An Experiment on the Effect of Sills with Orifices Under a Sluice Gate on Energy Dissipation and Hydraulic Jump

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ABSTRACT

In the present study, sills with orifices were utilized to enhance energy dissipation downstream of these structures. For this purpose, a sill with the same width as the channel, a fixed height, and 1 to 4 perforations with a constant diameter of 2 centimeters was experimentally investigated. The results indicated that in the presence of the sill, the specific energy and Froude number downstream of the gate decreased by an average of more than 13% across all models. The introduction of sills and the increase in their number in the orifice led to increased turbulence in the flow, resulting in a reduction in specific energy downstream of the gate. A quantitative analysis of specific energy downstream of the gate reveals that orifice sills, configured with 1, 2, 3, and 4 orifices, reduce particular energy employing 29%, 32%, 40%, and 48%, respectively, relative to a non-orifice sill. Furthermore, the non-orifice sill achieves a 14% reduction in specific energy compared to the baseline non-sill condition. Furthermore, the analysis of depth ratios and energy dissipation in hydraulic jumps revealed that the sill with 4 orifices sill the lowest depth ratio of the jump, while a decrease in the number of orifices increased the contribution of the hydraulic jump to the energy dissipation of the flow.

KEYWORDS
Energy Dissipation, Hydraulic Jump, Vertical Gate, Sill With Orifice.

1. Introduction

Sluice gates are one of the essential structures for controlling water flow in channels, dams, ports, basins, water reservoirs, and various irrigation and desalination structures. These structures are categorized differently based on their location and intended use. One of the most commonly used types of these structures is the sluice gate [1]. Downstream of the gates, the flow is supercritical and possesses destructive kinetic energy; therefore, it is necessary to implement measures to dissipate this energy. Such measures may include the use of sill upstream, downstream, and even beneath the gate, the use of blocks against supercritical flow, and the implementation of rough beds to prevent cavitation phenomena [2]. Numerous studies have been conducted on energy dissipation downstream of gates, and a brief overview of some of these studies is presented below.

The study investigated hydraulic jumps over a rough bed downstream of a gate and demonstrated that bed shear stress is dependent on the flow Froude number. Additionally, the characteristics of the hydraulic jump are influenced by shear stress and relative roughness[3]. Showed that using strip roughness reduces the length and depth of hydraulic jumps over a rough bed[4]. Experimentally investigated the effect of a wavy bed with relative roughness ranging from 0.19 to 0.324 and a Froude number range of 4 to 12 on the characteristics of hydraulic jumps. The results indicated that the wavy bed reduces the conjugate depth and length of the jump by approximately 20% and 35%, respectively[5]. A numerical simulation using four turbulence models for a vertical gate demonstrated that the turbulence model affects the contraction section and the calculation of the contraction coefficient. The results showed that T-shaped elements with a density percentage of 8 provided more favorable results compared to rectangular elements with a density percentage of 10[6]. Investigated energy dissipation in a vertical gate within a sloped channel. Their results showed that as the bed slope and relative opening height of the gate increased, energy dissipation decreased[7]. Experimentally investigated energy dissipation in a vertical gate with a prismatic sill. They showed that the prismatic sill located beneath the gate increases the flow energy dissipation by 10%[8]. Abdulmonem et al., (2018), used a pendulum sill to investigate the characteristics of hydraulic jumps. Their results indicated that the implementation of the pendulum sill increases the efficiency of the hydraulic jump by 20%[9]. Created an orifice in the vertical gate to experimentally examine the characteristics of the hydraulic jump downstream. Their results showed that the introduction of an orifice in the vertical gate increases the energy dissipation of the hydraulic jump[10]. Conducted an experimental study on energy dissipation of hydraulic jumps in a sluice gate within a channel with a reverse slope. Their study results showed that an increase in slope leads to greater energy dissipation[11]. Demonstrated that the characteristics of the formed hydraulic jump improve by creating a sudden opening downstream of the gate. Additionally, [12] demonstrated that sill with various geometric shapes placed beneath the gate resulted in the greatest depth downstream when using circular sills. Investigated experimentally the effect of gate opening and the presence of a sill with different widths on energy dissipation under free flow conditions. The results showed that in the case without a sill and at various openings, the relative energy loss has an inverse relationship with the gate opening. On average, at an opening of 2 centimeters, the energy loss compared to upstream and downstream is 67.47% and 47.71% greater than that at a 4-centimeter opening, respectively. Based on the experimental results, the relative energy loss in the presence of a sill is greater than in the case without a sill for all widths. Furthermore, as the width of the sill increases and consequently the total opening decreases, the relative energy loss increases compared to sills with smaller widths[13].

