Experimental analysis of hydraulic jump at high froude numbers

OGUZ SIMSEK¹, M. SAMI AKOZ²,* and N GOKSU SOYDAN OKSAL³

¹Department of Civil Engineering, Harran University, Sanliurfa, Turkey
²Department of Civil Engineering, Cukurova University, Adana, Turkey
³Department of Civil Engineering, Mersin University, Mersin, Turkey
e-mail: oguzsimsek@harran.edu.tr; msa@cu.edu.tr; goksusoydan@mersin.edu.tr

MS received 15 January 2021; revised 9 August 2021; accepted 26 December 2022

Abstract. The hydraulic jump is a rapid transition state from supercritical to subcritical flow that occurs commonly in rivers, prismatic channels, and downstream of spillways. In this study, the characteristics of the hydraulic jump in a stilling basin downstream of the spillway chute channel with the slopes of \( \alpha = 12^\circ\) and \( 30^\circ\) were investigated experimentally for different Froude numbers of incoming flow, \( Fr_1 = 7, 7.5, 8, 9, 10, \) and \( 12, \) and relative heights of sill in the range of \( 4 < h_s/h_1 < 13 \) (\( h_s \), the sill height, \( h_1 \) the flow depth at toe of the jump, \( S \) relative height). The velocity field was measured by laser Doppler Anemometry in the experiments; it was particularly focused on the effects of both different structural configurations and flow conditions on the hydraulic jump and energy dissipation ratio. Experimental measurements showed that the length of the hydraulic jump and roller zone increases with the decrease of the sill height for \( \alpha = 12^\circ\) and \( 30^\circ\). In addition, the length of the hydraulic jump and roller zone increased with decreasing Froude numbers. The turbulence intensity in the jump region was determined to be greater than the turbulence intensity in the region near the bottom of the stilling basin. The turbulence intensity, in general, tended to decrease with decreasing Froude number.

Keywords. LDA; hydraulic jump; stilling basin; sill; turbulence.

1. Introduction

Hydraulic jump is a complex flow problem and surface discontinuity event that occurs during the transition from a supercritical to a subcritical regime in free surface flow, its occurrence depends on different hydraulic structures such as threshold, weir, sluice gate, base piers, or stilling basin. These hydraulic structures cause the flow depth to increase and the flow to pass through the hydraulic jump process. The transition is an extremely turbulent flow associated with the development of large-scale turbulence, surface waves and spray, energy dissipation, and air entrainment, and it is characterized by strong dissipative processes [1]. A hydraulic jump can serve many purposes. For example, to disperse flow energy to prevent bed erosion, to provide ventilation, or to facilitate the mixing of chemicals used to purify water [2].

Stilling basins are designed and constructed to dissipate energy and thus reduce the erosive power of the high-velocity flow downstream of chute spillways. The geometric properties of a stilling basin depend upon the water depth and Froude number of the incoming flow and the required energy dissipation rate. Hydraulic jump stilling basins may include drops, expansion, sills, baffles, blocks, and steps, typically used to decrease the basin length and stabilize the jump toe position [1].

An early study on the hydraulic jumps on the sloped channel was presented by Bakhmeteff, Matzke [3]. Kindvater [4] classified jumps on the sloped channel according to their toe position relative to the channel bottom kink: A-jump for which the toe is at the kink, B-jump is the intermediate of A- and C-jumps, C-jump for which the end of the roller is above the kink, and D-jump where the entire roller region is on the sloping channel. After Kindvater’s study, many studies have been conducted on these types of jumps [5–19]. Their main findings can be summarized as follows; (i) The energy dissipation rate decreases from A jump to D jump due to a reduction in the force of the hydraulic jump with the increasing tailwater depth, (ii) The hydraulic characteristics of the classical jump and the A-jump are similar, (iii) Regarding the decay of bottom shear velocity, the sloping and the classical jumps are identical (iv) The roller lengths of C- and D-jumps are almost identical, (v) D-jumps are located between the classical jump and the classical wall jet as regards the decay of maximum forward velocity, (vi) The maximum bottom velocities and maximum surface velocities are near the side-walls and along the centerline of the channel, respectively. Peterka [20] summarized the extensive experimental tests conducted at the United States Bureau of Reclamation
reported that the erosion and hydraulic precision of the tail waterbed should be taken into consideration during the design process. Debabeche, Achour [28] investigated the effect of the broad and thin crested sill on both the minimum-B jump and the sill-controlled jump under various inflow conditions in a horizontal symmetrical triangular open channel. Either a thin-crested or a broad-crested sill is used to create hydraulic jumps, for the Froude numbers range from 2 to 10. The data obtained from a large number of experimental results were adapted to empirical relations to notice the effect of the inflow Froude number on the different parameters, for instance relative sill height and the non-dimensional toe position of the sill. Ozbay [29] investigated the energy dissipation ratios of stepped, trapezoidal, T-shaped, and wedge-type baffle blocks placed in the chute channels. From the experiments, it was found to be that the stepped baffle block type has slightly higher values of energy dissipation than the other baffle blocks tested in the study. Alikhani et al [30] conducted an experiment to interpret the effects of a sill and position of the sill on control of the length and depth of a forced jump in stilling basin regardless of tailwater depth. The hydraulic properties of the jump were measured in different discharges, compared with the hydraulic properties of the classical hydraulic jump. As a result of the comparison, they determined that the sill had important effects on energy dissipation. They have developed a new relationship between parameters affecting hydraulic jump, such as sill height, sill distance, stilling basin length, and sequential depth ratio. Hamidifar, Omid [31], conducted an experimental study to investigate the effect of a broad-crested sill on controlling the hydraulic jump formed in a horizontal and symmetrical triangular channel. Their results were compared with the previous experimental and theoretical studies and empirical equations were developed to predict the sequent depth ratio and the length of the jump and surface rollers. Padulano et al [32] carried out experimental studies on the USBR II type to figure out its hydraulic behavior and dissipation efficiency. The effect of a continuous, transverse sill on the hydraulic jump in a rectangular channel is experimentally analyzed by Hager, Li [27]. They classified submerged hydraulic jumps and hydraulic jump types from A-jump to spray. They provided the drag force and coefficients along with supposes of pressure extreme fluctuations. They also presented an assessment of dissipation efficiency for submerged and non-submerged jumps, and this assessment provided the opportunity to compare between different types of the jump and classical hydraulic jump.

