Investigation Of Hydraulic Flow Characteristics On Drop Structures

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Abstract. Drop structures are required if the slope of the ground level is steeper than the maximum allowable gradient channel. Drop structures become bigger as height increases. Its hydraulic capability may be reduced due to variations of jets falling on the stilling basin floor due to discharge changing. Drop structures should not be used if the change in energy level exceeds 1.50 m. The free-falling overflow on drop structures will hit the stilling basin and move downstream. As a result of overflows and turbulence in the pool below the nappe, some energy is dissipated at the front. The rest of the energy will be reduced downstream. The objectives of this study are to investigate the hydraulics flow behavior in straight and sloping drop structures and to investigate hydraulics flow behavior in a single and serial vertical drop (stepped drop). The hydraulic model results of single and stepped drop structures are compared to obtain flow behavior and energy dissipation information. The comparisons are specific to the flow parameters, including flow depth at the drop structures toe, flow depth after the jump, and hydraulic jump length.

keywords: drop structures, flow depth, hydraulic jump, stepped drop

1. Introduction

Direct observation for large problems or work can result in high costs and a long period. To avoid these obstacles, observations can be made by making miniatures of the problems encountered in the field. This method is known as a model study. Many variations or treatments can be carried out with model studies, and more data can be obtained. With this relatively large range of data, it is possible to use the results with a wider scope which can be a reference for solving problems in the field under similar conditions.

Hydraulic structures, such as spillways, energy dissipators, and stilling basin, have been widely constructed and researched with physical models. It is to ensure that the conditions that occur are as planned and can be operated properly. The reason for the repetition of this physical model is the uncertainty factor on the overall system performance of the hydraulic structures. Many laboratory experiments have been carried out by researchers, both individually and in groups, but each hydraulic structure has a different limitation [9].
2. Material And Methods

The hydraulic physical model test in this study was carried out in a laboratory and used several laboratory facilities, including:

a. A single drop, serial drops, and sloped drop structure models are made with a height of 100 cm and a width of 30 cm,

b. Rectangular open channel, 30 cm wide, 40 cm high, made from acrylic for observed turbulence.

c. Water pump to supply clean water flow to the model,

d. Water reservoir to supply water to the model which is equipped with a water control valve and a V-notch as a flow meter so that it can be ensured that the flow rate is constant,

e. Level meter (point gauge) to measure the level of water flow,

f. Pitot tube and current meter to measure flow velocity,

g. Stopwatch and measuring jug to measure flow rate,

h. The discharge flow in sloped, vertical and serial drops is given two variations of discharge: 4.92 l/s and 6.14 l/s.

This research is expected to be able to produce flow parameters in inclined and vertical drops by producing several flow hydraulic parameters:

a. the depth of flow at the drops toe ($y_1$),

b. the energy at the drops toe ($E_1$),

c. the height of the nappe under the water drops ($y_o$),

d. Drops floor-length ($L_d$),

e. hydraulic jump length ($L_j$),

f. depth of flow after the hydraulic jump ($y_2$), and

g. Drop number (D).

Flow through an open channel is uniform if the various flow variables are constant at each section along with the flow. The variables are flow depth, wet perimeter, flow velocity, and flow rate. In this uniform flow, energy lines, water level, and channel bottom are parallel so that the slopes of the lines are the same. The depth of flow in uniform flow is called the normal depth, $y_n$. Uniform flow cannot occur at large flow velocities or very large channel slopes. If the flow velocity exceeds a certain limit (critical velocity), the water level becomes unstable, and waves will occur. At very high speeds (more than 6 m/s), air will enter the water stream, and the flow becomes unstable [3].

Flow is called non-uniform flow or varied flow if the flow variables are not constant at each section along with the flow. The variables are flow depth, wet perimeter, flow velocity, and flow rate. When a change in flow occurs over a short distance, it is called a rapidly varied flow, whereas if it occurs over a long distance it is called a gradually varied flow. The flow of water is called steady flow if the variation of flow at a point does not change with time, and if it changes with time, it is called unsteady flow. In addition, the flow in the open channel can also be divided into subcritical, critical, and supercritical. The basis for determining this type of flow is the Froude number [1][7][8][10].

