal Coverage over scoured slope, 2 layer = 2.24*10*(2 layer)
provide additional Apron = 6m
Volume = 6*(3 layer).



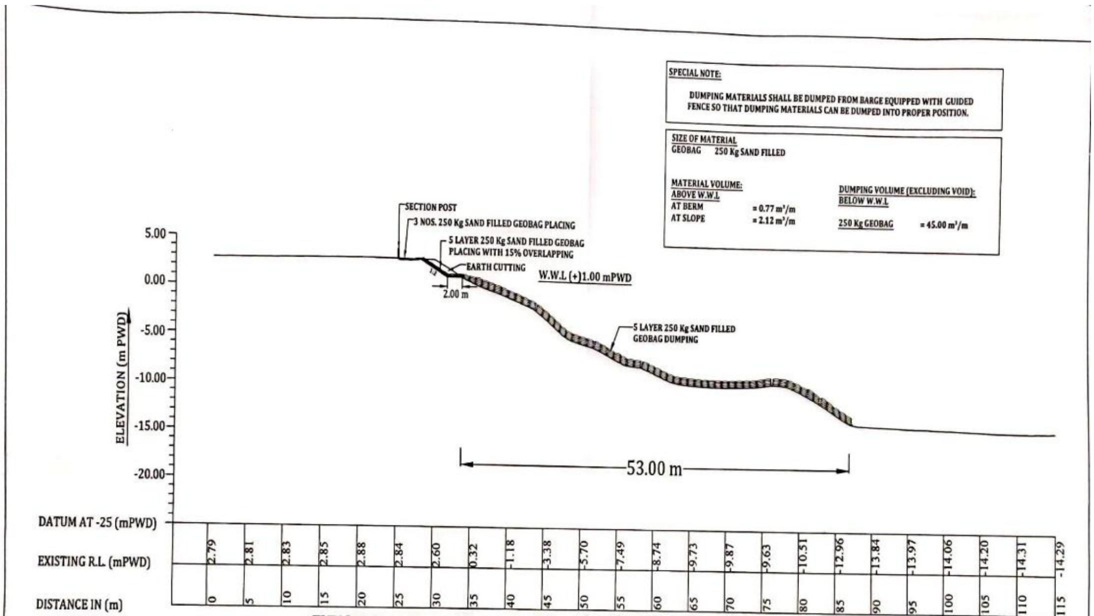
Note: ***Adaptation volume mentioned above are tentative one. Actual volume will be determined through field survey.***

Some important aspects Adaptation Work.

- Adaptation may be needed in second year or in third year and so on.
- In JMREMP, in Bera part (7km), which was completed on or before 2011, Adaptation not yet needed. This work still is in good condition.
- In JMREMP, in MDIP(11.40km), which was completed on or before 2011, Adaptation not yet needed. This work still is in good condition.
- In JMREMP, in Koijuri Part (10km), which was completed on or before 2011. Adaptation was needed, but could not be done, because of no project or no budget. The work is not in good condition.
- In FRERMIP, Trench 1, at Chouhali (5km), Horirampur (7km), Zafargonj (2km) Adaptation was needed, during first monsoon after completion and it was done. No remarkable damage observed during flood season of 2019 & 2020.

B) <u>River Stabilization Approach :</u>

- Protection work is done in two stage.
- To address the issue in a holistic approach.
- When relatively a long reach is needed for Protection.
- Time constraint for manufacturing of CC Blok is a major issue.
- Fund or Budget constraint is also an issue.
- It can be implement in two ways :
    1. In two phases
        - In First Phase, DPP will be prepared for initial protection only.
        - In Second Phase, DPP will be prepared for Adaptation & final work.
    2. Alternately DPP will be prepared for both initial protection and Adaptation & final work as we are doing now.



<u>TYPICAL SECTION OF PRECAUTIONARY BANK PROTECTION WORK ALONG THE BANKLINE</u>

1. This approach was proposed to address 26.40 km (in 5 spots) which will connect 60.44 km in the east coast of Bhola.
2. This approach was proposed to encircle whole Manpura Island, for a length of 37.74km.
3. This approach was proposed to address 7.50 km protection along the west bank of Jamuna on U/S of Sirajgonj Hardpoint.

