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Experimental Investigations on Scour Volume Upstream of a Slit Weir

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ABSTRACT

The frequent removal of sediment accumulation from reservoirs by dredging requires interruption of power generation. Alternatively, this can be avoided by using a slit weir. In the present study, the impact of sediment nonuniformity, slit weir dimensions, weir slit position, and discharge on the effectiveness of sediment removal was experimentally investigated using a flume with a length of 12 m, a width of 0.30 m, and a depth of 0.30 m. In the flume, a slit weir was tightly fixed at the end of a 2 m working section filled with nonuniform sediments up to 110mm. Results showed that using coarser sediment (d_{50} = 0.70 mm) reduces the scour volume by 22-folds compared to finer sediment (d_{50} =0.30 mm). This study tested five different slit weir dimensions using two weir slit positions (slit positioned in the center and slit positioned on the side). The maximum scour volume was recorded when the crest level, z of the slit weir, was 0 cm from the mobile bed. The study concluded that a 3-fold increase in discharge corresponds to a 10-fold increase in scour volume regardless of bed material nonuniformity. The existing model for estimating scour volume for uniform sediments was validated using the data of this study, and it was observed that the model predicts the scour volume in nonuniform sediments with sufficient accuracy. Thus, the model can determine the scour volume, and maximum scour depth occurring upstream of a slit weir near a hydropower intake in reservoirs.

Keywords: Nonuniform sediment, scour volume, slit weir, uniform flow

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INTRODUCTION

Erosion in river basins increases sediment loading in surface water runoff from the basins during a rainfall event. The runoff with the high sediment load will eventually reach rivers and storage reservoirs. In reservoirs, the sediments carried by the inflow water usually settle at different locations, including near the hydropower intake. The continuous accumulation of sediments in reservoirs reduces storage capacity and hence hydropower production. In addition, the passage of sediments through the hydropower intake can damage the turbine blades. Generally, the removal of sediments accumulation from reservoirs by dredging is a costly and time-consuming process and causes interruption to the hydropower generation process. Ota et al. (2017a) proposed an economical method by discharging the sediments utilizing flowing water through a slit weir.

However, the amount of water used to carry the sediment accumulation away from the hydropower intake should be controlled to minimize the wastage of water storage in reservoirs. The design and operation of the slit weir are essential for evaluating the volume of released sediment and temporal variation in scouring depth since it affects the structure's safety. Thus, the accurate estimation of sediment volume and temporal variation in scour depth at the site of the slit weir requires intensive research. However, the phenomena of scouring at slit weirs have not been researched sufficiently, and hence few solutions are available. In addition, studies on sediment removal by scouring near a hydropower intake are also limited. The major studies on scouring upstream of a slit weir were conducted by Ota and Sato (2015), Ota et al. (2016), Ota et al. (2017a), and Ota et al. (2017b). In order to simulate the scouring process around the slit weir, Ota and Sato (2015) proposed a numerical model based on solving the Reynolds-averaged Navier Stockes equation coupled with the Volume of Fluid Method, VOF, and the k-ω turbulence closure model. The concept of the above model was later utilized by Zhang et al. (2016) to predict the clear water scour depth below a submarine pipeline for a range of steady flow conditions.

Ota et al. (2016) modified the three-dimensional (3D) numerical model that was proposed by Ota and Sato (2015) and used it to produce a scour geometry around a slit weir. Also, Ota et al. (2017a) proposed another numerical model based on an ordinary differential equation that can compute the time variation of scouring volume and maximum scour depth upstream of a slit weir for steady and unsteady flow conditions. The data from experimental runs in a laboratory utilizing a mobile bed with uniform sediments were used by Ota et al. (2017a) to produce the following relationship between the scour volume, V_s, maximum scour depth, d_s, slit weir width, b_{sl}, and channel width, B for uniform flow (Equation 1):

$$d_s/(V_s)^{1/3}=0.39(b_{sl}/B)^{-0.383} \qquad [1]$$

A hybrid Euler-Lagrange numerical model that considers the interaction between the suspended sediment transport and bedload to reproduce temporal variation of the three-dimensional bed geometry around a weir-type structure with sufficient accuracy was proposed by Ota et al. (2017b).

Based on intensive experimental investigations on fine uniform sand, Wang et al. (2018) concluded that no upstream clear water scour depth was observed at a sloped submerged weir and that the downstream scour depth was independent of the upstream weir slope. In addition, Guan et al. (2019) used coarse uniform sand to study the time evolution of scouring downstream of submerged weirs. The analysis of sediment passage over a piano key weir (PKW) with different configurations was studied by Noseda et al. (2019). The impact of W-weir configuration and height on scour depth occurring downstream of the weir location were studied by Abdollahpour et al. (2017), while Khalili and Honar (2017) studied the impact of height and radius of a semi-circular labyrinth side weir on discharge. Muller et al. (2011) studied the impact of weir height and discharge on the size of the dunes formed in an open channel. Finally, Lauchlan (2004) undertook experimental investigations to model the bedload transport and suspended-load sediments over steep-sloped weirs.

Other experimental investigations on uniform mobile beds were carried out by Powell and Khan (2012) and Wang et al. (2019) where the former work was focused on scouring upstream of an orifice while the latter focused on the effectiveness of local scour countermeasure by using "anti-scour collar" around physical pier model.

Moreover, many soft computing methods were employed to predict the scour depths occurring in various hydraulic structures. For example, Azamathulla et al. (2008) used the neuro-fuzzy scheme for predicting scour depth downstream of ski-jump spillways, while Sayed et al. (2019) utilized genetic expression programming (GEP) and multivariate adaptive regression splines (MARS) to estimate clear-water local scour depth at pile groups while Rajkumar et al. (2016) utilized published data in the literature to demonstrate the efficiency of artificial neural network (ANN) and genetic algorithm (GA) in predicting scour depth within channel contractions.

In summary, the studies covered in the literature were experimental, numerical, and statistical. The numerical and statistical studies proposed models for scouring prediction, and these models were validated using experimental data. However, most studies were related to scouring downstream of weirs with different configurations and flow conditions. By reviewing the published literature, it is noted that the experimental studies on scouring upstream of a slit weir were limited, and studies that used numerical simulation models for estimation of scouring volume upstream of a slit weir have underestimated the experimental scour volume by up to 30% (Ota & Sato, 2015). The above findings highlighted the need for more experimental studies.

In addition, other cases covered in the literature were related to scouring upstream of a circular orifice, scour depth within channel contractions, scouring around a circular pier, scour depth below a submarine pipeline and scour depth for ski-jump type of spillways.

However, the findings of all the studies were mainly related to scouring mobile beds with uniform sediments.