As the studies in which hydraulic jump is controlled using the sill are examined, it has been observed that studies on determining the velocity field of hydraulic jump with LDA are not enough. The LDA system has a great advantage in obtaining the velocity and turbulence characteristics of the flow without any intervention in the flow field. In addition, in past studies, the effect of sill height on
energy dissipation ratio, turbulence intensity, and the length of hydraulic jump and roller was not examined in the case of the same Froude number. In addition, while the hydraulic jump occurring after the sluice gate was examined in the previous studies, in this study the hydraulic jump is evaluated in the stilling basin after the spillway chute channel [26, 33–37]. For these reasons, this study has differences from the existing literature, and it is thought to contribute to the literature.

It is well known that laser Doppler Anemometry (LDA) provides quantitative information on both instantaneous and time-averaged structures of the velocity field. Using instantaneous data, detailed information on the turbulent flow field could be obtained. In the event of a forced hydraulic jump, the determination of the velocity field with the LDA will contribute. In addition, turbulence intensity, hydraulic jump length, and characteristics of the roller region are determined in the case of different flows and sill heights. Some experimental study is available in the literature on the hydraulic jump; however, the further experimental effort is needed either to confirm the previous findings or to provide new information for different experimental and structural conditions. The present study aims to determine the hydraulic jump characteristics in a stilling basin downstream of the chute channel with

Table 1. Experimental conditions.

| $\alpha$  | $V_1$ (m/s) | $h_1/h_1$ | $h_2/h_1$ | $L_b/h_1$ | Jump Type |
|----------|-------------|------------|------------|------------|------------|
| $= 30^\circ$ |
| 12.0     | 2.48        | 9          | 8.60       | 89         | A/Free     |
|          | 8.00        | 8          | 8.00       | 97         | A/Free     |
|          | 7.60        | 7          | 7.60       | 100        | A/Free     |
| 10.0     | 1.85        | 11         | 6.75       | 100        | A/Free     |
|          | 6.45        | 10         | 6.45       | 100        | A/Free     |
|          | 6.10        | 9          | 6.10       | 100        | A/Free     |
| 9.0      | 1.57        | 13         | 6.45       | 103        | B/Sub.     |
|          | 6.25        | 11         | 6.25       | 116        | B/Sub.     |
|          | 6.10        | 10         | 6.10       | 110        | B/Sub.     |
| $= 12^\circ$ |
| 8.0      | 0.70        | 6          | 9.70       | 71         | B/Sub.     |
|          | 8.80        | 5          | 8.80       | 79         | B/Sub.     |
|          | 8.30        | 4          | 8.30       | 89         | B/Sub.     |
| 7.5      | 0.55        | 7          | 8.80       | 80         | B/Sub.     |
|          | 8.10        | 6          | 8.10       | 84         | B/Sub.     |
|          | 7.75        | 5          | 7.75       | 91         | B/Sub.     |
| 7.0      | 0.50        | 8          | 8.25       | 80         | B/Sub.     |
|          | 7.70        | 7          | 7.70       | 80         | B/Sub.     |
|          | 6.70        | 6          | 6.70       | 90         | B/Sub.     |
different slopes for the Froude numbers in the range of $7 < \text{Fr}_1 < 12$ and relative sill heights in the range of $4 < \text{h}_s/\text{h}_1 < 13$. The results from the measured velocity fields by the LDA, turbulence intensity distributions, flow profiles, energy dissipation ratios, and geometrical characteristics of the hydraulic jump are presented to provide a detailed evaluation of the jump in a stilling basin.

2. Experimental setup

The experiments were performed in a rectangular, hydraulically smooth, side surfaces and base made of glass, horizontal stilling basin downstream of a spillway chute channel shown in figure 1. The chute channel was 0.20 m, 0.20m, and 1.8m wide, deep, and long, respectively and the stilling basin was 0.20m, 0.20m, and 1.50m wide, deep, and long, respectively. In the horizontal stilling basin, as shown in figure 1, a single-row, continuous sill was installed. The slope of the downstream side of the sill was chosen as 1/2. The sill crest width ($L_s$) was determined as 2.5 cm for all sill heights. The width of the sill was the same as the width of the stilling basin. In order to control the depth of the water, a sluice gate was placed at the end of the stilling basin. The position and form of the hydraulic jump were controlled with the help of this gate. Two different spillway chute channel slopes, $\alpha = 30^\circ$ and $12^\circ$, were used in the experiments. The velocity field was measured under three different flow conditions for each slope. The origin of the coordinate system (x, y) is located at the bottom left corner of the stilling basin.

