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Investigation of energy attenuation, flow resistance and impending motion of downstream bed material in rock ramps

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Abstract: *Block ramps are ecofriendly drop structures, which ensure stable downstream river bed, peculiar to flows over macro roughness elements. It uniquely serves an essential paradigm in riverine management, to encounter deliveries in an ecologically sound manner. It permits safe fish passage, stabilizes stream banks and bed profiles and creates habitat diversity. Study of flows over block ramps are quite extensive and are associated with many intricacies. In this paper, flume experiments were conducted in the hydraulic laboratory of National Institute of Technology Patna. The particle densimetric Froude number (F^*) was calculated for the mobile bed and chosen to predict the hydraulic conditions for incipient sediment motion in the uniform beds and it is compared with the established literature formulations to estimate the stability of the beds under large-scale roughness conditions. Scour volumes from each experimental run is quantified and the intensity of sediment motion was determined. Experimental data analysis allowed describing the mechanism of incipient motion of the mobile bed in the stilling basin, energy dissipation, flow resistance and in the interstitial flow over rock ramps and intensity of block movement for various flow regimes. It was found that the dimensionless shields stress increases with ramp slope and the intensity of ramp motion decreases with the shear stress. The results indicated that friction resistance increases with relative submergence for the tested range of experiments. A comparison with previous literature with uniform sediment transport indicates that relative roughness of block is responsible for increasing the dimensionless Shields stress. The results of physical testing can be used to assess and predict the effective dissipation of energy and its impact on the stability of rock structures.*

Keywords: *Densimetric Froude number, energy dissipation, frictional resistance, incipient motion, intensity, rock ramps.*

1. Introduction

The restoration of longitudinal connectivity in riverine systems is one of the major requirements in river rehabilitation. Rock ramps or block ramps, also known as fish ramps, have notably replaced many anthropogenic barriers such as dams and weirs under reasonable costs. Not only had they satisfied the hydraulic criteria for fish migrations by stabilizing stream bed and limit the channel scour as well. Rock ramps are generally small section of a slopy channel which spans the entire river width, generating large-scale roughness in the form of boulders. They are generally used in mountainous terrains and differ by their bed material, size of boulders (mean diameter D ranging from 0.3 m to 1.5 m) and their arrangement. In lateral hydraulic structures, a huge quantity of kinetic energy gets dissipated by generating hydraulic jump at the toe. But a significant amount of energy (30-50%) still remains in the flow after the jump. This remaining energy, if not taken care, has high potential to further erode the bed. Rock ramps results in high energy dissipation due to confined variation of slope and presence of large roughness elements. Several investigations have been done to correlate the amount of energy dissipation and various ramp characteristics. Platzer (1983) performed experiments on block ramps with slope S equal to 0.1; energy dissipation on stepped channels for skimming flow conditions was explored by Christodoulou (1993). Empirical equations for energy dissipation at nappe and skimming flow conditions was given by Chanson (1994). Pagliara and Chiavaccini (2006a and 2006b) carried out a systematic study on energy dissipation in reinforced rock ramps. Ghare et al. (2010) proposed a dimensionless mathematical model correlating the bed material and step height of the rock ramp. Later, Pagliara et al. (2015) studied energy dissipation characteristics of both transition and uniform flow conditions in a tapered channel over large-scale roughness condition.

Rock ramps also provide high flow resistance due to the presence of traction, wake vortices, localized hydraulic jump and jetting flow bounded by every rough element. Extensive studies on flow resistance in block ramps have been done so far. Bathurst (1978) distinguished three roughness conditions, i.e., large-scale roughness h/d_{84}<1.2, intermediate-scale roughness 1.2< h/d_{84}<4 and small-scale roughness 4 < h/d_{84}, where h is the flow depth and d_{84} is the characteristic diameter of the bed. Morris (1961) and Baiamonte and Ferro (1997) investigated the outcome of large-scale roughness on frictional resistance. An experimental study on hilly sloped channels with angular rip rap was conducted by Abt et al. (1988) to determine the effect of slope on frictional resistance. Bathurst (2002) proposed the semi-logarithmic resistance relationship from in-situ site investigations. Frictional resistance for steep slope beds was investigated by Rice et al. (1998). In current research, Pagliara and Chiavaccini (2006c) examined frictional resistance for reinforced block ramps having projected boulders. Dey and Raikar (2007) evaluated rough bed friction for homogeneous bed for slope range of $0.28 < S < 0.80$. Pagliara et al. (2010) suggested that Darcy-Weisbach friction factor for rock chutes is a function of relative equivalent depth and chute inclination. Oertel and Bung (2015) analyzed scour and bed stability in cross bar block ramps. Although several investigations on rough inclined beds on in-situ and field situations have been performed, the effect of flows over block ramps in large-roughness conditions with steep slopes is yet to be explored.

