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Channel Hydraulics Simulation on a Fixed Weir Model

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Abstract

This study aims to analyze the hydraulic flow parameters influencing the stability of a fixed weir model and to determine the scour depth occurring around the weir based on variations in model scale, water level, and flow discharge. The research was conducted at the Hydraulics and River Laboratory of Bina Darma University using a channel model measuring 6 m in length, 0.5 m in width, and 0.40 m in height. The channel bed consisted of sand with specific gradation characteristics, and experiments were performed using various flow discharges via a calibrated water circulation system. A physical hydraulic modeling approach was employed to observe flow patterns, scour depths, and sediment deposition around the fixed weir over several testing intervals. Observed parameters included flow discharge, water level, local scour patterns, and sediment deposition resulting from the interaction between the flow and the weir structure. The results indicate that maximum local scour occurred on the upstream side of the weir due to the formation of a horseshoe vortex, while scoured sediment was transported downstream and deposited in the wake zone. The observed scour and sedimentation patterns align with hydraulic flow theory and previous research on local scour around hydraulic structures.
The study found a maximum local scour depth of -3.6 cm upstream of the weir at a transverse distance of 2–6 cm. Scour zones with depths exceeding -3.0 cm were concentrated at longitudinal distances of 0–12 cm and 26–34 cm, forming a horseshoe pattern that encompassed the upstream and left sides of the weir. Maximum sedimentation of +4.3 cm occurred downstream of the weir at a longitudinal distance of 34 cm and a transverse distance of 14 cm. Sedimentation heights of +4.0 cm were also identified at longitudinal distances of 22–24 cm and 50–52 cm, with transverse distances of 14–16 cm. Material eroded from the upstream zone is transported by the flow and redeposited in the wake vortex zone behind the weir.

***Keywords**: Channel hydraulic, river model, local scour, erosion and sedimentation*

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I. INTRODUCTION

Floods and droughts are among the major negative consequences of the imbalance between social, economic, and environmental development. The frequency and severity of these hydrological disasters have increased over time, with flood events transporting not only water but also mud, sediment, waste, and other debris. Flooding is caused not only by natural factors, such as high rainfall intensity, topographic conditions, and land-cover characteristics, but also by human activities related to the management and utilization of natural resources. Unsustainable human activities can exacerbate environmental problems that were previously less significant. The increasing occurrence of disasters such as landslides, floods, and droughts is therefore considered an indicator of ineffective natural resource management, particularly within the context of river basins (Kodoatie& Rustam, 2008).

The frequent occurrence of floods during the rainy season and droughts during the dry season has become an important hydrological indicator of watershed degradation. These phenomena are primarily associated with disruptions to the hydrological cycle, characterized by a substantial increase in surface runoff resulting from a reduction in the soil infiltration capacity. Consequently, a larger proportion of rainfall becomes overland flow rather than being infiltrated and stored within the soil profile (Maryono, 2003).

Physical hydraulic modeling is an effective approach for investigating hydraulic phenomena that cannot be adequately evaluated using full-scale prototypes. A physical model is commonly employed to simulate the hydraulic behavior of water-control structures, such as weirs, spillways, and river protection works, at a reduced scale. Physical hydraulic model testing enables researchers and engineers to evaluate various hydraulic scenarios and identify potential solutions to hydraulic problems before the actual construction of a structure. The results of physical model studies provide valuable information for optimizing the design and improving the performance of hydraulic structures. Therefore, hydraulic simulation using a fixed weir physical model is an important tool for analyzing open-channel flow behavior and supporting the planning and design of efficient and sustainable water-control infrastructure. Physical modeling of weirs provides an effective approach for understanding flood mitigation mechanisms, identifying potential structural damage, and developing appropriate mitigation strategies. Through controlled laboratory simulations, hydraulic behavior and sediment transport processes can be analyzed under various flow conditions, thereby providing valuable information for the design and optimization of hydraulic structures.

Wiyono, Nugroho, Widyaningtias, and Zaidun (2011) reported that, for a vertical-wall abutment without wing walls, the maximum scour depth occurred at the upstream section of the abutment, whereas for a vertical-wall abutment equipped with wing walls, the maximum scour developed at the central section of the abutment. These findings demonstrate that structural configuration significantly influences local flow patterns and the distribution of scour around hydraulic structures. Ikhsan (2007) demonstrated a clear relationship between increasing flow discharge and the corresponding increase in bed-load sediment transport rate through laboratory experiments and comparisons with the Einstein–Barbarossa analytical method. The study concluded that smaller sediment particle diameters resulted in greater bed-load transport, while higher water discharge produced a substantial increase in sediment transport capacity. These results indicate that both flow discharge and sediment characteristics play a crucial role in controlling bed-load transport and the associated scour processes in open-channel flow.

