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EXPERIMENTAL INVESTIGATION ON HYDRAULIC JUMP CHARACTERISTICS AT DOWNSTREAM OF A DAM WITH VARYING STILLING BASINS

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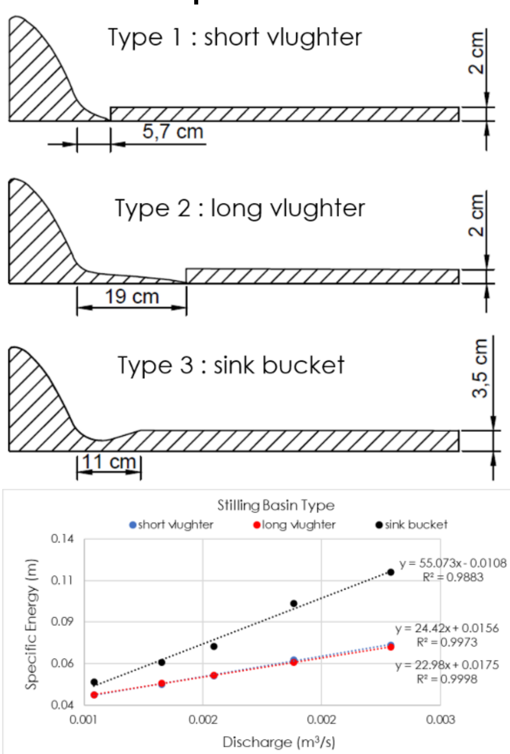
Graphic abstract



Abstract

The elevation of the water surface by damming causes rapid flow downstream of the dam. To dissipate the energy in this flow, an energy dissipating structure, called a stilling basin, is needed. The purpose of this study is to analyze and select the flow characteristics of types of stilling basins between short, long vlughter, and sink bucket. The research method used is experimental, utilizing a circulating flume with dimensions of 7.5x24x491 cm and an ogee spillway with variations in the stilling basin: vlughter with a length of 5.7 cm (Short vlughter type), vlughter with a length of 19 cm (Long vlughter type), and sink bucket with a length of 11 cm (Sink bucket type). The results of this study show that the greater the discharge, the greater the specific energy after the hydraulic jump. The largest specific energy after the jump is found in the sink bucket type, followed by the long vlughter type, and the smallest in the short vlughter type. The conclusion is that the variation in shape and dimensions of the stilling basin can affect the output characteristics of the hydraulic jump, with specific energy after the jump being greater in the sink bucket type, followed by the short vlughter and long vlughter types, which are relatively the same but smaller, with the difference becoming more significant as the discharge increases.

Keywords: Vlughter, Sink bucket, Energy Loss, Specific Energy, Relative Depth

1.0 INTRODUCTION

A structure built across a river to alter the flow characteristics is known as a dam [1], [2]. The increase in water level due to the dam results in rapid flow downstream of the dam [3]. The main function of a dam is to hold back the water flow to raise the water level above the initial water depth [4]. The dam also aims to control sediment transport, river geometry, and flow so that water can be used safely, optimally, and efficiently [5], [6]. In this characteristic change, after passing through the dam, the flow changes from supercritical to subcritical, resulting in a hydraulic jump [7], [8], [9]. To engineer the flow downstream of the dam, a stilling basin is constructed.

Stilling basins come in several models, including bucket, schoklitch, USBR, and vlughter [10]. The selection of the type of stilling basin is adjusted to the characteristics of the river flow and the dam design [11]. Due to its location downstream of the dam, the stilling basin significantly influences the characteristics of the hydraulic jump.

The hydraulic jump causes significant turbulence and erosion on the riverbed downstream of the dam, resulting in the soil surrounding it eroded [12,] [13], [14]. It can also cause damage to the dam structure and other downstream structures [15]. This damage can be caused by the pressure and impact of strong water flow due to the hydraulic jump [16]. To control the hydraulic jump, it is necessary to construct a stilling basin structure to dissipate energy so that the water flow stabilizes [17] [18]. The stilling basin is designed to protect the structure from scouring, thus ensuring its stability [19]. This study uses the vlughter and bucket models (sink bucket type) because these models are suitable for irrigation channels and safe against large rocks passing through the dam, making them suitable for Indonesia. To address the issue of hydraulic jump, efforts must be made to minimize scouring [20], [21]. Variations in the shape and dimensions of the stilling basin can affect the characteristics of the hydraulic jump, such as length, height, and depth. Therefore, it is necessary to conduct research on the influence of stilling basins on the characteristics of the hydraulic jump.

