

ADAPTIVE UNIFORM AND NON-UNIFORM CONFIGURATION OF BOULDERS ON BLOCK RAMPS FOR RIVER RESTORATION

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ABSTRACT

Block ramps are a cost-effective assembly in river restoration projects to sustain river morphology. This experimental study determines the various energy dissipation factors with uniform and non-uniform (NU) configuration of boulders, with the objective to translate the dissipation of excess energy in the flow to minimize river bed aggradation or degradation. Semi-hemispherical blocks of 5 sizes representing boulders in staggered pattern is adopted on 3ramp slopes as it was established that this arrangement is more effective in energy dissipation than the row or random arrangements. Energy dissipation increases as the spacing decreases for various sets of uniform arrangements. NU configuration of the boulders has been so far not investigated by previous researchers. This study incorporates experiments on the NU configuration and it was found that energy dissipation is greater in NU configuration than uniform arrangement in majority of the test conditions and that alternate spacing inherits the flow accordingly producing quantitative loss of energy due to increased localized energy dissipation. An empirical relation has been developed incorporating the uniform and non-uniform configurations for evaluating the relative energy dissipation, in terms of length of ramp, ramp height, critical flow depth, boulder concentration, and coefficients representing the relative boulder configuration. The relation is found to hold good within the $\pm 5\%$ deviation and may be conservatively used for formulation of design guidelines that can aid water resources engineers in practical applications of boulder block ramps for stream restoration works.

Keywords: macro-roughness, boulder concentration, uniform, non-uniform, energy dissipation

1. INTRODUCTION

Block ramps are a promising and cost-effective structure in river restoration projects to dissipate energy and assure river bed stability. 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 and are an effective assembly in retaining the stream morphology and hydraulic continuity. In practical applications, block ramps are generally made of boulders with mean diameter between 0.3 m and 1.5 m. 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. Based on an 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).

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

where, relative energy loss, $\Delta E = (\text{upstream energy } E_0) - (\text{energy at the toe of ramp } E_t)$; 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 (Pagliara and Chiavaccini, 2006a); coefficients E and F are

functions of arrangement and roughness of the boulders (Pagliara and Chiavaccini, 2006b). The boulder concentration (Γ) is equal to the ratio of ramp surface covered with the boulders and the total surface area of the ramp and given by Eq. (2),

$$\Gamma = \frac{N_B \pi D_B^2}{4WL} \quad (2)$$

where, D_B = mean size of the boulders; N_B = number of boulders; W = width of the ramp; and L = length of the ramp. Eq. (1) can be used only for a concentration Γ less than 33% (Pagliara and Chiavaccini 2006b). 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 $\pm 3\%$ error limit as given by Eq. (3).

$$\Delta E_{rB} = \left[A + (1 - A) e^{(B+CS) \frac{h_c}{H}} \right] \left[1 + \frac{\Gamma}{0.6 + 7.9(D_B/h_c)^{-0.9} \Gamma} \right] \quad (3)$$

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 (2006a). Pagliara *et al.*, (2017) analyzed the hydraulic behaviour of block ramps on a curved channel and developed a design relationship to evaluate the maximum scour depth taking into consideration the effect of channel curvature and the tailwater level. All the above studies have so far accrued on uniform to near-uniform arrangement of the boulder blocks on the ramp and with limited boulder sizes and flow discharge ranges. 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.

2. EXPERIMENTAL SET-UP AND STUDY APPROACH

Experiments were carried out at the Hydraulics Laboratory of the Department of Civil Engineering, Indian Institute of Technology Roorkee, India. Experiments were performed on a concrete flume having a rectangular ramp of width (W) 0.30 m, horizontal length 4.0 m with side walls of height 0.45 m. Three ramp slopes (S) in the order of 1V:5H, 1V:7H and 1V:9H were investigated (Romeji, 2013). It may be recalled that even-numbered ranges of slope have already been investigated by several researchers. A broad crested weir of width 0.20 m was provided at the upstream most section of the ramp with a curvilinear finish (radius 0.10 m) to facilitate smooth water flow. A schematic diagram of the experimental set-up is given in Figure 1.

