ISSN 2229-5518

Hydraulic Jump Characteristics Downstream of a Sluice Gate with an Orifice

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Abstract— The hydraulic jump phenomenon is often used to dissipate the kinetic energy of water downstream of hydraulic structures. This phenomenon occurs when the flow changes from a supercritical to a subcritical flow condition. This paper reports on laboratory experiments conducted to investigate the effect of the presence of an orifice in the sluice gate on hydraulic jump characteristics for different gate opening (G.O.) and orifice configurations. Considered hydraulic jump characteristics include sequent depth (y_2), jump height (H_j), and energy losses (E_2-E_1, where E_2 is sequent-specific energy and E_1 is initial specific energy). For this purpose, three orifice diameters (d) were used, with values of 10, 13, and 16 mm, and 0 (no orifice), with each orifice having three different locations in the gate 5 cm vertically apart. Seven upstream gate heads were used for each case, having values of 23, 24.5, 26, 28, 30.5, 32, and 35 cm. The characteristics of the developed hydraulic jump downstream of the sluice gate were obtained for the mentioned heads and locations. It was found that, in the case of the absence of any orifice, the hydraulic jump sequent depth ratio (y_2/y_1, where y_1 is initial depth) and jump height (H_j/y_1) increase with initial Froude's number (F_1), with values less than for the case of the presence of an orifice. Relative energy loss $(E_1-E_2)/E_1$ also increases with F_1, having greater values than that of orifice presence.

Index Terms— rectangular channel, hydraulic jump, energy dissipation, bed slope

1 Introduction

A substantial amount of the kinetic energy of water may occur downstream of the vertical gates of hydraulic structures because of the conversion of the potential energy upstream of the structures into kinetic energy. This energy should be dissipated to prevent erosion of the downstream channel bed, which may lead to a structural integrity failure. The hydraulic jump phenomenon is used as an efficient means of dissipating energy downstream of hydraulic structures. It has been studied by many researchers aiming to maximize energy dissipation and minimize the length of the hydraulic jump. For example, Kordi and Abustan [1], studied the transitional expanding hydraulic jump in a rectangular open channel, carrying out a series of experiments for Froude's numbers ranging between 2 and 6. Their results showed that the sequent depth (y_2) required to create an expanding jump is smaller than the depth required for classical jumps. They also noted that the expanding jump length was about 1.25 times the corresponding free jump length.

Formation of hydraulic jumps in a horizontal, wide, rectangular channel with a smooth surface has been well researched (e.g. Peterka [2], Rajaratnam [3], and McCorquodale [4]). Hager [5],[6] studied hydraulic jumps theoretically and experimentally. Chern and Syamsuri [7] studied the impact of a corrugated bed on hydraulic jumps, using a smoothed particle hydrodynamics (SPH) model. They considered different corrugated beds, including smooth, triangular, trapezoidal, and sinusoidal beds. The results of the study showed that the sinusoidal bed dissipated more energy than other beds. Chern and Syamsuri [7] concluded that corrugated beds could be used to increase energy dissipation of hydraulic jumps in channels, and that the SPH model could be used to simulate the effect of corrugated beds on hydraulic jump characteristics. Hughes and Flack [8] examined the characteristics of hydraulic jumps in horizontal rectangular channels with rough beds and smooth side walls. They observed a reduction in the length of the hydraulic jump and the sequent depth. This observed behavior was attributed to the initial Froude's number and degree of bed roughness. Hughes and Flack [8] noted that observations of hydraulic jump characteristics were in good agreement with the theory. Abdel-Azim [9] investigated experimentally the effect of changing bed slopes on hydraulic jumps, and found that, the initial Froude's number and the bed slope have significant effects on the depth ratio, whereas the initial inflow depth ratio had little effect on this ratio. Afzal et al. [10] studied the flow structure of a turbulent hydraulic jump over a rough rectangular bed. They concluded that the hydraulic jump formed on a rough bed can be predicted directly from classical smooth bed hydraulic jump theory, utilizing the effective upstream Froude's number rather than the Froude's number. Jan and Chang [11] and Smith and Chen [12] investigated hydraulic jump characteristics in an inclined rectangular channel, and developed empirical solutions for the sequent depth and sequent area ratios considering the effects of bed slope and contracting width. Beirami and Chamani [13] investigated hydraulic jumps in sloped bed channels, performing a series of experiments using a standard weir to develop supercritical flow and negative slopes. Analysis of their results demonstrated that a negative bed slope minimizes the sequent depth ratio, whereas a positive bed slope maximizes this ratio. Gandhi and Yadav [14] studied experimentally the supercritical flow characteristics in a rectangular channel. They considered various characteristics of the jump including sequent depth ratio, efficiency of jump, relative height of