Several empirical equations that apply to flow in open channels with a rectangular cross-sectional shape include [1][7][8][10]:

\[
Q = VA 
\]  
\[
V = \frac{1}{R} \left( \frac{R}{B} \right)^{\frac{1}{2}} \left( \frac{S}{S_0} \right)^{\frac{1}{2}} 
\]  
\[
A = BY 
\]  
\[
R = \frac{A}{P} 
\]
The energy contained in one unit weight of water flowing in an open channel consists of three forms: kinetic energy, pressure energy, and elevation energy above the reference line. The kinetic energy at a section in an open channel is given by the form $V^2/2g$. The pressure energy in the open channel is calculated by reference to the water level. The elevation of the energy flow height is measured to the horizontal reference line. The vertical distance from the reference line to the bottom of the channel is usually taken as the section's elevation (potential) energy height. For uniform flow conditions, then $S_f = S_w = S_0 = \sin \theta$. The equation used [7][9][10][11]:

$$z_1 + y_1 + \alpha_1 \frac{V_1^2}{2g} = z_2 + y_2 + \alpha_2 \frac{V_2^2}{2g} + h_f$$

(8)

$$S_0 \Delta x + y_1 + \alpha_1 \frac{V_1^2}{2g} = y_2 + \alpha_2 \frac{V_2^2}{2g} + S_f \Delta x$$

(9)

$$\Delta x = \frac{E_2 - E_1}{S_0 - S_f} = \frac{\Delta E}{S_0 - S_f}$$

(10)

$$S_f = \frac{n^3 \sqrt{V^2}}{R^{4/3}}$$

(11)

$$h_f = S_f \Delta x$$

(12)

Assuming $\alpha_1 = \alpha_2 = 0$, and $h_f = 0$, then:

$$z_1 + y_1 + \frac{V_1^2}{2g} = z_2 + y_2 + \frac{V_2^2}{2g} = \text{constant}$$

(13)

The specific energy/specific height is the energy at the channel cross-section, which is calculated from the channel bottom [7][8]:

$$E_s = y + \frac{\alpha V^2}{2g}$$

(14)

Where: $A =$ wet cross-sectional area ($m^2$), $B =$ channel bottom width ($m$), $E =$ energy height ($m$), $E_s =$ specific energy, energy measured from the bottom of the channel ($m$), $E_c =$ critical energy height ($m$), $E_0 =$ upstream energy height ($m$), $E_1 =$ energy height at the spillway toe ($m$), $E_2 =$ energy height downstream of the spillway ($m$), $E_L =$ energy loss height ($m$), $g =$ gravity acceleration ($m/s^2$), $h =$ drop height ($m$), $n =$ Manning roughness coefficient, $Q =$ flow rate ($m^3/s$), $q =$ discharge per unit width ($m^2/s$), $q = QB$, $R =$ average hydraulic radius ($m$), $S_0 =$ channel bottom slope, $S_f =$ energy line slope, $V =$ average velocity ($m/s$), $y =$ depth of water flow ($m$), $y_c =$ critical depth ($m$), $z_1 =$ base height of channel section 1 to the basic equation line ($m$), $z_2 =$ bottom height channel section 2 to the equation line base ($m$), $x =$ horizontal distance ($m$), $\alpha =$ energy coefficient.

