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Experimental study of flows over Block Ramps on stability of non-cohesive beds

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Abstract

Block ramps are ecofriendly drop structures, which ensure more stability in the downstream riverbed. The scouring in the stilling basin bed material generated by the rapidly varied flow transition affects the stability of the ramp structure. In the present study, a modified stilling basin bed configuration is tested along with the uniform conventional stilling basin bed arrangements to check the stability of non-cohesive beds downstream to block ramps. Uniform non-cohesive horizontal bed configurations and bed with sill arrangement are tested for varying block ramp slopes ($20\% \leq i \geq 30\%$). The critical particle densimetric Froude number (F_c*) is selected as the criteria 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 macroroughness conditions. Scour volumes from each experimental run is quantified and the intensity of sediment motion is determined and related with the critical particle densimetric Froude number. The findings of the paper also describe the effect of F_c* on dimensionless scour depth. Spatial shift in the maximum scour depth formation from the toe of the block ramp for the tested flows over the bed sill arrangement has been observed. Experimental observations and comparison of results show the effect of sill gradation pronounced for non-uniform bed configuration, which effectively reduce the scour depth henceforth it stabilizes the upstream block ramp structure relative to the uniform beds selected.

Keywords

Block ramps,
Critical particle densimetric Froude number
Intensity
Scour
Stability

1. Introduction

Block ramps are grade stabilization hydraulic structures commonly used to regulate sediment transport in eroding rivers. These structures maintain hydraulic as well as ecological conveyance during high and low flow conditions. When not adequately designed, scouring of bed sediments downstream of block ramps may cause insufficient depth in the embedment of the beds and finally causes the failure of hydraulic structures [1]. Particle stability is generally expressed as a function of the shear stress necessary to initiate the motion of individual particles [2]. The well-known and broadly used investigation on the initial movement of sediment particles is performed by Shields [3]. Considering the forces on sediment particles to be restricted to shear stress, it was known that the dimensionless critical shear stress governs the initial motion of bed sediments, and is a function of the Reynolds number of the bed particles. In general, sediment transport is expressed as a function of critical and actual shear stresses at the bed.

Kovacs and Parker [4] have carried out an extensive study on bed particle motion in a trapezoidal shaped channel and derived formulation based on bed load for the motion of coarse bed particles. Rajaratnam [5] carried out experiments on flows over uniform sand beds and concluded that the maximum scour depth is generally a function of densimetric Froude number. Gijs and Hoffmans[6] studied equilibrium scour processes on uniform beds caused by plunging and horizontal jets with no protections. Aguirre-Pe et al. [2] proposed a relationship to evaluate particle motion for (d/D < 10) as a function of critical particle densimetric Froude number (F_c^*), where d is the depth of flow and D is the diameter of the sediments. The authors concluded that the proposed F_c^* is a decent interpreter of bed transport for channels with steeper slopes ($0.005 < i < 0.10$) and large roughness ($0.2 < d/D < 10$). Bormann [7] derived equation for equilibrium scour depth based on the theory of diffusion of jets and stability of bed particles in scour hole downstream of a grade structure. Development of scour downstream of a ramp under different protection work like sills in the stilling basin was investigated by Pagliara and Palermo [8] and experiments with expanding stilling basins have been carried out by Pagliara et al. [9]. Several experimental investigation on ramps included the analysis of the flow characteristics over ramp, aeration properties and energy dissipation characteristics for aerated flows over intermediate and macroroughness conditions [10, 11, 12, 13]. Pagliara and Palermo [8] analyzed the scour morphologies in the stilling basin beds with rock sill arrangements for flows over block ramps. The scour morphologies for different rock sill arrangements in the stilling basin bed are analyzed and the effects due to the sill arrangements in the scour morphology are evaluated. Although numerous studies on bed stability of uniform beds are available till date, however, literature on the effect of block ramps on the incipient motion of downstream uniform bed and bed with sill arrangements have not much found. Oertel and Bung [1] studied the stability of cross-bars concerning the bed stability and concluded that stream flow conditions can be effectively explained by the critical particle densimetric Froude number.

This experimental study presents a performance investigation for various discharges and ramp slopes based on the incipient motion of two uniform bed configurations (BM_1 and BM_2) and one bed with sill arrangement (BM_3). The effect of flow depth to grain size (d/D) on the incipient motion of BM_1, BM_2 and BM_3 bed configurations is also studied. A quantitative definition of the scour volume based on the intensity of sediment motion is calculated and related with the critical particle densimetric Froude number. The present study also highlights the placement of gradually varied rock-sills in the BM_3 bed configuration and its efficiency in the stability of the block ramp structure. The results of the present study in the performance of gradually varied rock sills could be helpful in the design of various low environment impact basins downstream of grade control structures. The proposed rock sills could prevent gully cut head formation and channel bed scouring by reducing the stream slope and flow velocity [14, 15]. The study also indicated that the downstream bed material could be effectively sized to be immobile at the design discharge and slope. The placement of sills will enhance the overall environmental quality and could manage channel flow line for non-erosion benefits incorporating safe fish passages and reduced turbidity.

2. Experimental Facilities

To investigate the effects of block ramps on the incipient motion of bed sediments, 48 experimental runs were conducted in the hydraulic laboratory of NIT Patna, India. The channel dimensions of the rectangular flume used was 0.30 m wide, 7.0 m long and 0.50 m high. The experiments were performed using a ramp of length 0.8 m. The tests were conducted for ramp slopes ranging from 20 to 30%. The flume bed was horizontally paved with the sediments. Two kinds of bed sediments were used (BM_1 and BM_2). The uniformity coefficient ($C_u = D_{60}/D_{10}$), $C_u = D_{60}/D_{10}$ $C_u = D_{60}/D_{10}$ for BM_1, BM_2 and ramp material (RM) along with the other granulometric characteristics are shown in Table 1. The layout of the experimental setup is shown in Fig. 1, where, H is the height of the ramp, d is the depth of water measured at the toe of the ramp. The Z_{max} denotes the maximum scour depth from the bed level in Fig. 1. Additional tests were made to assess the scour hole geometry for beds with sill arrangements (BM_3) with a particular configuration that includes a graded rock sill of three different materials arranged in order of their gradually decreasing diameters, shown in Fig. 2. The geometric dimensions of the sills (S_1, S_2 and S_3) used for the BM_3 configuration are shown in Table 2. A centrifugal pump of 12 kW capacity feeds the flume and the flow rate Q is monitored by an electromagnetic flow meter of 0.000278 $m^3\ s^{-1}$ accuracy. Table 3 includes a summary of experimental range used for the present study. For ratios of water depth (d) to sediment diameter (D) less than 10 ($d/D < 10$), conventional approaches such as Shields parameter is not suitable to predict the critical flow conditions for initiation of particle motion [16]. Hence, in the present work, critical particle densimetric Froude number F_c*[2] as a function of bed stability is used for the analysis and is given by:

