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Analysis of Froude Number and Hydraulic Jump Type in the Flow Through a Sluice Gate in a Secondary Channel

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Abstract
This study analyses the Froude number and type of hydraulic jump in flow through a sluice gate in a secondary channel, both with and without a wide sill. Culverts, as important hydraulic elements in irrigation systems, often trigger hydraulic jumps that have the potential to cause scour. This research is motivated by the need to understand the characteristics of hydraulic jumps in more detail, as a basis for designing effective energy dissipators. Unlike previous studies that focus on contraction coefficient and discharge, this study specifically examines the Froude number and classification of springboard types. This study used secondary data from Sunik's (2001) research which included discharge, water level and flow velocity data for two channel configurations: with and without wide sill. The analysed discharge data varied from 10 to 30 litres/second with variations in door opening. The analytical method used was the calculation of Froude number based on secondary data to classify the type of hydraulic jump. The objectives of this study were to determine the Froude number value and identify the type of hydraulic jump that occurred. The findings showed that discharge and door opening influenced flow characteristics and springboard type. In channels without a sill, discharge affects the transition of flow from subcritical to supercritical. The presence of a wide sill creates a more linear relationship between water level, velocity and Froude number. Varying the door opening affects the type of surge, from choppy, to weak, to vibrating, as the flow energy increases. Larger discharges resulted in higher Froude numbers and stronger surge types. This research makes an important contribution to the understanding of hydraulic springing phenomena and the design of energy dissipator.

Keywords: Hydraulic jump, froude number, sluice gate.

I. Intrduction

The sluice gate is one of the most important hydraulic elements and is usually used in waterways and irrigation systems to control flow (Fahmiahsan et al., 2018). When the thrust door is operated with an open and close system, the flow through the bottom of the thrust door experiences a flow condition called a hydraulic jump. Hydraulic jump is a condition where the flow changes from sub critical to super critical and within a certain distance changes back to sub critical (Laksitaningtyas et al., 2020). This is what causes the formation of a water jump. As a result of the water jump, one of the problems caused is the occurrence of scour downstream of the channel (Nurnawaty et al., 2021). Using the Froude number (Fr), hydraulic surges can be divided into various categories, such as choppy, weak, vibrating, static and strong surges (Budiarsyad & Abdurrosyid, 2018). Understanding the types of hydraulic surges, including the Froude number and type of surge, is essential in designing energy-absorbing structures to reduce the detrimental effects of erosion. The following Figure 1 shows an illustration of a sluice, the flow, the door opening, and the hydraulic springboard that occurs.

Previous research by (Sunik, 2001) has simulated the operation of a sluice gate and studied the contraction coefficient (Cc) and discharge coefficient (Cd). However, the study has not specifically analysed the hydraulic springboard phenomenon that occurs. Therefore, this study aims to analyse the Froude number and type of hydraulic jump formed by the flow through the thrust gate in the secondary channel. This research is a follow-up study to the research of (Sunik, 2001) with a focus on hydraulic jump characteristics.

There have been many studies on hydraulic jumping and its effect on flow in open channels, especially with regard to sluice gates and related structures. (Nurnawaty et al., 2021) examined the effect of variations in the height of the sluice gate opening on the water level profile and the length of the water jump with and without a threshold downstream of the door, finding that variations in door opening affect water level fluctuations and the increase in discharge is directly proportional to the length of the water jump. Experimental research by (Aji & Darmadi, 2007) examined the hydraulic jump characteristics of sluice gates by varying the door opening and measuring the length and height of the jump. The results show that the Froude number varies with the door opening and affects the springboard characteristics. (Ain et al., 2016) examined the characteristics of hydraulic springing at a laboratory-scale rectangular irrigation canal sluice gate opening, observing changes in flow characteristics such as velocity, depth, discharge, Froude number, specific energy, and energy loss due to variations in door opening, and classifying the type of springing that occurs.

Suhudi & Pandawa (2022) analysed the effect of threshold length on specific energy in open channels, finding that threshold length affects specific energy and the type of flow that occurs. Sahitua et al. (2023) also examined the specific energy of water jumping, examining the effect of door opening height on flow characteristics and found that the higher the door opening, the speed, discharge, and specific energy upstream decreased, while downstream increased. Doloksaribu et al. (2021) examined the effect of sluice gate opening height on Froude number downstream of the primary channel, finding that opening height affects water discharge and Froude number, which classifies the type of flow. Kim et al. (2015) conducted experiments to compare the hydraulic jump and downstream flow characteristics between a sluice gate and a fixed weir, and analysed the effectiveness of energy absorbers in controlling flow.

Zhang et al. (2024) examined the hydraulic characteristics of doors in open channels, focusing on flow measurement and hydraulic behaviour around water gauge structures, using a combination of physical model experiments and theoretical analysis. Laishram, Devi, et al. (2022) compared the hydraulic springboard characteristics and energy dissipation between push doors and radial doors, finding that radial doors dissipate more energy and provide better flow control. Finally, Sunik et al. (2020) analysed the hydraulic springing characteristics through a push gate using baffle blocks as energy absorbers, examining the effect of baffle block placement on springing and classifying the type of springing based on Froude number. These studies provide a strong foundation for understanding the phenomenon of hydraulic springing and its importance in the design of efficient and safe hydraulic structures.

This study used secondary data from research (Sunik, 2001), including data on discharge (Q), water level (h1 and h2), and flow velocity (v1 and v2) in two channel configurations: (1) a sluice directly over the channel; and (2) a sluice over a wide sill. The analysed discharge data varied, namely: 10, 15, 20, 25, and 30 litres/sec, with variations in door opening a1 = 6, 9, 12 cm; a2 = 12 cm. The sluice is made of wood with a width (bp) = 50 cm and height (hp) = 50 cm. The sill is made of concrete masonry having a width (ba) = 5 cm and a height (ha) = 3 cm. This study limits the analysis to the calculation of Froude number (Fr) to classify the type of hydraulic jump, without discussing and analysing sediment, scour volume, energy loss, Reynold's number, or cost budget design aspects. The study assumed uniform flow and a model scale ratio of 1:3 (undistorted) was also applied.

Jurnal Teknik Sipil
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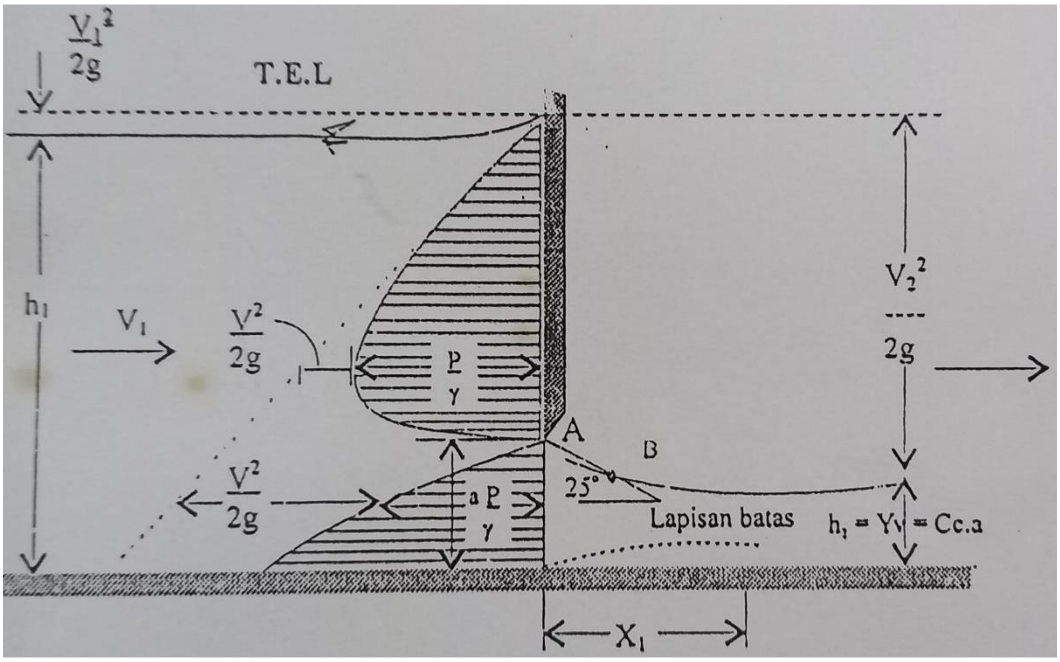

Figure 1 Sketch of Free Flow Through Under Door
Source: (Henderson, 1966)

Figure 1 illustrates the flow characteristics of a fluid passing through a sluice gate in an open channel. The sluice gate, which serves as a water discharge regulator, creates significant changes to the flow conditions. Before passing through the gate, the flow has a relatively high depth and low velocity, indicating subcritical flow conditions (Rustiati & Suciani, 2021). When water flows through the opening below the thrust gate, a significant contraction of the flow occurs (Sujatmoko et al., 2021). The cross-sectional area of the flow narrows, causing a drastic increase in flow velocity. This increase in velocity is accompanied by a decrease in flow depth and a change in flow conditions to supercritical. Supercritical flow is characterised by a Froude number (Fr) greater than 1.00, which indicates that inertial forces are dominant over gravitational forces (Nurhaliza et al., 2022). This flow has high kinetic energy and tends to flow with high velocities and undulating surfaces.

