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Hydro-environmental Characteristics for Flows Over Inclined Block Carpet

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Abstract: A significant oxygenation is associated with flows over most of the hydraulic structures due to the entrainment of air into the flow. Block carpets are low-head hydraulic structures, which aim to control the sediment transport, dissipation of flow energy and contribute to considerable oxygenation. Studies have been conducted to investigate the effects of block carpet on the hydraulic jump, scouring phenomenon and variation in the hydro-environmental parameters. The study also investigates the aeration efficiency created by the hydraulic jump inflows over block carpet. Dissolved oxygen as a principal hydro-environmental parameter was measured and analysed upstream of the block carpet, along the BC (heel, mid and toe) and post hydraulic jump in the channel bed. The results show that in the tested range of slopes (20%, 25% and 30%) and block carpet material, the flow has attained a maximum aeration efficiency of 0.181. The characteristics of the hydraulic jump for different inclinations of block carpet and for two-channel bed sediment sizes were observed. Predominantly, for higher discharges and steep slopes, considerable scouring takes place downstream of the block carpet. Based on the physical features of the downstream scour, a qualitative description of three scour forms has been distinguished.

Key words: Aeration efficiency, block carpets, energy dissipation, hydraulic jump, scour morphology.

Introduction

Hydraulic structures have an impact on increasing the amount of dissolved oxygen in a river system. Aeration in hydraulic structures is improved by varying the flow pattern through the hydraulic jump and hydraulic drop. The flows over block carpet (BC) simulate the flows over roughened channels and create turbulence, which activates the aerated flow and enables an aquatic pathway (Pagliara et al., 2011). Excess energy is dissipated for flows over roughened channels as well as in a hydraulic jump. Hydraulic jump at the toe of the inclined BC ensures high entrainment of air into the water. Gulliver et al. (1998) investigated the aeration characteristics of hydraulic jump and concluded that the maximum air entrance occurs at the beginning of the jump. Gameson (1957) specified that the flow condition has a significant effect on the determination of aeration efficiency. Avery and Novak (1978) studied expressions of aeration efficiency of a hydraulic jump using upstream Froude number. Experimental studies on the phenomenon of hydraulic jump date back to the 1800s (Belanger, 1828). The classical hydraulic jump has been extensively studied by Hager (1992). So far, numerous investigations have been conducted to detail the complex phenomenon of the hydraulic jump and to estimate its characteristics. Literature could be found in the analysis of hydraulic jump characteristics on horizontal smooth and rough beds (Felder and Chanson, 2018). In addition, several researchers have conducted experiments on types of hydraulic jumps on a smooth sloping bed (Kateb et al., 2017), adverse slopes (Pourabdollah et al., 2019) and rough sloping beds (Kumar and Lodhi, 2015).

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Scour process is a very complex phenomenon and is a function of granulometric characteristics and cohesive properties of the bed (Ahmad et al., 2014). Local scour that occurs downstream of the inclined block carpets is a serious concern for hydraulic engineers and water resources experts. Scour induced by the hydraulic structures has been investigated by many researchers (Dey and Raikar, 2005; Tammela et al., 2010). Experimental tests on BC with expanding stilling basins have been carried out by Pagliara et al. (2009). Oertel and Bung (2015) studied the stability of cross bars concerning the bed stability and concluded that flow conditions are effectively explained by the critical particle densimetric Froude number. Numerous studies on the characteristics and types of hydraulic jumps and local scours are available to date. However, a limited number of studies have addressed the phenomenon of scour morphology for flows over inclined BC considering the slopes of the BC and the downstream horizontal bed roughness conditions.

Very few studies have investigated the flow characteristics (Pagliara et al., 2010), aeration properties (Pagliara et al. 2010, 2011) and energy dissipation characteristics (Pagliara et al., 2015) for aerated flows over macro and intermediate roughness conditions. Based on the previous investigations, it was observed that the aeration efficiency for flows over inclined BC is not yet investigated. Hence, the present paper undertakes the study of aeration efficiency due to the hydraulic jump observed in the BC. The present study also examines and classifies the scour hole morphology formations in the downstream horizontal bed for flows over inclined BC and the enumeration of energy dissipation characteristics.

