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Energy dissipation using multi-pendulum sill downstream sluice gate

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ABSTRACT

Many researchers have already investigated different energy dissipator designs both theoretically and empirically in order to maximize energy dissipation and minimize length for the hydraulic jump. This study introduces a novel method to decrease the hydraulic structure's floor length and boost energy dissipation. To do this, a pendulum sill is used downstream of the hydraulic structure's sluice gate. The pendulum sills are hollow plastic cylinders, 29.5 cm long and diameter of 5.00 cm, with a wall thickness of 5 mm, and filled with constant stones. The sill location was changed with respect to the hydraulic jump by changing the string length. The number of sills was studied by using one; two and three sills tied each other by intermediate strings. The results showed that using the pendulum sill increased the energy dissipation. It was found that the best case is to use three cylinders, as the energy dissipation increases by approximately 55%.

1. Introduction

One of the best techniques for dissipating energy in hydraulic systems is the hydraulic jump. There is numerous research focusing on enhancing energy dissipation to increase jump performance. **Hager et al.** [**1**] utilized a one-dimensional, simplified method to investigate the first jump circumstances for flow across ventilated continuous sills. The study demonstrated that the height of the sill does not significantly impact the drag coefficient in gravity-free flow. It was possible to establish a connection between the sill's relative height and the initial Froude number. **Gupta** [**2**] creates an empirical relationship between the initial Froude number and the relative energy losses for various channel bed slopes by conducting an experimental examination into the relative energy losses in sloping channels. **Gupta et al.** [**3**] formulated an empirical formula for the relative energy losses and found that the free jump's relative energy loss rises with increasing approach Froude number. Using 14 different types of baffle piers, **Bestawy** [**4**] conducted an experimental investigation of the dissipation of water energy downstream of a heading-up structure. In general, the results indicate that models with concave surfaces dissipate more energy than other forms and cause the flow to change direction more than those with low turbulence intensity in the recirculation zone downstream of baffle piers. The study also demonstrates that, when it comes to dissipating water energy, the vertical semi-circular portion had the most impact among the other models that were studied. **Ahmed et al.** [**5**] investigated experimentally how utilizing triangular strip corrugations with varying spacing affected the properties of submerged hydraulic leaps. There were corrugated and smooth beds. The study was conducted on a variety of Froude numbers, ranging from 1.68 to

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9.29. The results demonstrated that while employing spaced triangular corrugated aprons increased the energy dissipation efficiency of the leap by 50.31%, it reduced the subsequent depth ratio by 15.14% and the hydraulic jump length by 21.03%. In order to examine the differences between each types of weir and resulting hydraulic jump, **Kim** [**6**] conducted experiments using a canal that had both a fixed weir and a movable weir installation of the sluice gate type. When compared to the installation status of non-dissipators, it was found that the energy dissipaters for energy reduction at the sluice gate would dissipate energy by more than 50% per unit length if placed at a height of 10% of the average river water depth in a location as far as roughly 70% of the average river water depth. **Eltoukhy** [**7**] carried out laboratory tests to look at the hydraulic jump properties of various rectangular open channels with various bed slopes. **Eltoukhy** creates an equation to determine the sill height and the relative energy losses in order to disperse the leap energy. FLOW-3D was used in a numerical study by **Mansoori et al.** [**8**] to examine and determine the energy dissipation rate. After reading the appropriate literature, the suggested model was created in FLOW-3D to establish the optimal geometry of the steps that would allow for the greatest amount of energy dissipation. Analyses were conducted utilizing the aforementioned techniques and trial and error in mesh network sizes in order to assess the suggested approach, and the outcomes were contrasted with those of other studies. Stated otherwise, a Λ-shaped step at a 25-degree angle produced the most ideal condition in terms of energy dissipation rate when compared to a smooth step.