The formulation of this research problem is: What is the value of the Froude number and the type of hydraulic jump generated due to the simulation of the sluice gate opening in the secondary channel? The purpose of this research is to determine the value of the Froude number and identify the type of hydraulic jump that occurs in the secondary channel model. The results of this study are expected to contribute as a reference for further research in the field of hydraulics, especially related to the design of energy absorbers.

II. Literature Review

2.1 Sluice Gate

Sluices gate, as described by (Henderson, 1966) and (K. Subramanya, 1982) are commonly used to control water discharge in irrigation and drainage channels. The flow of water passing under a sluice is supercritical flow which has high energy and can cause scouring problems downstream of the sluice, especially if the bed material is fine material (easily eroded). When a sluice is opened, there is generally a free flow followed by a hydraulic jump, as shown in Figure 2.

In Figure 2, we can see how water flows through an open sluice, forming a supercritical flow with high velocity and shallow depth. This supercritical flow then meets the subcritical flow downstream, resulting in a hydraulic shock. This hydraulic springboard is characterised by a sudden increase in water depth and significant energy dissipation, which aims to dampen the flow energy and prevent scouring.

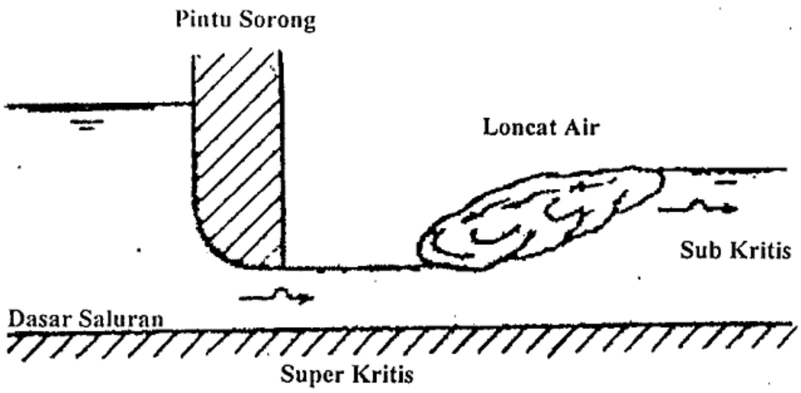

Figure 2 Flow Past the Sorong Gate
Source: (Henderson, 1966)

Sluice gates are buildings that cut river embankments that function as water flow regulators for the construction of drainage, tapping, and regulating water traffic (Mori, 2003). In terms of construction, floodgates can be divided into two types, namely open channel type floodgates or called channel floodgates (gates) and closed channel type floodgates or called tunnel floodgates (sluice). Channel floodgates are generally built on large waterways, while channel floodgates are generally built on relatively small waterways. (Bahri, 2012)

(Fahmiahsan et al., 2018) states that flow discharge is the amount of water volume that flows in a certain time through a cross section. Measurement of discharge (Q) can be divided into two types, namely direct measurement of discharge (volumetric) and indirect measurement of discharge.

Direct measurement of discharge:

$$Q = V / t \tag{1}$$

Indirect measurement of discharge:

$$Q = A \times V \tag{2}$$

Calculation of discharge through the thrust door for rectangular channels can be calculated using the following equation.

$$Q = (Cd) \text{ x } (b) \text{ x } (a) \text{ x } (\sqrt{(2) * (g) * (ho)}) \tag{3}$$

2.2 Froude Number

According to Hazanah (2023), the Froude number is a unitless number used to measure the resistance of an object moving through water and compare objects of different sizes. The effect of gravity on flow can be expressed by the Froude number. To calculate the Froude number at the beginning of the water jump and downstream after the water jump, the following equation is used (Chow, 1989).

$$Fr = \frac{V}{\sqrt{g * h}} \tag{4}$$

Where:

Fr = Froude Number
v = Flow velocity (m/s)
g = Gravity (m/s2)
h = heights (m)

2.3 Flow Properties and Classification

According to (Mandasari, 2018) in (Lawtanius et al., 2023) hydraulic stepping occurs when there is a change in flow from supercritical to subcritical due to water passing through a sluice or sluice gate. The sluice gates that are opened will bring together the subcritical flow with supercritical, which is called a hydraulic jump. This phenomenon is shown in Figure 3, where supercritical flow (Fr > 1) with high velocity (V1) and shallow depth (y1) suddenly turns into subcritical flow (Fr < 1) with lower velocity (V2) and greater depth (y2) after passing through a hydraulic springboard. The hydraulic springboard is characterised by strong whirlpools and significant energy dissipation. The hydraulic springboard length (Lj) is the horizontal distance between the point where the supercritical flow starts to rise and the point where the subcritical flow is fully established.

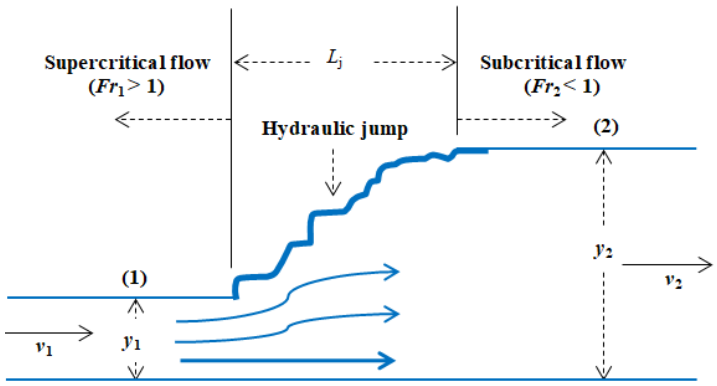

Figure 3 Hydraulic Jumps
Source: (Laishram, Ngangbam, et al., 2022)

Froude number (Fr), as described by (Anggrahini, 1997), is used as a parameter to distinguish flow conditions based on the ratio between inertial and gravitational forces. Tregaskis et al., (2022) and (Ali et al., 2018) classify flows based on Froude number values as follows:

1. Subcritical flow, if Fr < 1. Under these conditions, gravity is dominant. Flow tends to be calm and slow with a relatively smooth water surface. Changes downstream will affect the flow conditions upstream.
2. Critical flow, when large Fr = 1. The gravitational force and inertial force are in balance. This flow condition is a transition between subcritical and supercritical. The specific energy level is minimum for a given discharge.
3. Supercritical flow, when Fr > 1. Inertial forces are dominant, causing the flow to be fast and turbulent with an undulating water surface. Changes downstream do not affect the flow conditions upstream.

The change in flow conditions from subcritical to supercritical, and vice versa, can be observed in Figure 4. In Figure 4, it can be seen how subcritical flow (Fr < 1) with greater depth and lower velocity changes to supercritical flow (Fr > 1) with smaller depth and higher velocity after passing through an obstruction or change in channel geometry.

Jurnal Teknik Sipil
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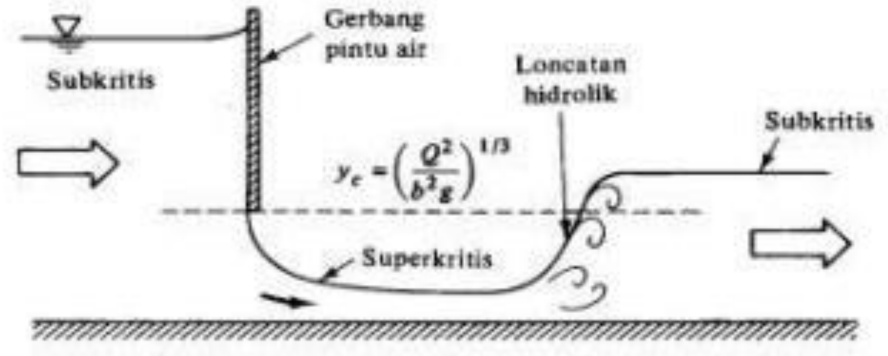

Figure 4 Subcritical to Supercritical Flow
Source: (Lawtanius et al., 2023)

Flow classification in open channels can be done based on various parameters. The two main parameters commonly used are time function and space function, as described by (Bahri, 2012) in (Lawtanius et al., 2023); (Rahayu, 2019); (Rauf & M., 2019); and (Kamiana, 2018) as follows:

1. Based on the time function, the flow can be classified as follows
   A. Permanent flow (steady flow). It is a flow where the discharge, velocity, and pressure at a point in the cross section do not change with time. That is, the flow conditions (e.g., depth and velocity) at each observation point will remain constant over time.
   B. Unsteady flow. In this flow, the discharge, velocity, and pressure at a point in the cross section change with time. A common example of impermanent flow is the flow of water in a flood wave, where the discharge and water level increase and decrease over time.
2. Based on the function of space, it can be classified as follows.
   A. Uniform flow. Uniform flow occurs when the depth of flow at each cross section of the channel is the same. This condition usually occurs in straight channels with constant cross-section and uniform bed slope. The flow velocity will also be constant along the channel.
   B. Ununiform flow. Non-uniform flow is characterised by changes in flow depth along the channel. This non-uniform flow can be further divided into:
      1) Gradually varied flow. Changes in flow depth occur slowly and gradually over a relatively long distance. Examples are flow in channels with gentle changes in slope or after obstacles that cause gradual changes in water level.
      2) Rapidly varied flow. Significant changes in flow depth occur over relatively short distances. Examples are flow through a significant drop, weir, or change in channel cross-section. These flow changes are often accompanied by large changes in velocity and energy.

