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Research Article

Experimental Study on USBR Type Stilling Basin Design

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Abstract

Energy of water is to be dissipated forming hydraulic jump. The strength of jump depends on initial Froude number. The length of jump depends on the alternate depths. . This study is purposed to examine the effect of upstream face slope of weir in three models at vertical faced ogee shape weir, 60 degree slope ogee shape and 45 degree slope ogee shape weir in the case of jump formation at downstream side. The experiments were conducted in three discharge variations of magnitude 100 cm^3/sec, 150cm3/sec and200cm^3/sec. The depths and velocity at upstream, at crest, at toe and at tail location were measured and analyzed. From the comparative study the water rise in upstream was more in vertical faced weir than in others. The variation in velocity, Froude number found increased with the increase in discharge in all cases. The hydraulic jump length and loss in energy were changed with the change in discharge. The most effective length of stilling basin was found in case of vertical faced weir on the basis of jump length whereas from the energy dissipation point of view the maximum energy was dissipated in 60 degree slope face weir but the length of jump was greater in this weir. The coefficient of discharge variations were observed for all models and found in the range of 1.5 to 1.8 which is very close to the textbook value that showed the robustness of the experiments conducted.

Keywords: Weir shape; hydraulic jump; Energy Loss; Stilling Basin.

Introduction

Nepal is rich in surface water resources. The rivers from high Himalayan and Mahabharata range are perennial in nature having sufficient potential. In hilly region the hydro potential can be trapped for hydropower development and in plain region of Nepal they are source of irrigation(Sharma and Awal 2013) .The flow rates in rivers are low in dry season and high in summer season. The variation in discharge becomes problems for the water distribution in dry seasons. The artificial open canal made for the use of river water need proper reliable headworks structure in suitable site selected. The main components of the intake structures are dam for large reservoir type project and weir for small runoff type project where base flow of river water is sufficient to meet the required water demand. It is important to note that the dam may cause heavy supercritical flow at downstream at overflow condition during high flood period that will results in bed scouring at the downstream of the dam and weir. To protect the scouring stilling basin is to be planned and the hydraulic jump is to be formed for energy dissipation.

For energy dissipation in dam and weir various studies have been carried out. Most common energy dissipation structures are hydraulic jump type stilling basin, roller bucket type energy dissipaters and sky jump type of energy dissipaters. Baffle wall and chute block incorporated in hydraulic jump type stilling basin are used for velocity control and to reduce energy of flow(Saleh and Khassaf 2023). Such structures are to be designed for probable peak flood in a river of at least 100 years return period(Basin, Khadka, and Bhaukajee n.d.). The most common spillway structure for the safe management of over flow in reservoir is ogee shaped spillway with stilling basin at the downstream side for energy reduction. In case of Nepal the most of the hydropower plant are of peaking type rather than the reservoir type(Khadka 2021). The regulations of the reservoir are carried out by gate operation provided over the weir. In high flood period the hydraulic gates are operated to spill out the over flow in river. As per water law 10% of river water is to be released from the reservoir for ecosystem(Shrestha, 2016). For this purpose gate should be opened. Also during the flushing of sediment from the settling basin the high flow may cause large scouring at downstream of the river (Elsaeed *et al*., 2016). To protect it we provide stilling basin for hydraulic jump formation also in flushing chamber at downstream side. The energy dissipation depends on the types of jump formed and its strength(Siuta 2018). The strong jump is necessary to be formed commonly so that the large energy can be dissipated and water flow at minimum energy after the stilling basin. The strength of jump determines the size of the Basin to be constructed (Amin, 2015).

This study is aimed to determine the effect of shape variation of weirs and type of stilling basin to be constructed for energy loss. This study is expected to be a reference in weir construction planning for selection in water structures in irrigation, water supply and hydropower development. The study is planned to carry out on ogee type weir having upstream face at vertical, 60 degree and 45 degree on open canal flume at hydraulic laboratory.

Governing Theories and Equations

Discharge over the weir/ spillway is given by the continuity equation .But often we express the discharge in term of the discharge coefficient C, effective length of the spillway (Le) and net crest head including velocity head (He) as given by the equation below(Garg 1976)

$$Q = CLeHe^{\frac{3}{2}} \qquad (1)$$

The coefficient of discharge depends on the shape of the spillway and relative depth. The uppermost part of the spillway is interrelated to the flowing water that affects the flow characteristics at downstream side. The most common type of weir/ spillway is of ogee shape in downstream side. For planning there are definite equations for downstream slope design of spillway. According to USBR the slope is designed by the equation as

$$x^n = KH^{(n-1)}y \qquad (2)$$

Where X and y are the coordinate of the slope, K and n are the parameters depend on the slope of the spillway at upstream side and H is the water level over the crest. The Table1 shows the value of parameters for different upstream slopes of weir.

Table 1: Parameters of weir design

Upstream slope	K	n
Vertical	2.00	1.85
3:2	1.939	1.81
3:1	1.936	1.836
1:1	1.873	1.776

Stilling Basin

Stilling basins is an integral structure constructed downstream of numerous hydraulic structures such as spillways, gates, and weirs to dissipate the high kinetic energy of the incoming flow. The energy of water is dissipated in stilling basin by forming hydraulic jump (Saleh and Khassaf, 2023). Water flows from super critical to subcritical in basin. The length of jump determines the length of basin required for a flood discharge that spills out over the weir. The length of jump is considered as(Wüthrich *et al*., 2020)

$$Lj = 5(y_2 - y_1) \qquad (3)$$

Where y1 and y2 are alternate depths. The corresponding alternate depth for initial depth is calculated by

$$y_2 = \frac{y_1}{2}\left(-1 + \sqrt{(1 + 8Fr_1{}^2}\right) \qquad (4)$$

$$Fr_1 = \frac{V_1}{\sqrt{gy_1}} \qquad (5)$$

At equation 5 above Fr1 is the Froude number at initial depth and velocity V1 and Y1. The energy loss depends on the initial Froude number that defines the strength of jump. Higher the value of the initial Froude number stronger the jump and more the energy dissipation. The energy dissipation due to a hydraulic jump can be calculated by the formulae

$$\Delta E = \frac{(y2 - y1)^3}{4y1y2} \qquad (6)$$

Where ΔE is the energy loss over the hydraulic jump length at alternate depths y1 and y2.