. **Tohamy et al.** [**9**] utilized Flow 3D software to numerically analyze the effects of using a vertical screen sill as an energy dissipator device downstream. The study shows that using a screen downstream a vertical gate is an effective tool to dissipate energy. **El-Saie et al.** [**10**] used Flow-3D software to investigate the properties of forced hydraulic jumps. To release more kinetic energy, they used semi-cylindrical and rectangular slices as barriers in a stilling basin. Energy dissipation ratios ranging from 48% to 63% were obtained with optimal arrangements. **Daneshfaraz** [**11**] studied experimentally using different baffle block geometries for energy dissipation. According to the findings, the energy loss in section A rose by 125, 119, 116, and 125% for pyramidal, semi-cylindrical, cylindrical, and rectangular designs, respectively, when sills of maximum width (b = 0.20 m) were used. The pyramidal sill is most suited for boosting energy dissipation, whilst the semi-cylindrical sill is best for raising the discharge coefficient. **Urbański** [**12**] carried out studies on the stilling basin and sluice gate model using two baffle block configurations: one and two rows. The study demonstrates that, in comparison to the length with a single row of blocks, the two rows of baffle blocks in the stilling basin allowed the hydraulic jump to be shortened by 5–10%. **El-Saie et al.** [**13**] investigated the characteristics of forced hydraulic jump quantitatively using Flow-3D software. As illustrated by the numerical findings, the impediments significantly improve the flow characteristics and increase energy dissipation. Installing seven rows of circular baffle blocks in the stilling basin at equal intervals is the optimum case; depending on the flow conditions, the relative energy loss can range from 50% to 60%. **Abdelmonem et al.** [**14**] conducted an experimental investigation to examine the impact of employing a hanging Pendulum sill with a fixed weight on the downstream sluice gate's energy dissipation. Due to its more than 20% energy dissipation, it was discovered that the pendulum sill increases the hydraulic jump's efficiency. Using a hanging Pendulum sill, **Abd El Ghany et al.** [**15**] conducted an experimental investigation. The usage of a pendulum sill was found to have the benefit of being a fixable approach for dissipating energy because its height and position may be changed. However, after evaluating various sill weights, heights, and locations, it was shown that staggered blocks with a specific intensity are still preferable to hanging sills.

In this study, a pendulum sill is hanging downstream of the gate to distribute the energy of the hydraulic jump. The number and placement of the pendulum sills are changed in order to determine the best location for energy dissipation under various flow conditions.

2. Experimental Study

The study was carried out in Egypt at Zagazig University's faculty of engineering and water and hydraulics engineering laboratory.

2.1. Experimental Flume

This investigation used a recirculating flume that was 15.6 m long, 0.3 m wide, and 0.468 m deep (see Fig. 1). The sides of the flume bed are made of glass, and it is constructed of stainless steel, which gives it a great degree of stability and rigidity. A centrifugal pump at the bottom of the flume recalculates water. The water flow in the flume is managed by a butterfly valve that may be manually regulated. The depth of the water level in a flume is precisely measured using a point gauge with a scale reading of (0.001) m. The gate opening (6 cm) stays the same during the entire process.

Fig. (1). Laboratory Flume

2.2. Pendulum Sill Models

The pendulum sills are hollow plastic cylinders which are 29.5 cm in length and 5.00 cm in diameter. They are filled with a fixed stone weight. The thread that hangs the pendulum sill is attached to the gate and encircles the hollow cylinder. In order to change the sill's location with respect to the hydraulic jump, the string length was changed. We looked at the number of sills using one, two, and three sills connected by intermediate strings.