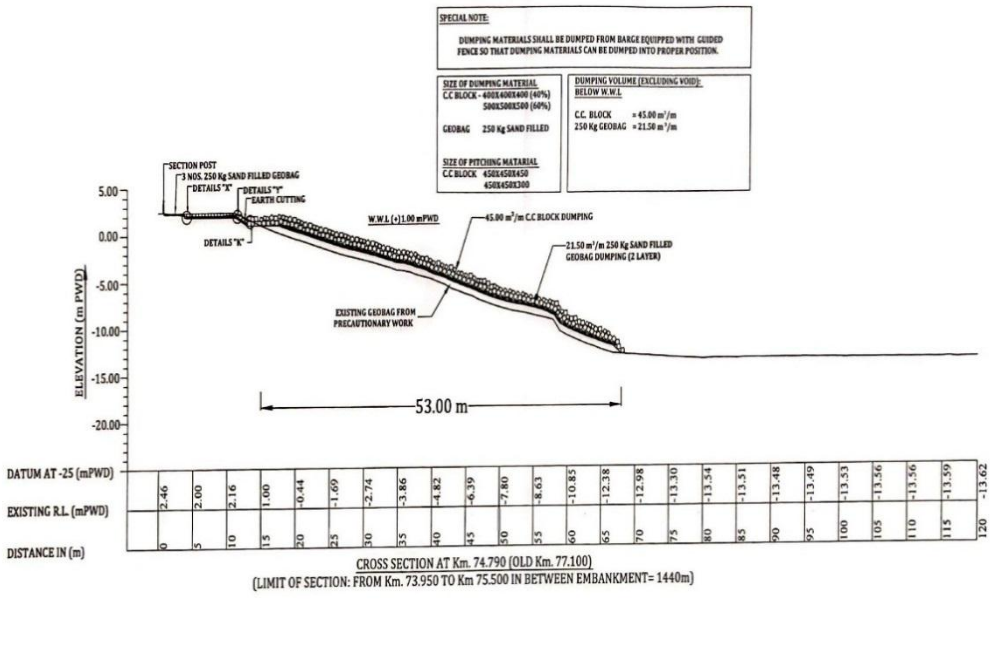
Procedure of Design & Implementation :

a) Initial Protection : On the basis of Calculated scour depth, quantity or amount of Initial protection work are determined. Initial Protection are done by Geobag.

   Above LWL :
   Use slope protection by Geobag.
   Either 1 layer with 15% overlapping or 1 layer with Geotextile filter. More layer may be used, if designer opted for higher safety or sustainability.

   Below LWL :
   D= Scour Depth from LWL
   Width of Falling Apron = 1.5 D
   T = Thickness, 5 layer Geobag
   V = 1.5 D * (5 layer Geobag)

   Keep 2-5 % stockpile (depending on the site condition) to address the emergency situation, in case of delay in adaptation work. Later, this stockpile will be adjusted with adaptation work.



CROSS SECTION AT Km. 74.790 (OLD Km. 77.100)
(LIMIT OF SECTION: FROM Km. 73.950 TO Km 75.500 IN BETWEEN EMBANKMENT= 1440m)

b) Adaption Work & Final Work:
   - 2-layer Geobag, to address the anticipated damage of Geobag, if needed.
   - Under water dumping of 2 layers CC Block over Geobag.
   - Pitching work by CC block above LWL

24. Geotechnical Issues
   a. Slope Stability Analysis : to determine stable slope above water & under water.

   b. Above water : Normally used Slope is 1V : 2H
      For Jamuna, Ganges & Meghna use 1V : 3H

      i. If it is unavoidable to prepare the slope as stated above, then use bullah or other protection measure against slope failure.
      ii. Always use Slope on Original Bank, by cutting earth.
      iii. Avoid making slope on filled earth. If it is unavoidable, then use bullah or other protection measure against slope failure.

   c. Under water : It is assumed that the material will launch on a Slope of 1V :2H

   d. Provide Berm at LWL or 1.50 m below LWL. Width of Berm shall be at least 1.50m to 2.00m.

