water

Article

Experimental Study of Geometric Shape and Size of Sill Effects on the Hydraulic Performance of Sluice Gates

Rasoul Daneshfaraz [1,*], Reza Norouzi [1], Parisa Ebadzadeh [1], Silvia Di Francesco [2] and John Patrick Abraham [3]

1 Department of Civil Engineering, Faculty of Engineering, University of Maragheh, Maragheh 5518183111, Iran
2 Department of Engineering, Niccolò Cusano University, 00166 Rome, Italy
3 School of Engineering, University of St. Thomas, St. Paul, MN 33901, USA
* Correspondence: daneshfaraz@maragheh.ac.ir; Tel.: +98-91-4320-2126

Abstract: The present research was conducted to investigate the effect of sill geometry and sill width on the discharge coefficient and hydraulic jump characteristics. For this purpose, sills with semi-cylindrical, cylindrical, pyramidal, and rectangular cube geometries with widths of 0.075, 0.10, 0.15, and 0.2 m were installed under a sluice gate. Results showed that increasing the sill width increased the sluice gate discharge coefficient compared to the no-sill mode. The results of placing a sill with different geometric shapes under a sluice gate indicate that using a semi-cylindrical sill increases the discharge coefficient. The ranked order of other sills, from the largest to smallest discharge coefficient, is: cylindrical, pyramidal, and rectangular cubic sills, respectively. The results show that the use of a sill increases the energy dissipation. Examining sills of different widths indicates that with increasing width, the increase in velocity and consequent decrease in the depth of the hydraulic jump causes an increase in energy loss. When employing sills of maximum width (b = 0.20 m) for pyramidal, semi-cylindrical, cylindrical, and rectangular shapes, the energy loss increased by 125, 119, 116, and 125% in section A, respectively. The semi-cylindrical sill is most effective in increasing the discharge coefficient, while the pyramidal sill is most effective for increasing energy dissipation.

Keywords: hydraulic jump; sill; sluice gate; free jump

Citation: Daneshfaraz, R.; Norouzi, R.; Ebadzadeh, P.; Di Francesco, S.; Abraham, J.P. Experimental Study of Geometric Shape and Size of Sill Effects on the Hydraulic Performance of Sluice Gates. *Water* **2023**, *15*, 314. https://doi.org/10.3390/w15020314

Academic Editors: Chia-Ren Chu and Chin H. Wu

Received: 11 October 2022
Revised: 8 January 2023
Accepted: 9 January 2023
Published: 11 January 2023

1. Introduction

The ease of installing sluice gates and the simplicity of their use has resulted in them becoming one of the most widely used hydraulic structures [1,2]. Several factors affect the discharge coefficients and energy loss of the sluice gate. Henry's experimental study is one of the first research publications in this field; since then, this area has become an active part of research [3]. The parameters that affect discharge coefficients of sluice gates were studied in [4]. Their results showed that the discharge coefficient is related to the dimensionless parameter G/H, where G and H are the gate opening and flow depth upstream of the sluice gate, respectively. The experimental study of [5] showed that the discharge coefficient is a function of the upstream water depth and the gate opening. Ferro proposed a dimensionless relationship for sluice gates using dimensional analysis and incomplete self-similarity theory. By combining the energy relationship and the critical depth of the channel, he presented a dimensionless relationship for the stage discharge. A comparison of the data with other experimental results showed good agreement [6]. Reda [7] modeled the flow characteristics under vertical and inclined gates using artificial networks. He applied the ANN intelligence model as a suitable model for predicting the discharge coefficient for vertical and inclined sluice gates. Salmasi and Abraham [8] examined the discharge coefficient of sluice gates with polygonal and non-polygonal sills. They concluded that trapezoidal sills have the least effect on the discharge coefficient. Pastor et al. [9] presented the procedure for assessing the safe operation of the sluice gate, on which places with permanent deformation and a broken part of the guide wheel flange were identified. Using numerical modeling, they identified critical stress values at the locations of reinforcing elements, which were modified. The stress values were reduced by approximately 15%. The discharge coefficient for vertical and inclined sluice gates was examined in [10]. Their tests included a sluice gate with four deflection angles of 0, 15, 30, and 45 degrees with respect to the vertical plane on the upstream side. Results showed that a change in the deflection angle of the gate increases the convergence of the flow and the passing discharge coefficient.

In addition to the above investigations of discharge, the high kinetic energy of flow downstream of hydraulic structures is another essential issue in hydraulics. A hydraulic jump is a flow energy dissipator; it results from the transformation of supercritical to subcritical flow. This phenomenon can be seen downstream of dams, rapids, and gates. Multiple methods, discussed below, have been used to reduce the kinetic energy of the flow passing through the sluice gates.

Hydraulic jump control using rough beds is another topic studied by researchers [11]. Rajaratnam investigated the shear stress of rough beds on hydraulic jump characteristics. The results showed that the bed shear force depends only on the Froude number. Subsequently, he conducted experiments in the range of Froude numbers from 3 to 10 with relative roughness from 0.02 to 0.43 and showed that the relative depth is a function of the initial Froude number and relative roughness [12]. The hydraulic jump on a rough bed with 0.0166 m cubic roughness elements was studied in [13]. The roughness elements occupied 10% of the surface of the basin and the author showed that the length of the jump on the rough bed compared to the length of the classic jump decreased on average by 4.47%.

More recently, Alhamid showed that secondary depth reduction is also a function of the density of the roughness elements by investigating the hydraulic jump on the roughness of the bed with wooden blocks of fixed size and different densities [14]. The hydraulic jump investigation on the corrugated bed in the range of Froude numbers from 4 to 10 with relative roughness of 0.25, 0.43, and 0.5 was performed by Ead and Rajaratnam [15]. By considering the shear stress as a function of the initial Froude number of the flow, they presented relations for both a smooth bed and a corrugated bed. The results showed that the corrugated bed with a 25% relative depth reduction performs better in reducing the secondary depth and forming a hydraulic jump. Tokyay experimentally investigated the effect of corrugated beds with relative roughness ranging from 0.19 to 0.324 and Froude numbers ranging from 4 to 12. That study focused on hydraulic jump characteristics as these variations were used [16]. The results showed that the corrugated bed reduced the conjugate depth and jump length by approximately 20 and 35%, respectively.

The effect of a trapezoidal corrugated bed on the hydraulic jump in the range of Froude numbers from 4 to 12 and four relative roughness values was investigated [17]. The authors showed that the depth of tailwater required to form a hydraulic jump on corrugated beds is less than the depth of tailwater related to a similar hydraulic jump on smooth beds. More recently, the effect of sinusoidal corrugated beds was evaluated on six beds with wave slopes ranging from 0.286 to 0.625 and Froude numbers ranging from 3.8 to 8.6 [18]. The results showed that the secondary depth and the length of the hydraulic jump on corrugated beds are smaller than on smooth beds under the same hydraulic conditions. The ratio of conjugate depths and hydraulic jump lengths on a rough bed with wedge-shaped elements for a range of Froude numbers from 3.06 to 10.95 and relative roughness values ranging from 0.22 to 1.4 was experimentally investigated [19]. The results showed that the rough bed with non-continuous wedge-shaped roughness elements reduced the secondary length and depth of the hydraulic jump compared to the smooth bed, by between 30 and 53% and 16.5 and 30%, respectively.

Hydraulic jump characteristics were investigated on more than six triangular corrugated beds over a Froude number range from 1.6 to 1.13 [20]. Their results showed that triangular corrugated beds reduced the secondary depth and jump length by 25% and 54.7%, respectively, compared to the smooth bed. The studies of hydraulic jump characteristics over a Froude number ranging from 4.7 to 12.3 showed that the secondary depth and the length of the jump both decreased with an increase of the roughness elements' height and the reverse slope [21].