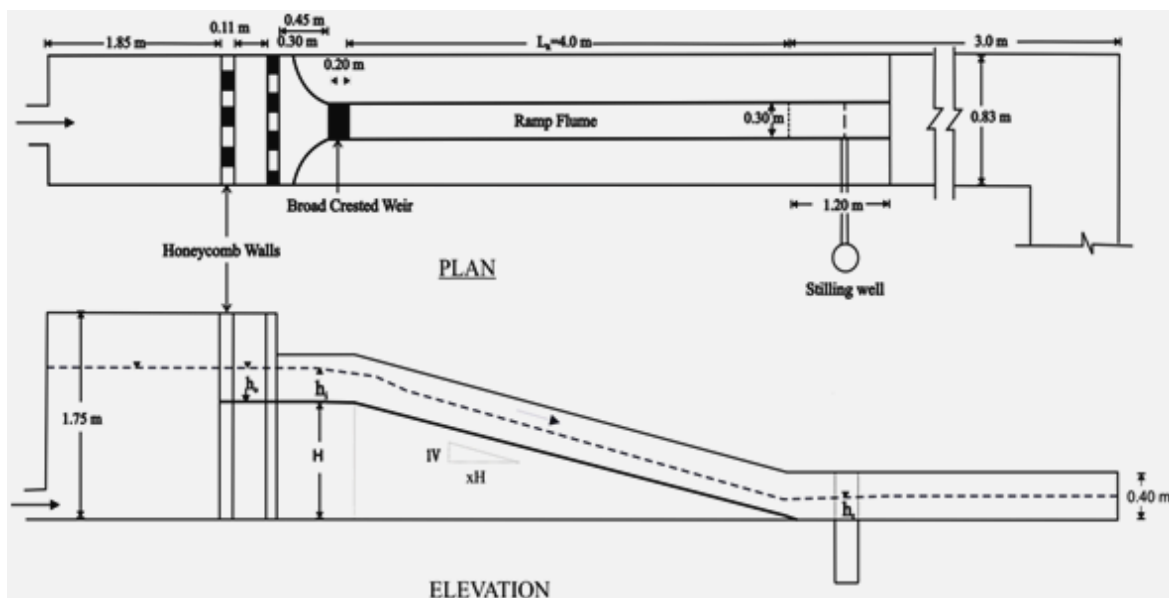


Figure 1. Schematic plan and elevation of the experimental set up (not to scale)

An ultrasonic flow meter (transit-type portable), with transducer fittings, was used to measure the instantaneous discharge through the supply pipe and the observations were used for the calibration of the broad crested weir. A bendmeter assembly with inclined manometer (at 15° with horizontal) was also fitted to

the supply pipe to measure the instantaneous head of inflow. Water level measurements were taken with the aid of digital and manual pointer gauges. At the downstream section of the ramp (approximately 1.0 m downstream from where the ramp slope ends), a stilling well assembly was used for the measurement of tail water depth in view of the high turbulence caused downstream.

2.1 Configuration and distribution of macro-roughness boulders

The spatial arrangement of boulders on block ramps was configured to symmetric or axisymmetric arrangements in the testing phase of the experiments as was also investigated by Pagliara and Palermo (2015) and Romeji (2013). 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 Figure 2. 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.

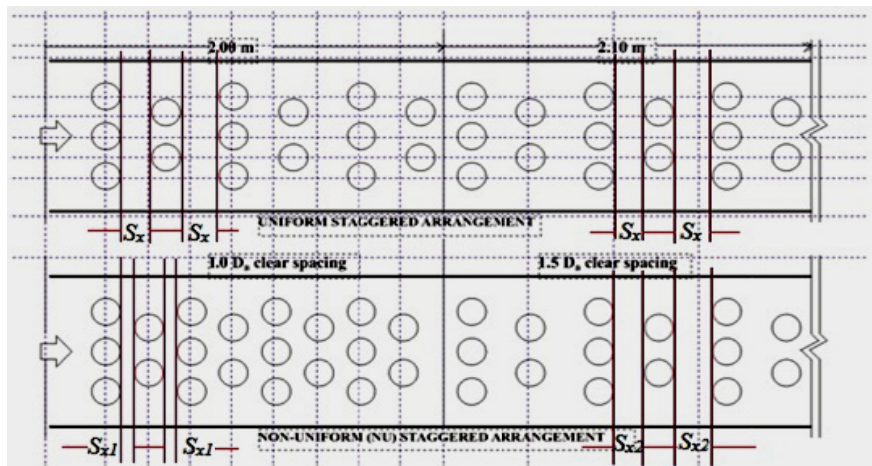


Figure 2. Sketch showing uniform and non-uniform staggered arrangement of boulders on the ramp

