Effect of Sluice Gate Opening Height on Spillway on Flow Characteristics
(Physical Model)

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ABSTRACT

The sluice gate is a measuring structure that controls the upstream discharge and water level. The varying height of the sluice gate opening will cause the water level to vary both upstream and downstream. The difference in water level upstream and downstream can potentially cause scouring downstream of the gate. This study aimed to determine the effect of the height of the sluice gate opening on the flow characteristics. This study used a research method in the form of a physical model on an open channel (*flume*) at the Integrated Laboratory of Sultan Ageng Tirtayasa University Sindangsari. The stages of this research included pitot pipe calibration and research of flow characteristics on the height of the gate opening with variations in the height of the sluice opening (9, 10, 11, 12, 13 cm). The sluice model used is made of wooden boards with the dimensions of the door width being 1/3 of the width of the channel. The results showed that the higher the sluice opening (*a*), the lower the upstream water level (*H*) and the greater the downstream water level (*Y*). While the upstream flow velocity (V_0) was greater and the downstream flow velocity (V_1) was getting smaller so were the upstream Froude numbers ($Fr_{upstream}$) and downstream Froude numbers ($Fr_{downstream}$). The upstream flow is classified as sub-critical flow (Fr<1), while the downstream flow is classified as super-critical flow (Fr>1).

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1. INTRODUCTION

Sluice gates are structures in the form of holes in the hydraulic structure to control the discharge and upstream water level [1]. The various openings of the sluice gates cause the water level to vary both upstream and downstream [2]. To optimize the role of the sluice gate as a controller of discharge and upstream water level of the gate, scour problems are often encountered [3]. When the sluice is operated, a flow pattern will occur in the area of the sluice gates opening, the current resulting from the flow pattern will interact with the surrounding material. This interaction will cause the material at the bottom of the channel to be eroded [4]. Scour downstream of the sluice gate occurs as a result of changes in flow characteristics upstream and downstream of the gate. This phenomenon can disrupt and endanger the construction of the sluice gates [5].

Various researchers have researched the flow through the sluice. The flow of water through the sluice gate opening will form a jet of water. Large jet speeds can cause local scour over layers that are easily eroded. Local scour that occurs continuously can eventually cause structural failure [6].

Research on flow characteristics becomes very important in planning water structures such as dams or other water structures. This is because the characteristics of the flow will determine the type of building that is selected according to needs [7]. Flow characteristics in a water structure can be in the form of water level, velocity, and the state of the flow itself [8].

The state of flow under the sluice gate depends on the depth of flow downstream of the sluice gate, while the depth of flow downstream of the sluice gate is affected by the slope and roughness of the bottom of the channel downstream of the sluice gate [9]. Changes in flow state often occur in open channels, from sub-critical flow to super-critical flow or vice versa. This change is a successive change of flow depth, either from high to low surface or from low to high [10]. Flow through the sluice gate can be influenced by several factors including the height of the sluice gate opening, the water level upstream of the sluice gate, and the water level downstream of the hydraulic jump [11]. There are two hydraulic flow conditions downstream of the sluice gate, namely free flow and submerged flow. Free flow occurs when the downstream water level is below the sluice gate and the downstream water level has no effect on the flow under the gate. Submerged flow occurs when the downstream water level rises so that the flow above the sluice gate and the downstream water level affects the upstream water level [12].

