Experimental Analysis of Hydraulic Jump at High Froude Numbers

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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° 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 $4 < h_s/h_1 (S) < 13$ (S relative height). In the experiments, in which velocity field measured by laser Doppler Anemometry, it was particularly focused on the effects of both different structural configuration and flow conditions on the hydraulic jump and energy dissipation ratio. Experimental measurements showed that the length of hydraulic jump and the roller zone increases with the decrease of the sill height for $\alpha = 12^\circ$ and 30° . 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 stilling basin. The turbulence intensity, in general, tended to decrease with decreasing Froude number.

1. Introduction

Hydraulic jump is a complex flow problem and surface discontinuity event that occurs during the transition from supercritical to 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 mixing of chemicals used to purify water [2].

Stilling basins are designed and constructed to dissipate energy and thus reduce erosive power of the high velocity flow downstream of chute spillways. 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]. Kindsvater [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 roller is above the kink, and D-jump where the entire roller region is on the sloping channel. After the 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 reduction in the force of hydraulic jump with the increasing tail water depth, (ii) Loading [MathJax]/jax/output/CommonHTML/fonts/TeX/fontdata.js e 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 (USBR) and presented the general design rules of USBR-type stilling basins. Ohtsu et al. [21] experimentally measured the pressure distributions in the upstream and downstream region of the continuous and vertical sill in order to design a stilling basin for the purpose of creating a force hydraulic jump. By examining the flow characteristics passing over the sill, an experimental approach to the impulse force acting on the sill is proposed. Hager, Li [22], experimentally examined the effect of cross and uninterrupted sill on jump in a rectangular open channel. Based on the classical hydraulic jump results, they reported that the sill controlled hydraulic jump can be shown as an example of a disturbed classical hydraulic jump, especially in the case of the jump pattern. It was also reported that the erosion and hydraulic precision of the tail waterbed should be taken into consideration during the design process. Vittal, Al-Garni [23] presented a new method of design for the type USBR III stilling basin over a major range of discharges passing the spillway structure. The modified new basin is arranged in double rows of the single row of friction blocks in the USBR basin, to set up the velocity distribution of the subcritical flow after the hydraulic jump in the basin. Debabeche, Achour [24] investigated the effect of 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 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. Izadjoo, Shafai-Bejestan [25] experimentally investigated the effect of trapezoidal shape corrugated bed on flow characteristics of hydraulic jump for different Froude numbers and relative roughness. They found that corrugated bed, namely roughness, decreased the conjugate depth and hydraulic jump length 20% and 50% respectively. Ozbay [26] investigated the energy dissipation ratios of stepped, trapezoidal, T-shaped and wedge type baffle blocks placed 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. [27] conducted an experiment to interpret the effects of a sill and position of sill on control of length and depth of a forced jump in stilling basin regardless of tailwater depth. The hydraulic properties of the jump measured in different discharges, compared with 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 [28], 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

Loading [MathJax]/jax/output/CommonHTML/fonts/TeX/fontdata.js, Sun [29] performed laboratory investigations

to appraise the effect of a rough bed on hydraulic jump. The experiments were carried out using an artificially roughened bed with wedge-shaped baffle blocks for the Froude numbers in the range of $3.06 \leq F_1 \leq 10.95$ and a relative bed roughness ranging $0.22 \leq K_R \leq 1.4$. They concluded that in the new stilling basin model, formed with the roughened bed with wedge-shaped baffle blocks, there was a reduction of 30–50% in the hydraulic jump length and 16.5–30% in the sequent depth compared to the smooth bed. Padulano et al. [30] carried out experimental studies on USBSR 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 [22]. 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 jump and classical hydraulic jump. Nandi et al. [31] experimentally and numerically investigated the hydraulic jump that occurs in flow conditions where the Froude number varies between 2.17 and 7 with three different channel base slopes. Using the data obtained as a result of experimental modeling, they developed an empirical formula to determine the location of the hydraulic jump by regression analysis. As a result of the study, the experimental results were compared with numerical model results and it was determined that the results were quite compatible with each other. Pourabdollah et al. [32], carried out experimentally free and submerged hydraulic jump in different stilling basins. The effects of different adverse slopes, rough beds and positive step heights on hydraulic jump characteristics in the range of $4.56 < Fr < 9.55$ were investigated. They stated that the submerged depth ratio, lengths of the free and submerged hydraulic jumps are less than the classical hydraulic jump.

