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ORIGINAL ARTICLE

Bed profile downstream compound sharp crested V-notch weir

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KEYWORDS

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Abstract Triangular weirs are commonly used to measure discharge in open channel flow. They represent an inexpensive, reliable methodology to monitor water allocation. A compound sharp-crested weir consisting of two triangular parts with different notch angles was used. The lower triangular part of the weir handles the normal range of discharges while the upper part measures the higher peak flows. This paper evaluates experimentally the local scour downstream compound sharp crested V-notch weir. Forty-eight (48) experimental runs were conducted. Three models of weirs with different geometries (combination of notch angles), four upstream water levels, three water levels at the tailgate, and two bed materials were used. Multiple regression equations based on energy principal and dimensional analysis theory were deduced to estimate the local scour downstream of the weir models. The developed equations were compared with the experimental data. The comparison between the local scour downstream classical V-notch weir and a compound sharp-crested weir consisting of two triangular parts with different notch angles was found to be unnoticed. The study recommended using the compound V-notch weir to pass high discharges instead of the classical V-notch weir.

1. Introduction

A weir as an overflow structure: It is built perpendicular to an open channel axis to measure the discharge. There are mainly two types of weirs: sharp-crested weirs and broad-crested weirs. For a weir to be considered sharp crested, the top thickness of the crest and side plates should be between 1 and 2 mm, Martínez et al. [1]. The plate edges of an angle of at least 45° or 60° are highly recommended for a V-notch, Bos [2]. The overflow nape should touch only the upstream faces of the crest and side plates and not cling to the downstream face of the weir. Scour in bed material downstream weirs is considered the most unfavorable process because it threats the overall stability of the weir. Scour leads to the removal of the boundary material by the action of flowing water. It occurs naturally as a part of the morphological changes of rivers and man-made structures; Sobeih et al. [3]. When the flow changes from supercritical to subcritical condition a hydraulic jump is formed; in this flow type no Hydraulic jump can form downstream the weir.

The characteristics and hydraulic behavior of plain weirs or standard weirs have been studied for a long time and the

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Notations

H	water head above the vertex of the V-notch weir (m)
y	water depth at the tailgate (m)
Q	water discharge through the flume (m^3/s)
V	the mean velocity at the downstream cross section of flume (m/s)
g	gravitational acceleration (m/s^2)
d_{50}	mean particle diameter (m)
L_{ap}	length of apron (m)
P	weir height (m)
d_s	maximum scour depth (m)
L_s	maximum scour length (m)
S_L	maximum silting length (m)
B	width of flume (m)
A	flow area above the vertex of the V-notch weir (m^2)
S_o	bed slope of the flume
F_r	Froude number

Greek symbols

θ_1	weir upper angle degrees
θ_2	weir lower angle degrees
μ	dynamic viscosity of the water (kg/m s)
ρ	water density of the flow (kg/m^3)
ρ_s	soil particle density (kg/m^3)

