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EXPERIMENTAL INVESTIGATION OF DOUBLE SILL CONFIGURATION TO ENHANCE ENERGY DISSIPATION

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ABSTRACT: Energy dissipation of water flow is an important factor in the planning of structures such as stilling basins. One of the standards set by the USBR (United States Bureau of Reclamation) that must be considered in the planning of the stilling basin is the Froude number (F_1) at the toe of the spillway. Various forms of planning can be used to meet these standards, one of which is by using a double-sill downstream of the chute channel with a certain distance and height. However, as an alternative to planning, this study aims to evaluate the level of attenuation of flow energy in a stilling basin by using a double-sill. Because this sill is more effective in breaking down and reducing the strength of the water flow. Hydraulic physical model tests were carried out in the laboratory by placing double sills in a fixed position and varying the height of the sills. Because several previous studies have shown that the shape and size of sills affect the level of energy dissipation. It is expected that the results of the hydraulic model test can provide better information about the flow behavior in the overflow system in terms of energy dissipation.

Keywords: Hydraulic jump, Double sill, Energy dissipation, Model test

1. INTRODUCTION

Stilling Basin is the main spillway structure that functions to reduce energy in the dam, responsible for dissipating the energy of overflowing air. When air flows through a deposition, the difference in air surface height between the top and bottom of the deposition causes significant energy changes, resulting in regular hydraulic shocks or disturbances in the airflow.

In this condition, there is a sudden transition from supercritical flow to subcritical flow[1]. The energy dissipation caused by hydraulic locating effectively protects downstream channels from erosion and damage. A hydraulic jump is a transition from supercritical to subcritical flow conditions involving varying amounts of energy dissipation, depending on the speed and depth of the supercritical flow, causing the cessation of the flow[2.3].

One way to control hydraulics is to use stilling basins. Stilling basins are typically constructed downstream of channels and gates to control the energy dissipation of hydraulic jump[4]. Sills and end sills are commonly used in energy dissipator structures to stabilize and prevent hydraulic disturbances. The design of head basins includes estimating spillway losses, determining the length and depth of the basin based on the characteristics of the hydraulic jump, and determining the size of the channel blocks and blocking blocks based on the jump's characteristics and guidelines. Relaxing bathtubs can be designed in a variety of shapes and sizes to suit airflow conditions.

Various modifications have been explored to improve energy dissipation in stilling basins[5,6]. Experimental investigations have been carried out on energy dissipator models using insulating blocks. Modifying the plan and profile of the stilling basin can also reduce costs. Research has examined the influence of adverse slope and divergence angle on hydraulic disturbances in gradually diverging channels. These studies show that free hydraulic jumps on adverse slopes can become unstable at low Froude numbers but that relatively stationary barrier jumps can be maintained at Froude numbers between 4 and 9. The size and geometry of the stilling basin significantly influence flow patterns, which in turn affects the overall performance of the hydraulic system.

Numerical simulations have been used to study hydraulic disturbance phenomena and optimize the design of the stilling basin[8]. Experimental tests at different scales have been carried out to transmit energy dissipator performance under various flood discharge conditions. These tests include measurements of the hydraulic jump regime, air surface height, velocity, and statistical and fluctuating pressure. The results are analyzed to identify the most effective energy dissipator design.

Further research is needed to determine the effectiveness of energy-dampening systems in spillways. Laboratory experiments should be carried out using a spillway with a steep slope to produce a strong hydraulic jump (Fr>9). Modified energy dissipators can use double sills, gap modifications, and predetermined sill dimensions, height, and distance from the spillway. By analyzing observed and measured flow conditions, the optimal dual threshold composition to produce maximum energy can be determined. This study investigates the effectiveness of double threshold structures for energy dissipation. The distance and height of the frames varied, and the shape used was different from previous studies, namely using a slanted upstream ogee threshold and a trapezoidal prism threshold. This research is expected to produce useful information to increase the effectiveness of energy dissipation construction with double frames.

2. RESEARCH SIGNIFICANCE

This study focused on hydraulic jumps and energy dissipation using a modified double sill. This research is particularly important as it sheds light on the effectiveness of double-sill stilling basins in achieving energy reduction. Stilling basins play a critical role in various aspects of water management by mitigating energy within the basin. This reduction in energy brings several advantages:

1. Reduced Erosion: High-velocity flows can significantly erode the downstream channel bed and banks. Stilling basins dampen the flow velocity, minimizing this erosion and safeguarding the channel's structural integrity.
2. Protected Hydraulic Structures: Spillways and weirs are designed for specific flow conditions. By reducing energy, stilling basins shield these structures from excessive forces that could lead to damage or failure.

There are 12 series that will be tested in this study, where there are 3 variations in sill height in each series. then each series will be tested with 7 flowrates (15, 17, 19, 21, 23, 25, and 27 liters/second).

Therefore, this research is considered important because it provides further insight into the use of double sill with a modified form to reduce energy.

3. PHYSICAL HYDRAULIC MODEL TESTS

3.1 Hydraulic Physical Model Data

The research was conducted in the River Engineering Laboratory, Department of Water Resources Engineering, Faculty of Engineering, Universitas Brawijaya.

The research implementation by testing the hydraulic physical model uses several laboratory facilities and equipment, including:

1) The width of the open channel, B = 0.4 m
2) A hydraulic physical model of a spillway with 1.0 m height
3) Chute way channel with 1:0.8 slope

3.2 Research Variable

In the double sill study, two types of sill with different characteristics were used. Sill-1 (Z_1) has a sloping head and a curved (round) crest (upstream slope ogee type) shown in Figure 1, while sill-2 (Z2) has a vertical head and a flat (wide) crest (trapezoidal prism sill type) shown in Figure 2. In this study, a hydraulic model test was carried out by varying the sill height. In addition, the distance between sill-1 and sill-2 (L_2) is also varied. The model test was carried out by testing seven flow rates, namely 15, 17, 19, 21, 23, 25, and 27 liters/second in each test series. The number of treatments performed in the laboratory was 84. The following are the dimensions and shapes of the two types of sill used in Table 1.