A hydraulic jump occurs when a supercritical flow changes into a subcritical flow. There is a sudden rise in the water level and a large energy loss in the hydraulic jump. Large turbulent eddies are formed.
at the beginning of the jump. These eddies draw energy from the main stream, and the eddies are broken up into smaller parts as they flow downstream [9][10]. In the event of a hydraulic jump, the basic component that affects the energy calculation is the momentum equation [5][6][7].

\[ P_1 - P_2 = \rho Q(V_1 - V_2) \]  
\[ \left( \frac{1}{2} \rho g y_1^2 - \frac{1}{2} \rho g y_2^2 \right) B = \rho V_1 y_2 (V_1 - V_2) \]  
\[ (y_1 - y_2)(y_1 + y_2) = \frac{2V_1 y_1}{g} (V_2 - V_1) \]

Meanwhile, from the continuity equation:

\[ q = V_1 y_1 = V_2 y_2 \]  
By combining the above equations, then:

\[ \frac{y_1 + y_2}{2} = \frac{2V_1^2 y_1}{g y_2} \]  
\[ y_2 = \frac{y_1}{1 + \frac{2}{F_1^2}} \]

By simplifying the above equation, we get the equation [1][3]:

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

Where \( y_1 \) and \( y_2 \) are the water depth before and after the hydraulic jump (m), \( F_1 \) is the Froude number of the first cross-section before the jump.

For supercritical flow in a horizontal rectangular channel, flow energy will be dissipated by channel friction resistance. It is causing a decrease in velocity and an increase in height in the direction of flow. There are several different types of hydraulic jumps that occur on a flat bottom. Following the United States Bureau of Reclamation research, these hydraulic jumps can be distinguished based on the Froude number \( F_1 \) [9][10].

Some of the basic properties of hydraulic jumps in a rectangular channel with a horizontal bottom can be described as follows [7]:

a. Energy Loss
The energy loss in the jump is equal to the difference in specific energy before and after the jump. The amount of energy loss is:

\[ \Delta E = E_1 - E_2 = \frac{(y_2 - y_1)^2}{4y_1 y_2} \]

b. Efficiency
The ratio between the specific energy after the jump to before the jump is defined as the jump efficiency. So the magnitude of the stepping efficiency is:

\[ \frac{E_2}{E_1} = \left( \frac{8F_1^2 + 1}{8F_1^2} \right)^{1/2} - 4F_1^2 + 1 \]

This equation shows that the jump efficiency is a dimensionless function and only depends on the Froude number of the flow after the jump. The relative loss equals \( 1 - E_2/E_1 \), and this quantity is also a dimensionless function of the Froude number.

c. Hydraulic Jump Height
The hydraulic jump height can be defined as the difference between the depth after and before the jump.
\[ y_j = y_2 - y_1 \] (24)

d. Jump Length

The length of the hydraulic jump is the distance between the front surface of the hydraulic jump to a point on the surface of the wave roll that immediately goes downstream. The jump length is difficult to determine theoretically but has been investigated experimentally by several hydraulics experts.

The sloped drops are carrier structures with supercritical flow conditions. A stilling basin structure is required if the ground level slope is steeper than the maximum allowable channel slope. The stilling basin functions as a hydraulic jump controller that occurs downstream. These structures have four functional sections, each of which has its unique characteristics [1]:

a. The upstream part of the controller, the part where the flow is supercritical,
b. The part where water flows to a lower elevation,
c. The downstream part where the energy is dissipated,
d. The channel transition section requires protection to prevent erosion.

In the first part of this drop structure, the flow is controlled. In the downstream part, hydraulic jump control is carried out to keep the jump in shape and control its position in various conditions, including the characteristics, length, and profile of the jump.

