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Impact of Outlet Configuration on Scour at Upstream of Cross River Structure: An Experimental Study

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ABSTRACT

This study is important since it investigates the effectiveness of sediment removal near hydropower intake by flushing. The method can replace the current expensive method for sediment removal by dredging. The sediment transport mechanism, maximum scour depth, volume, and scour area at the upstream of a cross-river structure model with different outlet configurations were investigated. The investigation included a series of experiments conducted in a laboratory on a 12-meter-long, 0.30-meter-wide, and 0.45-meter-deep flume. The shapes of the model outlets were circular, semicircular, and a three-quarter circle of the same diameter (D=11 cm). The cross-river structure was installed at the end of a 2 m working section with uniform sediment of median size(d_{50}) of 0.23 mm and geometrical standard deviation (σ_g) of 1.29. The total depth of the sediment in the working section was 10 cm. The collected data showed that the maximum scour volume was 1194.98 cm^3 with the circular outlet, while with semicircular and three-quarter circle outlets was found to be 613.48 cm^3 and 640.136 cm^3, respectively. Compared with the scour volume upstream of the circular outlet (D=11cm), results showed that the scour volumes were reduced by 48.6% and 46.4% for outlets with a semicircle and three-quarter circle, respectively.

Keywords: Discharge outlet, Sediment type, Scour upstream, Configuration outlet, Scour hole dimension.

1. INTRODUCTION

The growing trend in using hydropower necessitates a deeper understanding of the associated problem. One of the main challenges is the sediment accumulation near the hydropower intake. Accumulation of sediment in the vicinity of the intake of a turbine causes a reduction in production, economic loss, damage to turbine blades, and environmental concerns. Dam reservoir sedimentation impairs water storage **(Zakwan et al., 2018).**