Based on this background, a study was carried out to know the effect of the height of the sluice opening on the spillway on the flow characteristics. Previous research that has a similar discussion to this research includes research on "Characteristics of Hydraulic Parameters with Variations in the Height of Sliding Door Openings on Open Channels" by Misbar and Yunus (2017), research on "Effect of Sluice Gate Opening Height on Froude Numbers with Clay Base On Open Channels" by Latif et al (2019), research on "Study of the Effect of Height of Sluice Gate Opening on the Froude Number" by Albas and Permana (2016), research on "Study of the Effect of Height of Sluice Gate on the Froude Number in section Downstream Primary Channel" by Doloksaribu et al (2021), research on "Characteristics of Flow Velocity Near the Bottom of the Sluice Gate" by Laksitaningtyas et al (2020)and research on "Study of Flow Patterns at the Downstream of the Sorong Door with the Basic Material of Clay Sand Channels" by Rustiati et al (2022). Based on previous research, research on flow characteristics at sluice gates with a door model that has dimensions of 1/3 of the channel width has never been done before, so in this study, several limitations were determined including scour and water jumping were not taken into account, spillway wall pillars ignored, and model scaling against the prototype was not carried out. This research is expected to be useful for the development of science, namely as reference material for subsequent researchers, especially research on sluice gates in channels, and is expected to be used as a reference/input for practitioners in the field of Hydraulics, especially in open channels.

2. METHODS

This research is a physical model study on an open channel (flume) at the Integrated Laboratory of Sultan Ageng Tirtayasa Sindangsari University, Pabuaran District, Serang, Banten.

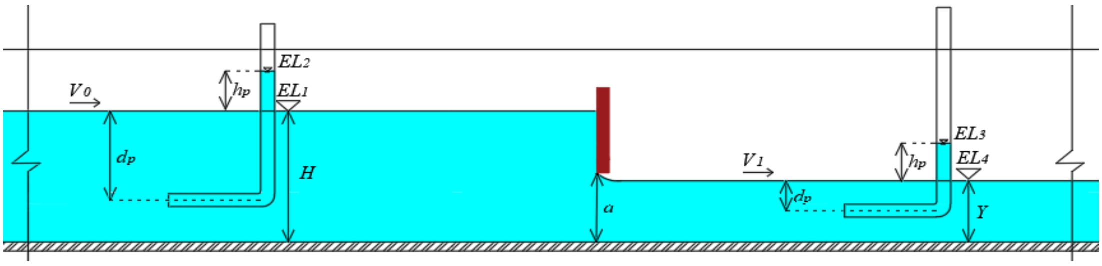

Figure 1 Sketches of Models and Pitot Pipe on Flume

The steps of this research include:
a. Literature and library studies
b. Formulate a problem
c. Modeling the sluice gate on the spillway
d. Non-dimensional analysis
e. Pitot pipe calibration
f. Models operation
g. Analysis of research results
h. Conclusion

2.1 Tools and Materials

The tools and materials used in this study include:

a. Flume

Glass-Sided Tilting Flume (Armfield S6-MKIII) is a set of open channel models with a channel length of 500 cm, a height of 46,5 cm, and a width of 30 cm. The flume base is made of stainless steel and the walls are made of 10 mm thick acrylic.

Figure 2 Flume (Armfield S6-MKIII)

b. Pitot pipe

A pitot pipe is a measuring instrument in the form of a glass pipe with a right angle which measures the velocity of flow in an open channel. This tool does not measure velocity directly but produces a quantity that can be measured and related to velocity. The orifice portion of the pipe is directed upstream so that flow will flow into the pipe and there is increased pressure in the pipe to resist the impact of velocity on it [13].

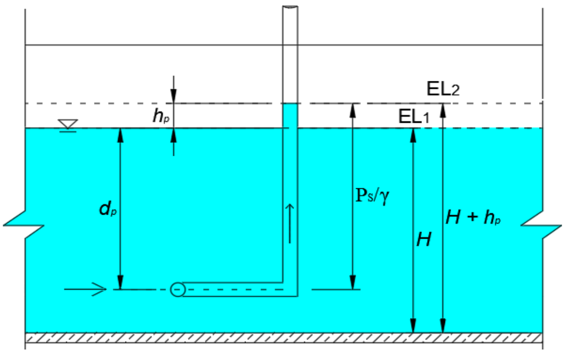

Figure 3 Pitot pipe

c. Sluice Gate

The sluice gate model used in this study has dimensions of the width of the gate 1/3 smaller than the width of the channel. The sluice gate model is made of wooden planks with a thickness of 2 cm and dimensions according to Figure 4.