II. MATERIAL AND METHODS

This research was conducted at the Hydraulics and River Laboratory of Bina Darma University, located at the former main campus at Jl. Jend. A. Yani No. 3, Palembang, South Sumatra, Indonesia. The laboratory is equipped with facilities for scaled river and channel modeling to enable experimental testing of open-channel flow and hydraulic structures, thereby allowing for the evaluation of flow behavior, scour development, and sediment transport at a laboratory scale.

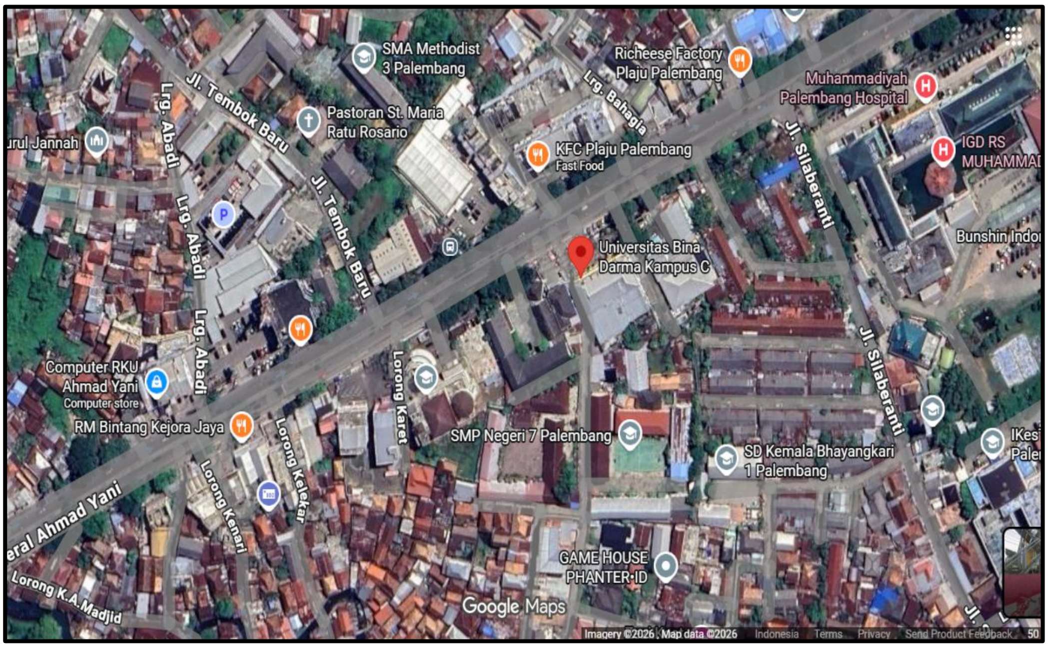

Figure 1: Research location

2.1. Research Materials and Experimental Equipment

To support the laboratory hydraulic model testing, the experimental setup used in the Hydrology and Hydraulics Laboratory of Bina Darma University consisted of the following equipment:

- An electric pump with a discharge capacity of 10 l/sec.
- A water storage tank with a capacity of 0.5 m^3.
- A water circulation system connecting the pump unit to the hydraulic model system.
- Equipment for constructing a physical hydraulic model that is geometrically and hydraulically similar to the prototype.
- Hydraulic measurement instruments, including:
- Current meter
- Point gauge
- Piezometer
- V-notch weir discharge measuring device
- Surveying and leveling instruments for accurately determining the elevation of the physical model, including:
- Automatic level
- Theodolite
- The water supply was provided by a pre-calibrated pump, and the experiments were conducted under several discharge variations.

The sediment material used in the physical model consisted of sand passing the No. 10 sieve, which served as the riverbed material. The sediment had the following grain-size characteristics: d35 = 0.285 mm, d50 = 0.330 mm, and d65 = 0.380 mm, with a specific gravity (Gs) of 2.65. These sediment properties were selected to represent the riverbed material and to facilitate the analysis of scour and sediment transport processes under controlled laboratory conditions.