2.4 Hydraulic Jumps and Their Types

Hydraulic springboard characteristics are strongly influenced by the Froude number (Fr) of the incoming flow. Based on research conducted by the United States Bureau of Reclamation as listed in (Chow, 1989) and referenced by (Nurjanah, 2014) hydraulic springboard can be classified into several types based on the Froude number range as shown in Table 1 below. This classification provides a deeper understanding of the behaviour and characteristics of each type of springboard.

Table 1 Classification of Hydraulic Jump Types

Fr	Classification	Description
1,00 - 1,70	Choppy jumps	There are waves on the water surface
1,70 - 2,50	Weak jumps	A series of wave rolls are formed on the surface of the springboard, but the water surface downstream remains smooth. The overall speed is uniform, and the energy loss is small and is called a weak springboard.
2,50 - 4,50	Oscillating jump	There are isolated bursts accompanying the base of the springboard moving to the surface and back again with no specific period.
4,50 - 9,00	Steady jump	The edges of the downstream surface will roll and the point where the velocity of the jet is high tends to break away from the flow. This kind of surge is very balanced and its characteristics are the best.
> 9,00	Strong jump	The flow has a high burst velocity that separates the rolling waves from the surge surface, giving rise to downstream waves.

The classification of hydraulic springboard types based on Froude number is very important in the design of energy absorbers in hydraulic structures such as dams, irrigation canals and spillways. To provide a clearer visual picture of the various types of hydraulic springboards based on the Froude number, Figure 5 illustrates each type of springboard.

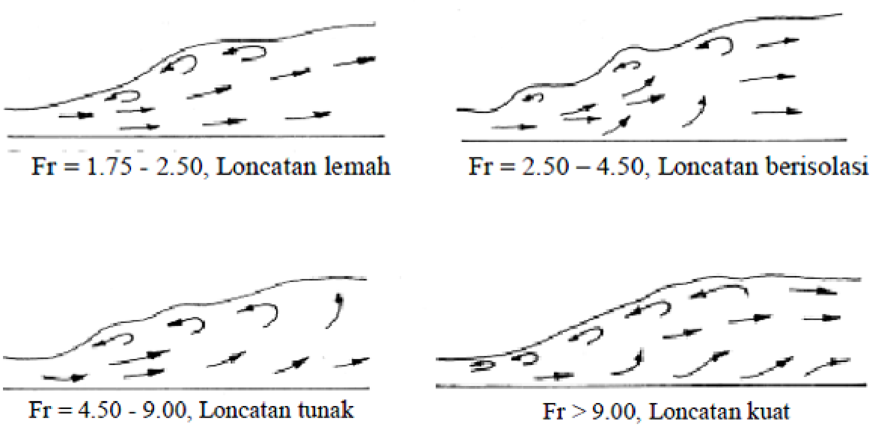

Figure 5 Classification of Hydraulic Jump Types Based on Froude Number
Source: (Raju, 1986) in (Ulfiana, 2018)

III. Material and Method

This research uses a quantitative method using secondary data. Secondary data is a data source that does not directly provide data to data collectors (Mulyani & Agustinus, 2022) in (Rachman et al., 2024). Secondary data obtained from simulating door operations in

Jurnal Teknik Sipil
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secondary channels using prototypes (Sunik, 2001). The data is in the form of experimental results that have been systematically measured and recorded by researchers in their research. In this research, the stages of data acquisition and processing carried out by the researcher are as follows.

1. Calibrate the flow rate according to the planned discharge. Calibration is carried out by measuring the discharge at the pump (Qp, reading according to the discharge curve) against the discharge through the sluice (Qa, measurement results based on discharge volume).
2. After the calibration is complete, stable flow conditions (+ 1.5-2 hours), a trial discharge is carried out until the same discharge value is obtained, Qp = Qa. The discharges used were 10, 15, 20, 25, 30 litres/second.

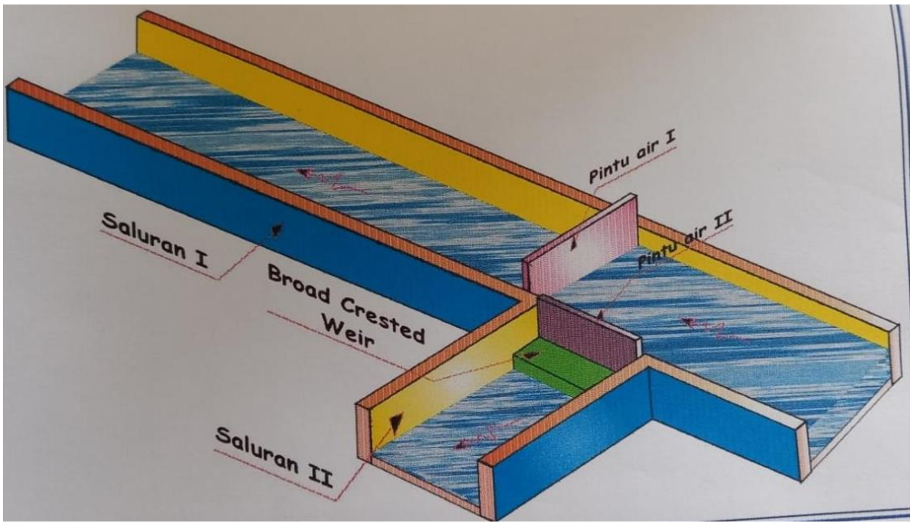

Figure 6 Secondary Channel Prototype

Figure 6 presents a schematic representation of the secondary channel prototype used in this study. The prototype was designed to simulate the flow conditions through the sluice gate and allow the hydraulic observations and measurements required for the analysis of Froude number and hydraulic stepping type. The main components of the prototype are as follows (Wigati et al., 2012; Wulandari, 2020).

1. Main Channel (Not shown): Although not explicitly shown in the drawing, the main channel is assumed to exist as the source of water supply for the secondary channels. The captions ‘Channel I’ and ‘Channel II’ indicate two different flows or sections in the secondary channel after passing through the sluice gate.
2. Sluice Gate I and Sluice Gate II: Two sluices, Sluice Gate I and Sluice Gate II, are important components in this prototype. These sluices serve to regulate and control the flow of water into the secondary channel. The sluice gates are opened simultaneously which will vary the discharge and flow velocity, which in turn affects the Froude number and the type of hydraulic surge formed.
3. Channel I and Channel II: After passing through the sluice gates, the water flow will flow into two channels, namely Channel I and Channel II. Both channels have the same geometry or shape and the same elevation height.
4. Threshold Width: A construction made across a secondary irrigation canal or river that has a significant width compared to the water level above it. The main function of the width threshold is to measure the water discharge flowing through the channel. This

Jurnal Teknik Sipil
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discharge measurement is important in water resources management, irrigation, and flood control.

5. Flow Direction: The red arrows indicate the direction of water flow through the prototype. Water flows from the main channel (not shown) through the sluice gate, over the wide sill, and then into Channel I and Channel II.