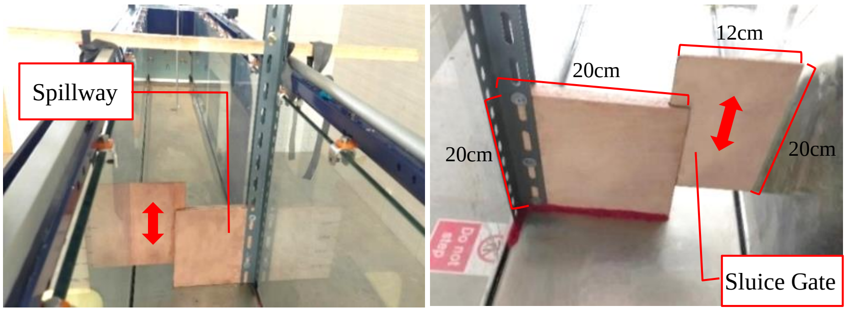

Figure 4 Sluice Gate Model

In Figure 4 it is known that the sluice model has dimensions of a total length of 30 cm and a height of 20 cm. The part marked with a red arrow in Figure 4 is a sluice gate whose height will be adjusted according to the variations in the height of the sluice opening to be studied. In contrast, the other part is a spillway in the form of a sharp threshold whose position is fixed and does not change during the study.

d. Point Gauge
A point gauge is a tool that measures the depth of flow when the experiment is carried out [14].

Figure 5 Point Gauge

e. Roll meter.

2.2 Variable

The variables examined in this study include discharge (*Q*), height of sluice gate opening (*a*), width of sluice gate (*b*), channel width (*B*), flow velocity (*V*), upstream water level (*H*), downstream water level (*Y*) and Froude number (*Fr*).

2.3 Nondimensional Analysis Methods

In this study, nondimensional analysis was carried out using the Buckingham method (phi theorem). If for example the relationship between physical variables that are expected to affect the flow at the sluice gate, namely: $V_1 = f(H, Y, a, g, b, B, S_0)$, then the results of the dimensional analysis are obtained as follows.

$$\frac{V_1}{\sqrt{gY}} = f\left(\frac{H}{Y}, \frac{a}{Y}, \frac{b}{B}, S_0\right) \qquad (1)$$

The values obtained from the analysis results in the laboratory are then made in the form of a graphical relationship between the variables according to the relationship obtained from the non-dimensional analysis of equation (1).

2.4 Pitot Pipe Velocity Calibration

Calibration is a checking process to ensure the accuracy of measuring instruments[15]. The calibration process is very necessary before conducting research. In this study, pitot pipe calibration was carried out to determine the actual velocity according to the condition of the pitot pipe when the study was carried out. Flow velocity measurements were carried out at three depths (d_p), namely 0,2H, 0,6H, and

0,8H. The actual velocity (V_a) is obtained using the graph "Calibration of the Pitot Pipe and Manometer S6-30" in Figure 6 while the theoretical velocity (V_t) is obtained using equation (2). The results of dividing the actual (V_a) and theoretical (V_t) velocity are in the form of a pitot pipe velocity coefficient (C_p) which can correct the theoretical flow velocity. The pitot pipe velocity coefficient (C_p) is obtained using equation (3).