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Runoff that carries eroded materials from river basins is the main source of sedimentation in reservoirs **(AL-Thamriy and AbdulAzeez, 2017).** The morphology and sediment transport of selected rivers were studied by using HEC-RAS software. Hydrological and topographical data for the selected rivers were used in the model, calibrated, validated, and applied **(Jassam and Abed, 2021; Abduljaleel et al., 2016; Daham and Abed, 2020)**. Traditional sediment removal by dredging is costly and disrupts turbine operation. However, sediment removal by hydro suction through a circular gated outlet located near the turbine outlet in the dam body is considered another method with a lower operating cost. However, the new proposed method for sediment removal requires further investigations to check the effectiveness of the method and to understand temporal variations in scour volume. **(Powell, 2007; Powell and Khan, 2011; Powell and Khan, 2012)** Conducted an experimental study to investigate the sediment transport mechanism and the factors affecting the formation of the scour hole upstream of a circular orifice, where water depth, particle size, and sediment uniformity significantly affect the depth, length, and width of the zone affected by scour. **(Zhang et al., 2020)** studied and investigated how various orifice sizes and shapes can influence the amount of sediment removed near the hydropower intakes. The study found that modifying the flow patterns around the intake structure, and the Elliptical orifices with sharp edges, helped reduce sediment deposition, The test showed that modifying the geometrical shapes of the orifices is important in controlling the sediment. **(Herbst et al., 2018)** conducted a lab-based experiment by creating a physical model to investigate the self-cleaning process in rectangular and trapezoidal labyrinth wires using four types of sediments. The examination was conducted on different flow intensities and conditions, This test demonstrated that sediment transport in trapezoidal-type weirs needs less discharge. The experiment also showed that the Froude number plays an important role in the process of sediment transport. **(Hajikandi et al., 2018)** used (circular & square) orifices, using the same area, then the formed upstream scour holes formed dimensions were compared with each other. The test showed that the shape of the scours was elliptical for both the square and the circular orifices. The study also showed that the depth and the area of the square-shaped orifices are larger than those of the circular orifices. **(Lauchlan, 2004)** performed a series of tests to simulate the transport and bed load sediments. The tests showed that two vortices were formed, one upstream of the vertical wall weir, creating a scour zone, and another vortex was formed below the weir, creating a sedimentation zone. **(Nagata et al., 2005)** Created a computer model to replicate the flow and scour dynamics at the hydraulic structure of the river. The model successfully addressed the whole three-dimensional Reynolds-averaged Navier-Stokes equation. A nonlinear turbulence model (k-ω) was used to forecast the flow around the structure, and the findings demonstrated convergence between the numerical and experimental data. **(Dreyer and Basson, 2018)** Conducted a series of experiments to investigate the effect of the shape of low-level outlets in hydropower dams on the dimensions of the formed upstream scour hole. A physical model was used, in addition to four different shapes of low-level outlets, three levels of nonuniform sediment, and three water levels. The results showed that the size of the scour hole increases with increasing discharge and sediment levels for all tested outlet shapes. Dreyer and Basson were able to develop a dimensionless equation to predict the size and dimensions of the scour hole. **(Abdollahpour et al., 2017)** performed an experimental investigation to examine the influence of w-weir geometry on a sinusoidal channel with curvature regarding the kind and amount of scour under varying hydraulic conditions. The investigation elicited findings about the design of the weir structure. **(Mohamed and Abdelhaleem, 2020)** studied the effect of the circular orifice utilized with sluice gates for energy dissipation in the downstream of the gates. The study showed that adding an orifice to the sluice gate reduced the hydraulic jump energy and reduced the downstream erosion, compared to traditional sluice gates. **(Beyvazpour et al., 2021)** observed that placing a pile upstream of the orifice affects the size of the scour cone, which in turn improves the cleaning efficiency. Five different pile shapes were tested at multiple distances from the orifice. The tests showed that a corner-on triangular pile increased the cleaning cone, also placing the pile closer to the orifice gave better results. **(Hajiahmadi et al., 2021)** Conducted an experimental study on orifices' effect on the efficiency of curved submerged vanes in removing sediments from the vortex settling basin. This study showed that vane performance is largely influenced by the orifice size, and arranging the vanes also played a role in improving the performance. **(Ghosh et al., 2021)** developed a sediment transport model based on the HEC-RAS software, and using real data, the model demonstrated its ability to predict the amount of erosion and sedimentation that occurs due to hydraulic structures. Experiments were carried out in two stages using a rectangular tank containing a large orifice **(Madadi et al., 2016**). First, it verified the flow behavior upstream of the orifice during the development of the scour. Then, a semi-confined structure was used in the area above the orifice to enhance the scouring process and verify the effect of the structure's geometric dimensions on the scour. The results showed the formation of strong vortices that led to an increase in the volume of scour. **(Madadi et al., 2017)** Conducted an experimental study to increase the efficiency of sediment removal from tanks using a semicircular structure with a prominent upper edge where the structure is connected to the tank outlet. The results showed an increase in the area and volume of the flushing cone formed towards the source. **(Moridi and Yazdi, 2017)** developed two numerical models to predict the amount of suspended sediments for the river and reservoir system, and based on the amount of suspended sediments and the flow density in the dry and wet seasons, they proposed flushing scenarios with minimal environmental impacts. **(Nakd et al., 2022; Hamdan et al., 2022**) conducted a series of experiments using a laboratory channel and a slit weir with different slit locations and heights and two types of sediments. A series of experiments were conducted to study the effect of changing slot location and dimensions, regularity, and roughness of sediments, and flow intensity on the dimensions of the scour hole formed upstream of the slit weir under steady and unsteady flow conditions. **(Ota and Sato, 2015)** developed an advanced computational model to replicate sediment movement over a slit weir. This model mimics fluid dynamics and sediment transport using the Reynolds-averaged Navier-Stokes equations, the interaction between water and sediment, and turbulence in water via the k-ω closure relation. **(Zhang et al., 2016)** used the aforementioned model to forecast scour depth under a pipeline, while **(Ota et al., 2016)** enhanced it for the analysis of three-dimensional sediment transport, namely the transitions of rolling bed load into suspension within the water column. **(Ota et al., 2017a)** constructed a model grounded in a nonlinear ordinary differential equation (ODE) to compute the temporal fluctuations of scour volume and maximum scour depth under both steady and turbulent flow conditions upstream of a slit weir. Subsequently, the model underwent further adjustments by **(Ota et al., 2017b).** Moreover, **(Taha et al., 2020)** used the commercial program FLOW 3D to investigate sediment removal in a cleaning hole under steady flow conditions. **(Suleiman and Ismael, 2021)** experimentally investigated to predict the erosion depth formed downstream of single-step inclined dams using a laboratory channel, and four models of inclined dams. Through the results of the experiments, the researchers were able to determine the best type of tested dams. **(Majeed et al., 2021)** applied computational fluid dynamics (CFD), including the turbulent (k-ω) model, to investigate the sedimentation problems due to improper operation of gates in a selected hydraulic structure. They concluded that the scouring depth and the amount of sediment removal increased directly with the Froude number. **(Abed and Azzubaidi, 2020)** studied the impact of variation in velocity distribution on sediment process and bed topography in the reservoir of Mandali Dam.