Experimentation

Testing Facilities

Experiments were conducted in a hydraulic flume at the Hydraulic and Water Resources Laboratory of National Institute of Technology, Patna. A centrifugal pump of 12 kW capacity feeds the flume and the flow is monitored by an electromagnetic flow meter of 2.78×10^{-3} l/s accuracy. Entry of water to the flume is smoothened and a laminar non-aerated flow is ensured at the flume inlet. The flume used had geometric dimensions of 0.30 m wide, 7.0 m long and 0.50 m high. The experiments were performed over an inclined BC of length 0.8 m and two-channel bed materials BM_1 and BM_2. The layout of the experimental setup is shown in Figure 1. The flow depths h_0, h_1 and h_2 are the depth of water at sections 0-0, 1-1 and 2-2, respectively, and were measured using a point gauge of 0.1 mm accuracy. The horizontal flat downstream bed was considered as the initial conditions for the measurements of flow depths and scour depths. The approaching Froude number ranged from 1.17-5.43 was tested. The tests were conducted for ramp slopes (S) ranging from 20% to 30%. Two channel bed materials, both uniform (BM_1 and BM_2) were tested for the present experiment.

A total of 30 tests were performed on a ramp of characteristic mean diameter (D_{50} = 34.05 mm). The uniform coefficient of BC (RM_1) and bed materials is expressed by the ratio between D_{60} and D_{10} (bed grain sizes for which 60% and 10% of bed grain is finer) is given in Table 1. The details of the experimental run are shown in Table 2.

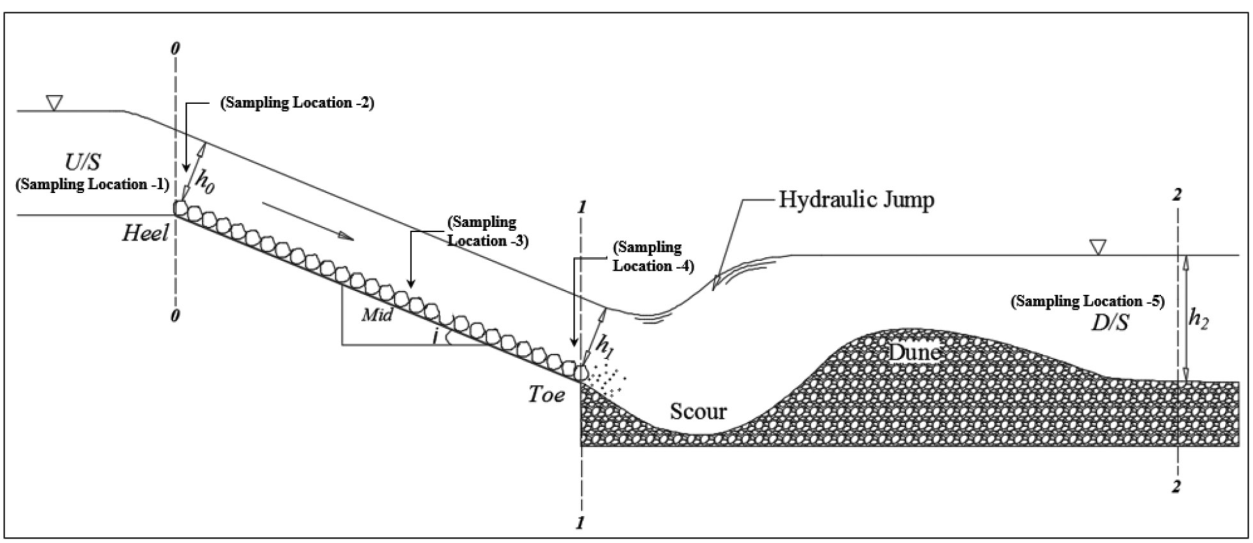


Figure 1: Schematic representation of the experimental setup.

Table 1: Granulometric characteristics of ramp and bed materials

Material	D_{60} *(mm)*	D_{50} *(mm)*	D_{10} *(mm)*	*Uniformity Coefficient* (C_u)
RM_1	35.00	34.05	22.0	1.60
BM_1	8	7.35	4.75	1.68
BM_2	6.63	6.12	4.37	1.52

Table 2: Ranges of data for the present experimental study

Parameter	*Range*
Slope (%)	20, 25,30
Approaching Froude number (F_1)	1.17-5.43
Critical depth, y_c (mm)	30.48-71.59

Theoretical Considerations

Oxygenation in BC

Dissolved oxygen was measured with a DO meter at five different sampling locations (Figure 1) having a measurement range of 4.36 mg/L to 7.53 mg/L and temperature 17.7°C to 27.1°C. Five runs were conducted for each slope by varying the discharge rate from 0.005 to 0.18 m^3/sec. The aeration efficiency E was determined using the expression (Raikar and Kamatagi, 2015).

$$E = \frac{C_{ds} - C_{us}}{C_s - C_{us}} \quad (1)$$

where C_{us} and C_{ds} = DO concentration (mg/L) at the upstream and downstream of BC, C_s = Saturation concentration of oxygen in the water in equilibrium at local air pressure and temperature. Hydro-environmental parameters like conductivity (µS/cm) and total dissolved solids were measured simultaneously both on the upstream side and also the downstream side of the ramp using hand held probes for each experimental run.