In this study, extensive experimental work was conducted on the occurrence of scouring upstream of a slit weir in a nonuniform mobile bed. The combined effect of slit weir location, dimensions, sediment coarseness, and flow intensity was studied. Thus, the present study aims to contribute to the gap currently found in the literature.

MATERIALS AND METHODS

A series of experimental investigations were conducted in a glass-sided tilting flume 0.30m wide, 12 m long, and 0.30 m deep. The flume is located at the hydraulics laboratory of the College of Engineering, University of Baghdad, Iraq. The slit weirs used in the trials were made up of Plexiglas with a thickness of 6mm. In this study, two different positions for the slit of the weir were tested, as shown in Figure 1. Table 1 shows the dimensions and positions of the weir slit used in this study.

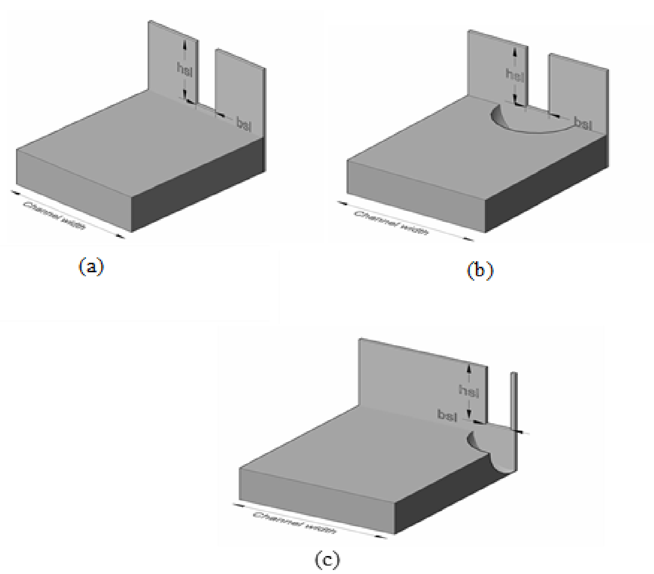


Figure 1. Diagrammatic sketch for the experimental investigations; (a) The working section before scouring; (b) The formation of scour hole (weir slit positioned in the center); (c) The formation of scour hole (the weir slit positioned in the side)

The slit weir was located at 9m from the flume inlet and was fixed and sealed at the end of the working section to eliminate leakage from the weir bottom and sides. The working section of the weir is 2 m long and 0.3 cm wide (the same width as the flume). The section was filled with sediments up to a depth of 11 cm. In a real-world scenario and according to Subramanya (2015), sediments have a nonuniform size distribution, and hence it is a common practice to use the median size, $d_{50,}$ as a representative size of sediments. In this study, two types of nonuniform sand were used in the working section of the flume, and these types were obtained by mixing sand with differing grading. The percentage finer and size of the sediments, which were determined from sieve analysis, are shown in Figure 2 and 3. The median size, d_{50} for the first type of sediments, was 0.30 mm (Figure 2), while the d_{50} for the second type of sediments was 0.70 mm. In addition, the values of geometric standard deviation, σ_g for the first type and the second type of the sediments were found to be 1.58 and 1.60, respectively. Therefore, the geometric standard deviation for nonuniform sediments should be more than 1.30, and it was calculated using the following Equation 2 (Melville & Coleman 2000):

$$\boldsymbol{\sigma_g = \sqrt{\frac{d_{84}}{d_{16}}}} \quad [2]$$

where sediment sizes with diameters of d_{84} and d_{16} were determined from the grading curve of each sediment type.

Table 1
Dimensions and locations of the slit weirs

Slit location	Dimensions (h_{sl} x b_{sl})	*z**
Center	11x6 cm	0cm
Center	10x6 cm	1cm
Center	9x6 cm	2cm
Center	8x6 cm	3cm
Center	7x6 cm	4cm
Side	10x6cm	1cm

*z** is the distance in cm between the crest of the weir and the bed of the working section before the commencement of the experiments

From the grading curves of nonuniform sediments (Figures 2 & 3), d_{max} and d_{min} can be determined. While the values of d_{50a} for the sediment used in the working section were calculated using the following Equation 3 (Melville & Coleman 2000):

$$\boldsymbol{d_{50a} = \frac{d_{max}}{1.8}} \quad [3]$$

where the d_{max} is the largest sediment size for the nonuniform sediments.

In practice, d_{90} can be used instead of d_{max}, which is unlikely to be known (Melville & Coleman 2000). However, in this study, the largest size of the sediment was taken as

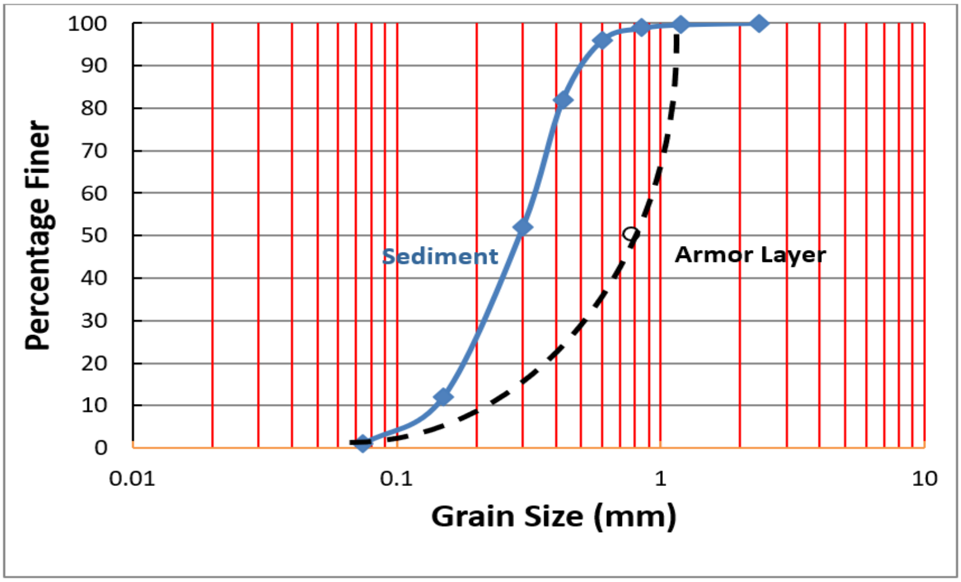


Figure 2. Grain size distribution curves for the sediments (d_{50}=0.30mm) and armor layer