USBR Criteria for Basin Length

Length of stilling basin is categorized depending on the initial Froude number Fr1. For this study USBR type I is purposed.

USBR Type 1 Stilling Basin:

According to USBR criteria the length and alternate depth ratio are given as in table 2 below. This type of basin is useful for the Froude number up to 6 and low initial velocity less than 5m/sec (Kamel, 2015). Fig. 1 is the schematic diagram of a USBR type 1 stilling basin without sill at the end.

Table 2: Criteria of USBR type I stilling basin

Fr1	2	3	4	6
L/y2	4.3	5.3	5.8	6

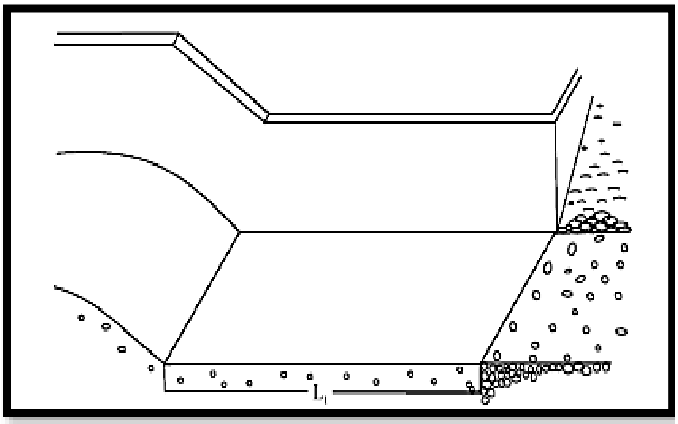

Fig.1: USBR type I stilling Basin for energy Dissipation

Literature Review on Stilling Basin Design

Various previous studies have been conducted in different approaches. Numerical as well as experimental examinations have been carried out on different shape of energy dissipaters on hydraulic jump type, roller bucket type and sky jump type(Ghamari, A., & Nekoufar 2015). Bdurrosyid and Pratiwi 2020 Conducted research on energy dissipation and hydraulic jumps with Ogee weir and stilling basin type solid roller bucket equipped with slotted and baffle blocks. The results showed that stilling basin type roller bucket with half-round slotted and concave type baffle blocks was the most effective against stream impact forces, reduced stream turbulence, reduced the length of hydraulic jump, and dissipated the energy. Abdurrosyid *et al.* (2018) conducted a study on the effect of variations in the weir slope of the downstream and the placement of baffle blocks in the stilling basin type solid roller bucket on hydraulic jumps and energy dissipation. He found the 1:1 slope was the most effective. Riman *et al.* (2017) conducted research on the study of flow behavior using a discharge instrument of round-crested weir on the water level. The study found that the relationship between discharge and the water level upstream, the water level downstream, the water level above threshold, and the discharge coefficient of round-crested weir. Ihsan (2017) carried out a study on the effect of the shape of the weir on the jump height of the stilling basin USBR-IV model (laboratory simulation). The amount of the discharge, the slope of the channel bottom, and the difference in the shape of the weir affected the height of hydraulic jump. The height of hydraulic jump on round-crested weir was higher than hydraulic jump on the width threshold. In comparison, the height of hydraulic jump over the stilling basin on width threshold was higher than that of the round- crested weir at the same discharge and slope.Nurjanah (2014) analyzed the height and length of hydraulic jump in the construction of an arched sharp-crested weir. The results of the study indicated that the length of hydraulic jump and the height of hydraulic jump was influenced by the cross-sectional diameter and velocity, in which the smaller the cross-sectional diameter and the greater the velocity, the longer the length of hydraulic jump occurs and lowered the height. Meanwhile, large cross-sectional diameter with a small velocity resulted in a smaller length of hydraulic jump and an increased the height(. 2014). The criteria recommended by Bureau of Indian Standards (BIS) code IS 4997-1968 for stilling basins of rectangular cross-section with horizontal apron hold good provided that the jet entering the basin is reasonably uniform in regard to both velocity and depth.(Sundarlal *et al.*, 2022)

Method and Materials

The research study is aimed to carry out in artificial open channel rectangular flume at Hydraulic Laboratory Hall of Purwanchal Campus Dharan, Institute of Engineering This study employed primary data from laboratory testing using a Recirculating Flume instrument of 5.0 m long, 0.30 m wide channel, and 0.30 m flume height. Fig. 3 is the sketch of the flume used. Three weir/spillway models were prepared in soil laboratory using cement concrete material in three different shapes as vertical face up stream, at slope of 45 and 60 degree as shown in Fig. 4 below**.** The physical models prepared were placed in the flume at mid position by length and experimentation were carried out for different discharges of 100,150 and 200 cm^3/sec measured by volumetric meter attached at the tail of flume. Experiments were conducted at a horizontal slope of canal, data were recorded and the calculation were carried out to make comparative study of the stilling basin design and energy dissipation due to hydraulic jump formed for each type of weir. The comparative study for discharge coefficient for each weir was calculated. Fig. 2 depicts the flowchart of the research methodology and Fig. 3 shows the experimental flow over each type of weir during experiment conducted.