$$V = \sqrt{2gh_p} \tag{2}$$

$$C_v = \frac{Vc}{V} \tag{3}$$

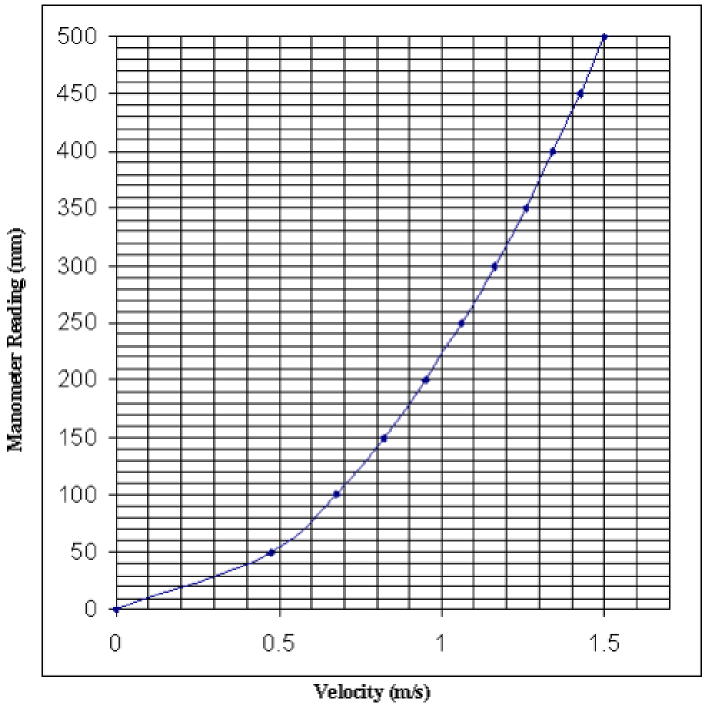

Figure 5 Pitot Pipe and Manometer Calibration Chart S6-30
(Source: Armfield, 2021)[16]

Legend :
V = Flow velocity (*m/s*)
g = The acceleration of gravity is 9,8 (m/s^2)
h_p = Water level in pitot pipe (*m*)
V_c = Actual velocity of contracted veins (*m/s*)
C_v = Velocity coefficient = C_p

2.5 Flow Characteristics Analysis

In this study, the flow characteristics upstream and downstream of the sluice gate were analyzed at different gate opening heights (a), namely 9, 10, 11, 12, and 13 cm with the condition that the velocity (pump rotation) remains constant. The flow characteristics referred to in this study are the water level, flow velocity, and flow conditions expressed in the Froude number. The flow velocity in the upstream (V_0) and downstream (V_1) channels is obtained using equation (4).

$$V = C_p\sqrt{2gh_p} \tag{4}$$

A flow includes sub-critical flow if (Fr<1), critical if (Fr=1), and super-critical if (Fr>1) [17]. The Froude number (Fr) at the upstream and downstream of the channel is obtained using equation (5).

$$Fr = \frac{V}{\sqrt{gy}} \quad (5)$$

Legend:
Fr = Froude number
Y = Depth of flow (m)

3. RESULTS AND DISCUSSION

The results of laboratory research will be discussed in several sub-discussions including pitot pipe calibration analysis, flow characteristic analysis, and nondimensional analysis. Pitot pipe calibration is intended to obtain the value of the velocity coefficient of pitot pipe (C_p) which will correct the velocity values upstream and downstream of the sluice gate. The analysis of flow characteristics will discuss the upstream and downstream flow conditions due to variations in the height of the sluice opening with the actual flow velocity value (corrected by the C_p value from the calibration results). Based on the data obtained from the results of the analysis, it is then included in equation (1) nondimensional analysis to determine the relationship that occurs between variables.

3.1 Pitot Pipe Calibration Analysis

A pitot pipe is a measuring tool that can be used to determine flow velocity by measuring the difference between the static pressure and the stagnation pressure. The data needed to obtain the actual velocity (V_a) on the graph is the water level elevation in the pitot pipe from datum (EL_2) and the average pressure head ($\frac{Ps}{\gamma}$) at depths of 0,2H, 0,6H, and 0,8H, while the data required to obtain the theoretical velocity (V_t) are the upstream water level (H), the water level elevation in the pitot pipe from the datum (EL_2), the acceleration due to gravity (g), and the water level in the pitot pipe (h_p).