Table 1

Granulometric Characteristics of Ramp and Bed Materials

Material	D_{60} (mm)	D_{50} (mm)	D_{10} (mm)	Uniformity Coefficient (C_u)	Specific Gravity(s)
RM	35.00	34.05	22.00	1.60	3.2
BM_1	8.00	7.35	4.75	1.68	3.1

Material	D_{60} (mm)	D_{50} (mm)	D_{10} (mm)	Uniformity Coefficient (C_u)	Specific Gravity(s)
BM_2	6.63	6.12	4.37	1.52	2.9

Fig.1

Diagram sketch of the channel setup

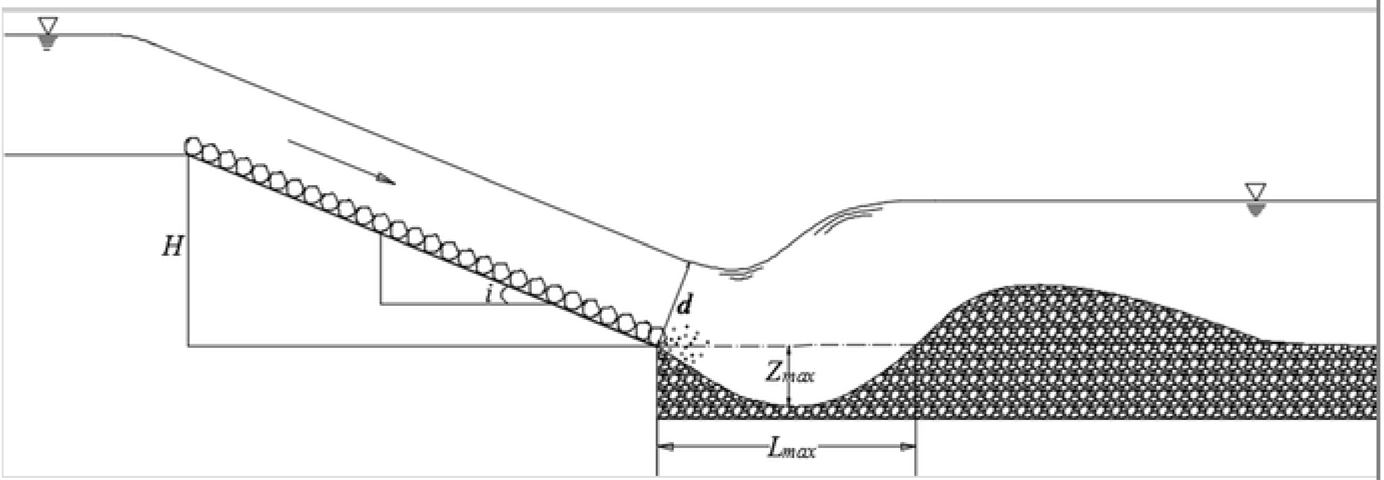


Fig. 2

Plan view of the used sill arrangement at the downstream of block ramp (BM_3)

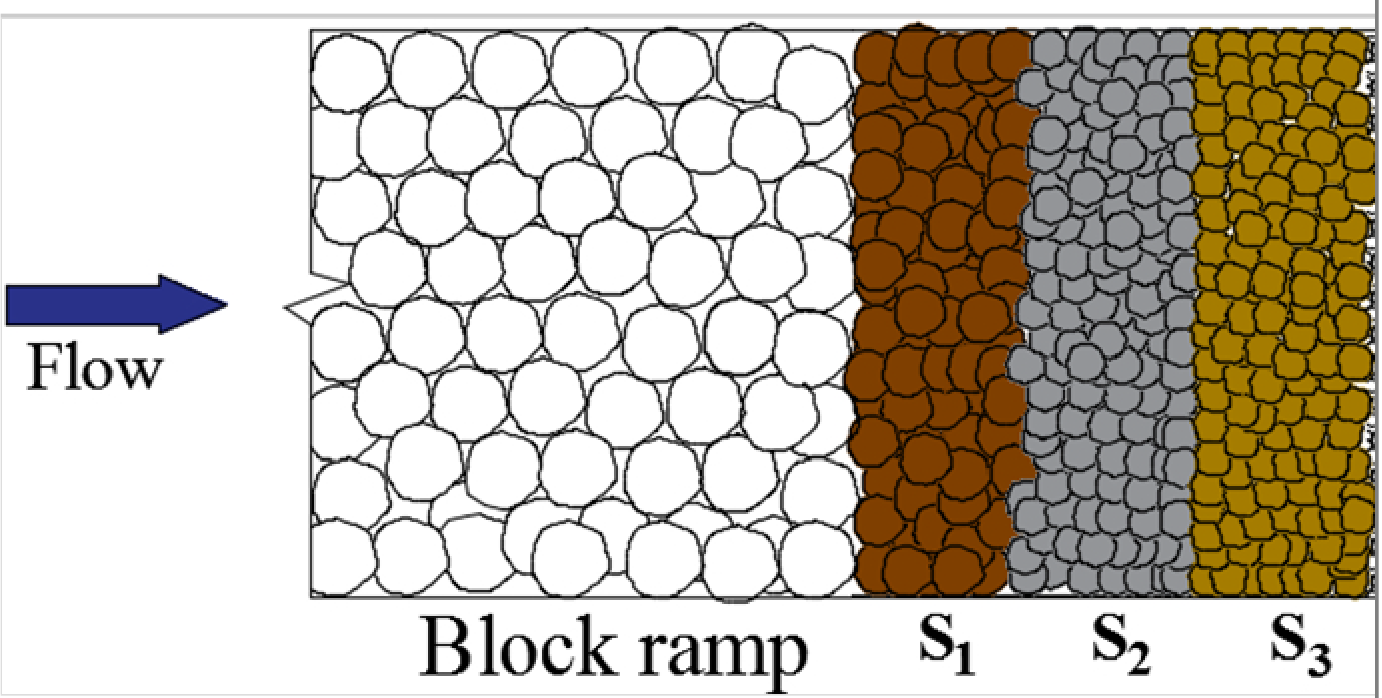


Table 2

Particle diameters of the proposed sills (BM_3)