Spatial Variation of Scour

For presenting the spatial variation of scour, equilibrium scour morphologies with maximum scour depths downstream of the BC has to be measured. For BM_1 and BM_2, the experimental tests were carried out by varying the discharge and slope. Before the beginning of each test run, the beds were compacted and leveled. Point gauge was then used to measure the depths at various points in the transverse and longitudinal cross sections downstream of the ramp. Transverse measurements were taken at every 7 cm interval, while in the longitudinal direction, an interval of 5 cm was selected.

Energy Dissipation

For the present study, the energy was calculated for sections 0-0 and 2-2. The total energy at section 0-0 is $E_0 = \frac{v_0^2}{2g} + h_0$, while the energy at sections 2-2 is $E_2 = \frac{v_2^2}{2g} + h_2$, where v_0 and v_2 are the average velocities at sections 0-0 and 2-2. The energy loss between sections 0-0 and 2-2 ($\Delta E_2 = E_0 - E_2$) and the relative energy dissipation ($\Delta E_R = \Delta E_2/E_0$) were estimated. The efficiency of the hydraulic jump is defined as the ratio of the loss of specific energy (ΔE) after the jump to the specific energy before the jump (Ahmad et al., 2014). An empirical expression developed by Pagliara et al. (2015) for determining the energy dissipation properties over different base materials in different ramp length conditions in two-phase flows is given below and is being utilised for comparison in the present study.

$$\Delta E_R = 0.33 + (1 - 0.33) \cdot e^{(30.S - 17.5) \cdot (yc/L_r)} \quad (2)$$

Experimental Results

Oxygenation in BC

The DO measurement at various locations of BC viz., heel, mid and toe (Figure 1) were measured to determine the efficiency of aeration. Comparing the environmental factors between the upstream region and downstream region of the ramp, it was found that there were no significant changes in the hydro-environmental parameters like water temperature, conductivity, pH and TDS, however, the concentrations of DO along the ramp changed significantly. The ramp influences the variation in DO concentrations between the upstream and downstream. As mentioned in the study by Pagliara et al. (2011), air entrains when there is a greater interaction between the rough bed and the water surface and the aerated flow carries along with the ramp length. Chanson (1995) calculated the free surface aeration and hydraulic jump aeration for flows over weirs and spillways and the combined aerations are used to predict the dissolved oxygen content downstream of the hydraulic structures. The results of Chanson (1995) indicated that self-aeration is a major contribution to the oxygenation for flows over hydraulics structures for low flows. In the present study, DO concentrations along the ramp showed an increasing trend in almost all the experimental runs due to the interaction between the flow of water and the BC and as shown in Figure

2. Figure 2(a,b) shows the fluctuations of DO along the ramp for BM_1 and BM_2 for three slopes (20%, 25% and 30%), respectively. A sudden increase in the dissolved oxygen at the heel of the ramp at Q = 0.00599 m^3/sec is observed, as shown in Figure 2(a-c). This may be due to the greater interaction of the flow with the ramp material due to low discharge and greater slope.

The overall improvement in the DO due to the flows over BC is shown in Figure 3. Figure 3(a-b) depicts the distribution of DO between an upstream and downstream part of the ramp. It was found that there was a maximum increase of up to 30% in DO at the downstream of the ramp for S = 0.3 and Q = 0.00599 m^3/s for BM_1 and a maximum of 14% increase in BM_2 for S = 0.3 and Q = 0.009 m^3/s, respectively. Other parameters, as discussed earlier showed minor differences between upstream and downstream, TDS (1-6 mg/L) and conductivity (1-2 µS/cm).