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jump and relative length of jump. Debabeche and Achour [15] examined experimentally hydraulic jumps formed in a V-shaped channel and the influence of a sill on their characteristics. Later, Alikhani et al. [16] investigated the development of a hydraulic jump in a stilling basin with a vertical end sill. They performed a series of experiments using an experimental model simulating a stilling basin and dam spillway. They assessed the influence of a vertical sill and its location on the depth and length of the formed jump. Their results demonstrated the major effect of the sill on energy dissipation. The height of the sill and its position downstream of the gate was proven to minimize basin and jump lengths. Abdel-Mageed [17] examined the influence of bed slope on jump characteristics; small bed slopes were considered in the study, ranging between 0.0027 and 0.011°.

Eltoukhy [18] studied hydraulic jump characteristics for various open channel and stilling basin configurations. Five different bed slopes ranging between 0.0175 and 0.0875 were used as open channel layouts, and a sill with three values of heights positioned at three different locations along the stilling basin. Eltoukhy [18] measured the characteristics of the jump, developed downstream of the gate, at different flow rates. Results of the study showed that the characteristics of the jump, including jump length, initial depth ratio, jump length, sequent depth ratio, relative energy loss and initial energy ratio, all increase with initial Froude's number. It was also observed that the sill has a major influence on energy dissipation. Empirical equations were developed to design the stilling basin; that is, the sill height (Eltoukhy [18], Eltoukhy and Fahmy [19], and Eltoukhy and Abdel-Mageed [20]). Eltoukhy and Elkashef [21] carried out the same procedures in the field but using a triangular channel.

Thus, previous works have studied many cases for hydraulic jumps; however, there are no studies concerned with studying the characteristics of a hydraulic jump downstream of a gate with an orifice. Therefore, the aim of this study is to explore and examine the characteristics of a hydraulic jump developed downstream of a vertical gate with an orifice using a rectangular channel.

2 Theory

The underlying theory describing the hydraulic jump phenomenon is based on the principle of momentum; that is, the rate of change of momentum between the start and the end of the hydraulic jump should equal the total force exerted on the moving water mass within the jump. In addition, dimensional analysis is implemented here. On this basis, the following functional relationship between the variables of the current study can be used to characterize the hydraulic jump formed downstream of a vertical gate and the sill height and location in a rectangular channel (see Fig. (1)):

$$f\left(y_1, y_2, V_1, d, g, \rho, \mu, H_j\right) = 0 \quad (1)$$

For the case of a horizontal open channel and turbulent flow condition, the influence of Reynolds number can be ignored, and the dimensionless groups can be written as:

$$f\left(\frac{y_2}{y_1}, \frac{H_j}{y_1}, \frac{E_1 - E_2}{E_1}, F_1\right) = 0 \qquad (2)$$

where:

$$E_1 = y_1 + \frac{V_1^2}{2g} \text{ and } E_2 = y_2 + \frac{V_2^2}{2g}$$

For a classical hydraulic jump, the ratio of the sequent depth is given by the well-known Belanger [22] equation, as:

$$\frac{y_2}{y_1} = \frac{1}{2}\left[-1 + \sqrt{1 + 8F_1^2}\right] \qquad (3)$$

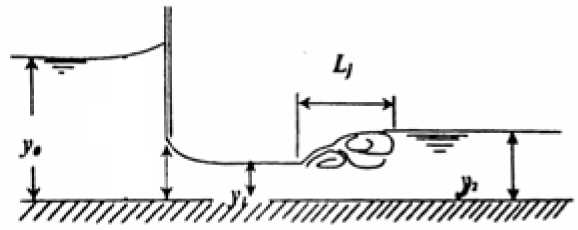


Fig. (1) Hydraulic jump formed downstream of vertical gate

3 Experimental Work

The experimental setup, whose schematics are shown in Fig. (2), consists of an experimental flume – a recirculation self-contained tilting glassy sided flume with dimensions 2.5 m long, 9 cm wide, and 50 cm high. The setup also consists of a water supply and control system that includes a water tank, two electric centrifugal pumps, a control valve, and a piping system. The centrifugal pumps were used to pump water into the flume from the water tank, while the control valve regulated the rate of flow.