Define the Research Problem, Aim and Literature Review

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Experiment Set up

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Laboratory Flume(5 m long,0.3 m wide,0.3 m depth)

↓

Preparation of Physical Models

↓

Laboratory experiments

↓

1.Three different Discharges are applied ranging from 100,150 and 200 cm^3//sec
2.Slope of canal is adjusted horizontal
3 For each discharge upstream velocity, crest velocity, initial and final velocity, Froude number, energy losses and coefficients of velocity for each model are measured.

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Data analysis ,Result Discussion and Conclusion and Recommendation

Fig. 2: flowchart of the research methodology

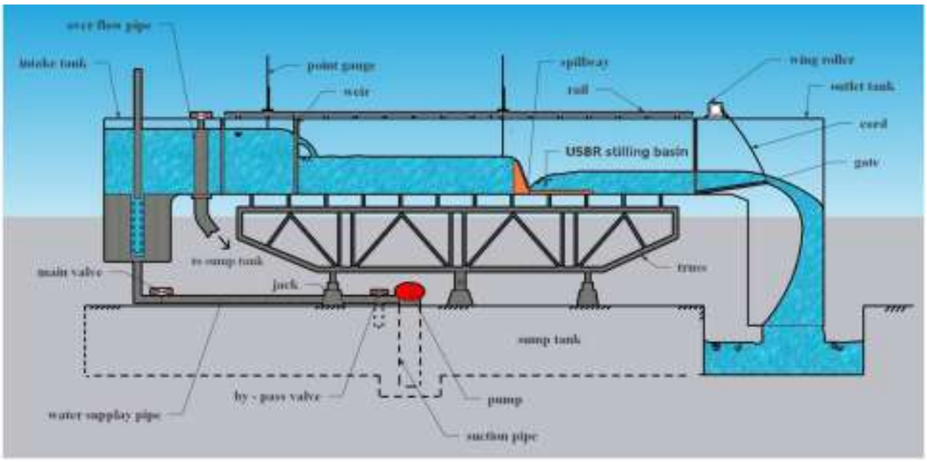


Fig. 3: Sketch of the Laboratory Flume

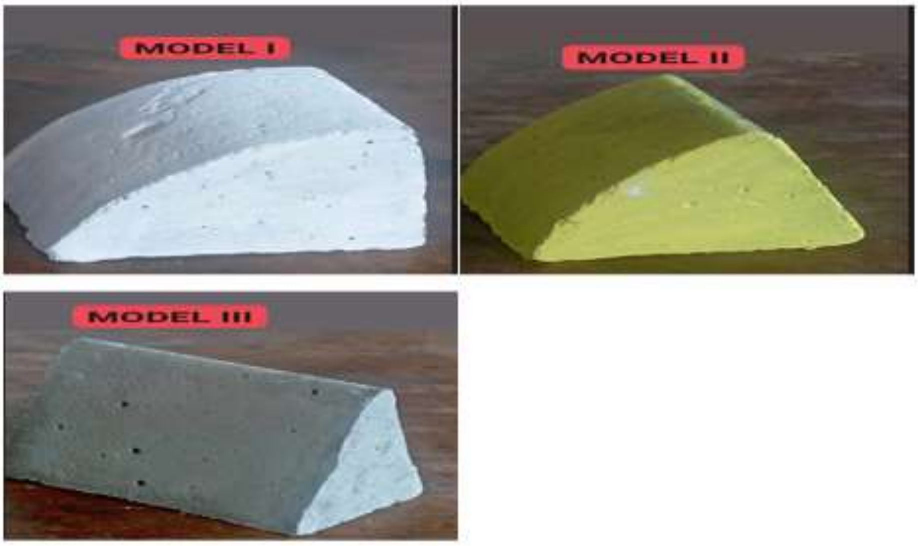
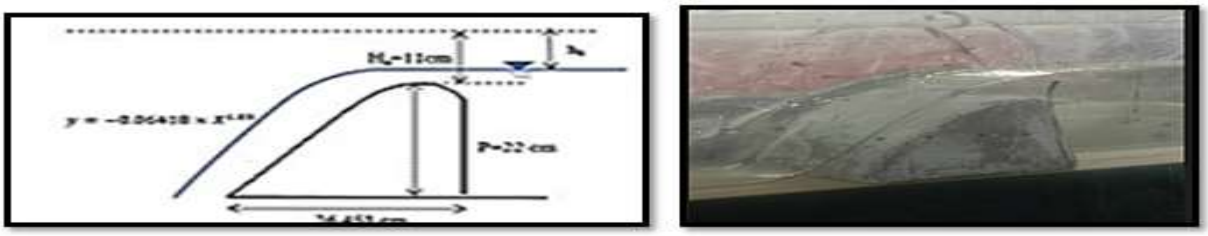
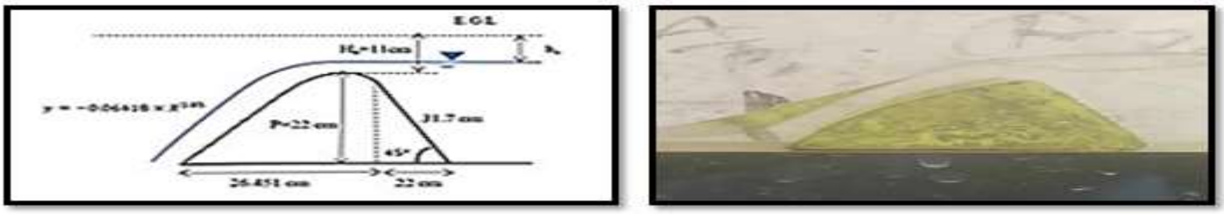