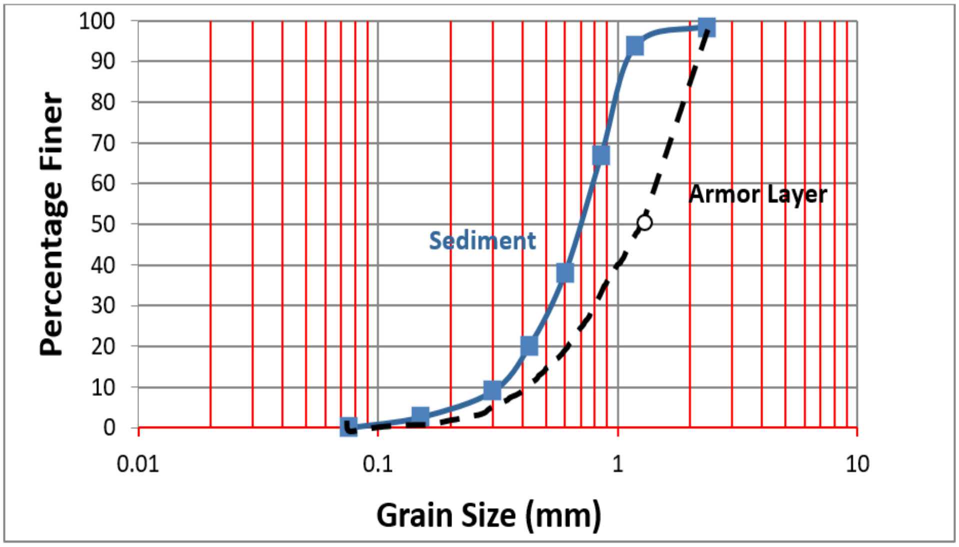
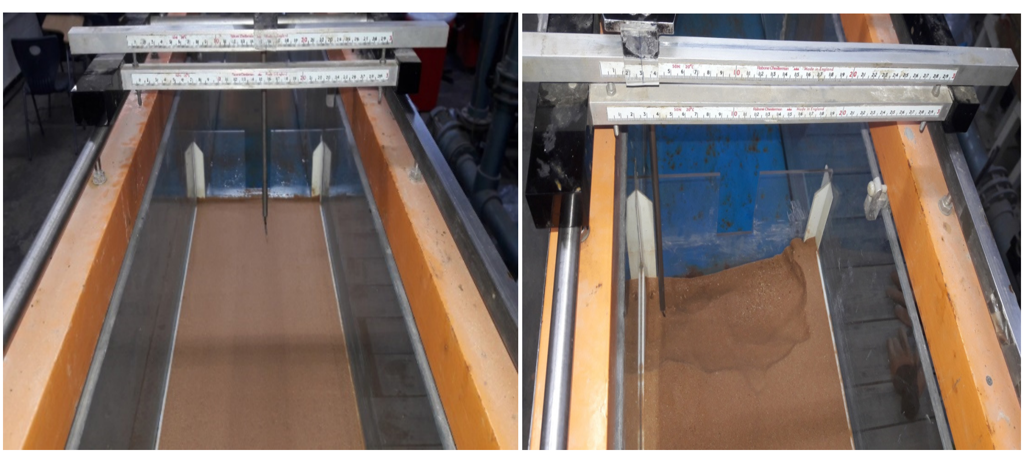


Figure 3. Grain size distribution curves for the sediments (d_{50}=0.70mm) and armor layer

$d_{max,}$ while the smallest size was taken as d_{min}. The values of dmax, d_{50a}, and d_{min} were used to plot the grading curves for the armor layers of the nonuniform sediments used in the working section (Figures 2 & 3). In the present study, the shapes of the plotted grading curves for the armor layer are similar to the typical grading curves for the armor layer presented by Melville and Coleman (2000). All experimental runs were carried out for 300 minutes under clear water scour conditions. The clear water scours conditions usually exist when the flow intensity $v/v_c<1$ (the approach velocity,v/critical velocity,v_c is less than one). The clear water scour conditions exist for both uniform and nonuniform sediments when flow intensity, $v/v_c<1$ or $[v-(v_a-v_c)]/v_c<1$ respectively. In this study, the maximum value of the flow intensity was 0.80. However, v_a is called the armor peak velocity (Melville & Coleman 2000). A general view of the working section before and after the experiments are shown in Figure 4.

The weir was calibrated before the experiments were carried out; the calibration was conducted by measuring the discharge and head above the weir crest. The head over the weir was measured at 50 cm upstream of the weir, while a volumetric method was used to measure the discharge. The discharge in the flume ranged from a minimum of 2.6 l/s to a maximum of 8l/s. At the flume entrance, a honeycomb flow straighter was used to eliminate the effect of flow turbulence on the sediment within the working section. In addition, a ramp with a slope of 1:10 was used to make a smooth flow transition from the original flume bed to the mobile bed of the working section. Although all the flows in the flume were steady and subcritical, the flow types were defined by the Froude number after measuring the approach velocity in the flume. The water depth was measured using a point gauge with an accuracy of ±1 mm. After each trial, the scour depth upstream of the slit weir was measured, as shown in Figure 4. Scour depth measurements were carried out on a 5mm grid basis around the scour hole.



a. Before the experiment fore b. After four hours (Experiment was completed)

Figure 4. The measurements of scour depth upstream of the slit weir; (a) Before the experiment; (b) after the experiment

After each run, the scouring data upstream of the slit weir were measured manually using a calibrated point gauge which was later fed into the Surfer® program. The Surfer® program was used to calculate the scouring volume and represent the contours of the areas affected by scouring.

RESULTS AND DISCUSSION

The velocity, $v_{a,}$ is called armor peak velocity, which marks the transition from clear water scour to live bed conditions for nonuniform sediments, and it is equivalent to v_c in the uniform sediment. For nonuniform sediment, the geometric standard deviation of the particle size distribution, $\sigma_{g,}$ should be more than 1.30. In this case, armoring occurs on the mobile bed of the working section and in the scour hole. Armor layer formation within the scour hole reduces the scour volume around the weir. The ratio v/v_a is a measure of flow intensity for the scouring that occurred within the nonuniform mobile bed, and it is equivalent to v/v_c for the uniform sediment. Therefore, the armor peak velocity, $v_{a,}$ marks the transition from clear water scours to live bed conditions for nonuniform sediments. In this study, two types of sediments were used in the working section; the first sediments type were with $d_{50} = 0.30$mm and geometric standard deviation, $\sigma_g = 1.60$, while the second sediments type were with $d_{50} = 0.70$mm and $\sigma_g = 1.58$. It showed that both sediments were nonuniform, and Equations 4 and 5 were used to calculate the v_c and $v_{a,}$ and these equations are based on a shields diagram or quartz sand in the water at 20°C. Equation 4 can be applied to determine the critical mean approach flow velocity for entrainment of bed sediment, v_c when 0.10mm $< d_{50} <$ 1mm. However, Equation 5 can be applied to determine the armor peak velocity, v_a when 0.10mm$<0.55d_{90}<$1mm.

$$v_c=0.049+0.053(d_{50})^{1.4}+\{0.066+0.072(d_{50})^{1.4}\}\log(y/d_{50}) \quad [4]$$

$$v_a=0.039+0.018(d_{90})^{1.4}+\{0.052+0.025(d_{90})^{1.4}\}\log(y/d_{90}) \quad [5]$$

where y is approach flow depth, and d_{90} is used in place of $d_{max,}$ which is unlikely to be known (Melville and Coleman 2000).