Material	D_p(mm)	Specific Gravity(s)
Sill-1(S_1)	24.5	3.0
Sill-2(S_2)	15.6	2.8
Sill-3(S_3)	11.2	2.9

Table 3

Ranges of data for the present experimental study

Variables and Non-dimensional parameters	Present study
Slope, i (%)	20–30
Discharge, Q ($m^3\ s^{-1}$)	0.004–0.018
d/D	0.54–1.63
$F_c{}^*$	1.20–2.19

$$F_c^* = \frac{U}{\left[(s-1)\,gD\right]^{0.5}} \quad (1)$$

where, U = Mean flow velocity, s = specific gravity of the sediment, g = acceleration due to gravity, and D = Sediment diameter.

A point gauge of 0.1 mm accuracy was used to measure the scour depths at various points in the transverse and longitudinal cross sections at the downstream of the ramp. Measurements were taken at every 5 cm in the longitudinal direction and at each longitudinal section, measurements were taken at every 7 cm in the transversal direction.

3. Experimental Results

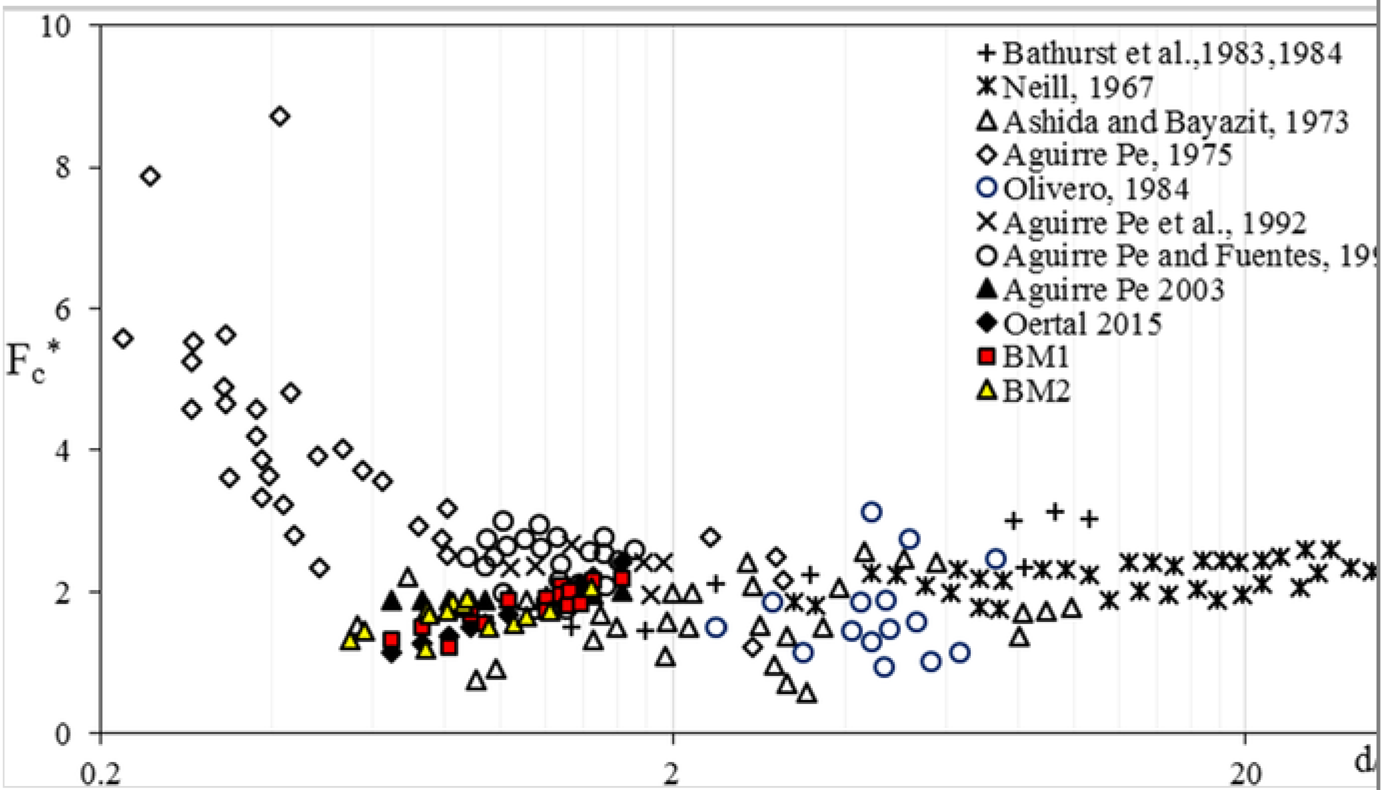
3.1. Incipient Motion in Uniform Bed

Critical conditions for initiation of motion of bed particles have been discussed by Aguirre-Pe [17], Aguirre-Pe and Fuentes [18], Aguirre-Pe et al. [2, 19]. In order to estimate the sediment transport, F_c*was calculated using Eq. 1 for BM_1 and BM_2 bed configurations and plotted as a function of relative depth (*d/D*) and is shown in Fig. 3. Figure 3 displays that the experimental data (for BM_1 and BM_2) from the present study, which lies in the range of large relative roughness $0.54 < d/D < 1.63$ [20]. Critical values for beginning of motion vary in the range of $1.2 < F_c^* < 2.19$ for $0.54 < d/D < 1.63$. The plot indicates a subsequent beginning of particle movement for the flow conditions for BM_1 and BM_2 bed configurations. Figure 3 depicts a broad picture of the dependency of F_c* on relative depth d/*D* and the experimental data of several authors. A significant agreement between the experimental data from the present study is evident over a wide range of *d*/*D*. Figure 3 also compares the equations (Eq. 2 and 3) given by Aguirre-Pe et al. [2] and Oertal and Bung [1] with similar approaches. Aguirre-Pe et al. [2] considered relative depth (*d/D*) being the principal factor in sediment transport and authors have derived a new relationship to estimate sediment transport as a function of F_c^*given by

$$F_c^* = 0.9 + 0.5ln\left(\frac{d}{D}\right) + 1.3\frac{D}{d} \tag{2}$$

Fig. 3

Critical particle densimetric Froude numbers as a function of relative roughness for initiation of sediment motion