As it was observed that the developing flow region generally prevailed up to approximately $1/3^{\text{rd}}$ to $1/4^{\text{th}}$ of the upstream portion of the ramp length in the tested conditions, and then a developed turbulent flow regime was observed in the downstream portion. The non-uniform arrangement was fabricated to introspect and compare the energy dissipation function with the uniform arrangement, by perturbing the homogeneity of flow characteristics that are generated by the macro-roughness boulders on the block ramp for the uniform configuration. The perception was whether a differential longitudinal spacing of the boulders along the block ramp could result in higher dissipation of energy. Four non-uniform arrangements were deployed for the study as described in Table 1. This type of configuration was not tested in related studies so far.

Table 1. Description of non-uniform configuration of boulders used in the experiments

Sl	Notation	Configuration	Description
1	NU-1	Non-uniform spacing -1	1.0 D_B clear spacing of the boulders covering 0.85 m upstream length of the ramp, followed by 1.5 D_B for remaining length of the ramp
2	NU-2	Non-uniform spacing -2	1.0 D_B clear spacing of the boulders covering 2.0 m upstream length of the ramp, followed by 1.5 D_B for remaining length of the ramp
3	NU-3	Non-uniform spacing -3	(reverse order of NU-2)
4	NU-4	Non-uniform spacing -4	Alternate 1.0 D_B and 1.5 D_B clear spacing of the boulders throughout the length of the ramp

2.2 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. Observations for each specific configuration and boulder geometry under different permutations and combinations of boulders were noted with the objective of ascribing its differential effect on the relative energy dissipation (ΔE_{rB}).

Table 2. 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)	m ³ /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}) (microroughness)	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) ($\times 10^4$)	–	2.55 – 7.47	4.55 – 9.29	5.86 – 10.68

A reduction coefficient ($\psi < 1$) is introduced to represent the effective bed arrangement, and is evaluated as the ratio between the effective volume occupied by the water in the control volume among the macro-roughness elements in the lower layer and the total volume of the lower layer for the bottom layer flow velocity (Canovaro and Solari, 2007). For staggered arrangement of the macro-roughness boulders, the reduction coefficient is evaluated using Eq. (4) as modified after Canovaro *et al.*, (2007).

$$\psi = 1 - \left[\frac{\pi}{4} D_B \left(\frac{N_B}{L_R W} \right)^{\frac{1}{2}} \right] \quad (4)$$

where, D_B is the mean diameter of the macro-roughness elements and N_B is the number of macro-roughness elements arranged on a unit bed area along the channel.

2.3 Test procedure

Experiments were performed for uniform spacing of boulders in staggered pattern for $D_B=0.042$ m boulders at ramp slope $S = 0.20$ (1V:5H) for uniform L-spacings: $S_x/D_B = 1.0, 1.5, 2.0, 3.0,$ and 4.0 , followed by the four sets for non-uniform configuration of boulders: NU-1, NU-2, NU-3, NU-4 respectively. Tests were performed for the sets for the other boulder dimensions under the same slope as: $S = 0.20, D_B = 0.055$ m; $S = 0.20, D_B = 0.065$ m; $S = 0.20, D_B = 0.080$ m; $S = 0.20, D_B = 0.10$ m, respectively. These completes one full experiment cycle for a particular slope 1V:5H. Similarly the experiments were carried out for the second and third full cycles for slopes 1V:7H and 1V:9H. Three flow conditions were observed in the experimental study viz., undulating or tumbling flow, wake interference flow and quasi-smooth or skimming flow. Each condition seem to quite dependent on Γ and flow discharge.

3. DATA ANALYSIS AND RESULTS

The energy dissipation on the block ramp is evaluated in terms of the energy per unit weight of water volume i.e. the head of water. In the present study, the head loss between the upstream section and downstream toe section is taken as the energy loss of flow over the block ramp. The basic Bernoulli theorem and Bélanger principle has been adopted for the various computations of energy dissipation.