Previous studies may have discussed the characteristics of the hydraulic jump downstream of the dam, but these studies did not compare the vlughter and sink bucket stilling basins, making this study a novel finding. The purpose of this research is to analyze and select the flow characteristics of the short vlughter, long vlughter, and sink bucket stilling basin types.

2.0 METHODOLOGY

2.1 Location of Research

This research was conducted at the Civil Engineering Department Hydrotechnical Laboratory, Faculty of Engineering, University of Lampung, located at coordinates -5° 21' 43.73" S, 105° 14' 31.07" E.

2.2 Data Capture

This research is experimental, conducted by flowing the discharge on the simulation equipment and observing the water level before and after the hydraulic jump, as well as the height and length of the hydraulic jump that occurs at each discharge and stilling basin variation. After obtaining the primary data, calculations and analysis were carried out by comparing the flow characteristics (length, height, velocity, and froud number) for each stilling basin variation.

In this research, a dam model is used with dimensions adjusted to the open flow simulation equipment available in the laboratory. The dam model used was an ogee crest type with a height of 18 cm, along with 3 types of stilling basin. The short vlughter type has a length of 5.7 cm, the long vlughter type has a length of 19 cm, and the sink bucket type has a length of 11 cm. For clarity, the research models are shown in Figure 2.

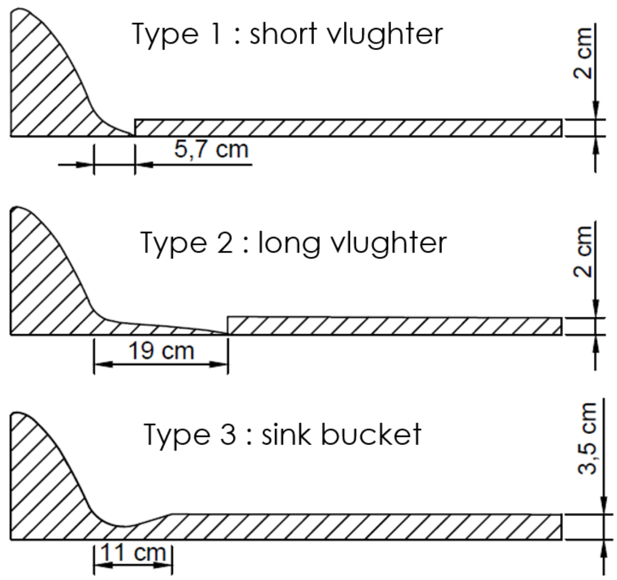


Figure 1 Research Model Type 1, 2, and 3

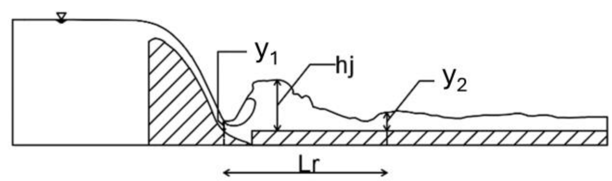


Figure 2 Research Data Location

Primary data were obtained from experiments conducted at the Hydrotechnical Laboratory of the University of Lampung, with the data collection procedure as follows.

1. Place the wooden dam and short vlughter type stilling basin on the open circulating flume.
2. Turn on the pump and set it to the first flow rate variation, which is 1.04×10^{-3} m^3/s. The flow rate is adjusted by turning the lever on the hydraulic table so that the water in the open circulating flume can be controlled.
3. After the flow stabilizes, where there is no more change in water level, measure the primary data, namely the water surface height before the jump (y_1), water surface height after the jump (y_2), jump length (Lr), and hydraulic jump height (hj) as shown in Figure 2.

4. After the primary data is collected, increase the flow rate by turning the lever on the hydraulic table. Repeat until the 5th flow rate variation.
5. Once the primary data for the short vlughter type stilling basin at 5 flow rate variations is collected, turn off the pump, then replace the stilling basin with the 2nd type. Repeat steps 2-4.
6. After completing the long vlughter type, proceed to the sink bucket type, and the data collection is finished.

2.3 Research Tools and Materials

The tools and materials used in the research are as follows:

1. Open Circulating flume

An artificial construction device that can hold the required amount of water and is used for observation, measurement, or testing with water flow. This open channel model has a height of 24 cm, a channel width of 7.5 cm, and a length of 491 cm. The channel sides are made of acrylic with a thickness of 0.5 cm. See Figure 3.