Oertal and Bung [4] considered the data for moderate sediment transport of grain size 8–16 mm and also derived a relation for F_c^* given by

$$F_c^* = 0.6\left(\frac{D}{d}\right)^{0.2} + \left(\frac{d}{D}\right)^{0.6} \quad (3)$$

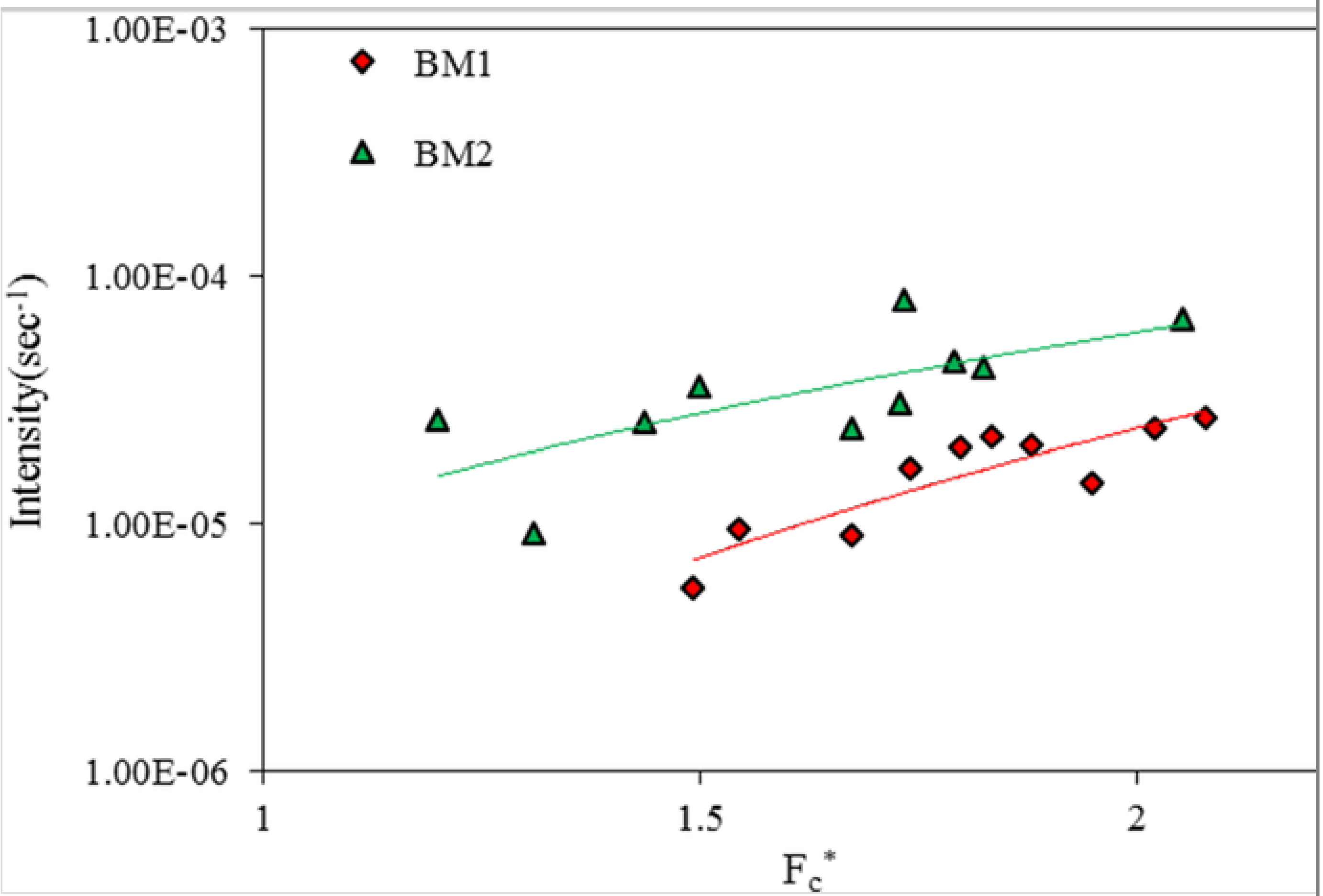
As mentioned in the experimental study of Aguirre-Pe et al. [2], the bed particle transport analysis was carried for flows over inclined macrorough beds. Oertal and Bung [4] conducted experiments on inclined cross-bars for the analysis of single boulder stability and stability of bed sediments.

3.2. Scouring Characteristics in Uniform Beds

The values of F_c^*depends on the initiation of bed particle transport. A plot of $F_c^*$with different intensities of sediment transport (Fraction of sediments scoured from the surface of bed per unit time) for BM_1 and BM_2 bed configuration is presented in Fig. 4. Figure 4 depicts the variation of intensity of sediment transport ranging from rare sediment motion (10^{-5} s^{-1}) to critical sediment motion (10^{-4} s^{-1}) [2, 21]. The BM_1 bed configuration depicts a weaker displacement of single particles in terms of intensity, although the sediment intensity in BM_2 is moving towards the threshold sediment motion (one in 10,000 surface particles in motion per second) [21]. The plot shows an increase in intensity of sediment motion along with F_c^*.

Fig. 4

Variation of intensity of sediments motion with critical particle densimetric Froude number for BM_1 and BM_2 bed configuration



For BM_1 and BM_2 bed configurations for all flow conditions, a prominent scour was observed in the bed immediately after the ramp toe. Scour parameters were measured and varied with flow, ramp slope, and bed material. According to Pagliara [15], with increasing flow rates, the bed material is mobilized and gets transported. Figure 5 compares the scour depth expressed as the ratio between Z_{max}/D_{84}, resulting from the present experiment (Z_{max}/D_{84} measured) and determined with equations given by various authors with similar approaches (Table 4) i.e., (Z_{max}/D_{84} calculated). The trend of the present data is well represented with the equation valid for scour at the downstream of block ramps [15] with similar ranges of ramp slopes ($1/12 < i < 1/4$), non-uniformity parameter $1 < \sigma < 2.8$ and $F_{D_{50}}$ and closer to the line of agreement compared to the other equations.