understanding of them is rather deep. Most of past studies were focused on discharge coefficient of combined flow. However, few studies have been done on the scouring action downstream weirs placed in the flow. Regarding the flow of water over weirs, many studies have been reported in the literature such as Kindsvater and Carter [4], Ackers et al. [5], Swamee et al. [6], Borghei et al. [7], Johnson [8], Clemmens et al. [9], and Aydin et al. [10]. Ferro [11] used the dimensional analysis and the incomplete self-similarity theory to study the outflow process over a sharp-crested and broad weir. Ramamurthy et al. [12] carried out experimental study on silt weirs to permit measuring both very low and very high discharge rates accurately. Many other studies were focused on V-notch weirs. Ogden et al. [13] used a scale model to identify discharge coefficients with quantified uncertainty to identify the effect of sedimentation on the performance of a 140° sharp-edged V-notch weir. The changed variables were the discharge, channel slope, and degree of sedimentation. Results indicated that sedimentation increases the discharge coefficient for a given channel slope. Murthy and Giridhar [14] presented a practical linear proportional weir of simple geometric shape in the form of an inverted V-notch or inward trapezium. They demonstrated that, nearly 75% of the depth of inverted V-notch can be used effectively as the measuring range. Also, experiments showed excellent agreement with the theory by giving an average coefficient of discharge for each weir varying from 0.61 to 0.62. Eli [15] used 90° V-notch weirs to measure discharge at outfalls, and he used two techniques to measure the flow depth over the weir notch. They have the advantage of not requiring that an elevation datum to be established. Both techniques yielded reliable measurements using a sample data set. Prakash and Shivapur [16] studied the flow over an inclined inverted V-notch weir. They developed an equation for discharge in terms of the inclination angle of the weir plane with the plane normal to the flow axis. Ramamurthy et al. [17] conducted experimental studies to determine the discharge coefficients of V-shaped weirs over a wide range of weir Reynolds numbers. Their study provided a single relation between the weir discharge coefficient and the weir Reynolds number for both the rectangular and V-shaped weir systems. Bautista-Capetillo et al. [18] used a low-speed photographic technique to characterize the upper and lower nape profiles of flow over fully aerated triangular weirs covering a range of weir vertex angles (from 30° to 90°). A predictive equation for the weir discharge coefficient was derived. Hamed et al. [19] conducted laboratory experiments to test four weir models of different V-notch angles. Experiments were conducted at three different Froude numbers and four different oblique angles of the weir. The results showed that scour parameters decreased by placing the V-notch weir at small oblique angle. The changes in scour parameters for V-notch angles 30°, 60° and 90° were insignificant while it decreased significantly by using 120° weir. Chanson and Hang [20] studied the discharge calibration of a large 90° V-notch thin plate weir using an unsteady volume per time technique. The findings showed that the unsteady discharge calibration of the V-notch weir yielded similar results to a more traditional calibration approach based upon steady flow experiments, allowing a rapid testing over abroad range of flow rates.

The triangular V-notch weir is a precise measurement tool in open channel, but a compound V-notch weir that consists of two parts can provide the ability to release high discharge with a good accuracy. The main objective of this paper was to evaluate the local scour downstream of compound triangular V-notch and compare these values with the corresponding produced from classical V-notch under the same flow conditions. Three variables were tested; the upstream, the water level at the tailgate, and the geometry of V-notch to identify their effect on the local scour downstream of compound sharp crested V-notch weir considering two bed materials.

2. Materials and methods

The experimental work of this study was conducted in a flume located at experimental hall of the Hydraulics Research Institute (HRI), National Water Research Center, Egypt.

The flume channel was 21 m long, 0.6 m wide, 0.5 m deep, and the side walls along the entire length of the flume were made of brick. The flume was equipped with a steel wooden

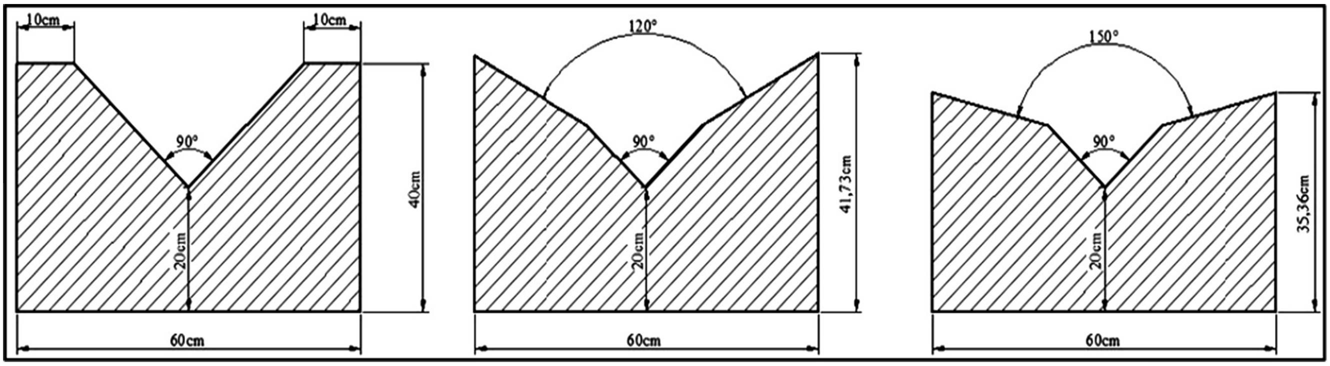

Figure 1 Definition sketch of the used models.

gate with an orifice with a rectangular shape, also has movable downstream gate located at the end of the flume. Centrifugal pump driven by induction motor re-circulates the flow from an underground reservoir to the flume. The weir models were made of steel with a 0.02 m thick, 0.3 m height and 0.6 m width. Three models of weir were used with changeable upper notch angles, 90°, 120°, and 150° (Fig. 1). The tested upstream water levels were 6, 9, 12, and 15 cm measured from the notch vertex, while the tested water levels at the tailgate were 10, 14, and 18 cm. The research investigates the influence of the above variables on 2 bed materials, including sand (d_{50} = 0.0593 cm), and plastic (d_{50} = 0.31 cm).