25. Seepage Issue
   a. Three layers of filter are used :
      i. Sand Filter 100mm
      ii. Geotextile Filter 3mm
      iii. Granular Filter 100-150mm (khoa or pea gravels or stone chips)
   b. Filter Gallery may be used.
   c. Fill up the diches on C/S with local earth at least for 50 to 100m, before start of pitching work.

26. Stockpile

   Stockpile must be kept.
   Stockpile may be CC Block / Geobag / Boulder / Hard Rock
   Large River : 2 - 5% of Dumping Volume
   Medium River : 2 % of Dumping Volume
   Small River : 1- 2 % of Dumping Volume or may be decided on the basis of site condition

27. Miscellaneous Issue
   a. Compressive Strength of concrete of CC Block shall be 18 N/mm^2 for saline area and 12 N/mm^2 for Non-saline area.
   b. Life Time of Geobag shall be minimum of 30/50/100 years.
   c. Dumping shall be Complete by 30^{th} April.
   d. Dumping shall be done by Berge. A Dumping Plan shall be prepared.
   e. 1 Layer Geobag with 15% overlapping on slope above WL as a precautionary measure to prevent Bank Line Shifting.

or, 1 Layer Geobag with geotextile on slope above WL as a precautionary measure to prevent Bank Line Shifting.

f. Top of pitching Block must match with GL. Top block shall not obstruct free drainage or shall not cause water logging.

g. 2 to 3 Geobag shall place at the Top end of Pitching Block, when Bank Line is subjected to submergence.

h. Construction material shall not heap along Bankline. Water from curing or casting shall not allowed entire into bank slope. Proper drainage shall be ensured.

i. Excavated Earth of slope preparation shall not dump into river. It shall not be used to build key. Excavated Earth shall not heap along the Bankline. Key Shall not be constructed on Filled material.

j. Section post shall construct at each section at “Zero point of section or as shown in drawing”. All Monitoring survey or survey for repairing or rehabilitation or adaptation, shall use this “Zero point”.

k. Bathymetric survey shall be done from July to October at an interval of minimum 30days.

   Minimum 300m from bankline for Jamuna, Padma, Meghna, Teesta and Coastal large river.

   Minimum upto thalweg, from bankline for other rivers.

l. No Dredging shall be done within 1.00km from the “End of Apron” and U/S & D/S End of Protective Work for Jamuna, Padma, Meghna, Teesta and Coastal large river

   Location, length & alignment of dredging shall be selected carefully in consultation design office in the vicinity of Protective Work for other rivers.

m. Work shall be started, preferably from U/S.
n. Khal Crossing or Armoring.
o. Recreational Area, Stair, Changing Room etc.
p. Harbor area and capstan.
q. Plantation.
r. KM Post, Section post, Sign Board etc.

28. Maintain a file for Hard Copy of design.
Store all Soft copy. Create a Folder for individual “BWDB Division”. Store all soft copy by creating a Sub-Folder under the name of each Project.

29. For Design, BWDB Design Manual, Text Book, Other manual, Model Test Report etc. may also be followed in addition to this Design Guideline.

Annexure A

Some Observed Data

Velocity (m/s)			
	Bahadurabad	Baruria Transit	Mawa
June to September	Max =3.68 Min =3.00	Max =4.23 Min =3.00	Max =4.35 Min =3.02
Average =	3.28	3.37	3.45

Maximum Velocity : (from FAP 24)	
Jamuna	Kamarjani = 3.2 m/s Bahadurabad = 3.7 m/s
Ganges	Gorai oftake = 4.0 m/s

Design Velocity used in Padma Bridge, Mawa is 4.60 m/s

JMREMP Mannual (As per Halcrow)	Wind Speed	
	m/s	km/h
Faridpur	18.00	64.80
Sirajgonj	18.00	64.80
Bogra	15.40	55.44
Mymensingh	15.40	55.44