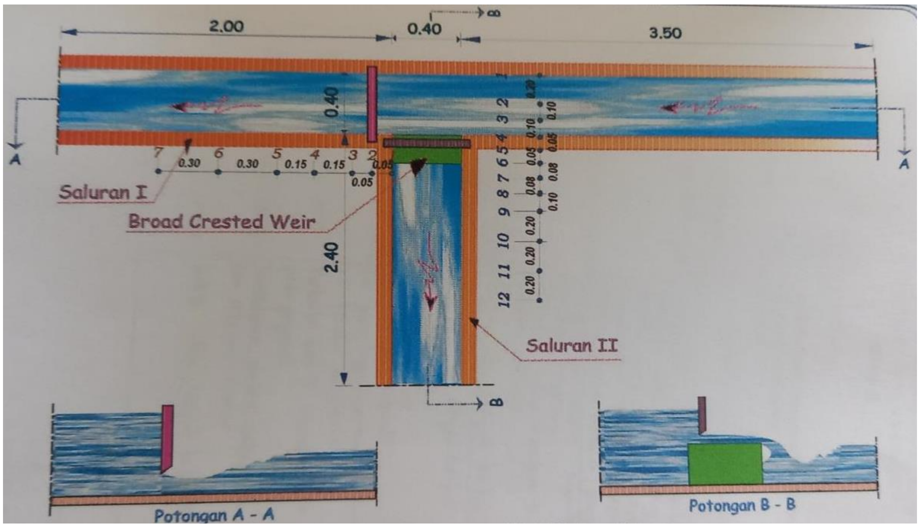

Figure 7 Section Division of Channel 1 and Channel 2

Figure 7 presents detailed cross-sections of Channel 1 and Channel 2, providing more detailed visual information on the dimensions and geometry of the two channels. These cross sections are taken at specific locations along the channel, providing a clear visual representation of how the two channels differ from each other. This information is critical to understanding the flow characteristics within each channel and how these differences can affect the Froude number and the type of hydraulic surge formed. Some of the details in Figure 7 include:

1. Section A-A: From this figure, we can see the dimensions of the channel, including width and depth. These dimensions are important for calculating the wetted cross-sectional area, which is one of the key parameters in hydraulic calculations. In addition, a visual detail on the A-A cut shows the shape of the channel, quadrilateral. This channel shape also affects the hydraulic resistance and flow velocity distribution.
2. Section B-B: Similar to Section A-A, this cut provides information on the dimensions and shape of Channel 2. Comparison between Section A-A and Section B-B allows us to see specific differences between the two channels. These differences may include differences in width, depth, cross-sectional shape, or slope of the channel walls.
3. Dimensions: Figure III-2 lists the cross-sectional dimensions of the channels in metres (m). These dimensions include channel width (2.00 m for both channels), water depth downstream of the sill (0.40 m for both channels), and sill height (0.05 m). This information is very important for hydraulic calculations and flow analyses. In addition, the figure also shows other dimensions such as the distance between measurement points (0.30 m, 0.15 m, 0.10 m, 0.08 m, and 0.05 m), indicating the location of possible measurement points conducted by Sunik (2001).
4. Point numbering: The figure shows numbered points (1 to 12) along the channel. These points likely mark the locations of measurements of velocity, water depth, or other hydraulic parameters made by Sunik (2001). This numbering makes it easy to refer to data taken at specific locations within the channel.

5. Location of the broad threshold: Figure III-2 clearly shows the location of the broad crested weir relative to the two cross sections. The broad sill is an important hydraulic structure for discharge measurement and flow control. Information on the dimensions and placement of the broad sill is critical to understanding how this prototype operates.

The data used in this study are the results of analyses and tests by (Sunik, 2001). The data collected includes:

1. Shape, geometry and materials of the duct prototype. The geometry of the prototype is: channel width, channel height, and cross-sectional area.
2. Sluice characteristics, in the form of sluice dimension data, and variations in sluice opening height in each channel.
3. Flow measurement data, in the form of: flow discharge (Q), water level (h), and flow velocity (v) at the thrust gate opening of channel 2: a2 = 12 cm, channel 1: a1 = 6, 9, 12 cm.

This research is focused on analysing the Froude number and type of hydraulic jump in the flow through the sluice gate in the secondary channel. The data used in this study were sourced from previous research, namely Sunik's thesis (2001). The available sluice opening data from the study are sluice opening 1 of 6 cm, 9 cm, and 12 cm, and sluice opening 2 of the same size.

The selection of this sluice opening was based on several considerations. Firstly, the availability of data from previous studies was the main reference. This research utilises existing data to maximise research efficiency and avoid unnecessary repetition of similar research. Secondly, a variety of sluice openings were chosen to represent diverse flow conditions. Culvert 1 openings of 6 cm, 9 cm and 12 cm will result in different Froude number and hydraulic jump types. These variations allow for a comprehensive analysis of the hydraulic jump phenomenon in the secondary channel.

In addition, this study also focuses on the change in the type of hydraulic jump that occurs due to changes in the sluice opening. Therefore, the thrust gate opening 2 was selected at 12 cm to be compared with the thrust gate opening 1 under the same conditions. This comparison aims to identify whether there is a difference in flow characteristics and types of hydraulic jumps between the two sluices at the same opening. Although 6 cm and 9 cm opening data of push gate 2 were available, they were not used in this study due to time constraints. This study focused on analysing the most relevant and significant data to achieve the research objectives.

Thus, the selection of passageway openings in this study was based on the availability of data, representation of diverse flow conditions, focus on changing the type of hydraulic springing, and the time constraints of the study. The selected variation of the passageway opening is expected to provide a better understanding of the phenomenon of hydraulic jumping in secondary channels and make a significant contribution to the field of hydraulic engineering. The data processing method carried out, namely existing secondary data processed using a simple Microsoft Excel programme. The data processing are:

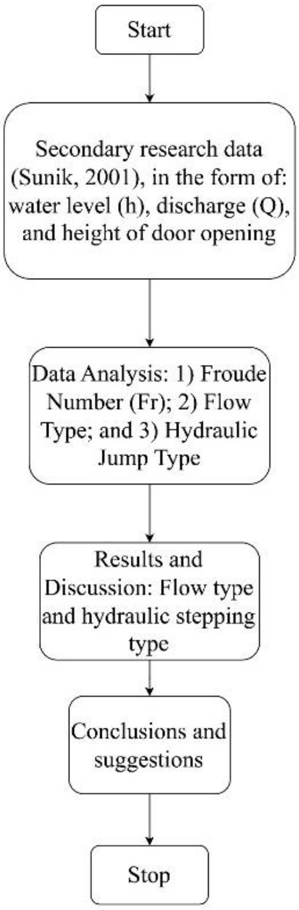

Figure 8 Research Flowchart

IV. Results and Discussion

Tables 2 to 4 present the results of the calculation of the Froude number (Fr) and the type of hydraulic jump that occurs in the secondary channel with door opening 1 of 6 cm and door 2 of 12 cm, door opening 1 of 9 cm and door 2 of 12 cm, and door opening 1 of 12 cm and door 2 of 12 cm. These data were obtained through a series of experiments with variations in total discharge, which were divided into five experimental sections. Each section represents a different total discharge, ranging from 10 litres/second in section 1 to 30 litres/second in section 5.

The columns in Tables 2 to 4 include the identification of the test section, the amount of water flowing, the measurement points within the section, the water depth at the measurement points, the water flow velocity, the Froude number calculated based on the data, and the type of hydraulic jump observed. These data will be used to analyse the effect of variations in door opening and discharge on flow characteristics, including the Froude number and the type of hydraulic jump that occurs. A detailed description of each column is as follows.

1. Section: This column indicates the section number or test section of the channel. Each section represents a different flow condition resulting from a variation in total discharge. The section number is sequential from 1 to 5, indicating the order in which the tests were conducted.
2. Discharge (cm^3/sec): This column indicates the amount of water flowing through the channel at that section. This discharge is measured in cubic centimetres per second (cm^3/second). This discharge data is the total discharge which is a combination of channel 1 discharge and channel 2 discharge.

3. Testing Point (Titik Pengujian): This column indicates the point of measurement in the section. Measurements were taken at several points along the channel to get a more detailed picture of the flow variations. Each measurement point has different flow characteristics, such as depth and velocity.
4. h (cm): This column shows the water depth at the measurement point, measured in centimetres (cm). This water depth is one of the important parameters in the calculation of Froude number.
5. V (m/sec): This column shows the speed of water flow at the measurement point, measured in metres per second (m/sec). This flow velocity is calculated based on the discharge and the wet cross-sectional area of the channel.
6. Fr: This column shows the Froude number at the measurement point. Froude number is a dimensionless number that describes the ratio between inertial force and gravitational force.

Table 2 below presents the calculation results for door opening 1 = 6 cm and door 2 = 12 cm. In this condition, the variations of total discharge tested are 10 litres/second (Section 1), 15 litres/second (Section 2), 20 litres/second (Section 3), 25 litres/second (Section 4), and 30 litres/second (Section 5).

