

Size and weight of stone for protection of River banks and embankments

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Abstract

Stone pitching is popularly used for protection of guide banks, river banks and embankments to prevent erosion by flood water. Size and weight of stone and thickness of mattress on sloping and launching apron are to be found carefully so that it can resist the erosive forces and for stability. IRC: 89(1997) and IS codes IS 8408(1994), IS10751(1994), IS12094(2000), IS 14262(1995) provide guidelines for determining the size and weight of stones to be used for pitching in terms of mean velocity of flow (V). However, U.S. Army Corps of Engineers(1991), CWPRS (1991-92), Pilarczyk (1997) and other research scientists have proposed equations not only in terms of velocity but several other parameters governing stability of stones. Starting from fundamentals, author has derived the basic equations for size and weight of stones to prevent erosion and provide embankment/bank stability and compared the equations given by IRC, IS, Pilarczyk and U.S. Army Corps of Engineers. He has also introduced a new concept of drag for computing size and weight of stones and thickness of wire crated stones. An example has been worked out with some assumed data at the end. Size and weight of stones obtained by the different equations have been compared in table-1.

Key Words: *River , Erosion, Bank Protection, Stone Size and weight, Gabions*

1.0 INTRODUCTION

One of the major causes of flooding and flood damages is erosion and subsequent damage to guide banks, river banks and flood embankments. Use of loose stone pitching is a common practice to prevent erosion for protection of guide banks, banks and embankments in river. Stone gabions made up of packed stones in GI double twisted wire mesh, geo-textile bags (filled with sand, stones, debris etc.) have also been popular, since size and weight of loose stones determined theoretically may sometimes be too large resulting in handling and placement difficulties. In case of gabions, however, smaller stone size (depending upon the mesh size) can be used. Wire crates are machine made with galvanized wire of about 3 to 4mm size with sufficient tensile strength, flexibility and resistance against puncturing.

Indian codes e.g.:IRC-89(1997) and IS: 14262(1995), IS8408(1994), IS10751(1994), IS 12094 (2000) specify size and weight of stones in terms of mean flow velocity of flow in the river in order to prevent dislodgement of stones used in banks and embankments, spurs/groyens, guide bunds, afflux bunds etc. Stone pitching, also known as rip-rap, is used in earthen dams, bridge piers and abutments and approach embankments in bridges. Some of the important criteria which govern the performance of pitching/mattresses are size and weight, gradation, shape and angularity of stones and their proper placement. A layer of either graded filter or geo- textiles (woven or non-woven, depending upon size of river bed/bank materials), must be placed below

the pitching and mattress to prevent winnowing of the bed/bank materials through the pores and joints of pitching/mattress to prevent caving and cracks and subsequent wash out. Spring(1903,Gales (1938) and Inglis (1949) have done extensive study on Indian rivers and recommended weight and thickness of stones for river bank protection and guide bunds. Chitale (2006), Maynord (1989), Mittal and Kothyari (2003), Mazumder (2010), US Army Corps of Engineers (1989,1991), Austoroads (1994) have developed several equations for finding size and weight of stones. Pylarczyk (1997) made most exhaustive study and proposed a unified general equation in terms of several parameters e.g. stability factor, bank slope factor, turbulence factor, critical tractive stress factor, velocity profile factor and roughness factor. U.S.Army Corps of Engineers introduced several factors e.g. safety factor, slope factor, stability coefficient, velocity profile factor etc. in determining stone size and weight. Considering the enormous cost of the protection works and their annual maintenance cost, it is necessary that the IS/IRC equations for computing the size and weight of stones in India should be reviewed.

In this paper, author has made an attempt to derive from fundamentals the size and weight of stones in pitching and thickness of wire crated stone gabion and compare them by different methods through an illustrative example assuming some river flow data. A new concept of drag has been introduced to determine size and weight of stones and thickness of mattresses.