The effect of artificial roughness parameters and Froude numbers ranging from 3 to 11.68 on the hydraulic jump of a backward-facing step was studied in [22]. They found that increasing the length of the roughness element does not have a significant effect on reducing energy loss. However, the height of the roughness elements has a significant effect on the characteristics of the hydraulic jump. Parsamehr et al. used semi-cylindrical roughness elements to study the characteristics of jumps in stilling basins for a range of Froude numbers from 4.6 to 7.3, with three roughness heights and four different distances between the roughness elements. Their results showed that the conjugate depth and length of the hydraulic jump on the rough bed compared to the smooth bed were reduced by 25.35 and 38.5% on average, respectively, and the energy loss increased by 18% compared to the classic jump [23].

Neisi and Shafai-Bejestan studied jumps on a rough bed with non-continuous elements, a zigzag arrangement, divergence ratios of 0.67, 0.5, and 0.33, and Froude numbers ranging from 2 to 10. The results showed that the conjugate depth ratio in the rough bed was reduced between 16 and 20% compared to the smooth bed [24].

The review of previous studies shows that the use of obstacles and roughness elements downstream of a gate decreases the secondary depth of the jump and increases energy dissipation. In a laboratory study, Jalil and Abdolsattar changed the location of a barrier and its application under the sluice gate. They studied the characteristics of the hydraulic jump. The results showed that placing a pyramid sill under the sluice gate increased energy dissipation by 10% compared to the state without a sill [25].

The purpose of this study is to investigate the effect of a sill on both flow rate and energy dissipation. Placing the sill under the sluice gate is important and it changes the flow characteristics, including the initial depth of the jump. The change in the dimensions and geometry of the sill is one of the most important factors governing the impact to the flow. Therefore, the current research was conducted to investigate the effect of a sill with different geometric shapes and widths on the discharge coefficient and energy loss.

2. Materials and Methods

Experimental Set-Up

The experiments were performed in a laboratory flume that was 5 m long, 0.30 m wide, and 0.45 m high. The laboratory channel has a floor and walls made of plexiglass and is equipped with a point depth gauge with an accuracy of ± 1 mm. The inflow discharge is supplied by two pumps, each with a capacity of 700 L/min. A 0.01 m thick sluice gate was installed 1 m away from the upstream end of the flume. The gate opening was fixed and equal to 0.04 m. The discharge ranged from 459 to 700 L/min. Semi-cylindrical, cylindrical, pyramidal, and rectangular sills with different widths of 0.075, 0.10, 0.15, and 0.20 m were used. Figure 1 and Table 1 show the laboratory flume and physical characteristics of the sills used in the present study.

Table 1. Physical characteristics of the sills used in this study.

Sill Geometry	Height (m)	Length (m)	Width (m)
Rectangular cubic	0.03	0.03	0.075–0.20
Pyramidal	0.03	0.03	0.075–0.20
Cylindrical	Cylindrical diameter = 0.03		
Semi-cylindrical	Semi-cylindrical diameter = 0.03		

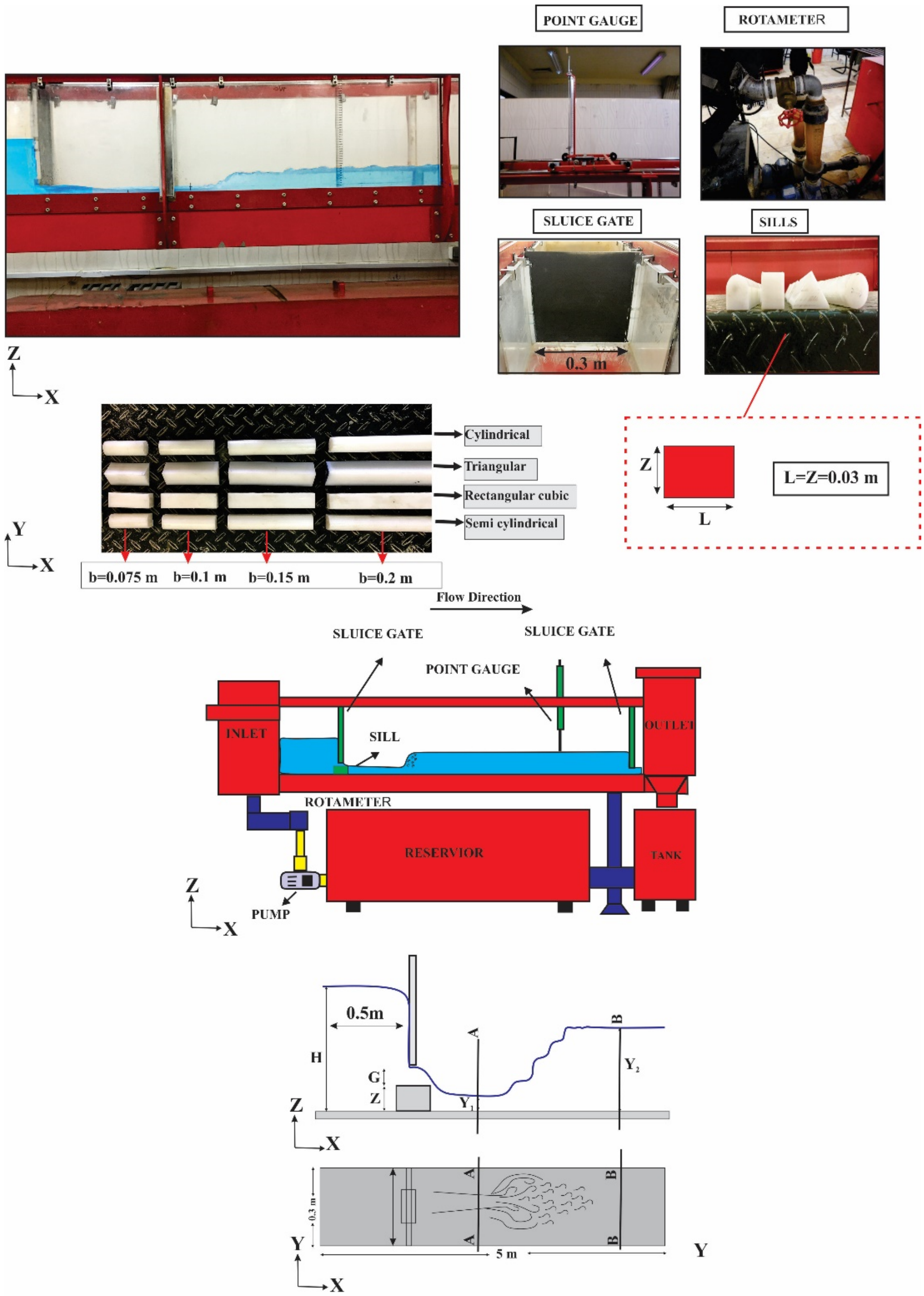

Figure 1. Schematic view of the channel and sills used in the present study.

The parameters affecting the discharge coefficient of the sluice gate with a sill lead to the functional relationship shown below [26].

$$f_1\ (C_d, \rho, Q, g, \mu, H, G, Z, b, B) = 0 \quad (1)$$

Here, Cd is the discharge coefficient, ρ is the water density, Q is the flow rate, g is the gravitational acceleration, μ is the dynamic viscosity, H is the water depth behind the gate, G is the gate opening, Z is the sill height, b is the sill width, and B is the channel width.