The relative energy dissipation at the downstream toe section of the ramp with respect to the upstream measured head is the ratio of difference of energy heads between the two sections (ΔE) and the upstream energy (E_0) as by Eq. (5):

$$\Delta E_r = \frac{E_0 - E_t}{E_0} = \frac{\Delta E}{E_0} \quad (5)$$

where the upstream energy or head is calculated under critical flow conditions at depth (h_c) and downstream energy head at the toe of the ramp at depth for the flow over the block ramp measured via the stilling well (h_t) are evaluated as given by Eq. (6) respectively.

$$E_0 = \left(H + \frac{3}{2} h_c \right) \quad \text{and} \quad E_t = \left(h_t + \frac{q^2}{2gh_t^2} \right) \quad (6)$$

3.1 Energy dissipation computations and observations

The relative energy dissipation term is denoted by ΔE_{rB} for the case of block ramps with boulders over base material. In general, ΔE_r denotes the relative energy dissipation term for the smooth ramp case or ramp with base material. It may be noted that the relative energy dissipation is a dimensionless variable. 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. On steep slopes, the normal depth is less than the critical depth, so the flow profiles do not follow the general hydraulic asymptotes. In the case the profile tends to be irregular with the flow decelerating with increasing depth downstream. It can also be observed that there was a gradual dispersion of energy as flow tumble downstream of the ramp in a waveform profile due to the effect of localized jumps imparted by the tumbling flow regime as shown in Figure 4.

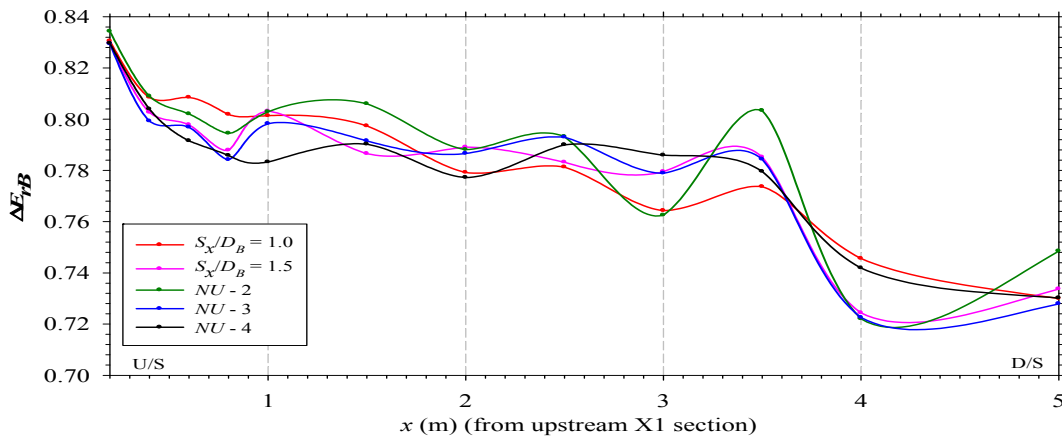


Figure 4. Variation of relative energy loss along the ramp L-section with $D_B = 0.055\text{m}$ at $Q \approx 0.025\text{ m}^3/\text{s}$ (1V:5H)

To introspect into the relative energy dissipation on ramp slope 1V:5H for each respective boulder under varied concentrations and spacing, the observed ΔE_{rB} values are plotted with respect to the (h_c/H) as given in Figures 5a to 5e. 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.

From the observations made, there is no clear perception of the effect of boulder concentration on the relative energy dissipation for the tested slope ($S = 0.20$). The spacing of boulders, its distribution and size also seem to collectively influence the relative energy dissipation factor. Though it could be noted that the small spacing as $S_x/D_B = 1.0$, exhibited a steady energy dissipation profile among the tested configurations which indicate that closer boulder spacing is accountable for achieving stable energy dissipation. For the largest boulder size tested ($D_B = 0.10\text{ m}$), it may be observed that any boulder size exceeding this ratio has no significant impact with respect to its spacing or distribution in describing the relative energy dissipation at this slope.