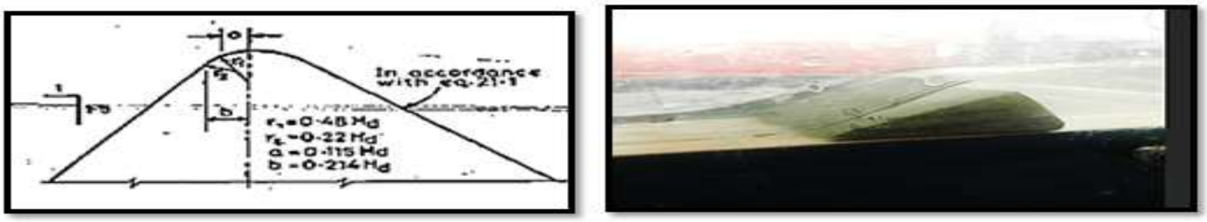
Fig. 4: Physical models prepared in Soil Laboratory (model I vertical ,Model II 45 degree,model III 60 degree upstream face.



An ogee weir with vertical up stream face



An ogee shaped weir 45 Degree upstream Face



An Ogee shaped weir 60 Degree Upstream Face

Fig. 5: Experimental observation in each weir

Results and Discussions

Next the results of the experimental study were analyzed by the equations available and graphical representations were presented. The hydraulic jump formations were studied on three different models as developed and shown above. The experiment was carried out on three different discharge variation of 100,150 and 200 cm^3/sec regulated by the gate valve and measured by volumetric bench attached at the end of the flume. The result analysis includes the following descriptions.

Flow velocity, Froude number and hydraulic jump length analysis with Discharge variation

The locations for the depth measurements were upstream of the weir section, crest, initial position of the jump (toe) and end point of the jump. The velocities at these locations Vup, Vcrest, V1, and V2 were calculated for each weir at discharge of 100 cm^3/sec, 150cm3/sec and 200 cm^3/sec. For the initial velocity the corresponding Froude number was calculated. The jump lengths were calculated using the equation for hydraulic jump and energy dissipation were estimated for each discharge case. The relationships of variation of flow velocities in all location with the discharge variation were plotted. The Figure 6 is the graphical results obtained for vertical upstream face ogee shaped weir. From the analysis the corresponding velocities are found increased with the increase in discharges. Also the coefficient of discharge for the weir was calculated at each discharge and the relationship with discharge variation were plotted as shown in Fig. 7. Similarly, the relationship of velocities, and hydraulic jump were plotted for 45 degree and 60 degree upstream faced weir were plotted. The Fig. 8 and 10 are the graphical results for both weirs. The coefficient of discharge for both weirs was calculated and the resultant graphs were plotted as shown in Fig. 9 and Fig. 11. Fig. 12 shows the variation of initial Froude number with the increase in discharge and a comparison could be made for each weir tested. Similarly, a comparative graphical result was made for discharge coefficients as shown in Figure 13. From the analysis the coefficient of discharge for all weir were found increased with the increased in discharge. The graph plotted showed the R value 1 for each weir that showed the robustness of the experimental observation. The comparative study was carried out for length of jump. The jump length for 60-degree weir was found largest and smallest for vertical faced ogee weir. The Figure 14 is the comparative graphs plotted for the hydraulic jump. From the observation it was found higher the discharge greater was the length of the jump in each weir that satisfied the fundamental principles of rapid varied flow and hydraulic jump formation conditions. The stilling basin length to be provided is equal to the jump length. From the analysis the vertical faced weir found more effective than other for the stilling basin length in same channel condition. The shortest length of basin is suitable for the weir at downstream from economic point of view.

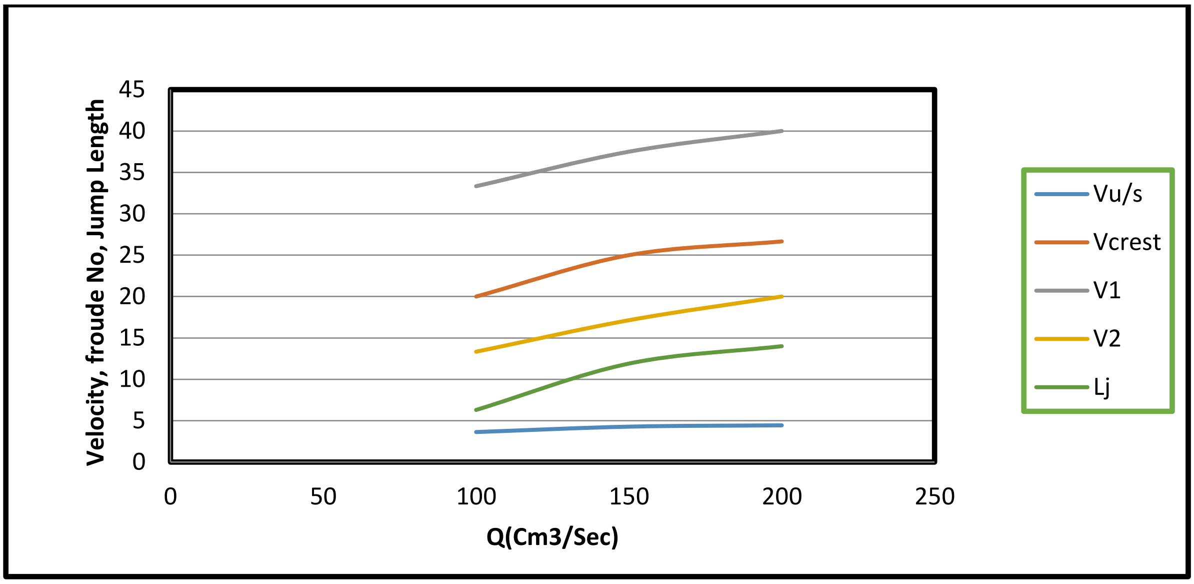


Fig. 6: Relationship between Discharge variation and Velocities, Froude Number and Hydraulic jump length for ogee shaped weir vertical upstream face