Similarly, particle stability in the downstream stilling basin is also a salient feature for the design of block ramps. The bed material resting at the downstream of rock ramps must remain steady unless the shear stress exceeds the critical counterpart. Hence a critical flow parameter must be identified and investigated. Particle stability is generally estimated by comparing acting shear stress with the critical counterpart (Aguirre Pe et al. 2003). The most notable work on the initial movement of sediment particles has been performed by Shields (1936). Shields (1936) empirically established a functional relationship between critical shear stress τ_c^* and grain Reynolds number R_e^*, using different flume data. The original Shields diagram has been reproduced and modified by many researchers. Some significant deviations of the observed critical shear stress from those predicted by Shields curve can be observed. For instance, Knoroz (1953) obtained a threshold curve from experiments with sand without the characteristic dip in the transitional zone. Furthermore, Shields curve has been modified using extensive flume studies by Miller et al. (1977). The revised threshold curve was drawn for rough, turbulent flows with a similar shape as original Shields graph but with a lower value of $R_e^* = 0.045$. Similarly, Yalin and Karahan (1979) derived the modified graph using empirical evidence. Overall, the compiled data sets by both investigators exhibited significant scatter for rough, turbulent flow conditions.

Profuse studies have been done based on particle motion so far. Rajaratnam and Macdougall (1993) performed flume experiments for homogeneous sand beds and disclosed the dependency of densimetric Froude number on maximum scour depth. A comprehensive work on the motion of bed sediment in a trapezoidal flume channel was carried out by Kovacs and Parker (1994). Later, Aguirre Pe et al. (2003) determined particle movement based on critical particle densimetric Froude number (F_c^*) and relative depth ($d/D<10$), with d indicating the flow depth and D the characteristic diameter of the bed material. The outcomes of study indicated that F_c^* can be a better interpreter for particle motion in steeper slopes ($0.005<S<0.10$) and large-roughness conditions ($0.2<d/D<10$). Oertel and Bung (2015) also investigated the stability of cross bars in terms of critical particle densimetric Froude number. Rawat et al. (2021) conducted flume investigations for a range of flow rates and ramp slopes, involving two homogeneous stilling basin materials and an additional arrangement with rock sills. In doing so, authors analyzed the effect of d/D on the incipient motion at various bed configurations.

Although many studies have been carried out to determine the application of rock ramps with steeper gradient for dissipation of energy and to maintain reasonable riverine stability, a more comprehensive research is needed to improve current design approaches of rock ramps. The present experimental study investigates energy dissipation and frictional resistance on the ramp. Furthermore, stilling basin material stability is also studied. Large-roughness conditions were reproduced, and the hydraulic process was analyzed.

2. Experimental programme

Experiments were carried out in hydraulics engineering laboratory of Department of Civil Engineering, National Institute of Technology Patna, Bihar, India. Experiments were planned to explore the flows over rock ramps and its characteristics in the downstream stilling basin. Tests were conducted for different ramp slopes in a 0.8 m wide, 0.50 m high and 7 m long flume (Fig. 1). The walls of the flume were made by glass to facilitate visualization during the experiments. The recirculating flume includes a downstream plunge pool to receive water and send it back upstream through an excavated channel in the ground connecting both sides of the flume. The ramp was placed at a distance of 2 m from the outlet to guarantee a well distributed flow across the flume. A point gauge is mounted on the flume for measurement. The flume is kept horizontal during the experiments and the slope of block ramps were changed at the beginning of each test. All experiments were conducted with a fixed ramp length of 1.5 m; whereas the height of the ramp varied to adjust the slope S that ranged from 0.1 to 0.2. Table 1 reports the ranges of variation of tested parameters for this present work.