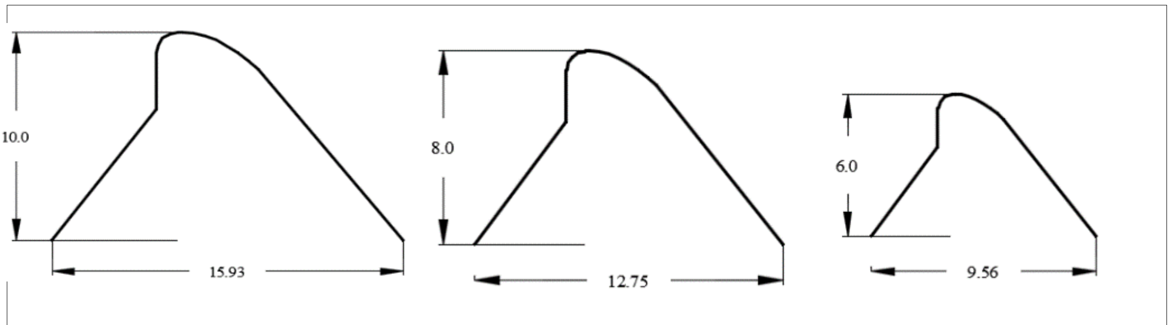

Fig. 1 Dimension of sill 1 (Z_1)

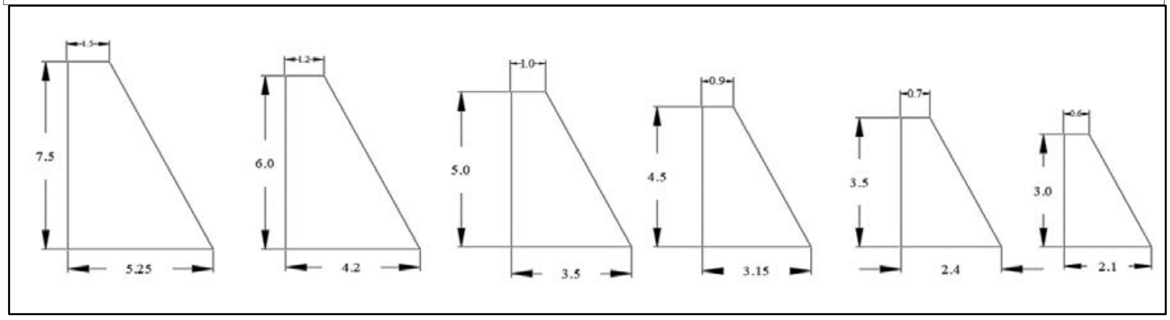

Fig. 2 Dimension of sill 2 (Z_2)

Table 1. Variations of sill dimention

Series	Q (lt/sec)	L_1 (cm)	Z_1 (cm)	Z_2 (cm)	L_2 (cm)
1	15;17;19;21;23;25;27	80	10	7,5	40
2	15;17;19;21;23;25;27	80	10	5	40
3	15;17;19;21;23;25;27	80	8	6	40
4	15;17;19;21;23;25;27	80	8	4	40
5	15;17;19;21;23;25;27	80	6	4.5	40
6	15;17;19;21;23;25;27	80	6	3	40
7	15;17;19;21;23;25;27	80	10	7.5	20
8	15;17;19;21;23;25;27	80	10	5	20
9	15;17;19;21;23;25;27	80	8	6	20
10	15;17;19;21;23;25;27	80	8	4	20
11	15;17;19;21;23;25;27	80	6	4.5	20
12	15;17;19;21;23;25;27	80	6	3	20

In Figure 1, Figure 2 the shape is explained, and in Table 1 the size of each series is explained. Figure 3 shows the double sill form used in this study.

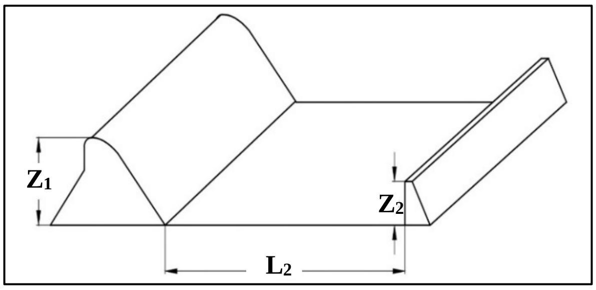

Fig. 3 Double Sill Sketch

3.3 Flow in Open Channels

Flow through an open channel is called uniform flow if the various flow variables present, such as flow depth, wetted area, flow velocity, and flow rate at each section along the flow are constant. In this uniform flow, the energy line, water level line, and channel bed are parallel so that the slopes of these 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 [7]. If the flow velocity exceeds a certain limit (critical speed), then the water surface
Becomes unstable and waves will occur. At very high velocities (more than 6 m/s), air will enter the stream and the flow may become unsteady. The flow is called non-uniform or changing (non-uniform flow or varied flow) if the flow variables such as flow depth, wetted area, flow rate, and flow rate at each section along the flow are not constant or change.

If the 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. Water flow 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, flow in open channels can also be divided into subcritical (flowing), critical, and supercritical (sliding) flows. The basis for determining this type of flow is the Froude number.

Some empirical equations that apply to the flow in an open channel with a square cross-section, among others [9] :

$$Q = V\ \mathrm{A} \quad (1)$$

$$V = \frac{1}{n} R^{2/3} {S_0}^{1/2} \quad (2)$$

$$A = B\ \mathrm{y} \quad (3)$$

$$R = \frac{A}{P} \quad (4)$$

$$P = B + 2y \quad (5)$$

$$F = \frac{V}{\sqrt{\frac{gy}{\alpha}}} \quad (6)$$

$$y_c = \sqrt[3]{\frac{\alpha q^2}{g}} \quad (7)$$

3.4 Specific Energy

The energy contained in one unit weight of water flowing in an open channel consists of three forms, namely kinetic energy, pressure energy, and elevation energy above the reference line. The kinetic energy at a section in an open channel is given the form $V^2/2g$. The pressure energy in the open channel is calculated concerning the water level. The elevation of the flow head is measured concerning a horizontal reference line. The vertical distance from the reference line to the bottom of the channel is usually taken as the elevation energy (potential) height of the section. For uniform flow conditions, then Sf = Sw = S_0 = SinΘ. The equation used [10]

