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Adaptive Uniform and Non-uniform Configuration of Boulders on Block Ramps for River Restoration

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1.0 INTRODUCTION & REVIEW OF STUDIES

Block ramps are a promising and cost-effective structure in river restoration projects. They are adopted in place of traditional hydraulic structures because of their ability to sustain the morphological river continuity. Block ramps are characterized with high turbulent flow on large roughness elements resulting in substantial energy dissipation. In practical applications, block ramps are generally made of boulders with mean diameter between 0.3 m and 1.5 m. **Fig.1** shows a typical block ramp application.

Based on experimental study, Pagliara and Chiavaccini (2006a) have proposed a relation to compute the relative energy dissipation on smooth ramp and ramp with base material. Further the same authors (2006b) also proposed a relation for computing the relative energy loss on block ramps with boulders in row and random arrangements as given by Eq. (1). :

$$\Delta E_{rB} = \left[A + (1-A)e^{(B+CS)\frac{h_c}{H}}\right]\left(1 + \frac{\Gamma}{E + F\Gamma}\right) \quad \text{.................. (1)}$$

Fig.1. A typical Block Ramp Application (Rock Ramp Fishway) on Goulburn River, Victoria (© ResearchGate)

Fig.4. A typical block ramp in the experimental flume [Hydraulics Lab., CED, IIT Roorkee]

where, $\Delta E = (E_o - E_t)$; E_o = upstream energy, E_o = energy at the toe of ramp E_t; H = height of the ramp; h_c = critical depth of flow; S = slope of the ramp; and A, B, C are coefficients, which depend on the scale roughness of the flow over the ramp. For $h_c/d_{50} < 2.5$, A = 0.33, B = -1.3, and C = -14.5; for $2.5 < h_c/d_{50} < 6.6$, A = 0.25, B = -1.5, and C = -12; and for $h_c/d_{50} < 6.6$, A = 0.15, B = -1.0, and C = -11.5. where, coefficients E and F are functions of arrangement and roughness of the boulders. For random arrangement and rounded boulders (i.e., river stones), E = 0.6 and F = 13.3; for row arrangement and rounded boulders, E= 0.55 and F = 10.5, and so forth.

Ahmad *et al.*, (2009) developed a relation for the estimation of energy loss for block ramps with staggered arrangements of boulders on base material within a ±3% error limit as given by Eq. (2) for which R^2=0.75:

$$\Delta E_{rB} = \left[A + (1-A)e^{(B+CS)\frac{h_c}{H}}\right]\left(1 + \frac{\Gamma}{0.6 + 7.9(D_B/h_c)^{-0.9}\Gamma}\right) \quad \text{...............(2)}$$

In this equation, Γ varies from 0.074 to 0.21 and D_B/h_C from 0.506 to 2.307. The values of coefficients A, B, and C will be assigned as suggested by Pagliara and Chiavaccini (2006b).

Different studies have been conducted in order to determine a relationship between the energy dissipation and the characteristics of the ramp in various designs (Robinson et al. 1997, Pagliara and Chiavaccini 2004, 2006a, 2006b; Janisch and Weichert, 2006; Pagliara *et al.*, 2008; Ahmad *et al.*, 2009; Oertel and Schlenkhoff, 2012). Schleiss and Dubois (1999) proposed a relation to compute head loss for sheet or skimming flow in and over macro-roughness elements for both laminar and turbulent flows when the depth of water is significant with regard to the roughness factor.

2.0 OBJECTIVES OF THE STUDY

NU configuration of the boulders has been so far not investigated by previous researchers. The study is primarily concentrated to simulate the effect of various permutations and combinations of macro-roughness boulders under mainly staggered arrangements, on varying ramp slopes under both uniform and non-uniform (NU) configurations in a wider range of test conditions (Γ, D_B, Q, S_x, S_y, etc) so as to ascertain the variation in resultant energy dissipation, which should reinforce in formulating adaptive design application of block ramps for stream restoration and related works.

3.0 EXPERIMENTS AND DATA

Experiments were carried out at the Hydraulics Laboratory of Department of Civil Engineering, Indian Institute of Technology Roorkee, Roorkee on a rectangular ramp of flume width 0.30 m at slopes (S) 1V:4H, 1V:5H, 1V:7H and 1V:9H. Semi–hemispherical blocks with diameters ranging between 0.042 m to 0.10 m, representing boulders with protruding part equal to half the diameter, were placed on the rough ramp bed (**Fig.2**). The rough bed composed of a uniform layer of river bed pebbles of mean diameter d_{50} = 0.018 m.