According to the π—Buckingham method, and considering (H, g, ρ) as iterative variables, the dimensionless parameters for the gate with the sill are presented as Equation (2):

$$f_2\left(C_d, \frac{1}{Fr}, \frac{1}{R_e}, \frac{G}{H}, \frac{Z}{H}, \frac{b}{H}, \frac{B}{H}\right) = 0 \tag{2}$$

Fr represents the flow Froude number and Re represents the Reynolds number. Since 11,286 < Re < 38,866, the flow is fully turbulent, and the effect of the Reynolds number can be ignored [27]. The effect of the dimensionless H/Z parameter was ignored due to the constant height of the sills, with the channel width as a fixed parameter. Finally, Equation (2) can be rewritten as Equation (3):

$$C_d = f_3\left(\frac{b}{H}, \frac{G}{H}\right) \tag{3}$$

In the current research, the effective parameters on current energy dissipation can be shown as Equation (4):

$$f_1(Q, B, b, Z, G, E_A, E_B, Y_A, Y_B, g, \rho, \mu) = 0 \tag{4}$$

Y_A and Y_B are the water depths in sections A and B, and E_A and E_B are the specific energies in sections A and B, respectively. Equation (4) can be rewritten as:

$$f_2\left(Fr_A, \frac{B}{Y_A}, \frac{b}{Y_A}, \frac{z}{Y_A}, \frac{E_A}{Y_A}, \frac{E_B}{Y_A}, \frac{Y_B}{Y_A}, Re_A\right) = 0 \tag{5}$$

In Equation (5), Fr_A and Re_A represent the dimensionless Froude and Reynolds numbers, respectively. Finally, to provide a more compact relationship, Equation (5) is modified by forming ratios as follows:

$$\frac{\Delta EAB}{EA}, \frac{\Delta EAB}{EB} = F_3\left(Fr_A, \frac{b}{Y_A}, \frac{Y_B}{Y_A}\right) \tag{6}$$

3. Results

3.1. Effect of Sill Geometry and Width on Discharge Coefficient

In the present study, the sluice gate discharge coefficients with the various sills were investigated and the results were compared with the no-sill situation. In Figure 2, the horizontal axis is the dimensionless sill width over the upstream water depth and the vertical axis is the discharge coefficient.

The effect of sill geometry on the discharge coefficient shows that the highest discharge coefficient occurs with the semi-cylindrical, cylindrical, pyramidal, and rectangular prism sills, respectively (Figure 2). The presence of a significant energy drop at the cylindrical sills leads to a decrease in the discharge coefficient [28].

Estimation of the discharge coefficient with different sill geometries shows that the semi-cylindrical sill of smallest width (b = 0.2 m) increased the discharge coefficient compared to the cylindrical, pyramidal, and rectangular prism sills by 1.6, 3.7, and 5.9%, respectively [29]. Figure 3 shows the vertical and horizontal axes that represent the discharge coefficient and dimensionless parameter (b/h), respectively. Table 2 shows the increase of the discharge coefficient for various sills compared to the no-sill case. Calculations are based on Equation (7).

$$\frac{C_{d\ \text{silled gate}} - C_{d\ \text{non silled gate}}}{C_{d\ \text{non silled gate}}} \times 100 \tag{7}$$

Figure 3 shows the sluice gate discharge coefficients for sills with widths of 0.075, 0.1, 0.15, and 0.20 m. Using a sill with a larger width reduces the cross-section of the flow below the sluice gate. Decreasing the sluice gate opening increases the discharge coefficient by increasing the velocity.

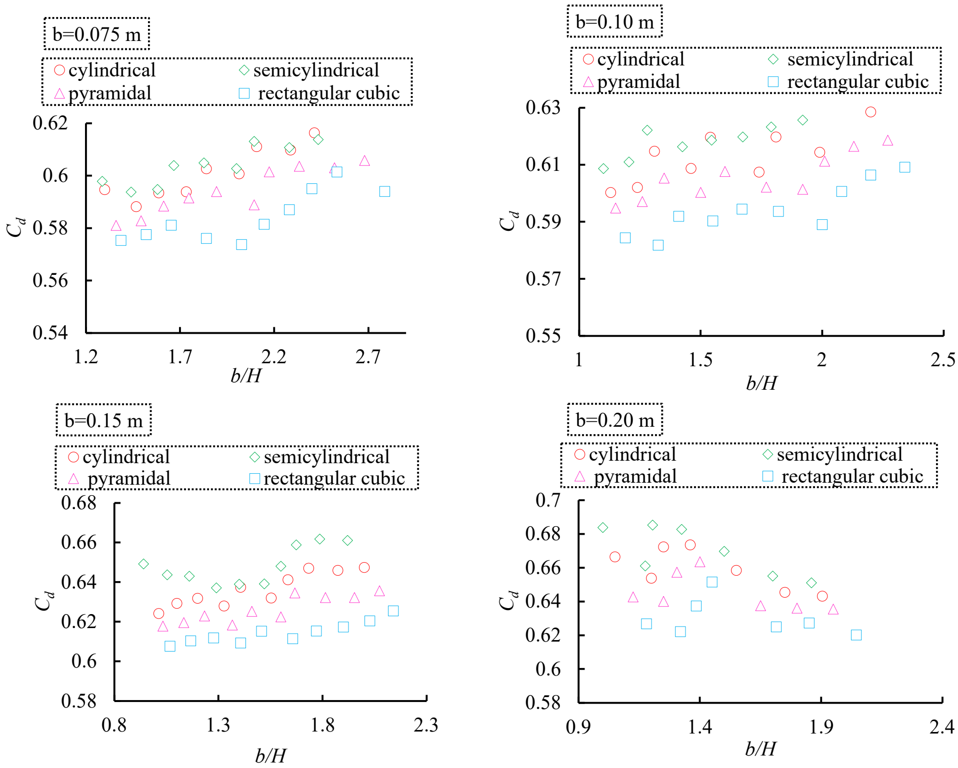

Figure 2. Effect of sill shape on the discharge coefficient.

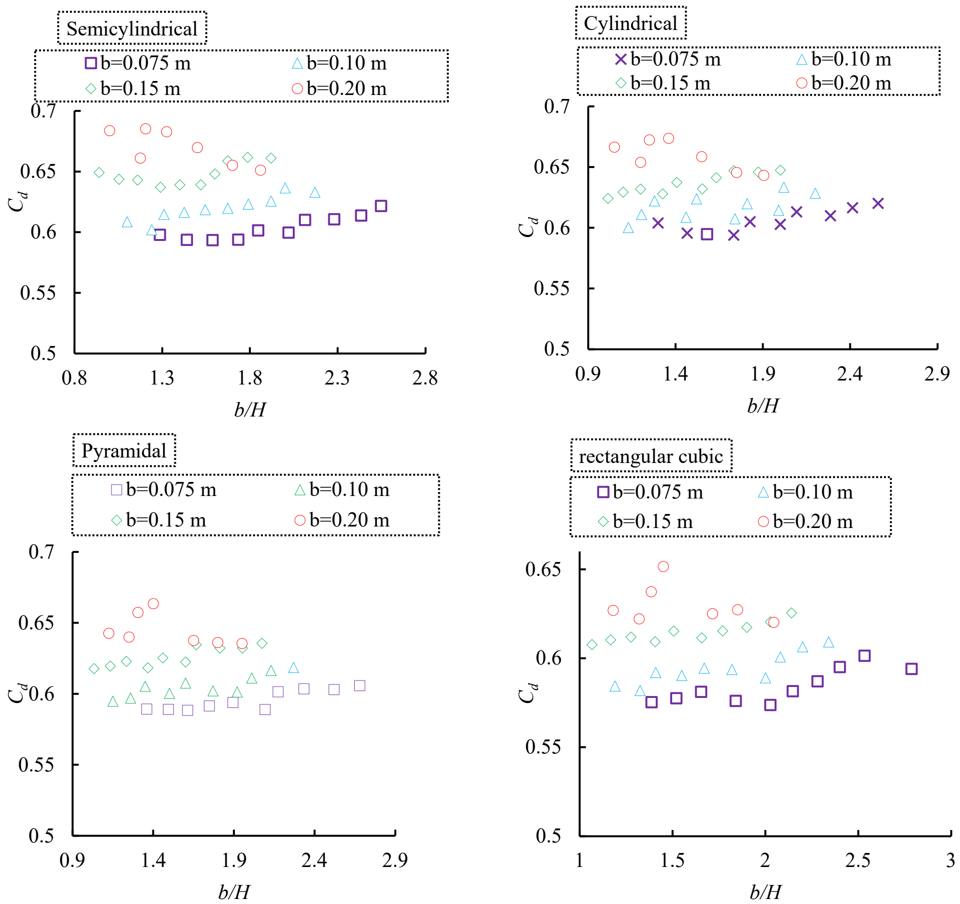

Figure 3. Discharge coefficients for different widths of sills.