The flume is provided with a screw jack positioned at the upstream end to control bed slope. Flume bed slope was determined directly using a slope indicator. The tail-water surface depth was controlled using a downstream adjustable gate. The sidewalls along the entire length of the flume were made of clear plexiglass with steel frames, which enabled visual observation of the flow patterns. The flume bed was fabricated of steel and supplied with a PVC pipe to circulate water from the flume into the water tank. Water was pumped into the flume via two pumps with different flow rates. A series of experiments were performed at different flow rates, for which hydraulic jumps were formed downstream of the sluice gate. For each experimental run, the initial depth y_1 and sequent depth y_2 were measured directly using a point gauge providing an accuracy of ±0.1 mm. The size of the gate opening (G.O.) was altered through the experiments. In this study, seven different water depths y_o ranging between 23 and 35 cm were used upstream of the gate. Three different orifice sizes were used with measured diameters of 10, 13, and 16 mm. These orifices were located in the sluice gate at three different positions 5 cm vertically apart. The experimental program is summarized in Table 1.

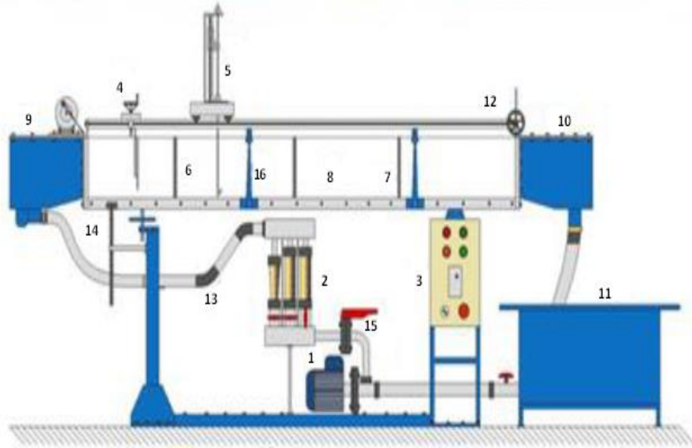


Fig. (2) Schematic layout of experimental setup

TABLE 1
THE EXPERIMENTAL PROGRAM

Orifice diameter, d (cm)	Orifice location	Gate upstream water depth, y_o (cm)
0 (without orifice)	-	23, 24.5, 26, 28, 30.5, 32, 35
1.0	Lower	23, 24.5, 26, 28, 30.5, 32, 35
	Middle	23, 24.5, 26, 28, 30.5, 32, 35
	Upper	23, 24.5, 26, 28, 30.5, 32, 35
1.3	Lower	23, 24.5, 26, 28, 30.5, 32, 35
	Middle	23, 24.5, 26, 28, 30.5, 32, 35
	Upper	23, 24.5, 26, 28, 30.5, 32, 35
1.6	Lower	23, 24.5, 26, 28, 30.5, 32, 35
	Middle	23, 24.5, 26, 28, 30.5, 32, 35
	Upper	23, 24.5, 26, 28, 30.5, 32, 35

4 Results and Discussion

First, the experimental flume used in this study was calibrated. Five experimental runs were performed for the horizontal flume bed. The obtained results concur with the Belanger equation (see Fig. (3)).

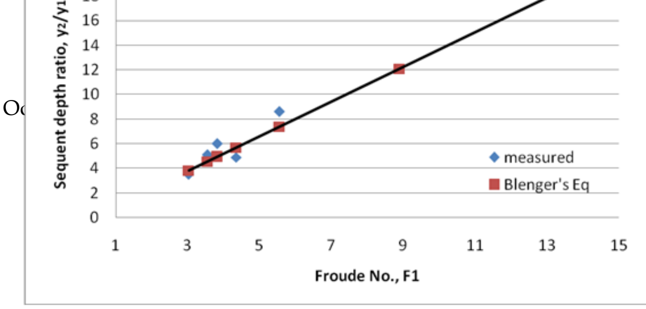


Fig. (3) Experimental flume calibration chart

4.1 Sequent Depth Ratio for Different Orifice Locations and Diameters

A series of experiments was performed to investigate the characteristics of hydraulic jumps as sequent depth ratio, y_2/y_1 for different orifice locations and diameters d. Fig. (4a and b) shows the different orifice locations and experimental run using the upper orifice. The obtained results show that for orifice diameter of 1.6 cm at the lower location, the sequent depth ratio, y_2/y_1 increases as the Froude's number F_1 increases. For example, the sequent depth ratio changes from 12.2 to 14.89 as the initial Froude's number changes from 7.583 to 15.94. This means that an 110% increase in the Froude's number results in a 22% increase in the sequent depth ratio for the lower location 1.6 cm orifice (see Figs (5 to 7)).

a.

b.