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3. Dimensional Analysis

As shown in fig. (2), several variables influencing the energy dissipation through the sluice gate might be expressed in the dimensionless equation that follows using the dimensional analysis principles: Using the dimensional analysis principles, the many factors influencing the energy dissipation through the sluice gate in the previously mentioned case can be expressed as follows:

$$f\,(y_{up}, y_1, y_2, y_3, L_j, \theta, V, \rho, G, \mu, g, D, L, X, N,) = 0 \qquad (1)$$

Where G is the gate opening, yup is the water depth upstream the gate, y1 is the initial water depth of the jump, y3 is the backup water depth downstream of the jump, y2 is the depth of water at the end of the jump, and Lj is the jump length. g is the gravitational acceleration, E1 is the total energy just after the gate, E2 is the total energy at y2, and ΔE is the energy loss through the jump. ρ is the mass density of water, μ is the dynamic viscosity of water, μ is the dynamic viscosity of water, D is the diameter of the cylinder, L is the string length, X is the distance between the gate and the beginning of the string length, N is the number of cylinders, and θ is the angle of inclination of the string length with the vertical axis. According to Buckingham π-theorem and taking (G, v, and ρ) as repeated variables, the general form of relationship between these variables may be written as follows:

$$\frac{\Delta E}{E_1} = f\left(F_G, N, \Theta, \frac{y_2}{G}, \frac{X}{G}, \frac{L}{G}\right) \qquad (2)$$

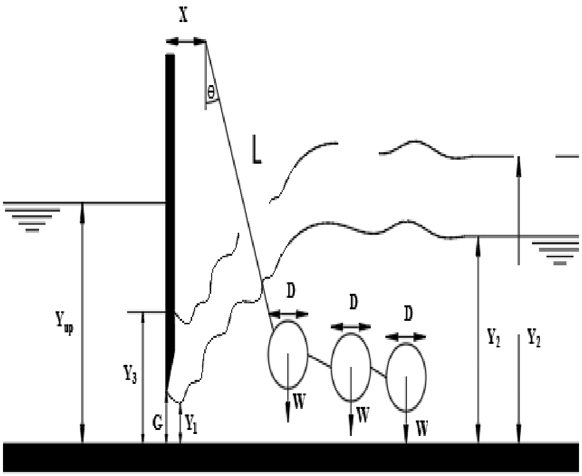

Fig. (2). Definition sketch.

4. Analysis And Discussion

The study investigated the impact of using a pendulum sill with varying locations and numbers downstream of the gate to dissipate hydraulic jump energy.

4.1. Case: No pendulum sill (Classical Jump)

The study compared the case of the free hydraulic jump with **Hager's'** equation **[1]** and **Abdelmonem et al.'s** results **[14]** to ensure accuracy in analyzing relative energy loss. As shown in fig. (3), it presents the variation of the relative energy loss (ΔE/E1) with the supercritical Froude number. The following equation by Vischer and Hager [**1**] is also plotted for comparison for the range of this study.

$$\frac{\Delta E}{E_1} = \frac{1}{8}\frac{\left(\sqrt{1+8F_1^2}-3\right)^3}{\left(2+F_1^2\right)\left(\sqrt{1+8F_1^2}-1\right)} \qquad (3)$$

The figure shows a good agreement between Eq. (3) and the experimental data of this study. The error between this experimental study's results and Hager's equation was about 12%.

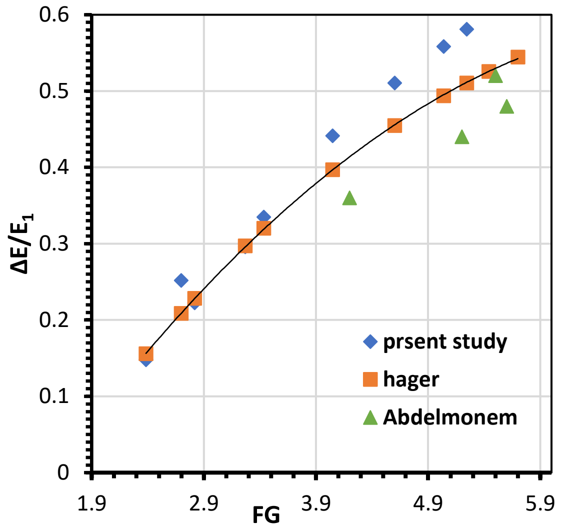

Fig. (3). Relation between the gate Froude number F_G and the relative energy dissipation ΔE/E1.