Max Wave Height is 1.0 m
Wave Period is 3.00 sec (Halcrow-1994)

Location	River	Observed Scour Level (m PWD)	Design Scour Depth (m)
Sirajgonj	Jamuna	-33	
		-44	
Sailabari	Jamuna	-40	
Mawa	Padma	-50	
Noria	Padma	-65	
Hakimuddin, Bhola	Meghna	-65	
Ilisha, Bhola	Meghna	-32	
Monpura	Meghna	-37.96	
Jamuna Bridge guide bundh			40 to 45

Record of Scour in Jamuna :		
Location	Scour Depth (m)	Time (day)
Bahadurabad	6.0	10
	8.0	24
	12.0	30
Sirajgonj	5.3	1
	20.0	24
Kalitala	5.0	3
Mathurapara	12.0	10

	Padma Bridge	Halcrow for Jamuna	Jamuna, JMREMP	
			1:100	1:25
Wave Height, Hs (m) =	1.40	1.00	1.30	1.00
Wave Period, Tm (sce)=	3.40	3.00		

BWDB Manual	minimum	maximum
Wave Height, Hs (m) =	0.70	2.00
Wave Period, Tm (sce)=	2.80	5.00

Annexure B

Basic Wind Speed V & V_b

In comparing the basic wind speeds given between BNBC 1993 and BNBC 2010, it is important to note that BNBC 1993 specifies fastest-mile wind speeds whereas **BNBC 2010 provides basic wind speed in terms of 3-second gust wind speeds**. The fastest mile speed is the average speed of a particle traveling with the wind over the distance of one mile. The 3-second gust speed is the peak gust speed averaged over a short time interval of 3 seconds duration.

Both BNBC 1993 and BNBC 2010 provide basic wind speed associated with an annual probability of occurrence of 0.02 (**50 year recurrence interval**) measured at a point **10m** (33 ft) above the mean ground level in a flat and open terrain. In both BNBC 1993 & BNBC 2010, tornadoes have not been considered in developing the basic wind speed distribution.

Since square of the basic wind speed is used in determining sustained wind pressure, the increased wind speed results in approximately 26.58 percent increase in sustained wind pressure. Following equation is found satisfactory for converting fastest mile per hour wind speed into three second gust wind speed and used later for comparison –

$$V_{3s}=0.2986*V_{fmph}+2.986$$

Where,

V_{3s}= three second gust wind speed in m/s
V_{fmph}= Fastest mile per hour wind speed in Km/hr ;
(Faysal, 2013:Chap 4-Page 15) (INC, 2009: Chap16-page 319)

Comparison of BNBC 1993 & BNBC 2010 with respect to basic wind speeds

LOCATION	BNBC 2010 Basic Wind Speed V (m/s)	BNBC 1993 Basic Wind Speed, V_b (km/hr)	BNBC 1993 Basic Wind Speed, V_b(m/s)	RATIO, V/V_b	RATIO^2, $(V/V_b)^2$	% INCREASE
Angarpota	47.8	150	41.67	1.15	1.32	31.61
Bagerhat	77.5	252	70.00	1.11	1.23	22.58
Bandarban	62.5	200	55.56	1.13	1.27	26.56
Barguna	80.0	260	72.22	1.11	1.23	22.70
Barisal	78.7	256	71.11	1.11	1.22	22.48
Bhola	69.5	225	62.50	1.11	1.24	23.65
Bogra	61.9	198	55.00	1.13	1.27	26.66
Brahmanbaria	56.7	180	50.00	1.13	1.29	28.60
Chandpur	50.6	160	44.44	1.14	1.30	29.62
Chapai Nawabganj	41.4	130	36.11	1.15	1.31	31.44
Chittagong	80.0	260	72.22	1.11	1.23	22.70
Chuadanga	61.9	198	55.00	1.13	1.27	26.66
Comilla	61.4	196	54.44	1.13	1.27	27.18