To further examine the relative energy dissipation trend at the ramp slope 1V:7H for each respective boulder size under varied concentrations and spacing, the observed ΔE_{rB} values are plotted against (h_c/H) as shown in Figures 6a and 6b in respect of the 5 boulder sizes (**due to the paging limitations, the remaining 3 plots are not shown*). The results indicated that closer spacing do not exactly yield the anticipated higher energy dissipation. There is an intermingling trend that intermediate L-spacing for the smaller-sized boulders ($D_B \leq 0.055\text{ m}$) exhibited slightly higher dissipation of energy than the closer spacing. As the boulder size increases, the relative flow depth decreases, there is an indication that the spacing factor of boulders play a dividend role when the macro-roughness size is prominent relative to the flow depth. Here the NU configuration exhibited higher dissipation of energy than the uniform configuration especially in the case of boulders ($D_B \geq 0.065\text{ m}$). With reduction in slope from 1V:5H to 1V:7H, the increase in flow submergence illustrated a substantial drop in ΔE_{rB} .

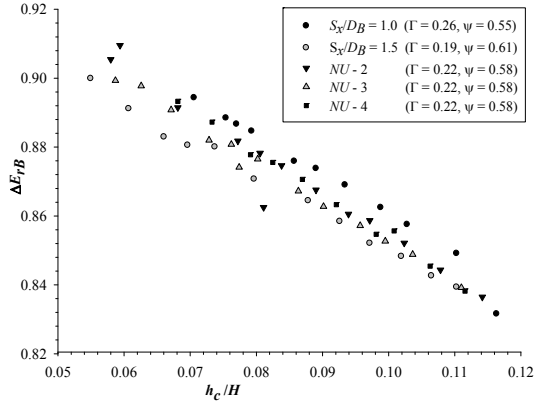


Figure 5a. Variation of ΔE_{rB} for $D_B = 0.042$ m in uniform & non-uniform configurations (1V:5H)

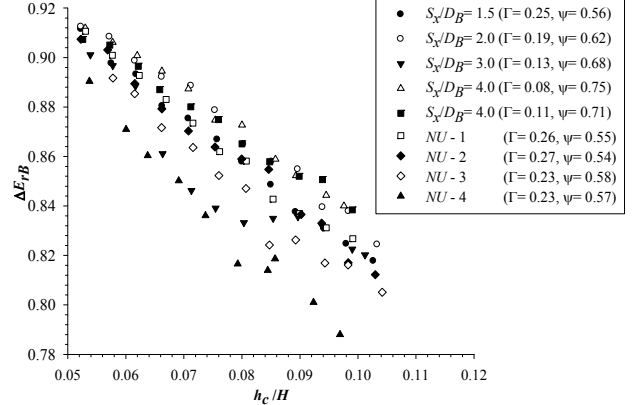


Figure 5b. Variation of ΔE_{rB} for $D_B = 0.055$ m in uniform & non-uniform configurations (1V:5H)

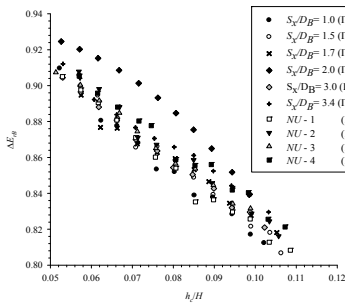


Figure 5c. Variation of ΔE_{rB} for $D_B = 0.065$ m in uniform & NU configurations (1V:5H)

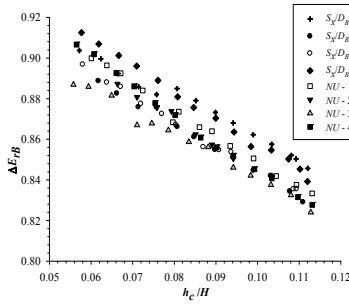


Figure 5d. Variation of ΔE_{rB} for $D_B = 0.080$ m in uniform & NU configurations (1V:5H)

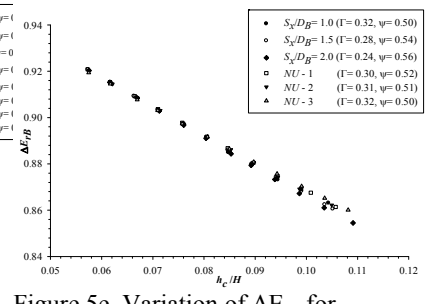


Figure 5e. Variation of ΔE_{rB} for $D_B = 0.10$ m in uniform & NU configurations (1V:5H)