2.0 SIZE AND WEIGHT OF STONES ON SLOPING PLAIN

Size and weight of stones lying on side slope should be sufficient so that it does not get dislodged from its position due to erosive forces owing to forward flow drag as well as the component of its own weight trying to pull down the stone along the slope. Referring to Fig.1, a Spherical stone 'P' lying on the side slope are subjected to the following forces:

- (i) Submerged stone weight – W_s
- (ii) Component of submerged stone weight along the sloping plain – $W_s \sin \theta$
- (iii) Flow drag in the forward direction - $F_d = \tau_{0cb} a_s$

Where, θ = angle of inclination of the side slope with horizontal, τ_{0cb} = tractive or shear stress for bed material along flow at critical stage, a_s = area of stone normal to flow = $(\pi / 4) D^2$, where D is the diameter of the stone assumed to be spherical.

Resultant force (R) acting on the inclined plane is given by

$$R = (W_s^2 \sin^2 \theta + \tau_{0cb}^2 a_s^2)^{0.5} \quad \dots(1)$$

Resisting force (F_R) on the stone due to its angle of internal friction (ϕ) is given by

$$F_R = W_s \cos \theta \tan \phi \quad \dots(2)$$

Under equilibrium condition, $R = F_R$, From equations (1) and (2),therefore

$$W_s^2 \sin^2 \theta + \tau_{0cb}^2 a_s^2 = W_s^2 \cos^2 \theta \tan^2 \phi$$

$$\text{or, } W_s = \tau_{0cb} a_s / (\cos^2 \theta \tan^2 \phi - \sin^2 \theta)^{0.5} \quad \dots(3)$$

In turbulent flow,

$$\tau_{0cb} = KV^2 = \text{where } K = 0.5\rho C_d$$

where,

C_d is coefficient of drag, ρ is density of water, $(\cos^2 \theta \tan^2 \phi - \sin^2 \theta)^{0.5} = [1 - (\sin^2 \theta / \sin^2 \phi)]^{0.5} = k_i$

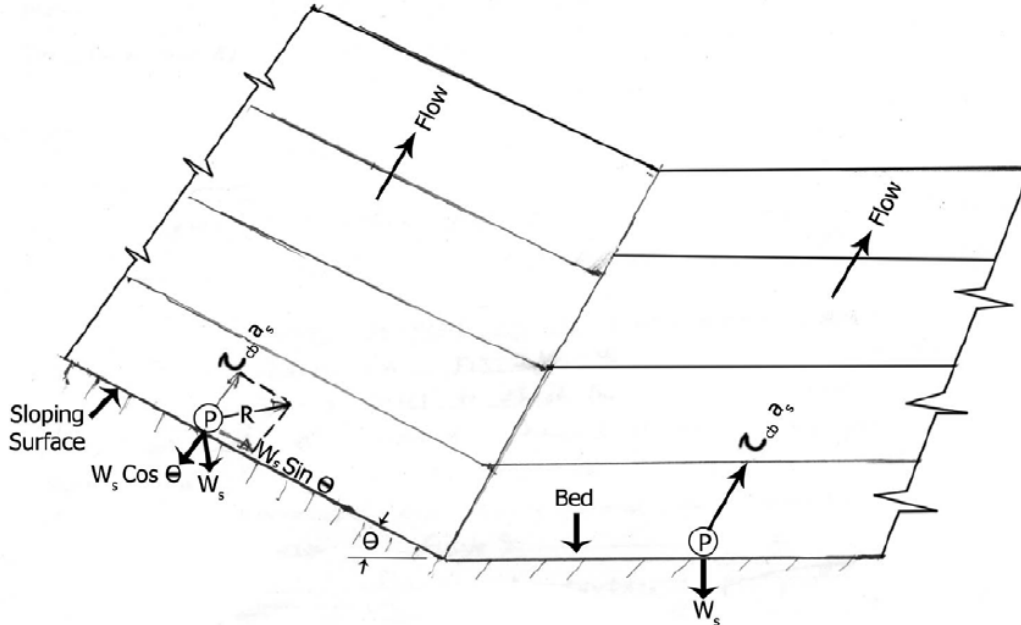


Fig. 1, Showing the various forces on a particle 'P' line on bed and sloping surface in a straight channel.

V_s is the velocity on the stone surface, V is mean velocity of flow,

$$W_s = C V^2 \quad \text{from equation (3)} \quad \dots(4)$$

where,

$$C = (K/K_i) a_s = (K/K_i) (\pi/4) D^2$$

For the stability of the stone, θ must be less than ϕ . It may be noted that as θ -value increases, K_i decreases and hence submerged weight of stone W_s must increase.