Fig. 5

Evaluation of measured scour depth with the calculated scour depth (Z_{max}/D_{84}) for beds **a** BM_1 and **b** BM_2

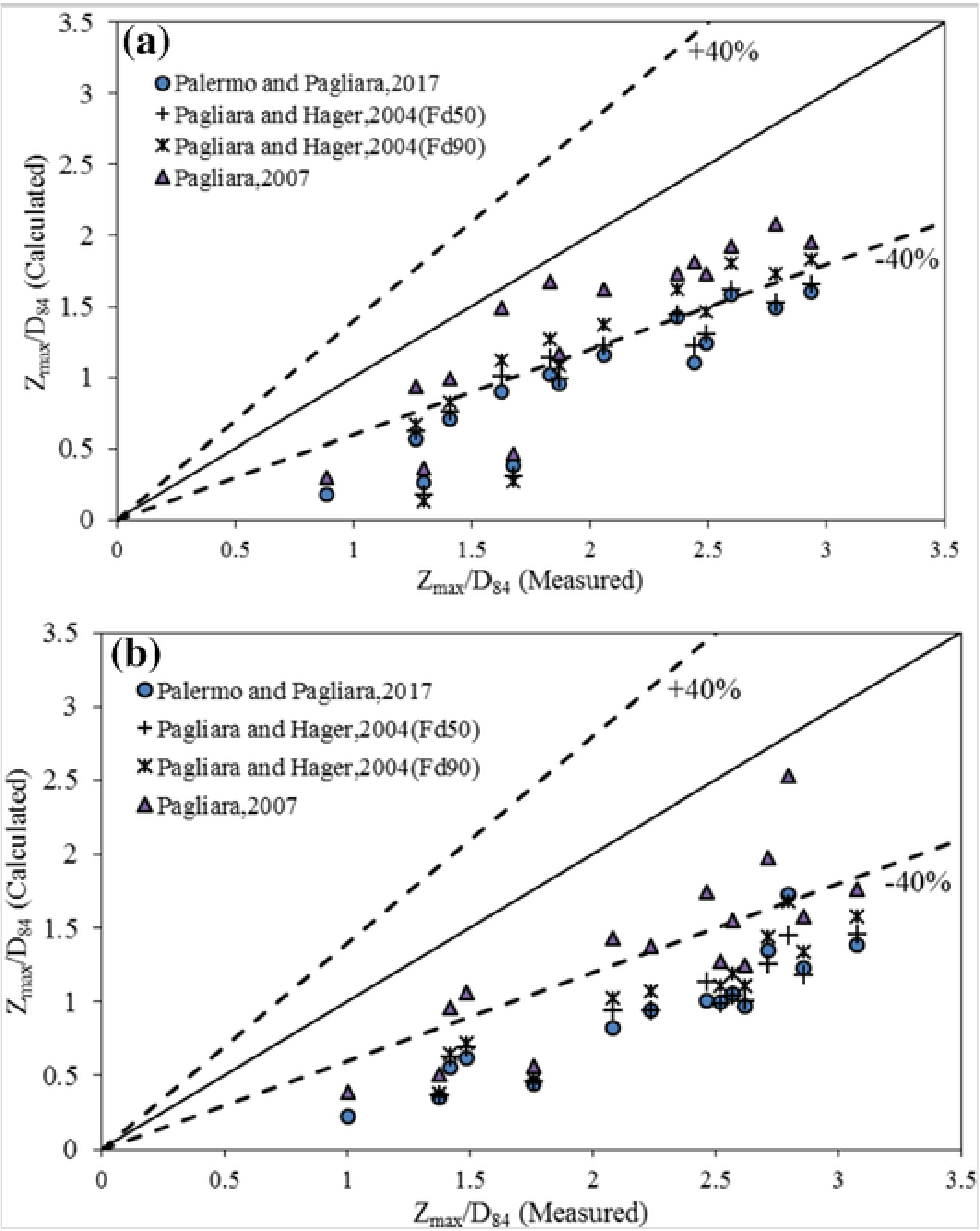


Table 4

Literature Experimental Range and Maximum dimensionless scour depths

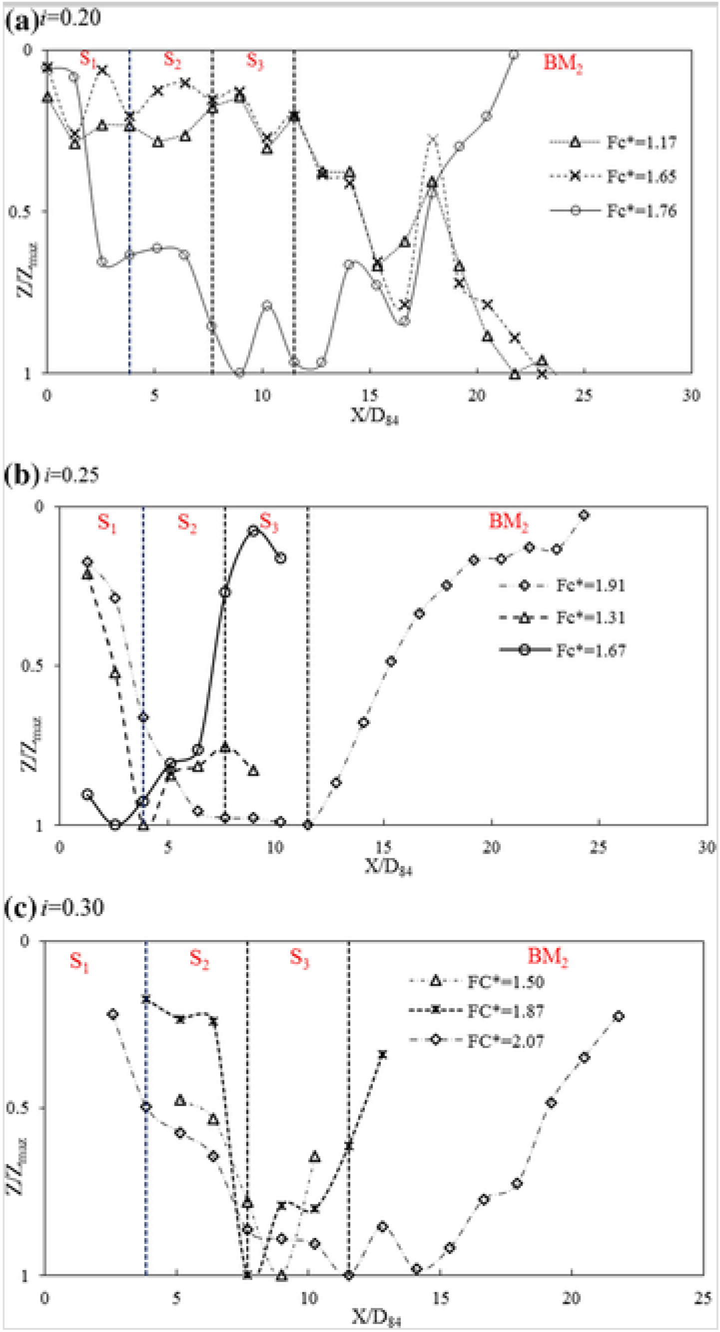
Authors	Experimental Range	Maximum dimensionless Scour depth(Z_m)	Notes
Pagliara and Hager [23]	$1/12 \leq i \leq 1/4$ $1.11 \leq \sigma \leq 1.44$ $1.5 \leq F_{D_{50}} \leq 4.7$ $1.5 \leq F_{D_{90}} \leq 3.8$	$Z_m = A.\ln(F_{D_{50}}) + B$ $Z_m = C.\ln(F_{D_{90}}) + D$	Maximum scour depth at the downstream of block ramps. A, B, C and D are coefficients based on ramp slope (i). $F_{D_{50}}$ and $F_{D_{90}}$ are densimetric Froude numbers
Pagliara [15]	$1/12 \leq i \leq 1/4$ $1 \leq \sigma \leq 2.8$ $1.5 \leq F_{D_{50}} \leq 5$	$Z_m = 0.58\sigma^{-0.55} i^{0.75} F_{D_{50}}^{1.8}$	Maximum scour depth at the downstream of block ramps. σ = non-uniformity coefficient$(D_{84}/D_{16})^{0.5}$
Palermo &Pagliara [5]	$\sigma = 1.3$ $Q = 0.005–0.01 m^3 s^{-1}$	$Z_m = 0.58 i^{0.75} F_{D_{50}}^{1.8} 0.912$	Maximum scour depth in the downstream of curved rock sills