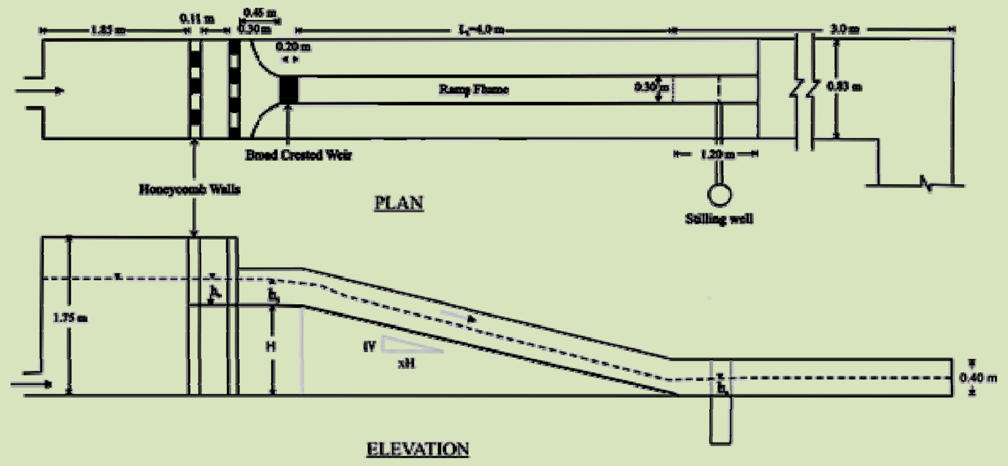

Fig.2. Experimental set-up of the study

3.1 Configuration and distribution of macro-roughness boulders

In the present study, the staggered pattern in uniform and non–uniform arrangement of boulders along the L-section of the ramp flume has been investigated as depicted in Fig. 3. The boulders were placed on the block ramp in various concentrations (Γ) under varied longitudinal spacing (S_x) and transverse spacing (S_y) in staggered arrangement over the base material. A set of uniform spacing of boulders were examined followed by non-uniform spacing (in terms of longitudinal spacing s_x and transverse spacing s_y).

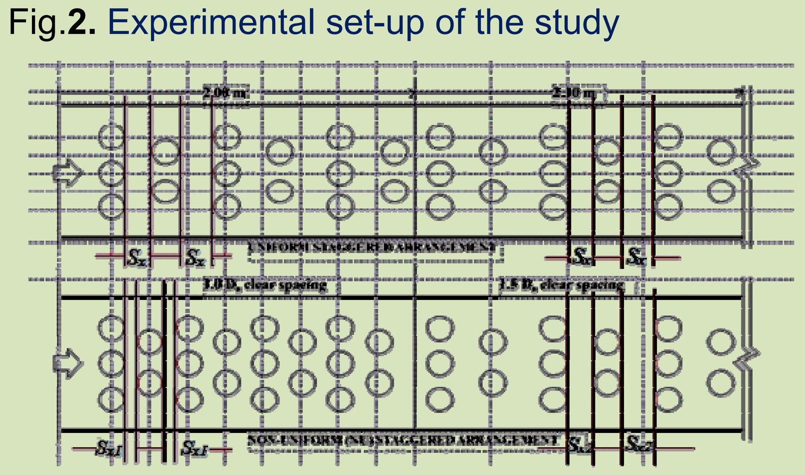

Fig.3. Non-Uniform arrangement of boulders

3.2 Data characteristics

The experimental dataset for various configurations of block ramps investigated in the present study were recorded for various flow conditions. The experiments entailed a range of flows with Reynolds number of 25,500 to 106,800 under 3 ramp slopes with varied boulder spacing and arrangement covering S_x/D_B = 1.0 to 4.0 (as shown in Table **1**).