In this study, laboratory measurement showed that the maximum value of the flow intensity, $[v-(v_a-v_c)]/v_{c,}$ was 0.80, which is less than 1 and confirms that clear-water conditions for nonuniform sediments occurred during the experimental runs. Ota et al. (2017a) mathematically simulated the local scour upstream of a slit weir using an ordinary differential equation and laboratory data for scour holes formed in uniform sediments. In addition, Ota et al. (2017a) recommended researching the influence of sediment nonuniformity on the scour volume and scouring depth upstream of a slit weir. Based on this recommendation, two types of nonuniform sediments were tested in the present study. However, the temporal variation of scour volume, V_s and scour depth, d_s of nonuniform sediments recorded upstream of the slit weir were compared with that of uniform sediments, as shown in Figures 5 and 6. The comparison was made to demonstrate the difference in behavior between uniform and nonuniform sediments, and the temporal scour data (t = 3000 seconds) were taken from Ota et al. (2017a). Since the objective of this study is to compare the data with Ota et al. (2017a), the comparison between the two studies can only be carried out on the scour data up to 3000 seconds. After t = 3000 seconds, the scour volumes and depths occurring in uniform sediments and nonuniform sediments upstream of a slit weir were 20 folds and 4 folds, respectively. The difference between them can be attributed to forming an armor layer within the scour hole of the nonuniform sediments, which did not occur in the scour hole of uniform sediments.

However, previous experimental works on local scour around hydraulic structures indicate that the scour depth tends to decrease with the increase in the nonuniformity of the sediments (Ota et al., 2017a). In addition, Figures 5 and 6 demonstrate the impact of σ_g for uniform and nonuniform sediments on scour volume and scour depth upstream of a slit weir. In the present study, the median size, $d_{50,}$ and geometric standard deviation, $\sigma_{g,}$ for the nonuniform sediments were 0.70 mm and 1.60, respectively, while Ota et al. (2017a) used uniform sediments with d_{50} = 0.77mm and σ_g 1.30. Therefore, a comparison was made between uniform and nonuniform sediments of approximate d_{50}. In addition, the bed shear stress in a scour hole decreases as the scour hole develops over time; this contributes to the expansion in the flow area as the scour develops (Ota et al., 2017a).

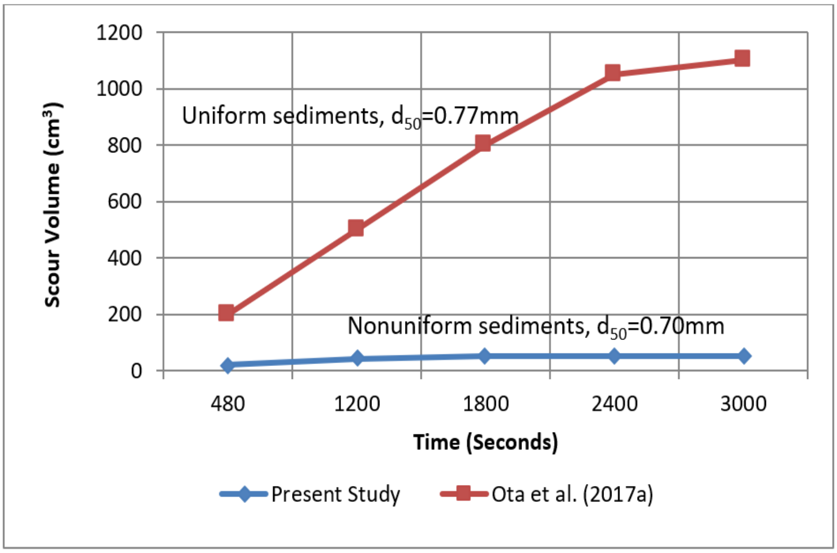


Figure 5. Impact of sediment nonuniformity on scour volume

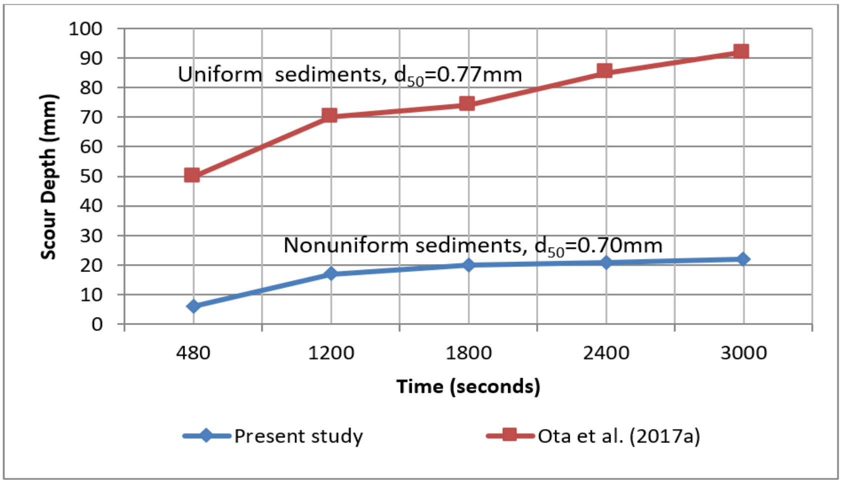


Figure 6. Impact of sediment nonuniformity on scour depth

In this study, it was observed that the increment in scour volume after 300 minutes was not significant, although it is recommended that future studies extend the experimental runs beyond 300 minutes. Figure 7 shows temporal scour data for both types of nonuniform sediments (d_{50} = 0.70 mm and d_{50} = 0.30 mm), slit weir positioned in the center, slit weir crest level, z =1 cm, and Q = 8 l/s. In this study, the coarseness of nonuniform sediments was also investigated. Two sediments were used for this objective; the first sediment had a median size, d_{50} = 0.30 mm, while the second type had d_{50} = 0.70 mm. Table 2 shows the behavior of the nonuniform sediments under low and high discharges. For weir dimensions of 50 mm x 110 mm (slit positioned at the center), z = 0 cm, and the same sediment size, when the discharge increased by three folds, the scour volume increased by 10 folds.

