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Effect of roughness on sequent depth in hydraulic jumps over rough bed

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Preliminary note

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Hydraulic jump is an important phenomenon in open channel flows such as rivers and spillways. Hydraulic jump is mainly used for kinetic energy dissipation at the downstream side of a spillway with the assist of baffle blocks. It has been demonstrated that corrugated or rough beds show considerably more energy dissipation than smooth beds. The experimental research evaluating the effect of crushed stones on the hydraulic jump is presented in this paper. Five different-size sets of crushed stones were used. Results show that the effect of rough bed does not increase after a certain height of crushed stone is reached.

Key words:

hydraulic jump, sequent depth, rough bed, height of roughness

Prethodno priopćenje

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Utjecaj hrapavosti na spregnutu dubinu kod vodnih skokova na neravnoj podlozi

Vodni skok je značajna pojava karakteristična za otvorene tokove kao što su rijeke i preljevi. Vodni se skokovi uglavnom koriste za raspršivanje kinetičke energije na nizvodnoj strani preljeva i to uz pomoć skretnih blokova. Pokazalo se da je rasap energije mnogo djelotvorniji kada se umjesto glatkog korita koristi hrapavo korito. U ovom se radu prikazuje eksperimentalno istraživanje koje ocjenjuje utjecaj drobljenog kamenog materijala na vodni skok. U istraživanju je korišteno pet serija drobljenog kamena definiranih prema veličini kamena. Rezultati pokazuju da se utjecaj hrapavog korita ne povećava nakon određene visine kamene obloge.

Ključne riječi:

vodni skok, spregnuta dubina, hrapavo korito, visina nabora

Vorherige Mitteilung

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Auswirkung der Rauheit auf die kombinierte Tiefe bei Wassersprüngen auf unebenen Untergründen

Der Wassersprung ist eine bedeutende Erscheinung, die für offene Strömungen wie Flüsse und Überläufe charakteristisch ist. Die Wassersprünge werden hauptsächlich für die Verteilung der kinetischen Energie auf der stromabwärtigen Seite des Überlaufs genutzt, und dies mithilfe von Lenkblöcken. Es hat sich gezeigt, dass die Energieverteilung weitaus wirksamer ist, wenn man statt eines glatten Flussbettes ein raues Bett verwendet. In dieser Abhandlung wird eine experimentelle Untersuchung dargestellt, welche die Auswirkung von gebrochenen Steinmaterial auf den Wassersprung beurteilt. In der Untersuchung wurden fünf Serien von Schotter verwendet, definiert gemäß der Steingröße. Die Ergebnisse zeigen, dass sich die Auswirkung des rauen Bettes nach einer bestimmen Höhe der Steinauskleidung nicht erhöht.

Schlüsselwörter:

Wassersprung, kombinierte Tiefe, raues Flussbett, Faltenhöhe

1. Introduction

Hydraulic jump is a phenomenon that is used for the purpose of dissipating energy in most hydraulic structures. Hydraulic jump occurs at the position of the flow where the transition from supercritical flow to subcritical flow occurs. The jump formed in a smooth bed, wide and horizontal rectangular channel is known as the classical jump. This classical jump has been studied extensively by many researchers (Hager [1], Rajaratnam [2]). Gravity is the driving force behind the flow through open channels. Hence, it stands to reason that the ratio of inertial forces to gravitational forces will play a major role in the open-channel flow analysis. Following the convention of using the first power law of velocity, we define the dimensionless number, i.e. the Froude No. If y_1 is the supercritical stream depth, y_2 the depth of subcritical stream, and F_{r1} the Froude number for supercritical stream, then the sequent depth ratio of a hydraulic jump can be given by the Belanger momentum equation [3] as folows in (1):

$$\frac{y_2}{y_1}=\frac{1}{2}\left[\sqrt{1+8F_{r1}^2}-1\right] \tag{1}$$

where:
F_r - Froude number
F_{r1} - Froude number for the incoming flow
y_1 - upstream flow depth
y_2 - tail water depth.

The investigations by many researchers have shown that if the bed over which the jump is formed is rough, the tail water depth y_2' required to form the jump will be considerably less than the sequent depth y_2 [4, 5]. Many researchers documented that the jump length is also reduced notably. This led to an idea that the length of the jump can be reduced using roughness on the bed which will eventually lead to the reduction of length of the apron used to control hydraulic jump in hydraulic structures.