2.2 Flume Scale Model

The experimental flume model used in this study had dimensions of 6.0 m in length, 0.50 m in width, and 0.40 m in height, as illustrated in Figure 2. The flume was designed to simulate open-channel flow under controlled laboratory conditions and to investigate the hydraulic behavior, scour development, and sediment transport processes around the hydraulic structure model. The flume dimensions were selected to provide sufficient flow length for the establishment of uniform flow conditions before the flow reached the test section.

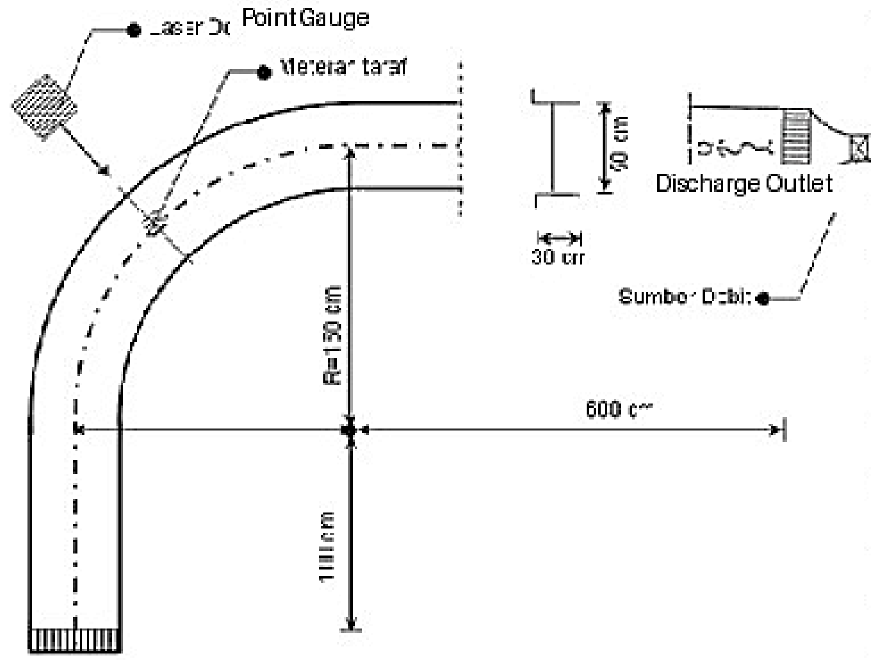

Figure 2: Plan view of the experimental flume (river channel) model used in the laboratory.

III. RESULTS AND DISCUSSION

3.1. Test of Material

The experiment employed a rectangular wooden block as the test specimen, with dimensions of 0.60 m in length and 0.40 m in height. The wooden block was installed within the open-channel flume to simulate the hydraulic obstruction and to observe the scour development around the structure under controlled laboratory conditions.

The sediment material consisted of natural river sand with a non-uniform grain-size distribution. Prior to testing, the sediment was thoroughly cleaned to remove debris and impurities. The sediment was then uniformly placed along the bed of the flume to a thickness of 0.05 m, forming the initial movable-bed condition for the hydraulic experiments. This sediment layer was used to evaluate local scour and sediment transport processes generated by the interaction between the flow and the wooden block model.

3.2. Laboratory Test Setup

A laboratory testing scheme was developed to evaluate the hydraulic behavior and scour characteristics of the experimental model. The test specimen consisted of a rectangular wooden block representing a fixed weir structure. The wooden block was installed transversely across the open-channel flume at a predetermined location. A sediment bed composed of river sand was placed along the flume bed to a thickness of 0.05 m, beginning 2.0 m downstream from the upstream collecting tank wall and extending over a length of 3.0 m. This sediment layer served as the movable-bed section for observing scour and sediment deposition around the hydraulic structure during the experiments.

Preparation of Test Specimens and Experimental Apparatus

Prior to each experiment, the following preparation procedures were carried out:

1. The entire flume was thoroughly cleaned and drained to remove any remaining water, sediment, and debris.
2. The location of the rectangular wooden block was measured and marked at a distance of 2.0 m from the upstream collecting tank, and the block was installed perpendicular to the direction of flow across the flume.
3. The sediment material (river sand) was placed within the flume starting at the 2.0 m position, forming a uniform bed with a thickness of 0.05 m, and the surface was leveled using a spatula or scoop.
4. The sediment bed elevation was checked using an automatic level to ensure uniformity in both the longitudinal and transverse directions of the flume.
5. After the wooden block and sediment bed had been properly installed, water was supplied to both the upstream and downstream collecting tanks using a calibrated water pump.
6. Two video recording cameras were installed to monitor the experiment from the front and side views. Once all equipment had been properly arranged and calibrated, the hydraulic experiment was initiated.