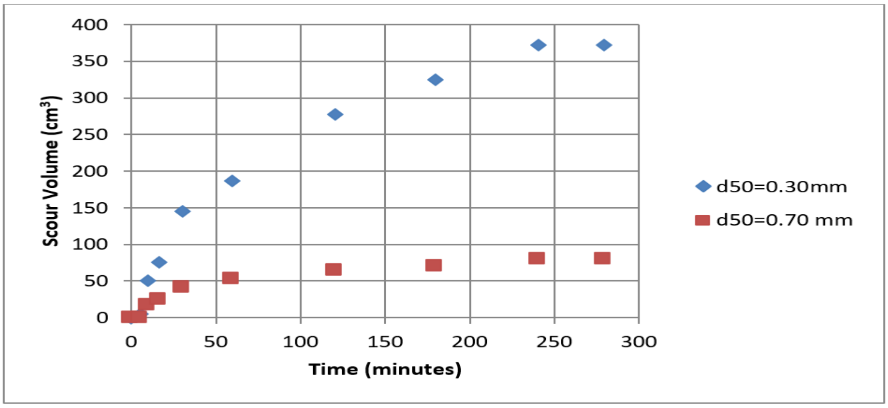


Figure 7. The temporal scour data for Q= 8 l/s, z=1 cm, and weir with slit located in the center

Table 2
The behavior of different sediment sizes used in the working section

Slit location	Discharge (l/s)	d_{50} (mm)	z (mm)	Scour depth (mm)	Scour Volume (mm^3)	Scour Time (hour)
center	2.60 l/s	0.30	0	28	34894	4
center	8 l/s	0.30	0	42	371532	4
center	2.60 l/s	0.70	0	6	1560	4
center	8 l/s	0.70	0	30	16340	4

d_{50} is the median size, and *z* is the weir crest level from the mobile bed

On the contrary, when the sediments in the working section of the flume were changed from d_{50} = 0.30 mm to d_{50} = 0.70mm, the scour volume was reduced by 22 folds. The reduction in the scour volume can be attributed to the armoring layer that develops at the top of the nonuniform sediments and requires greater shear stresses for particles' incipient motion.

However, the incipient motion for nonuniform sediments with d_{50} = 0.70mm requires greater shear stress than that for nonuniform sediments with d_{50} = 0.30mm. All the above laboratory trials were conducted under steady flow conditions. Steady and unsteady flow may be encountered in real-world scenarios. This study demonstrated the time variation of V_s and d_s under steady and unsteady flow conditions for engineering applications. The behavior of the nonuniform sediments under unsteady flow conditions was achieved when the flow rate was increased step-wise from 3 to 5 l/s and decreased in a step-wise manner. This used step-wise procedure matches the procedure used by Ota et al. (2017a) to demonstrate the behavior of uniform sediments under unsteady flow conditions. In addition, the flow ranges and time duration in this study for unsteady flow were similar to that used by Ota et al. (2017a). Figures 8 and 9 show the time-varying flow rate with scouring volume and depth. The peak scour volume was observed at the peak flow rate (5 l/s) and decreased afterward. The scour volume continued to develop after the peak flow rate until it reached a value of 150 cm^3 for the sediments with d_{50} = 0.30mm, while it reached a value of 54 cm^3 for sediment with d_{50} = 0.70mm. For unsteady flow, when the median size of the sediments was changed from 0.30 mm to 0.70 mm, the scour volume was decreased by three folds, while the scour depth was decreased by 60%. However, for the same gradual increment in flow rate (from 3-5 l/s) and time, the scour volume obtained by Ota et al. (2017a) for uniform sediments was approximately 20 folds greater than scour volume occurred in the nonuniform sediments. So, in this study, the behavior of nonuniform and uniform sediments was demonstrated under steady and unsteady flow conditions.

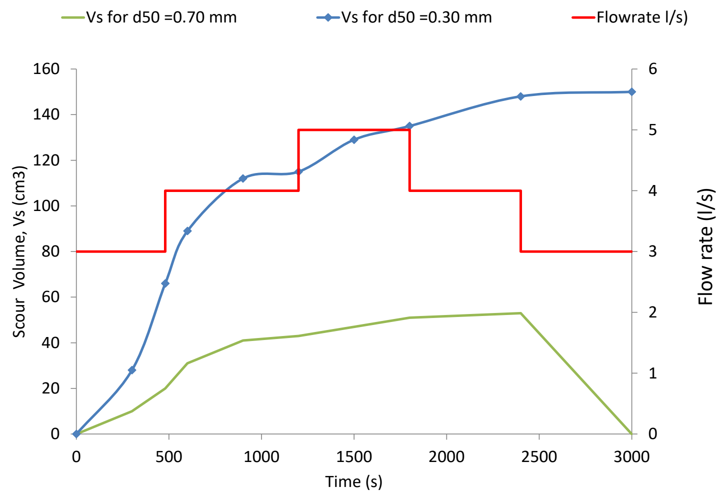


Figure 8. Temporal variation of scouring volume under stepwise unsteady flow

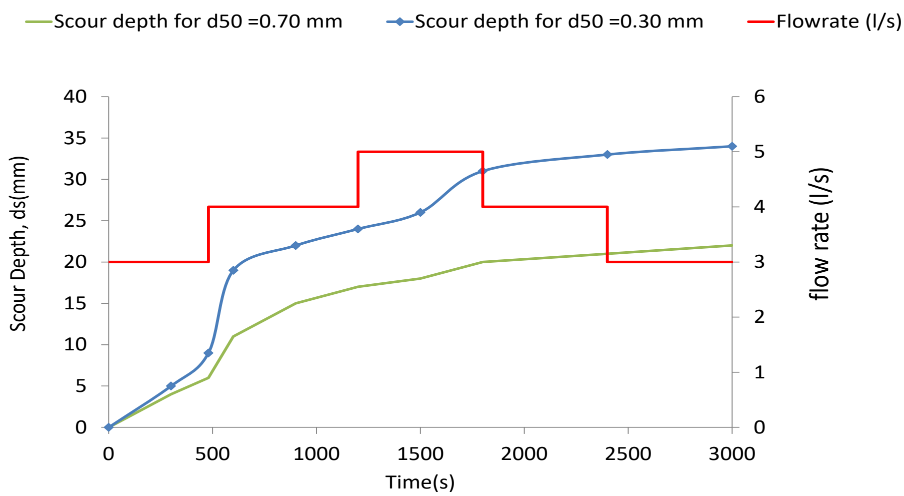


Figure 9. Temporal variation of scour depth under stepwise unsteady flow

Ota et al. (2017a) proposed Equation 1 based on multi regression analysis by considering the geometric features of the scour hole formed upstream of the slit weir for different flows and noncohesive uniform sediments. In addition, they recommend applying Equation 1 without calibration for uniform sediment when $0.10b_{sl}/B<0.40$, $q_{sl}/q<8.70$, and $v/v_c<1$, where b_{sl} is the width of the weir notch, B is the channel width, q_{sl} is the flow rate passing through the slit per unit slit width and q is the flow rate per unit width of the channel.