As discussed in the literature review, hydraulic jumps are commonly used to dissipate energy downstream of sluice gates. Various strategies have been employed to improve the characteristics of hydraulic jumps in stilling basins. Since energy dissipation increases due to increased turbulence and shear forces on the bed, it is necessary to utilize appropriate methods to enhance energy dissipation while also protecting the channel bed. In this study, in order to improve the efficiency of vertical gates in energy dissipation downstream, for the first time, channel-width-aligned sills with fixed-diameter orifices placed at different numbers and symmetrically spaced transversely beneath the gate have been utilized.

2. Materials and Methods

2.1. Dimensional Analysis

Considering Figure 1, the parameters influencing energy dissipation downstream of the sluice gate equipped with an orifice sill are expressed as equation (1):

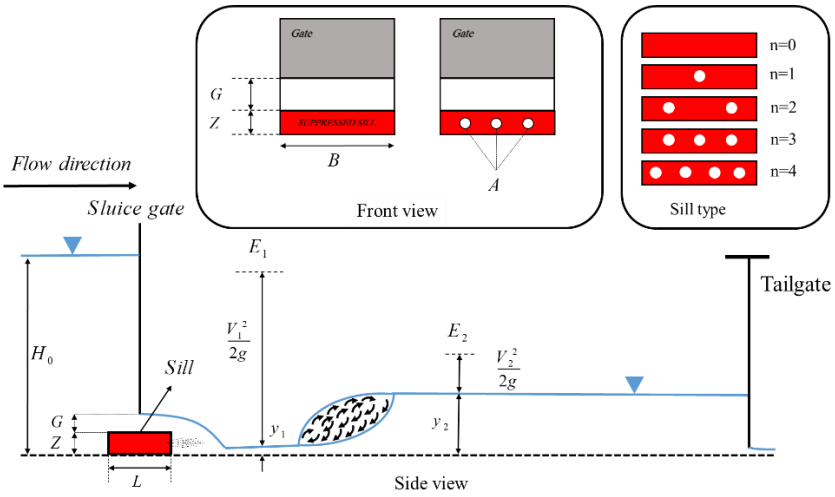


Figure 1. Schematic of flow in a sluice gate with an orifice sill

$$\Delta E = f_1(q.\mu.\rho.n.A.Z.B.g.G.\sigma.y_1.y_2) \quad (1)$$

In the above equation, ΔE represents the energy loss between sections 1 and 2, (L) denotes the length, q is the unit discharge (L^3T^{-1}), is the dynamic viscosity of water ($ML^{-1}T^{-1}$), Specific gravity of water (ML^{-3}), n refers to the number of orifices (dimensionless), A is the cross-sectional area of the orifice (L^2), Z is the height of the threshold (L), B is the length of the sill or width of the channel (L), g is the acceleration due to gravity (LT^{-2}), G is the height of the gate opening (L), σ is the surface tensionof water (ML^{-2}), y_1 is water depth upstream the jump, and y_2 is the water depth downstream the hydraulic jump (L). According to the Buckingham theorem and considering y_1, q, and μ as repeating variables, the dimensionless parameters are presented as equation (2).

$$\frac{\Delta E}{y_1} = f_2(n.\frac{q^2}{y_1^3 g}.\frac{\rho q}{\mu}.\frac{A}{y_1^2}.\frac{Z}{y_1}.\frac{B}{y_1}.\frac{G}{y_1}.\frac{q\sigma}{y_1\mu}.\frac{y_2}{y_1}) \quad (2)$$