The vertical drops become larger when the height is increased. Its hydraulic ability can be reduced due to variations in the jet falls on the floor if there is a change in flow rate. Vertical drops should not be used if the change in energy height exceeds 1.5 m.

\[ \frac{L_j}{h} = 4.30D^{0.27} \] (25)
\[ \frac{y_j}{h} = 1.00 D^{0.22} \] (26)
\[ \frac{y_j}{h} = 0.54D^{0.25} \] (27)
\[ \frac{y_j}{h} = 1.66D^{0.27} \] (28)

Based on Dominguez’s research (1958, 1974), in a horizontal rectangular channel condition, several flow parameter formulations were obtained as follows [8]:

\[ \frac{L_j}{y_c} = 3 \left( \frac{h}{y_c} \right)^{0.3} \] (29)

Figure 1. Flow geometry in vertical drops [7]
Rand (1943):

$$\frac{L_d}{y_c} = 4.8 \left( \frac{h}{y_c} \right)^{0.19} \tag{30}$$

Dominguez (1944):

$$\frac{L_i}{y_c} = 18 - 20 \left( \frac{y_i}{y_c} \right) \tag{31}$$

It is assumed that the length of the jump should give the minimum length of stilling basin:

$$\frac{L_p}{y_c} = 3 \left( \frac{h}{y_c} \right)^{0.3} + \left( 18 - 20 \left( \frac{y_i}{y_c} \right) \right) \tag{32}$$

The high energy that occurs can be formulated [3]:

$$E_o = H_{daw} + 1.5y_c \tag{33}$$

By conducting research on a single drop and based on 28 data of observational data on a physical laboratory model, Musavi-Jahromi, et al. (2004) make an equation to find several flow parameters as follows [8]:

$$\frac{L_d}{h} = 4.181 \left( \frac{y_c}{h} \right)^3 - 6.288 \left( \frac{y_c}{h} \right)^2 + 4.860 \left( \frac{y_c}{h} \right) \tag{34}$$

$$\frac{y_c}{h} = 1.772 \left( \frac{y_c}{h} \right)^{0.879} \tag{35}$$

$$\frac{y_c}{h} = 0.496 \left( \frac{y_c}{h} \right) \tag{36}$$

$$\frac{y_c}{h} = 1.857 \left( \frac{y_c}{h} \right)^{0.952} \tag{37}$$

![Figure 2. Flow parameters in vertical drops [8]](image)

On vertical drops with sloping aprons shown that for small discharges, the flow is subcritical downstream of the drop. By increasing the discharge, the second regime occurs where the flow is supercritical downstream of the drop. It was found that for a specific $y_c/h$, the relative pool depth
increases by increasing the sloping inverts' angle. The values of the relative downstream depth for sloping inverts are slightly larger than those with a horizontal downstream channel. Experimental results show that for a specific $\frac{y_c}{h}$, the relative energy loss almost increases with increasing the angle of the sloping invert, and the maximum increase is for the 5° slope [2].

3. Results And Discussion

Based on this theoretical calculation, it is found that:

a. the flow conditions at the toe of the spillway ($y_1$) are supercritical flow ($F_1>1$) and in subcritical flow conditions ($F_2<1$) downstream of the spillway after a hydraulic jump,

b. the hydraulic jump condition is steady jump category ($F_1 = 4.5$ to $9$),

c. the energy loss that occurs due to the channel roughness at the inclined drop toe is theoretically 78.60%,

d. energy loss due to hydraulic jump is 67.49%,

e. the total energy loss from the spillway crest to the downstream after tranquil flow (subcritical conditions) is 93.03%.

| Table 1. Theoretical calculation at sloped/inclined drops |
| No | $y_c$ (cm) | $q$ (cm²/s) | $Q$ (l/s) | $y_1$ (cm) | $y_2$ (cm) | $E_0$ (cm) | $E_1$ (cm) | $E_2$ (cm) | $F_1$ | $F_2$ | $L_j$ (cm) |
|----|----------|------------|---------|--------|--------|--------|--------|--------|------|------|----------|
| 1  | 3.0      | 162.7      | 4.92    | 0.76   | 8.49   | 104.50 | 26.72  | 8.70   | 8.29 | 0.22 | 54.48    |
| 2  | 3.5      | 205.1      | 6.14    | 0.89   | 9.85   | 105.25 | 30.57  | 10.09  | 8.16 | 0.22 | 60.55    |