Jurnal Teknik Sipil
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Table 2 Calculation of Froude Number and Hydraulic Jump at Channel 1 = 6 cm and Channel 2 = 12 cm

Section	Debit	Titik	Saluran 2 = 12 cm				Section	Debit	Titik	Saluran 1 (a1 = 6 cm)			
	(cm3/det)	Pengujian	h	v	Fr	Jenis Loncatan		(cm3/det)	Pengujian	h	v	Fr	Jenis Loncatan
1	5838,01	1	14,85	29,49	0,24	Tidak terdefinisi	1	4112,61	1	14,85	20,8	0,17	Tidak terdefinisi
	5835,4	2	14,843	29,49	0,24	Tidak terdefinisi		4212,29	2	3,76	84	1,38	Berombak
	5816,11	3	14,85	29,38	0,24	Tidak terdefinisi		4111,89	3	5,12	60,3	0,85	Tidak terdefinisi
	5838,01	4	3,83	29,49	0,48	Tidak terdefinisi		4222,65	4	5,88	53,9	0,71	Tidak terdefinisi
	5483,05	5	1,3	33,44	0,94	Tidak terdefinisi		4248,38	5	6,41	49,7	0,63	Tidak terdefinisi
	5842,5	6	1,18	35,98	1,06	Berombak		4112,19	6	6,93	44,5	0,54	Tidak terdefinisi
	5811,71	7	3,48	125,28	2,14	Lemah		4263,01	7	7,22	44,3	0,53	Tidak terdefinisi
	5834,24	8	3,35	130,65	2,28	Lemah							
	5831,6	9	3,23	135,44	2,41	Lemah							
	5832,82	10	3,02	144,89	2,66	Bergetar							
	5834,66	11	3	145,9	2,69	Bergetar							
	5835,69	12	2,98	146,9	2,72	Bergetar							
2	7380,42	1	17,01	32,55	0,25	Tidak terdefinisi	2	7644,39	1	17,00	33,7	0,26	Tidak terdefinisi
	7377,52	2	17,00	32,55	0,25	Tidak terdefinisi		7596,87	2	4,11	139	2,18	Lemah
	7376,08	3	17,00	32,55	0,25	Tidak terdefinisi		7648,84	3	6,04	95	1,23	Berombak
	7376,08	4	6,00	32,55	0,42	Tidak terdefinisi		7624,41	4	7,13	80,2	0,96	Tidak terdefinisi
	7362,36	5	2,00	42,49	0,96	Tidak terdefinisi		7615,02	5	7,82	73,1	0,83	Tidak terdefinisi
	7439,71	6	1,86	43,4	1,02	Berombak		7614,38	6	8,06	70,9	0,80	Tidak terdefinisi
	7389,27	7	4,51	122,9	1,85	Lemah		7572,46	7	8,55	66,4	0,73	Tidak terdefinisi
	7375,17	8	4,37	126,69	1,93	Lemah							
	7370,49	9	4,22	131,02	2,04	Lemah							
	7370,49	10	4,05	136,52	2,17	Lemah							
	7375,32	11	3,98	139,02	2,22	Lemah							
	7379,16	12	3,97	139,44	2,23	Lemah							
3	9284,39	1	19,92	34,973	0,25	Tidak terdefinisi	3	10710,01	1	19,91	40,4	0,29	Tidak terdefinisi
	9284,38	2	19,92	34,973	0,25	Tidak terdefinisi		10713,68	2	5,28	152	2,12	Lemah
	9281,28	3	19,91	34,973	0,25	Tidak terdefinisi		10711,65	3	5,67	###	1,57	Berombak
	9256,5	4	8,91	34,88	0,37	Tidak terdefinisi		10712,48	4	7,66	105	1,21	Berombak
	9290,31	5	2,80	50,5	0,96	Tidak terdefinisi		10712,91	5	8,05	99,8	1,12	Berombak
	9309,13	6	2,62	51,27	1,01	Berombak		10712,45	6	8,62	93,2	1,01	Berombak
	9272,06	7	6,00	115,93	1,51	Berombak		10712,08	7	9,14	87,9	0,93	Tidak terdefinisi
	9282,41	8	5,90	118,03	1,55	Berombak							
	9287,69	9	5,81	119,92	1,59	Berombak							
	9283,75	10	5,78	120,49	1,60	Berombak							
	9285,35	11	5,75	121,14	1,61	Berombak							
	9284,25	12	5,70	122,19	1,63	Berombak							
4	10096,92	1	22,08	34,31	0,23	Tidak terdefinisi	4	14914,81	1	22,07	50,7	0,34	Tidak terdefinisi
	10068,76	2	22,08	34,213	0,23	Tidak terdefinisi		14913,92	2	5,76	194	2,58	Bergetar
	10070,27	3	22,08	34,213	0,23	Tidak terdefinisi		14908,90	3	7,00	160	1,93	Lemah
	10098,44	4	11,08	34,31	0,33	Tidak terdefinisi		14899,87	4	7,98	140	1,58	Berombak
	10046,29	5	3,13	53,34	0,96	Tidak terdefinisi		14907,10	5	8,54	131	1,43	Berombak
	10087,87	6	2,95	54,25	1,01	Berombak		14891,74	6	9,43	118	1,23	Berombak
	10080,77	7	7,12	106,21	1,27	Berombak		14908,74	7	10,10	111	1,11	Berombak
	10081,76	8	7,00	108,05	1,30	Berombak							
	10085,16	9	6,95	108,86	1,32	Berombak							
	10086,93	10	6,90	109,67	1,33	Berombak							
	10087,08	11	6,85	110,47	1,35	Berombak							
	10085,63	12	6,80	111,27	1,36	Berombak							
5	11091,82	1	24,46	34,02	0,22	Tidak terdefinisi	5	18995,87	1	24,46	58,3	0,38	Tidak terdefinisi
	11061,86	2	24,46	33,9233	0,22	Tidak terdefinisi		18952,89	2	6,11	233	3,01	Bergetar
	11030,39	3	24,46	33,8267	0,22	Tidak terdefinisi		19013,92	3	7,72	185	2,12	Lemah
	11061,86	4	13,46	33,9233	0,30	Tidak terdefinisi		19018,82	4	8,43	169	1,86	Lemah
	10252,13	5	3,52	52,97	0,90	Tidak terdefinisi		18927,47	5	8,96	158	1,69	Berombak
	11128,81	6	3,33	58,26	1,02	Berombak		19004,95	6	9,84	145	1,47	Berombak
	11045,17	7	8,05	102,93	1,16	Berombak		19003,19	7	10,87	131	1,27	Berombak
	11108,19	8	7,88	105,75	1,20	Berombak							
	11068,75	9	7,75	107,13	1,23	Berombak							
	11043,24	10	7,70	107,59	1,24	Berombak							
	11014,55	11	7,68	107,59	1,24	Berombak							
	11093,04	12	7,67	108,5	1,25	Berombak							

Table 3 only has 4 experimental sections in channel 2, starting from Section 2 to Section 5 and 5 experimental sections in channel 1. This is because at this door opening, Section 1 in channel 2 produces a very small flow that cannot be measured accurately.

Jurnal Teknik Sipil
Vol. 2, No. 2, Desember 2024
e-ISSN: 3021-8705, p-ISSN: 3021-8713, Hal. 43-68

Table 3 Calculation of Froude Number and Hydraulic Jump at Channel 1 = 9 cm and Channel 2 = 12 cm

Section	Debit	Titik	Saluran 2 = 12 cm				Section	Debit	Titik	Saluran 1 (a1 = 9 cm)			
	(cm3/det)	Pengujia	h	v	Fr	Jenis Loncatan		(cm3/det)	Pengujian	h	v	Fr	Jenis Loncatan
1	-	-	-	-	-	-	1	14995,64	1	11,00	102,26	0,98	Tidak terdefinisi
	-	-	-	-	-	-		14992,16	2	5,96	188,71	2,47	Lemah
	-	-	-	-	-	-		14995,04	3	6,12	183,81	2,37	Lemah
	-	-	-	-	-	-		14993,16	4	8,83	127,38	1,37	Berombak
	-	-	-	-	-	-		14996,75	5	9,97	112,84	1,14	Berombak
	-	-	-	-	-	-		14998,60	6	10,21	110,2	1,10	Berombak
	-	-	-	-	-	-		14997,87	7	10,51	106,95	1,05	Berombak
	-	-	-	-	-	-							
	-	-	-	-	-	-							
	-	-	-	-	-	-							
	-	-	-	-	-	-							
	-	-	-	-	-	-							
2	6831,14	1	####	39,37	0,35	Tidak terdefinisi	2	13159,05	1	13,02	75,82	0,67	Tidak terdefinisi
	6845,51	2	####	39,453	0,35	Tidak terdefinisi		13165,05	2	6,22	158,78	2,03	Lemah
	6832,89	3	####	39,37	0,35	Tidak terdefinisi		13165,07	3	6,45	153,12	1,92	Lemah
	6832,89	4	2,02	39,37	0,88	Tidak terdefinisi		13178,31	4	9,00	109,85	1,17	Berombak
	6738,69	5	1,76	39,62	0,95	Tidak terdefinisi		13159,79	5	10,11	97,65	0,98	Tidak terdefinisi
	6871,83	6	1,55	41,08	1,05	Berombak		13145,00	6	10,46	94,28	0,93	Tidak terdefinisi
	6832,89	7	3,71	138,17	2,29	Lemah		13153,27	7	10,87	90,78	0,88	Tidak terdefinisi
	6838,4	8	3,50	146,57	2,50	Bergetar							
	6839,38	9	3,33	154,08	2,70	Bergetar							
	6834,98	10	3,04	168,67	3,09	Bergetar							
	6837,3	11	2,98	172,12	3,18	Bergetar							
	6831,06	12	2,87	178,56	3,37	Bergetar							
3	11221,99	1	####	48,52	0,37	Tidak terdefinisi	3	13782,20	1	17,35	59,59	0,46	Tidak terdefinisi
	11219,83	2	####	48,52	0,37	Tidak terdefinisi		13778,83	2	6,51	158,78	1,99	Lemah
	11221,99	3	####	48,52	0,37	Tidak terdefinisi		13779,05	3	6,93	149,16	1,81	Lemah
	11221,99	4	6,35	48,52	0,61	Tidak terdefinisi		13774,59	4	9,54	108,32	1,12	Berombak
	11054,75	5	3,62	56,72	0,95	Tidak terdefinisi		13780,46	5	10,72	96,44	0,94	Tidak terdefinisi
	11367,57	6	3,35	59,43	1,04	Berombak		13773,33	6	10,90	94,79	0,92	Tidak terdefinisi
	11222,08	7	4,78	176,12	2,57	Bergetar		13773,02	7	11,21	92,17	0,88	Tidak terdefinisi
	11220,84	8	4,44	189,59	2,87	Bergetar							
	11227,78	9	4,00	210,57	3,36	Bergetar							
	11223,36	10	3,86	218,12	3,54	Bergetar							
	11229,67	11	3,80	221,69	3,63	Bergetar							
	11226,17	12	3,78	222,8	3,66	Bergetar							
4	12437,97	1	####	48,52	0,35	Tidak terdefinisi	4	17699,54	1	19,23	69,05	0,50	Tidak terdefinisi
	12433,66	2	####	48,52	0,35	Tidak terdefinisi		17720,79	2	6,80	195,5	2,39	Lemah
	12435,82	3	####	48,52	0,35	Tidak terdefinisi		17722,42	3	7,25	183,38	2,17	Lemah
	12437,97	4	8,23	48,52	0,54	Tidak terdefinisi		17713,41	4	9,88	134,5	1,37	Berombak
	10709,77	5	3,81	54,25	0,89	Tidak terdefinisi		17722,35	5	9,34	142,29	1,49	Berombak
	12191,23	6	3,60	62,64	1,05	Berombak		17721,89	6	10,95	#######	1,17	Berombak
	12435,23	7	5,55	168,09	2,28	Lemah		17722,32	7	11,57	114,91	1,08	Berombak
	12426,63	8	5,06	184,24	2,62	Bergetar							
	12435,69	9	4,91	190	2,74	Bergetar							
	12435,42	10	4,89	190,77	2,75	Bergetar							
	12434,73	11	4,80	194,34	2,83	Bergetar							
	12431,36	12	4,79	194,69	2,84	Bergetar							