In the above equation, Fr_1 is the Froude number of the flow before the hydraulic jump, *Re* is the Reynolds number, and *We* is the Weber number. Given that the cross-sectional area of the orifice, channel width, and height of the threshold are constant, the expressions B/y_1 and Z/y_1 can be disregarded. Finally, by performing these simplifications, equation (3) is simplified as follows:

$$\frac{\Delta E}{y_1} = f_3(Fr_1.Re.n.We.\frac{G}{y_1}.\frac{y_2}{y_1}) \quad (3)$$

Considering that the flow is turbulent, the Reynolds number and Weber number can be disregarded (Raju, 1984, and Loria et al., 2020), and equation (3) can be expressed as equation (4):

$$\frac{\Delta E}{y_1} = f_4(Fr_1.n.\frac{G}{y_1}.\frac{y_2}{y_1}) \quad (4)$$

In equation (4), the relative energy dissipation between sections 1 and 2 is

represented and is usually expressed as ΔE. Therefore, energy dissipation can be written as a function of other parameters:

$$\frac{\Delta E}{E_1} = f_5(Fr_1.n.\frac{y_2}{y_1}.\frac{G}{y_1}) \quad (5)$$

Considering that in the above equation, the Froude number and the ratio of depths of the hydraulic jump depend on the upstream flow characteristics, particularly the geometric characteristics of the threshold, equation (5) is simplified as follows:

$$\frac{\Delta E}{E_1} = f_6(Fr_1.n.\frac{G}{y_1}) \quad (6)$$

$$\frac{y_2}{y_1} = f_7(Fr_1.n.\frac{G}{y_1}) \quad (7)$$

2.2. Experimental setup

A rectangular flume with a horizontal bottom slope was used for experiments, measuring 5 meters in length, 0.325 meters in width, and 0.45 meters in height [14, 15]. The walls are made of tempered glass, and the bottom is made of steel. This flume is equipped with a storage tank where water is pumped in by two pumps. After traveling the length of the flume (5 meters), the water is returned to the storage tank in a circular manner from the end of the flume. A vertical gate made of polyethylene with a sharp edge was selected, with an opening height of 2 and 3 centimeters. The length of the tank behind the gate was considered to be one meter.

The sills made of polyethylene have dimensions of length, width, and height of 3cm, 0.325 m, and 4cm, respectively. They were constructed with 1, 2, 3, and 4 gate openings, each with a diameter of 2cm. The arrangement of the sill with orifice was such that they were positioned symmetrically along the width. To create a tailwater depth and form a hydraulic jump downstream of the flume, a sluice gate was used. After installing the sluice gate and sill, the pump was turned on and then adjusted using a rotameter with an accuracy of ±2. Once the flow conditions stabilized, which took some time, the tailwater depth was adjusted so that the jump toe remained fixed at a specific location and the flow conditions over the sluice gate were free [16]. With the stabilization of the hydraulic jump toe, the initial and secondary jump depths were measured using a point depth gauge with an accuracy of one millimeter. To reduce device error and human error, data collection was performed at several points across a cross-section.



a) The flow and hydraulic jump state of an orifice with a constant flow rate of 650 liters per minute.



b) The hydraulic flow and jump in the two-orifice condition with a constant flow rate of 650 liters per minute.



c) Hydraulic flow and jump in a three-orifice configuration with a constant discharge of 650 liters per minute in top view.



d) Hydraulic flow and jump in a three-orifice configuration with a constant discharge of 650 liters per minute in front view



e) Hydraulic jump and flow in the four-orifice state with a constant flow rate of 650 liters per minute.

Figure 2. The hydraulic jump formed under the laboratory conditions of the current research

3. Results and Discussion

In Figure 3, the relationship between flow rate (Q) and dimensionless height (H/G) behind the gate was analyzed. The results show a clear upward trend in water height with increasing flow rate. As the flow rate increases, the height behind the gate rises, demonstrating the direct impact of discharge on water levels in the system. This is consistent with the expectations of hydraulic flow dynamics, where higher flow rates typically result in greater water depths due to the increased energy in the system.