The main concern with hydraulic jump on rough bed is that the roughness on the upstream will be subjected to cavitation. Further studies by Ead et al. [3] led to the conclusion that the effect of cavitation can be reduced by keeping the level of the crest of the roughness at the same level of the bed such that no portion will be protruding over the bed level.

Further, several researchers Carollo, Ferro and Pampalone [6], Ead and Rajaratnam [3], Ghorbani and Bazaz [7]) presented the effect of "shape of the roughness", for which triangular, trapezoidal, and semi-circular strips made of wood, plastic etc. were introduced to the bed for roughness.

In this study, the effect of roughness on sequent depth of hydraulic jump is studied for different roughness elements. Hence an experimental investigation was conducted on hydraulic jump over rough bed, and the results are presented here with an aim that this idea will prove useful for further investigations in this field.

2. Experimental setup and experimentation

The experiments were conducted in Hydraulics and Fluid Mechanics Laboratory of the Civil Engineering Department at Visvesvaraya National Institute of Technology, Nagpur, Maharashtra, India. The flume used for experimental work was rectangular and horizontal in nature with adjustable bed slope (Tilting Mechanism) having 0.6 m in bed width and 21 m in length as shown in Figure 1. A 30 HP pump of proper rating curve and standard make, drives the circulating mechanism to work efficiently for the flume. A perplex

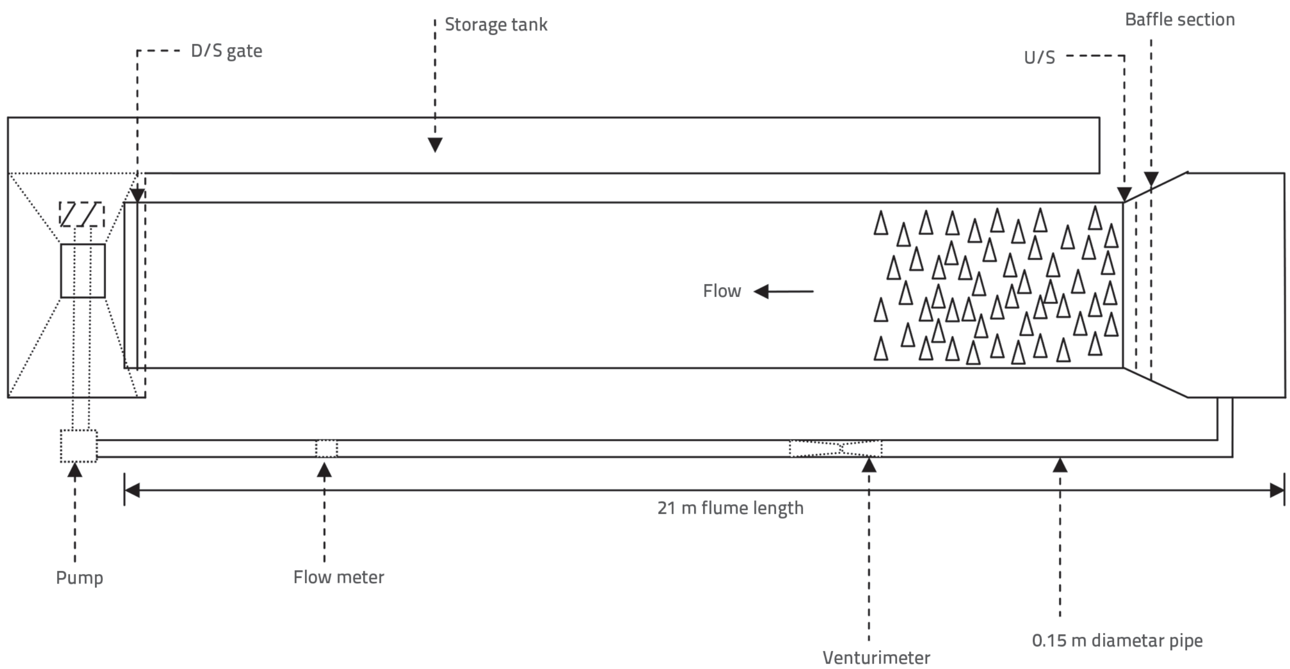

Figure 1. Top view (plan) of experimental setup

Table 1. Rough bed properties

Serial number	Rough bed attributes		Number of readings	Range of Froude number
	Aggregate size [mm]	**Nomenclature**		
1	25 - 31.5	Series A	46	3.00 - 7.00
2	31.5 - 40	Series B	48	2.00 - 7.00
3	40 - 50	Series C	52	2.50 - 10.00
4	50 - 63	Series D	42	2.50 - 9.50
5	63 - 75	Series E	48	3.00 - 9.00