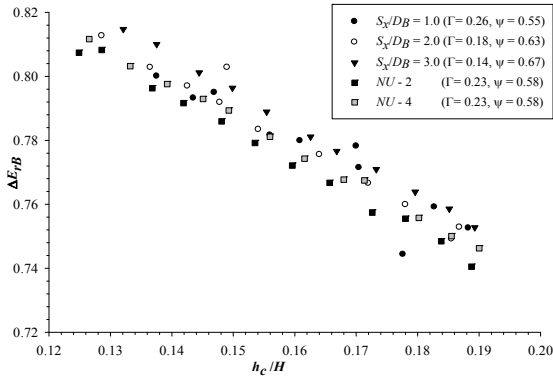


Figure 6a. Variation of ΔE_{rB} for $D_B = 0.055$ m in uniform & non-uniform configurations (1V:7H)

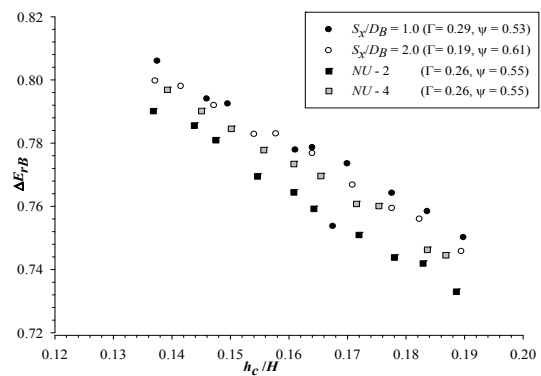


Figure 6b. Variation of ΔE_{rB} for $D_B = 0.065$ m in uniform & non-uniform configurations (1V:7H)

For detailed examination of the relative energy dissipation trend for each respective boulder under varied concentrations and spacing at the ramp slope 1V:9H, the observed ΔE_{rB} values are plotted against (h_c/H) as shown in Figures 7a and 7b in respect of the 5 boulder sizes (**due to the paging limitations, the remaining 3 plots are not shown*). An examination of the plots indicated that closer spacing ($S_x/D_B \leq 1.0$) yielded slightly lower energy dissipation as the boulder size increases. For the smallest boulder size tested ($D_B = 0.042$ m), all the points lie asymptotically indicating that there is no significant impact of spacing or distribution at larger flow depths, as was similarly found at 1V:7H slope.

As the boulder size increases, the degree of variation of ΔE_{rB} along gets segregated for each spacing and configuration, with the flow parameter. The spacing factor of boulders can be said to have a distributed function when the relative flow depth (h/D_B) is significant. Another interesting observation was that, the non-uniform (NU-4) configuration exhibited higher dissipation of energy than the other tested configurations in the case of bigger-sized boulders (for $D_B = 0.065$ m and 0.080 m) for this slope; this configuration array may

have generated cyclic interferences with the wake formation. It can also be observed that there is almost a similar percentage range (on an average 7%) of energy dissipation as flow traverses downstream of the ramp with the prominence of a quasi-skimming flow regime. Further it can be marked that, there are substantial drops of the NU-2 configuration with the 0.065 m size boulders and $S_x/D_B = 1.0$ configuration with the 0.080 m size boulders from the general ΔE_{rB} variation line for each case. This can be an indication that boulder distribution is a critical parameter for the ΔE_{rB} function across boulder block ramps, when relatively large boulders are used at flatter slopes.

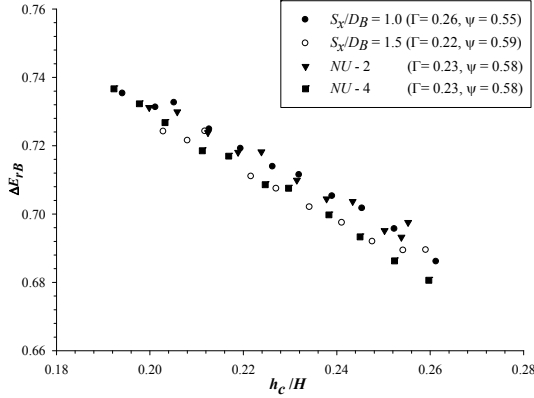


Figure 7a. Variation of ΔE_{rB} for $D_B = 0.055$ m in uniform & non-uniform configurations (1V:9H)

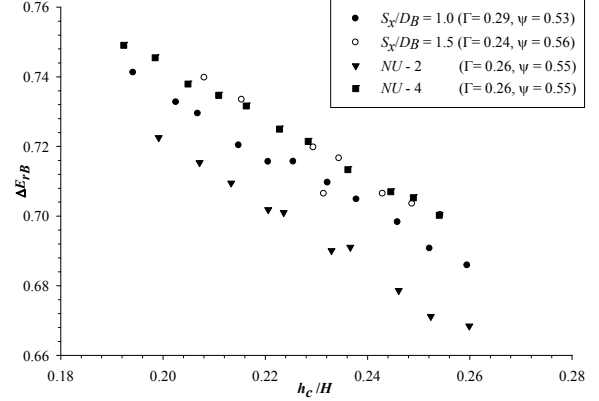


Figure 7b. Variation of ΔE_{rB} for $D_B = 0.065$ m in uniform & non-uniform configurations (1V:9H)

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 4.