The experiments were repeated for each sill height with different chute slopes. Experimental conditions are shown in table 1. In the table, $V_1$ is the average flow velocity in the pre-jump section, $h_2$ is the water depth of the cross-section after the jump, $L_b$ is the length of the stilling basin, Fr is the Froude number of the incoming flow and $\alpha$ is the slope angle of the chute channel. $h_1$ is the depth normal to the surface. As can be seen from table 1, when the Froude number is 12 and 10, type A and free hydraulic jump occur, while under other flow and sill conditions, type B and submerged hydraulic jump occur. A major limitation of this experimental work is the small size of the flume (20 cm wide), which will make the flow motions different from a full-scale hydraulic jump in stilling basin in many ways (roller development, air entrainment, surface deformation, etc.). The possible scale effects can be hardly ignored when velocity, turbulence, and energy dissipation are investigated at the centerline of the channel.

In the experiments, the flow velocities in the channel axis were measured with Laser Doppler Anemometer (LDA) and recorded with a Dantec LDA 62N04 flow explorer 1D high-power system, including a burst spectrum analyzer (BSA) F30 processor and integrated photo multiplier unit with BSA flow software. The laser output is supplied by operating at a wavelength of 660 nm. Beam spacing is 60 mm, and the measurable velocity fluctuation varies from 0.7 $\mu$m = s to 4.6 mm/s. The time-averaged velocity at a

![Figure 3](image_url). Streamwise velocity profiles at different sections in the stilling basin for Fr = 12 and $h_s/h_1 = 7, 8, \text{ and } 9$.
Figure 4. Streamwise velocity profiles at different sections in the stilling basin for $Fr_1 = 10$ and $h_s/h_1 = 9$, 10, and 11.

Figure 5. Streamwise velocity profiles at different sections in the stilling basin for $Fr_1 = 9$ and $h_s/h_1 = 10$, 11, and 13.
Figure 6. Streamwise velocity profiles at different sections in the stilling basin for Fr$_1$ = 8 and h$_s$/h$_1$ = 4, 5, and 6.

Figure 7. Streamwise velocity profiles at different sections in the stilling basin for Fr$_1$ = 7.5 and h$_s$/h$_1$ = 5, 6, and 7.
A point was detected by postprocessing of the measured instantaneous velocities. Some turbulence characteristics of the flow can also be determined from the time series containing instantaneous velocity values. Using the LDA system, the measurement time is adjusted to obtain flow parameters such as turbulence and velocity over a certain time interval or by using the number of measured data. Depending on the properties of the flow at the measurement point, the frequency, and the measured data validation levels of the LDA system can vary. Since these data are seen as insufficient, the measured turbulence and velocity values were not used especially in the roller region. The LDA performs instantaneous velocity measurements with ±1% accuracy within a 95% confidence interval. The postprocessing of the measured instantaneous velocities is carried out by BSA Flow software. This software includes both classic and advanced Spectrum algorithms. With the advanced Spectrum algorithm, turbulence spectra can be correctly estimated to frequencies near the mean data rate. The upper-frequency limit is thus higher than that of the classic Spectrum algorithm, which shows low-pass filtering behavior, with a cut-off frequency equal to half the mean data rate. This process is done automatically by the BSA Flow software.

The relative sill height at the same Froude numbers has not clearly effect on the variation of the relative length of the hydraulic jump, \( \frac{L_j}{h_1} \), and the relative roller zone, \( \frac{L_r}{h_1} \). The change of the \( \frac{h_s}{h_1} \) ratio according to the number of Fr1 is given in Figure 2. When the figure is examined, it is seen that the previous studies do not contain cases where the \( \frac{h_s}{h_1} \) ratio is greater than 8. Also, it is seen that the \( \frac{h_s}{h_1} \) ratio used for \( 6 < Fr_1 < 8 \) in the current study, has not been addressed in the literature. The difference in the tendencies of the S-Fr1 relation in previous studies and the one presented here, is because the hydraulic jump is observed after the sluice gate in the previous studies. In addition, in the present study, a free hydraulic jump occurs in some flow conditions, while a submerged hydraulic jump (B type) on the sloping base occurs in different flow cases. It may be considered that the type of hydraulic jump influences the absence of this definite relationship.

3. Results and discussions

The experimental velocity profiles, free surface flow profiles, geometrical properties of hydraulic jump, turbulence intensity distributions, and energy dissipation rates for different flow and sill conditions were presented. The velocities at the chute channel and the stilling basin were measured by an ultrasonic flow meter and limnimeter, respectively. As a result of the LDA measurement, the flow average velocity obtained along the depth is compared. In addition, discharge was measured with the help of a 60 × 60 × 20 chamber at the end of the channel. Thus, LDA velocity values were verified by 2 different methods.

The relative sill height at the same Froude numbers has not clearly effect on the variation of the relative length of the hydraulic jump, \( \frac{L_j}{h_1} \), and the relative roller zone, \( \frac{L_r}{h_1} \).

The change of the \( \frac{h_s}{h_1} \) ratio according to the number of Fr1 is given in Figure 2. When the figure is examined, it is seen that the previous studies do not contain cases where the \( \frac{h_s}{h_1} \) ratio is greater than 8. Also, it is seen that the \( \frac{h_s}{h_1} \) ratio used for \( 6 < Fr_1 < 8 \) in the current study, has not been addressed in the literature. The difference in the tendencies of the S-Fr1 relation in previous studies and the one presented here, is because the hydraulic jump is observed after the sluice gate in the previous studies. In addition, in the present study, a free hydraulic jump occurs in some flow conditions, while a submerged hydraulic jump (B type) on the sloping base occurs in different flow cases. It may be considered that the type of hydraulic jump influences the absence of this definite relationship.