Based on the results of the pitot pipe calibration analysis, the average is obtained as the value of the pitot pipe velocity coefficient (C_p) as follows.

Table 1 Analysis Results of the Pitot Pipe Calibration Velocity Coefficient (C_p)

No	Pump Rotate	H (m)	EL_2 (m)	h_p (m)	Ps/γ (mm)	V_a (m/s)	V_t (m/s)	C_p
1	3,45	0,0549	0,0744	0,0195	49,67	0,48	0,6180	0,7768
2	3,70	0,0615	0,0831	0,0216	55,53	0,50	0,6513	0,7677
3	3,95	0,0655	0,0898	0,0243	60,40	0,54	0,6902	0,7752
4	4,20	0,0735	0,0991	0,0256	66,05	0,55	0,7085	0,7763
5	4,45	0,0792	0,1056	0,0264	69,94	0,59	0,7193	0,8133
Average								**0,7818**

The results of the calculation of the pitot pipe velocity coefficient (C_p) in Table 1, show that the average value of C_p obtained is close to the value of the pitot pipe velocity coefficient in theory, namely C_p = 0,98 [18]. So for the calculation of flow velocity in the following discussion, C_p = 0,7818 is used.

The following shows a graph of the relationship between theoretical flow velocity (V_t) and actual velocity (V_a) = corrected velocity.

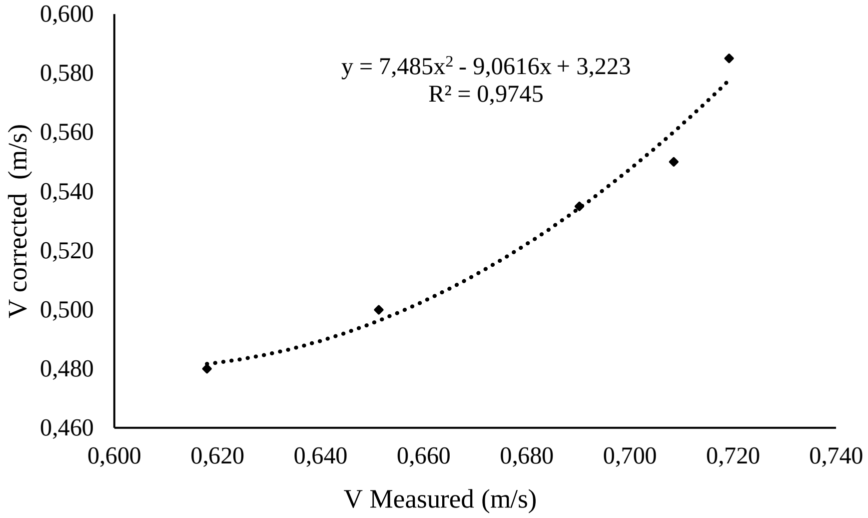

Figure 6 Relationship of Measured V_t and Corrected V_a

Based on Figure 7, the equation $y = 7{,}485x^2 - 9{,}0616x + 3{,}223$ is obtained with a correlation coefficient, $R^2 = 0{,}9745$, which means that the correlation between theoretical flow velocity (V_t) and actual velocity (V_a) is very strong.

3.2 Flow Characteristics Analysis

In this study, the flow characteristics upstream and downstream of the sluice gate include water level, flow velocity, and flow conditions expressed in the Froude number. In order to know the Froude number of the flow, it is necessary to calculate the flow velocity upstream and downstream of the sluice gate. The flow velocity is obtained using a pitot pipe measuring instrument so that the data required includes upstream water level (H), upstream pitot pipe water level from datum (EL_2), downstream water level (Y), the water level elevation in the pitot pipe downstream from the datum (EL_3), the acceleration due to gravity (g) and the water level in the pitot pipe (h_p).