$$z_1 + y_1 + \alpha_1 \frac{{V_1}^2}{2g} = z_2 + y_2 + \alpha_2 \frac{{V_2}^2}{2g} + h_f \quad (8)$$

$$S_0 \Delta x + y_1 + \alpha_1 \frac{{V_1}^2}{2g} = y_2 + \alpha_2 \frac{{V_2}^2}{2g} + S_f \Delta x \quad (9)$$

$$\Delta x = \frac{E_2 - E_1}{S_o - S_f} = \frac{\Delta E}{S_o - S_f} \quad (10)$$

$$S_f = \frac{n^2 \overline{V}^2}{\overline{R}^{4/3}} \quad (11)$$

$$h_f = S_f \Delta x \quad (12)$$

Eddy loss (hel) can be obtained with the equation:

$$h_{el} = C_{el} \left| \frac{\alpha_1 V_1 - \alpha_2 V_2}{2g} \right| \quad (13)$$

Assuming $\boldsymbol{\alpha}_1$=$\boldsymbol{\alpha}_2$=1, and h_f=0, then:

$$z_1 + y_1 + \frac{{V_1}^2}{2g} = z_2 + y_2 + \frac{{V_2}^2}{2g} = constant \quad (14)$$

The energy at the cross-section of the channel, which is calculated against the bottom of the channel is called the specific energy or specific height [11]:

$$E_s = y + \frac{\alpha V^2}{2g} \quad (15)$$

With:

A = wet cross-sectional area (m^2),
B = channel bottom width (m),
E = energy height (m),
Es = specific energy, the energy measured from the channel bottom (m),
Ec = critical energy height above sill (m),
E0 = energy head upstream (m),
E1 = energy head at the foot of the spillway (m),
E2 = energy head downstream of the spillway (m),
ΔE = loss of energy head (m),
g = acceleration gravity (m/s^2),
h = drop height (m),
n = Manning roughness coefficient,
Q = flow rate (m/s),
q = discharge per unit width (m^2/s),
q = Q/B,
R = average hydraulic radius (m),
S0 = canal bottom slope,
Sf = slope of the energy line,
V = average velocity (m/s),
y = depth of water flow (m),
yc = critical depth (m),
z_1 = base height of channel section 1 to the basic equation line (m),
z_2 = base height of channel section 2 to the basic equation line (m),
x = horizontal distance between plates (m), energy coefficient.

3.5 Hydraulic Jump

A hydraulic jump occurs when a supercritical flow must change into a subcritical flow. There is a sudden rise in the water level and a large loss of energy in the hydraulic jump. A large turbulent vortex forms at the start of the jump. This eddy draws energy from the mainstream and the eddy breaks into smaller pieces while flowing downstream [12] General hydraulic jump conditions are depicted in Figure 2.

In the event of a hydraulic jump, the basic component that influences the energy calculation is the momentum equation [13], [14]

$$\text{P1} - \text{P2} = \rho Q (V_1 - V_2) \quad (16)$$

$$\left(\frac{1}{2}\rho g {y_1}^2 - \frac{1}{2}\rho g {y_2}^2\right) B = \rho V_1 y_2 (V_1 - V_2) \quad (17)$$

$$(y_1 - y_2)(y_1 + y_2) = \frac{2 V_1 y_1}{g}(V_2 - V_1) \quad (18)$$

Meanwhile, from the continuity equation:

$$q = V_1 y_1 = V_2 y_2 \quad (19)$$

by combining the above equations, then:

$$(y_1 + y_2) = \frac{2{V_1}^2}{g}\frac{y_1}{y_2} \quad (20)$$

$$\frac{y_2}{y_1}\left(1 + \frac{y_2}{y_1}\right) = 2F_1^2 \quad (21)$$

By simplifying the above equation, the equation is obtained:

$$\frac{y_2}{y_1} = \frac{1}{2}\left(\sqrt{1 + 8{F_1}^2} - 1\right) \quad (22)$$

Where y1 and y2 are the water depths before and after the jump (m), and F_1 is the Froude number of the first section before the jump.

For supercritical flow in a horizontal rectangular channel, the flow energy will be damped by the channel frictional resistance, causing a reduction in velocity and an increase in height in the flow direction.

Hydraulic jumps, which occur on a horizontal surface, are of several different types. By research conducted by the United States Bureau of Reclamation, these hydraulic jumps can be distinguished based on the flow Froude number [15]:

1. Critical flow, for F_1 = 1 there is critical flow, so no jumps can be formed.
2. Wavy jump, for F_1 = 1 to F_1 = 1.7 there are waves on the surface of the water.

3. The jump is weak, for F_1 = 1.7 to F_1 = 2.5 a network of wave rolls is formed on the surface of the jump, but the water surface downstream remains smooth. Overall the speed is uniform, and the energy loss is small.
4. Oscillating jumps, for F_1 = 2.5 to F_1 = 4.5 there are oscillating bursts accompanying the base of the jump moving to the surface and back again without a certain period. Each oscillation generates huge irregular waves and causes unlimited damage to the embankment.
5. Steady jump, for F_1 = 4.5 to F_1 = 9, the edges of the downstream surface will roll and the point where the jet velocity is high tends to break away from the flow. In general, both of these occur on the same vertical surface. The movements and jumps that occur are not so influenced by the depth of the water below. The hydraulic jump is perfectly balanced, the characteristics are the best. The energy dissipation is 45% - 70%.
6. Strong jumps, for $F_1 > 9$ and greater, high burst velocities will separate the crashing rolling waves from the braking surface, creating waves downstream. If the surface is rough it will affect the waves that occur. Stepping movements are rare, but effective because their energy dissipation can be up to 85%.

Some of the basic properties of hydraulic jumps in rectangular channels with a horizontal base can be described as follows [14]:

3.5.1 *Loss of Energy*

The energy loss in a jump is equal to the difference in specific energy before and after the jump [11,12]. The amount of energy loss is [15], [16]:

$$\boldsymbol{\Delta E = E_1 - E_2 = \frac{(y_2-y_1)^3}{4y_1y_2}} \quad (23)$$

3.5.2 Efficiency

The ratio between the specific energies after the jump and before the jump is defined as the jump efficiency. So the magnitude of the jump efficiency is:

$$\frac{E_2}{E_1} = \frac{\left(8F_1^2+1\right)^{3/2}-4F_1{}^2+1}{8F_1{}^2\left(2+F_1{}^2\right)} \quad (24)$$

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 – E2/E1, this quantity is also a dimensionless function of the Froude number [13].