LOCATION	BNBC 2010 Basic Wind Speed V (m/s)	BNBC 1993 Basic Wind Speed, V_b (km/hr)	BNBC 1993 Basic Wind Speed, V_b(m/s)	RATIO, V/V_b	RATIO^2, $(V/V_b)^2$	% INCREASE
Cox's Bazar	80.0	260	72.22	1.11	1.23	22.70
Dahagram	47.8	150	41.67	1.15	1.32	31.61
Dhaka	65.7	210	58.33	1.13	1.27	26.85
Dinajpur	41.4	130	36.11	1.15	1.31	31.44
Faridpur	63.1	202	56.11	1.12	1.26	26.46
Feni	64.1	205	56.94	1.13	1.27	26.71
Gaibandha	65.6	210	58.33	1.12	1.26	26.47
Gazipur	66.5	215	59.72	1.11	1.24	23.99
Gopalganj	74.5	242	67.22	1.11	1.23	22.83
Habiganj	54.2	172	47.78	1.13	1.29	28.69
Hatiya	80.0	260	72.22	1.11	1.23	22.70
Ishurdi	69.5	225	62.50	1.11	1.24	23.65
Joypurhat	56.7	180	50.00	1.13	1.29	28.60
Jamalpur	56.7	180	50.00	1.13	1.29	28.60
Jessore	64.1	205	56.94	1.13	1.27	26.71
Jhalakati	80.0	260	72.22	1.11	1.23	22.70
Jhenaidah	65.0	208	57.78	1.13	1.27	26.56
Khagrachhari	56.7	180	50.00	1.13	1.29	28.60
Khulna	73.3	238	66.11	1.11	1.23	22.93
Kutubdia	80.0	260	72.22	1.11	1.23	22.70
Kishoreganj	64.7	207	57.50	1.13	1.27	26.61
Kurigram	65.6	210	58.33	1.12	1.26	26.47
Kushtia	66.9	215	59.72	1.12	1.25	25.48
Lakshmipur	51.2	162	45.00	1.14	1.29	29.45
Lalmonirhat	63.7	204	56.67	1.12	1.26	26.36
Madaripur	68.1	220	61.11	1.11	1.24	24.18
Magura	65.0	208	57.78	1.13	1.27	26.56
Manikganj	58.2	185	51.39	1.13	1.28	28.26
Meherpur	58.2	185	51.39	1.13	1.28	28.26
Maheshkhali	80.0	260	72.22	1.11	1.23	22.70
Moulvibazar	53.0	168	46.67	1.14	1.29	28.98
Munshiganj	57.1	184	51.11	1.12	1.25	24.81
Mymensingh	67.4	217	60.28	1.12	1.25	25.03
Naogaon	55.2	175	48.61	1.14	1.29	28.95
Narail	68.6	222	61.67	1.11	1.24	23.75
Narayanganj	61.1	195	54.17	1.13	1.27	27.24
Narsinghdi	59.7	190	52.78	1.13	1.28	27.95
Natore	61.9	198	55.00	1.13	1.27	26.66