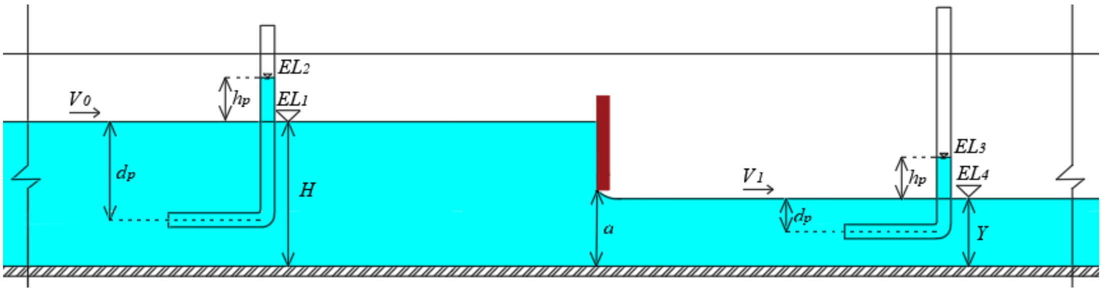

Figure 7 Sketch of Flow Characteristic Data Retrieval

In the following, the data needed to analyze the flow characteristics both upstream and downstream of the sluice gate are presented.

Table 2 Flow Data in Upstream and Downstream Sluice Gate

No	a (m)	Upstream Flow			Downstream Flow		
		H (m)	EL_2 (m)	$h_{p\,(upstream)}$ (m)	Y (m)	EL_3 (m)	$h_{p\,(downstream)}$ (m)
1	0,09	0,2115	0,2135	0,0020	0,0290	0,1153	0,0863
2	0,10	0,1955	0,1979	0,0024	0,0320	0,1139	0,0819
3	0,11	0,1820	0,1849	0,0029	0,0340	0,1130	0,0790
4	0,12	0,1710	0,1753	0,0043	0,0360	0,1120	0,0760
5	0,13	0,1655	0,1705	0,0050	0,0380	0,1106	0,0726

The results of the analysis of flow characteristics at each height of the sluice gate opening are presented in Table 3 as follows.

Table 3 Results of Analysis of Flow Characteristics

No	*a* (m)	Upstream Flow Characteristics				Downstream Flow Characteristics			
		H (m)	V_0 (m/s)	*Fr* Upstream		*Y* (m)	V_1 (m/s)	*Fr* Downstream	
1	0,09	0,2115	0,1562	0,1084	$Fr < 1$	0,0290	1,0176	1,9078	$Fr > 1$
2	0,10	0,1955	0,1708	0,1234	$Fr < 1$	0,0320	0,9913	1,7693	$Fr > 1$
3	0,11	0,1820	0,1876	0,1404	$Fr < 1$	0,0340	0,9734	1,6854	$Fr > 1$
4	0,12	0,1710	0,2280	0,1760	$Fr < 1$	0,0360	0,9547	1,6065	$Fr > 1$
5	0,13	0,1655	0,2449	0,1922	$Fr < 1$	0,0380	0,9333	1,5287	$Fr > 1$

Based on the results of the analysis of Table 3, it is known that under the same flow conditions and opening height of the sluice gate (*a*), the upstream water level (*H*) is greater than the downstream water level (*Y*) because of the dam by the spillway and the door that is not fully open, meanwhile downstream flow velocity (V_1) bigger than upstream flow velocity (V_0). The greater the height of the sluice gate opening (*a*), the lower the upstream water level (*H*) and the greater the downstream water level (*Y*). In contrast, the upstream flow velocity (V_0) is greater and the downstream flow velocity (V_1) is smaller.