3.5.3 Hydraulic Jump Height

The height of the jump can be defined as the difference between the depth before and after the jump.

$$y_j = y_2 - y_1 \quad (24)$$

3.5.4 Hydraulic Jump Length

The length of the hydraulic jump, defined as the distance between the front turbulent zone where the supercritical flow transitions to subcritical flow and the point on the downstream surface where the wave roll subsides, is a crucial parameter in hydraulic engineering design. However, unlike other hydraulic properties, determining the length of the jump purely through theoretical calculations proves to be a complex challenge. This is due to the highly turbulent nature of the flow within the jump zone, making it difficult to model the energy dissipation and momentum transfer processes accurately**.** [14,15].

3.6 Energy Dissipator

In general, tumbling basins are rarely designed to withstand the full length of the free jump, as this would be very expensive. For this reason, equipment to control jumping is usually installed in the stilling basin. The main use of this controller is to shorten the interval between jumps, thereby reducing the size and cost of the stilling basin. Control has several advantages, namely improving the function of the churning basin dissipation, stabilizing the jumping motion, and in some cases also increasing the safety factor [13].

The recommended approach in planning a stilling basin for a Froude number of $2.5 < Fr < 4.5$ is to increase or decrease (but it is better to increase) the Froude number until it exceeds the magnitude of this quantity. The Froude number can be increased by increasing the velocity v or decreasing the depth of water, y. The two are connected via discharge per unit width q, which can be added by reducing the width of the building (q = Q/B). If the above approach is not possible, then two types of stilling basins can be used, namely: (1) USBR type IV stilling basins, feature a large face block that helps strengthen the vortex. (2) sill-basin type stilling basins. . The big drawback of this pool is that in this structure all floating and drifting objects can get stuck. This causes the basin to overflow and the barrier blocks to break. Also, the manufacture of barrier blocks requires reinforcing concrete

For Froude numbers above 4.5, the water jump can be steady and energy dissipation can be achieved well. The USBR type III pulse pool was specially developed for these numbers. If the use of baffle blocks and front blocks is not feasible (because the building is made of masonry) the basin should be designed as a plunge pool with end lintels. This pool will be long but shallow

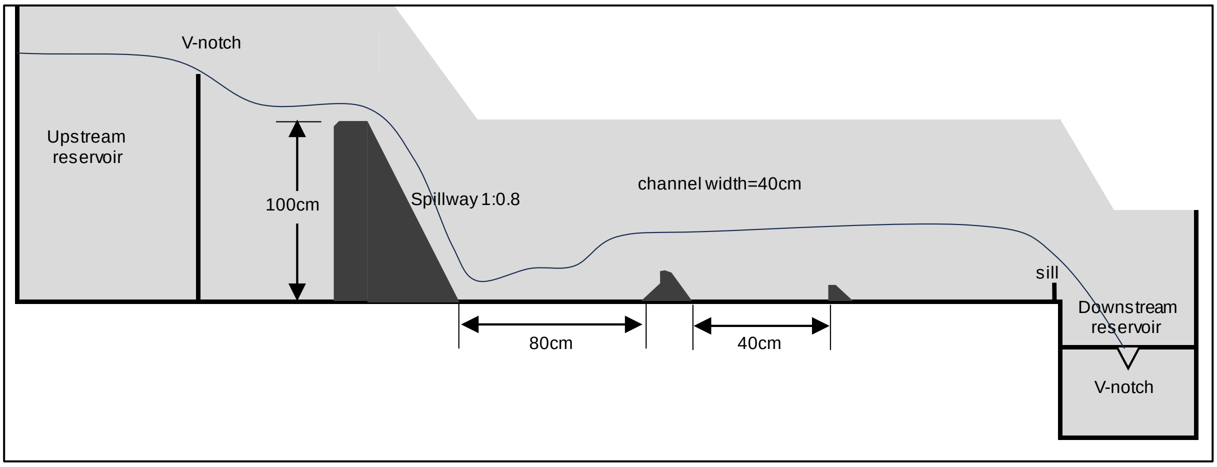

Fig. 4 Sketch depiction of double sill research hydraulics model test

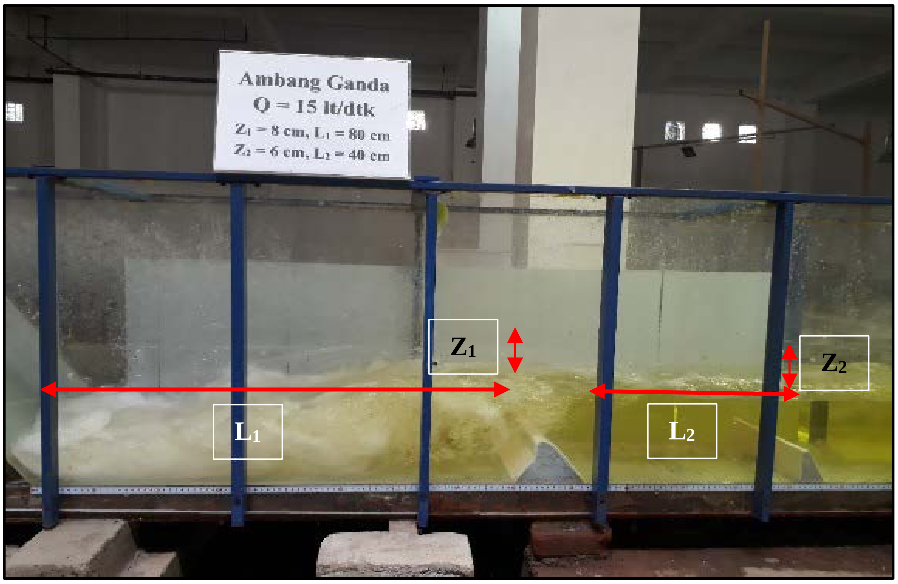

Fig. 5 Sketch depiction of double sill research hydraulics model test

4. RESULT

Figures 4 and 5 show the results of research in the laboratory

4.1 Measurement Results Of Flow Depth And Velocity

Measurements made on the hydraulic model test consisted of measuring flow depth, velocity, and pressure, and observing hydraulic jump conditions. In this research energy dissipation due to supercritical flow was developed at the initial design conditions, Q = 15-27 liters/second, chute way slope 1:0.8 (Figure 4). Theoretically, this condition will result in supercritical flow with Fr = 11-13 which will result in a strong hydraulic jump.