Figure 3 Open Circulating Flume

2. Dam

The dam is constructed with an ogee-type crest made of wood with a height of 18 cm. The dam is used to raise the water level; after passing the dam, the flow will experience a hydraulic jump.

3. Hydraulic Table

The hydraulic table is located downstream of the open channel and is used to collect water that exits the open channel and pump it back to the upstream of the open channel. There is a lever to regulate the flow rate entering the open circulating flume.

4. Stilling Basin

In this research, one dam model of the ogee type, with a height of 18 cm and a width of 7.5 cm, is used. There is a hole beneath the dam model to anchor it in place during the experiments. For the downstream part of the dam, there are three variations of stilling basin models: dam with vlughter-type stilling basin (length: 5.7 cm and 19 cm) and sink bucket (11 cm). The models used are made of wood.

5. Stopwatch

A stopwatch is used to measure the time to calculate the discharge. The time is measured each time 10 liters of water is collected on the hydraulic table.

6. Ruler

A ruler is used to measure the flow height as well as the height and length of the hydraulic jump. The ruler used has an accuracy of 0.001 m.

2.4 Research Data

Data is required to describe field conditions, especially research that involves modeling. Research with accurate data will yield appropriate results, but the data must be interrelated to ensure the model closely approximates actual conditions. The discharge magnitude uses secondary data with five variations: 1.04×10^{-3} m^3/s, 1.33×10^{-3} m^3/s, 1.55×10^{-3} m^3/s, 1.88×10^{-3} m^3/s, and 2.29×10^{-3} m^3/s.

2.5. Data Analysis

The analysis is conducted by correlating the increase in discharge with the research parameters. The data analysis procedure is as follows:

1. Calculate the area using data (y) where the channel width b = 0.075 m, then the wet cross-sectional area at each observed point can be calculated.
2. Calculate the flow velocity using the channel area data with Equation 1 [22].

$$Q = A \cdot V \quad (1)$$

where:
Q = flow discharge (m^3/s)
A = cross-sectional area (m^2)
V = flow velocity (m/s)

3. Calculate the Froude number at points before and after the hydraulic jump using height (y_1, y_2) and velocity (v_1, v_2) data with Equation 2 [23].

$$F = V / (\sqrt{g \cdot h}) \quad (2)$$

where:
F = Froude number
V = flow velocity (m/s)
g = gravity (m/s^2)
h = height (m)

4. Calculate the specific energy before and after the jump using height data (y_2) and velocity (v_2) with Equation 3 [24].

$E = y + (V^2/2g)$ .... (3)

where:

E = specific energy (m)

y = normal depth (m)

g = earth gravitational force (m/s^2)

V = flow velocity (m/s)

5. Calculate the energy loss using the height data before and after the hydraulic jump (y_1, y_2) with equation 4 [25].

$\Delta E = (y_2-y_1)^3/(4y_1y_2)$ .... (4)

where:

ΔE = energy loss (m)

y_1 = depth before the jump (m)

y_2 = depth after the jump (m)

6. Calculate the jump efficiency using the Froude number data before the jump (F_1) with equation 5 [26].

$E_2/E_1 = ((8F_1+1)^{3/2} -4F_1+1)/(8F_1(2+F_1^2))$ ... (5)

where:

E_2/E_1 = hydraulic jump efficiency

F_1 = Froude number before the jump

7. Calculate the initial and continued depth ratio using the Froude number data before the hydraulic jump with equation 6 [27].

$y_2/y_1 = 0,5(\sqrt{(1+8F_1^2)}-1)$ .... (6)

where:

F_1 = Froude number before the jump

y_1 = depth before the jump (m)

y_2 = depth after the jump (m)

8. Calculate the relative depth using the Froude number data before the hydraulic jump with equation 7 [28].

$Hj/E_1= ((\sqrt{(1+8F_1^2)}-3)/(F_1^2+2))$ .... (7)

where:

Hj/E_1 = Relative depth

F_1 = Froude number before the jump

9. Plot the results and conclude the characteristics of the hydraulic jump occurring at each stilling basin variation.

3.0 RESULTS AND DISCUSSION

3.1 Research Data Analysis

Primary data from the data collection is presented in Table 1. It shows that the lowest height before the hydraulic jump (y_1) occurs in the long vlughter type, while the highest height after the hydraulic jump (y_2) occurs in the short vlughter type. The highest hydraulic jump occurs in the short vlughter type stilling basin, and the longest occurs in the sink bucket type.