| Table 2. Observation data on sloped/inclined drop model |
| No | $y_c$ (cm) | $q$ (cm²/s) | $Q$ (l/s) | $y_1$ (cm) | $y_2$ (cm) | $E_0$ (cm) | $E_1$ (cm) | $E_2$ (cm) | $F_1$ | $F_2$ | $L_j$ (cm) |
|----|----------|------------|---------|--------|--------|--------|--------|--------|------|------|----------|
| 1  | 3.0      | 162.7      | 4.92    | 0.50   | 5.50   | 104.65 | 59.90  | 5.99   | 15.41 | 0.42 | 73.00    |
| 2  | 3.5      | 205.1      | 6.14    | 0.80   | 7.00   | 105.43 | 37.65  | 7.48   | 9.60 | 0.37 | 85.00    |

Based on calculations from the measurement data of the inclined drop model, it was found that:

a. The flow conditions at the spillway of the model occur critical flow, $y_c$, which is located at an average position of $3.7y_c$.

b. The theoretical conditions and the conditions of the hydraulic physical model are suitable for all flow conditions. The flow conditions at the spillway which are in critical flow condition ($F=1$), flow conditions at the spillway toe which is in supercritical condition ($F_1>1$), and flow conditions downstream of the spillway after the hydraulic jump were in subcritical conditions ($F_2<1$). This condition is a form of verification of flow conditions between the hydraulic physical model test and theoretical calculations. It is concluded that the flow conditions in the physical model test can describe the flow conditions on the spillway.

The measurement results of $y_1$, $y_2$, and $L_j$ on the hydraulic physical model test significantly differ from the theoretical calculation results. The difference is manifested by the relative error of the results of the hydraulic physical model test measurement data against the theoretical calculation results:

a. for $y_1$ the average is 26.81%,

b. for $y_2$ of 29.62%, and

c. for $L_j$ is 35.26%.

With the difference between theoretical results and test results of this hydraulic physical model, it is necessary to study the assumption of the Manning coefficient of roughness (n) used in theoretical
calculations, which uses Manning’s n value of 0.009 for glass materials. For glass materials, n Manning has a minimum value of 0.009, normal 0.010, and a maximum value of 0.013.

Based on the test measurement conditions of the hydraulic physical model, it was found that the average value of Manning’s n was 0.005. From the physical model test, it is found that the Manning n roughness number is finer from 0.009 to 0.013, as the Manning n roughness value range for glass materials. Given the large difference in results between the theoretical and the physical model, it is necessary to adjust the Manning n value in the theoretical using the assumption value i of 0.009. Suppose an average Manning n value of 0.005 is used. In that case, the relative error of the measurement results to the theoretical calculation is for y\(_1\) an average of 20.48%, y\(_2\) of 23.37%, and L\(_j\) of 17.54%. Manning’s n value for each angle for theoretical calculations gives a better value, closer to the theoretical calculation results and measurements in the hydraulic physical model.

The difference between the theoretical calculation results and the physical model test results can be caused by several things, including:

a. the occurrence of air inflow in the flow (air) in the hydraulic physical model test, the aeration conditions are not included in the theoretical calculation formulation,

b. due to aeration, the depth of flow at the toe of the spillway becomes relatively higher than the theoretical calculation results, which causes changes in the Froude number before the jump, the Froude number after the jump, and the conjugate depth of flow downstream of the spillway,

c. with changes in flow depth due to aeration, Froude number, and conjugate depth of flow downstream, it will affect the length of the hydraulic jump.

Based on the consideration of the suitability between the theoretical calculation results and the results of the hydraulic physical model test, then the theoretical calculation is carried out again for the inclined drop by adjustments to the roughness value of n Manning, the results are given in Table 3.