Table 2. Increase in sill gate discharge coefficients compared to non-sill gates (%).

Rectangular Cubic	Pyramidal	Cylindrical	Semi-Cylindrical	Sill Width (m)
3.9	5.7	7.4	7.4	b = 0.075
12.1	14.7	17.2	19.1	b = 0.20

3.1.1. Hydraulic Jump Characteristic with Sill

By using non-suppressed sills under the sluice gate, the effect of the shape and width of the sill on energy dissipation was investigated. Sill placement is such that the center of the upper surface of the sill coincides with the bottom of the gate. At first, the primary and secondary hydraulic jump depth parameters were investigated in the non-sill mode. A sill with semi-cylindrical, cylindrical, pyramidal, or rectangular shape was then installed under the gate to investigate the effect of the shape. Four different widths ranging from 0.075 to 0.20 m were used. The height of the sills and the gate opening were held fixed and equal to 0.03 and 0.04 m, respectively. In each test, the depth of water in the primary and secondary sections of the jump was measured along three transverse sections and their average was recorded as the final depth.

3.1.2. Non-Sill Mode

To investigate the energy dissipation of the sluice gate in the control mode (without a sill), a discharge in the range of 500–700 L per minute was applied to the experiments. It was found that with an increase in discharge, the energy loss increases. In Figure 4, the vertical and horizontal graphs express the percentage of energy dissipation and the dimensionless Froude parameter. Figure 5 shows the changes in conjugate depths in the non-sill mode.

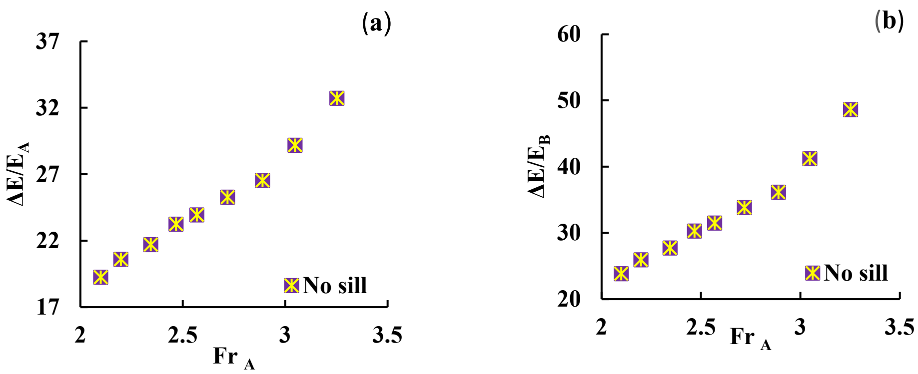

Figure 4. Energy loss compared to the (**a**) upstream and (**b**) downstream sections of the jump.

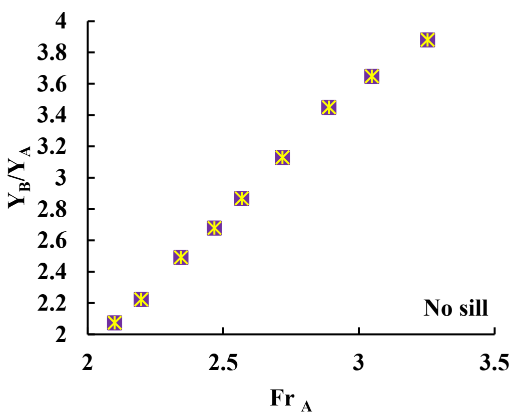

Figure 5. Relative depth changes.

The energy dissipation of the sluice gate was investigated in the non-sill mode and with increasing discharge. The results showed that increasing the discharge from 500 to 700 L per minute increases energy dissipation in sections A and B by 69 and 103%, respectively.

3.1.3. The Effect of Sill Width on Hydraulic Jump Performance

In this research, the sill width was as an influencing factor on the energy dissipation of the sluice gate. Rectangular cubic, pyramidal, cylindrical, and semi-cylindrical sills with widths of 0.075, 0.10, 0.15, and 0.20 m were installed under the sluice gate. The discharge varied from 450 to 750 L per second. Figure 6 shows the laboratory images of the formation of hydraulic jumps with sills of different widths.

Figure 6. Laboratory images of hydraulic jump formation with rectangular cubic sills of different widths.

To investigate the amount of energy loss due to the placement of sills with different widths, Figure 7 is presented. The vertical axis is the relative energy loss for sections A and B, while the horizontal axis represents the dimensionless parameter of the Froude number in section A.