glass sheet was fixed as side walls for visualization. For discharge, measurement was recorded using the electromagnetic flow meter connected to a 0.150 m diameter pipe. At the downstream end of the flume, the water was collected in a tank measuring 3m in width and 1 m in depth. For preventing instrumental error, calibration is necessary before every run of the experiment. Discharge is maintained for individual run.

Kako bi se olakšalo formiranje skoka, uzvodni zasun žlijeba u svim The hydraulic jump was formed in this flume measuring 21 x 0.6 x 0.5 m in size, with Plexiglas sides. The rough bed was made using crushed stones. The selection of crushed stones was motivated by the fact that they are used as coarse aggregate in concrete during construction of the lined channels. These stones are locally available and can be broken as per the size required. An additional advantage of these stones is that they have a very high "degree of angularity", and hence a rougher surface area can be exposed to the flow. Because of the high angularity their laying on the bed of the channel is also easy, as a high level of anchorage can be achieved. They were anchored to the bed of the flume in such a way that no portion of the crushed stones affected the upstream bed where the supercritical stream was formed. In such a way, the gap between individual stones acts as a depression on the bed. The arrangement created in this way formed the system of turbulent eddies that might increase the bed shear stresses [3]. Five sets of crushed stones were used in the whole experimentation. Individual sets were made by sieving crushed stones in such a way that they passed through a higher sieve and were retained on a lower one. After the sieving process, the aggregates were systematically classified into different series. The details are given in Table 1.

To facilitate jump formation, the upstream sluice gate of the flume was adjusted in all the experiments to generate a supercritical flow, and the rough bed was placed immediately after the upstream gate, Figure 4. Actual photograph of hydraulic jump is shown on figure 5. A total of 236 experimental readings were taken (for all five series). The upstream and downstream depth were measured over the top level of the rough bed which was taken as 28 mm for series A, 35.5 mm for series B, 45 mm for series C, 56.5 mm for series D, and 69 mm for series E, using a point gauge with the least count of 0.1 mm, Figure 6. The Froude number for the experiments mostly ranged from 3 to 10.

The water was made to enter the flume under a sluice gate, which produces a uniform supercritical

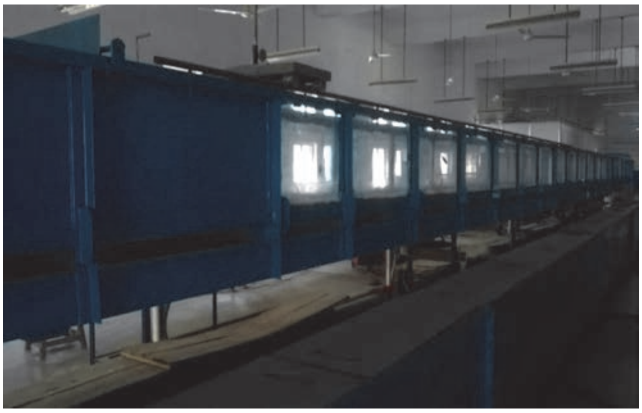

Figure 2. Photograph of tilting flume used in experiment

Figure 3. Photograph of crushed stones glued onto flume bed to form rough bed for experiment

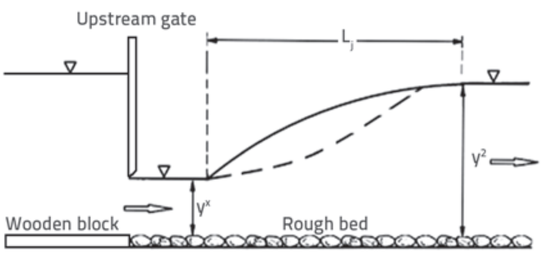

Figure 4. Schematic diagram showing rough bed

Figure 5. Actual photograph of hydraulic jump

Figure 6. Photograph of electromagnetic flow meter used in experiment

3. Results and analysis

The supercritical and subcritical depths were measured at the sections as shown in Figure 4. The supercritical depth was measured just before the start of the jump, and the subcritical depth was measured at the end of the jump, which can be defined as the section beyond which the water surface is nearly horizontal.