Fig. (4) a. Different orifice locations and b. Run for gate with upper orifice

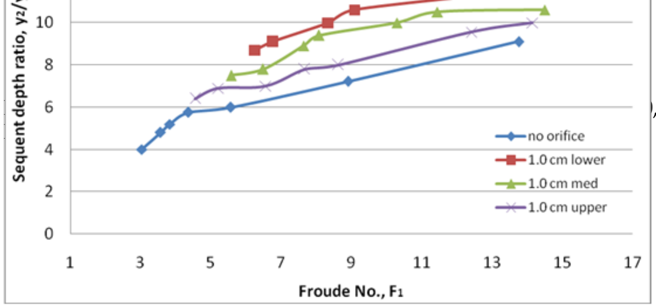


Fig. (5) Sequent depth ratio for different 1.0 cm orifice locations

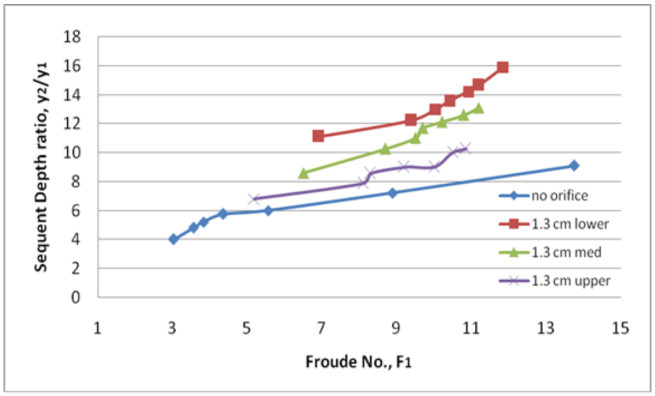


Fig. (6) Sequent depth ratio for different 1.3 cm orifice locations

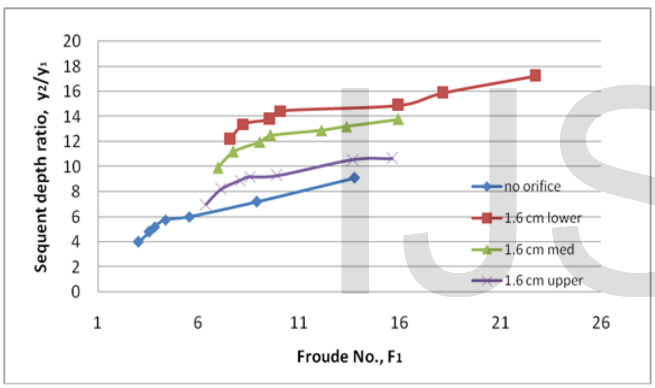


Fig. (7) Sequent depth ratio for different 1.6 cm orifice locations

Figs (5 to 7) show that the sequent depth ratio increases as the head over the orifice increases; that is, the orifice in the lower location gives a sequent depth ratio with larger values than that in the medium and upper locations for the same Froude's number. That is because the orifice in the lower location has more head than over the medium and upper locations. In the case of the gate without an orifice, the sequent depth ratio increases with the Froude's number with values less than those in the case of the presence of an orifice.

The results also show that the sequent depth ratio increases as the orifice diameter increases at the same location. For example, for the upper orifice location and Froude's number of 8.94, changing the orifice diameter from 1.3 cm to 1.6 cm leads to changing of the sequent depth ratio from 11.65 to 13.25. This means that increasing the upper orifice diameter by 23% results in sequent depth increasing by 13.7% (see Figs (8 to 10)).

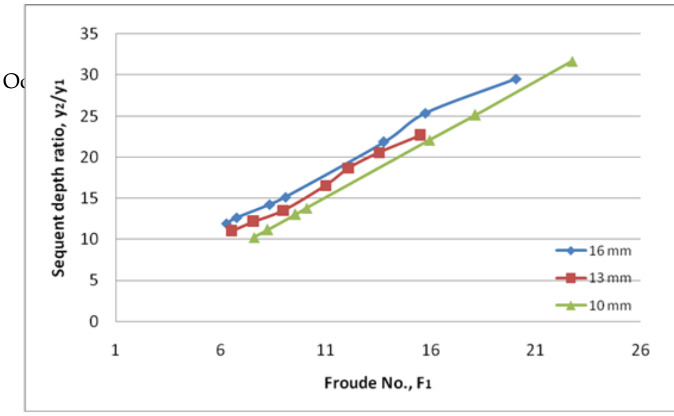


Fig (8) Sequent depth ratio for lower orifice location for different orifice diameters