Furthermore, this behavior aligns with findings from previous research. In various studies, similar trends have been observed, where higher flow rates lead to an increase in water depth behind sluice gates or weirs. These results support the general understanding in fluid mechanics that flow rate is a key determinant in controlling water depth, especially in systems where flow is regulated by gates or barriers.

By comparing the data obtained in this study with previous works, it is evident that the trends are consistent across different experimental setups. The relationship between discharge and water depth observed here supports the conclusions drawn in earlier studies, reinforcing the validity and reliability of the current findings. Therefore, this study contributes to the existing body of knowledge on hydraulic flow behavior, showing that increased discharge correlates with increased water height, as previously established by other researchers in the field.

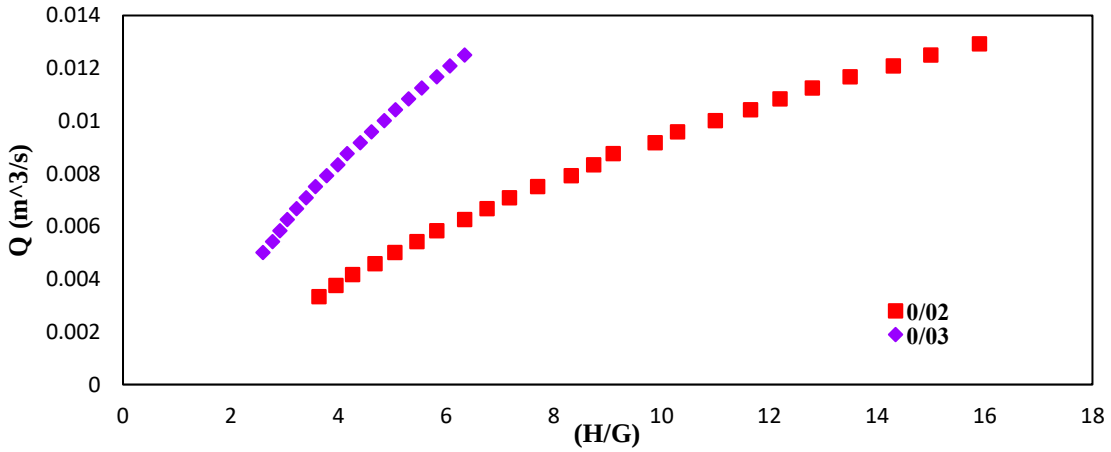


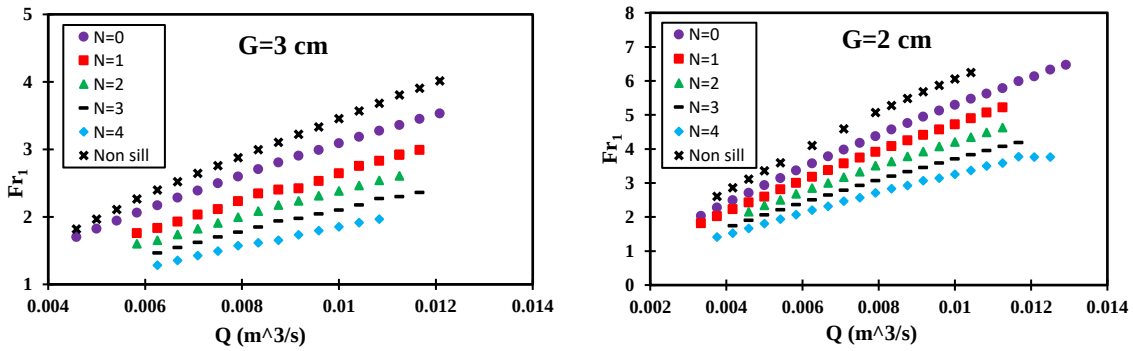
Figure 3. Graph showing the relationship between dimensionless height (H/G) and discharge for gate openings.