When 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 is 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 the past studies, the effect of sill height on energy dissipation ratio, turbulence intensity, 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 ([33, 34, 12, 35, 36, 21, 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 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, further experimental effort is needed either to confirm the previous findings or to provide new information for different experimental and structural conditions. The aim of the present study is to determine the

hydraulic jump characteristics in a stilling basin downstream of the chute channel with different slopes for the Froude numbers in the range of $7 < Fr_1 < 12$ and relative sill heights in the range of $4 < h_s/h_1 < 13$, where h_s is the sill height and h_1 is the flow depth at the toe of jump. The results from the measured velocity fields by the LDA, turbulence intensity distributions, flow profiles, energy dissipation ratios and geometrical characteristics of 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 Fig. 1. The chute channel was 0.20 m, 0.20 m and 1.8 m wide, deep, long, respectively and the stilling basin was 0.20 m, 0.20 m and 1.50 m wide, deep, long, respectively. In the horizontal stilling basin, as shown in Fig. 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 was controlled with the help of this gate. Two different spillway chute channel slopes, $\alpha = 30^\circ$ and 12° , were used in the experiments. The velocity field was measured under three different flow conditions for each slope.

The experiments were repeated for each sill height with different chute slopes. Experimental conditions are shown in Table 1. In the table, h_s sill height, h_1 is the water depth in the pre-jump section, 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_1 is the Froude number of the incoming flow and α is slope angle of the chute channel. As can be seen from Table 1, when the Froude number is 12 and 10, type A and free hydraulic jump occurs, while under other flow and sill conditions, type B and submerged hydraulic jump occurs.

Table 1
Experimental conditions

Fr_1	V_1 (m/s)	h_s/h_1	h_2/h_1	L_b/h_1	Jump Type
$\alpha = 30^\circ$					
12.0	2.48	9	8.60	89	A/Free
		8	8.00	97	A/Free
		7	7.60	100	A/Free
10.0	1.85	11	6.75	100	A/Free
		10	6.45	100	A/Free
		9	6.10	100	A/Free
9.0	1.57	13	6.45	103	B/Sub.
		11	6.25	116	B/Sub.
		10	6.10	110	B/Sub.
$\alpha = 12^\circ$					
8.0	0.70	6	9.70	71	B/Sub.
		5	8.80	79	B/Sub.
		4	8.30	126	B/Sub.
7.5	0.55	7	8.80	80	B/Sub.
		6	8.10	84	B/Sub.
		5	7.75	91	B/Sub.
7.0	0.50	8	8.25	80	B/Sub.
		7	7.70	80	B/Sub.
		6	6.70	90	B/Sub.

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. Laser output is supplied by operating in a wavelength of 660 nm. Beam spacing is 60 mm, and the measurable velocity fluctuation varies from $0.7 \mu\text{m/s}$ to 4.6 mm/s . The time-averaged velocity at a point was detected by postprocessing of the measured instantaneous velocities. Some turbulence

values. Using 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 insufficient, the measured turbulence and velocity values were not used especially in the roller region. The LDA performs instantaneous velocity measurements with $\pm 1\%$ accuracy within 95% confidence interval. The postprocessing of the measured instantaneous velocities are 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 discharge and free surface level were measured by 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 60x60x20 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 relative length of the hydraulic jump, L_j/h_1 , and the relative roller zone, L_r/h_1 .

The change of h_s / h_1 ratio according to the number of Fr_1 is given in Fig. 2. When the figure is examined, it is seen that the previous studies is not contain the cases where the h_s / h_1 ratio is greater than 8. Also, it is seen that the h_s / h_1 ratio used for $6 < Fr_1 < 8$ in the current studies, has not been addressed in the literature.