Figure 8. Streamwise velocity profiles at different sections in the stilling basin for \( Fr_1 = 7 \) and \( \frac{h_s}{h_1} = 6, 7, \) and 8.
measured parallel to the bottom of the channel base with the LDA system. The instantaneous velocities in the channel middle axis are measured and recorded with LDA and the time-averaged velocity at a point was determined by postprocessing of the measured instantaneous velocities. The Froude numbers of incoming flows for different flow and sill conditions were calculated from the velocity measurements at the chute channel. The velocities at the region where the air mixture is dense could not be measured with LDA.

3.1 Velocity profiles

The streamwise velocity profiles at various sections of the stilling basin were presented in figures 3–8 for the ranges of $h_s/h_1 = 4–13$, chute channel slopes, $\alpha = 30^\circ$ and $\alpha = 12^\circ$; Froude numbers, $Fr_1 = 7, 7.5, 8, 9, 10, 12$. The velocity profiles under the circulatory flow region are similar to those of a plane turbulent wall jet. The streamwise velocities increase from zero at the stilling basin wall to a maximum value at $y = \delta_0$, which is the thickness of the
boundary layer. As can be seen from the figures, the boundary layer thickness increases with the distance from the entrance of stilling basin. The jet layer extends up to the inflexion point (change of slope of streamwise velocity, du²/dy² = 0), which is the lower boundary of the roller region. A roller region that is divided by the line u = 0 into the inner- and outer regions of circulatory flow takes place above the wall-jet flow layer. Momentum exchange occurs through the null streamwise velocity line within the circulatory flow layer [38]. It can also be seen from the figures of the velocity profiles that the dimensionless streamwise velocity value (u/V₁), in general, tends to decrease with increasing Froude number. On the other hand, the streamwise velocity values are in a decreasing trend with increasing sill height.

The maximum streamwise velocity occurs immediately upon entering the stilling basin for all the experiments and the intensity of the maximum streamwise velocity decreases as it moves downstream. It is clearly seen from the figures that the peak velocity values in the stilling basin for the chute channel slopes, α = 12° are higher than those of the α = 30°. The point at which streamwise velocity attained its peak value slightly shifts toward the free surface as moving in the streamwise direction. At the same Fr numbers, the maximum streamwise velocity, in general, decreases with the increase of the sill height. The values of peak velocity decrease as the Froude number are decreased at the same height of sill for both α = 12° and α = 30°. The rate of decay of maximum wall-jet velocity for α = 30° is slightly greater than that for α = 12°. The mean rate of decay of the maximum values is approximately 80% for all experiments.

The thickness of the roller region increases with increasing both the Froude number and sill height. The thickness of the roller zone gradually decreases as it moves downstream. The flow separation from the bed surface of the basin occurs in the just upstream of the sill. These boundary layer separations result from the increased pressure gradient and the inability of the flow to follow the geometric shape of the sill structure. The starting point of separation is located approximately at 0.5hₛ from the sill structure and the thickness of the separation region is approximately 0.15hₛ for all experiments. Boundary layer separation on the crest of the sill and channel bottom downstream of the sill occurs in almost all cases. In the same flow condition, the density of the air mixture in the hydraulic jump increases as the sill height decreases. In addition, the density of the air mixture increases with increasing inflow Froude number.

The height of the side walls of the stilling basin is directly associated with the depth of water (h₂) formed after the hydraulic jump. The high enough side wall height prevents effective hydraulic jumping but also plays a role in ensuring the safety of structures and riverbeds in the downstream region. For α = 12° and 30° chute channel slopes, experimental water surface profiles obtained using a limnimeter are obtained for the different Froude numbers (Fr₁ = 12, 10, 9, 8, 7.5, and 7) and relative sill heights, hₛ/h₁ ranging from 4 to 13. The flow profiles in the jump zone were determined on average at the entrance of the stilling basin, due to the dynamic nature of the hydraulic jump and the dense air mixture.
The figures show that with the decrease in the sill height, the amount of swelling that occurs at the upstream of the water depth and sill structure does not decrease. There is almost a uniform depth in the downstream region of the sill. Another result is that with the decrease in the Froude number, the water depth after the hydraulic jump is reduced.

For different sill heights and Froude numbers, in different sections of the stilling basin, the ratio of the maximum horizontal velocity component obtained along the water depth to the mean flow velocity before the hydraulic jump, the change of the cross-section distance according to the depth before the hydraulic jump is given in figure 9. It can be seen from the figure that the maximum value of \( \frac{u_{\text{max}}}{V_1} \) decreases with increasing sill height. For all sill heights and Froude numbers, it is determined that when the \( \frac{x}{y_1} \) value is about 50, the jet flow loses its effect. Namely, the hydraulic jump is about to be completed. It is seen that the \( \frac{u_{\text{max}}}{V_1} \) value increases again in the region close to the sill for all the heights of sill and Froude numbers.