Present study	$1/5 \leq i \leq 1/3.33$ $1.29 \leq \sigma \leq 1.36$ $1.5 \leq F_{D_{50}} \leq 3.4$ $1.3 \leq F_{D_{90}} \leq 2.9$		Maximum scour depth in the downstream of block ramps in the presence of gradually varied rock sills

3.3. Scouring in Beds with Sill Arrangement

Three different sill materials (S_1, S_2 and S_3) were arranged in the order of their gradually decreasing diameters and the geometric dimensions of the sills have already been explained in the experimental facilities (Table 2). The sediment transport is observed for all tested discharges and slopes ($20 < i < 30$) and is plotted in Figs. 6a–c and the scour morphology is differentiated along the longitudinal axis of BM_3 bed configuration. Where, Z denotes the scour depth and D_{84} is the characteristic diameter of the ramp material. Here, F_c^* is calculated with the average diameter (D_{50}) of the ramp material. The general impression from Fig. 6a–c is that maximum scour happens in the S_3 sill and BM_2 bed of BM_3 bed configuration. The scour occurred in S_1 and S_2 sills is negligible compared to the maximum scour of the tested discharges and slopes.

Fig. 6

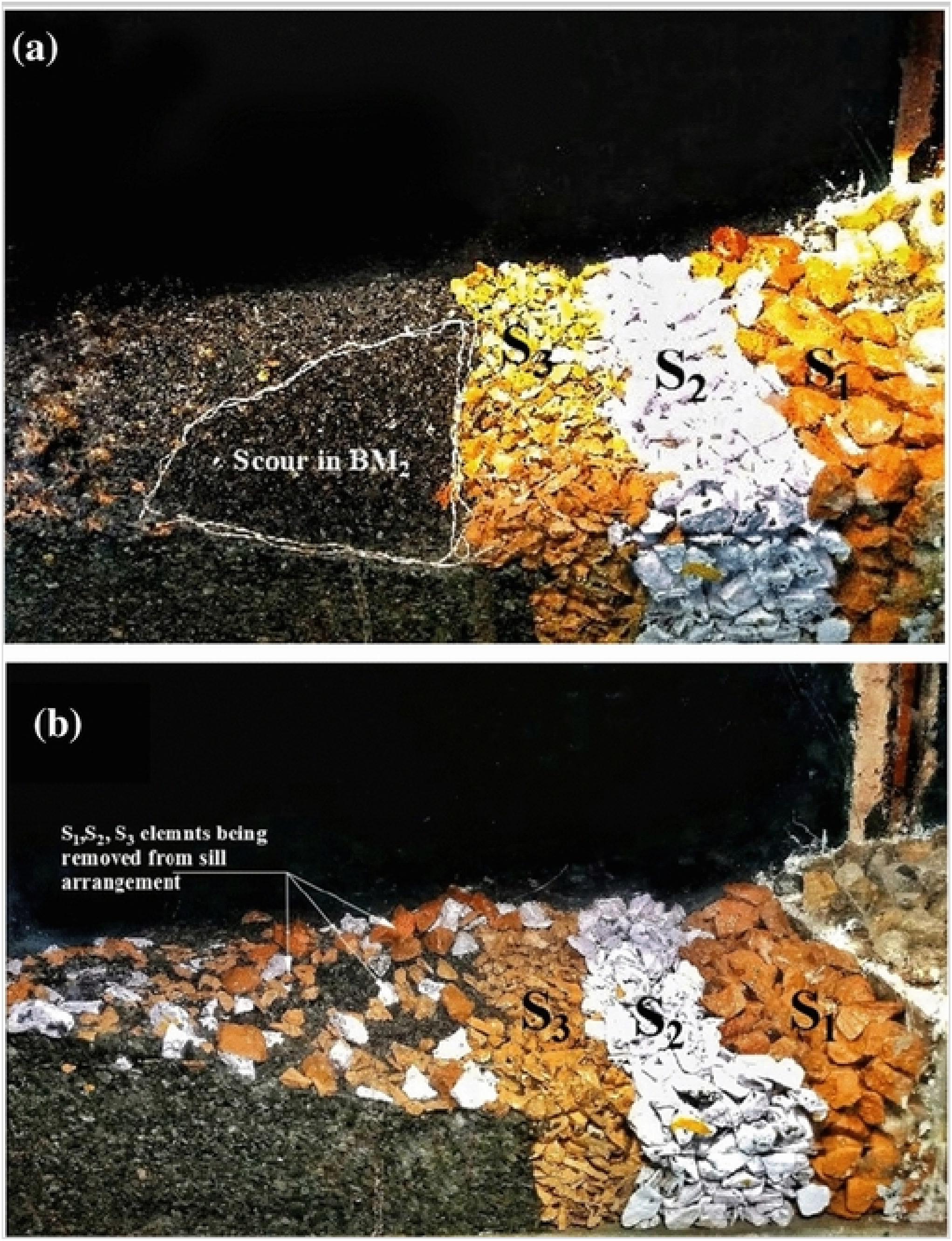
Maximum Scour depth morphologies as a function of placement of particle size in the longitudinal direction for **a** $i = 0.2$, **b** $i = 0.25$, **c** $i = 0.3$