### Table 3. Theoretical calculation on sloped/inclined drop with n Manning of 0.005

| No | y\(_c\) (cm) | q (cm\(^2\)/s) | Q (l/s) | y\(_1\) (cm) | y\(_2\) (cm) | E\(_0\) (cm) | E\(_1\) (cm) | E\(_2\) (cm) | L\(_2\) (cm) | L\(_j\) (cm) |
|----|--------------|----------------|--------|--------------|--------------|------------|------------|------------|------------|------------|
| 1  | 3.0          | 162.7          | 4.92   | 0.5195       | 10.44        | 104.65     | 55.54      | 10.57      | 14.55      | 77.49      |
| 2  | 3.5          | 205.1          | 6.15   | 0.6279       | 11.95        | 105.43     | 60.44      | 12.11      | 13.80      | 83.22      |

Based on analytical or theoretical calculations using the Manning n roughness value, it is found that:

a. the flow conditions at the toe of the drop (y\(_1\)) are supercritical flow (F\(_1\)>1) and in subcritical flow conditions (F\(_2\)<1) downstream of the plunge after a hydraulic jump occurs,

b. the hydraulic jump condition that occurs is included in the category of strong jump (F\(_1\)>9) for all angles of inclined plunge,

c. the energy loss that occurs due to the channel roughness at the sloped drop toe is theoretically 53.41%,

d. energy loss due to hydraulic jump is 81.87%,

e. the total energy loss from the peak of the downstream sloping after the flow is calm (subcritical conditions) is 91.44%.

The measurement data in the physical model for flow in single vertical and serial vertical drops obtained are:

a. y\(_c\) = critical flow depth, the parameter that is set to determine the flow rate and this depth is measured at the spillway crest,

b. y\(_1\) = depth of flow at the toe of the spillway,

c. y\(_2\) = depth of flow downstream after the hydraulic jump,

d. L\(_j\) = hydraulic jump length,

The specialization of the serial drop data was carried out because based on observations in the hydraulic physical model test, the condition of the flow parameters had similar properties in a single
drop and fulfilled the analysis with a single vertical drop equation approach. These data will be analyzed by comparing them with the results of parameter determination equations in a single vertical drop that have been investigated by Rand (1955), Dominguez (1944), White (1943), and Musavi-Jahromi, et al. (2004).

The data referred to in the flow parameters in this serial drop are flow parameters such as in the stepped spillway ($y_1$, $y_2$, $L_d$):

a. $y_p =$ depth of nappe under the drop face,

b. $L_d =$ distance of water jet downstream of the spillway toe.

**Table 4. Theoretical calculation on single vertical drop structures [2]**

| No | $y_c$ (cm) | $Q$ (cm²/s) | $Q$ (l/s) | $D$ | $L_d$ (cm) | $y_p$ (cm) | $y_1$ (cm) | $y_2$ (cm) | $F_1$ (cm) | $F_2$ (cm) | $L_d$ (cm) |
|----|------------|-------------|-----------|-----|------------|------------|------------|------------|------------|------------|------------|
| 1  | 3.00       | 162.70      | 4.92      | 2.70*10⁻⁵ | 25.11      | 9.88       | 0.62       | 9.69       | 10.71      | 0.17       | 62.63       |
| 2  | 3.50       | 205.10      | 6.14      | 4.29*10⁻⁵ | 28.46      | 10.94      | 0.75       | 10.99      | 10.05      | 0.18       | 70.61       |

**Table 5. Theoretical calculation on single vertical drop based on Dominguez (1944)**

| No | $y_c$ (cm) | $Q$ (cm²/s) | $Q$ (l/s) | $K$ | $L_d$ (cm) | $y_1/y_c$ (cm) | $y_2/y_c$ (cm) | $y_1$ (cm) | $y_2$ (cm) | $F_1$ (cm) | $F_2$ (cm) | $L_d$ (cm) |
|----|------------|-------------|-----------|-----|------------|----------------|----------------|------------|------------|------------|------------|------------|
| 1  | 3.00       | 162.70      | 4.92      | 33.33 | 25.77      | 0.40           | 0.40           | 2.10       | 2.10       | 1.30       | 1.30       | 18.59      |
| 2  | 3.50       | 205.10      | 6.14      | 28.57 | 28.71      | 0.40           | 0.40           | 2.10       | 2.10       | 1.40       | 1.40       | 104.50     |