Table 4. Overall summary of the 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

3.2 Boulder spacing criteria

It has been observed from the assay of test results that the slope, boulder concentration and boulder size has integral and differential effects on the relative energy dissipation function on boulder block ramps. In Closer spacing (in the order of $S_x/D_B \leq 1.0$) yielded higher energy loss, and in some cases the trend gets reversed. Based on Sayre and Albertson (1961) criterion for macro-roughness spacing, a relation (Eq. 7) is formulated to evaluate the longitudinal and transverse spacing of boulders for a particular boulder concentration for staggered uniform configuration for boulders on block ramps within $\pm 95\%$ prediction margin.

$$\Gamma_{\text{calc}} = 0.86 \left[\frac{D_B^2}{2(S_x + D_B)(S_y + D_B)} \right]^{1.11} \quad (7)$$

where S_x and S_y are the longitudinal and transverse clear spacing between the boulders respectively. It may be noted that S_x was generally kept equal to S_y for the configurations, except in the case of larger boulders i.e for $D_B = 0.080$ m and 0.10 m. The relation can be satisfactorily adopted for the range $\Gamma = 5$ to 35 %.

3.3 Equations inferred for computing energy dissipation on boulder block ramps

It has been noted that a single functional parameter is not able to adequately correlate the energy dissipation. Considering the Reynolds number implicitly within the parameter h_c/H , a functional relation is inferred for ΔE_{rB} (Eq. 8) in respect of the dominant parameters (h_c/H , Γ and ψ) using multi-regression analyses, treating each dominant parameter as equally significant in estimation of the ΔE_{rB} .

$$\Delta E_{rB} = -0.151 - 1.826 \left(\frac{h_c}{H} \right) + 1.386(\Gamma) + 1.411(\psi) \quad (8)$$

Further, discriminant and principal component analyses were performed to select those optimal dataset that best reflected the functional energy dissipation variables h_c/H and Γ implicitly and compositely. Other researchers as Pagliara and Chiavaccini (2006b), Ahmad et al. (2009), etc have proposed relations taking the above factors explicitly. Deploying a non-linear regression procedure on an exponential 3-parameter decay function with 75 % of sorted dataset ($R^2 = 0.92$); a generalized equation is developed to compute ΔE_{rB} as given by Eq. (9) within the 95% confidence line and a standard error of estimate of 0.005. The coefficients a_1 , a_2 and a_3 are introduced in place of numerical values with the best fit correlations primarily with the range of boulder concentration tested for both uniform and non-uniform staggered configurations; and secondarily in terms of ramp slope, flow parameter, etc.

$$\Delta E_{rB} = L_R \times a_1 \exp\left[\frac{a_2}{a_3 + \Gamma(h_c / H)}\right] \quad (9)$$

The proposed relation is validated using 25% of the remaining dataset for the sorted range of $\Gamma = 17$ to 30% within the $\pm 5\%$ deviation (the marginally scattered points may be attributed to the slope and boulder concentration factor) as shown in Figure 8. Thus Eq. (9) can be effectively applied for the optimal boulder concentration range of $\Gamma = 0.17 - 0.30$ and $0.05 < h_c/H < 0.29$. However for a wider range, a particulate relationship specific for the boulder concentration should be adopted.