Further, a clear picture of bed scour for F_c^* 1.65 and 2.07 over BM_3 bed configurations is shown in Figs. 7a–b. In Fig. 7a a small scour is visible in the BM_2 region and in Fig. 7b, some of the elements of S_1, S_2 and S_3 is scoured and covered up in the scoured bed of BM_2 region. Hence, no prominent scour is marked in any of the tested discharges and slopes.

Fig. 7

Initiation of motion in BM_3 for **a** $i = 0.2$, $F_c^* = 1.65$ **b** $i = 0.3$, $F_c^* = 2.07$

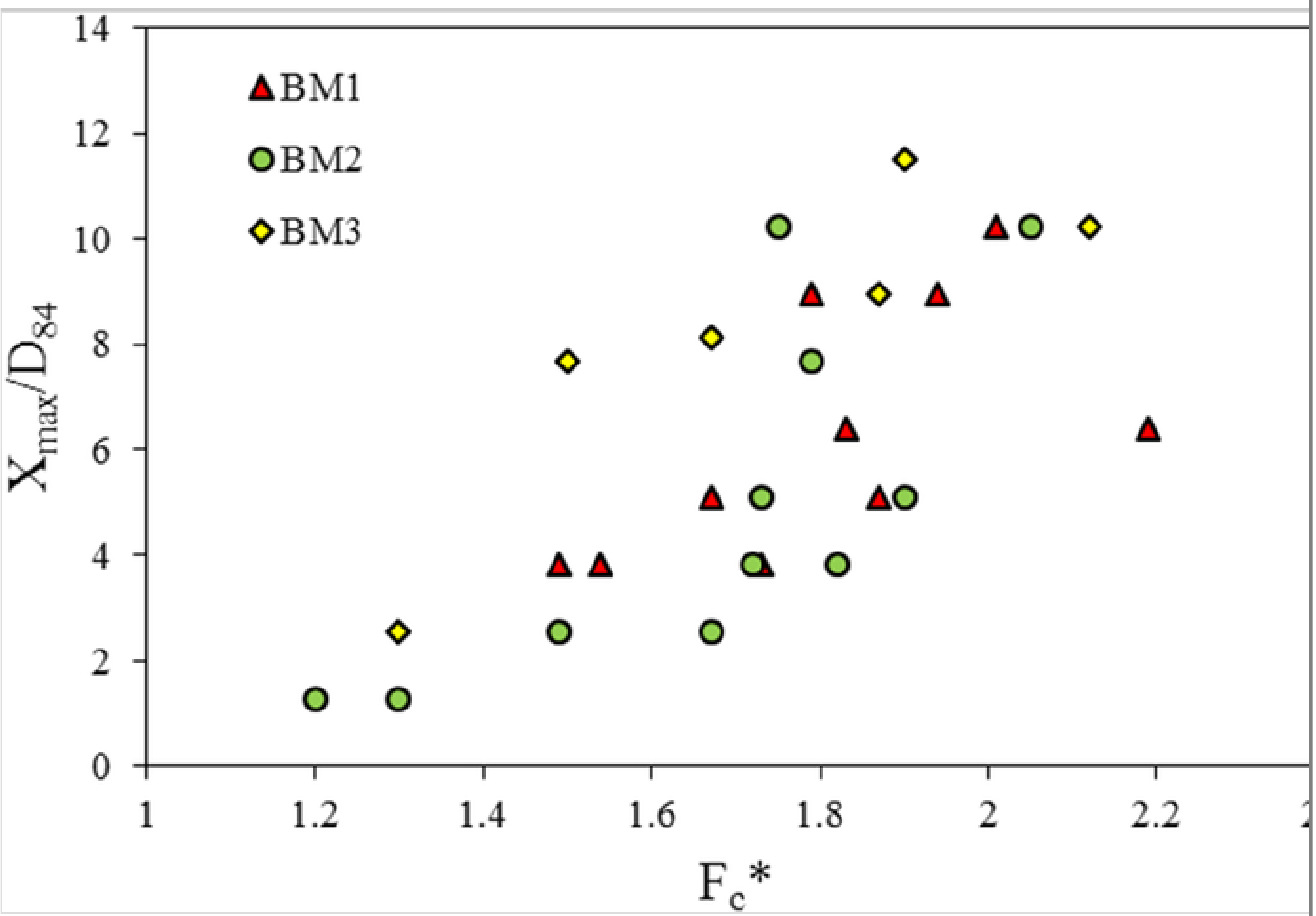


3.4. Comparison of Stability Analysis for flows over BM_1, BM_2 and BM_3

In order to illustrate the influence of proposed rock sills on the position of maximum scour in the beds, a dimensionless ratio (X_{max}/D_{84}), (where X_{max} is the scour length for maximum scour depth) is plotted as a function of critical densimetric Froude number in Fig. 8. The figure shows the spatial shifting of the maximum scour depth along the longitudinal direction for all flows in BM_1, BM_2 and BM_3. Size of bed increases in the order of BM_2, BM_1 and then BM_3, and there is a considerable shift in the maximum scour development. With the placement of sill assembly in the BM_3 bed configuration, the initiation of scour activities was observed at a distance from the toe of the block ramp.