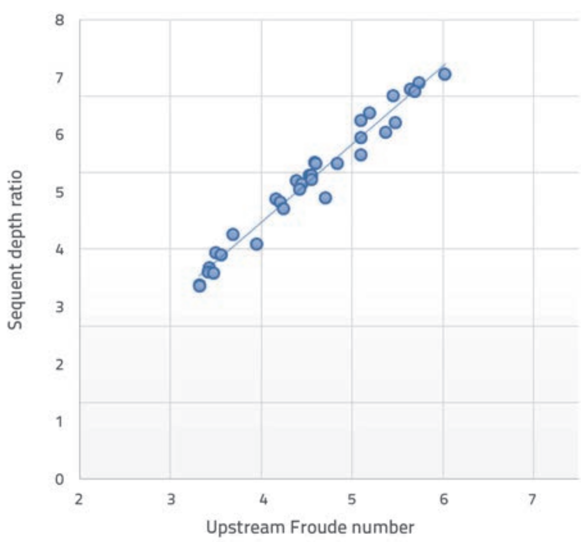

Figure 7. Variation of sequent depth ratio with respect to Froude number

For every set, the variation of the sequent depth ratio with Froude number was compared to the readings from previous studies. The variation of the sequent depth ratio with respect to Froude number is shown for smooth bed in Figure 7. The variation shows a clear linear pattern. The pattern is almost the same as that of the Belanger's equation. The regression result obtained from the graph shows an R^2 value of 0.9672 for

$$\frac{y_2}{y_1} = 1.0247 \cdot F_{r1} + 1.2463 \quad (2)$$

Figure 8 shows a comparison between variation of the sequent depth ratio with respect to Froude number in smooth bed and the Belanger's equation.

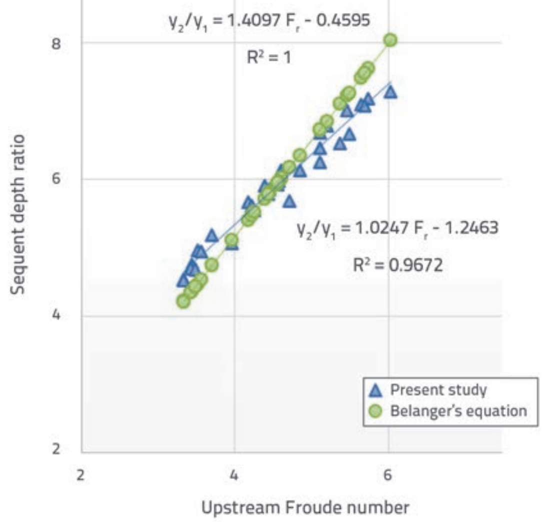

Figure 8. Comparison between present study and Belanger's equation in smooth bed

This comparison shows that the results obtained in the present study are very close to theoretical values obtained by the Belanger's equation for the sequent depth ratio in the rectangular channel over a smooth bed. The variation of the sequent depth ratio with Froude number for series A is shown in Figure 9.

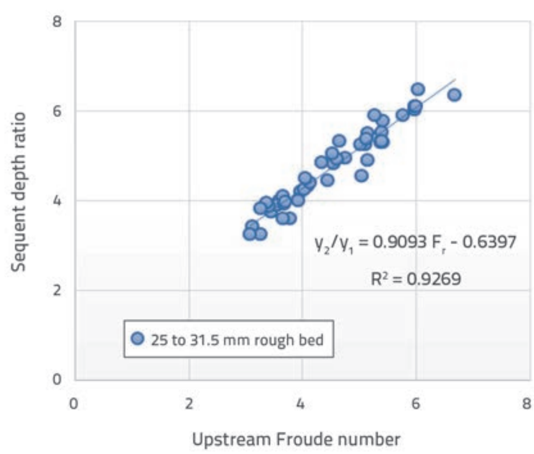

Figure 9. Variation of sequent depth ratio with repect to Froude Number for Series A (25 to 31.5 mm)

The results show a linear trend, and the regression result obtained for this is

$$\frac{y_2}{y_1} = 0.9093 \cdot F_{r1} + 0.6397 \quad (3)$$

with an R^2 value of 0.9269 and the Froude number values varying between 3 and 7.