The variation of aeration efficiency with increasing discharge is shown in Figure 4, which exhibits a data are scattered and could not show any clear demarcation for slopes and discharges. This may be due to the restriction in the ramp length. This figure displays that the aeration efficiency increases with discharge for all flows over inclined BC in the tested range of experiments. For a given discharge, the aeration efficiency increases for a smaller slope due to better interaction between water and air downstream of BC. The maximum aeration efficiency of BC was found to be 0.181 for 0.015 m^3/sec discharge and a slope of 20%. In the experimental study, the effect of different Froude numbers on the oxygen transfer was investigated at the toe of BC. During the hydraulic jump, the most important parameter affecting the efficiency of aeration is the upstream Froude number (F_1). In this study, a fully developed hydraulic jump was created for different upstream Froude numbers. Figure

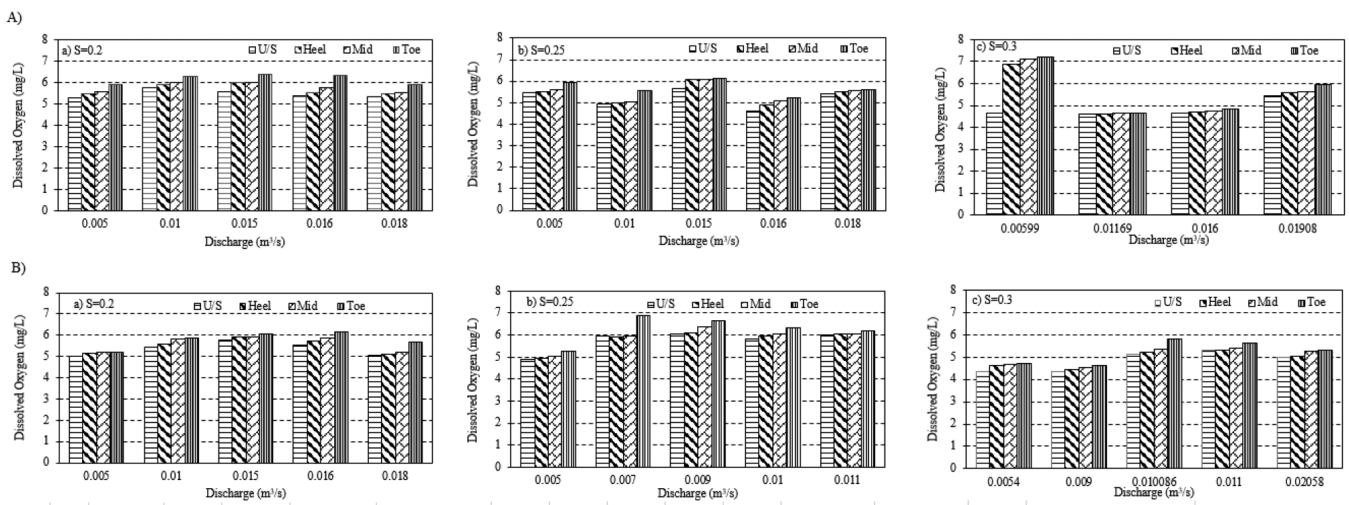


Figure 2: Fluctuations of dissolved oxygen along the ramp (U/S, heel, mid and toe) with increasing flow rates for (A) BM_1 and (B) BM_2.