In this study, although the sediment used was nonuniform but values of $b_{sl}/B = 0.20$, $q_{sl}/q=5$, and $[v-(v_a-v_c)]/v_c<1$, the slope between V_s and d_s was found to be approximately equal to 3 (Figure 10). The maximum scour depth for the flow conditions of the present study were predicted using Equation 1, and the results were compared with the measured values, as shown in Figure 11. The accuracy of the prediction was tested using the coefficient of determination, R^2, and the model efficiency, ME, which is described by the following Equation 6:

$$ME=1-[\sum)d_{s,e}-d_{s,p})^2/(d_{s,e}-d_{s,a})^2\ ] \quad [6]$$

where the $d_{s,e}$ is the measured experimental maximum scour depth for n experiments, $d_{s,p}$ is the predicted scour depth for n number of cases, d_{sa} is the mean of measured scours depth for n number of experiments. The value of R^2 between d_{se} and d_{sp} was found to be 0.87, reflecting the accuracy of the prediction since it is closer to 1. In statistics, ME compares calculated values with measured values to indicate the model prediction accuracy or efficiency. A value of 1 means a perfect fit between measured and predicted data, and this value can be negative. The ME value was calculated and found to be 0.87, which confirms the efficiency of Equation 1.

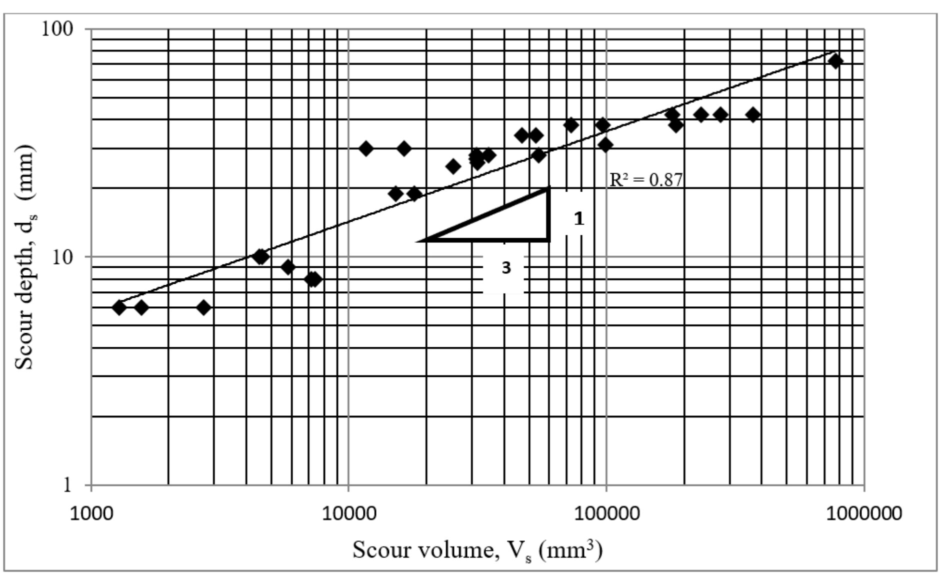


Figure 10. Relationship between maximum scour depth and scour volume for nonuniform sediments

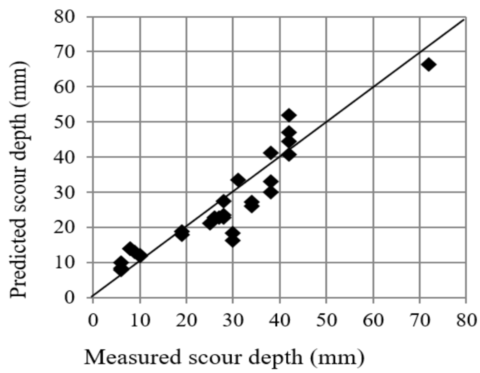


Figure 11. Validation of Equation 1

In addition, Ota et al. (2017a) recommended the application of Equation 1 for uniform sediments only; however, the authors of this study recommend the application of Equation 1 for nonuniform sediments as well the impact of slit weir crest level from the mobile bed upstream, z and the location of the slit weir in the flume on scouring volume were investigated. The temporal variation of scouring volume was monitored for slit weirs with fixed width (b_{sl} = 6 cm) and different crest levels (z = 0, 1, 2, 3, and 4cm) or different slit heights, h_{sl} (h_{sl} = 11, 10, 9, 8 and 7cm). The maximum scours volume was recorded in a slit weir with crest level, *z* = 0cm or h_{sl} = 11cm (i.e., the crest was at the same level of the mobile bed before the commencement of scouring) and for maximum flow intensity. Figure 12 shows the recorded scour volume after 2 and 4 hours from the commencement of the scour for a flow rate of 8 l/s and different slit weir crest levels. In addition, the maximum scour depth for the scour hole resulted from using slit weirs with different crest levels or different slit height was recorded, and the results are shown in Figure 13. For nonuniform sediments with a median size of 0.30mm, it was observed that the crest level or slit height influenced the size of the scour hole and scour depth. The maximum volume of scour occurred when the crest level, z, was 0 cm from the mobile bed (when h_{sl} = 11cm). Therefore, the efficiency of sediment removal from the mobile bed was greatly affected by the location of the slit weir (at the side or the center), crest weir level, z or slit height, h_{sl}. From the present study results, it can be concluded that the maximum efficiency of the slit weir in sediment removal was obtained when the slit weir is positioned at the center and when the weir crest level is minimum (z = 0 cm).

When the flowing water impinges the right and left wings of the slit weir, a flow vortex develops near the slit weir and causes a circulating flow. Later, the circulating flow caused the sediment particles to entrain into suspension, and the flowing water carried the sediments through the weir notch or slit. At the initial stage, two small scour holes were formed on the left and right of the slit, and with time, the scour holes grew, as shown in Figure 14(a). Finally, the scour holes extended and merged with time to form one larger scour hole, as shown in Figure 14(b). The scour hole reached its maximum volume when the sediment entrained within the scour hole decreased as the scour developed temporally. It can be explained by the increase in flow area and hence a reduction in shear stress. The above explanation of the scour mechanism is based on continuous observation throughout the laboratory work.