4.0 DATA ANALYSIS & RESULTS:

Boulders of mean diameters 0.042m, 0.055m, 0.065m, 0.080m and 0.10m were tested under varied spacing in staggered configuration over the three ramp slopes (fig.**4**). On steep slopes, the normal depth is less than the critical depth, so the flow profiles do not follow the general hydraulic asymptotes; there is a gradual dispersion of energy as flow tumble downstream on the ramp in a waveform profile due to the effect of localized jumps imparted by the tumbling flow regime as shown in Figure **5**.

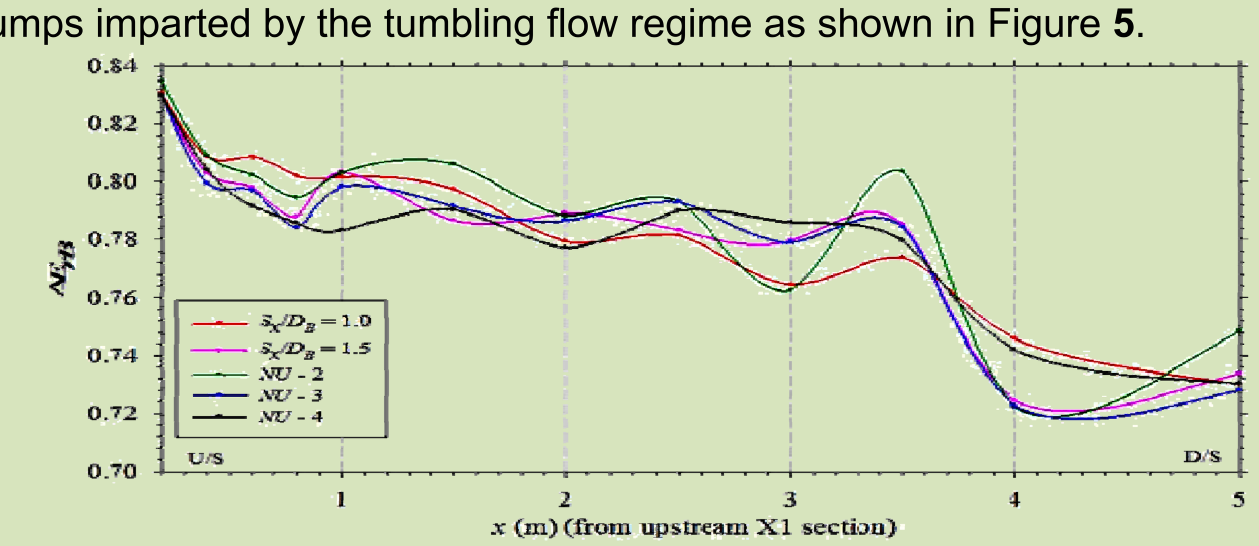

Fig.5. Variation of ΔE_{rB} along the ramp with D_B = 0.055m at Q ≈ 0.025 m³/s (1V:5H)

Relative energy dissipation (observed ΔE_{rB}) on ramp slope 1V:5H, 1V:7H and 1V:9H for each respective boulder under varied concentrations and spacing, are plotted with respect to the (h_c/H) as given in Figures 6a to 6c. The plots were presented in respect of the boulder longitudinal spacing and distribution along with Γ and ψ. Closer spacing and certain non-uniform configurations exhibited higher dissipation of energy. Also bigger–sized boulders tend to produce higher ΔE_{rB} it may be noted that for some configurations, boulder sizes of 0.080 m diameter produced slightly lower energy dissipation as compared to that produced by the smaller-sized boulders of 0.055m or 0.065 m diameter. There is negligible effect of Γ with the 0.10 m size boulders, on the energy dissipation. ψ inversely varies with Γ, and indicated that lesser values yielded higher energy loss with boulders of 0.042m diameter and a reverse case was observed with the larger-sized boulders of 0.065m and 0.080 m.