The calculation results are presented in Table 2. It can be seen that the flow velocity before the hydraulic jump (V1) in the short vlughter type is the lowest, while in the long vlughter type it is higher. For the sink bucket type, the flow velocity before the hydraulic jump is the highest at the first discharge but decreases as the discharge rate increases.

The flow velocity after the hydraulic jump (V2) in the short vlughter type is the lowest, followed by the long vlughter type with a higher velocity, and the sink bucket type with the highest velocity. This indicates that the sink bucket type can causes the most downstream scour.

The Froude number before the hydraulic jump (F1) is the highest in the short vlughter type, and the highest in the long vlughter type. In the sink bucket type, there is a variation as the Froude number decreases with increasing discharge.

Table 1 Research Data Capture

Stilling Basing Type	Discharge (m^3/s)	y_1 (m)	y_2 (m)	Hj (m)	Lr (m)
Type 1 (short vlughter)	$1.04x10^{-3}$	0.018	0.031	0.086	0.275
	$1.33x10^{-3}$	0.015	0.030	0.093	0.299
	$1.55x10^{-3}$	0.016	0.035	0.104	0.348
	$1.88x10^{-3}$	0.019	0.033	0.099	0.404
	$2.29x10^{-3}$	0.025	0.038	0.091	0.432
Type 2 (long vlughter)	$1.04x10^{-3}$	0.009	0.031	0.047	0.386
	$1.33x10^{-3}$	0.008	0.028	0.052	0.414
	$1.55x10^{-3}$	0.008	0.033	0.061	0.395
	$1.88x10^{-3}$	0.010	0.036	0.062	0.414
	$2.29x10^{-3}$	0.009	0.039	0.078	0.437
Type 3 (sink bucket)	$1.04x10^{-3}$	0.005	0.018	0.030	0.205
	$1.33x10^{-3}$	0.008	0.020	0.030	0.194
	$1.55x10^{-3}$	0.009	0.021	0.031	0.210
	$1.88x10^{-3}$	0.011	0.021	0.029	0.197
	$2.29x10^{-3}$	0.017	0.023	0.047	0.256

Table 2 Flow Parameter Calculation Results

Stilling Basing Type	Discharge (m^3/s)	V_1 (m/s)	V_2 (m/s)	F_1	E_1 (m)	E_2 (m)	ΔE (m)	E_2/E_1	y_2/y_1	Hj/E_1
Type 1 (short vlughter)	1.04×10^{-3}	0.778	0.443	1.859	0.049	0.041	0.001	0.700	2.1758	0.4311
	1.33×10^{-3}	1.186	0.584	3.102	0.087	0.048	0.002	0.415	3.9149	0.5017
	1.55×10^{-3}	1.311	0.588	3.338	0.103	0.053	0.003	0.380	4.2477	0.4941
	1.88×10^{-3}	1.312	0.760	3.029	0.107	0.062	0.001	0.427	3.8123	0.5034
	2.29×10^{-3}	1.200	0.813	2.401	0.099	0.071	0.000	0.551	2.9326	0.4977
Type 2 (long vlughter)	1.04×10^{-3}	1.587	0.573	5.414	0.137	0.041	0.010	0.202	7.1728	0.3943
	1.33×10^{-3}	2.239	0.563	8.044	0.263	0.048	0.009	0.116	10.8865	0.2964
	1.55×10^{-3}	2.466	0.697	8.611	0.318	0.053	0.014	0.105	11.6880	0.2807
	1.88×10^{-3}	2.633	1.051	8.613	0.363	0.061	0.014	0.105	11.6908	0.2807
	2.29×10^{-3}	3.570	1.148	12.318	0.658	0.070	0.021	0.062	16.9271	0.2072
Type 3 (sink bucket)	1.04×10^{-3}	2.642	0.780	11.631	0.361	0.049	0.005	0.068	15.9563	0.2179
	1.33×10^{-3}	2.621	0.900	7.129	0.265	0.061	0.003	0.115	10.9428	0.2953
	1.55×10^{-3}	2.066	0.987	9.431	0.305	0.071	0.003	0.110	11.2725	0.2887
	1.88×10^{-3}	2.199	1.219	6.572	0.258	0.096	0.001	0.154	8.8073	0.3455
	2.29×10^{-3}	1.821	1.346	4.486	0.186	0.115	0.000	0.261	5.8644	0.4397