Fig. 8

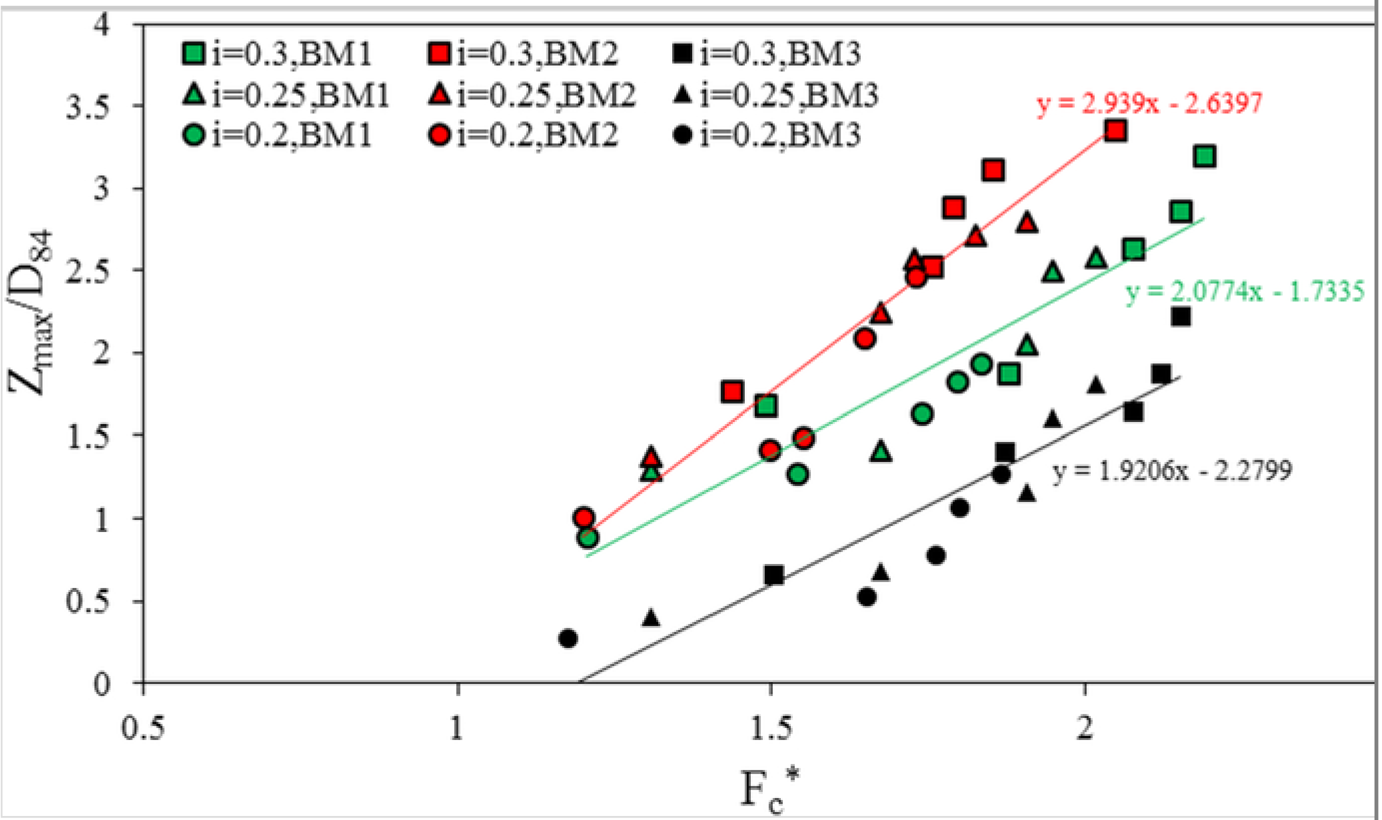
Initiation of motion in BM_3 for **a** $i = 0.2$, $F_c^* = 1.65$ **b** $i = 0.3$, $F_c^* = 2.07$



The non-dimensional parameter Z_{max}/D_{84} was plotted with F_c^* for BM_1, BM_2 and BM_3 for $20 < i < 30$ slopes and is plotted in Fig. 9. The amount of scour reduction in the beds can be seen significantly in Fig. 9. Coarsening of bed material by incorporating sills increased the bed stability. It was experimentally seen that the stability of the bed depends on the mobilization of bed material and also observed that more structured bed (BM_3) indicated lesser mobility.

Fig. 9

Variation of (Z_{max}/ D_{84}) with F_c* for BM_1, BM_2 and BM_3



4. Conclusions

Block ramps are roughened inclined channels that maintain both hydraulic and ecological conveyance through high flow conditions. The stability of the block ramp structure in addition to the study of flow characteristics is of prime concern in this study. The F_c^* which is a distinctive constraint for the determination of critical conditions for the incipient sediment motion is described for flows over inclined block ramps. Tests were conducted over non-cohesive horizontal uniform beds: BM_1 and BM_2 and horizontal bed with sill arrangements BM_3 for $20 < i < 30$ and $1.2 < F_c^* < 2.19$. Bed materials were scoured for all test runs and significant scouring was observed only in BM_1, BM_2 beds. In regard to the stability analysis, it is concluded that the bed configuration BM_3 is less prone to mobilization and hence more stable than the $BM_1$and BM_2 bed configurations. It was also found that as the bed material size increases from BM_2 to BM_1 and then to BM_3, there is a visible shift in the occurrence of maximum scour depth and in the initiation of scour over the bed materials. Furthermore, there is a considerable reduction in the maximum scour depth over BM_3 bed configuration compared to other two uniform beds.

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Data Availability

All data measured are presented in the figures and tables. If required, it is available upon request.

Compliance with ethical standards

Conflict of interest Authors would like to thank DST-SERB for providing fund to complete the work. We also declare that we do not have any commercial or associative interest that represents a conflict of interest in connection with the work submitted.

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