The variation of the sequent depth ratio with Froude number for series B is shown in Figure 10.

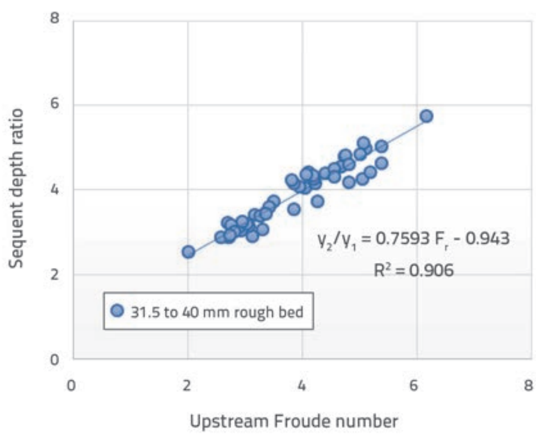

Figure 10. Variation of sequent depth ratio with Froude number for series B (31.5 to 40 mm)

A linear trend is also obtained in series B, and the regression result is

$$\frac{y_2}{y_1} = 0.759 \cdot F_{r1} + 0.943 \quad (4)$$

The R^2 value obtained is 0.906 and the Froude number varies between 2 to 7.

The variation of Sequent Depth ratio with Froude number for series C is shown in Figure 11.

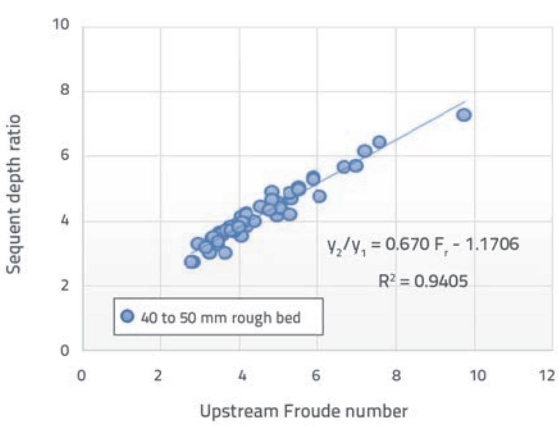

Figure 11. Variation of sequent depth ratio with Froude number for series C (40 to 50 mm)

In series C, the regression result is

$$\frac{y_2}{y_1} = 0.6704 \cdot F_{r1} + 1.1706 \quad (5)$$

The R^2 value obtained is 0.9405 and the Froude number varies between 2.5 to 10. Here the trend is also linear.

The variation of Sequent Depth ratio with Froude number for series D is shown in Figure 12.

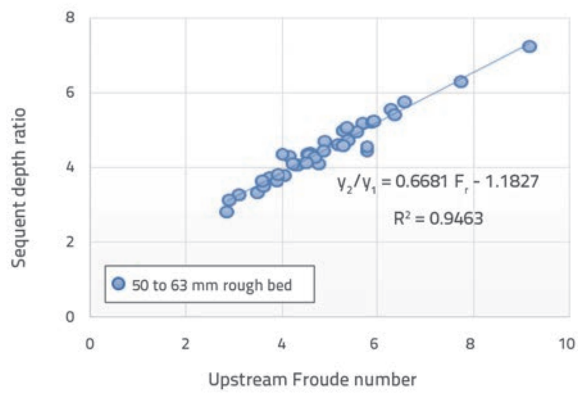

Figure 12. Variation of sequent depth ratio with Froude number for series D (50 to 63 mm)

In series D, the equation obtained by regression analysis is

$$\frac{y_2}{y_1} = 0.6681 \cdot F_{r1} + 1.1827 \quad (6)$$

The R^2 value obtained is 0.9463 and the Froude number varies between 2.5 to 9.5. The variation of Sequent Depth ratio with Froude number for series E is shown in Figure 13.