Table 1. Ranges of experimental data

Hydraulic Parameters	Present study
Ramp slope, S (%)	10-20
Discharge, Q (m^3 s^{-1})	0.02-0.04
F_c^*	2.41-3.89

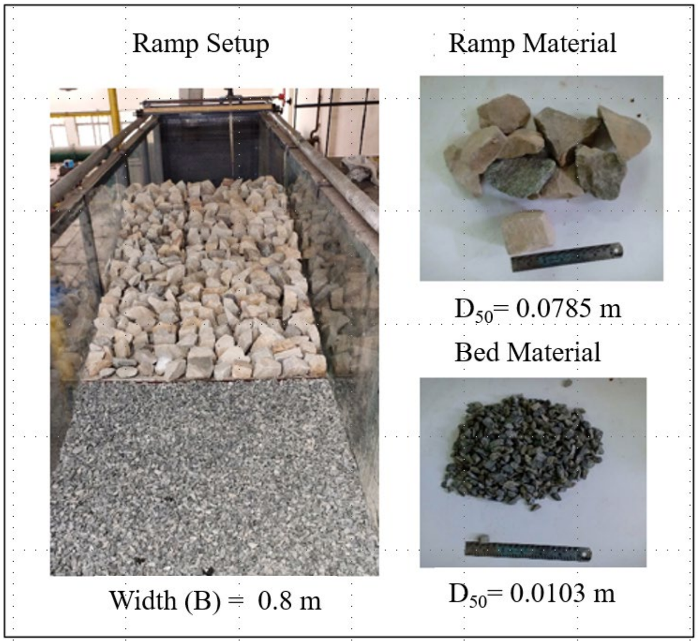

Figure 1. Photograph of experimental setup with ramp (top right side) and bed material (bottom right side)

3. Results and discussion

3.1. Energy dissipation

In the present study, energy dissipation mechanism over rock ramps was analyzed. The relative energy dissipation (ΔE_r) between the inlet and the toe of rock ramps was evaluated for various slopes (i.e., $0.1 \leq S \leq 0.2$) and plotted as function of Y_c/H (Pagliara and Chiavaccini 2006a), where Y_c is the critical depth and H is the height of the ramp. Figure 2 represents the variation of relative energy dissipation with Y_c/H derived from present study and previous investigators. Results show that relative energy dissipation $\Delta E_r=(E_0-E_2)/E_0$ (with E_0 and E_2 indicating the total energy at the beginning and the toe of the ramp, respectively) decreases with Y_c/H for similar flow rates, ramp inclinations and rock ramp length. Consequently, the amount of energy dissipation depends on ramp height, all other parameters being constant. Moreover, the present experimental data lie in the large-scale roughness condition which tends to dissipate more energy compared to small-scale and intermediate-scale roughness counterpart. The present experimental values were contrasted against empirical expression for base block ramps developed by Pagliara and Chiavaccini (2006a).

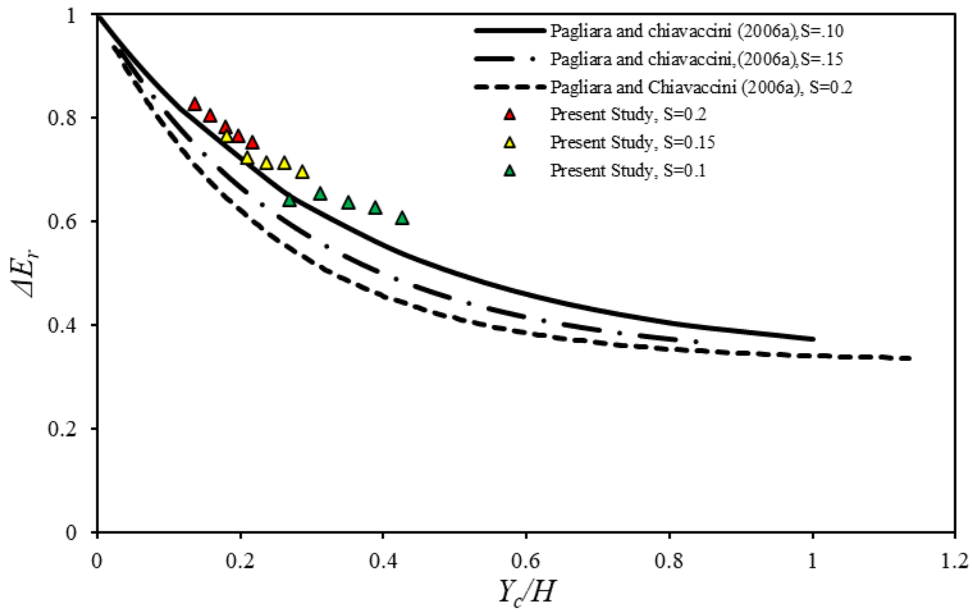

Figure 2. Variation of relative energy dissipation with Y_c/H for flows over rock ramps