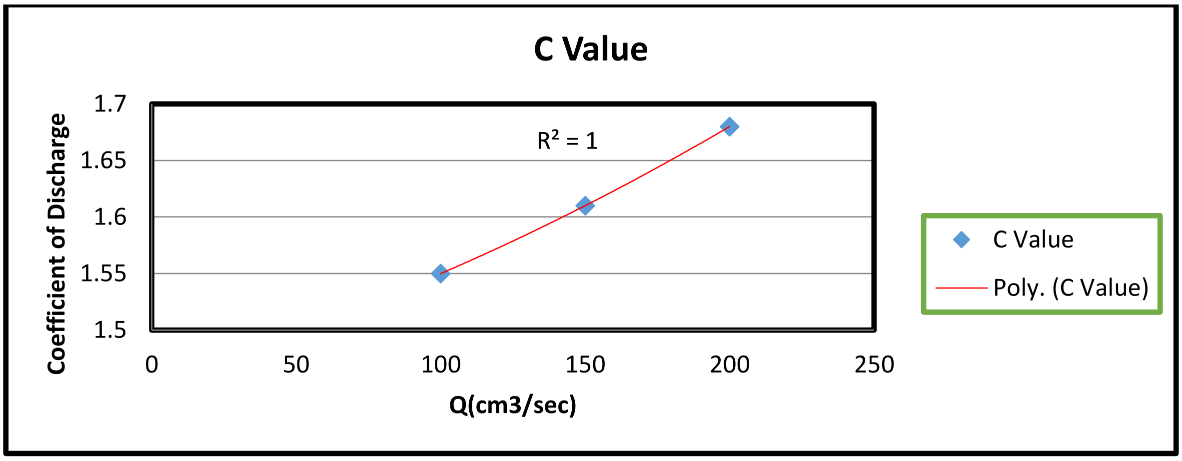


Fig.7: Relationship between Discharge Variation and Coefficient of Discharge for vertical upstream faced ogee shaped weir

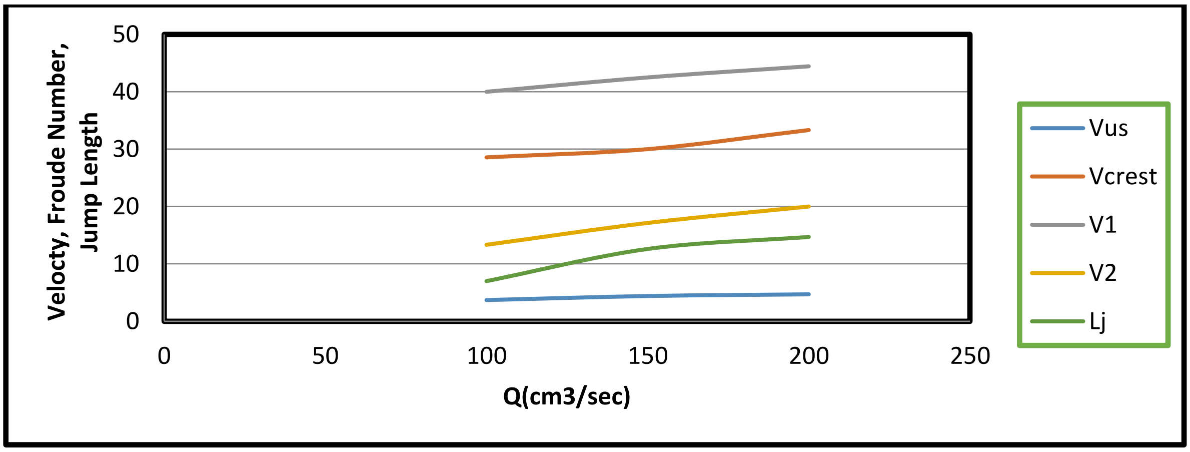


Fig. 8: Relationship between Discharge variation and Velocities, Froude Number and Hydraulic jump length for ogee shaped weir 45 Degree upstream face.