In summary, the studies covered in the literature were experimental, numerical, and statistical. Each study has contributed to the understanding of how sediment behaves under various hydraulic conditions, and this can help in the design and maintenance of hydraulic structures. The review of the published literature showed that the experimental studies on sediment removal by scouring near a hydropower intake were limited, and the findings of the published studies highlighted the need for more experimental studies. In this study, extensive experimental work was conducted to investigate the impact of discharge outlet configuration on the volume of the removed sediment from the area near the hydropower intake.

2. THE LABORATORY WORK

The experimental work included sediment preparations, describing the apparatus used in this study, and testing the effect of variables.

2.1 The Flume

A glass-sided flume that was 0.30 meters wide, 12 meters long, and 0.45 meters deep was used for different cases of outlet configurations. The flume is situated in the Ministry of Water Resources' hydraulics lab in Iraq. The design of the flume was altered to incorporate a working section of 2m long and 0.3m wide that was conducted in the flume and filled to a depth of 10 cm with sediments. At the entrance of the working section, a ramp was installed to ensure a smooth flow transition from the original bed of the flume to the mobile bed in the working section, the types of flows in the flume were determined according to the Froude number and approach velocity measurement, where all flows were steady and subcritical. **Figs. 1(A)** and **(B)** show the flume and the arrangement of the working section in the flume.

(A) **(B)**

Figure 1. (A) Laboratory Flume and (B) The arrangement of the Working Section in the Laboratory.

In this study, a propeller velocity flowmeter was used to measure velocities at specific sections upstream of the discharge outlet. The velocity range measured by the device is 25 to 1500 mm/s **(Ghazal et al., 2015).** A point gauge with an accuracy of ±1 mm was used to measure the area and depth of the resultant scour, as well as the water depth. After each experiment, the sediment loss resulting from scour was compensated for, and the surface and prepared for operation for the next experiment.

2.2 The Model Outlets

A model outlet wall constructed from 4 mm-thick Plexiglas was put at the end of the working section, sealed to prevent leaking from the bottom and sides, and positioned six meters from the channel entry. Three opening shapes (circle, semicircle, three-quarter circle) were tested. **Fig. 2** shows the dimensions and shapes of the opening used in this study. While **Fig. 3** shows the arrangement inside the laboratory flume.

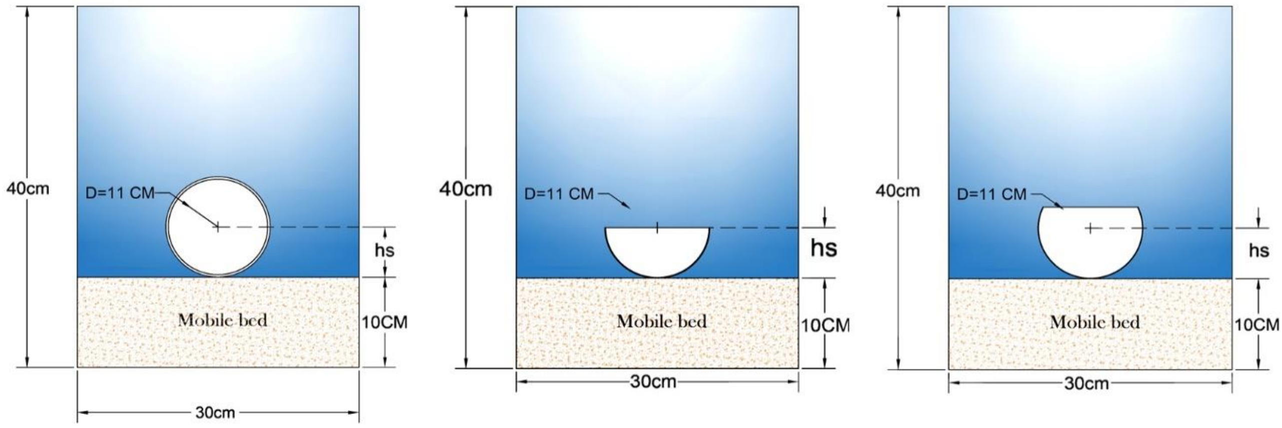

Figure 2. The shapes, locations, and dimensions of the model structure used in this study.