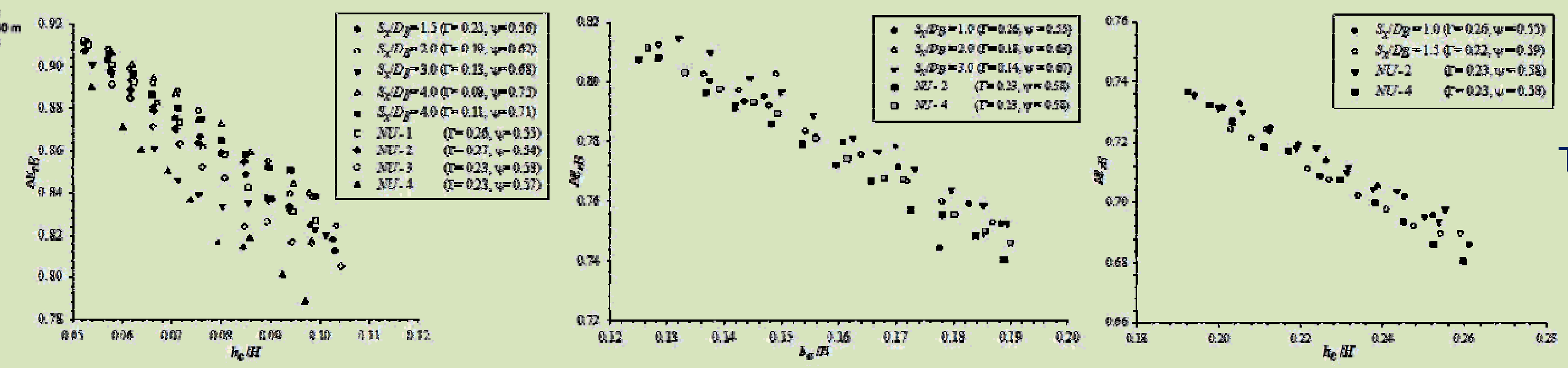

Fig.6. Variation of ΔE_{rB} for D_B = 0.055 m in uniform & non-uniform configurations on ramp slopes: (**a**) 1V:5H, (**b**) 1V:7H, and (**c**) 1V:9H

Subjective examinations show that the relative energy dissipation decreases as the slope gets flatter. If the upper limits of the ΔE_{rB} are taken for each slope, then it can be concluded that there is an overall 10 % increase in the energy dissipation when boulders are placed in staggered configurations over the block ramp. Also, this scale seemed to amplify with decrease in slope as was marked by a 14 % increase for the 1V:9H slope. The overall summary of the test results are presented in Table 2.

Table **1**. Range of the data collected in the experimental study

Sl	Parameter	Unit	Range of data for ramp bed slopes: 1V:5H	1V:7H	1V:9H
1	**Discharge (Q)**	**m³/s**	0.0073 – 0.0308	0.0128 – 0.0339	0.0176 – 0.0387
2	**Head at Bendmeter (Δh)**	**m**	0.0037 – 0.0753	0.0122 – 0.0919	0.0236 – 0.1209
3	**Upstream head (h_0)**	**m**	0.0504 – 0.1223	0.0807 – 0.1625	0.1057 – 0.1859
4	**Depth at downstream toe (h_t)**	**m**	0.0095 – 0.0565	0.0185 – 0.0728	0.0226 – 0.0591
5	**Base material size (d_{xx})**	**m**	0.016 – 0.025	0.016 – 0.025	0.016 – 0.025
6	**Boulder size (D_B) (macro-roughness)**	**m**	0.042 – 0.100	0.042 – 0.100	0.042 – 0.100
7	**Boulder concentration (Γ)**	**%**	7.76 – 32.07	13.72 – 28.74	16.52 – 28.86
8	**Reynolds Number (Re) (×10⁴)**	**–**	2.55 – 7.47	4.55 – 9.29	5.86 – 10.68

5.0 CONCLUSIONS:

- The existing relationships and parameters for energy dissipation on block ramps were tested using the collected dataset and the congruities or variances found have been reported (Figs. **7** and **8**).
- A relation (Eq. 3) is proposed for boulder spacing criteria and for computing ΔE_{rB} for block ramps with boulders in staggered uniform and NU configurations (within ± 5% deviation margin). The Reynolds no ranged from (2.55 to 10.68) × 10^4 with a distinct association with ΔE_{rB} for each tested slope; Froude no ranged from 1.64 to 3.98 and had low correlation with ΔE_{rB}.
- A threshold boulder concentration was found to be in the range 0.22 – 0.25 for the tested configurations (0.08 ≤ Γ ≤ 0.32) was found optimal for imparting efficient energy dissipation.
- Adaptive relations (Eqs. 4 and 5) have been formulated and proposed for computation of ΔE_{rB} on block ramps with staggered arrangement of boulders for both uniform and NU configurations. The relation can be used satisfactorily within ± 5% error limits for the range Γ = 0.17 – 0.30 and 0.05 < h_c/H < 0.29.