Results of the Hydraulic Experiment

The hydraulic experiments were conducted using a laboratory flume with the following geometric characteristics:

- Channel width (B): 0.60 m
- Channel height: 0.50 m
- Flume length: 6.00 m
- Channel bend angle: 90° at a distance of 3.00 m from the upstream section
- Sediment layer thickness: 0.05 m

The discharge values used in the experiments are presented in Table 1.

Table 1. Experimental discharge values

Number of simulation	Discharge (ml/sec)	Discharge (m^3/sec)
1	215.00	0.000215
2	343.33	0.000343
3	340.00	0.000340

The cross-sectional flow area was calculated as:

$$A = B \times y$$

where B = 0.60 m is the channel width and y = 0.05 m is the flow depth corresponding to the sediment layer thickness.

$A = 0.60 \times 0.05 = 0.03\ m^2$

The average flow velocity for each experimental condition was calculated using the continuity equation:

$V = Q / A$

where V is the flow velocity (m/s), Q is the discharge (m^3/s), and A is the cross-sectional flow area (m^2).

For Experiment 1 ($Q = 0.000215\ m^3/s$):

$V = 0.000215 / 0.03 = 0.0072$ m/s

For Experiment 2 ($Q = 0.000343\ m^3/s$):

$V = 0.000343 / 0.03 = 0.0114$ m/s

For Experiment 3 ($Q = 0.000340\ m^3/s$):

$V = 0.000340 / 0.03 = 0.0113$ m/s

The calculated flow velocities are summarized in Table 2.

Table 2. Flow velocity for each experimental condition

Number of simulation	Discharge (m^3/sec)	Cross-sectional Area (m^2)	F;owVelocity (m/sec)
1	0.000215	0.03	0.0072
2	0.000343	0.03	0.0114
3	0.000340	0.03	0.0113

The results indicate that the increase in discharge produced a corresponding increase in velocity. The highest flow velocity, 0.0114 m/sec, occurred in simulation 2, while simulation 3 produced a similar flow velocity of 0.0113 m/sec. In contrast, Experiment 1 generated the lowest velocity, 0.0072 m/sec.

3.3 Froude Number

3.3.1 Simulation 1 (V = 0.0072 m/sec)

The flow velocity was used to calculate the Froude number (Fr) as follows:

$$Fr = \frac{V}{\sqrt{gy}}$$

$$= \sqrt{(9,81 \times 0,05)}$$

$$= 0,700 \text{ m/s}$$

$$Fr = \frac{0,0072}{0,700}$$

$$Fr = 0,010$$

3.3.2 Simulation 2 (V = 0,0114 m/sec)

$$Fr = \frac{V}{\sqrt{gy}}$$

$$= \sqrt{9,81 \times 0,05)}$$

$$= 0,700 \text{ m/s}$$

$$Fr = \frac{0,0114}{0,700}$$

$$Fr = 0,0163$$

3.3.3 Simulation 3 (V = 0,0113 m/sec)

$$Fr = \frac{V}{\sqrt{gy}}$$

$$= \sqrt{(9,81 \times 0,05)}$$

$$= 0,700 \text{ m/s}$$

$$Fr = \frac{0,0113}{0,700}$$

$$Fr = 0,0161$$

Table 3. Froude number for each experimental condition

Simulation	Discharge (m^3/sec)	Flow Velocity (m/s)	Froude Number
1	0.000215	0.0072	0.0100
2	0.000343	0.0114	0.0163
3	0.000340	0.0113	0.0161

3.4 Dimensional Analysis
3.4.1 Simulation 1

The channel-bed elevation measurements revealed changes in bed elevation over a longitudinal distance of 0–60 cm and a transverse distance of 0–30 cm, with a measurement interval of 2 cm. The measured data identified the occurrence of local scour and sediment deposition around the fixed weir. The column of data with a value of 0 at the transverse distance of 22 cm represents the location of the weir, indicating that no bed-elevation change occurred within the footprint of the structure. In contrast, the region between 24 and 30 cm in the transverse direction exhibited relatively stable bed elevations ranging from −4.3 cm to −5.0 cm along the entire longitudinal distance of 0–60 cm, suggesting that the flow in this zone was not significantly affected by the presence of the weir and had returned to undisturbed flow conditions.