When the flow and the opening height of the sluice gate (*a*) are in the same condition, the Froude number of the downstream flow is greater than the upstream flow Froude number (directly proportional to the flow velocity), whereas when the height of the sluice gate opening (*a*) is greater, the upstream Froude number ($Fr_{upstream}$) is greater and the downstream Froude number ($Fr_{downstream}$) is smaller. The Froude number of the upstream flow has a value of less than 1 ($Fr_{upstream}<1$) so the flow is classified as sub-critical flow, while the downstream Froude number has a value of more than 1 ($Fr_{downstream}>1$) which is classified as super-critical flow.

Figure 8 Water Flow Conditions When The Sluice Gate is Opened (*a* = 13 cm)

3.3 Nondimensional Analysis

Based on the results of nondimensional analysis, the following relationship is obtained.

$$\frac{V_1}{\sqrt{gY}} = f\left(\frac{H}{Y}, \frac{a}{Y}, \frac{b}{B}, S_0\right)$$

Based on the results of the analysis in Table 3, the relationship obtained between the research variables is presented in Table 4 as follows.

Table 4 Calculation Result Variables

No	*a* (m)	V_1 (m/s)	*Y* (m)	*H* (m)	*b* (m)	*B* (m)	$V_1/\sqrt{gY}$ (m/s/m/s)	*H/Y* (m/m)	*a/Y* (m/m)
1	0,09	1,0176	0,0290	0,2115	0,2	0,3	1,9078	7,2931	0,3222
2	0,10	0,9913	0,0320	0,1955	0,2	0,3	1,7693	6,1094	0,3200
3	0,11	0,9734	0,0340	0,1820	0,2	0,3	1,6854	5,3529	0,3091
4	0,12	0,9547	0,0360	0,1710	0,2	0,3	1,6065	4,7500	0,3000
5	0,13	0,9333	0,0380	0,1655	0,2	0,3	1,5287	4,3553	0,2923

Legend :

$V_1/\sqrt{gY}$ = Froude number downstream = $Fr_{downstream}$

Based on Table 4 it is known that at a channel slope of 0° and the width of the sluice (*b*) is one-third of the width of the channel (*B*)(b=B/3), the greater the height of the sluice gate opening (*a*) the ratio of the upstream water level (*H*) and the downstream water level (*Y*) is getting smaller, so is the ratio of the sluice gate opening height (*a*) and the downstream water level (*Y*).

The following shows the relationship between $\frac{V}{\sqrt{gY}} = f\left(\frac{H}{Y}\right)$ on the slope of the channel ($S_0 = 0°$) for the width of the sluice (*b*) one-third of the channel width (*B*)(*b=B/3*).