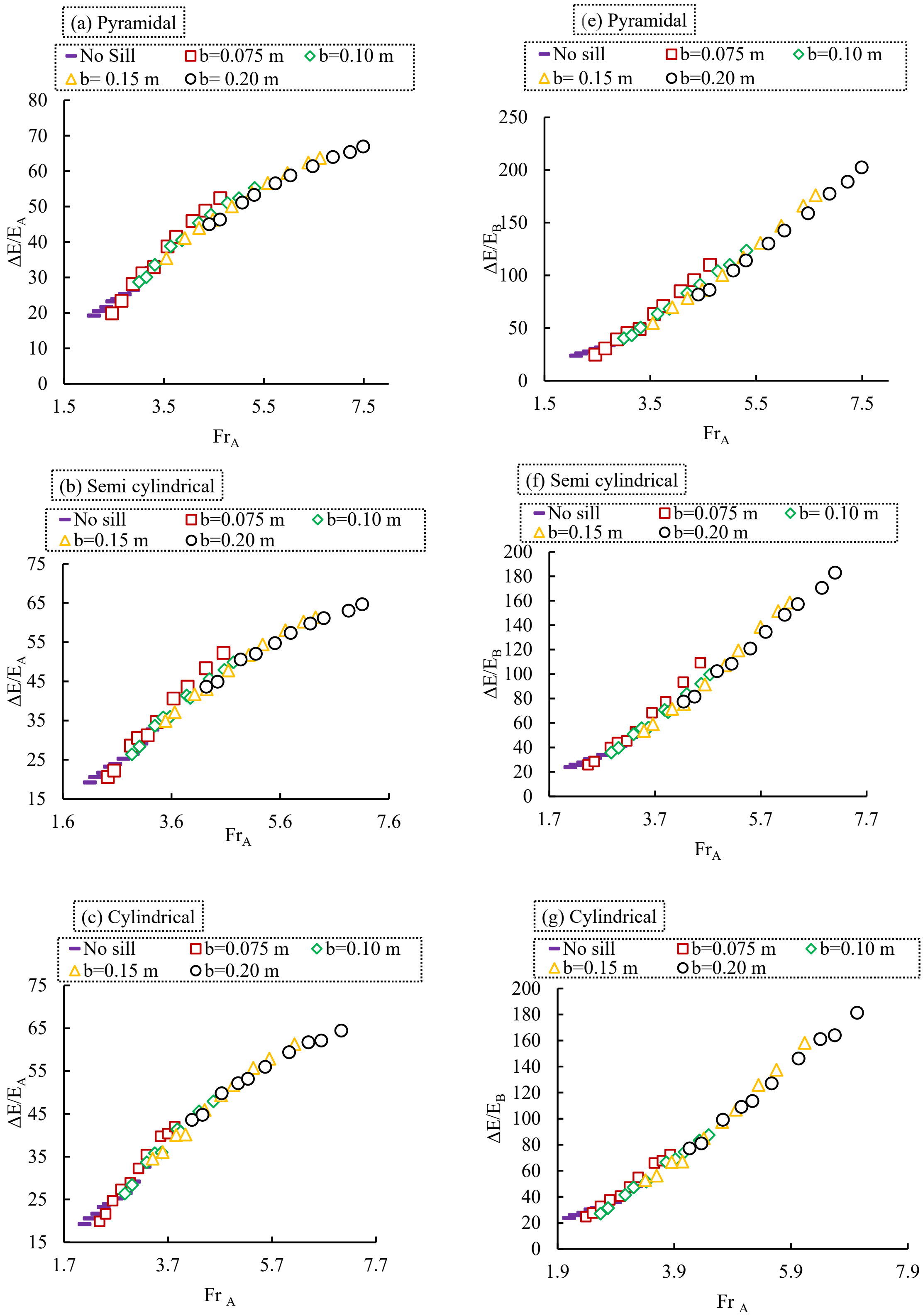

Figure 7. *Cont.*

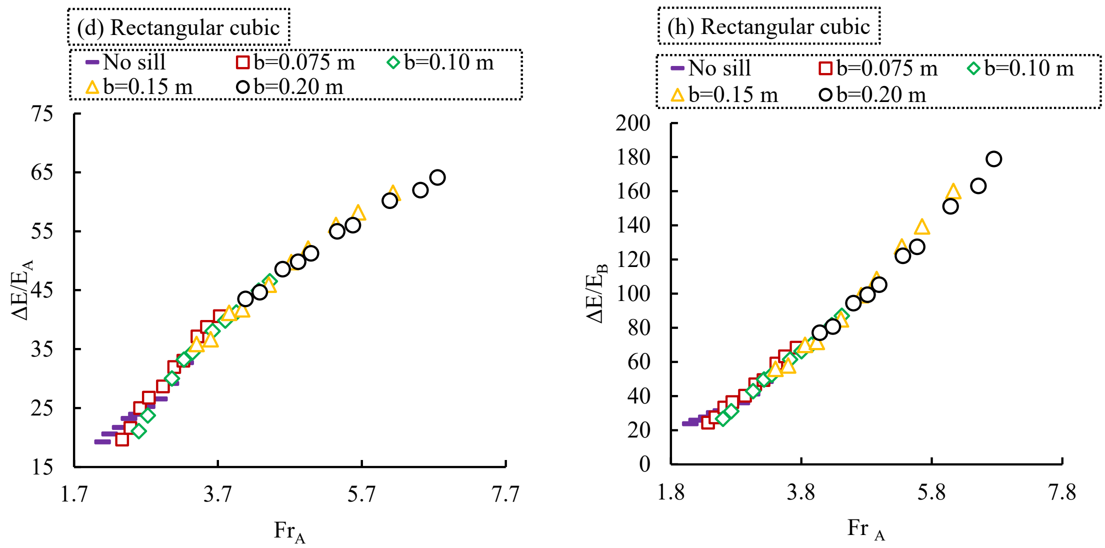

Figure 7. Relative energy loss for the (**a–d**) upstream and (**e–h**) downstream sections of the jump with sill.

The placement sills with different widths influence the hydraulic jump. Larger-width sills increase the energy loss. A sill with a larger width increases the flow velocity by reducing the cross-sectional area of the flow below the gate. The amount of energy loss compared to the energy in section A for a pyramid sill with the smallest width (b = 0.075 m) and the largest width (b = 0.20 m) compared to the non-sill mode resulted in an increase of energy loss (39.4 and 125%, respectively). This value decreased to 34.9 and 119%, 22.3 and 116%, and 2.21 and 3.12% for semi-cylindrical, cylindrical, and rectangular cube sills, respectively.

3.1.4. The Effect of Sill Width on the Performance of Hydraulic Jump Relative Depths

To investigate the changes in the relative depths of the hydraulic jump, sills with cubic, rectangular, pyramidal, cylindrical, and semi-cylindrical geometry with widths of 0.075, 0.10, 0.15, and 0.20 m were investigated. In Figure 8, the vertical axis is the relative conjugate depth, while the horizontal axis represents the parameter without the Froude number.

The graphs of hydraulic jump conjugate depth versus the Froude number indicate that placing the sill below the sluice gate causes an increase in the relative conjugate depth compared to the non-sill mode. Results obtained with a sill of different widths show that the conjugate depths are affected by the width of the sill. By increasing the sill width and consequently increasing the Froude number in section A, the sequent depth in section B and the hydraulic jump increases.

3.1.5. Effect of Sill Geometry on Hydraulic Jump Performance

The sills were placed under the sluice gate, with Figure 9 showing the position of the sills under the sluice gate. In this study, after numerical modeling, the streamlines were extracted using Tecplot software. The results showed that the flow pattern changes with the placement of the sill in different geometries. Thus, the pyramidal sill has caused an increase in the uniformity of the streamlines compared to the cubic and circular sills. This factor has caused a change in the initial depth of the jump and flow rate. According to the dimensional analysis, the percentage of relative energy loss compared to sections A and B was investigated versus the Froude number. The effect of sill geometries with widths of 0.075, 0.10, 0.15, and 0.20 m on energy dissipation was compared, as shown in Figure 10. The vertical axis indicates the energy loss in sections A and B, while the horizontal axis is the dimensionless Froude number.

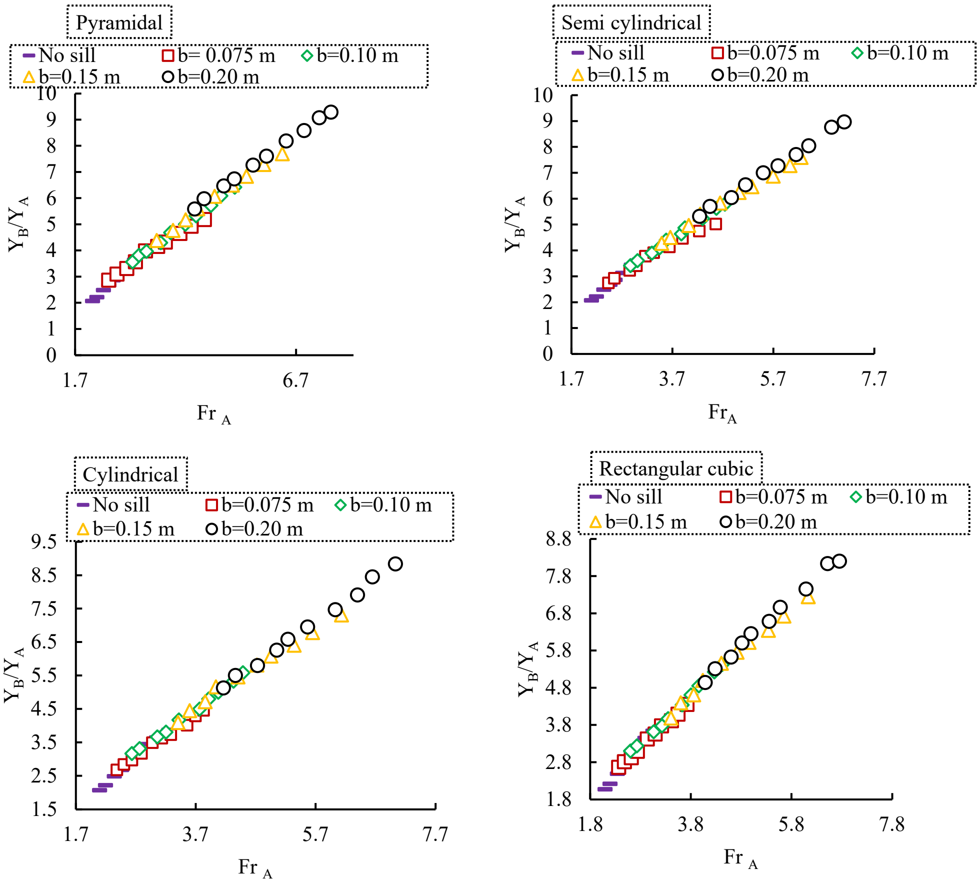

Figure 8. Effect of sill width on hydraulic depths.