Carvalho et al [39] determined that the velocity profiles obtained in different sections experimentally for \( \text{Fr}_1 = 6 \) are generally compatible with the velocity profiles given in figures 3 to 8, and the velocity magnitudes differ from each other depending on the flow velocity in the inlet section. Similarly, the velocity field of a submerged hydraulic jump occurred with \( \text{Fr}_1 = 8.19 \) and \( S_1 = 0.24 \) (\( S_1 \), submergence factor) was measured with LDA by Long et al [40]. They also determined that submerged jump for \( 3.01 \leq \text{Fr}_1 \leq 8.19 \) and \( 0.22 \leq S \leq 1.69 \), the \( \frac{u_{\text{max}}}{U_1} \) value decreased with the increase of \( \frac{x}{y_1} \). This finding is similar to the distribution given in figure 9. Hager, Li [27] measured the velocity field of the sill-controlled hydraulic jump at \( \text{Fr}_1 = 5.23 \) and \( h_1 = 1.42 \) m. From the velocity field obtained in the study, it was determined that the sill increased the amount of energy dissipation and could not completely control the hydraulic jump. In the present study, it has been seen that the sluice gate used in the control of tailwater depth is effective for the control of hydraulic jumps.

### 3.2 Geometric properties of hydraulic jumps

Figure 10 gives the geometric properties of the hydraulic jump. The lengths of the hydraulic jump and roller zone are determined by a large number of color experiments. In this case, the experiments of hydraulic jumps were recorded with a high-resolution camera. The lengths of the hydraulic jump and roller region are determined from the videos recorded. In addition, the beginning and the end section of the hydraulic jump and roller region are controlled and verified by the measurement of the velocity profiles using LDA. In the case of the same Froude number, \( \text{L}_b/h_1 \) and \( \text{L}_r/h_1 \) ratios decrease with the increase of the relative sill height. In addition, as the slope of the chute channel changes from 12° to 30°, the \( \text{L}_b/h_1 \) and \( \text{L}_r/h_1 \) ratios obtained for different Froude numbers highly decreases. In cases chute channel slope is \( \alpha = 12^\circ \), the ratio of \( \text{L}_b/h_1 \) and \( \text{L}_r/h_1 \) generally decreases with the decrease of the Froude number, while in the case of \( \alpha = 30^\circ \), the ratios of \( \text{L}_b/h_1 \) and \( \text{L}_r/h_1 \) increases as the Froude number increases due to the change of hydraulic jump type is from A type to B type, are given in table 1.

The comparison of the change of the \( \text{L}_b/h_1 \) according to the Froude number with the results of previous studies is given in figure 11 [34, 41–44]. While the results of this study are found to be consistent with the results of Kucukali, Chanson [41], there is a slight difference in the results of the Froude numbers 11 and 12. The discrepancy between the present study and previous studies is thought to be due to the creation of the hydraulic jump.

The length of the hydraulic jump is calculated as approximately 5 to 7 times “\( h_2-h_1 \)” [45]. Alikhani et al [30] suggested that the length of the stilling basin where controlled hydraulic jump by the sill is 3 to 5 times “\( h_2-h_1 \)” for the inflow Froude numbers ranging from 4 to 12 and \( S \) from 2 to 8. In this study, the lengths of the stilling basin are obtained as \( 4(h_2-h_1) \leq L_b \leq 7(h_2-h_1) \) for \( 7 \leq \text{Fr}_1 \leq 12 \) and \( 4 \leq S \leq 13 \). It is determined that the \( \text{L}_b/(h_2-h_1) \) ratio increased as the spillway slope decreased from 30° to 12°. From the results, it is concluded that a larger stilling basin length is required to control the hydraulic jump that occurs at the downstream of the spillway compared to the hydraulic jump formed on the downstream region of the sluice gate. Carvalho et al [39] concluded that the length of the roller zone, the length of the hydraulic jump, and the length of the area where there are air bubbles on the downstream of the spillway for \( \text{Fr}_1 = 6 \) were about 5 (\( h_2-h_1 \)), 7.1 (\( h_2-h_1 \)), and 8.52 (\( h_2-h_1 \)), respectively. For the

![Figure 12. The comparison of the \( L_b/h_1 \) according to the \( \text{Fr}_1 \) with Alikhani et al [30].](image-url)
hydraulic jump stilling basin with a continuous square baffle, the length of the hydraulic jump and the length of the area where there are air bubbles were 5.8(h₃-h₁) and 8.3(h₃-h₁), respectively (h₃ = tail water depth). In the case of the stilling basin with a continuous square baffle, it was seen that the hydraulic jump exceeded the continuous square baffle and could not be fully controlled by the continuous square baffle.

The variation of the Froude number depending on the inlet flow height of the sill distance for different S ratios is given by Alikhani et al [30]. A comparison of the present study with theirs is given in figure 12. By the comparison of the results, it is determined that the chute channel slope is effective on the length and roller region of the hydraulic jump occurring at the downstream of the spillway. It is seen that higher Lₒ/h₁ values occur for the hydraulic jump that at

Figure 13. Turbulence intensity for Fr₁ = 12, (a) hₒ/h₁ = 7, (b) hₒ/h₁ = 8 and (c) hₒ/h₁ = 9, α = 30°.

Figure 14. Turbulence intensity for Fr₁ = 9, (a) hₒ/h₁ = 10, (b) hₒ/h₁ = 11 and (c) hₒ/h₁ = 13, α = 30°.
higher Froude numbers with smaller discharges, depending on the slope. In addition, although larger $S$ values did not occur because of the $h_1$ value in the calculation of the $S$ value, it can be clearly said that the $S$ values of this study exceed 10. It has been determined that the results obtained for $Fr_1 = 12$ are quite compatible with each other.