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 parallel to the bottom of the channel base with 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 chute channel. The velocities at the region where 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 Figs. 3–8 for the ranges of $h_s/h_1 = 4 - 13$, chute channel slopes, $\alpha = 30^\circ$ and $\alpha = 12^\circ$; Froude numbers, $Fr = 7, 7.5, 8, 9, 10, 12$. The velocity profiles under the circulatory flow region are similar to those of plane turbulent wall jet.

g basin wall to a maximum value at $y = \delta_0$,

which is thickness of 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, $du^2/dy^2 = 0$), which is the lower boundary of the roller region. A roller region that is divided by the line $u = 0$ into 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 (Dey et al. [38]). It can also be seen from the figures of the velocity profiles that the streamwise velocity, 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, $\alpha = 12^\circ$ are higher than those of the $\alpha = 30^\circ$. The point at which streamwise velocity attained its peak value slightly shifts to toward 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 $\alpha = 12^\circ$ and $\alpha = 30^\circ$. The rate of decay of maximum wall- jet velocity for $\alpha = 30^\circ$ is slightly greater than that for $\alpha = 12^\circ$. The mean rate of the decay of the maximum values is approximately 80% for all experiments.

The thickness of the roller region increases with increasing both 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 $0.5h_s$ from the sill structure and the thickness of the separation region is approximately $0.15h_s$ for all experiments. Boundary layer separation on the crest of sill and channel bottom downstream of the sill occurs for 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 (h_2) formed after hydraulic jump. The high enough side wall height prevents effective hydraulic jumping, but also plays a role in ensuring the safety of structures and riverbed in the downstream region. For $\alpha = 12^\circ$ and 30° chute channel slopes, experimental water surface profiles obtained using limnimeter are obtained for the different Froude numbers ($Fr_1 = 12, 10, 9, 8, 7.5$ and 7) and relative sill heights, h_s/h_1 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 Fig. 9. It can be seen from the figure that the maximum value of $u_{\max} / V_1$ 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. It is seen that the $u_{\max} / V_1$ value increases again in the region close to the sill for all the heights of sill and Froude numbers.

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 the large amount of color experiment. In this case, the experiments of hydraulic jump recorded with high resolution camera. The lengths of 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 by using LDA. In the case of the same Froude number, L_j/h_1 and 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 L_j/h_1 and L_r/h_1 ratios obtained for different Froude numbers are highly decreases. In cases chute channel slope is $\alpha = 12^\circ$, the ratio of L_j/h_1 and L_r/h_1 generally decreases with the decrease of the Froude number, while in the case of $\alpha = 30^\circ$, the ratios of L_j/h_1 and 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 the Table 1.

The comparison of the change of the L_r / h_1 according to the Froude number with the results of previous studies is given in Fig. 11 [39–41, 37, 42]. While the results of this study are found to be consistent with the results of Kucukali, Chanson [39], 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.

3.3 Turbulence Intensity

The flow has low velocity in the upstream of spillway (subcritical region) passes through the structure crest (the critical depth) and reaches high velocities on the chute channel (the super critical region). This flow, has a very high energy, is subjected to hydraulic jump to create excessive turbulence and 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. Using these values, The turbulence intensity (I) is calculated as given in Eq. 1 with the help of

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instantaneous point velocities in the flow region obtained by one-dimensional LDA used in the experiments:

$$I = \frac{\sqrt{\overline{u'^2}}}{\bar{u}}$$

1

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

Figures 12-15 show that the wall-normal profiles of streamwise turbulence intensities at the different section 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 bottom take place in the region $0.003 < y/d_0 < 0.8$, y is wall-normal ordinate and d_0 is vertical distance where $u=u_{\max}$. 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.

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 spillway chute channel. This high velocity flow may cause serious scour and erosion of 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 16-a shows the energy losses in the hydraulic jump calculated using Eq. (2) for different Froude numbers of incoming flow and chute slope of $\alpha = 12^\circ$ and 30° . 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° . The dissipation energy rate is increasing with Froude number at a faster rate for $\alpha = 12^\circ$ than $\alpha = 30^\circ$. In Fig. 20-b, the changes of energy dissipation ratio according to h_s/h_1 are presented for the chute channel slopes $\alpha = 30^\circ$ and 12° . The dissipated energy decreases when the relative sill height, h_s/h_1 , is increased for both $\alpha = 12^\circ$ and 30° . 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 $h_s/h_1 = 7$.