LOCATION	BNBC 2010 Basic Wind Speed V (m/s)	BNBC 1993 Basic Wind Speed, V_b (km/hr)	BNBC 1993 Basic Wind Speed, V_b(m/s)	RATIO, V/V_b	RATIO^2, $(V/V_b)^2$	% INCREASE
Netrokona	65.6	210	58.33	1.12	1.26	26.47
Nilphamari	44.7	140	38.89	1.15	1.32	32.12
Noakhali	57.1	184	51.11	1.12	1.25	24.81
Pabna	63.1	202	56.11	1.12	1.26	26.46
Panchagarh	41.4	130	36.11	1.15	1.31	31.44
Patuakhali	80.0	260	72.22	1.11	1.23	22.70
Pirojpur	80.0	260	72.22	1.11	1.23	22.70
Rajbari	59.1	188	52.22	1.13	1.28	28.07
Rajshahi	49.2	155	43.06	1.14	1.31	30.58
Rangamati	56.7	180	50.00	1.13	1.29	28.60
Rangpur	65.3	209	58.06	1.12	1.27	26.51
Satkhira	57.6	183	50.83	1.13	1.28	28.39
Shariatpur	61.9	198	55.00	1.13	1.27	26.66
Sherpur	62.5	200	55.56	1.13	1.27	26.56
Sirajganj	50.6	160	44.44	1.14	1.30	29.62
Srimangal	50.6	160	44.44	1.14	1.30	29.62
St. Martin's Island	80.0	260	72.22	1.11	1.23	22.70
Sunamganj	61.1	195	54.17	1.13	1.27	27.24
Sylhet	61.1	195	54.17	1.13	1.27	27.24
Sandwip	80.0	260	72.22	1.11	1.23	22.70
Tangail	50.6	160	44.44	1.14	1.30	29.62
Teknaf	80.0	260	72.22	1.11	1.23	22.70
Thakurgaon	41.4	130	36.11	1.15	1.31	31.44
					Average	26.58

Statistical wave forecasting

The development of the wave theory began a long time ago, back in the late nineteenth century. But there was no direct study and model development to predict the waves' behavior before the Second World War. During and after the war, a base of observations that allowed us to start developing empirical models has been gathered.

The main tenet of the method of empirical forecasting is the assertion that the relationship between the dimensionless parameters of the waves obey universal laws (and all the models, in general, are trying to pick up the coefficients for the relations between the parameters so that they are close enough to conform to the parameters obtained as a result of actual observations).

One of the main laws is **fetch-growth law**. This law states that at constant **wind speed** and direction over a fixed distance (fetch), it can be expected that the waves will reach a stationary state, depending on the length of the acceleration (fetch-limited state of development). In such a situation, the wave height will be constant (**in a statistical sense**) over time but will vary along with the acceleration.

Acceleration - is a term used in Russian literature. The length of the body of water, where the wind affects the sea's surface in a constant direction, is understood as the acceleration of wind. It would seem that with an increase of time and length of the wind acceleration, the wave can grow indefinitely, but that doesn't occur.

In the 1950s, researchers have found that the formation of waves is best described by the wave spectrum (distribution of wave energy depending on frequency) and the transfer of energy from the wind to the wave. As mentioned above, the wave ceases to grow, reaching a steady-state energy balance, and it becomes **fully developed sea**.

The empirical relation for the height of the fully formed waves, which can serve as the upper limit of the wave height assessment for any wind speed, has been derived.

$$H_f = \frac{\lambda_5 u^2}{g}$$

where,

H_f - height of the fully formed wave
λ_5 - dimensionless coefficient approximately equal to 0.27
u - wind speed
g - acceleration of gravity.

Everything got more complicated. A large array of measurements, in particular in the research project on the North Atlantic JONSWAP (Joint North Sea Wave Project), was assembled. At the place of the first generation's wave prediction models came the second-generation model using the energy spectrum. In the early 1980s, there were wave models of the third-generation (3G). Actually, we hadn't reached the fourth-generation models yet. The most commonly used model is the third generation WAM model (Hasselmann, S., et al., WAMDI Group, The WAM model - A third-generation ocean wave prediction model, J. Phys. Oceanogr., 18, 1775–1810, 1988.). Of course, there are still shortcomings. For example, these models cannot predict the waves in rapidly changing wind situations, but still, 3G models provide a good result.

In the pre-computer era, you could use a model built on the nomogram for wave heights forecasting in relatively simple situations, such as pre-assessment or small projects given, for example, in Shore Protection Manual.

There are 3 situations possible when the simplified prediction will give quite an exact estimation.