**Table 6. Theoretical calculation on single vertical drop based on Rand (1943)**

| No | $y_c$ (cm) | $Q$ (cm²/s) | $Q$ (l/s) | $K$ | $L_d$ (cm) | $y_1/y_c$ (cm) | $y_2/y_c$ (cm) | $y_1$ (cm) | $y_2$ (cm) | $F_1$ (cm) | $F_2$ (cm) |
|----|------------|-------------|-----------|-----|------------|----------------|----------------|------------|------------|------------|------------|
| 1  | 3.00       | 162.70      | 4.92      | 33.33 | 25.12      | 0.30           | 0.30           | 2.20       | 2.20       | 1.39       | 1.39       | 6.08       |
| 2  | 3.50       | 205.10      | 6.14      | 28.46 | 28.17      | 0.30           | 0.30           | 2.20       | 2.20       | 1.45       | 1.45       | 6.09       |

**Table 7. Theoretical calculation on single vertical drop based on Mushavi-Jahromi, et al. (2004)**

| No | $y_c$ (cm) | $Q$ (cm²/s) | $Q$ (l/s) | $L_d$ (cm) | $y_p$ (cm) | $y_1$ (cm) | $y_2$ (cm) | $F_1$ (cm) | $F_2$ (cm) |
|----|------------|-------------|-----------|------------|------------|------------|------------|------------|------------|
| 1  | 3.00       | 162.70      | 4.92      | 14.03      | 8.13       | 6.59       | 2.86       | 0.31       |
| 2  | 3.50       | 205.10      | 6.14      | 16.26      | 9.30       | 7.63       | 2.86       | 0.31       |

**Table 8. Observation data and calculation of flow parameters in serial drops**

| No | $y_c$ (cm) | $Q$ (cm²/s) | $Q$ (l/s) | $y_1$ (cm) | $y_2$ (cm) | $L_d$ (cm) | $L_d$ (cm) | $F_1$ (cm) | $F_2$ (cm) |
|----|------------|-------------|-----------|------------|------------|------------|------------|------------|------------|
| 1  | 3.00       | 162.70      | 4.92      | 10.50      | 11.00      | 33.00      | 62.00      | 0.15       | 0.14       |
| 2  | 3.50       | 205.10      | 6.14      | 9.50       | 10.00      | 35.00      | 65.00      | 0.22       | 0.21       |

**Figure 3. Flow parameters in serial drops**
The hydraulic model test results of the inclined and serial drops are compared to obtain information, especially for the flow behavior and energy dissipation. The comparisons made are devoted to flow parameters, including the parameters of the depth of flow at the toe of the spillway ($y_1$), the depth of flow after the jump ($y_2$), and the length of the hydraulic jump ($L_j$).

The recapitulation of the results of the comparison between the model test results of the inclined and serial drops on the parameters $y_1$, $y_2$, $L_j$, are as follows:

a. The change in $y_1$ is 2082.50%,
b. The change in $y_2$ is 72.70%, and
c. The change in $L_j$ is -60.90%.

4. Conclusion

The results of the comparison between inclined drop and serial drop in the hydraulic physical model test on variables $y_1$, $y_2$, $L_j$ has shown that:

a. the serial drops increase the flow depth at the toe of the spillway ($y_1$), by an average of 2082.50% compared to the inclined plunge,
b. the serial drop increases the flow depth after the jump ($y_2$), by 72.70% compared to the inclined drop, and
c. the serial drop can shorten the hydraulic jump length downstream of the spillway ($L_j$), an average of 60.90% compared to the inclined drop.

The measurement results of the variables $y_1$, $y_2$, $L_j$, $y_p$ and $L_d$ in the serial drop indicate that the number of drops influences the magnitude of the flow parameter.

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