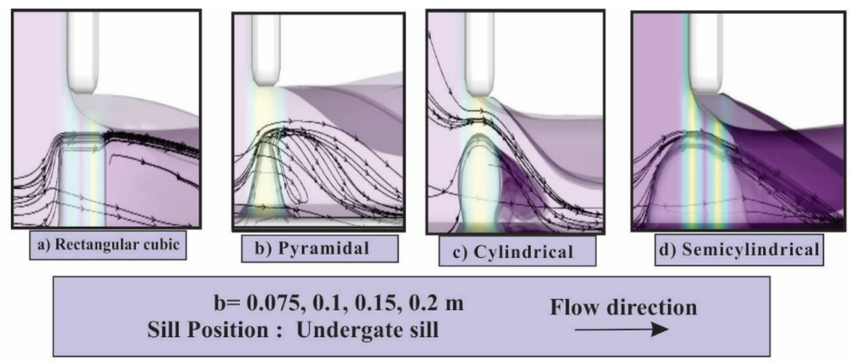

Figure 9. Schematic view of sill geometries.

Investigating the relative energy loss in sills with different geometries showed that the sill shape affects the hydraulic jump parameters. Sills with pyramidal, semi-cylindrical, cylindrical, and rectangular cube shapes resulted in the highest amount of energy dissipation, respectively. Examining the flow pattern downstream of the sill with different geometric shapes shows that the pyramidal sill causes a significant increase in velocity in section A. Sills with circular surfaces (semi-cylindrical and cylindrical) reduce the uniformity of the flow lines compared to the pyramidal sill. Using a cubic sill under the sluice gate forms a jet flow from the sill and leads to the formation of a region with a rotational flow. The decrease in the primary depth of the flow and the consequent increase in the secondary depth of the jump is the most important factor for increasing the energy loss. Therefore, considering the laboratory results, the greatest energy dissipation is related to pyramidal, semi-cylindrical, cylindrical, and rectangular cube geometries, respectively.

Examining sills with different geometrical shapes shows that they all increase energy dissipation compared to a no-sill situation. Sills of pyramidal, semi-cylindrical, cylindrical, and cubic shapes increased energy dissipation for locations A and B by 39.4 and 68%, 34.9 and 59%, 22.3 and 35.4%, and 21.2 and 33%, respectively. The values increased to 125 and 296%, 119 and 268%, 116 and 260%, and 115 and 260%, respectively, for the maximum width (Table 3).

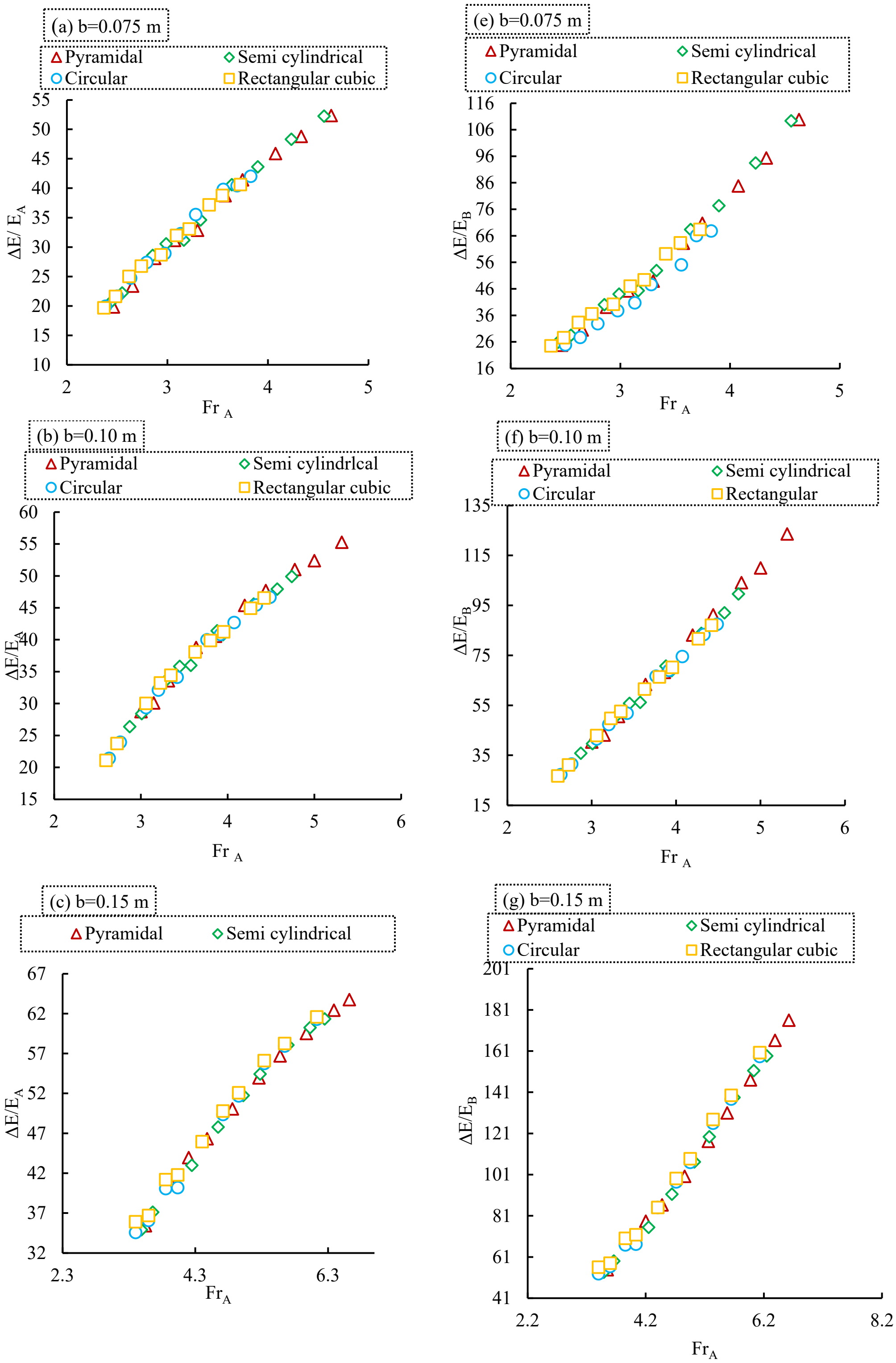

Figure 10. *Cont.*

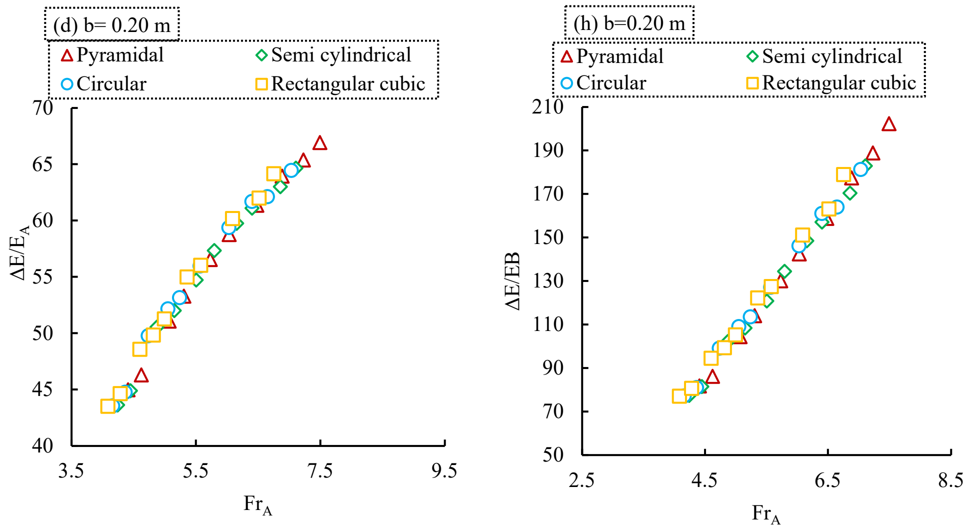

Figure 10. Energy loss values for the (**a–d**) upstream and (**e–h**) downstream sections of the jump with sill.

Table 3. Percentage increase in energy consumption of the sluice gate with a sill in sections A and B compared to non-sill state.