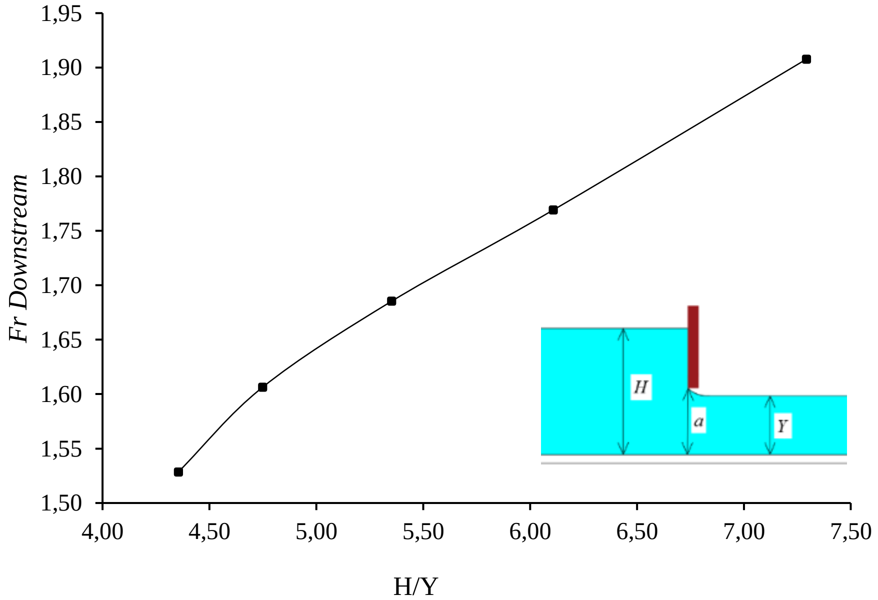

Figure 9 Graph of $Fr_{downstream}$ and *H/Y* at $S_0 = 0°$ for *b =B/3*

Based on Figure 10, it is known that when the sluice gate is open with variations in the height of the sluice opening (*a*), the slope of the channel is 0° and the width of the sluice gate (*b*) is one-third of the width of the channel (B)(b=B/3), the greater the ratio of the upstream water level (*H*) and downstream water level (*Y*), the greater the Froude number produced downstream of the sluice gate ($Fr_{downstream}$)

The following shows the relationship between $\frac{V}{\sqrt{gY}} = f\left(\frac{a}{Y}\right)$ on the slope of the channel ($S_0 = 0°$) for the width of the sluice (*b*) one-third of the channel width (*B*)(*b=B/3*).

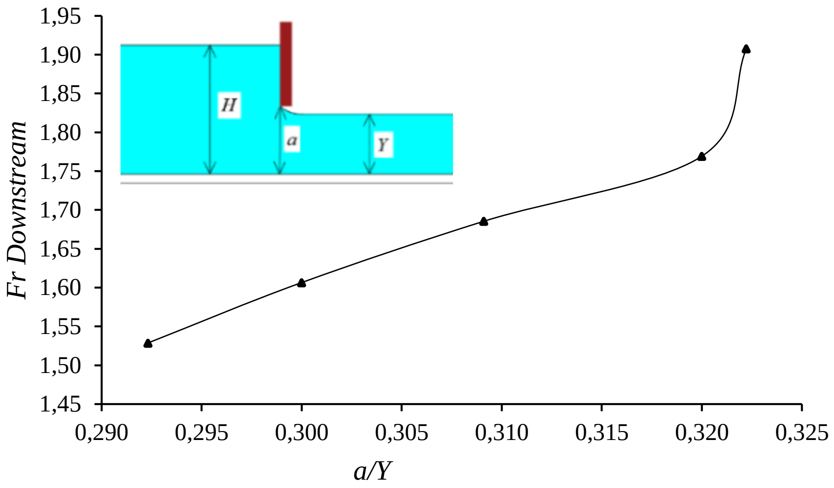

Figure 10 Graph of the $Fr_{downstream}$ and a/Y at $S_0 = 0°$ for $b = B/3$

Based on Figure 11, it is known that when the sluice gate is open with variations in the height of the sluice opening (*a*), the slope of the channel is 0° and the width of the sluice gate (*b*) is one-third of the width of the channel (B)(b=B/3), the greater the ratio of the height of the sluice gate opening (*a*) and the downstream water level (*Y*) the greater the Froude number produced downstream of the sluice gate ($Fr_{downstream}$).

4. CONCLUSION

This study concludes that the greater the height of the sluice gate opening (*a*), the lower the upstream water level (*H*) and the higher the downstream water level (*Y*), while the upstream flow velocity (V_0) is greater and the downstream flow velocity (V_1) is smaller as well as the upstream Froude number ($Fr_{upstream}$) and downstream Froude number ($Fr_{downstream}$) (directly proportional to the flow velocity). At the same flow and opening height of the sluice (*a*) conditions, the upstream water level (*H*) is greater than the downstream water level (*Y*), while the upstream flow velocity (V_0) is smaller than the downstream flow velocity (V_1), as well as the upstream Froude number ($Fr_{upstream}$) is smaller than the downstream Froude number ($Fr_{downstream}$). The upstream flow is classified as sub-critical flow ($Fr_{upstream}$ <1), while the downstream flow is classified as super-critical flow ($Fr_{downstream}$ >1).

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