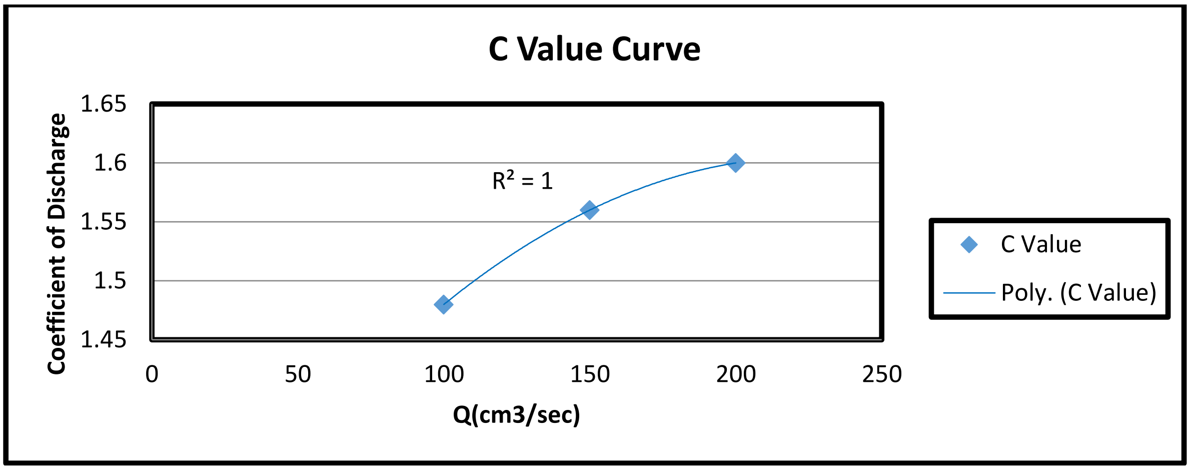


Fig.9: Relationship between Discharge Variation and Coefficient of Discharge for 45 Degree upstream faced ogee shaped weir.

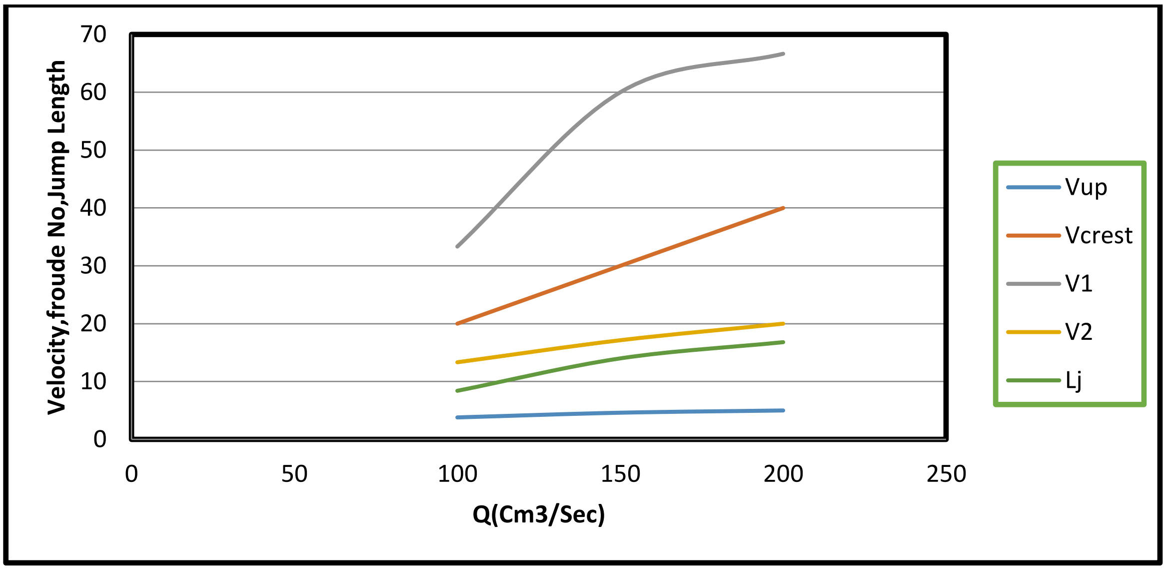


Fig.10: Relationship between Discharge variation and Velocities, and Hydraulic jump length for ogee shaped weir 60 Degree upstream face.

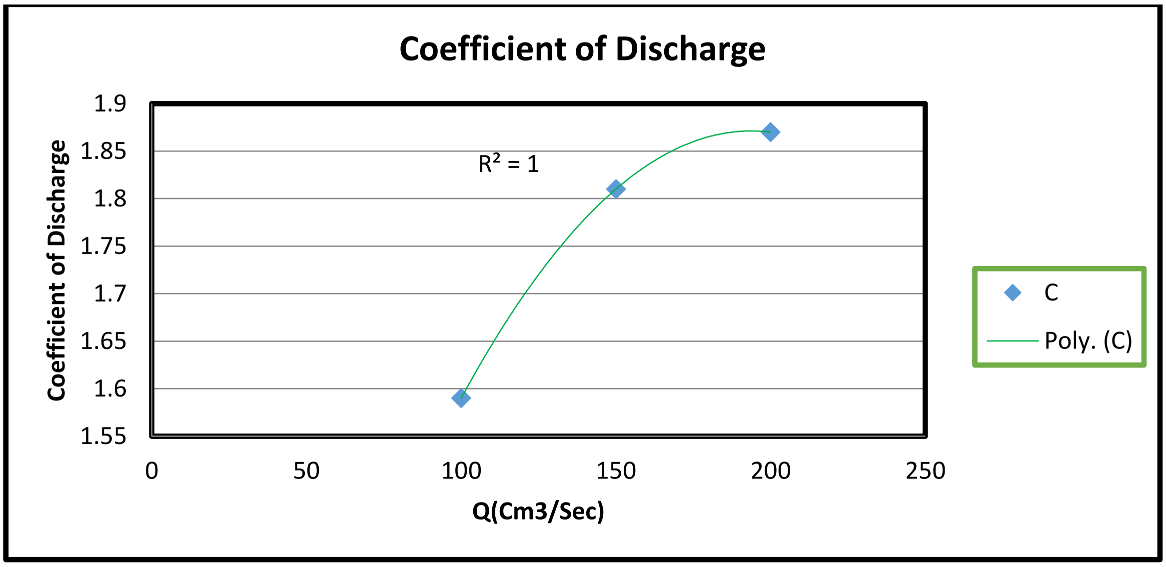


Fig.11: Relationship between Discharge Variation and Coefficient of Discharge for 60 Degree upstream faced ogee shaped weir.