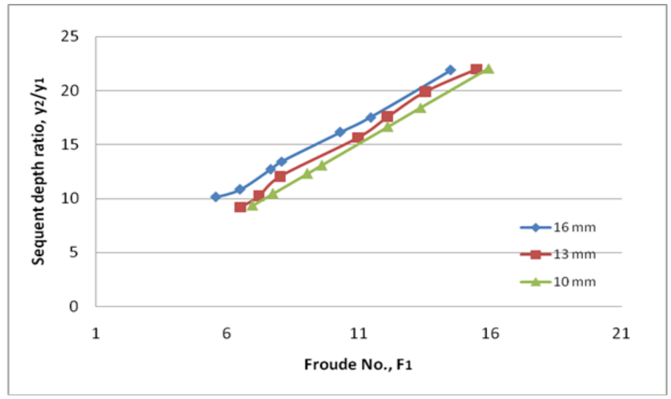


Fig (9) Sequent depth ratio for medium orifice location for different orifice diameters

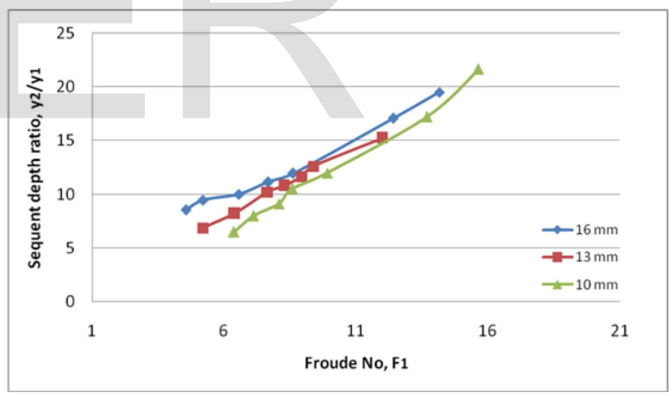


Fig (10) Sequent depth ratio for upper orifice location for different orifice diameters

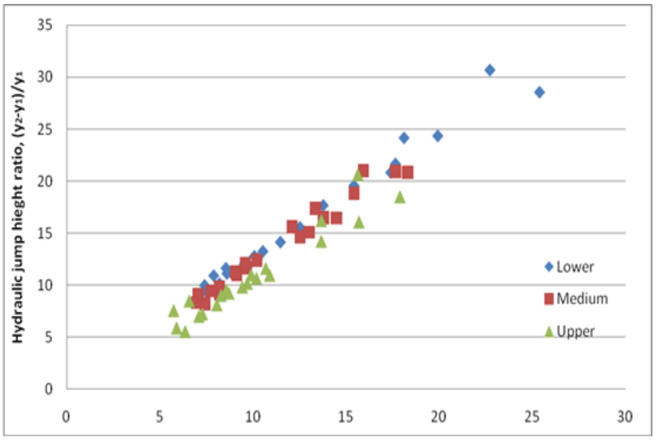
4.2 Hydraulic Jump Height Ratio for Different Orifice Locations and Diameters

The hydraulic jump height ratio is equal to the sequent depth ratio minus one:

$$\frac{y_2 - y_1}{y_1} = \frac{y_2}{y_1} - 1 \qquad (4)$$

Equation (4) shows that the hydraulic jump height ratio experiences the same changes as the sequent depth ratio; thus, the hydraulic jump height ratio increases as the

Froude's number's F_1 increases in approximately the same trend for different orifice locations. Also, the hydraulic jump height ratio increases for orifices at the lower location more than for the medium and upper orifice locations. As with the sequent depth ratio, the hydraulic jump height ratio increases as the orifice diameter increases (see Fig (11)).



$$\left(F_1\sqrt{\frac{d}{G.O.}}\right)$$

Fig (11) Variation of hydraulic jump height ratio with Froude's number, orifice location and orifice diameter

4.3 Energy Loss Ratio Through Hydraulic Jump Downstream Sluice Gate With an Orifice

Figs (12 to 14) show the initial Froude's number F_1 as a function of the energy loss ratio $(E_1 - E_2)/E_1$ for different orifice locations and orifice diameters. It can be seen that the energy loss ratio increases non-linearly with the initial Froude's number, and with approximately the same trend. For example, for the lower orifice location and orifice diameter of 1.3 cm, changing the initial Froude's number from 8.7 to 10.21 resulted in changing the energy loss ratio from 0.161 to 0.224; that is, a 17.4% increase in the Froude's number caused an increase of 39% in the energy loss ratio. In contrast, the energy loss ratio at a given initial Froude's number and orifice diameter decreases for lower orifice location more than for medium and upper orifice locations, because of the increase in the sequent depth, as discussed above, which causes the specific energy, E_1, downstream of the jump to increase. Also, the energy loss ratio decreases with orifice diameter.