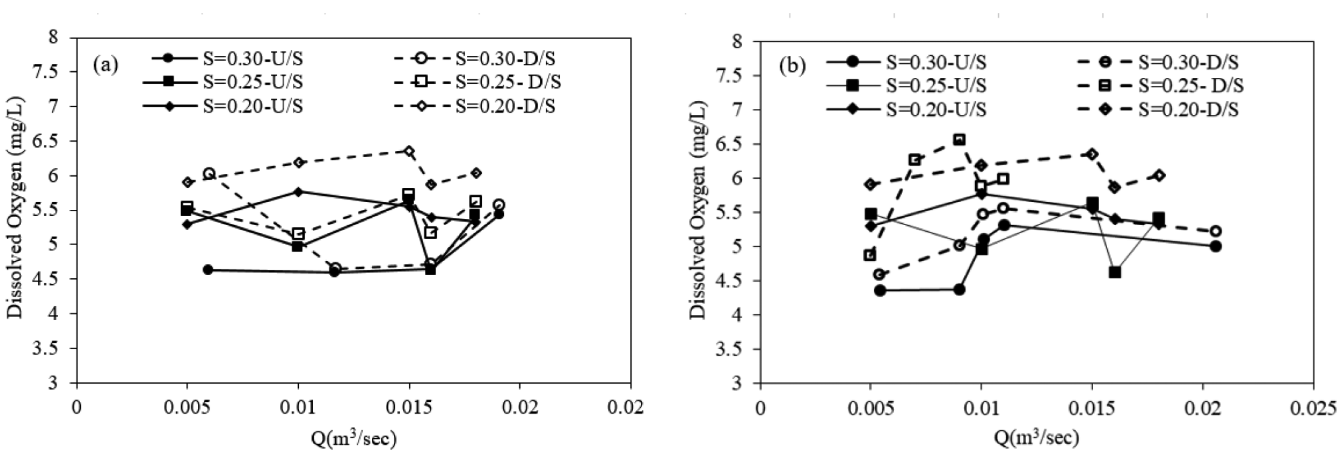


Figure 3: Distribution of dissolved oxygen concentrations in upstream (solid line) and downstream (dotted line) of the ramp for varying slopes for (a) BM_1 and (b) BM_2.

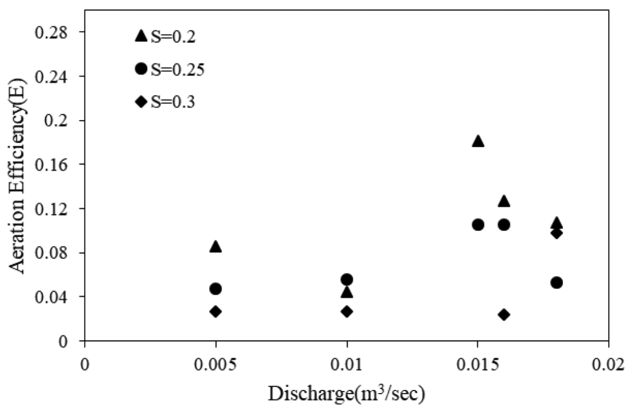


Figure 4: Variation of aeration efficiency *E* with discharge.

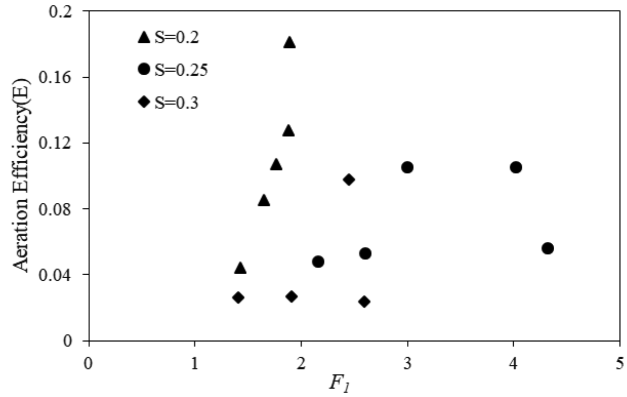


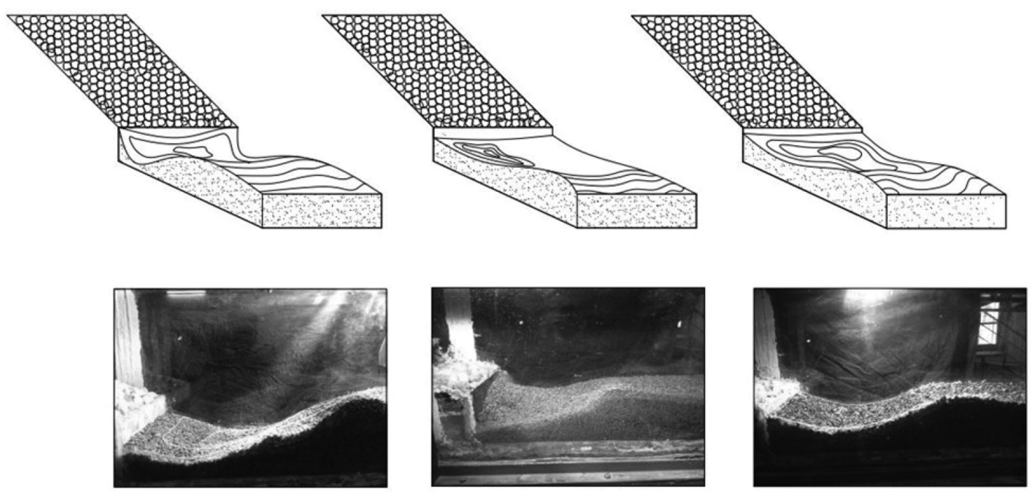
Figure 5: Variation of aeration efficiency *E* with approaching Froude number F_1.