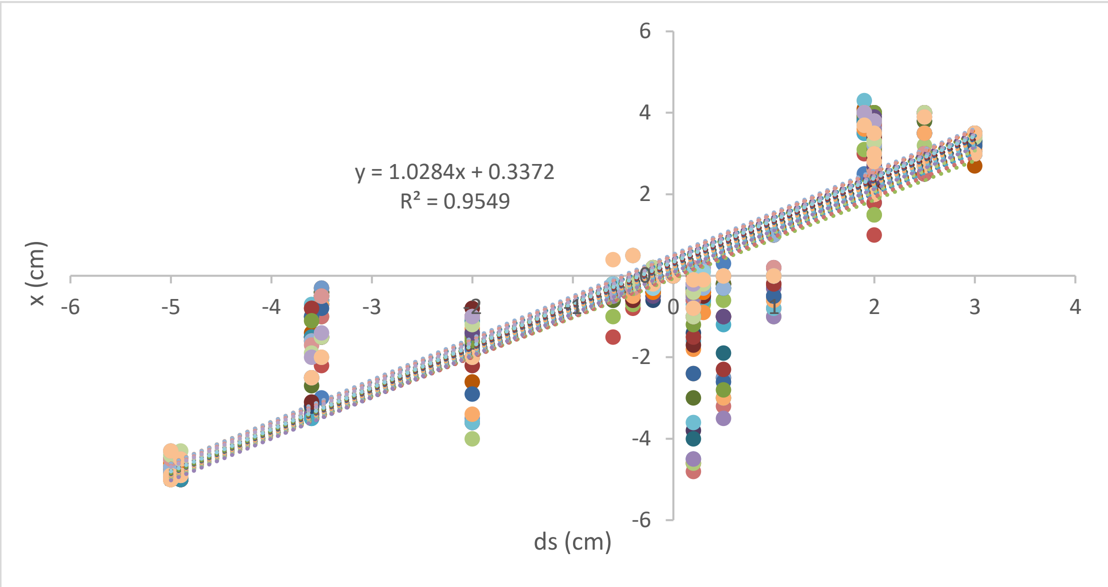

Figure 3: Scour pattern around the fixed weir after 15 minutes of simulation.

3.4.2 Simulation 2

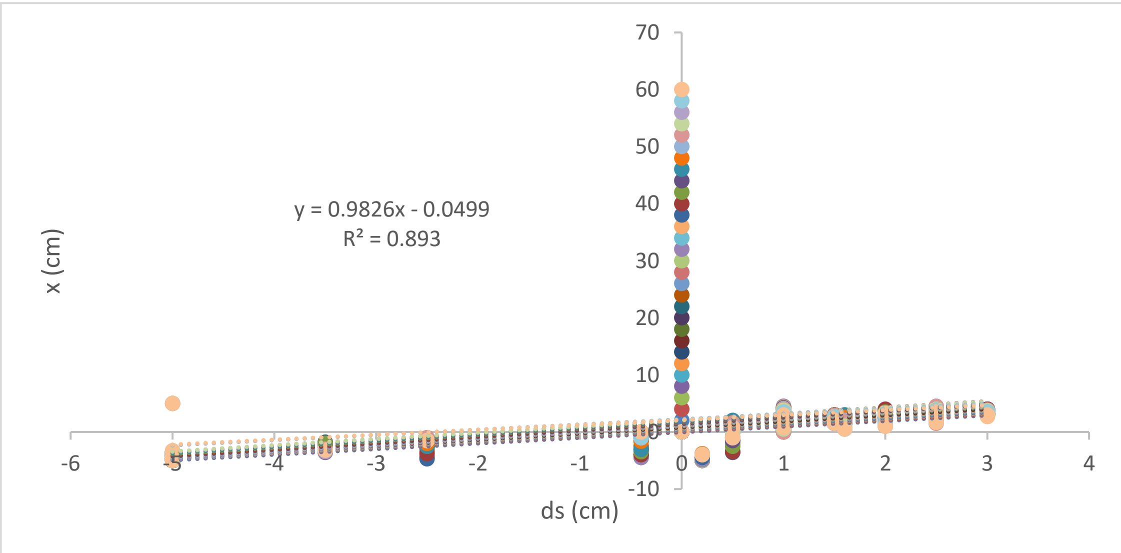

Figure 4: Scour pattern around the fixed weir after 30 minutes.