3.2 Discussion of Research Results

3.2.1 *Length of Hydraulic Jump*

The graph in Figure 4 shows the types of short and long vlughter. As the discharge increases, the length of the hydraulic jump also increases. For short vlughter at a discharge of 1.04×10^{-3} m^3/s, the jump length is 0.307 m and increases to 0.43 m at a discharge of 2.29×10^{-3} m^3/s. The hydraulic jump length for the sink bucket type tends to be shorter, ranging from 0.194 to 0.256 m. In the vlughter stilling basin type, the flow hits the end of the stilling basin, making the flow length longer than the sink bucket type.

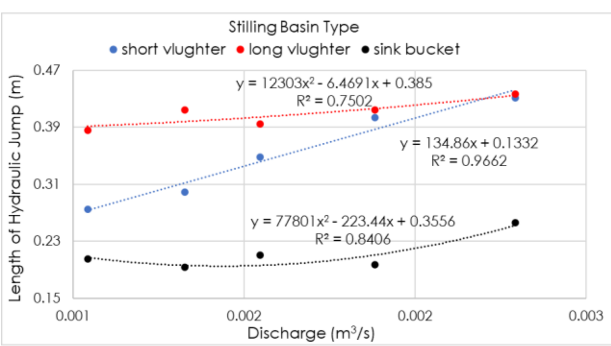


Figure 4 Relationship between Length of Hydraulic Jump and Discharge

3.2.2 *Height of Hydaulic Jump*

In Figure 5, for the short vlughter type, the longest hydraulic jump occurs at a discharge of 1.55×10^{-3} m^3/s. For the long vlughter and sink bucket types, the greater the discharge, the higher the hydraulic jump. This is due to the increase in velocity before the hydraulic jump as the discharge increases. The highest hydraulic jump is in the short vlughter type, followed by the long vlughter type, and the shortest in the sink bucket type. This is because the short and long vlughter types have a dam end that holds the flow, resulting in a higher energy jump compared to the sink bucket type. The hydraulic jump in the short vlughter type is higher than in the long vlughter type because the eddies in the short vlughter type are shorter than those in the long vlughter type.

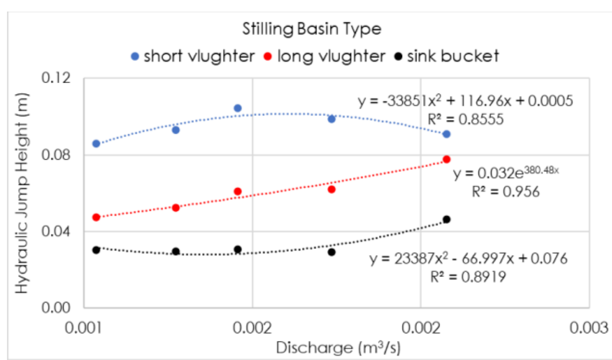


Figure 5 Relationship between Height of Hydraulic Jump and Dischage

3.2.3 *Energy Loss*

Figure 6 shows that for the short vlughter and sink bucket types, the larger the discharge, the smaller the energy loss of the flow. This indicates that for these two types, the ability of the stilling basin to dissipate energy decreases with the increase in discharge. For the long vlughter stilling basin type, the energy loss is greater compared to the other two types, ranging from 0.010 to 0.021 m, and shows an increasing trend with increasing discharge. This indicates that the ability of the long vlughter stilling basin to dissipate energy also increases with increasing discharge.