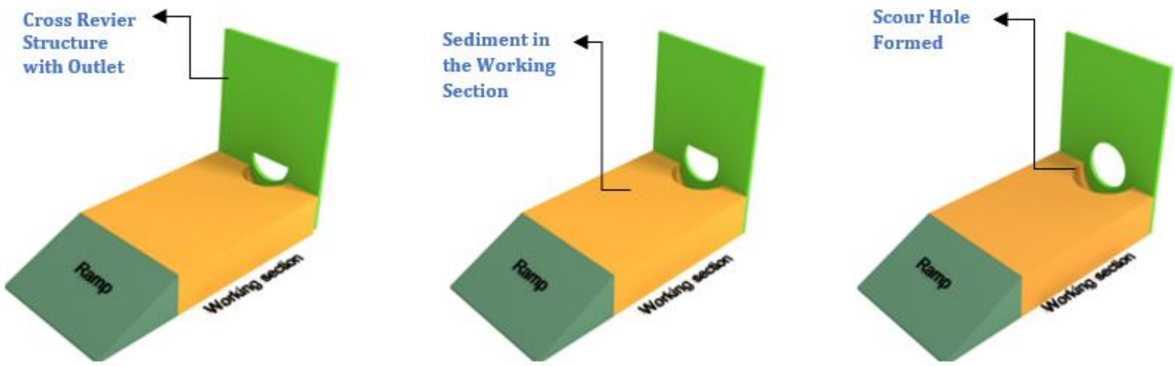

Figure 3. The position of the model outlets, the working section, and the ramp is arranged in the flume.

2.3 Sediment Properties Used in the Experiments

The sand of varying grades was mixed to create the homogeneous sediment used in the working section of the flume in this investigation. Sieve analysis was used to determine the sizes and distribution of finer particles within the uniform sediments, as seen in **Fig. 4**. The homogeneous sediment with a median size of d_{50} = 0.23mm up to 10 cm filled the working portion. It was determined that the geometric standard deviation, or σg, for uniform sediment was 1.29. According to **(Melville and Coleman, 2000),** the geometric standard deviation for homogeneous sediments should be smaller than 1.30. The value of this standard deviation was calculated using Equation (1).

$$Cap\ Sigma\sigma g = \sqrt{\frac{d84}{d16}} \tag{1}$$

The grading curve was used to determine the sizes of sediments with diameters of d_{84} and d_{16}. The values of them are 0.28 and 0.17, respectively.

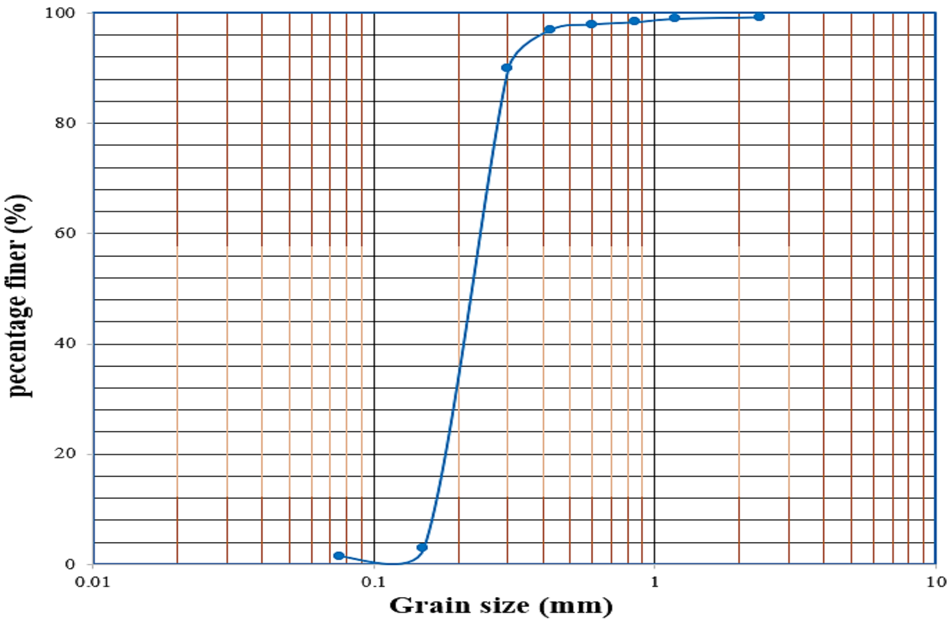

Figure 4. Uniform Bed Material Grain Size Distribution Curve σg=1.29.