5 shows the variation of aeration efficiency *E* with approaching Froude number. It is clear that the value of aeration efficiency increases with the Froude number during the hydraulic jump due to the increased mass transfer from air to water. Raikar and Kamatagi (2015) also reported similar results of increasing aeration efficiency with approaching the Froude number.

Scour Morphology

The knowledge of various scour morphologies due to block ramps is essential for the proper design of hydraulic structures and also for fish refuge. In the present experimental run, three types of scour morphologies were identified i.e., Type A, B and C, as shown in Figure 6.

- Type A results in a single scour segment or two symmetric scour segments with a deeper scour depth and wider scour length observed in the center of the bed shown in Figure 6(a). Notably, for intermediate slope (S = 0.25) the scour region near the toe is deeper.
- Figure 6(b) depicts Type-B scour morphology predominant in the lower slope (S = 0.2). A significant modification of bed morphology as observed in most of the experimental runs under the same ramp slope. Elongated scour is formed downstream of the ramp particularly confined near the side walls. Compared to Type A, where the scour hole is formed at the central axis, in Type B scour hole reaches the side walls. In this case, the scour pushes the dune from either direction thereby restricting the scour to the central axis of the stilling basin.
- Notably, in the case of higher inclinations (S = 0.3), a third type of scour morphology denoted by Type C was predominant. Figure 6(c) depicts Type C



(a) Type- A Scour (b) Type- B Scour (c) Type- C Scour

Figure 6: Sketches of different scour morphologies.

scour morphology the downstream of block ramp. Increased flow rates resulted in higher intensity of scour. The amount of scouring was observed more in the vertical direction than in the longitudinal direction. Diffusion of bed and sediment movement occurred due to the diverted flows from the jet action. From the experimental run in the same slopes, it was observed that the development of scour increased in the longitudinal direction as the eroded sediment of the scour moved gradually downstream.

The scour phenomenon evidence that by increasing the inclination, a transition is seen from type A to B and then finally C can be achieved. This occurrence can be explained considering the higher values of flow rates corresponding to a reduction in diffusion resulting in a stable or more flatter scour formation. In general, the transition between the scour types occurs at a higher inclination. The three types of scour patterns for BM_1 and BM_2 beds are plotted as a function of slope (%) and discharge (l/s) and are shown in Figure 7(a-b).

Figure 8 shows the non-dimensional transversal scour hole profiles for different ramp slopes and flow rates in both the beds. Here, Y/B is the non-dimensional transverse coordinate with Y as transverse coordinate, B= width of the flume and Z/Z_{max} is the non-dimensional vertical coordinate. The non-dimensional scour depth ratio (Z/Z_{max}) at various cross sections of the downstream varies from 0.13 to 1. Where Z is the depth of scour at any point and the Z_{max} is the maximum scour depth obtained for a particular discharge.

Sequent Depth

The hydraulic jump occurs to be compatible for momentum between the upstream and downstream flow. This study was conducted to analyse the outcome of the slope and bed on the sequent depth ratio for a given value of approaching Froude number (F_1). The variation of the sequent depth ratio (h_2/h_1) with F_1 for BM_1 and BM_2 bed materials for different slopes is shown in Figure 9. It was seen that the sequent depth ratio (h_2/h_1) increases with the increase in the ramp slopes. It was also observed that BM_2 has higher values of sequent depths for a given value of F_1. In the present study, the sequent depth relationship for a classical hydraulic jump given by Momentum equation is used for comparison, as it can be employed for comparing other complex cases, like the hydraulic jump over arbitrary cross-sections or gradually varying width or sections with different roughness beds and over inclined or under submerged conditions. According to Momentum