Table 4 only has 3 experimental sections, starting from Section 3 to Section 5. Just like Table 3, Section 1 and Section 2 of this door opening produce flows that are too small to measure.

Jurnal Teknik Sipil
Vol. 2, No. 2, Desember 2024
e-ISSN: 3021-8705, p-ISSN: 3021-8713, Hal. 43-68

Table 4 Calculation of Froude Number and Hydraulic Jump at Channel 1 = 12 cm and Channel 2 = 12 cm

Section	Debit	Titik	Saluran 2 = 12 cm				Section	Debit	Titik	Saluran 1 (a1 = 9 cm)			
	(cm3/det)	Pengujian	h	v	Fr	Jenis Loncatan		(cm3/det)	Pengujian	h	v	Fr	Jenis Loncatan
	3956,86	1	11,8467	25,06	0,23	Tidak terdefinisi		16046,89	1	11,85	101,59	0,94	Tidak terdefinisi
	3955,75	2	11,8467	25,06	0,23	Tidak terdefinisi		16053,23	2	5,40	223,02	3,06	Bergetar
	3957,97	3	11,85	25,06	0,23	Tidak terdefinisi		16034,94	3	5,70	211,04	2,82	Bergetar
	3937,2	4	0,85	24,9267	0,86	Tidak terdefinisi		16043,18	4	6,25	192,57	2,46	Lemah
	3790,25	5	0,72	24,26	0,91	Tidak terdefinisi		16045,79	5	6,66	180,74	2,24	Lemah
1	4052,02	6	0,6	26,2	1,08	Berombak	1	16025,81	6	6,85	175,51	2,14	Lemah
	3887,53	7	1,7	171,55	4,20	Bergetar		16039,64	7	6,90	174,39	2,12	Lemah
	3942,92	8	1,68	176,07	4,34	Bergetar							
	3940,71	9	1,6	184,77	4,66	Tetap							
	3940,71	10	1,57	188,97	4,82	Tetap							
	3957,6	11	1,55	191,54	4,91	Tetap							
	3953,04	12	1,54	192,57	4,95	Tetap							
	7991,01	1	14,7667	40,6	0,34	Tidak terdefinisi		17059,66	1	14,77	86,65	0,72	Tidak terdefinisi
	8005,01	2	14,7633	40,68	0,34	Tidak terdefinisi		17059,83	2	5,93	215,82	2,83	Bergetar
	7992,82	3	14,77	40,6	0,34	Tidak terdefinisi		17058,46	3	6,30	203,13	2,58	Bergetar
	7992,82	4	3,77	40,6	0,67	Tidak terdefinisi		17061,26	4	6,91	185,223	2,25	Lemah
	7819,43	5	2,31	44,07	0,93	Tidak terdefinisi		17061,18	5	7,33	174,61	2,06	Lemah
2	8050,43	6	2	46,46	1,05	Berombak	2	17058,51	6	7,64	167,5	1,93	Lemah
	7516,71	7	2,45	230,16	4,69	Tetap		17051,75	7	7,86	162,75	1,85	Lemah
	7986,42	8	2,41	248,6	5,11	Tetap							
	7980,47	9	2,36	253,68	5,27	Tetap							
	7976,59	10	2,3	260,17	5,48	Tetap							
	7971,01	11	2,25	265,77	5,66	Tetap							
	7973,22	12	2,23	269,43	5,76	Tetap							
	10567	1	17,8967	44,29	0,33	Tidak terdefinisi		19574,01	1	17,90	82,03	0,62	Tidak terdefinisi
	10565,03	2	17,8933	44,29	0,33	Tidak terdefinisi		19588,95	2	6,22	236,26	3,02	Bergetar
	10551,31	3	17,9	66,325	0,50	Tidak terdefinisi		19596,59	3	7,06	208,23	2,50	Bergetar
	10568,97	4	6,9	44,29	0,54	Tidak terdefinisi		19585,79	4	7,61	193,08	2,23	Lemah
	8700,66	5	3,05	46,46	0,85	Tidak terdefinisi		19599,78	5	8,11	181,3	2,03	Lemah
3	10527,16	6	2,88	56,9	1,07	Berombak	3	19596,25	6	8,44	174,39	1,92	Lemah
	10556,42	7	3,32	238,53	4,18	Bergetar		19600,60	7	8,92	164,84	1,76	Lemah
	10554,81	8	3,18	249	4,46	Bergetar							
	10553,95	9	3	263,91	4,86	Tetap							
	10552	10	2,95	268,34	4,99	Tetap							
	10555,27	11	2,9	273,05	5,12	Tetap							
	10538,93	12	2,84	278,39	5,27	Tetap							

The data in these tables can be further analysed to see how variations in door opening and discharge affect the Froude number and the type of hydraulic jump that occurs. Some of the things that can be observed include:

1. Effect of Discharge: How changes in total discharge affect the Froude number and type of hydraulic jump at each section and test point.
2. Effect of Door Opening: How different door openings in the two channels affect the flow characteristics at each section and test point.
3. Hydraulic Jump Types: Identify the types of hydraulic surges that occur based on the Froude number value. Hydraulic jumps can be classified into several types, such as weak jumps, choppy jumps, vibrating jumps, and others.

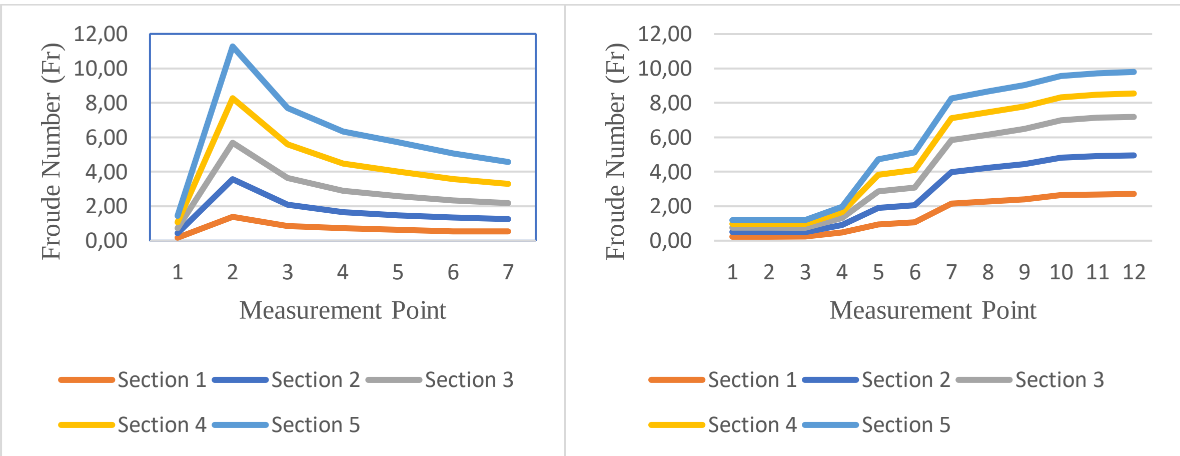
4.1 Froude Number

Channel 1 in each thrust gate opening has several sections with 12 measurement points each. Meanwhile, channel 2 in each sluice opening has several sections with 7 measurement points each. The location and distance of measurement points on each channel can be seen in Figure 7. Research conducted by (Sunik, 2001) obtained a different number of sections in each variation of the door opening of each channel. For example, channel 1 6 cm door opening with channel 2 12 cm door opening has 5 sections, channel 1 9 cm door opening has 4 sections, and channel 2 12 cm door opening on channel 1 9 cm door opening and channel 1 12 cm door opening with channel 2 12 cm door opening each has 3 sections. The data in the sections obtained can vary because the discharge flowed has a different value, such as section 1 of 10 litres/second, section 2 of 15 litres/second, section 3 of 20 litres/second, section 4 of 25 litres/second, section 5 of 30 litres/second. The difference in flowing discharge results in some of the flow in the section on the channel being very small and not measured.