Rectangular Cubic		**Cylindrical**		**Semi-Cylindrical**		**Pyramidal**		**Sill Width (m)**
ΔE/EB	ΔE/EA	ΔE/EB	ΔE/EA	ΔE/EB	ΔE/EA	ΔE/EB	ΔE/EA	Sill withs
33	21.2	35.4	22.3	59	34.9	68	39.4	b = 0.075 m
260	115.3	260.2	116	268	118.9	295.9	125.4	b = 0.20 m

Results showed that the semi-cylindrical sill is most effective for increasing the discharge coefficient, while the pyramidal sill is most effective for increasing energy dissipation (Tables 2 and 3).

3.1.6. The Effect of Sill Geometry on the Performance of Hydraulic Jump Relative Depths

The ratio of the water depth in section B to the flow depth in section A was evaluated versus the Froude number of the supercritical flow. Figure 11 shows the water depth changes for sills with different geometries and with widths of 0.075, 0.10, 0.15, and 0.20 m.

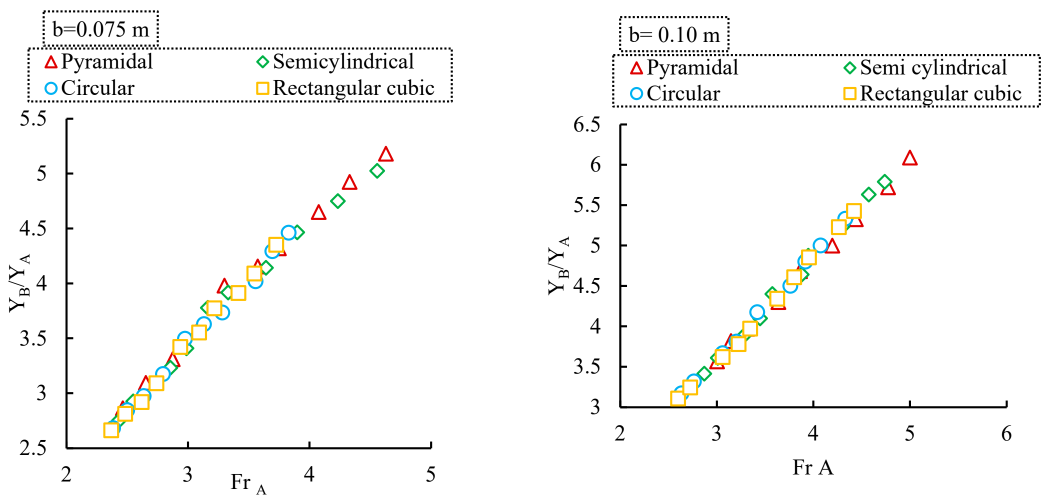

Figure 11. *Cont.*

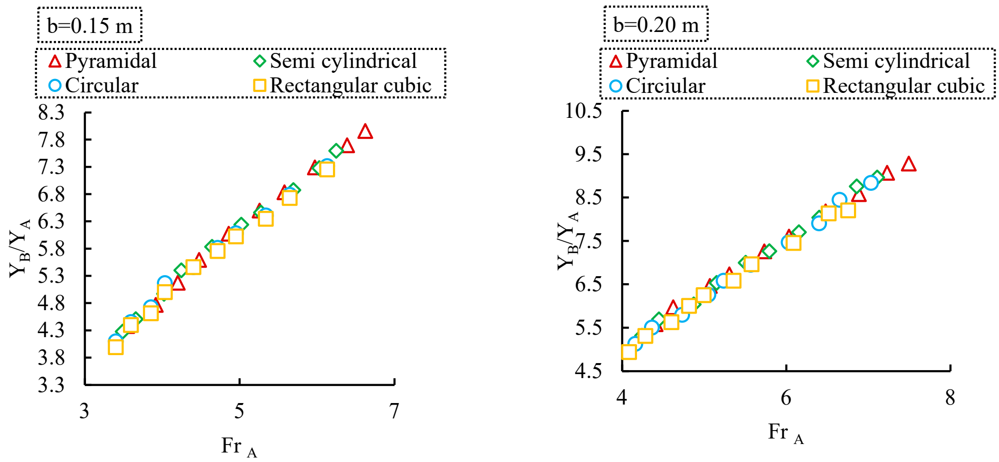

Figure 11. Effect of sill geometry on hydraulic depths.

Using the changes in water depth in sections A and B, the effect of sill geometry on jump conjugate depths can be determined. The results showed that the use of a rectangular cubic sill dramatically reduces the flow velocity in section A and, as a result, increases the flow depth compared to other sills. The decrease in the initial depth of the hydraulic jump with a pyramid sill increases the velocity downstream of the sill and reduces the flow depth. Using a sill with a circular surface (cylindrical and semi-cylindrical sills) causes a decrease in velocity compared to a pyramidal sill and an increase in velocity compared to a cubic sill.

4. Discussion

In this research, the simultaneous effect of the sill on the discharge coefficient and energy consumption was investigated. The results showed that the use of the sill affects the hydraulic parameters. In the following discussion, the impact of the scale effect has been investigated by considering previous studies. Hydraulic models are very useful tools to better understand the hydrodynamic behavior of flow. However, the effects of scale in the hydraulic modeling process led to the deviation of the results from the prototype. The results of the scale difference in the physical models showed that the smaller the scale, the greater the influence of fluid properties such as viscosity and surface tension. Therefore, in order to ignore the effect of viscosity, the Reynolds number in the laboratory model was chosen between 11,286 and 38,866. When the liquid is the same and the temperature is constant, in the experimental set-up, R_e and W_e are dependent on each other and vary with the opening of the gate, so one of the two must be eliminated; therefore, the effect of the Weber number was ignored. In order to check the effect of scale in the walls as well as possible, the experiments should be repeated for different widths of the flume and the results should be compared with the prototype. This research was conducted in a constant flume width in the laboratory and there was no prototype for this research. Therefore, the effect of scale has not been investigated, so the results can be correct for the flow conditions in this research [29–33].

5. Conclusions

The current research investigated the effect of a sill under a sluice gate on the discharge coefficient, conjugate depths, and energy loss. Sills of pyramidal, semi-cylindrical, cylindrical, and rectangular cube shapes and with widths of 0.075, 0.10, 0.15, and 0.20 m were installed below the sluice gate. It was found that:

The half-cylinder, cylinder, pyramid, and rectangular prism sills have the highest dis-charge coefficients, respectively. Experiments performed on the sluice gate discharge coefficient with different widths showed that at the lowest width (b = 0.20 m), the semi-cylindrical, cylindrical, pyramidal, and rectangular prism sills increased the discharge coefficient by 19.1, 17.2, 14.7, and 12.1%, respectively, compared to the no-sill case.

The results showed that the hydraulic jump characteristics are affected by the location of the sill. The amount of energy loss upstream and downstream of the hydraulic jump increases when a sill is used. The effect of the sill width on energy dissipation and conjugate depth was studied. The pyramidal sill increases the velocity of the flow due to the slope and therefore causes a decrease in the initial depth of the flow. Circular sills (semi-cylindrical and cylindrical) and the rectangular cube had the highest initial depth, respectively. The pyramid, semi-cylindrical, cylindrical, and rectangular cube sills in-creased the energy loss in sections A and B compared to the non-sill mode by 125 and 296%, 119 and 268%, 116 and 260%, and 115 and 260%, respectively. The greatest amount of energy dissipation was related to the pyramidal sill with the largest width.

The semi-cylindrical sill is most effective for increasing the discharge coefficient, while the pyramidal sill is most effective for increasing energy dissipation.