Local scour in front of the weir reached a maximum depth of −3.6 cm at a longitudinal distance of 8 cm and a transverse distance of 2 cm from the reference point. The scour zone with a depth greater than −3.0 cm was distributed over a longitudinal distance of 0–20 cm and a transverse distance of 2–6 cm. This pattern indicates the formation of a horseshoe-shaped scour hole upstream of the weir, caused by the influence of the horseshoe vortex.

3.4.3 Simulation 3

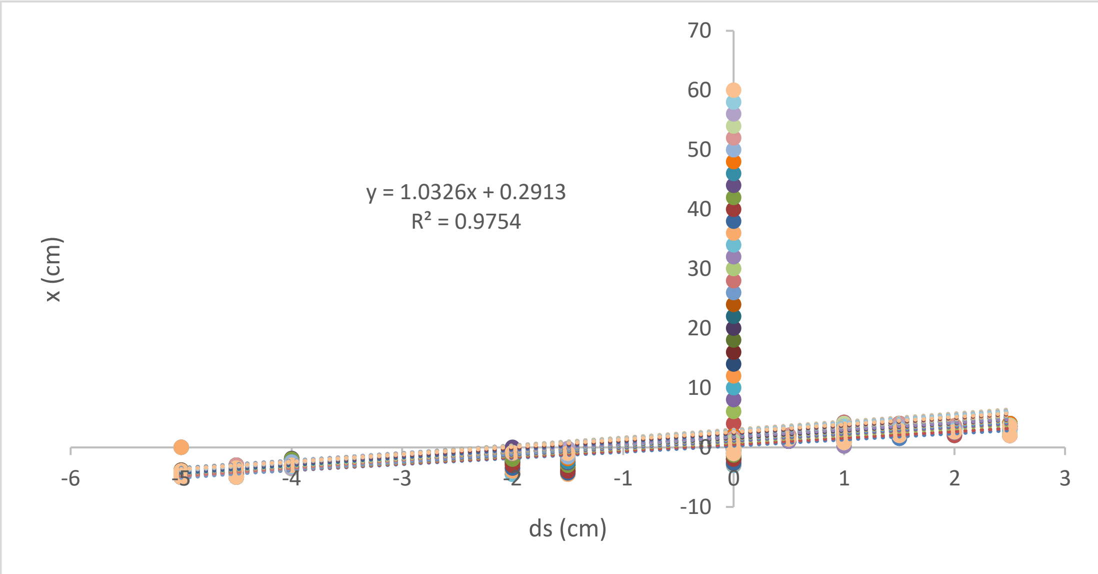

Figure 5: Scour pattern around the fixed weir after 45 minutes.

Based on the scour and sedimentation measurements, local scour was identified with a maximum depth of −4.0 cm, occurring at three points: a longitudinal distance of 0 cm with a transverse distance of 2 cm, a longitudinal distance of 52 cm with a transverse distance of 2 cm, and a longitudinal distance of 60 cm with a transverse distance of 2 cm.

The scour zones with depths greater than −3.0 cm were concentrated at longitudinal distances of 0–14 cm and 50–60 cm, with transverse distances of 2–6 cm. This pattern formed a horseshoe-shaped curve encompassing the upstream section and the left side of the pier. The data column with a value of 0 at a transverse distance of 22 cm indicates the position of the weir, where no elevation changes occurred in this area.

IV. CONCLUSION

Based on the data analysis and discussion, the conclusions of this study are as follows:

1. The test results show that an increase in discharge leads to an increase in flow velocity and the Froude number. In the three experiments, the flow velocities were 0.0072 m/sec, 0.0114 m/s, and 0.0113 m/sec, respectively, with corresponding Froude numbers of 0.010, 0.0163, and 0.0161. All Froude number values were less than 1 (Fr < 1), indicating that the flow characteristics were subcritical, which is characterized by relatively calm flow and flow conditions that remain controlled by the flow depth.
2. The local scour formed around the weir exhibited a horseshoe-shaped scour pattern (horseshoe scour) upstream of the weir due to the formation of a horseshoe vortex. The maximum scour depth in the first and second experiments reached −3.6 cm, while in the third experiment it increased to −4.0 cm. This indicates that as the simulation duration increases, the scour process tends to develop further, resulting in greater scour depths.

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