3. Test procedure

3.1. Run duration

At the beginning of the experimental works, a set of trial tests were carried out to define the run duration throughout monitoring the local scour with time in case of the two bed materials. Fig. 2 was plotted for fixed classical 90° V-notch weir under 15, and 18 cm upstream and downstream water levels, respectively to define the relationship between maximum scour depths and time. It was found that, after 20 min from starting, the local bed scour reached around 75–85% its maximum value at time equal to four hours. Consequently, each test was run for four-hours, which were sufficient for most of the tests to reach a quasi-equilibrium state of scour, where there are no appreciable changes in bed profile.

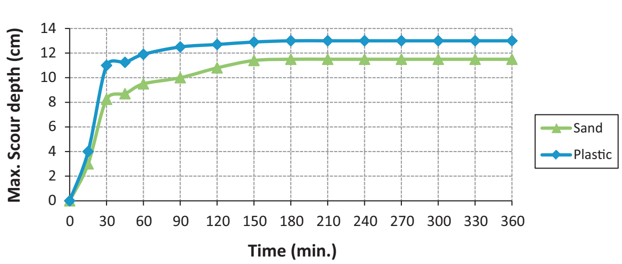

Figure 2 Relationship between maximum scour depths and time in case of sand and plastic bed materials.

3.2. Run procedure

The test procedure was as follows. 1. The selected weir model was fixed carefully in the flume in its place. 2. At the beginning of each run the bed material was leveled at the apron level (20 cm in depth, Fig. 2), and the leveling accuracy was checked by a mobile point gauge with an accuracy of +0.1 mm and leveling device. 3. The tailgate was completely closed, and backwater feeding was started first until its depth reached higher than the desired downstream water depth. 4. The pump was activated and the discharge was adjusted using a control valve. 5. The exact water discharge was measured using an ultrasonic flow-meter with an accuracy of +1%. 6. The tailgate was screwed gradually until the required downstream water depth was reached using the point gauge. 7. The running time of the test was started. 8. After four-hours (where there is no appreciable change in bed profile), the velocity measurements were recorded. 9. The pump was switched off, and the flume was emptied from water by the tailgate very slowly in order not to disturb the bed level changes. 10. The bed profile was recorded using point gauge and ordinary scale through a fixed grid. 11. The previous steps were repeated for each run.

4. Dimensional analysis

In the analysis of the scour problem downstream V-notch weir, the considered variables were as follows: H = the water head above the vertex of the V-notch weir, y = water depth at tailgate, Q = water discharge through the flume, V = the mean velocity at the downstream cross section of flume, g = gravitational acceleration, ρ = water density of the flow, μ = dynamic viscosity of the water, d_{50} = mean particle diameter, ρ_s = soil particle density, L_{ap} = length of apron, P = weir height, S_o = flume bed slope, B = flume width, θ_1 = weir upper angle, θ_2 = weir lower angle, d_s = maximum scour depth (Fig. 3).

The functional relationship for the maximum local scour depth d_s, could be expressed as follows:

$$\phi(B, P, H, Y, L_{ap}, V, d_{50}, g, Q, \rho_s, \rho, \mu, S_o, \theta_1, \theta_2) = 0 \qquad (1)$$

In this study P, B, S_o, ρ_s, θ_2, and L_{ap} were kept constant. Then, Eq. (1) might be written in the following form:

Using π-theorem, it yields

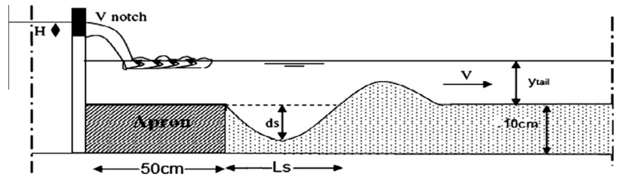

Figure 3 Schematic diagram showing the geometry of the scour and silting.