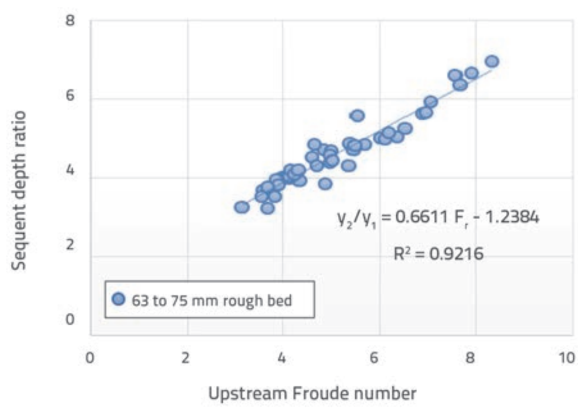

Figure 13. Variation of sequent depth ratio with Froude number for series E (63 to 75 mm)

In series E, the equation obtained by regression analysis is

$$\frac{y_2}{y_1} = 0.6611 \cdot F_{r1} + 1.2384 \quad (7)$$

The R^2 value obtained is 0.9216 and the Froude number varies between 3 to 9. In this case, the trend is also linear.

The comparison of all series with Belanger's equation and Hughes data is shown in Figure 14. The smooth bed condition is represented by the Belanger equation and the data collected from W.C Hughes' work is also used to show that the same trend is seen in the present study. The comparison shows that the lines representing the variations in rough bed deviate from the smooth bed at higher values of Froude number. It can also be observed that the deviations from the adjacent graphs reduce as the roughness height increases. The graphs of series D and series E coincide with one another. That shows that there is a limit in reduction of the sequent depth ratio, i.e. after a particular roughness height, no additional reduction in sequent depth ratio will be produced even if the height of roughness continues to increase.

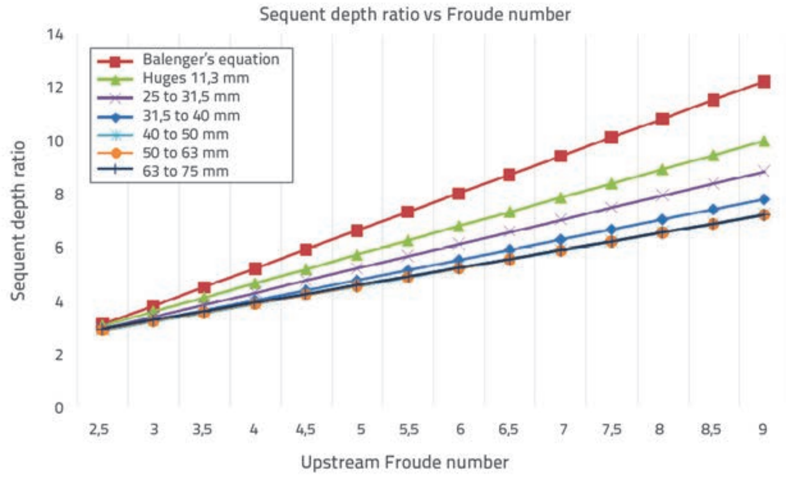

Figure 14. Comparison of present study with Belanger Equation and W. C Hughes' data

4. Conclusions

The behaviour of hydraulic jump properties over a rough bed is evaluated in this study. The height of the roughness was changed after each set so as to define the behavioural change in hydraulic jump when the roughness height is increased. The following conclusions can be drawn from this study:

- The introduction of a rough bed will always reduce the tail water depth considerably. It is due to the shear force that develops on the bed due to the roughness that was introduced artificially.
- Tail water depth reduces with an increase in roughness height.
- It was observed that the lines representing consecutive roughness come closer and closer as the height of the roughness increases. This indicates that there is a limiting value for the height of roughness after which no effect of increase in height is observed. In series D and E of this study, it has been observed that the lines are so close to one another that they can not be separately identified without employing the regression analysis equation.
- Rough bed can be used as an effective replacement for the stilling basins with baffle walls, as the latter are much costlier than a rough bed. Even though this has experimentally been proved in laboratory, testing on a large scale model is needed before actual implementation.

Only one characteristic of the hydraulic jump, i.e. the tail water depth or sequent depth ratio, is considered in this study. Future research should concentrate on other characteristics of jump such as the jump length, roller length, and shear stress exerted by rough bed.

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