3.1. Downstream Froude number of the gate

In Figure 4, the gate of the downstream Froude number of the gate is shown against discharge for two gate opening heights. As observed, the use of a sill compared to the non-sill condition reduces the range of the Froude number at both gate opening heights. This occurs due to the turbulence caused by the backflow towards the sill. On the other hand, the presence of orifices and the increase in the number of orifices at the sill lead to increased turbulence and disruption of flow lines after the gate, resulting in a decrease in the Froude number of the flow at both gate opening heights. Therefore, the lowest gate of the Froude number occurs for the sill gate with 4 orifices, while the highest range of the Froude number corresponds to the gate without a sill. At both gate opening heights, the sill with 1, 2, 3, and 4 orifices reduces

the range of the Froude number by an average of 12.5%, 20.5%, 27%, and 36.3%, respectively, compared to the non-orifice condition. The sill gate without orifices also reduces the range of the Froude number by 13% compared to the gate without a sill.

Considering the gates of the Froude number at both gate opening heights, for gates with orifice sills, Type 1 and Type 4 stilling basins can be used for energy dissipation. Specifically, for the gate with orifice sills at a gate opening height of 3 centimeters, a Type 1 stilling basin can be used, while for the gate without orifices and the gate without a sill, both types of stilling basins can be utilized. On the other hand, for a gate opening height of 2 centimeters in the non-sill condition and a discharge exceeding 8 liters per second, Types 2 and 3 stilling basins are recommended. For the sill without orifices, stilling basins of Type 2 and Type 3 are suggested for discharges exceeding 10 liters per second.



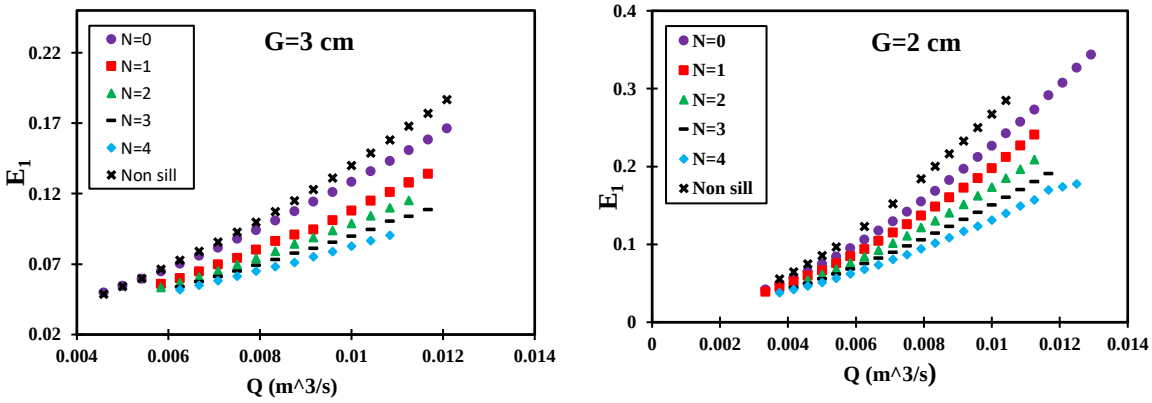
a) G=3 cm **b) G=2 cm**

Figure 4. Downstream Froude number of the gate versus discharge

3.2. Specific energy downstream of the gate

The specific energy downstream of the gate for all models in the current study is shown against the flow discharge for two gate opening heights in Figure 5. As observed, the results indicate that at both gate opening heights, with an increase in discharge, the specific energy increases, and the highest specific energy corresponds to the non-sill condition, while the lowest value is associated with the sill gate with 4 orifices. The increase in the number of orifices at the sill leads to a reduction in the specific energy downstream of the gate. The turbulence generated in the flow after the gate is one of the main causes of this phenomenon. Part of the turbulence occurs due to the backflow towards the sill, and another part is created by the flow passing through the orifices. As the number of orifices increases, the flow exiting from them interferes with each other, and this flow interference causes disruption of the flow lines and increases turbulence. Comparing the specific energy values at a constant discharge for all models shows that an increase in gate opening height also leads to a decrease in specific energy after the gate.