$$\frac{d_s}{y} = \phi\left(\frac{H}{y}, \frac{d_{50}}{y}, \frac{V}{\sqrt{gy}}, \frac{\rho Q}{d\mu}, \theta_1\right) \tag{2}$$

in which $\frac{V}{\sqrt{gy}}$ = Froude number, and $\frac{\rho Q}{d\mu}$ = Reynold number. In open channel flow, the Reynolds number effect may be neglected. Eq. (2) may take the following form:

$$\frac{d_s}{y} = \phi\left(\frac{H}{y}, \frac{d_{50}}{y}, F_r, \theta_1\right) \tag{3}$$

5. Model runs

Forty-eight experimental runs using three different V-notch weir models were done. The experiments were designed to vary the independent variables of upstream water level, water level at the tailgate, V-notch weir upper angle, and the bed material. A designed mesh was used for velocity and bed profile measurements, (Fig. 4). The velocity components were measured at 0.2, 0.4, 0.6, and 0.8 from water depth, to define the 3-D velocity. Also, the density of bed profile measuring nodes decreases as the distance from weir increases to define the bed local scour in a high accuracy.

6. Results and discussion

6.1. Influence of upstream water level

Figs. 5 and 6 show the longitudinal bed profiles at the center line of channel for different upstream water levels for the two considered tested bed materials. The upstream water levels were measured from the vertex of the V-weir. The figures were plotted for fixed water level at the tailgate of 18 cm and 90° upper weir angle. Similar curves trend was found. Also, the figures clarified that the sensitivity of the bed configurations to the plastic bed was more than the sand bed, which emphasizes the geometry of local scour and silting was found in a large

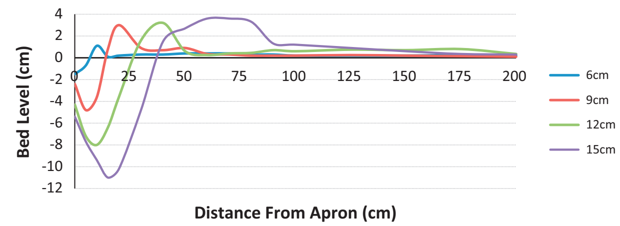

Figure 5 The longitudinal bed profiles for sand material at different upstream water levels.

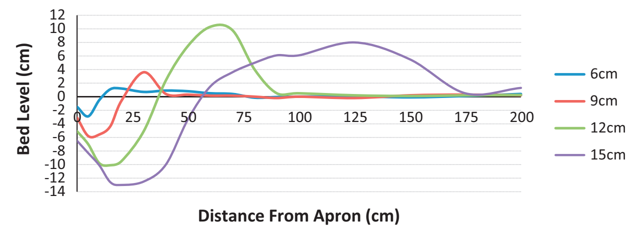

Figure 6 The longitudinal bed profiles for plastic material at different upstream water levels.

scale in the case of plastic bed when compared to the sandy bed. Moreover, the configurations in the silting region were less than the scour region. After the first 0.5 m from the apron, the silting was unnoticed for the tested upstream water levels except at the 15 cm. The figures also showed that, both maximum local scour depth and silting height were directly proportional to the upstream water level. Consequently, as the upstream water level increases, both local maximum scour depth and silting height were located far away from the apron.

6.2. Influence of water level at the tailgate

Figs. 7 and 8 show the longitudinal bed profiles at the center line of channel for the tested water levels at the tailgate for the two considered tested bed materials. The figures were plotted for fixed upstream water level of 15 cm and 90° upper weir angle. Similar trend was found for the tested water levels at the tailgate. The figures showed that the locations and lengths of local scour and silting were uninfluenced by the water levels at the tailgate. Moreover, the local scour depth and silting height were directly proportional to the water levels at the tailgate. In the case of sandy bed soil, Fig. 7 illustrates that the bed level changes were focused at the first 1 m; also no focal

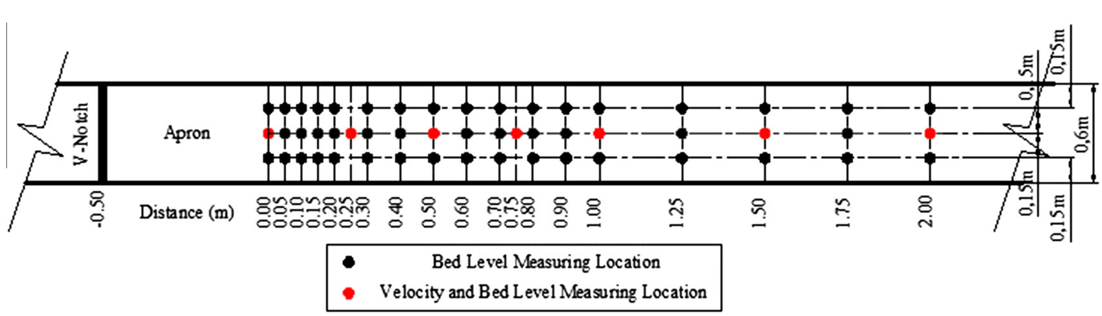

Figure 4 The Location of velocity and bed profile measuring points.