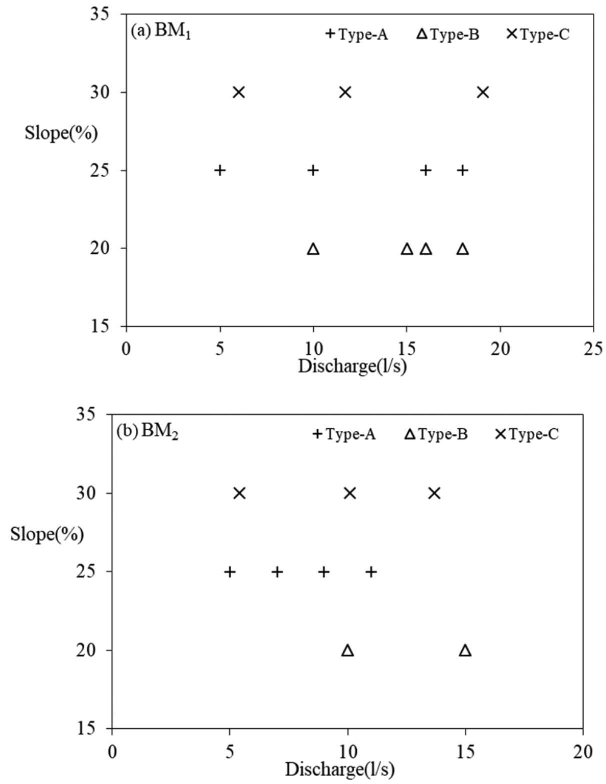


Figure 7: Different scour regimes for increasing flows over (a) BM_1 and (b) BM_2 bed material.

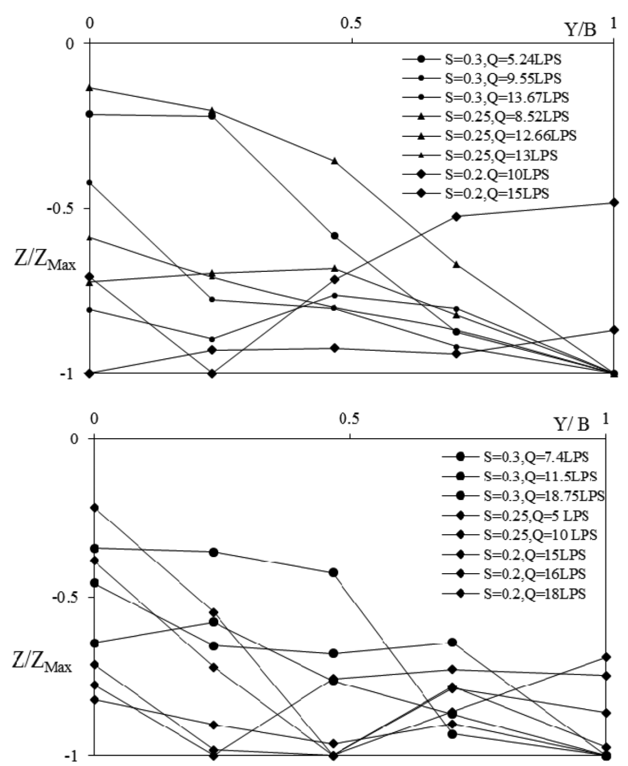


Figure 8: Non-dimensional scour-hole profiles for bed material BM_1 and BM_2.

equation, the subsequent depth is expressed in the terms of approaching Froude number and is given by:

$$h_2/h_1 = \tfrac{1}{2}\left(\sqrt{1+8F_1^2}-1\right) \qquad (3)$$

A slight reduction in the conjugate depth relationship for BM_1 and BM_2 from Momentum equation is observed, as shown in Figure 9. The slight variation may be due to the fact that the classical hydraulic jump is given by Momentum equation and takes place over a smooth horizontal rectangular channel, however, in the present study, the jump occurs on roughened beds.

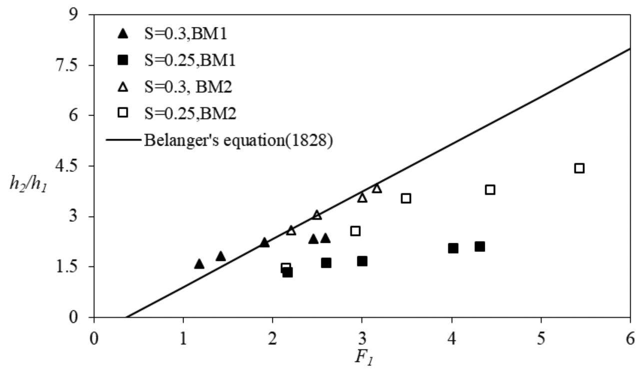


Figure 9: Variation of (h_2/h_1) with F_1 for changing values of slopes (25% and 30%) for BM_1 and BM_2.

Energy Dissipation

The relative energy dissipation for flows over BM_1 and BM_2 beds was calculated and is plotted as a function of y_c/H for three ramp slopes is shown in Figure 10 (a-b). It is evident from the figure the relative energy dissipation increases with the drop in y_c/H. However, it was seen that for each slope, greater energy dissipation has occurred at larger flow rates. When compared to BM_1 and BM_2 beds, it was observed that the energy dissipation rate decreases with the decrease in bed size. Further on, the comparison of data plotted on the figures reveals that the energy dissipation computed using Pagliara et al. (2015) equation (Eq. 2) is in good agreement for all the slope (S = 20%, 25% and 30%) for BM_1 bed material (Figure 10a). While it deviates from the observed values for BM_2 bed material (Figure 10b) as it is overestimating against the observed values. The relation proposed by Pagliara et al. (2015) is independent of the bed material size. This clearly indicates that the bed material size is also a significant parameter in the calculation of energy dissipation.