1. **Fetch-Limited** : The wind is blowi3ng in a constant direction over some distance and not limited by time (enough time) - then the growth of the wave is determined and limited by the length of acceleration.
2. **Duration-Limited** : The wind rapidly increases within a short period of time and is not limited by distance (enough distance) - then the growth of the wave is determined and limited by elapsed time. This occurs very rarely in nature.
3. **Fully Developed Wave** : The wind is blowing in a constant direction at a sufficient distance and for a sufficient time so the wave will be fully formed under these conditions. Note that even in the open ocean, waves rarely reach the limit values at wind speeds greater than 50 knots. Empirically, we obtained the following dependence when the length of the acceleration limits wave growth.

The time waves require under the wind influence at the velocity u on the distance X to achieve the maximum possible for a given distance height.

$$t_{x,u} = 77.23\frac{X^{0.67}}{u^{0.34}g^{0.33}}$$

The relationship between the significant wave height and H_{m0} the distance X

$$\frac{gH_{m_0}}{u_f^2} = 4.13 * 10^{-2} * (\frac{gX}{u_f^2})^{\frac{1}{2}}$$

The relationship between the period of the wave T_p and the distance X

$$\frac{gT_p}{u_f} = 0.751 * (\frac{gX}{u_f^2})^{\frac{1}{3}}$$

The drag coefficient

$$C_D = \frac{u_f^2}{U_{10}^2}$$

$$C_D = 0.001(1.1 + 0.035U_{10})$$

For Fully Developed Waves :

$$\frac{gH_{m_0}}{u_f^2} = 2.115 * 10^2$$

$$\frac{gT_p}{u_f} = 2.398 * 10^2$$

Also the transition from the duration of the wind to the length of the acceleration (i.e. the wind impact for some time can be replaced by the wind at a distance)

$$\frac{gX}{u_f^2} = 5.23 * 10^{-3} * (\frac{gt}{u_f})^{\frac{3}{2}}$$

where

U_{10}- wind speed at 10 meters height

u_f- friction velocity.

Thus, if the duration of action and length of the wind's acceleration is known, it is necessary to select the most restrictive value. If the wave generation height is limited by time, it is necessary to replace it with an equivalent distance.

In case of shallow water, equations remain valid except for the additional limitations under which the wave period cannot exceed the following ratios:

$$T_p \approx 9.78(\frac{d}{g})^{\frac{1}{2}},$$

where d - depth

Then the order of the wave height prediction for the shallow water is as follows:

1. Assess the wave period for a given distance and wind speed using the conventional formula.
2. In the case of shallow water, verify the conditions of the period and depth. If they are exceeded, take the boundary value.
3. In the case of the wave boundary value, find the distance corresponding to the generation of waves with such a period.
4. Calculate the height by the value of the distance.
5. If the wave height exceeds 0.6 of the depth values, limit this value.

Some more important notes

1. These empirical formulas are derived for relatively normal weather conditions and are not applicable for the assessment of the wave height in the event of, for example, a hurricane. Nomograms contained in the directory are built for the wind speed no higher than 37.5 m/s. For comparison, 33-42 m/s wind speed - the first category hurricane on the Saffir-Simpson scale.
2. These empirical formulas are used for **statistical forecasting** of wave heights, so the height of these formulas is nothing more than a **significant wave height** determined by the dispersion of the wave spectrum as follows: . $H_{m_0} = 4\sqrt{M_0}$

This is a more modern definition of significant height of the waves, and the very first definition, which was given to Walter Munk during World War II, was: "The average height of the one-third of the highest waves." It was assumed that it mathematically expresses the estimate of wave heights, which a "trained observer usually gives." There is a few percent difference between these two definitions. The older definition commonly referred to $H_{1/3}$

Thus, getting an assessment of significant wave height for the given conditions, it is necessary to realize that most waves (about 2/3) are below this height, BUT we can find waves that are larger than this height. It is believed that the Rayleigh distribution well approximates the statistical distribution of the wave height, so if we estimate 10-meter height, it can be expected that one of the 10 waves is greater than 10.7 meters, one of 100 waves is greater than 15.1 meters, one of 1000 waves is more than meters 18.6.

In reality, due to the constantly changing conditions, a nearly two-fold excess is, of course, rare, but sometimes happens Rogue wave.

(Ref :"Coastal Engineering Manual," 2008)