A quantitative comparison of the results obtained from the specific energy downstream of the gate shows that the gate with orifice sills, with 1, 2, 3, and 4 orifices, reduces the specific energy downstream of the gate by an average of 29%, 32%, 40%, and 48%, respectively, compared to the non-orifice sill. Additionally, the non-orifice sill reduces the specific energy downstream of the gate by 14% compared to the non-sill condition.

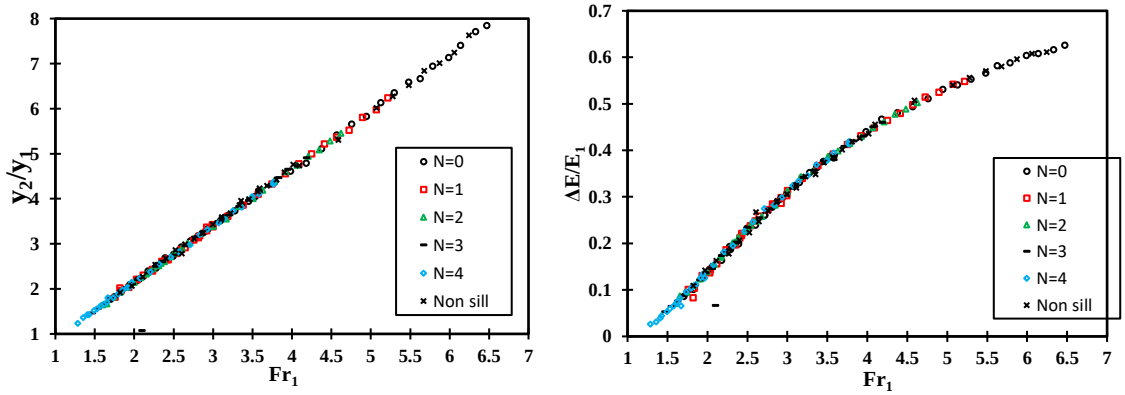


a) G=3cm **b) G=2cm**

Figure 5. Specific energy downstream of the gate versus flow rate

3.3. Depth ratio and energy consumption in hydraulic jump

In Figure 6, the gates of energy dissipation and the ratio of hydraulic jump depths downstream of gates equipped with a sill orifice are presented against the Froude number. It can be seen that the energy dissipation. It is a power function of the Froude number and increases with its increase. On the other hand, due to the fact that sills with the number of apertures 4 have a lower Froude number range than other models, it creates a lower energy dissipation range at a constant flow rate; Because a major part of the depreciation created in it happened before the hydraulic jump and by the turbulence caused by the impact of the flow coming out of the holes. Therefore, the contribution of the hydraulic jump to its energy dissipation is lower than in other models. This statement is also true for the hydraulic jump depth ratio, and it can be seen that the highest gate of depth ratio is specific to the model without a sill. Reducing the depth ratio of the hydraulic jump is important because it can reduce the height of the wall for the construction of the relaxation pond, and lead to the reduction of the materials used and the cost of the construction of the relaxation pond. On the other hand, due to the fact that the length of the hydraulic jump is a function of the Froude number and the secondary depth of the hydraulic jump, therefore, it can be said that the gate with a sill with 4 orifices, compared to other models, since the range of the Froude number and depth ratio It is less, it creates a shorter length of hydraulic jump and it will be economical in this sense.



a) Energy consumption **b) Depth ratio**

Figure 6. Energy and depth ratio in hydraulic jump

3.4. Checking the flow pattern

Examining the flow pattern and consequently the flow lines is one of the important factors in identifying the flow regime and understanding the flow characteristics. In this research, the effect of using the aperture on the sill on the flow through the sluice gate was investigated. Figure (7) shows the flow pattern governing the downstream of the sluice gate with a sill with the orifice. In the state without an orifice, smooth and unbroken flow lines dominated the flow. Because no deviation was seen. By using a sill with 2 orifices, high-speed currents were observed downstream. These lines are shown in blue in Figure (7). By using the sill with 3 and 4 orifices, the amount of high-speed currents increased, respectively. The hydraulic reason for this is the presence of small-diameter holes. With the increase in the number of gate openings, the high-speed currents in the downstream increased. The yellow lines indicate the flow lines with lower speed. These lines include currents that pass over the crest of the sill, and due to the larger orifice surface, they have a lower speed than the blue lines.