For spherical submerged stones, $a_s = (\pi/4) D^2$ and $W_s = (\gamma_s - \gamma) (\pi/6) D^3$

Therefore,

$$(\gamma_s - \gamma) (\pi/6) D^3 = (K/K_i) (\pi/4) D^2 V^2 \quad \text{from eq.(4)} \quad \dots(5)$$

$$\text{Or, } D = (3/2) V^2 (K/K_i) [1/(\gamma_s - \gamma)] \quad \dots(6)$$

$$\text{i.e. } D \propto V^2$$

Since $W \propto D^3$, therefore

$$W \propto V^6 \quad \dots(7)$$

where, γ_s and γ are unit weights of stones and unit weight of water respectively. W is the weight of stone corresponding to diameter D.

2.1 Weight of Individual Stone on Sloping Apron by Different Methods

Stone weights prescribed by different methods, are given under the clauses 2.1.1, 2.1.2 and 2.1.3 and 2.1.4 below.

2.1.1 As per IRC Code

IRC-89 (1997) on river training, recommends Eq. (8) and (9) given below for size and weight of stones on sloping apron with 2(H):1(V) slope ($\theta = 26.5^\circ$), $\phi = 43^\circ$ and $S_s = 2.65$)

$$D = 0.028 V^2 \quad \dots(8)$$

and $W = 0.0312 V^6 \quad \dots(9)$

2.1.2 As per IS codes

In the IS codes IS:14262 (1995), IS:8408 (1995), IS:10751 (1994), IS:12094 (2000)- all related to river training- equation(10) is recommended for finding stone weight, W

$$W = 0.02323 S_s V^6 / K_i (S_s - 1)^3 \quad \dots(10)$$

Where, $K_i = (\cos^2 \theta \tan^2 \phi - \sin^2 \theta)^{0.5} = (1 - \sin^2 \theta / \sin^2 \phi)^{0.5}$ and S_s is the specific gravity of stone. With 2 (H) : 1 (V) side slope, $\theta = 26.5^\circ$; $\phi = 43^\circ$ for stones and $S_s = 2.65$ for stones, $K_i = 0.76$

Putting the above values in Eq. (10)

$$W = 0.018 V^6 \quad \dots(11)$$

And, $D_{50} = 0.0236 V^2 \quad \dots(12)$

Where, W is in Kg, D_{50} is the median stone diameter in m and V is in m/sec units

Remarks:

Stone size and weight given by IS formula give lesser value compared to the IRC formula due to the incorrect IS equation (10). The correct equation should be as follows: (See Eq.24 derived under section-4)

$$W = 0.02323 S_s V^6 / [k_i (S_s - 1)]^3 \quad \dots(13a)$$

With $K_i = 0.76$ (for 2:1 slope), $S_s = 2.65$

$$W = 0.0312 V^6 \quad \dots(13b)$$

The corresponding diameter of stones D shall be

$$D_{50} = 0.028 V^2 \quad \dots(14)$$

The corrected IS equations (13b) and (14) are the same as IRC equations (9) and (8) respectively and hence equation (6) given in all IS codes should be replaced by equations (13a) and (14).

2.1.3 As per Pylarczyk (1997)

Pylarczyk (1997) proposed a unified general formula (Eq 15) for stone size

$$(S_s - 1) D_n = [(0.035 \phi_c k_h k_t) / (\theta_c k_i)] V^2 / 2g \quad \dots(15)$$

Where, $D_n = 0.84 D_{50}$, k_t = turbulence factor, S_s = Specific gravity of stones, θ_c = shear stress factor, K_i = bank slope factor = $[1 - (\sin^2 \theta / \sin^2 \phi)]^{0.5}$, V = Mean velocity of flow, ϕ_c = stability factor and k_h = velocity profile correction factor given by the relation:

$$K_h = (1 + Y/D_n)^{-0.2} \text{ for not fully developed velocity profile}$$

$$K_h = 2 / \log^2 [(1 + (12Y/D_n))] \text{ for fully developed velocity profile}$$