3.2. Flow resistance

In the present study, experimental runs have been performed in rough slopy beds to estimate the effect of ramp roughness on flow resistance. Figure 3 depicts the variation of friction factor with relative roughness (Y_c/D_{50}), where D_{50} is the characteristic bed diameter of the ramp. Following the classification of roughness scales made by Pagliara and Chiavaccini (2006), present tests (with $0.5\leq Y_c/D_{50}\leq 0.8$) pertain to large-scale roughness condition (i.e., $Y_c/D_{50}<$ 2.5). Overall, Figure 3 indicates that the Darcy-Weisbach friction factor $(8/f)^{0.5}$ (estimated using the equation proposed by Rice et al. (1998)) is a function of the relative roughness (Y_c/D_{50}) and the ramp slope. Namely, the parameter $(8/f)^{0.5}$ is a monotonic decreasing function of Y_c/D_{50} and S., i.e., lesser the ramp slope, more will be the interaction between the flow surface and ramp material, and, consequently, higher will be the drag resistance.

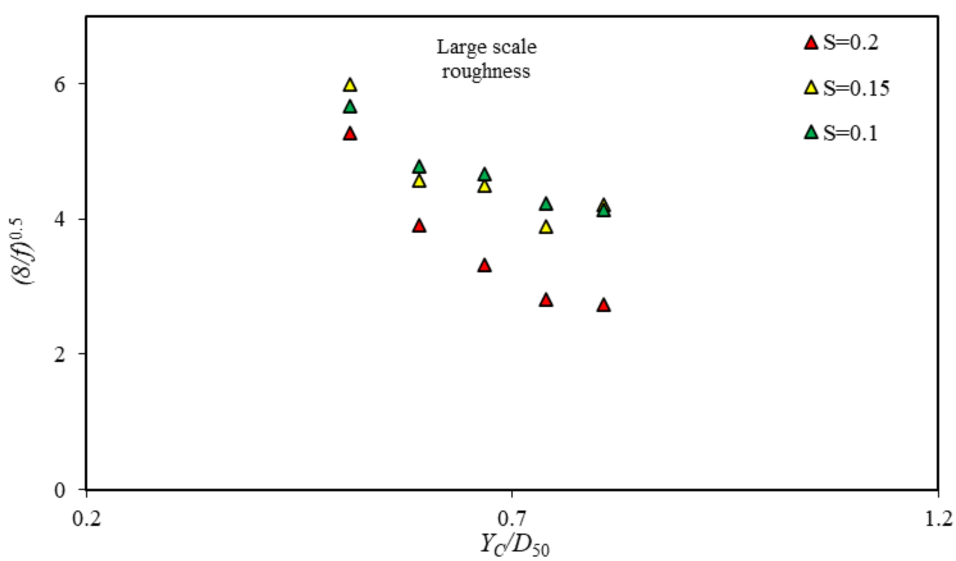

Figure 3. Variation of friction factor $(8/f)^{0.5}$ with Y_c/D_{50} for large-scale roughness condition.

Flow resistance as a function of Froude number at the toe of the ramp is also shown in Fig. 4. Data from previous literature (Abt et al. 1988, Rice et al. 1998, and Pagliara and Chiavaccini 2006) were also included for comparison. Overall, present results appear to be consistent with those of former investigations. Namely, the flow resistance increases with ramp slope. In addition, for large-scale roughness, Froude number also affects flow resistance around ramp roughness elements (via the drag force).