2.4 Equations Governing the Flow Intensity (v/vc) of Sediment

When the flow that causes the scour does not replenish the sediment in the scour hole, clear-water scour takes place, there was a clear-water scour condition where the flow-induced shear stress did not surpass the critical shear stress needed for the bed material to begin moving and the velocity (v) was below the critical velocity (vc). For uniform sediment, **(Melville and Coleman, 2000)** defined the clear water scour as when the flow intensity should be $v/v_c < 1$ with $\sigma_g < 1.3$. **(Melville, 1997)** presented the critical velocity for uniform sediments using Eqs (2) and (3) based on the Shields (1936) figure for quartz sand in water at 20°C. This study's flow intensity (v/v_c) was determined to be 0.322. The experiments were conducted under clear water scour conditions.

$$\frac{v_c}{u_c} = 5.75 \log\left(5.53 \frac{y}{d_{50}}\right) \qquad \text{for } 0.1\text{mm} < d_{50} < 1\text{mm} \tag{2}$$

$$u_c = 0.0115 + 0.0125\,(d_{50})^{1.4} \qquad \text{for } 0.1\text{mm} < d_{50} < 1\text{mm} \tag{3}$$

Where v is approach velocity(m/s), v_c is the critical velocity (cm/s), σg is geometrical standard deviation, y: is the flow depth (m), d_{50} is the median grain size (mm), and u_c: is the critical shear velocity (m/s).

2. 5 Experimental Procedures

1. After the working section was filled with uniform sand at a depth of 10 cm.
2. To ensure smooth transmission from the flume bed to the working section, A ramp was utilized that had a 1:10 slope.
3. Before each operation, the working section is flooded to expel water bubbles and saturate the sand.
4. Different discharge outlet shapes were studied to verify their effect on the scour hole dimensions.
5. Using a propeller Velocity Flowmeter to measure the velocity upstream of the discharge outlet for each model, **Fig. 7**.
6. The scour depth is monitored in the scour-affected area upstream of the discharge outlet, where the depth is measured by using a point gauge.
7. When the maximum scour depth is reached, the experiment is terminated, which took 7 hours from the start of operation. Almost 80-90% of the scour hole is formed between 6-8 hours after the commencement of the experiments (**Rasool et al.,2024; Rasool and Mohamed, 2023)**
8. The coordinates of the scour hole (x, y, z) are taken after dividing the scour area into squares using a point gauge, and then the coordinates are exported to the Surfer program to draw the scour contour line and calculate the volume and area of the scour hole. **Fig.9** shows the scour hole topography resulting from using the scour hole coordinates as input data for the Surfer program.
9. The sand lost due to scour is replaced, and the surface is leveled before starting the second experiment.

3. RESULTS AND ANALYSES

3.1 Impact of the Shape of the Discharge Outlet on Scour Volume, Maximum Scour Depth, and Scour Area

To demonstrate the effect of the study variables on the scour volume, depth, and area, different shapes of discharge outlets (circle, semicircle, three-quarter circle, with the same diameter of 11 cm) were investigated under a discharge value (Q=6.3 l/s) for uniform sand, as shown in **Figs. 5 and 6.**

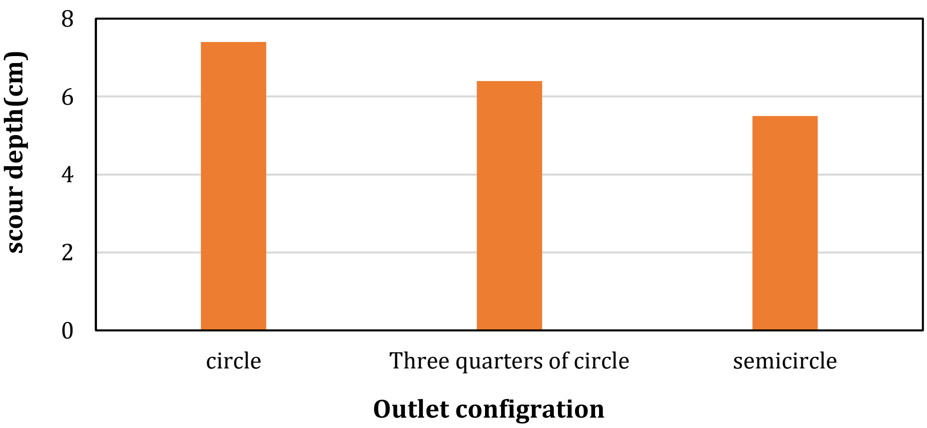

Figure 5. Impact of Outlet Configurations on Maximum Scour Depth (cm)