With $\theta = 26.5^\circ$, $\phi = 43^\circ$, $k_i = 0.76$, $k_t = 1.0$ (for normal turbulence), $\theta_c = 0.035$ for angular rock, $S_s = 2.65$, n = porosity of rock mass = 0.3, $\phi_c = 0.75$ (common value for angular rock) as given in table-9.8 (Melville & Coleman, 2000) and $K_h = 0.57$ (assuming $Y = 3\text{m}$ and $D_n = 0.2\text{m}$) it may be proved that the general unified equation reduces to

$$D_{50} = 0.029 V^2 \quad \dots(16)$$

Equation (16) is almost same as equation (8) and (14). Incidentally, Pylarczyk's Equation (15) shows that $D_{50} \propto V^2 / K_i (S_s - 1)$ and hence $W \propto V^6 / [K_i (S_s - 1)]^3$ i.e same as in the corrected IS equation 13(a).

2.1.4 U.S.Army Corps of Engineers Formula

After extensive research and comprehensive experimentations, U.S.Army Corps of Engineers (1989) proposed the following equation:

$$D_{30}/Y = [S_f \cdot C_s \cdot C_v \cdot C_t \cdot F_r^{2.5}] / [K_i^{1.25} (S_s - 1)^{1.25}] \quad \dots (17)$$

Where D_{30} is stone size of which 30% is finer by weight, S_f is safety factor (1.2 minimum), Y is depth of flow, F_r is Froude number of flow, C_s is stability coefficient (= 0.30 for angular rock), C_v is velocity profile correction factor (=1.0 for straight channel), C_t is layer thickness reduction factor

(=1.0 for thickness of stones equal to D_{100}), K_i is slope correction factor(=0.76 for $\theta = 26.5^0$ and $\phi = 43^0$, $S_s=2.65$). With above values of different factors taken from table-9.7 (Mellville & Coleman, 2000), equation (17) reduces to

$$D_{30}/Y = 0.271 F_r^{2.5} \quad \dots(18)$$

4.0 DRAG APPROACH FOR FINDING INDIVIDUAL STONE WEIGHT

From equation (6),

$$D_{50} = 3/2 V^2 (K/K_i) [1/(\gamma_s - \gamma)]$$

Putting $k = 0.5\rho C_d$ and $\rho = \gamma/g$, the above expression reduces to

$$D_{50} = \left[\frac{(3/2)C_d}{K_i(S_s - 1)} \right] \times V^2 / 2g \quad \dots(19)$$

For spherical stone with Reynold's number more than 5.5×10^5 , $C_d = 0.45$ (Garde and Mirajgaonkar, 1977), $S_s = 2.65$, $k_i = 0.76$ (for $\theta = 26.5^0$ and $\phi = 43^0$), $k = 0.9$ (for normal turbulent flow in a straight channel) and $g = 9.8 \text{ m}^2/\text{sec}$

$$D_{50} = 0.027 V^2 \quad \dots (20)$$

Equation (20) is almost same as IRC and corrected IS equations and Pylarczyk,s equation

Since weight of stone is given by

$$W = \gamma S_s (\pi/6) D^3 = \gamma S_s (\pi/6) \left[\frac{(3/2)(C_d)/8g^3}{k_i(S_s - 1)} \right]^3 \times V^6 / 8g^3 \text{ -from eq. (19)}$$

$$W = [\gamma(\pi/6) \times (27/8)(C_d^3/8g^3)] S_s / [k_i(S_s - 1)]^3 V^6 = 0.0213 V^6 S_s / [k_i(S_s - 1)]^3$$

With a safety factor of 1.1

$$W = 0.023 V^6 S_s / [k_i(S_s - 1)]^3 = 0.031 V^6 \text{ (for 2:1 side slope and } \phi = 43^0) \quad \dots(21)$$

Equation (21) is almost same as corrected IS Eq. 13(a)

5.0 DRAG APPROACH FOR FINDING THICKNESS OF WIRE CRATED GABIONS

Weight of mattress will depend on its thickness for a given size, say, $a_s = a.b$. Where 'a' is the length and 'b' is the breadth of the apron. 't' is the thickness required and e as the void ratio, then