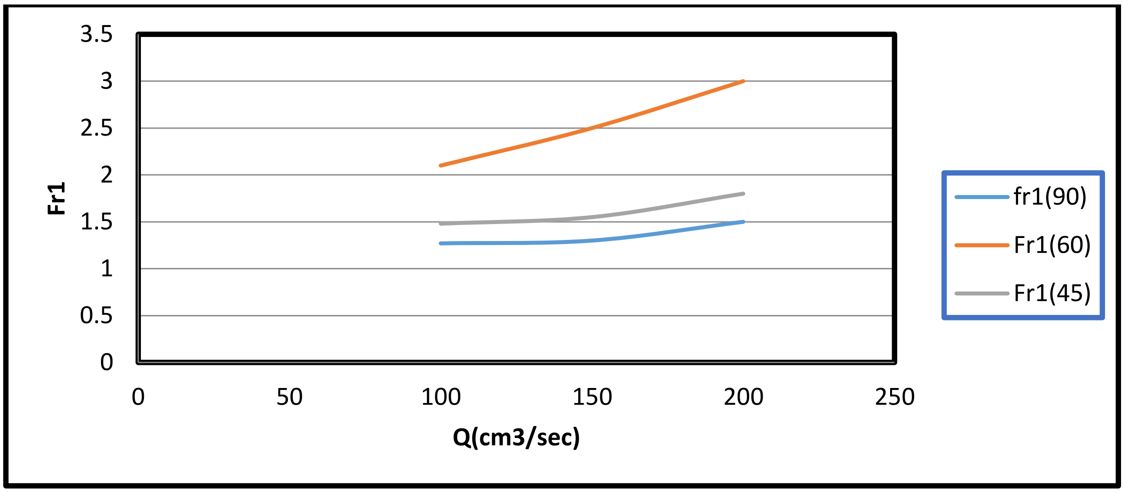


Fig.12: Relationship between Discharge Variation and initial Froude number for 60 Degree upstream faced ogee shaped weir.

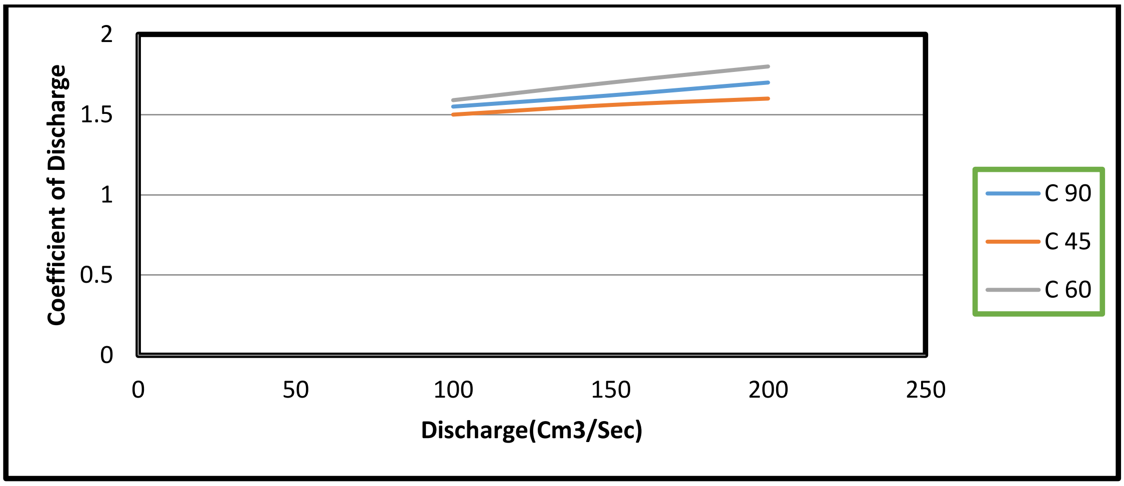


Fig. 13: Coefficient of Discharge Curve for Each weir (vertical faced, 45 and 60 degree) with Discharge variation