Conclusions

In this experimental study, the aeration efficiency of inclined BC was calculated to analyse the DO concentration using hydraulic jump. For the measurements calculated for increasing Froude numbers, it was found that the turbulence created by the hydraulic jump at the toe of the inclined BC enhances the air entrainment, hence increasing the oxygen efficiency. The slope is considered to be one of the critical parameters influencing the oxygen transfer for flows over BC. The aeration efficiency increased with decreasing slope and the maximum aeration efficiency was found for the slope (S = 0.2). It was also seen that increased discharge leads to greater oxygen efficiency for smaller slopes. The DO measurements show an increase in DO concentration along the BC for the tested flow conditions and show a significant increase of DO in the downstream bed up to a maximum of 30% increase for BM_1 bed and 14% increase for BM_2 bed.

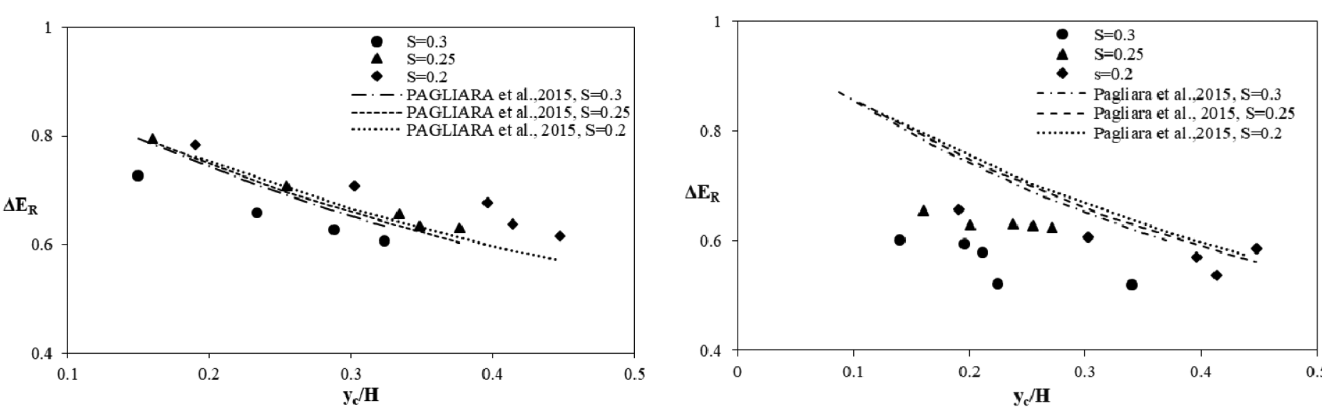


Figure 10: Relative energy dissipation between sections 0-0 and 2-2 and comparison of equation developed by Pagliara et al. (2015) for (a) BM_1 and (b) BM_2.

This experimental study also includes the enumeration of energy loss and variation of dissolved oxygen for flows over inclined BC for slopes varying from 20% to 30%. The experimental results reveal that, in the tested range of parameters, for equal hydraulic and geometric conditions, the increase in discharge and slope causes an increase of the scour hole depth. Based on visual observations and conferring to the development of scour holes along with hydraulic and geometric conditions, three hydraulic scour forms were distinguished, namely Type-A, Type-B and Type-C scour, respectively. Characteristics of hydraulic jump were also measured in the experimental flume with channel bed materials BM_1 and BM_2. For a given approaching Froude number F_1, the sequent depth ratio (h_2/h_1) was found to be decreasing with the increase in the bed roughness.

The relative energy dissipation was calculated for all flow conditions and found that it decreases for larger y_c/h values between sections 0-0 and 2-2 for flows over BM_1 and BM_2 beds. In addition to that, flows over BM_1 bed show more relative energy dissipation than that flows over BM_2 bed. The energy dissipation computed using Pagliara et al. (2015)'s equation is found to be in good agreement for all the slopes for BM_1 bed material and deviated largely for the BM_2 bed material.

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Conflict of Interest

The authors confirm no conflict of interest in this work.

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