4.2. Case: Using a pendulum sill

This study investigates the impact of hanging string length and cylinder number on energy dissipation downstream of a sluice gate, involving 35 runs in six series. Table 1 provides the primary details of these experiments.

Table 1 Primary details of experiments.

series	*Q L/s*	*LX cm*	*N*
Case without	Ranged Between 15.42 and 21.231		
Case1-1		32	1
Case1-2		42	1
Case1-3		32	2
Case1-4		32	3
Case1-5		42	2
Case1-6		42	3

4.2.1. Effect of changing the string length.

Figure 4 shows the relationships between the relative energy dissipation and gate Froude number for different string lengths. From this figure, as the gate Froude number increases, the energy dissipation also increases. By increasing the string length, it was found that the energy dissipation increases. Observing the location of the cylinder in both cases, it was found that in the shorter string length case the cylinder was in the middle third of the hydraulic jump, and the larger length it was in the last third. On the other hand, it was difficult to fix the cylinder in the first third due to the limitations in available discharges and the channel dimensions. Thus, by comparing the effect of the cylinder in the two places, it was found that the last third has a better effect than the middle third because the effect of the cylinder is close to the effect of the end sill, and thus it is more effective in dissipating energy than the case of the middle third within the studied flow conditions. For long string length, it was found that the energy dissipation increases about 11% more than the short one.

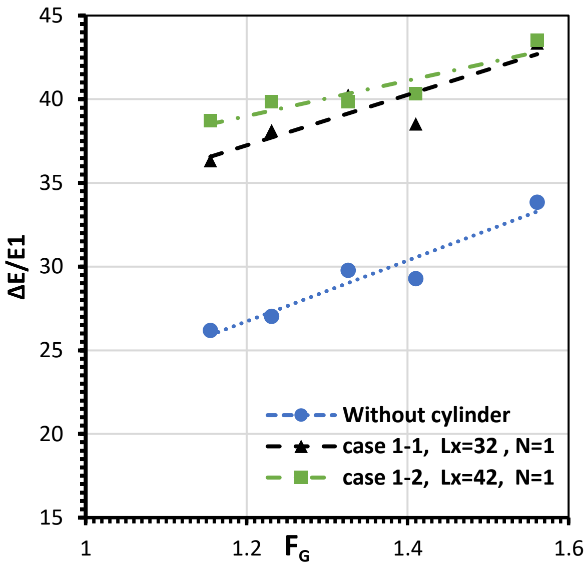

Fig. (4). Relation between the gate Froude number F_G and the relative energy dissipation ΔE/E1 for different relative string lengths L/G at constant W.

4.2.2. Effect of changing the number of cylinders

Figures 5, 6, and 7 show the relationships between the relative energy dissipation and gate Froude number for changing the number of cylinders. From this figure, as the gate Froude number increases, the energy dissipation also increases. By increasing the number of cylinders, it was found that the energy dissipation increases, regardless of the change in diameter or length of the rope. This is due to the increase in obstacles in the jump, which increases the reverse force on the flow and increases the dissipation of energy, but the model length and its effect on the length of the basin must be taken into consideration.

Figure 8 shows the relationship between the number of cylinders and the energy dissipation ratio for the two string lengths L_1, L2. From the figure, it is clear that in the case of constant F_G By increasing the number of cylinders, it was found that the energy dissipation increases; when the number was constant, it was found that case L1 was better at dispersing energy than case 2. It was found that the best case is to use three cylinders, as the energy dissipation increases by approximately 55%.