3.3 Turbulence intensity

The flow has low velocity in the upstream of the spillway (subcritical region) passes through the structure crest (the critical depth) and reaches high velocities on the chute channel (the supercritical region). This flow has very high energy, is subjected to hydraulic jump to create excessive

![Figure 15. Turbulence intensity for $Fr_1 = 8$, (a) $h_s/h_1 = 4$, (b) $h_s/h_1 = 5$ and (c) $h_s/h_1 = 6$, $\alpha = 12^\circ$.](image)

![Figure 16. Turbulence intensity for $Fr_1 = 7$, (a) $h_s/h_1 = 6$, (b) $h_s/h_1 = 7$ and (c) $h_s/h_1 = 8$, $\alpha = 12^\circ$.](image)
turbulence, and is de-energized without damaging the structure and riverbed.

The LDA measures the instantaneous velocity values at the point where the velocity of the flow is determined and gives the opportunity to obtain the average velocity and velocity deviations related to the flow by using these values. The turbulence intensity ($I$) is calculated as given in equation 1 with the help of instantaneous point velocities in the flow region obtained by one-dimensional LDA used in the experiments:

$$I = \frac{\sqrt{u^2}}{\bar{u}}$$  (1)

where $u$ and $\bar{u}$ refers to the turbulence velocity deviation and the mean velocity value at the measured point, respectively.

Figures 13–16 show that the wall-normal profiles of streamwise turbulence intensities at the different sections of the stilling basin for Froude numbers and relative sill heights used in the present study. At the entrance to the stilling basin, the streamwise turbulence intensities first increase rapidly in the near-wall region and reach at a peak value then decreases and then increases again as it moves towards the free surface. The value of maximum streamwise turbulence intensity is higher than that of the free surface in the entrance region of the basin. The peak values of the turbulence intensities take place only in the roller region of the jump as it moves towards the downstream in the hydraulic jump region. In the roller region, the maximum streamwise turbulence intensity occurs around the line $u = 0$, where momentum exchange occurs. When the jump zone ends, the peak values of the streamwise turbulence intensity take place in the near-wall region as in the classical open channel flow. The peak values of streamwise turbulence intensity close to the bottom take place in the region $0.003 < y/\delta_0 < 0.8$, $y$ is wall-normal ordinate, and $\delta_0$ is the vertical distance where $u = u_{\text{max}}$. When the maximum values were compared, it was observed that the turbulent intensity values in the roller region were larger than those close to the bottom. It can be said from the experimental measurements that the streamwise turbulence intensity, in general, tends to increase with increasing Froude number. $\alpha = 12^\circ$ creates larger turbulence intensities at the entrance to the stilling base compared to $\alpha = 30^\circ$. No clear influences of the relative sill height on the variation of the streamwise turbulence intensities.

### Table 2. Energy dissipation ratios at the hydraulic jump for different structure and flow conditions.

| $\alpha = 30^\circ$ | $\alpha = 12^\circ$ |
|---------------------|---------------------|
| $F_1$  | $h_1$ | $E_1/E_1$ (%) | $F_1$  | $h_1$ | $E_1/E_1$ (%) |
| 12.0   | 9    | 73           | 8.0   | 6    | 57           |
| 9.0    | 11   | 62           | 7.5   | 7    | 46           |
| 10.0   | 11   | 62           | 7.5   | 7    | 46           |
| 9.0    | 11   | 51           | 7.0   | 8    | 36           |
| 10.0   | 10   | 52           | 7.0   | 8    | 36           |

Figure 17. Energy dissipation ratio according to $F_1$ and $S$.

### 3.4 Energy dissipation ratio in hydraulic jump

The water discharged over a spillway crest attains a very high kinetic energy and velocity at the end of the spillway chute channel. This high-velocity flow may cause serious scour and erosion of the riverbed downstream. Hydraulic jumps are used for the reduction of energy and velocity downstream of a spillway chute. The hydraulic jump can be seen in various forms depending on the pre-jump flow conditions. The energy losses can reach up to 65-85% depending on the Froude number of the incoming flow in the classical jump as in the jump occurs after the sluice gate (jump on the flat base). On the other hand, the energy losses in the hydraulic jumps occurring in the stilling basin at the downstream region of the spillway chute channel are slightly lower. The energy dissipated in the jump is represented by the loss of specific energy:

$$E_L = E_1 - E_2 = \left( h_1 + \frac{V_1^2}{2g} \right) - \left( h_2 + \frac{V_2^2}{2g} \right)$$  (2)
Figure 17(a) shows the energy losses in the hydraulic jump calculated using equation (2) for different Froude numbers of the incoming flow and chute slope of $\alpha = 12^\circ$ and $30^\circ$. It is clearly seen from the figure that dissipated energy considerably increases because of the stronger jump when the Froude number is increased for both $\alpha = 12^\circ$ and $30^\circ$. The dissipation energy rate is increasing with the Froude number at a faster rate for $\alpha = 12^\circ$ than $\alpha = 30^\circ$. In figure 17(b), the changes in energy dissipation ratio according to $h_s/h_1$ are presented for the chute channel slopes $\alpha = 30^\circ$ and $12^\circ$. The dissipated energy decreases when the relative sill height, $h_s/h_1$, is increased for both $\alpha = 12^\circ$ and $30^\circ$. Table 2 shows the ratios of dissipated energy at the hydraulic jump for different sill heights and Froude numbers. It is seen from the table that the maximum dissipated energy rate occurs for $Fr_1 = 12$ and $h_s/h_1 = 7$.

In addition, in figure 18, the changes in energy dissipation ratio according to $h_s/h_2$ are presented for $\alpha = 30^\circ$ and $12^\circ$. As can be seen from the figures, the energy losses in the hydraulic jump increase with increasing Froude number at the same ratio of $h_s/h_2$. Under conditions where the Froude number is constant, the energy loss decreases with the reduction of the $h_s/h_1$ ratio.