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(2) The big drawback of this pool is that in this structure all floating and drifting objects can get stuck. This causes the basin to overflow and the

4.2 Froude Calculation Results

Based on the measured water level, the Froude values for y_1 and y_2 can be calculated and it can be concluded that the Froude value varies. There are characteristics of each flow behavior: at y_1, the resulting Froude value is 2.5-4.5 so it is included in the oscillating jump which causes irregular isolated bursts and produces large waves heading downstream, this can erode or erode the embankment. At y_2, the resulting Froude value, namely <1, is included in the subcritical flow. In this case, it shows that energy dissipation is very influential on the amount of the resulting Froude value.

Table 2. Froude Value

Series	Variable	Q (l/sec) 15	17	19	21	23	25	27
1	Fr_1	5,98	5,97	6,10	6,04	6,41	6,59	5,28
	Fr_2	0,18	0,20	0,21	0,22	0,24	0,23	0,25
2	Fr_1	6,77	5,98	5,76	5,88	5,70	5,98	5,89
	Fr_2	0,19	0,20	0,21	0,22	0,24	0,23	0,23
3	Fr_1	6,94	6,72	6,37	6,81	6,36	6,54	5,59
	Fr_2	0,20	0,20	0,23	0,22	0,24	0,23	0,24
4	Fr_1	5,98	5,69	5,80	5,89	5,81	5,57	5,72
	Fr_2	0,20	0,20	0,21	0,22	0,24	0,23	0,24
5	Fr_1	7,37	5,39	5,83	6,20	5,99	6,17	5,41
	Fr_2	0,19	0,20	0,20	0,22	0,24	0,23	0,24
6	Fr_1	6,38	5,92	5,95	6,27	5,91	5,72	5,39
	Fr_2	0,18	0,20	0,20	0,22	0,24	0,23	0,24
7	Fr_1	6,98	6,74	6,33	6,68	6,48	6,01	5,69
	Fr_2	0,19	0,21	0,23	0,22	0,23	0,23	0,24
8	Fr_1	6,05	5,76	5,79	5,52	6,01	6,15	6,24
	Fr_2	0,18	0,20	0,20	0,21	0,24	0,23	0,25
9	Fr_1	6,15	5,56	5,64	5,59	5,61	5,88	5,99
	Fr_2	0,19	0,21	0,22	0,22	0,24	0,24	0,25
10	Fr_1	6,15	5,93	6,40	6,27	5,89	6,07	5,36
	Fr_2	0,19	0,21	0,22	0,22	0,23	0,23	0,22
11	Fr_1	7,45	5,50	5,46	5,40	5,51	5,58	5,84
	Fr_2	0,19	0,20	0,21	0,21	0,23	0,23	0,23
12	Fr_1	8,01	6,00	6,26	6,48	6,31	6,55	5,86
	Fr_2	0,19	0,20	0,20	0,22	0,22	0,23	0,24

Based on table 2. shows that the obtained Froude number varies. At y1. the resulting Froude number is Fr_1=5-8 so that it is included in the supercritical jump. At y_2, the resulting Froude number. namely Fr_2<1. is included in the subcritical flow. In this case it shows that energy dissipation is very influential on the amount of the resulting Froude number. The Froude value was obtained which proves that the jump that occurs after the sill is a subcritical jump, after that the minimum value and average value of Fr_2 are calculated in the following Table 3.

Table 3. Minimum and Avarage of Fr_2

Series	Minimum Fr_2	Avarage Fr_2
1	0.18	0.21
2	0.19	0.21
3	0.20	0.22
4	0.20	0.22
5	0.19	0.21
6	0.18	0.21
7	0.19	0.21
8	0.18	0.21
9	0.19	0.22
10	0.19	0.21
11	0.19	0.21
12	0.19	0.21

So it can be seen that the minimum Fr_2 yield is in Series 1(L_1= 80 cm; L_2= 40 cm; Z_1= 10 cm; Z_2= 7.5 cm).

4.3 Energy Dissipation

The effectiveness of energy dissipation can be seen based on the comparison of the specific energy before the jump with the specific energy after the jump. This comparison is defined as the efficiency of the jump. the greater the efficiency of the jump. the more effective the energy dissipation is. Based on the data analysis and discussion carried out. the resulting jump efficiency is quite varied.

The jump efficiency in one series with several discharges produces an average jump efficiency. where the one with the largest jump efficiency value is the most effective series. As for the double sill energy dissipation. the series 11 (L_1 = 80; L_2 = 20; Z_1 = 6; Z_2 = 4.5) with the highest average jump efficiency result being E2/E1 = 0.59 or 59%.

This energy dissipation is accompanied by energy losses that occur due to hydraulic jumps. E1-E2 whose nature varies depending on the value of the efficiency of the jump. Table 4 shows the values of the jump efficiency generated in the double energy dissipations in each series.