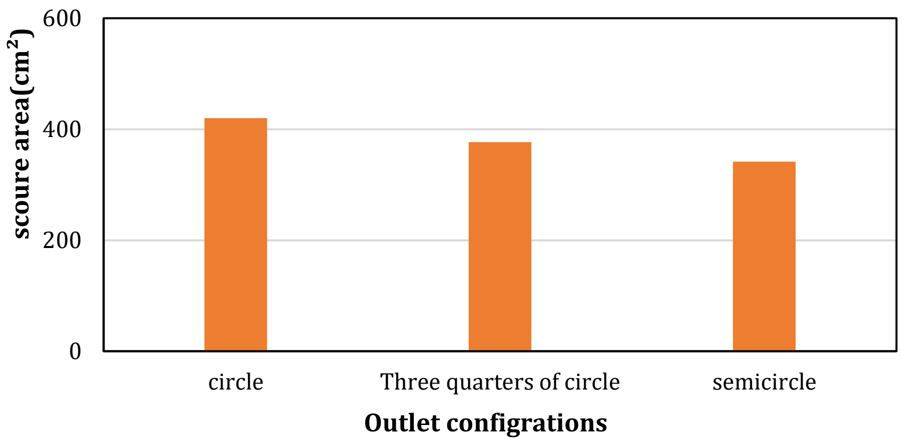

Figure 6. Impact of Outlet Configurations on Scour Area (cm^2).

The effect of the shape of the discharge outlet was analyzed by comparing the dimensions of the associated scour hole. Larger volume, depth, and area were considered better because this meant greater scour and efficiency. The formation of two vortices near the discharge outlet was the reason for the development of the scour hole **Fig. 8c.** The circular outlet performed better because it gave the largest scour hole. However, the results showed a certain decrease in the depth, volume, and area of the resulting scour with the change in the outlet shape. **Fig. 8** shows the mobile bed shape before and after the formation of the scour hole. All laboratory experiments were conducted under constant flow.

From **Table 1**, it was clear that changing the shape of the outlet from circular to semicircular and three-quarter circle had a certain effect on the resulting values of scour depth, volume, and scour area with similar flow regimes and initial and boundary conditions. The highest value of scour volume was observed in this study at 1194.985 cm^3 using the circular outlet, and these values decreased to 613.48 cm^3 and 640.136 cm^3 for the semicircular and three-quarter circle, respectively. There was also a decrease in the scour depth and area, but the decrease in them was less compared to the decrease in the erosion volume. Changing the shape of the outlet caused a decrease in the value of the sediment released above the outlet. It was observed from the experiments that the outlet area is related to the formation of vortices and their sediment-carrying capacity.

Table 1. Scour Hole Dimension (Scour Volume, Scour Depth, Scour Area) for Outlet Configuration.

No.	Outlet Configuration	Uniform sediment		
		Scour volume(cm^3)	Scour depth(cm)	Scour area(cm^2)
1	circle A=94.9 cm^2	1194.98	7.4	420
2	Three-quarters of a circle A=71.2 cm^2	640.136	6.4	367.97
3	semicircle A =47.4 cm^2	613.48	5.5	341.38

Fig. 7 shows the velocity distribution in the area upstream of the discharge outlet for the three shapes (circle, semicircle, and three-quarter circle) where the velocity was measured on specific sections starting from the entrance of the working section towards the discharge outlet and the last section was 10 cm upstream the outlet (same sections for the three shapes). The flow near the discharge outlet is high due to the high value of shear stress because the repetition of the maximum velocity is in the center of the open flow and results

in turbulent and high kinetic energy leading to the generation of vortices upstream of the discharge outlet and these vortices work to lift the sediments and release them with the main flow and cauterize the scour hole and the dimensions of the scour hole increase with the increase in flow velocity and the formation of vortices which are related to the area of the outlet, this explains why the largest scour hole dimension occurs when using the full circular.

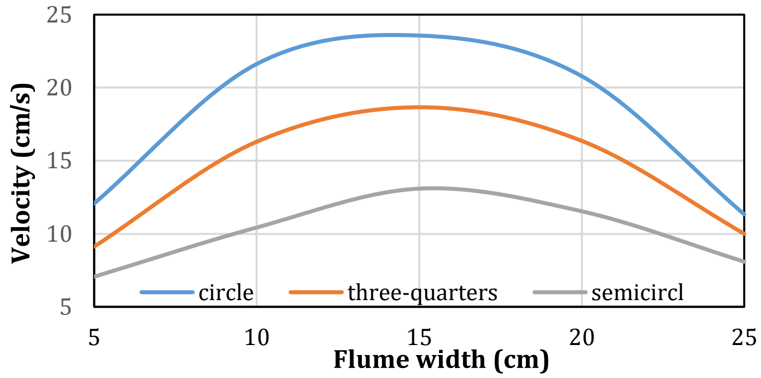

Figure 7. Velocity Distribution at 10 cm Upstream of the Different Outlet Configurations.