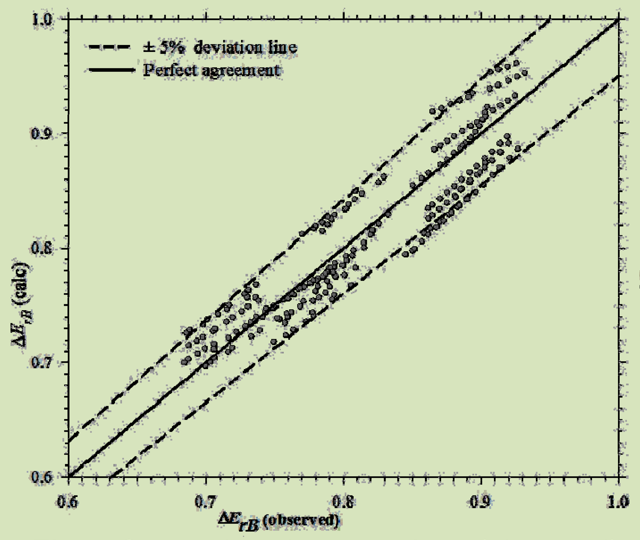

Fig.7. Comparison between ΔE_{rB} (observed) and ΔE_{rB} (calculated) as per Eq.(5)

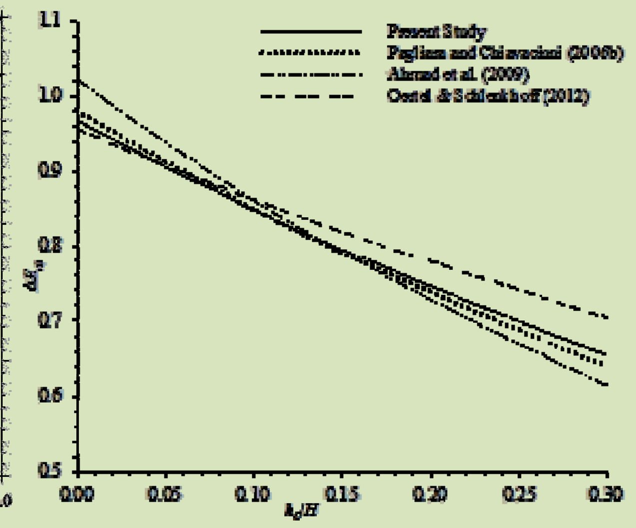

Fig.8. Comparison of ΔE_{rB} computed using Eq. (5) &relations by other investigators

$$\Gamma_{calc} = 0.86\left[\frac{D_B^{\,2}}{2(S_x + D_B)(S_y + D_B)}\right]^{1.11} \quad \text{................ (3)}$$

$$\Delta E_{rB} = -0.151 - 1.826\left(\frac{h_c}{H}\right) + 1.386(\Gamma) + 1.411(\psi) \quad \text{...... (4)}$$

$$\Delta E_{rB} = L_R \times a_1 \exp\left[\frac{a_2}{a_3 + \Gamma(h_c/H)}\right] \quad \text{................ (5)}$$

Table **2**. Summary of Experimental test results on Boulder Block Ramps

Parameter	1V:5H	1V:7H	1V:9H
Γ	0.08 – 0.32	0.14 – 0.29	0.19 – 0.29
h_c/H	0.048 – 0.125	0.111 – 0.190	0.179 – 0.261
ΔE_{rB}	0.726 – 0.927	0.742 – 0.833	0.671 – 0.769

Table **3**. Values of coefficients to be adopted in Eq. (5) for range of Γ

Sl	Γ	coefficient a_1	coefficient a_2	coefficient a_3	R^2
1	0.17 – 0.19	0.110	0.053	0.064	0.98
2	0.20 – 0.21	0.020	0.834	0.332	0.99
3	0.22 – 0.24	0.051	0.323	0.207	0.96
4	0.25 – 0.26	0.074	0.173	0.140	0.98
5	0.27 – 0.30	0.012	1.616	0.530	0.99

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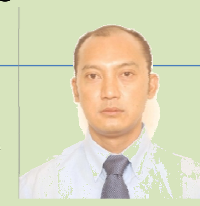

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