Table 4. Efficiency of hydraulic jump in double sill

Se-ri-es	Q (m^3/dt)	E_1 (m)	E_2 (m)	Relative loss (%) (E_1-E_2)/E_1	Hydrau-lic jump efficiency E_2/E_1	Average jump efficiency
1	0.015	5.98	0.30	40.64	0.59	0.54
	0.017	5.97	0.33	40.41	0.60	
	0.019	6.10	0.36	46.56	0.53	
	0.021	6.04	0.38	46.64	0.53	
	0.023	6.41	0.43	51.75	0.48	
	0.025	6.59	0.48	52.75	0.47	
	0.027	5.28	0.38	39.83	0.60	
2	0.015	6.77	0.35	51.40	0.49	0.55
	0.017	5.98	0.33	41.20	0.59	
	0.019	5.76	0.34	42.02	0.58	
	0.021	5.88	0.37	44.88	0.55	
	0.023	5.70	0.38	44.71	0.55	
	0.025	5.98	0.42	47.20	0.53	
	0.027	5.89	0.44	44.99	0.55	
3	0.015	6.94	0.36	52.57	0.47	0.50
	0.017	6.72	0.38	50.37	0.50	
	0.019	6.37	0.38	49.25	0.51	
	0.021	6.81	0.44	54.43	0.46	
	0.023	6.36	0.43	50.77	0.49	
	0.025	6.54	0.47	52.30	0.48	
	0.027	5.59	0.41	43.61	0.56	
4	0.015	5.98	0.30	40.83	0.59	0.57
	0.017	5.69	0.31	39.04	0.61	
	0.019	5.80	0.34	44.37	0.56	
	0.021	5.89	0.37	43.38	0.57	
	0.023	5.81	0.38	44.43	0.56	

Cotinued Table 4. Efficiency of hydraulic jump in double sill

Se-ri-es	Q	E_1	E_2	Relative loss (%)	Hydrau-lic jump efficiency	Average jump
	(m^3/dt)	(m)	(m)	(E_1-E_2)/E_1	E_2/E_1	efficiency
	0.025	5.57	0.39	43.95	0.56	
	0.027	5.72	0.42	44.79	0.55	
5	0.015	7.37	0.39	56.56	0.43	0.55
	0.017	5.39	0.29	34.65	0.65	
	0.019	5.83	0.34	41.91	0.58	
	0.021	6.20	0.39	48.05	0.52	
	0.023	5.99	0.40	46.81	0.53	
	0.025	6.17	0.44	49.16	0.51	
	0.027	5.41	0.39	40.07	0.60	
6	0.015	6.38	0.33	47.12	0.53	0.56
	0.017	5.92	0.32	41.42	0.59	
	0.019	5.95	0.35	44.47	0.56	
	0.021	6.27	0.40	48.55	0.51	
	0.023	5.91	0.39	45.90	0.54	
	0.025	5.72	0.40	42.76	0.57	
	0.027	5.39	0.39	39.07	0.61	
7	0.015	6.98	0.36	51.80	0.48	0.50
	0.017	6.74	0.38	51.12	0.49	
	0.019	6.33	0.38	49.30	0.51	
	0.021	6.68	0.43	52.15	0.48	
	0.023	6.48	0.44	53.14	0.47	
	0.025	6.01	0.42	47.65	0.52	
	0.027	5.69	0.42	44.04	0.56	
8	0.015	6.05	0.30	42.83	0.57	0.56
	0.017	5.76	0.31	39.79	0.60	
	0.019	5.79	0.34	41.99	0.58	
	0.021	5.52	0.34	39.27	0.61	
	0.023	6.01	0.40	47.78	0.52	
	0.025	6.15	0.44	48.26	0.52	
	0.027	6.24	0.47	51.28	0.49	
9	0.015	6.15	0.31	45.23	0.55	0.56
	0.017	5.56	0.30	38.10	0.62	
	0.019	5.64	0.33	42.73	0.57	
	0.021	5.59	0.35	40.14	0.60	
	0.023	5.61	0.37	43.99	0.56	
	0.025	5.88	0.41	48.47	0.52	
	0.027	5.99	0.44	48.31	0.52	

Cotinued Table 4. Efficiency of hydraulic jump in double sill

Se-ri-es	Q	E_1	E_2	Relative loss (%)	Hydrau-lic jump efficiency	Average jump
	(m^3/dt)	(m)	(m)	(E_1-E_2)/E_1	E_2/E_1	efficiency
10	0.015	6.15	0.31	45.18	0.55	0.55
	0.017	5.93	0.32	43.65	0.56	
	0.019	6.40	0.38	50.64	0.49	
	0.021	6.27	0.40	49.77	0.50	
	0.023	5.89	0.39	47.31	0.53	
	0.025	6.07	0.43	49.03	0.51	
	0.027	5.36	0.39	29.82	0.70	
11	0.015	7.45	0.39	56.95	0.43	0.59
	0.017	5.50	0.29	34.79	0.65	
	0.019	5.46	0.31	38.25	0.62	
	0.021	5.40	0.33	33.97	0.66	
	0.023	5.51	0.36	40.27	0.60	
	0.025	5.58	0.39	41.19	0.59	
	0.027	5.84	0.43	43.33	0.57	
12	0.015	8.01	0.43	60.51	0.39	0.51
	0.017	6.00	0.33	42.31	0.58	
	0.019	6.26	0.37	46.19	0.54	
	0.021	6.48	0.41	49.41	0.51	
	0.023	6.31	0.43	48.08	0.52	
	0.025	6.55	0.47	51.11	0.49	
	0.027	5.86	0.43	44.20	0.56	

4.4 Length and Height of the Hydraulic Jump Results

The hydraulic jump results obtained are in the form of the length and height of the hydraulic jump. as follows Table 5.

Table 5. Recapitulation of the hydraulic jump length of the double sill stilling basin

Series	Q(l/s)						
	15	17	19	21	23	25	27
1	217	232	241	255	267	272	292
2	211	223	235	244	257	264	273
3	218	225	233	248	256	269	279
4	194	214	228	248	257	266	277
5	196	212	231	245	261	275	287
6	203	215	234	251	267	275	283
7	207	218	231	245	256	264	270
8	195	210	222	236	247	262	274
9	202	218	233	247	260	272	280
10	191	207	221	236	249	260	273
11	196	219	237	253	266	275	284
12	201	215	231	248	262	276	284
Lj Minimum				191			

Based on the table above. it shows that the greater the flow. the longer the hydraulic jump. Based on the results obtained. the minimum hydraulic jump length is in the double sill energy dissipator variation series 10(L_1 = 80; L_2 = 20; Z_1 = 8; Z_2 = 4). with L_j = 191 cm. With this composition. a short hydraulic jump is formed which is an indicator of the effectiveness and efficiency of the energy dissipator in reducing the energy of a flow. This is also related to the height of the jumps formed in all series. as follows Table 6.