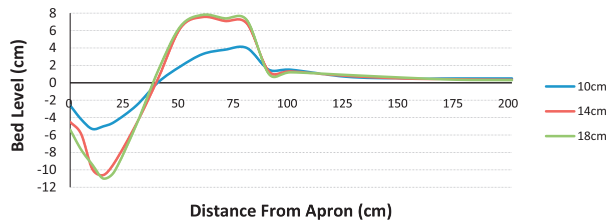

Figure 7 The longitudinal bed profiles for sand material at different water levels at the tailgate.

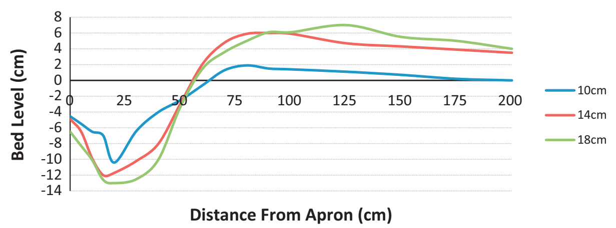

Figure 8 The longitudinal bed profiles for plastic material at different water levels at the tailgate.

changes were found for bed levels in case of 14 and 18 cm. The rest of the entire tested length (i.e. the last 1 m), and the influence of water levels at the tailgate were vanished. However, in the case of plastic bed, it was found that the longitudinal changes in bed profiles were extended to consume the considered tested length.

6.3. Influence of weir upper angle

Figs. 9–11 were plotted to investigate the influence of weir upper angle on the longitudinal changes in bed profile and velocity profile at the center line of channel. The figures were plotted under fixed upstream water levels of 15 and 18 cm, respectively. The figures demonstrated no focal differences in curves trend. Investigating Fig. 11, it was noticed that minimum and maximum velocity values were located at 25 and 75 cm from the apron respectively. Also, the peak velocity values were inversely proportional to the weir upper angle. Hence, it illustrates the findings in Figs. 9 and 10 as the maximum local scour depth and silting height were found at the weir model of 90° upper angle. However, the influence of weir upper angles on local scour and silting lengths was

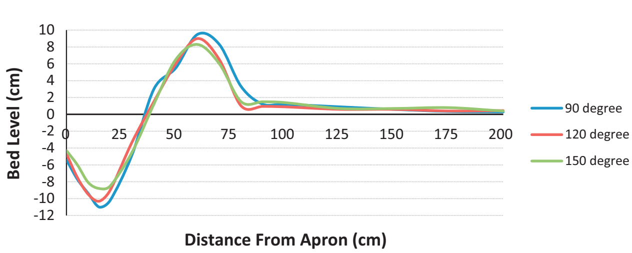

Figure 9 The longitudinal bed profiles for sand material at different weir upper angles.

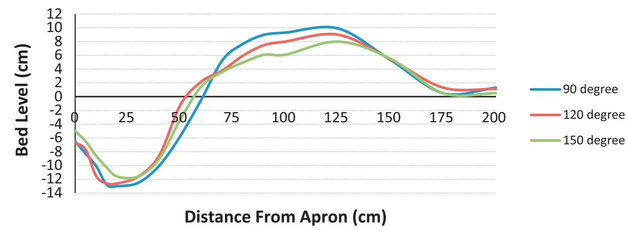

Figure 10 The longitudinal bed profiles for plastic material at different weir upper angles.

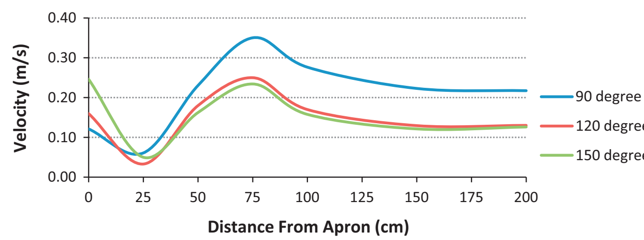

Figure 11 The velocity profile for sandy bed at different weir upper angles.

inconsiderable for the same bed material. Also, the local scour and silting lengths in the case of sandy bed were less than the corresponding in the case of plastic bed.