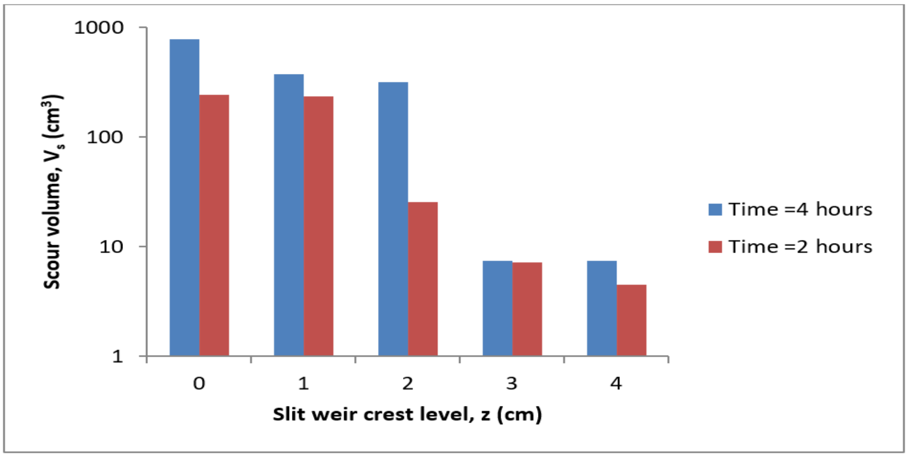


Figure 12. Variation of scour volume with slit weir crest level for a flow rate of 8 l/s and sediment size of 0.30mm

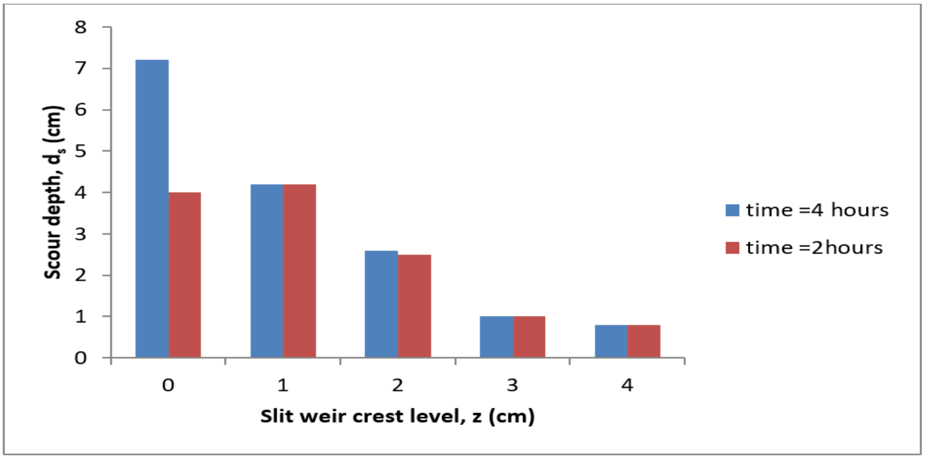
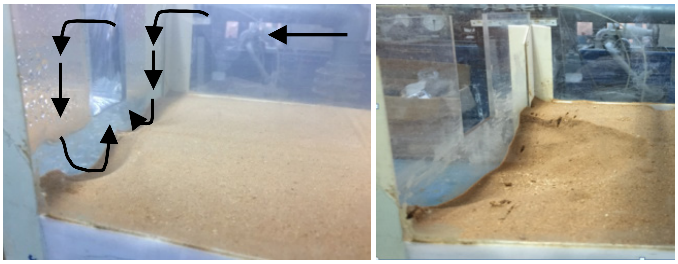


Figure 13. Variation of maximum scour depth with slit weir crest level for a flow rate of 8 l/s and sediment size of 0.30mm



(a) (b)

Figure 14. The mechanism of scour hole development upstream of slit weir; (a) The formation of two holes; (b) the final resulting hole

Ota et al. (2017a) also observed the above-described phenomena. The circulating flows were stretched by the contracting flow, accompanied by the overfalling nappe. As a result, the bed shear stresses were amplified around the weir; hence, the occurrence of local scour at the weir site. In this case, vortices caused more sediments entrainment, and these sediments passed over the slit weir downstream. However, when the crest was at a higher level from the flume bed, fewer sediment particles crossed over the slit weir downstream. It is because sediment particles require strong vortices to overcome the effect of gravity to be entrained and carried by the flowing water through the slit weir. Figure 15 illustrates how the flow intensity was affected by the crest level of the slit weir, which is presented in dimensionless form, z/b_{sl} (z is the vertical distance between the slit weir crest and the mobile bed while b_{sl} is the width of the slit weir). Figure 16 shows a sample of contours for scour holes measured after 2 hours and 4 hours from the commencement of the experiments for slits weirs with z =1cm, Q = 8 l/s and slit positioned in the center and the side of the channel. For example, when a slit weir with a dimension of 60 mm x 100 mm (z=1 cm) was positioned in the center of the flume, the scour volume in the working section with sediments of d_{50} = 0.30mm after 4 hours was found to be approximately 6.80 folds greater than the scour occurring in a slit weir with the same conditions but with the weir slit positioned in the side of the flume.

In open channel flow, the maximum velocity occurs in the center of the channel in both longitudinal and transverse sections, while the minimum velocity occurs to the sides of the open channel. Therefore, it justifies why the maximum scour volume was observed when the slit of the weir was positioned within the center of the channel. In this study, it was observed that when the weir's slit was positioned near the side of the flume, the formed vortices were weaker, which generated a smaller scour hole. Reservoir sedimentation endangers the sustainability of all types of hydropower plants located in impoundments and/or rivers. For impoundment hydropower plants, sedimentation of reservoirs is causing various issues such as increasing flood risk of infrastructure and decreasing the active water capacity of reservoirs, leading to a loss of power generation. Many hydropower reservoirs worldwide exhibit sedimentation issues and the loss of power generation associated with it.

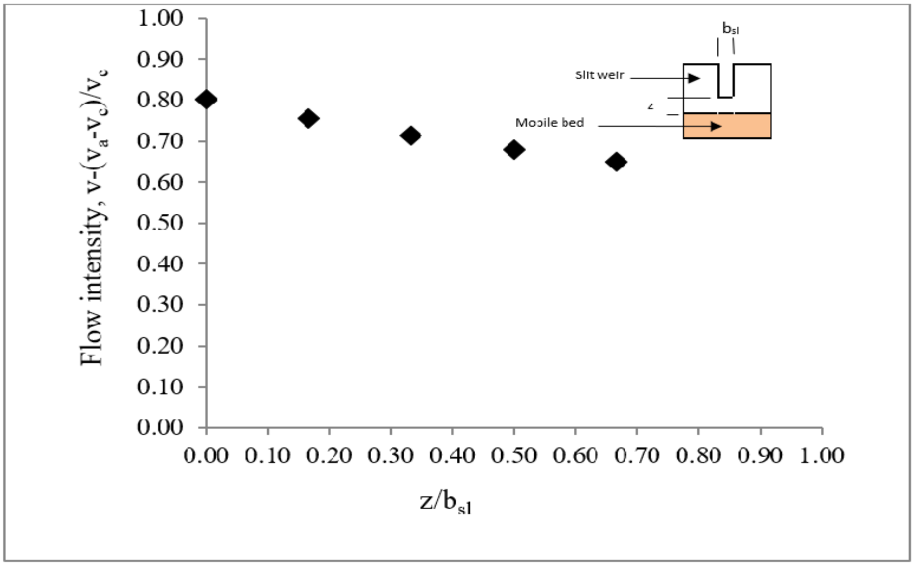


Figure 15. Variation of flow intensities with slit weir crest level for nonuniform sediment with d_{50}=0.30mm