The energy dissipation rate in the hydraulic jump in the downstream region of the spillway is less than the classical hydraulic jump after the sluice gate. In the cases where the $Fr_1 = 12$, $10$, and $9$, the energy dissipation rate for $h_s = 4$ cm is 72.6, 61.9, and 49.6%, the energy dissipation rate for $h_s = 3.5$ cm is 74.4%, 63.5 and 51.2, respectively, for $h_s = 3$ cm this ratio is 75.7, 65.4, and 52.3%, respectively.

Figure 19 shows the comparison of the energy dissipation rate according to the Froude number with Fathi-Moghadam et al [37]. The energy dissipation rate obtained for $Fr_1 = 12$ is quite similar to the results obtained by Fathi-Moghadam et al [37]. Besides, for $Fr_1 = 8$, there is about a 10% difference in energy dissipation rate obtained with the same $h_s/h_1$ ratio as the results obtained by Fathi-Moghadam et al [37]. Due to the submerged hydraulic jump occurring in the downstream region of the spillway, the energy dissipation rate obtained in this study is less for other flow conditions. In addition, the tailwater depth influences reducing the energy dissipation rates.

4. Conclusions

In this study, experimental measurements were performed by using different Froude numbers and sill heights to determine the hydraulic jump characteristics in the stilling basin downstream of the spillway chute channel. From the measured velocity fields by LDA, the effects of Froude numbers and sill heights on hydraulic jump characteristics were investigated. The following results were found:

Results show that the maximum streamwise velocity occurs immediately upon entering the stilling basin for all the experiments and the intensity of the maximum streamwise velocity decreases as it moves downstream. At the same $Fr$ numbers, the maximum streamwise velocity, in general, decreases with the increase of the sill height. The values of peak velocity decrease as the Froude number are decreased at the same height of sill for both chute channel.
slopes $\alpha = 12^\circ$ and $\alpha = 30^\circ$. Furthermore, the maximum value of $u_{max}/V_i$ decreases with increasing sill height. For all sill heights and Froude numbers, it is determined that when the $x/y_1$ value is about 50, the jet flow loses its effect. Namely, the hydraulic jump is about to be completed.

The relative length of the hydraulic jump and the relative roller zone increase with the decrease of the relative sill height for chute channel slope $\alpha = 30^\circ$ and $\alpha = 12^\circ$. The experimental data show that the length of the roller region and hydraulic jump for $\alpha = 30^\circ$ are greater than those of $\alpha = 12^\circ$. The thickness of the roller region increases with increasing both the Froude number and sill height. The thickness of the roller zone gradually decreases as it moves downstream in the stilling basin. It can be concluded that the relative sill height at the same Froude numbers has not clearly effect on the variation of the relative length of the hydraulic jump, $L_j/h_1$, and the relative roller zone, $L_r/h_1$.

When the maximum values were compared, it was observed that the turbulent intensity values in the roller region were larger than those close to the bottom. In the roller region, the maximum streamwise turbulence intensity occurs around the line $u = 0$, where momentum exchange occurs.

Energy dissipation considerably increases because of the stronger jump as the Froude number is increased for both $\alpha = 12^\circ$ and $30^\circ$. The dissipated energy in the stilling basin decreases when the relative sill height is increased for both $\alpha = 12^\circ$ and $30^\circ$. In addition, the tailwater depth has an effect on reducing the energy dissipation rates.