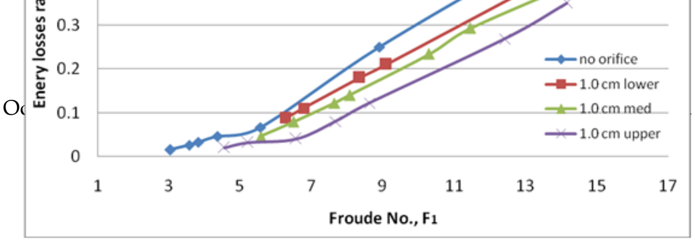


Fig (12) Energy loss ratio for lower 1.0 cm orifice diameter for different orifice locations

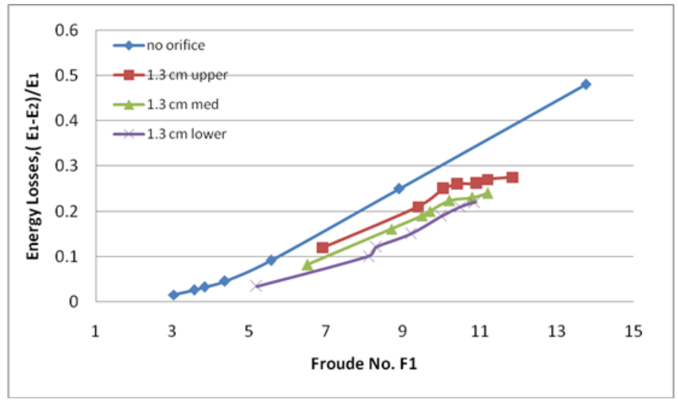


Fig (13) Energy loss ratio for lower 1.3 cm orifice diameter for different orifice locations

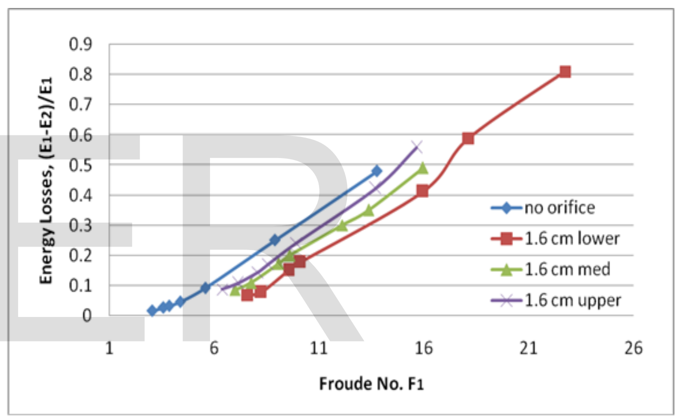


Fig (14) Energy loss ratio for lower 1.6 cm orifice diameter for different orifice locations

CONCLUSIONS

The analysis of the results obtained by carrying out experimental runs to study hydraulic jump characteristics formed downstream of a sluice gate with an orifice leads to the following conclusions:

1. For the case of a sluice gate without an orifice, the obtained values for the sequent depth ratio and the hydraulic jump height ratio were lower than those for gates with an orifice, but the energy loss ratio was higher in the case of no orifice.
2. Experimental results of this study infer that the sequent depth ratio, y_2 / y_1 for a hydraulic jump formed downstream of a gate with an orifice increases with the Froude's number for a given orifice diameter and location.
3. For a given Froude's number and orifice location, it was found that the sequent depth ratio increases as the orifice diameter increases.
4. The sequent depth ratio was found to have greater values in lower locations than in medium and upper

locations for a given Froude's number and orifice diameter.

5. The hydraulic jump height ratio increases as the initial Froude's number and orifice diameter increase, with a higher ratio for the lower orifice compared with those in the middle and upper locations.
6. The energy loss ratio increases with the Froude's number and decreases as the orifice diameter increases.
7. A lower orifice location gives an energy loss ratio lower than those of medium and upper locations.

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