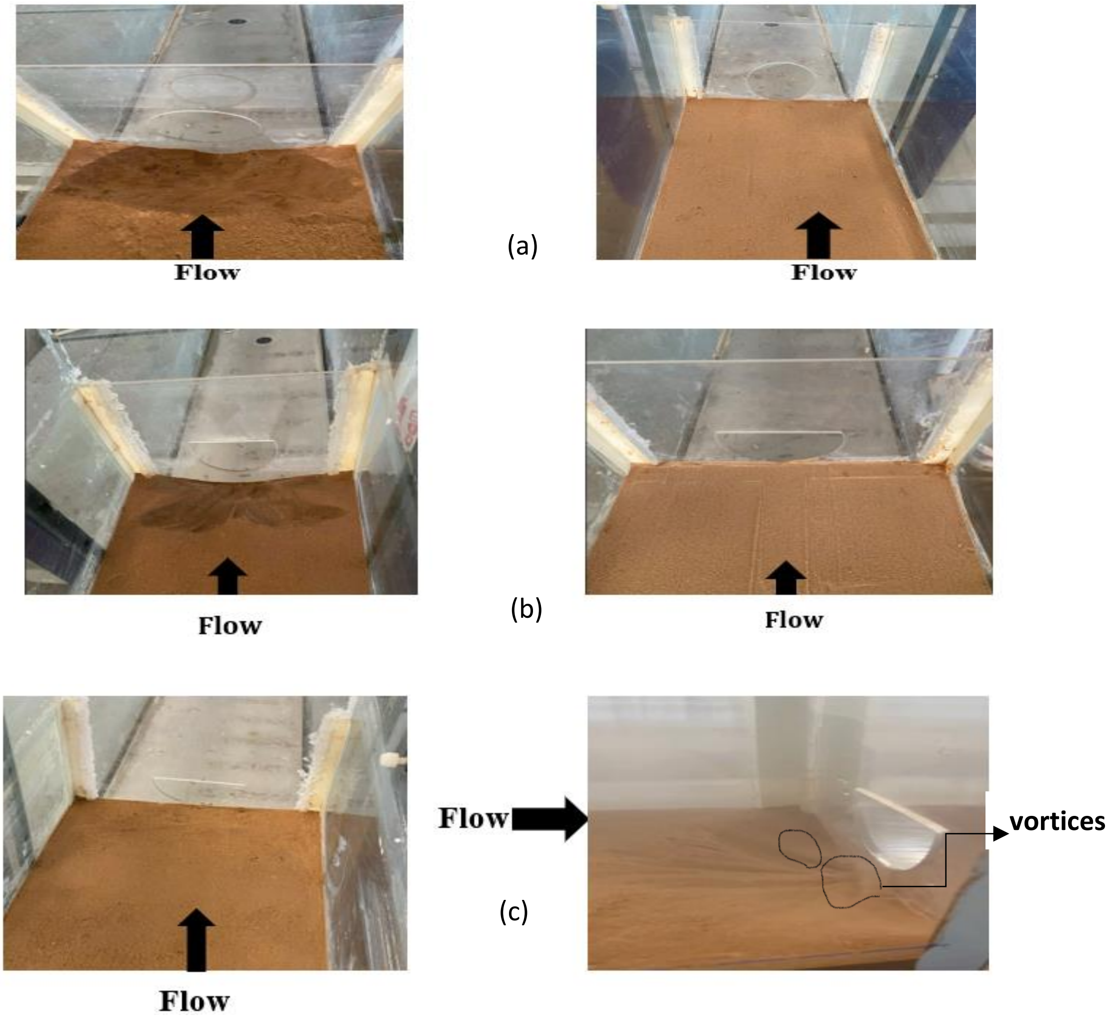

Figure 8. The mobile bed before and after Scour Hole Formation (a) Circular (b) Three-quarters of a circle (c) semicircle

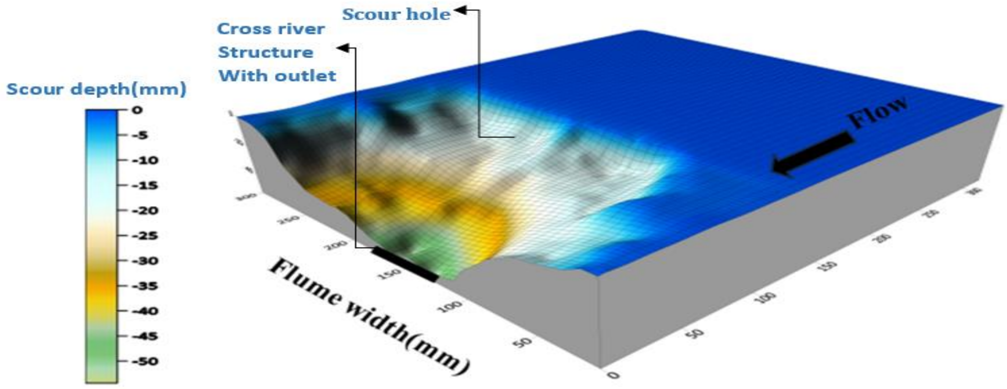

Figure 9. 3D Scour Hole Formed Upstream of the Outlet.