Data availability The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] Chanson H 2015 Energy Dissipation in Hydraulic Structures. Taylor & Francis Group, London
[2] Gumus V, Simsek O, Soydan N G, Akoz M S and Kirkgoz M S 2016 Numerical modeling of submerged hydraulic jump from a sluice gate. J. Irrig. Drain. Eng. 142(1): 04015037
[3] Bakhmeteff B and Matzke A 1938 The hydraulic jump in sloping channels. Trans. ASME 60(HYD-60): 111–118
[4] Kingsvater C E 1944 The hydraulic jump in sloping channels. Trans. ASCE 109: 1107–1154
[5] Bradley J and Peterka A 1957 The hydraulic design of stilling basins: hydraulic jumps on a horizontal apron (basin i). J. Hydraul. Div. 83(5): 1–24
[6] Bunyan J 1958 Some aspects of the design of hydraulic structures in alluvium. Proc. Inst. Civ. Eng. 10(2): 145–162
[7] Smith D W and Walker J H 1959 Skin-Friction Measurements in Incompressible Flow. National Advisory Committee for Aeronautics
[8] Rao N and Rajaratnam N 1963 The submerged hydraulic jump. J. Hydraul. Div. 89(1): 139–162
[9] Mahmood K 1964 Effect of apron slope on hydraulic jump performance. MSc Thesis, University of Washington, Washington
[10] Wielogorski J and Wilson E 1970 Non-dimensional profile area coefficients for hydraulic jump in sloping rectangular channels. Water Power 22(4): 144–150
[11] Hari V M 1973 Plane jet on sloping floors under finite submergence. J. Hydraul. Div. 99(9): 1449–1460
[12] Rajaratnam N and Murahari V 1974 Flow characteristics of sloping channel jumps. J. Hydraul. Div. 100(6): 731–740
[13] Mikhalev M and Am H T 1976 Kinematic characteristics of a hydraulic jump on a sloping apron. Hydrotech. Constr. 10(7): 686–690
[14] Hager W H 1988 B-jump in sloping channel. J. Hydraul. Res. 26(5): 539–558
[15] Sene K, Thomas N and Goldring B 1989 Planar plunge-zone flow patterns and entrained bubble transport. J. Hydraul. Res. 27(3): 363–383
[16] Kawagoshi N and Hager W 1990 B-jump in sloping channel, II. J. Hydraul. Res. 28(4): 461–480
[17] Ohtsu I and Yasuda Y 1991 Hydraulic jump in sloping channels. J. Hydraul. Eng. 117(7): 905–921
[18] Kazemi F, Khodashenas S R and Sarkardeh H 2016 Experimental study of pressure fluctuation in stilling basins. Int. J. Civ. Eng. 14(1): 13–21
[19] Chern M-J and Vaziri N 2020 Effect of porous media on hydraulic jump characteristics by using smooth particle hydrodynamics method. Int. J. Civ. Eng. 18(3): 367–379
[20] Peterka A 1958 Hydraulic Design of Still Basins and Energy Dissipators Engineering Monograph No. 25. US Bureau of Reclamation, Denver Colorado
[21] Vittal N and Al-Garni A M 1992 Modified type III stilling basin-new method of design. J. Hydraul. Res. 30(4): 485–498
[22] Pourabollah N, Heidarpour M and Abedi Koupai J 2020 Characteristics of free and submerged hydraulic jumps in different stilling basins. In: Proceedings of the Institution of Civil Engineers-Water Management, vol. 3. Thomas Telford Ltd, pp. 121–131
[23] Izadjoo F and Shafai-Bejestan M 2007 Corrugated bed hydraulic jump stilling basin. J. Appl. Sci. 7(8): 1164–1169
[24] Ellayn A F and Sun Z-i 2012 Hydraulic jump basins with wedge-shaped baffles. J. Zhejiang Univ. Sci. A 13(7): 519–525
[25] Nandi B, Das S and Mazumdar A 2020 Experimental analysis and numerical simulation of hydraulic jump. In: IOP Conference Series: Earth and Environmental Science, vol. 1. IOP Publishing, p 012-024
[26] Ohtsu I, Yasuda Y and Yamanaka Y 1991 Drag on vertical sill of forced jump. J. Hydraul. Res. 29(1): 29–47
[27] Hager W H and Li D 1992 Sill-controlled energy dissipator. J. Hydraul. Res. 30(2): 165–181
[28] Debabeche M and Achour B 2007 Effect of sill in the hydraulic jump in a triangular channel/Effet du seuil sur le ressaut hydraulique dans un canal triangulaire. J. Hydraul. Res. 45(1): 135–139
[29] Ozbay O 2009 An investigation of energy dissipation ratios of different type energy dissipator blocks in chute channels. MSc, Firat University, Elazig
[30] Alikhani A, Behrozi-Rad R and Fathi-Moghadam M 2010 Hydraulic jump in stilling basin with vertical end sill. *Int. J. Phys. Sci.* 5(1): 25–29
[31] Hamidifar H and Omid M 2011 Using a broad crested sill to control hydraulic jump in a triangular channel. *J. Civ. Eng. (IEB)* 39(2): 103–110
[32] Padulano R, Fecarotta O, Del Giudice G and Caravetta A 2017 Hydraulic design of a USBR type II stilling basin. *J. Irrig. Drain. Eng.* 143(5): 04017001
[33] Rand W 1965 Flow over a vertical sill in an open channel. *J. Hydraul. Div.* 91(4): 97–121
[34] Hager W H, Bremen R and Kawagoshi N 1990 Classical hydraulic jump: length of roller. *J. Hydraul. Res.* 28(5): 591–608
[35] Karki K and Kumar S 1992 Drag on vertical sill of forced jump-discussion. *J. Hydraul. Res.* 30(2): 280–284
[36] Ohtsu I, Yasuda Y and Hashiba H 1996 Incipient jump conditions for flows over a vertical sill. *J. Hydraul. Eng.* 122(8): 465–469
[37] Fathi-Moghadam M, Kiani S, Asiaban P and Behrozi-Rad R 2017 Modeling of perforated sill-controlled hydraulic jump. *Int. J. Civ. Eng.* 15(4): 689–695
[38] Dey S, Nath T K and Bose S K 2010 Fully rough submerged plane wall-jets. *J. Hydro-environ. Res.* 4(4): 301–316
[39] Carvalho R, Lemos C and Ramos C 2008 Numerical computation of the flow in hydraulic jump stilling basins. *J. Hydraul. Res.* 46(6): 739–752
[40] Long D, Steffler P and Rajaratnam N 1990 LDA study of flow structure in submerged hydraulic jump. *J. Hydraul. Res.* 28(4): 437–460
[41] Kucukali S and Chanson H 2008 Turbulence measurements in the bubbly flow region of hydraulic jumps. *Exp. Therm. Fluid Sci.* 33(1): 41–53
[42] Murzyn F and Chanson H 2008 Experimental assessment of scale effects affecting two-phase flow properties in hydraulic jumps. *Exp. Fluids* 45(3): 513–521
[43] Murzyn F and Chanson H 2009 Free-surface fluctuations in hydraulic jumps: Experimental observations. *Exp. Therm. Fluid Sci.* 33(7): 1055–1064
[44] Wang H and Chanson H 2015 Experimental study of turbulent fluctuations in hydraulic jumps. *J. Hydraul. Eng.* 141(7): 04015010
[45] Kirkgoz MS 2018 Çözümlü Problemlerle Akişkanlar Mekaniği. Birsen Yaynevi, İstanbul, Türkiye