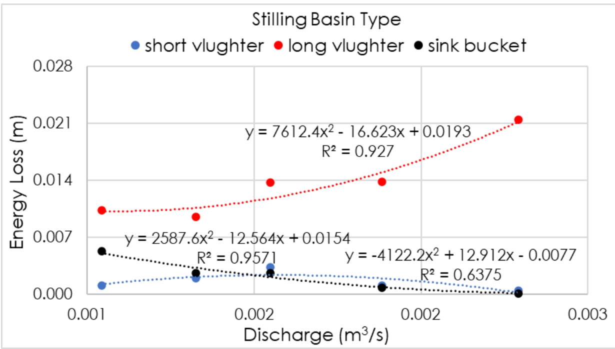


Figure 6 Relationship between Energy Loss and Dischage

3.2.4 *Efficiency of Hydraulic Jump*

In Figure 7, it can be seen that for the short vlughter stilling basin type, the jump efficiency is the highest. This indicates that for this type, the hydraulic jump is effective in dissipating the kinetic energy of the water flow. The upward concave polynomial shape of the graph shows that the hydraulic jump efficiency is high at the highest and lowest discharges, making this type ineffective at dissipating the hydraulic jump at medium discharges. For the long vlughter type, the hydraulic jump efficiency trend decreases with increasing discharge. This can be seen from the hydraulic jump that occurs in the long vlughter stilling basin being smaller and shorter than in the short vlughter type. The decreasing efficiency trend with increasing discharge indicates that the hydraulic jump becomes less effective at dissipating the kinetic energy of the water as the flow discharge increases. For the sink bucket type, the hydraulic jump efficiency trend increases with increasing discharge, indicating that the hydraulic jump efficiency in dissipating kinetic energy increases with increasing discharge.

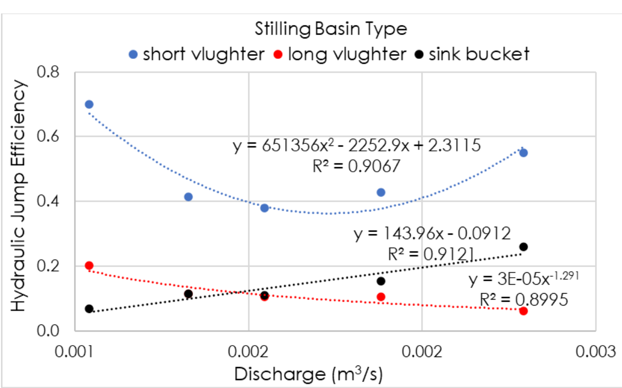


Figure 7 Relationship between Efficiency of Hydraulic Jump and Discharge

3.2.5 *Ratio of Initial Depth and Continued Depth*

In Figure 8, it can be seen that for the short vlughter type, the initial and continued depth ratio trend is the smallest compared to the other two types, indicating a small kinetic energy dissipation, meaning the hydraulic jump is not effective at dissipating the flowing water energy. For the long vlughter type, the larger the flow discharge, the larger the initial and continued depth ratio significantly. This indicates that with each increase in discharge of 0.3125 m^3/s, the hydraulic jump becomes more effective at dissipating the kinetic energy of the flow, with the highest value being at a discharge of 2.29×10^{-3} m^3/s at 16.9271. For the sink bucket type, it is the opposite of the long vlughter type, with the larger the flow discharge, the smaller the initial and continued depth ratio significantly. This indicates that for the sink bucket stilling basin type, the larger the discharge, the less effective the hydraulic jump is at dissipating the flow energy.

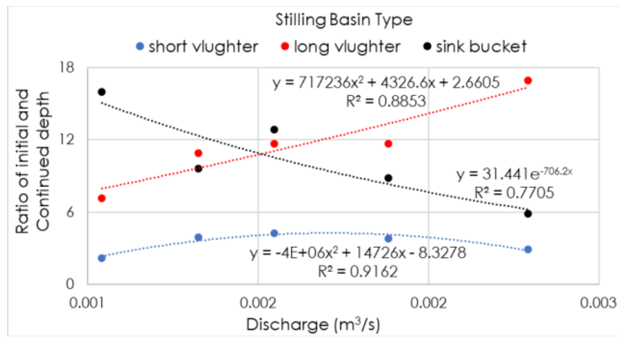


Figure 8 Relationship between Ratio of Initial Depth and Continued Depth and Dischage

3.2.6 *Relative Depth*

From Figure 9, it can be seen that for the short vlughter type, the relative depth trend increases with increasing discharge, and for this type, it is the largest relative depth compared to the other two types. This indicates that for the short vlughter type, the hydraulic jump has the most kinetic energy and indicates that more kinetic energy of the flow is converted to potential energy compared to the other two types. For the long vlughter type, the larger the discharge, the smaller the relative depth. This indicates that the hydraulic jump that occurs in the long vlughter stilling basin type becomes smaller with increasing discharge. For the sink bucket type, it is the opposite of the long vlughter type, with the larger the discharge, the larger the relative depth significantly with the coefficient of 157.34. This indicates that for the sink bucket stilling basin type, the larger the discharge, the more kinetic energy the hydraulic jump has. Observing Figures 8 and 9, the graphs tend to be opposite because relative depth and jump efficiency are indirectly inversely related. This is important in designing more effective and safer structures.