Jurnal Teknik Sipil
Vol. 2, No. 2, Desember 2024
e-ISSN: 3021-8705, p-ISSN: 3021-8713, Hal. 43-68

Table 2 is the result of Froude number, flow type, and hydraulic jump type at channel opening 1 of 6 cm (a1 = 6 cm) and channel opening 2 of 12 cm (a1 = 12 cm). The results of the analysis of Froude number and type of flow in the table look significant as the discharge changes in each section. In section 1, which has the lowest discharge than the other 4 sections, has an average Froude number of 0.69 and a sub-critical flow type of 1 at point 2. In section 2 with a greater discharge than section 1, an increase in super-critical flow began to be seen to 2 points at points 2 and 3. Section 3, 4, and 5, the number of super-critical flows increased along with the increase in discharge upstream.

Figure 8 presents a visualisation graph comparing the change in Froude number (Fr) along the section measurement points in two channel configurations, namely Channel 1 with a 6 cm opening (upper graph) and Channel 2 with a 12 cm opening (lower graph). In both graphs, the horizontal axis represents the section measurement points (Measurement Point) sequentially from downstream to upstream of the channel, namely Section 1 to Section 7 for Channel 1 and Section 1 to Section 12 for Channel 2. The vertical axis in both graphs shows the magnitude of the Froude Number (Fr). Each coloured line on the graph represents a variation of the initial flow rate, marked with the legend ‘Section 1’ to ‘Section 5’ which refers to the gradual increase of the initial flow rate according to the test configuration described in the previous table.



(a) (b)

Figure 9 Graph of Froude Number at Measurement Point of Each Section at (a) Door 1 Opening 6 cm (a1 = 6 cm); (b) Door 2 Opening 12 cm (a2 = 12m)

For all discharge variations, the Froude number increases significantly between measurement point 1 and measurement point 2, reaching the highest peak value at measurement point 2 under all discharge conditions. After reaching the peak at measurement point 2, the Froude number values then showed a gradual decreasing trend from measurement point 3 to measurement point 7. The peak Froude number value at measurement point 2 indicates that at this point, the flow tends to have the most dominant supercritical characteristics in Channel 1. Comparison between sections in this graph shows that as the initial discharge increases, the overall Froude number value increases at all measurement points. This confirms that increasing initial discharge consistently pushes the flow conditions in Channel 1 towards a more supercritical regime along the channel, although the pattern of increasing and decreasing Froude Number with a peak at measurement point 2 remains consistent.

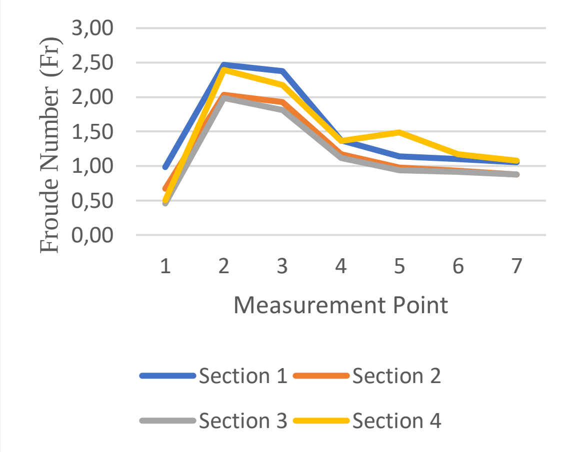
Figure 8 Graph b representing Channel 2 with a 12 cm opening shows significantly different Froude number behaviour compared to Channel 1. In Channel 2, the trend of change in Froude number tends to be more gentle and progressive. From measurement point 1 to measurement point 6, the Froude number value is relatively low and stable, indicating a dominant subcritical flow in the early part of the channel. Starting from measurement point 6, a steeper increase in Froude number is observed and continues until measurement point 12, although the increase is not as sharp as the spike that occurs at measurement point 2 in Channel 1. The peak Froude number value in Channel 2 occurs at measurement point 12, the most upstream section, indicating the strongest supercritical conditions are formed at this end of the channel. Just as in Channel 1, the increase in initial discharge in Channel 2 also consistently increases the Froude Number value throughout the section, but this increase occurs more evenly and progressively along the channel without a sharp peak in a particular section.

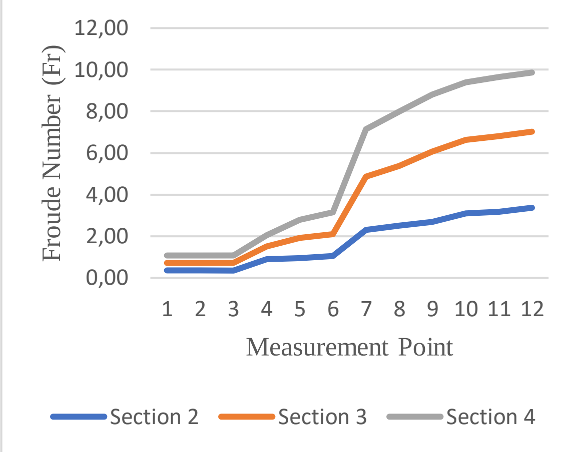
Comparison of the two graphs visually confirmed the fundamental difference in hydraulic behaviour between Channel 1 (6 cm opening) and Channel 2 (12 cm opening). The narrower door opening of Channel 1 tends to concentrate the flow energy and results in a more dramatic flow transition, characterised by a sharp Froude number spike at measurement point 2. In contrast, the wider Channel 2 allows the flow to develop more gently and gradually towards supercritical conditions downstream of the channel. This difference underscores the significant influence of channel geometry, particularly opening width, in controlling flow characteristics and the potential for supercritical flow formation and hydraulic jumps in open channel systems.

Table 3 is channel 1 with 9 cm section with channel 2 opening of 12 cm. The results of this analysis show that in channel 1, which has a low discharge of 6830.59 cm^3/sec, the flow tends to be subcritical at higher water levels, then turns supercritical as the water level decreases and the velocity increases. In contrast, at higher discharges, for example at 14995.5 cm^3/sec, the range of water levels that produce supercritical flow is wider, and even at some points, the flow remains supercritical even though the water level increases again. Meanwhile, the flow velocity (v1) was inversely proportional to the water level (h1) at each discharge. When the water level decreased, the flow velocity increased. The calculation results of channel 2 = 12 cm against channel 1 = 6 cm, and channel 2 = 12 cm against channel 1 = 9 cm show a consistent pattern. This consistent pattern indicates that as the water level decreases, the flow velocity increases, which then causes the Froude number to increase and the flow changes from subcritical to supercritical flow. In other words, this pattern shows that the sluices above the width threshold have the same relationship, i.e., the decrease of h_1 is directly proportional to the increase of v_1 and Fr, and the transition from subcritical to supercritical flow.

Figure 9 presents a comparative visualisation of the change in Froude number (Fr) along the section measurement points for the two tested channel configurations: part (a) represents Channel 1 with a 9 cm opening (a1 = 9 cm), and part (b) of the graph represents Channel 2 with a 12 cm opening (a2 = 12 cm). For Channel 1 (9 cm aperture), the measurement points include number 1 to number 7, while for Channel 2 (12 cm aperture) the measurement points include number 1 to number 12 in each section. The vertical axis of both graphs displays the Froude Number (Fr) value. Each coloured line in the graph represents a variation of the flowing discharge, indicated in the legend as ‘Section 1’, ‘Section 2’, ‘Section 3’, and ‘Section 4’ referring to increasing stages of the initial discharge tested (as indicated in the previous data table).