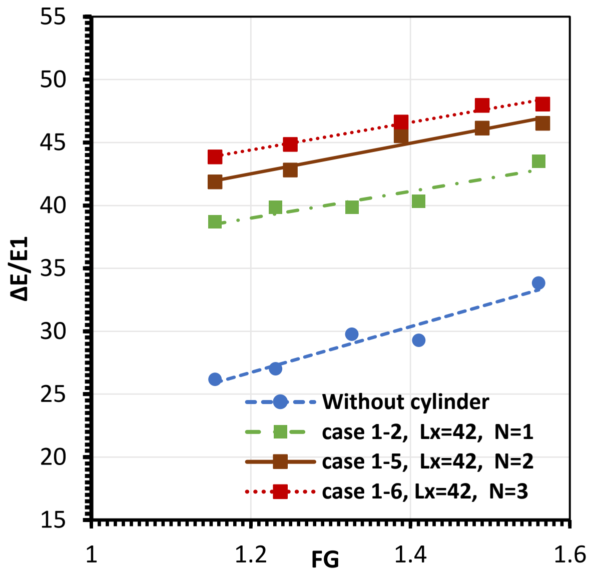

Fig. (5). Relation between the gate Froude number FG and the relative energy dissipation ΔE/E1 for different relative the number of cylinders N at constant Lx=42

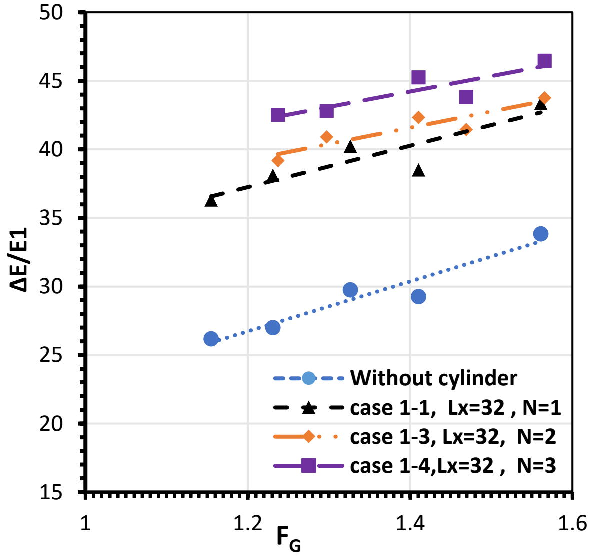

Fig. (6). Relation between the gate Froude number F_G and the relative energy dissipation ΔE/E1 for different relative the number of cylinders N at constant Lx=32.

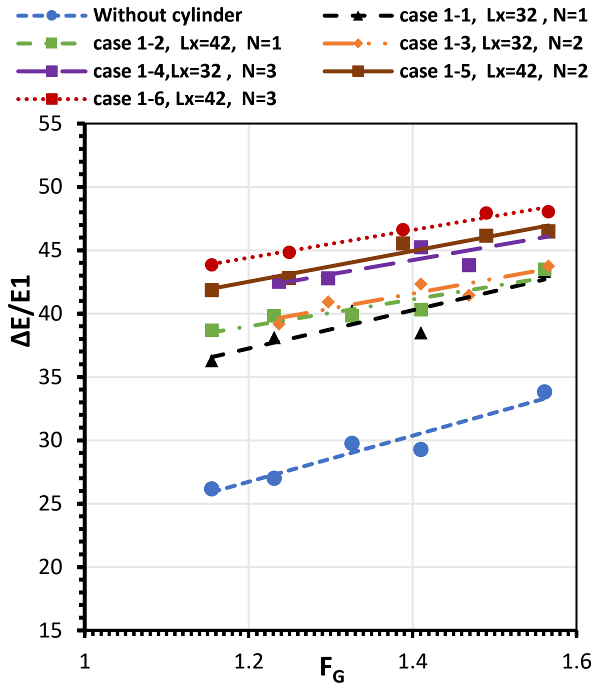

Fig. (7). Relation between the gate Froude number F_G and the relative energy dissipation ΔE/E1 for different relative the number of cylinders N