Author Contributions: Conceptualization, R.D., R.N., P.E., S.D.F. and J.P.A.; methodology, R.D., R.N. and P.E.; software, R.D., R.N. and P.E.; validation, R.D., R.N. and P.E; formal analysis, R.D., R.N. and P.E.; investigation, R.D., R.N., P.E., S.D.F. and J.P.A.; resources, R.D., R.N. and P.E.; data curation, P.E.; writing—original draft preparation, R.D., R.N., P.E., S.D.F. and J.P.A.; writing—review and editing, R.D., R.N., P.E., S.D.F. and J.P.A.; visualization, R.D., R.N. and P.E.; supervision, R.D.; project administration, P.E. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are contained within the article.

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

References

1. Seyed Hoshiyar, S.M.; Pirmoradian, N.; Ashrafzadeh, A.; Parvaresh Rizi, A. Performance Assessment of a Water Deliery Canal to Improve Agricultural Water Distribution. *Water Resour. Manag.* **2021**, *35*, 2487–2501. [CrossRef]
2. Daneshfaraz, R.; Norouzi, R.; Abbaszadeh, H.; Kuriqi, A.; Di Francesco, S. Influence of Sill on the Hydraulic Regime in Sluice Gates: An Experimental and Numerical Analysis. *Fluids* **2022**, *7*, 244. [CrossRef]
3. Henry, H. Discussion of Diffusion of Submerged Jets, by Albertson, ML, Dai, YB. *Trans. Am. Soc. Civ. Eng.* **1950**, *115*, 687–694.
4. Rajaratnam, N.; Subramanya, K. Flow Equation for the Sluice Gate. *J. Irrig. Drain. Div.* **1967**, *93*, 167–186. [CrossRef]
5. Swamee, P.K. Sluice-gate discharge equations. *J. Irrig. Drain. Eng.* **1992**, *118*, 56–60. [CrossRef]
6. Ferro, V. Simultaneous Flow over and under a gate. *Irrig. Drain. Eng.* **2000**, *126*, 190–193.
7. Reda, A.E.R. Modeling of flow characteristics beneath vertical and inclined sluice gates using artificial neural networks. *Ain Shams Eng. J.* **2016**, *7*, 917–924.
8. Salmasi, F.; Abraham, J. Prediction of discharge coefficients for sluice gates equipped with different geometric sills under the gate using multiple non-linear regression (MNLR). *J. Hydrol.* **2020**, *597*, 125728. [CrossRef]
9. Pástor, M.; Bocko, J.; Lengvarský, P.; Sivák, P.; Šarga, P. Experimental and Numerical Analysis of 60-Year-Old Sluice Gate Affected by Long-Term Operation. *Materials* **2020**, *13*, 5201. [CrossRef]
10. Shivapur, A.V.; Prakash, M.N.S. Inclined sluice gate for flow measurement. *ISH J. Hydraul. Eng.* **2005**, *11*, 46–56. [CrossRef]
11. Rajaratnam, N. Hydraulic jumps. In *Advances in Hydroscience*; Elsevier: Amsterdam, The Netherlands, 1967; Volume 4, pp. 197–280.
12. Rajaratnam, N. Hydraulic jump on rough bed. *Trans. Eng. Inst. Can.* **1968**, *11*, 1–8.
13. Ali, H.S.M. Effect of Roughened-Bed Stilling Basin on Length of Rectangular Hydraulic Jump. *J. Hydraul. Eng.* **1991**, *117*, 83–93. [CrossRef]
14. Alhamid, A.A. Effective roughness on horizontal rectangular stilling basins. *Trans. Ecol. Environ.* **1994**, *8*, 8.
15. Ead, S.A.; Rajaratnam, N. Hydraulic jumps on corrugated beds. *J. Hydraul. Eng.* **2002**, *128*, 656–663. [CrossRef]
16. Tokyay, N.D. Effect of Channel Bed Corrugations on Hydraulic Jumps. In *Impacts of Global Climate Change*; ASCE: Reston, VA, USA, 2005; pp. 1–9. [CrossRef]
17. Izadjoo, F.; Shafai-Bejestan, M. Corrugated bed hydraulic jump stilling basin. *J. Appl. Sci.* **2007**, *7*, 1164–1169. [CrossRef]
18. Abbaspour, A.; Dalir, A.H.; Farsadizadeh, D.; Sadraddini, A.A. Effect of sinusoidal corrugated bed on hydraulic jump characteristics. *J. Hydro-Environ. Res.* **2009**, *3*, 109–117. [CrossRef]
19. Ellayn, A.F.; Sun, Z.-L. Hydraulic jump basins with wedge-shaped baffles. *J. Zhejiang Univ. A* **2012**, *13*, 519–525. [CrossRef]

20. Samadi-Boroujeni, H.; Ghazali, M.; Gorbani, B.; Nafchi, R.F. Effect of triangular corrugated beds on the hydraulic jump characteristics. *Can. J. Civ. Eng.* **2013**, *40*, 841–847. [CrossRef]
21. Parsamehr, P.; Farsadizadeh, D.; Dalir, A.H.; Abbaspour, A.; Esfahani, M.J.N. Characteristics of hydraulic jump on rough bed with adverse slope. *ISH J. Hydraul. Eng.* **2017**, *23*, 301–307. [CrossRef]
22. Nasr Esfahani, M.J.; Shafai Bejestan, M. Design of stilling sasins using artificial roughness. *J. Civ. Eng.* **2012**, *2*, 159–163.
23. Parsamehr, P.; Hosseinzadeh Dalir, A.; Farsadi, D.; Abbaspour, A. Hydraulic jump on the bed with semi-cylindrical roughness. *J. Water Soil* **2012**, *26*, 775–785. [CrossRef]
24. Neisi, K.; Shafai, B.M. Characteristics of S-jump on Roughened Bed Stilling Basin. *J. Water Sci. Res.* **2013**, *5*, 25–34.
25. Jalil, S.A.; Sarhan, S.A.; Yaseen, M.S. Hydraulic Jump Properties Downstream a Sluice Gate with Prismatic Sill. *Res. J. Appl. Sci. Eng. Technol.* **2015**, *11*, 447–453. [CrossRef]
26. Daneshfaraz, R.; Norouzi, R.; Ebadzadeh, P. Experimental and numerical study of sluice gate flow pattern with non- suppressed sill and its effect on discharge coefficient in free-flow conditions. *J. Hydr. Struct.* **2022**, *8*, 1–20. [CrossRef]
27. Daneshfaraz, R.; Hasannia, V.; Norouzi, R.; Sihag, P.; Sadeghfam, S. Investigating the Effect of Horizontal Screen on Hydraulic Parameters of Vertical Drop. *Iran. J. Sci. Technol. Trans. Civ. Eng.* **2021**, *45*, 1909–1917. [CrossRef]
28. Daneshfaraz, R.; Noruzi, R.; Ebadzadeh, P. Experimental Investigation of non-suppressed sill effect with different geometry on flow pattern and discharge coefficient of sluice. *J. Hydr.* **2022**, *17*, 47–63. [CrossRef]
29. Daneshfaraz, R.; Norouzi, R.; Ebadzadeh, P. Evaluation Effect of changing the sill geometries and positions on discharge coefficient of vertical sluice gate. *J. Civ. Environ. Eng.* **2022**, *10*, 46–68. [CrossRef]
30. Lauria, A.; Calomino, F.; Alfonsi, G.; D'Ippolito, A. Discharge coefficients for sluice gates set in weirs at different upstream wall inclinations. *Water* **2020**, *12*, 245. [CrossRef]
31. Madadi, M.R.; Hosseinzadeh, D.A.; Farsadizadeh, D. Investigation of flow characteristics above trapezoidal broad-crested weirs. *Flow Meas. Instrument.* **2014**, *38*, 139–148. [CrossRef]
32. Nasrabadi, M.; Mehri, Y.; Ghassemi, A.; Omid, M.H. Predicting submerged hydraulic jump characteristics using machine learning methods. *Water Supply* **2021**, *21*, 4180–4194. [CrossRef]
33. Raju, R. Scale effects in analysis of discharge characteristics of weir and sluice gates. In *Scale Effects in Modeling Hydraulic Structures*; Kobus, H., Ed.; Springer: Esslingen am Neckar, Germany, 1984.