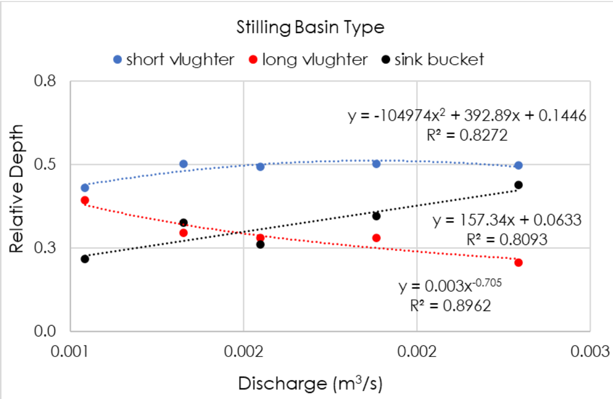


Figure 9 Relationship between Relative depth and Dischage

3.2.7 Specific Energy Before Hydraulic Jump

Referring to Figure 10, it can be observed that at the point before the hydraulic jump in the short vlughter stilling basin, the specific energy trend rises but not significantly and is the smallest with a range of 0.049-0.107 m compared to the specific energy of the other two types. This indicates that the height and flow velocity in the short vlughter type are the smallest compared to the other two types. For the long vlughter type, the specific energy trend increases significantly as the discharge increases. This indicates that in the long vlughter stilling basin, the height and flow velocity increase significantly with increasing flow discharge. For the sink bucket stilling basin type, the specific energy trend decreases with increasing discharge, which means that the height and flow velocity decrease as the discharge increases.

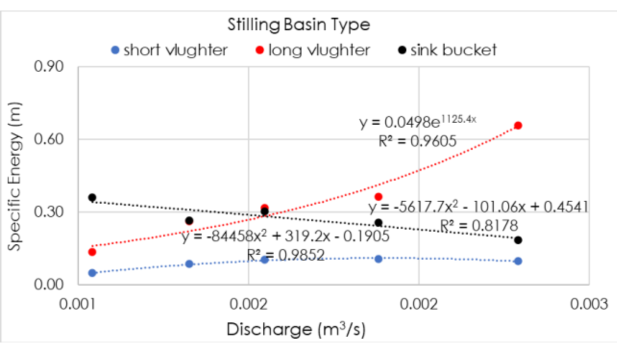


Figure 10 Relationship between Spesific Energy before Hyraulic Jump and Dischage

3.2.8 Specific Energy after Hydraulic Jump

In Figure 11, it can be seen that at the point after the hydraulic jump, the larger the discharge, the greater the specific energy with a positive gradient in the three types of stilling basins. This occurs because the flow velocity also increases with increasing discharge. The highest specific energy is in the sink bucket type with a maximum value of 0.115 m at a discharge of 2.29×10^{-3} m³/s. In the long vlughter and short vlughter types, the specific energy after the hydraulic jump tends to be the same, with a maximum value of 0.070 at a discharge of 2.29×10^{-3} m³/s, indicating that the scour that occurs is smaller compared to the sink bucket type. This shows that the short vlughter and long vlughter types produce flow output that causes less scour compared to the sink bucket type.

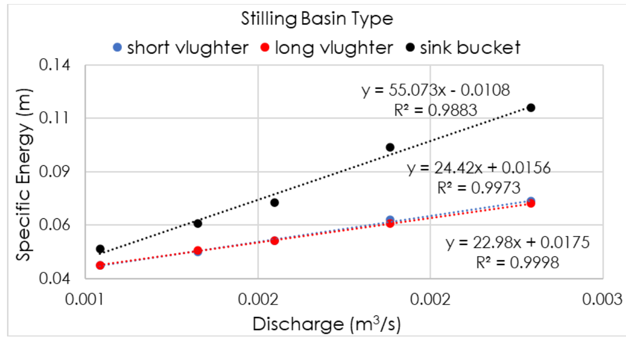


Figure 11 Relationship between Spesific Energy after Hyraulic Jump and Dischage

4.0 CONCLUSION

Stilling basins can affect the output characteristics of the hydraulic jump; the specific energy after the hydraulic jump is greater in the sink bucket type, followed by the short vlughter and long vlughter types, which are relatively the same and smaller, with the difference becoming more significant as the discharge increases.

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Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper.

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