5. CONCLUSIONS

In this study, experiments were conducted to investigate how the shape of the outlet in the cross-river structure and the discharge affect the size of the scour hole formed upstream. The main objective of the study is to demonstrate the effectiveness of an outlet in the cross-river structure in removing sediment accumulation in the vicinity of the hydropower intake. From the analysis of the experimental data on scour volume, scour area, and maximum scour depth, the following conclusions can be drawn:

1- For fixed discharge through outlets of different sizes, it is found that the scour volume is proportional to the outlet size. When the discharge was 6.3 l/s, the scour volume upstream of the cross-river structure with the outlet of the semicircular area was about 51% of that formed when the outsize was a full circle with the same diameter. However, the increase was found to be marginal (2.35%) when the outlet size increased from a semicircle to a three-quarters circle.

2- Concerning the scour area, it was found that the outlet with a semicircular opening resulted in a scour area equivalent to 81.28% compared with that resulting when the outlet of a full circle opening was used. However, the scour area resulting from using a quarter outlet opening was 89.75%.

3- The scour depths at the upstream of the cross-river structure for the same above outlet openings were found to be 74.32% and 86.5% for semicircle and three-quarter circle, respectively.

NOMENCLATURE

Symbol	Description	Symbol	Description
d_{50}	Median size of sediment.	m^3	Volume, cubic meters.
σ_g	Geometric standard deviation.	L/s	Discharge, litter/second.
Vc	Critical velocity.	cm/s	Velocity, centimeter / second.
V	Approach velocity.	cm	Depth, centimeters.
cm^2	Area, square centimeters.	Sec	Time, second.
u_c	Critical shear velocity	m/s	Velocity, meter / second
y	Flow depth	m	Depth, meters.
d_{84}	Sizes of sediments	d_{16}	Sizes of sediments

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Credit Authorship Contribution Statement

Rana. S. Ahmed: Writing –review & editing, Writing –original draft, validation, software. Thamer A. Mohammed: Writing –review & editing, Methodology

Declaration of Competing Interest

The authors confirm that they do not have any competing financial interests or personal relationships that could have influenced the work reported in this paper.

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تأثير شكل مخرج التصريف على التآكل في مقدم المنشأت القاطعة : دراسة تجريبية

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الخلاصة

هذه الدراسة مهمة لأنها تبحث في فعالية إزالة الرواسب بالقرب من مأخذ الطاقة الكهرومائية عن طريق التنظيف. يمكن أن تحل هذه الطريقة محل الطريقة الحالية المكلفة لإزالة الرواسب عن طريق التجريف. تم التحقيق في آلية نقل الرواسب وأقصى عمق للتآكل والحجم ومنطقة التآكل عند المنبع لنموذج هيكل عبر النهر مع تكوينات مخرج مختلفة. تضمن البحث سلسلة من التجارب التي أجريت في مختبر على قناة بطول 12 مترًا وعرض 0.30 مترًا وعمق 0.45 مترًا. كانت أشكال منافذ النموذج دائرية ونصف دائرية وثلاثة أرباع الدائرة بنفس القطر (D = 11 سم). تم تثبيت الهيكل عبر النهر في نهاية قسم عمل بطول 2 متر برواسب موحدة ذات حجم متوسط (d_{50}) يبلغ 0.23 مم وانحراف معياري هندسي (σ_g) يبلغ 1.29. كان العمق الإجمالي للرواسب في قسم العمل 10 سم. أظهرت البيانات المُجمعة أن أقصى حجم للتآكل بلغ 1194.98 سم^3 مع المخرج الدائري، بينما بلغ 613.48 سم^3 و640.136 سم^3 مع المخرجين نصف الدائري وثلاثة أرباع الدائرة على التوالي. وبالمقارنة مع حجم التآكل أعلى المخرج الدائري (D=11 سم)، أظهرت النتائج انخفاضًا في أحجام التآكل بنسبة 48.6% و46.4% مع المخرجين نصف الدائري وثلاثة أرباع الدائرة على التوالي

الكلمات المفتاحية: شكل مخرج التصريف، نوع الرواسب، التجريف في المنبع، ابعاد حفرة التجريف.