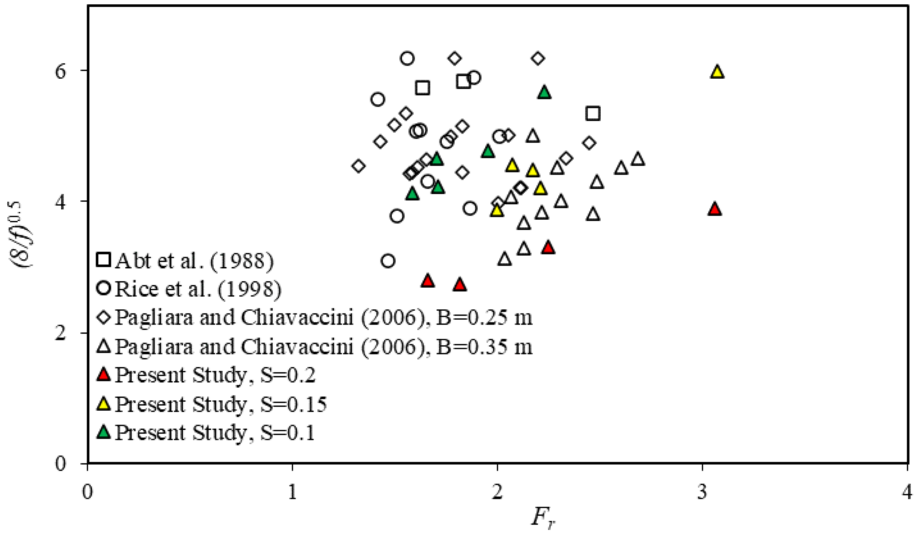

Figure 4. Variation of Friction factor $(8/f)^{0.5}$ with Froude number F_r

3.3. Mobilization of stilling basin material

As for the stilling basin sediment stability, the densimetric Froude number (F^*) at the toe of the ramp was calculated. The densimetric Froude number is defind as $F^* = U/[(s\text{-}1)\ gD]^{1/2}$ (where U = approaching flow velocity to the stilling basin, s=ratio of sediment and fluid densities, g=acceleration due to gravity, and D=characteristic diameter of stilling basin bed particle). Figure 5 shows experimental data from the existing study, which falls in the range of large-scale roughness $0.54<d/D<1.63$ (Bathurst et al.1983). It can be observed that present values of densimetric Froude number vary between 2.1 and 3.89 for $2.44 < d/D < 6.18$. Figure 5 also shows dependency of densimetric Froude number on relative depth d/D (where d is the flow depth) and compared with the critical densimetric Froude number of the previous studies. The previous studies include equations proposed by Aguirre-Pe et al. (2003) and Oertel and Bung (2015) and data from literature with similar experimental approaches (e.g., Lischtvan and Libediev 1959, Bathurst et al. 1983, Bathurst et al. 1984, Neil 1967, Ashida and Bayazit 1973, Aguirre Pe 1975, Olivero 1984 and Rawat et al. 2021). This plot infers that if the ramp bed is made with similar bed material of that of stilling basin, it would have been mobilized corresponding to the incoming flow.

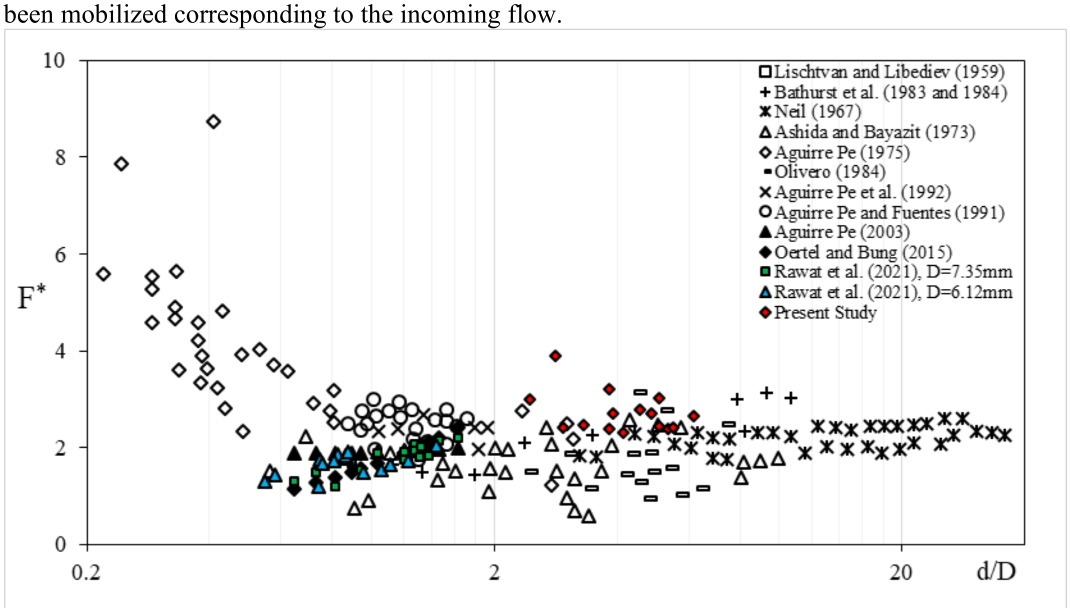

Figure 5. Variation of critical particle densimetric Froude numbers with relative roughness