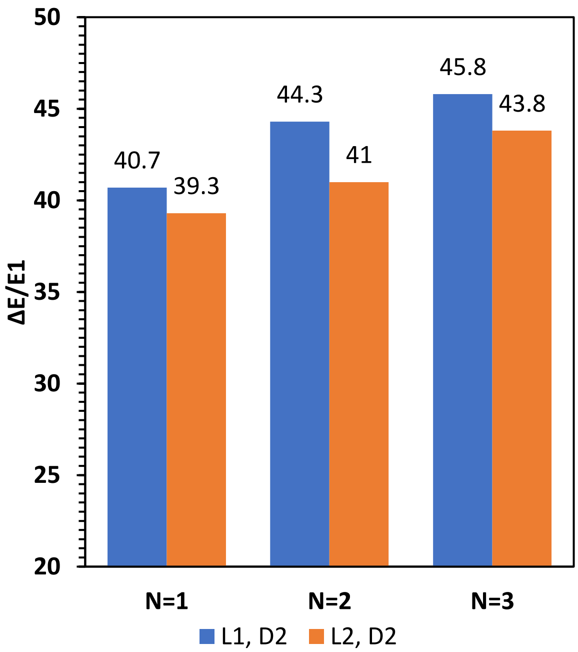

Fig. (8). Relation between N and ΔE/E1 for different LX at FG=1.35 N

4.2.3. Water surface profiles

Fig. 9 shows the water surface profile along the jump length for the same gate opening and a discharge of 16.50 L/s, thus the gate Froude number, FG = 1.41 for the case with no pendulum sill and the cases with pendulum sill at different X-locations. Results showed that in the case of the free hydraulic jump, the water profile takes the natural shape without a clear fluctuation. For all cases of pendulum sills, results showed that there was a normal jump, and the disturbance appeared clearly, but the most affected case was Case 1-6, where the water level along the area was higher than the levels in all cases. This is due to the distance of the first cylinder from the gate opening, in addition to the number of cylinders (3), which leads to the presence of what looks like an obstacle in the path of the water due to the high levels above it and the presence of a backwater carve that reaches the gate and causes the highest rate of immersion in it. From these results, we find that in these cases, despite their impact, it has a positive effect on dissipating energy, but it will affect the length of the basin used behind the gate.

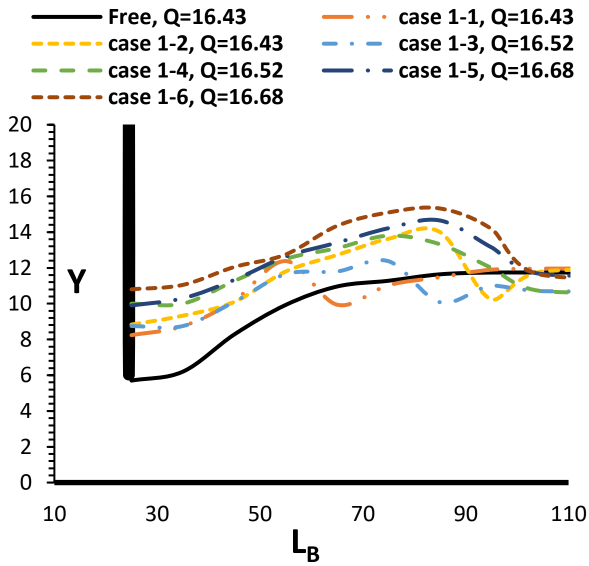

Fig. (9). Surface water profile for all cases at FG=1.41.

5. CONCLUSIONS

In the present study, the effect of pendulum sill number and the string length on the energy dissipation was examined. Performance of the pendulum sill was investigated experimentally. Conclusions obtained from the analysis of the experimental data are as follows:

1. It was determined that the results of the experiment for the case of classical jump closely matches the equations of classical jump found in the literature, given the small number of values for the variables used and each case examined.
2. By increasing the string length, it was found that the energy dissipation increases, regardless of the weight or diameter of the cylinder.
3. By increasing the number of cylinders, it was found that the energy dissipation increases, regardless of the change in diameter or length of the string.
4. The pendulum sill increased the energy dissipation. It was found that the best case is to use three cylinders, as the energy dissipation increases by approximately 55%.

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