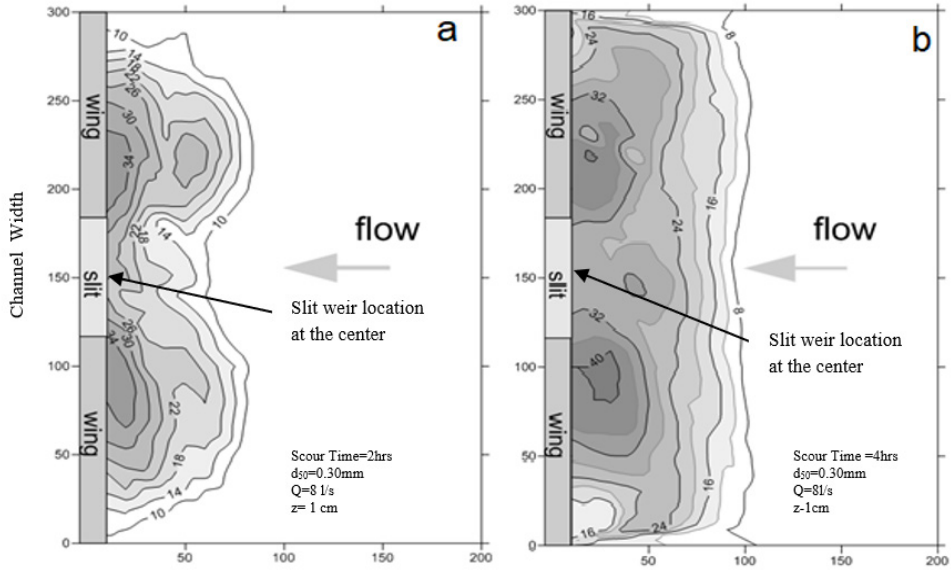


Figure 16. Contours of scour holes for different weir notch locations

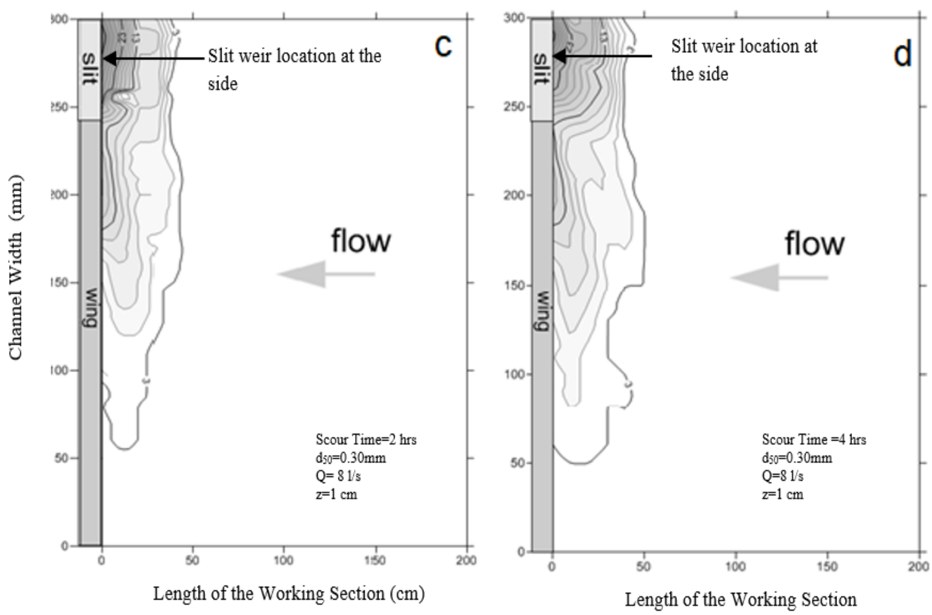


Figure 16. (Continue)

According to Okumura and Sumi (2012), reservoirs of hydropower plants in Japan were affected by increasing sedimentation and flood risk. Boroujeni (2012) estimated the volume of sediments accumulation in the Dez Dam hydropower reservoir, Iran, for 50 years, and it was estimated at approximately 840 million cubic meters (million m^3). Kamarudin et al. (2018) discussed the sedimentation problem in the lake of Kenyir dam, Terengganu, Malaysia, which affected the production of the Sultan Muhmud hydroelectric power station. Reisenbüchler et al. (2020) warned that the run of a river hydropower plant located on the Saalach River in southeastern Germany was subjected to sedimentation. Given the above issues, the results of this study can be used by design engineers, project operators, and other stakeholders doing business in hydropower production. Using a slit weir to cause scouring upstream in or around a hydropower intake is a sustainable method for sedimentation management. The results of scouring depth upstream of the slit weir can be used in the design of the weir floor. On the one hand, fine sediments are causing erosion of turbine blades, and this can be mitigated by conveying more fine sediments from upstream to downstream by utilizing structures such as a slit weir.

CONCLUSION

In this study, a 2 m working section with a mobile bed and Plexiglass slit weir models have been arranged in a glass-sided tilting flume (12 m in length, 0.30 m in width, and 0.30 m deep) to be used for investigating the impact of sediment nonuniformity, slit weir crest level, slit weir location, and flow intensity on the scour volume upstream of the slit weir location. Nonuniform sediments with median diameters of 0.30 mm and 0.70 mm were tested. For a discharge of 8 l/s, the scour volume upstream of the weir with the slit at the center was reduced by 22 folds when the median size of sediments in the working section, $d_{50,}$ was increased from 0.30mm to 0.70mm. In addition, the temporal variation of scours volume was monitored and compared with the published data of uniform sediments (d_{50} = 0.77mm) with similar flow conditions. Comparisons show that the scour volume and maximum scour depth in uniform sediments of d_{50} = 0.77 mm were 20 folds and 4 folds, respectively, greater than those used in this study in nonuniform sediments with a d_{50} = 0.7mm.

In addition, the experimental results revealed that the scour volume was affected significantly by the level and location of the weir's slit. For the same flow conditions, slit level from the mobile bed, z, and sediment median size, d_{50}, the scour volume was much higher when the slit of the weir was positioned at the center than that position at the side. For Q = 8 l/s, z = 1 cm, and d_{50} = 0.30 mm, the scour volume was 14 folds greater when the slit was positioned at the center compared to a slit position at the side. The strength of the formed vortices is affected by slit location, which eventually affects the size of the scour hole. Therefore, maximum efficiency of the slit weir in removing sediments can be obtained when the slit weir is positioned in the center of the flume in conjunction with the weir crest level is at the same level as the mobile bed before the commencement of the scouring phenomena (z = 0 cm).

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