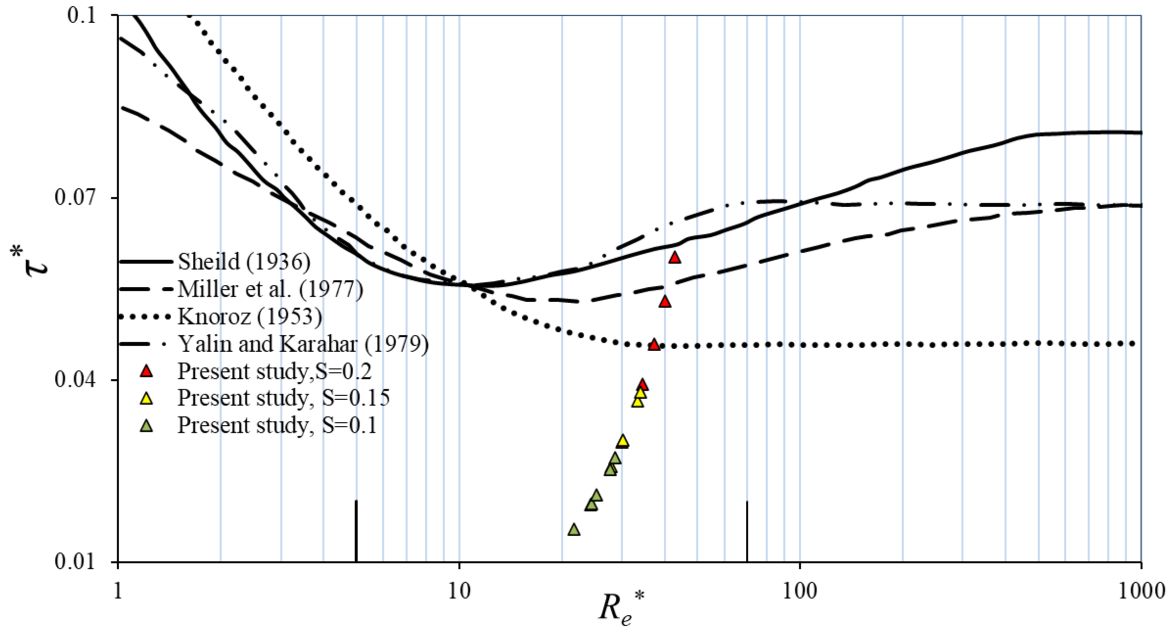

Figure 6. Dimensionless shear stress versus grain particle Reynolds number

To assess the mobility of stilling basin bed material, dimensionless shear stress (τ^*) was evaluated and compared with the critical shear stress or threshold shear stress from Shields diagram. Dimensionless shear stress is calculated as $\tau^* = \frac{\tau_b}{(\rho_s - \rho) g D_{50}}$, where τ^*= Dimensionless shear stress, τ_b = bed shear stress of the ramp, g = gravitational acceleration, D_{50} = median diameter of stilling basin, ρ_s=sediment density of stilling basin bed material, ρ = fluid density. Figure 6 depicts the variation of dimensionless shear stress for different grain particle Reynolds number ($R_e{}^* = \frac{V^* D}{\upsilon}$), where $V^*$is the shear velocity, and υ is the kinematic viscosity of water. Several observations were made for different flow rates, ramp slopes and bed shear stress (Shield 1936). Namely, in Fig. 6, curves relative to incipient motion conditions (obtained by several researchers for horizontal beds) are contrasted against current experimental data. Based on the traditional interpretation of Shields diagram, sediment motion is only possible if shear stress exceeds the critical counterpart (i.e., experimental points are located above transition curves). However, for flows over inclined ramps ($0.1 \le S \le 0.2$), mobilization of bed sediments occurred for all ranges tested in the present study. This is consistent with the findings of Bolhassani et al. (2015), who argued that, for flows over different bed slopes, the threshold shear stress cannot be evaluated via the Shields curve, which is valid only for flows over horizontal beds. In fact, present results reveal that also data below the Shield curve pertain to test characterized by particle transport. Consequently, further analyses of the effect of slope on incipient motion condition are needed.