The experimental results were used for developing the following empirical formulae (using statics software program) for the considered bed material:

$$d_s/y = 0.273\ H/y + 7.423\ d_{50}/y + 0.968F_r - 0.0021\theta_1 + 0.448 \tag{4}$$

The correlation factors $(R^2) = 0.847$

The Standard Error of Estimation (SEE) = 0.076

$$L_s/y = 3.483\ H/y + 62.59\ d_{50}/y + 1.014F_r - 0.0061\theta_1 - 2.073 \tag{5}$$

The correlation factors $(R^2) = 0.939$

The Standard Error of Estimation (SEE) = 0.416

$$S_L/y = 8.854\ H/y + 189.09\ d_{50}/y + 1.681F_r + 0.0122\theta_1 - 7.133 \tag{6}$$

The correlation factors $(R^2) = 0.891$

The Standard Error of Estimation (SEE) = 1.468

It should be mentioned that the equation of silting height was neglected as the produced correlation factors were small ($R^2 = 0.41$).

Fig. 12 presents photographs for some tests carefully selected to present the influence of weir upper angle on bed profile changes. The photographs were taken for tests under fixed upstream and downstream water levels of 15 and 18 cm respectively.

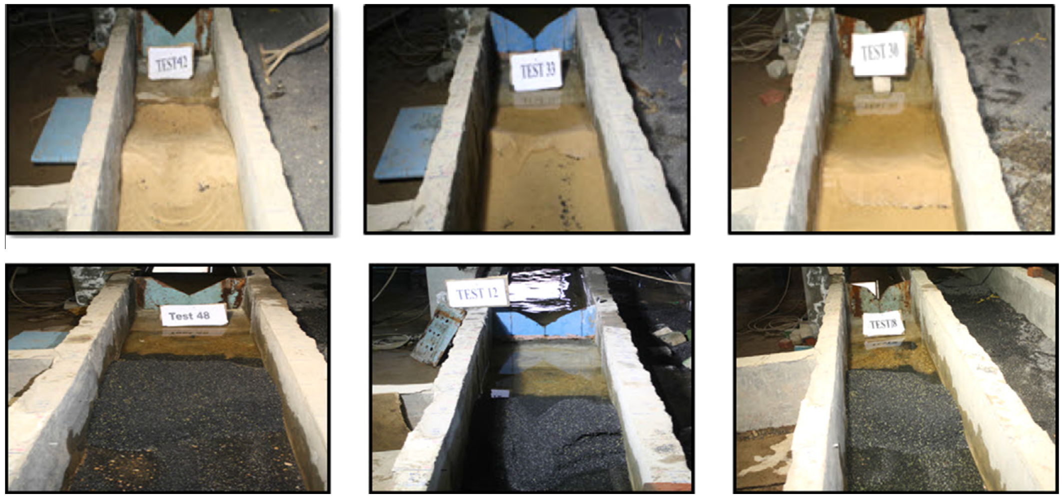

Figure 12 The bed profile at different weir upper angles for sand and plastic materials.

7. Conclusions

The experimental study of the influence of upstream, downstream water levels, and weir upper angles on the longitudinal bed profile changes led to the following conclusions:

- The longitudinal bed profile changes were much larger when using plastic bed compared to sandy bed.
- The longitudinal bed profile changes in the scour region were larger than the silting region.
- The longitudinal bed profile changes due to flow on sandy bed material were restricted for the first 1 m after the apron, while the changes extend to 2 m in the case of plastic bed material.
- The geometry of local scour and silting was significantly sensitive to upstream water level than the water levels at the tailgate and weir upper angle, because the upstream water level controls the discharge since the notch was running under free flow conditions.
- The geometry of local scour and silting was directly proportional to the upstream and water levels at the tailgate.
- The location of the maximum local scour depth was directly proportional to the upstream water level, while it was insensitive to the water levels at the tailgate and the weir upper angle.
- The influence of water levels at the tailgate and weir upper angle on local scour and silting lengths was unnoticed.
- The maximum local scour depth and silting height were inversely proportional to weir upper angle.
- The peak velocity was inversely proportional to the weir upper angle.

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