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

$\alpha = 30^\circ$			$\alpha = 12^\circ$		
Fr_1	h_s/h_1	E_L/E_1 (%)	Fr_1	h_s/h_1	E_L/E_1 (%)
12.0	9	73	8.0	6	57
	8	74		5	61
	7	76		4	63
10.0	11	62	7.5	7	46
	10	64		6	50
	9	65		5	52
9.0	13	50	7.0	8	36
	11	51		7	40
	10	52		6	48

In addition, in Fig. 17, the changes of energy dissipation ratio according to h_1/h_2 are presented for $\alpha = 30^\circ$ and 12° . 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_1/h_2 . Under conditions where the Froude number is constant, the energy loss decreases with the reduction of the h_2/h_1 ratio.

The energy dissipation rate in the hydraulic jump in the downstream region of 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 18 shows the comparison of the energy dissipation rate according to the Froude number with Fathi-Moghadam et al. [34]. The energy dissipation rate obtained for $Fr_1 = 12$ is quite similar to the results obtained by Fathi-Moghadam et al. [34]. Besides, for $Fr_1 = 8$, there is about 10% difference in energy dissipation rate obtained with the same h_s / h_1 ratio as the results obtained by Fathi-Moghadam et al. [34]. 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 tail water 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 a 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 slope $\alpha = 12^\circ$ and $\alpha = 30^\circ$. Furthermore, the maximum value of u_{max} / V_1 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 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 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° . The dissipated energy in the stilling basin decreases when the relative sill height is increased for both $\alpha = 12^\circ$ and 30° . In addition, the tail water depth has an effect on reducing the energy dissipation rates.

Declarations

DECLARATION OF COMPETING 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.

DATA AVAILABILITY STATEMENT

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

Author statement

Oguz SIMSEK: Conceptualization, Methodology, Validation, Formal analysis Investigation, Resources, Writing – original draft, Writing – review & editing.

M. Sami AKOZ: Conceptualization, Methodology, Validation, Investigation, Writing – original draft, Writing – review & editing, Supervision.

N. Goksu SOYDAN OKSAL: Methodology, Investigation, Formal analysis, Writing – review & editing.

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Figures

Figure 1

Schematic and plan views of the experiment model.

Figure 2

The comparison of the change of h_s / h_1 ratio according to Fr_1 with previous studies

Figure 3

Streamwise velocity profiles at different sections in the stilling basin for $Fr_1=12$ and $h_s/h_1 = 7, 8, 9$.

Figure 4

Streamwise velocity profiles at different sections in the stilling basin for $Fr_1=10$ and $h_s/h_1 = 9, 10, 11$.

Figure 5

Streamwise velocity profiles at different sections in the stilling basin for $Fr_1=9$ and $h_s/h_1 = 10, 11, 13$.

Figure 6

Streamwise velocity profiles at different sections in the stilling basin for $Fr_1=8$ and $h_s/h_1 = 4, 5, 6$.

Figure 7

Streamwise velocity profiles at different sections in the stilling basin for $Fr_1=7.5$ and $h_s/h_1 = 5, 6, 7$.

Figure 8

Streamwise velocity profiles at different sections in the stilling basin for $Fr_1=7$ and $h_s/h_1 = 6, 7, 8$.

Figure 9

u_{mak}/V_1 according to x/y_1 for the different height of sill and Froude numbers

Figure 10

L_j/h_1 and L_r/h_1 according to h_s/h_1 for the different Froude numbers

The comparison of the change of the L_r / h_1 according to the Fr_1 with previous studies

Figure 12

Turbulence intensity for $Fr_1=12$, a) $h_s/h_1=7$, b) $h_s/h_1=8$ and c) $h_s/h_1=9$, $\alpha=30^\circ$.

Figure 13

Turbulence intensity for $Fr_1=9$, a) $h_s/h_1=10$, b) $h_s/h_1=11$ and c) $h_s/h_1=13$, $\alpha=30^\circ$

Figure 14

Turbulence intensity for $Fr_1=8$, a) $h_s/h_1=4$, b) $h_s/h_1=5$ and c) $h_s/h_1=6$, $\alpha=12^\circ$

Figure 15

Turbulence intensity for $Fr_1=7$, a) $h_s/h_1=6$, b) $h_s/h_1=7$ and c) $h_s/h_1=8$, $\alpha=12^\circ$

Figure 16

Energy dissipation ratio according to Fr_1 and h_1/h_1 .

Figure 17

Energy dissipation ratio according to h_2/h_1 .

Figure 18

The comparison of the E_L/E_1 according to the Fr_1 with Fathi-Moghadam et al. [34]