Table 6. Recapitulation of hydraulic jump height in double sill energy dissipator

Series	Q(l/s)							Yj
	15	17	19	21	23	25	27	Min
1	15.91	17.27	16.96	17.83	18.38	19.81	19.75	15.91
2	15.24	17.07	17.09	17.79	18.02	19.47	20.92	15.24
3	15.36	16.70	17.02	17.78	18.57	19.80	19.94	15.36
4	15.81	16.51	16.50	18.39	18.65	18.76	20.18	15.81
5	15.22	16.55	17.51	17.96	18.59	19.51	20.39	15.22
6	15.38	16.76	17.13	18.07	18.57	20.00	20.68	15.38
7	15.77	16.51	16.81	18.25	18.10	19.37	20.27	15.77
8	15.52	16.63	17.30	18.10	18.30	19.81	19.82	15.52
9	15.14	16.29	16.37	18.12	17.90	18.44	19.95	15.14
10	15.14	16.06	16.62	17.57	17.97	19.09	24.07	15.14
11	15.33	16.97	17.02	19.27	18.77	19.86	21.41	15.33
12	15.49	16.78	17.80	18.62	19.56	20.40	21.12	15.49
Yj Minimum					**15.4**			**15.14**

Based on the table above. it shows that the greater the flow. the higher the hydraulic jump. The results of the minimum hydraulic jump height are in the double sill stilling basin variation series 10 (L_1 = 80; L_2 = 20; Z_1 = 8; Z_2 = 4). with y_j = 15.4 cm which shows the effectiveness of the distance and height of the sill tested.

Table 7. Selected average value of every variable

Variable	Average value	Series
y_j (smallest hydraulic jump height)	15.4	10
L_j (smallest hydraulic jump length)	191	10
Fr_2 (smallest Froude's value at y_2)	0.18	1
Greatest jump efficiency	0.59	11

Based on the measurement results in each series will be analyzed and produce dimensionless parameters. The equation with the number of R^2 is the result of the relationship curve of each number being compared. The following Table 8 is the result of the correlation curve among dimensionless

Table 8. Results of analysis of combined between dimensional variables.

Number	X-Axis	Y-Axis	Regression line equation	R^2
1	y_1/y_2	y_j/y_2	$(y_j/y_2) = -1(y_1/y_2) + 1$	1
2	y_1/y_2	y_j/y_1	$(y_j/y_1) = -107.93(y_1/y_2) + 19.838$	0.9889
3	y_1/y_2	y_2/y_1	$(y_2/y_1) = -107.93(y_1/y_2) + 20.838$	0.9889
4	y_1/y_2	L_j/y_1	$(L_j/y_1) = -1071.8(y_1/y_2) + 229.95$	0.7095
5	y_j/y_2	y_j/y_1	$(y_j/y_1) = 107.93(y_j/y_2) - 88.094$	0.9889
6	y_j/y_2	y_2/y_1	$(y_2/y_1) = 107.93(y_j/y_2) - 87.094$	0.9889
7	$y_2 1/2.g1/2)$	L_j/y_1	$(L_j/y_1) = 16.024(v1/(y_2 1/2.g1/2)) + 27.358$	0.7717
8	$y_2 1/2.g1/2)$	y_c/y_2	$(y_c/y_2) = 0.7235(v_2/(y_2 1/2.g1/2)) + 0.168$	0.7146
9	y_2/y_1	y_j/y_1	$(y_j/y_1) = 1(y_2/y_1) – 1$	1
10	y_2/y_1	L_j/y_1	$(L_j/y_1) = 10.084(y_2/y_1) + 21.452$	0.74
11	L_j/y_1	$v_1/(y_2 1/2.g1/2$	$(v_1/(y_2 1/2.g1/2)) = 0.0482(L_j/y_1) + 0.0666$	0.7717

From the Table 8 above. the best regression equation relationship is taken. the best graph can be seen in the Figure 6 until Figure 8.

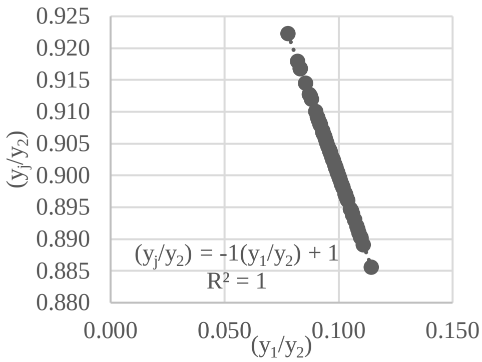

Fig. 6 The y_1/y_2 and y_j/y_2 relationship curves

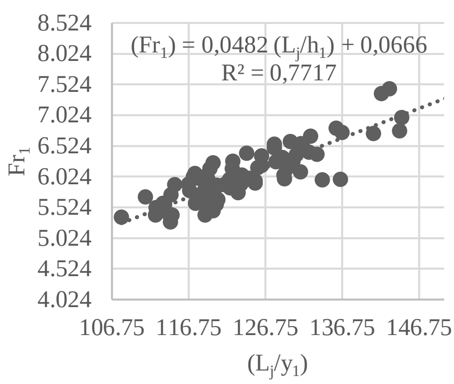

Fig. 7 The Fr_1 and L_j/y_1 relationship curves

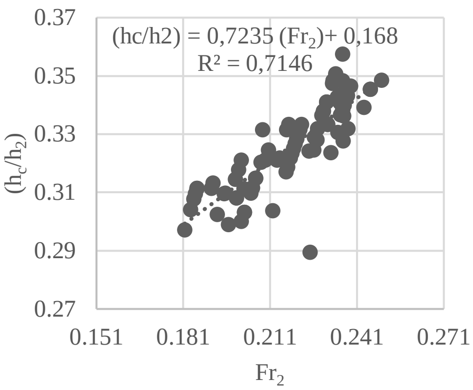

Fig. 8 The Fr_2 and y_c/y_2 relationship curves

In this study, the variables used were the Fr_2 value and jump efficiency, so it could be concluded as Table 9.