From equation (4),

$$W_s = CV^2$$

Here, $W_s = a b t e (\gamma_s - \gamma)$, and $C = (k/k_i) a_s$,

$$\text{or, } a b t e (\gamma_s - \gamma) = (k/k_i) a b V^2 \quad \dots(22)$$

$$\text{hence, } t = KV^2/eK_i = C_d/[eK_i(S_s-1)] \times V^2/2g \quad \dots(23)$$

with $C_d = 0.45$, $S_s = 2.65$, $k_i = 0.76$ (for $\theta = 26.5^\circ$ and $\phi = 43^\circ$), $e = 0.7$ (IS:8408,1995), and $g = 9.8 \text{ m}^2/\text{s}$

$$t = 0.025 V^2 \quad \dots(24)$$

Where, t is in meter and V is the mean velocity of flow in m/sec.

It may, however, be noted that wire crated gabions will offer a much smoother surface compared to an individual isolated stone and hence C_d will be much less. Assuming C_d for crated stones to be only 60% of an individual stone i.e. $C_d = 0.27$, thickness of wire crated gabion will be

$$t = 0.015 V^2 \quad \dots(25)$$

Sizes and weights of loose stones and thickness of wire crated stones as computed by different methods for the given example under section-6 are summarized in table-1 below.

6.0 ILLUSTRATIVE EXAMPLE

Diameter (D_{50}) and Weight (W) of spherical stones and thickness of Gabions used for protection of side slopes/aprons have been computed by using IS and IRC formulae given in the respective codes and compared with the values obtained from Pilarczyk's and Army Corps of Engineers equations used in USA as well as those obtained from the formulae derived from drag approach. The following data are assumed for computations.

- (i) Mean Velocity of flow: $V = 3 \text{ m/sec}$
- (ii) Flow Depth: $Y = 4 \text{ m}$
- (iii) Side Slope: 2(H):1 (V)
- (iv) Angle of internal friction for stones: $\Phi = 43^\circ$
- (v) Specific gravity of stone: $S_s = 2.65$
- (vi) Unit weight of water : $\gamma = 1000 \text{ kg/cu. m.}$
- (vii) Unit weight of stone $\gamma_s = S_s \cdot \gamma = 2650 \text{ Kg/m}^3$
- (viii) Coefficient of kinematic viscosity of water at normal temperature, $\nu = 10^{-6} / \text{m}^2 \text{sec}$
- (ix) Froude's no. of Flow, $Fr = V / \sqrt{(gY)} = 0.48$
- (x) Reynold's no. of flow, $Re = VY/\nu = 12 \times 10^6$

CONCLUSIONS

- (i) Size and weight of stones computed by IS equation given in different IS codes differ considerably when compared with other methods.
- (ii) Corrected IS equation (13) gives the same result as in IRC equation (8) & (9)
- (iii) Pilarczyk's equation (15) & (16) as well as U.S. Army Corps of Engineers (17) & (18), popularly used in USA, give almost similar results as IRC equation.
- (iv) In Pilarczyk's unified type general equation (15) and U.S. Army Corps of Engineers Equation (17) several other parameters e.g. safety factor, stability factor, turbulence factor, velocity and shear stress factor, side slope factor etc. have been considered unlike IS and IRC equation where only slope factor is considered.

(v) Author has introduced a new concept of drag for finding stone size and weight and for computing thickness of wire crated stone mattress.

(vi) Considering the enormous cost of protection works and their annual maintenance, it is recommended that more in depth study with field data should be made in the subject.

Table –1: SIZE & WEIGHT OF STONES/GABIONS BY DIFFERENT METHODS

<u>Methods</u>	<u>D₅₀(cm)</u>	<u>t (cm)</u>	<u>W (Kg)</u>	<u>Remarks</u>
IS Equation	21.0	---	13.0	Eq. (10),(11), (12)
IRC Equation/corrected IS Equation	25.4	---	22.6	Eq.(8), (9),(13), (14)
Pilarczyk Equation	26.3	---	25.2	Eq.(15), (16)
U.S.Army Corps Eq.	24.2	---	19.7	Eq.(17),(18)
Eq from Drag Concept	25.2	---	22.5	Eq. (20), (21)
Thickness of wire crated Stones (Rough Surface)	---	22.5	---	Eq.(23), (24)
Thickness of wire crated Stones (Smooth Surface)	---	13.5	---	Eq.(25)

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