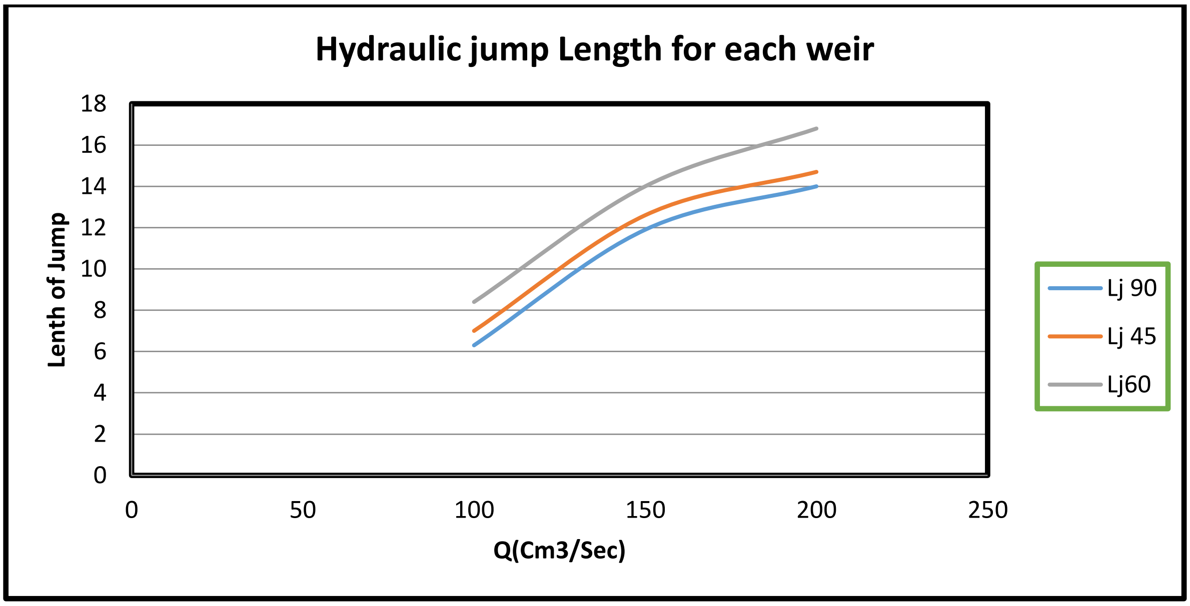


Fig.14: Variation of hydraulic jump length Curve for Each weir (vertical faced, 45 and 60 degree) with Discharge variation.

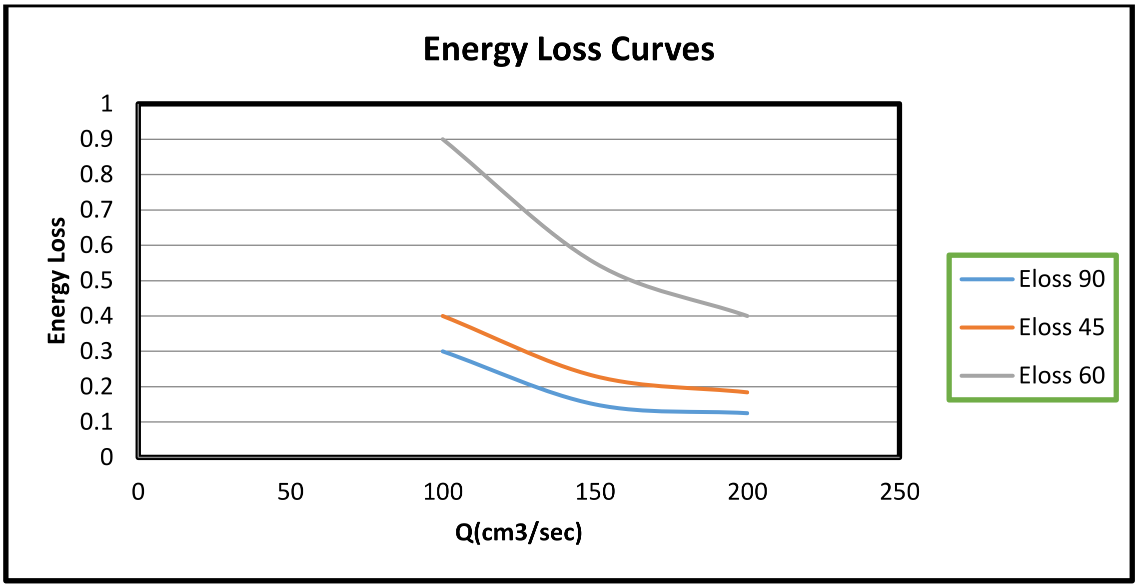


Fig.15: Energy Loss curve for each weir (vertical faced, 45 and 60 degree) with Discharge variation

Energy Loss with Discharge Variation

Fig. 15 below is the energy loss result plotted in graph from the study. Each weir has different energy dissipation capacity. For the horizontal bed slope the energy dissipation capacity was found decreased with the increase in discharge. The maximum energy dissipation was found in 60 degree ogee shaped weir and minimum energy loss was in case of vertical faced weir. Thus it can be concluded the 60 degree ogee shaped weir found effective for energy dissipation for the same channel condition.

Conclusion and Recommendation

Stilling basin is required for energy dissipation constructed at the downstream of weir; spillway and gate structures. Hydraulic jump occurs causes energy dissipation. The dimension of basin depends on the length of the hydraulic jump formed which depends on the shape of the weir constructed across the river and canal. So to determine the characteristic length and energy dissipation of the jump formed were studied experimentally in three cases of physical model developed in laboratory as explained above in section 3. From the study and analysis of the results plotted some conclusions could be made as listed below.

1. The greater the discharge grater is the Froude number, larger the jump length but lesser is the energy dissipation.in each weir type. From the comparative study energy dissipation is higher in case of 60 degree upstream slope face ogee shape weir but the jump length is higher. In case of vertical faced weir the energy dissipation is low but length of jump is shorter. Vertical faced ogee shape weir found more effective for short stilling basin design. However the upstream water level is highest in case of vertical weir that must be capable to resist higher hydrostatic force in reservoir side. Due to small downstream slope in 60 degree upstream face weir, the flow is of more super critical and the length of jump is larger. In this type of weir the energy dissipation is found larger in longer hydraulic jump in same channel bed conditions. From the study for economical stilling basin the vertical face ogee shape weir fond suitable.
2. The coefficient of discharge varies from 1.5 to 1.8 for three weirs that satisfied to the text book value for coefficient of discharge for weir.

Recommendation

Despite the large depth in upstream and large hydrostatic force, for the short stilling basin length the vertical faced ogee shape weir found more effective and economical from this experimental study.

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The authors state no funding involved.

Conflict of Interest

The author states no conflict of interest with the present research

Data Availability Statement

Most datasets generated and analyzed in this study are in this submitted manuscript. The other datasets are available on a reasonable request from the corresponding author with the attached information.

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