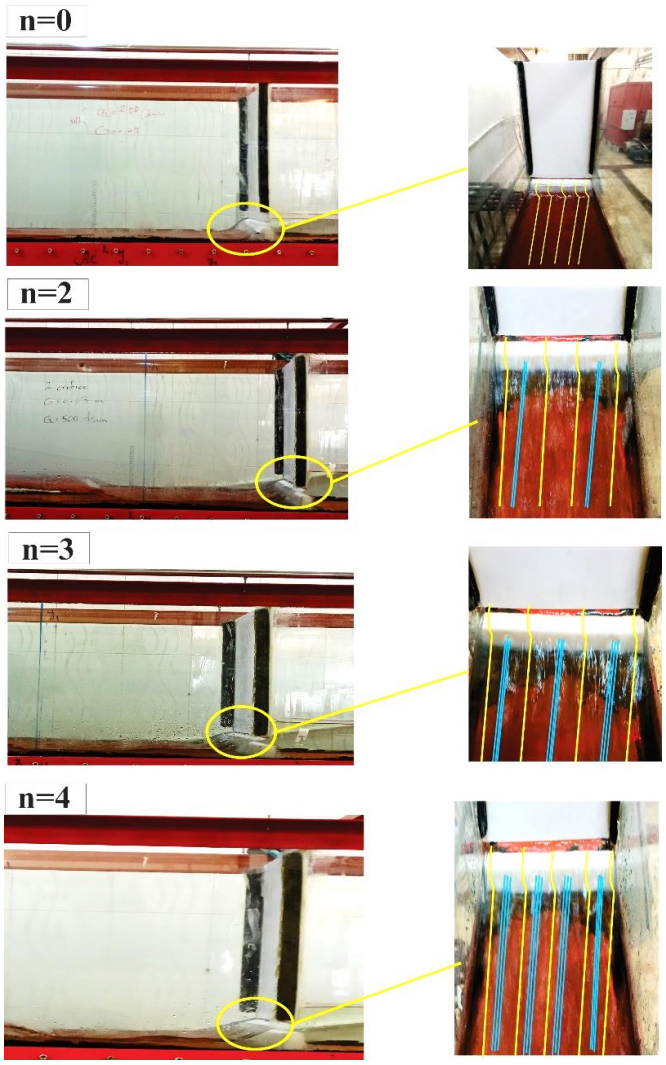


Figure 7. The flow pattern governing the downstream of the sluice gate with a sill with an orifice

4. Conclusion

In the present research, the downstream energy dissipation of a gate equipped with an orifice lower sill with two gate opening heights was investigated. Sills with fixed aperture orifices and aperture numbers 1, 2, 3, and 4 orifices were considered. The flow limit for the experiments was considered between 200 and 750 liters per minute. The results showed that due to the use of a sill under the gate, the range of landing number and specific energy downstream of the gate decreased compared to the case of non-sill, and the presence of orifice in the sill and the increase in the number of orifice also reduced the range compared to the case without a sill. Landing number and special energy after hatch. After reducing the range of Froud number, for the energy dissipation of the flow downstream of the gate, the results of the hydraulic jump formation downstream of the sill gate showed that, for sills with orifice, a large part of the energy di occurs in the section before the formation of the jump, and the sill with the number of orifice 4, it includes the lowest ratio of hydraulic jump depths. Since the consumption of energy downstream of the gate is an important and necessary thing to prevent the destruction and erosion of the bed, therefore, the use of a sill with an orifice is recommended, considering that it helps to reduce the energy of the flow before the hydraulic jump is formed.

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Conflict of Interest:
The authors declare that they have no conflict of interest.

Author Contributions
All authors contributed to the study conception and design.

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