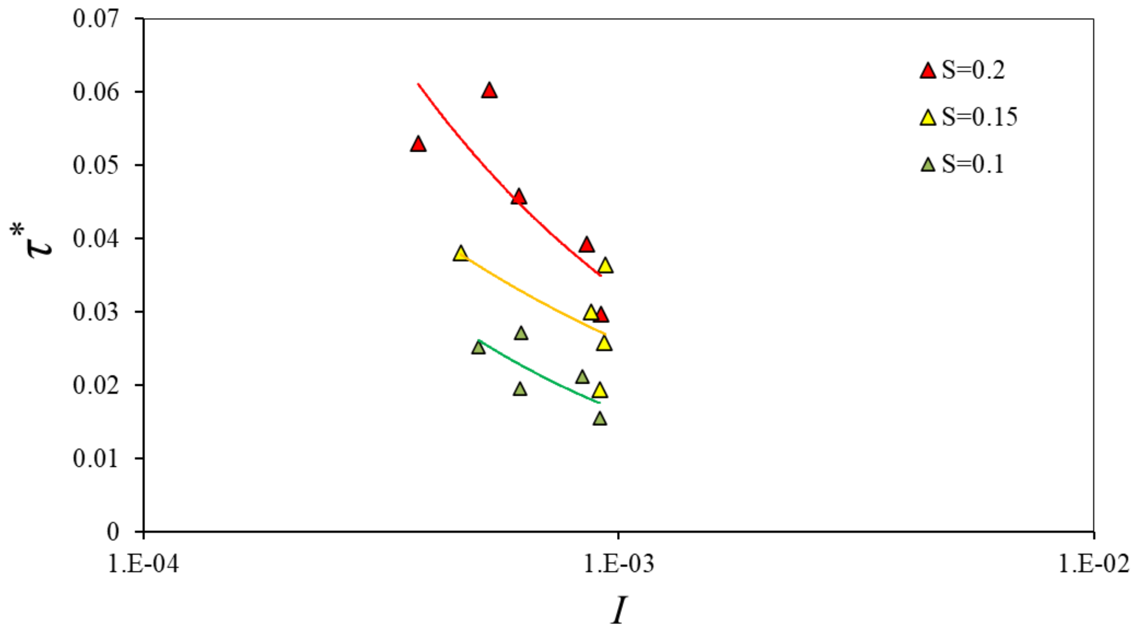

Figure 7. Variation of intensity of sediments motion with dimensionless Shields stress

Likewise, Figure 7 shows the variation of intensity of sediments motion (I) with dimensionless shields stress for flows over inclined block ramps. Intensity is a fraction of all particles in the bed surface moved every second given by $I = \frac{\mathrm{m}}{\mathrm{NT}}$, where m is the number of particle displacements observed during the time interval T on the area of the surface of a mobile bed, and N is the number of surface particles in the area A. Shvidchenko and Pender (2000) defined the intensity I as the relative number of bed sediments moving away from the ramp during each experimental run. Overall, Figure 7 evidences that, for current tests, I ranged from 10^{-4} s^{-1} (one in 10,000 surface particles in motion per second) to 10^{-3} s^{-1} (one in 1000 surface particles in motion per second). Furthermore, as it should be expected, the dimensionless shields stress decreases with the intensity of sediment motion and ramp slope.

4. Conclusions

Rock ramps are huge, macro-roughened, eco-friendly components, randomly dropped on the riverbed. The present experimental study aims to provide further understanding on energy dissipation, frictional resistance and incipient motion occurring in the flows over rock ramps. The nature of flows over rock ramps and the dissipative mechanism under large-scale roughness conditions have been investigated. The dependence of energy dissipation on the dimensionless parameter Y_c/H revealed that ΔE_r decreases with the ramp slope. Experimental evidence revealed that the Darcy-Weisbach friction factor is a function of relative roughness (Y_c/D_{50}), ramp inclination and incoming Froude number. Experimental data were compared with those derived from previous literature to corroborate present analysis. Namely, incipient motion of bed sediment for rock ramps and the effects of ramp slopes on the dimensionless shields stress (τ^*) were also analysed. To describe the flows over rock ramps, the densimetric Froude number (F^*) was calculated and plotted as a function of relative depth (d/D). It was found that the dimensionless shields stress (τ^*) decreases with the intensity of sediment motion. Conversely, an opposite trend occur for increasing values of ramp slope and R_e^*.

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