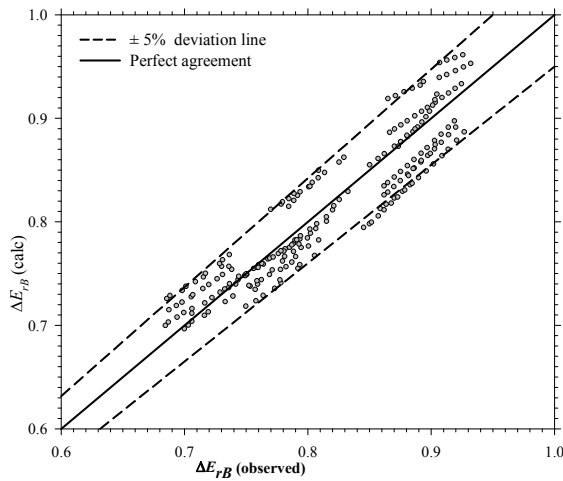


Figure 8. Comparison between ΔE_{rB} (observed) and ΔE_{rB} (calculated) as per Eq.(9)

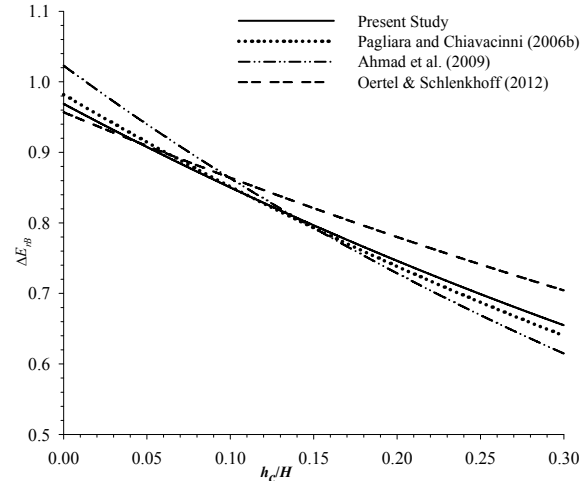


Figure 9. Comparison of ΔE_{rB} computed using Eq. (9) and equations by other investigators

The values of coefficients a_1 , a_2 and a_3 for specific ranges of boulder concentration are given in Table 5. These values were specifically obtained using the same analysis procedure for each respective Γ range.

Table 5. Values of coefficients to be adopted in Eq. (9) 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

To check the variation of the proposed equation (Eq. 9) with that postulated by other investigators, the optimal observed dataset of the present study was applied correspondingly, and plotted in Figure 9. It can be seen that the relative energy dissipation trend of the present study almost followed a similar profile with the others at an almost equal intercept at $\Delta E_{rB} = 0.82$ and $h_c/H = 0.13$, except to that depicted by Oertel and Schlenkhoff (2012) (their study was based on crossbar block ramps). The equivalent intercept could reveal that the overestimation or underestimation of ΔE_{rB} from this point may only be due to the different experimental conditions adopted by the authors. The proposed relation may thereby be considered acceptable for use in estimation of ΔE_{rB} on block ramps for both uniform and non-uniform staggered configurations of boulders within the prescribed boundary conditions.

4. CONCLUSIONS

This present study was endeavored to delve the energy dissipation characteristics on block ramps with boulders in uniform and non-uniform arrangements and find an adaptive relation for both configurations. The existing relationships and associated parameters for energy dissipation on block ramps were tested using the collected dataset and the congruities or variances found have been reported. The variables were examined and analyzed implicitly or explicitly for its effect on the energy dissipation, from which the dominant hydraulic parameters were selected for analyses. A relation is proposed for boulder spacing criteria and for computing ΔE_{rB} for block ramps with boulders in staggered uniform and NU configurations (with $\pm 5\%$ deviation margin). The Reynolds number ranged from $(2.55 \text{ to } 10.68) \times 10^4$ with a distinct association with ΔE_{rB} for each tested slope; Froude number ranged from 1.64 to 3.98 and had low correlation with ΔE_{rB} .

As there was a rise in the relative energy dissipation trend with increase of Γ upto a certain range beyond which further increase of boulder density led either to decay of the $\Delta E_{rB}/\Delta E_r$ function or remained constant. This threshold boulder concentration was found to be in the range 0.22 – 0.25 for the tested boulder sizes and configurations ($0.08 \leq \Gamma \leq 0.32$). Thereby, a boulder concentration of 0.23 was found optimal for imparting efficient energy dissipation. An adaptive relation has 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 $\pm 5\%$ error limits for the range $\Gamma = 0.17 - 0.30$ and $0.05 < h_c/H < 0.29$. Design recommendations and guidelines for practical application of boulder block ramps have also been formulated based on the findings of the present study ([#]*not presented in the present paper; Romeji, 2013*).

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