Table 9. Conclusions on the double sill research (1 upstream slope ogee sill; trapezoidal prism sill)

Variabel	Nilai	Series
Fr_2 (smallest Froude's value at y_2)	0.18	1
Greatest jump efficiency	0.59	11

Based on Table 9, it can be concluded that the jump control that produces downstream depth with the smallest average Froude (Fr_2) value is in Series 1 (L_1= 80 cm, L_2= 40 cm, Z_1= 10 cm, Z_2= 7.5 cm) as shown in Figure 8. Meanwhile, jump control that provides the highest average jump efficiency is found in series 11 (L_1= 80 cm, L_2= 20 cm, Z_1= 6 cm, Z_2= 4,5 cm) with a ratio of L_2:L_1 is 1:4 and Z_2:Z_1 = 3:4 as shown in Figure 10. So Series 12 and Series 11 were chosen as the best series in this double sill study (1 upstresm slope ogee sill; trapezoidal prism sill)

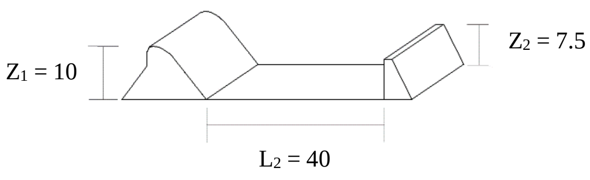

Fig. 9 Double sill of series 1

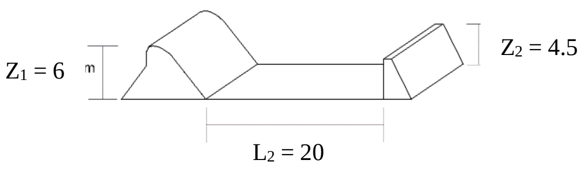

Fig. 10 Double sill of series 11

5. CONCLUSIONS

Following are the conditions of depth, flow velocity, and energy dissipation in double-sill stilling basin:

1. In series 10, there is a lower hydraulic jump value compared to the other series. The hydraulic jump is longer as the amount of discharge that flows increases.
2. Jump control that produces downstream depth with the smallest average Froude (Fr_2) value is in Series 1 (L_1= 80 cm, L_2= 40 cm, Z_1= 10 cm, Z_2= 7.5 cm) with a ratio of L_2:L_1 is 1:4 and Z_2:Z_1 = 4:3 as shown in Figure 9.
3. Jump control that provides the highest average jump efficiency is found in series 11 (L_1= 80 cm, L_2= 20 cm, Z_1= 6 cm, Z_2= 4,5 cm) with a ratio of L_2:L_1 is 1:4 and Z_2:Z_1 = 3:4 as shown in Figure 10.

So Series 12 and Series 11 were chosen as the best series in this double sill study (1 upstresm slope ogee sill; trapezoidal prism sill)

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7. REFERENCES

[1] Nugroho R. A., Rahman D. A., & Nugroho, M. F. A., The Effects of Air Flow on Hydraulic Jumps in Open Channels. Journal of Hydraulic Engineering, vol.149, issue 2, 2023, pp.1-12.

[2] Hossain S. M. A., Alam M. R., & Hossain M. A., The Influence of Air Flow on Hydraulic Jumps in Open Channels with Rough Bottoms. Journal of Hydrology, vol.597, Issue 126486, 2021, pp. 1-13.

[3] Elkady T. Y., Dafalla M. A., Moghal A. A. B., & Al-Shamrani M. A., The Influence of Soil Type on the Strength and Durability of Lime-Stabilized Soil. International Journal of GEOMATE, vol.7, issue 14, 2014, pp.154-162

[4] Dermawan V., Dermawan D. R., Ismoyo M. J., & Wicaksono P. H., Investigation of Hydraulic Flow Characteristics on Drop Structures. In IOP Conference Series: Earth and Environmental Science, vol. 930, No.1, 2021, p.1-10.

[5] Triwibowo P. T., Budiono M. S., & Putra I. G. A. S., Effect of Double-Crest Weir on Hydraulic Jump Characteristics. Journal of

Irrigation and Drainage Engineering, vol. 149, issue 1, 2023, pp. 325-331.

[6] Al-Sharafi H. S. A., Al-Ameeri M. A., & Al-Khafaji A. A., Experimental Study on Hydraulic Jump Characteristics in a Channel with Submerged Roughness. Journal of Hydrodynamics, vol. 33, issue 6, 2021, pp. 792-802.

[7] White Frank M. Fluid Mechanics. Edisi 8. McGraw-Hill Education. Edition 8, 2021, pp. 1-864.

[8] Babaali H., Shamsai A., Vosoughifar H. Computational Modelling of the Hydraulic Jump in the Stilling Basin with Covergence Walls Using CFD Codes. Arab Journal Science Engineering, 2014, vol.40, pp. 381-395.

[9] Chow V.T., Open-Channel Hydraulics. McGraw-Hill Book Company, Edition 3, 1989. Pp. 422-426

[10] Smith D., & Watts G.Hydraulic performance of a triangular crest spillway. Journal of Hydraulic Engineering. Vol. 144, issue 10, 2018, pp. 1-12

[11] B. Triatmodjo, Hidraulika II. Yogyakarta: Beta. Offset, 1995, pp. 1-121

[12] R. K. G. , Raju, Flow Through Open Channels. Jakarta: Erlangga, 1986.pp. 1-330

[13] Abdel-Mageed, Neveen Badawy, et al. "Review of The Energy Dissipation Over Stepped Weir." Engineering Research Journal-Faculty of Engineering (Shoubra) Vol. 42.Issue 1, 2019, pp. 132-137.

[14] Alshami A.H., Hussein H.A., Ibrahim M.A., and H. Hussein H., “Investigation of Blocks Performance at Stilling Basin Using Computation Fluid Dynamics View project Hydraulics View project,” Journal of Engineering and Applied Science, vol. 14, no. 17, 2019, pp. 6312–6316,

[15] Rezaei M., Shirvani A., & Tabatabaei M. H. Experimental and numerical investigation of hydraulic jumps on horizontal surfaces. Journal of Hydraulic Engineering, vol. 150, issue 1, 2023, pp. 1-26

[16] Anam S., Dermawan V., and Sambah A.B., “Modeling Of Usbr Type Ii Energy Reducer To Improve Energy Reduction In Stilling Basins With Hydraulic Physical Model Test,” International Journal of GEOMATE, vol. 18, no. 70, 2020, pp. 215–220