Jurnal Teknik Sipil
Vol. 2, No. 2, Desember 2024
e-ISSN: 3021-8705, p-ISSN: 3021-8713, Hal. 43-68





(a) (b)

Figure 10 Graph of Froude Number at Measurement Point of Each Section at (a) Door 1 Opening 9 cm (a1 = 9 cm); (b) Door 2 Opening 12 cm (a2 = 12m)

Figure 9a for Channel 1 with a 9 cm opening shows the characteristic Froude number change pattern along the channel. In general, it can be observed that for all tested discharge variations, the Froude number values tend to increase gradually from test point 1 to test point 2 of each discharge section, reaching a peak at test point 2, and then showing a continuous decreasing trend until test point 7. The peak Froude number occurring at test point 2 under all discharge conditions signifies this point as the location where the flow is most likely to reach supercritical conditions within Channel 1. Comparison between the lines representing the variation in discharge shows that as the initial discharge increases (from the line ‘Section 1’ to ‘Section 4’ in the legend, referring to the increase in initial discharge), the overall Froude number value tends to increase at each measurement point. This confirms that increasing initial discharge consistently pushes the flow in Channel 1 towards more supercritical conditions along the channel, although the general pattern of increase and decrease with a peak in Section 2 is maintained at various discharge levels.

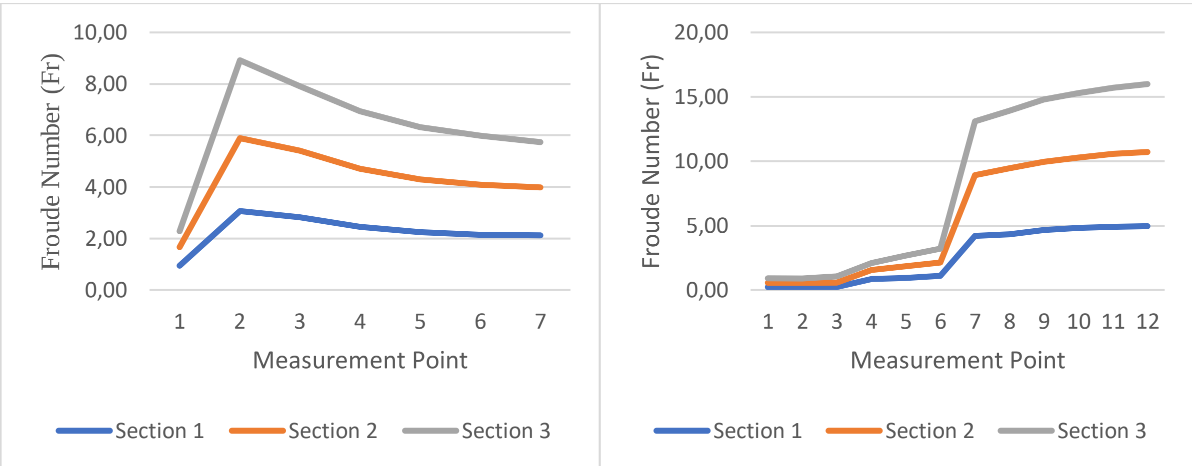
Figure 9b, which visualises the data for Channel 2 with a 12 cm opening, shows a different Froude number behaviour compared to Channel 1. In Channel 2, the trend of change in Froude number tends to be more progressive and shows a more gradual increase along the test points. From test point 1 to test point 7, the Froude number values are relatively low and tend to be stable, indicating the dominance of subcritical flow in the early to middle part of the channel. Starting from test point 7, there is a more significant increase in Froude number values, which continues until test point 12, the most upstream section. This increase in Froude Number in Channel 2 is not as sharp as the spike observed at test point 2 in Channel 1, but rather a gradual and continuous increase. The highest value of Froude Number in Channel 2 occurs at test point 12, which is the endmost test point, indicating the most intense supercritical conditions are reached at this end of the channel. Similar to Channel 1, the increase in initial discharge in Channel 2 also resulted in an overall increase in Froude number values in each section, but the pattern of increase was more even and progressive throughout the channel with no peak values localised in any particular section.

Table 4 represents channel 1 with 12 cm section with channel 2 opening of 12 cm. The results of this analysis show that in channel 1 with the lowest discharge of 3940.55 cm^3/sec, it can be seen that at relatively high water levels (11.85 cm and 14.77 cm in sections 1 and 2), the flow velocity is low and produces a Froude number of less than 1.00, indicating that the flow is subcritical. In each section, test points that had lower water levels had greater flow velocities, resulting in higher Froude numbers. For example, the pattern at the higher

Jurnal Teknik Sipil
Vol. 2, No. 2, Desember 2024
e-ISSN: 3021-8705, p-ISSN: 3021-8713, Hal. 43-68

discharge (7937.99 cm³/sec), where the decrease in water level was also followed by an increase in velocity and Froude number, resulted in a transition from subcritical to supercritical. In channel 2 = 12 cm (a2 = 12 cm) against channel 1 = 12 cm (a1 = 12 cm), at each discharge the initial water level tends to be high, and as the water level decreases, there is an increase in flow velocity (v_1). This increase in velocity has a direct impact on the Froude number (Fr) value. In general, when the water level is still relatively high, the Froude number value is below 1, which indicates subcritical flow. However, as the water level decreased and the velocity increased, the Froude number increased and surpassed 1. This pattern was consistent across all tested sections.

Figure 10 presents a comparative visualisation of the variation of the Froude Number (Fr) along the section measurement points for two door configurations with identical openings of 12 cm: graph (a) represents the data for Door 1 with an opening of 12 cm (a1 = 12 cm), and graph (b) visualises the data for Door 2 which also has an opening of 12 cm (a2 = 12m). The horizontal axis in both graphs shows the measurement points, which are arranged in order. For both door configurations (Door 1 and Door 2 with a 12 cm opening), the measurement points include Section 1 to Section 7 for Graph 10a and measurement points 1 to Section 12 for Graph 10b. The vertical axis in both graphs displays the Froude Number (Fr) values. Each coloured line in the graph represents a variation in the initial flow rate, marked with the legends ‘Section 1’, ‘Section 2’ and ‘Section 3’ which represent the stages of increase in the initial flow rate tested, as detailed in the previous data table.



(a) (b)

Figure 11 Graph of Froude Number at Measurement Point of Each Section at (a) Door 1 Opening 12 cm (a1 = 12 cm); (b) Door 2 Opening 12 cm (a2 = 12m)

Figure 10a is a graph for Door 1 with a 12 cm opening showing that at the lowest discharge (represented by the line ‘Section 1’ in the legend), the Froude number values at this discharge are generally below 1.0 throughout the measurement points, indicating that the flow is subcritical throughout the measurement points at this discharge. However, what is interesting is the pattern of Froude number changes with measurement point. At the beginning of the channel (measurement point 1 and measurement point 2), despite the smallest discharge, the Froude number values tend to be relatively low due to the relatively high water depth (as described in the literature view section). As the flow progresses to the later measurement points, and as the water depth decreases and the flow velocity increases, the Froude Number value gradually increases, although it remains below the critical limit. An increase in the initial higher discharge (Section 2 and Section 3) consistently resulted in

Jurnal Teknik Sipil
Vol. 2, No. 2, Desember 2024
e-ISSN: 3021-8705, p-ISSN: 3021-8713, Hal. 43-68

higher Froude Number values throughout the section, and even at the highest discharge, Section 3, there was a tendency to approach or slightly exceed the value of 1.0 at some measurement points, indicating a transition towards critical or supercritical flow at some points. The general pattern observed is that decreasing water depth (as the flow moves downstream) is positively correlated with increasing flow velocity and Froude Number, supporting the description in the introductory text that flow velocity (v_1) is inversely proportional to water depth (h_1) at each discharge.

Figure 10b for Door 2 with a 12 m opening shows a different pattern of Froude number changes compared to Door 1. In Door 2, the increasing trend of Froude number tends to be more progressive and significant along the channel. From measurement point 1 to measurement point 6, the Froude number values are relatively low, similar to the initial conditions at Door 1. However, starting from measurement point 7, there is a very sharp increase in Froude number and it continues dramatically until measurement point 12, the uppermost section. At higher initial discharges (Section 2 and Section 3), the Froude number value at Door 2 quickly surpasses the value of 1.0 and reaches much higher values compared to Door 1 at the downstream gauging points (especially gauging point 7 onwards). The peak Froude Number value of Door 2 was reached at Section 12, signalling the dominant supercritical flow conditions at this end of the channel, the measurement point at higher discharge. A consistent pattern observed at Gate 2 is that the decrease in water depth (as the flow moves downstream) significantly triggers an increase in flow velocity and Froude number, which then results in a more pronounced and robust transition of flow from subcritical to supercritical compared to Gate 1.

In this study, no analysis results were found that showed critical flow conditions (Fr = 1). This is because the critical flow point is located just below the push door, namely in the vena contracta section (Chaudhry, 2013; Klaas, 2010). Vena contracta is the point of maximum flow constriction that occurs below the door opening, where the flow changes from supercritical to subcritical (Amril Amril et al., 2017; Putranto et al., 2014). Critical flow (Fr = 1) was not observed because measurements were not taken at the vena contracta point, but rather at a location after the vena contracta as shown in Figure III-2, where flow conditions have evolved to subcritical or supercritical. Thus, the non-appearance of critical flow data (Fr = 1) in this study is due to the improper location of the measurement at the vena contracta, i.e. the area below the push door where the flow undergoes maximum constriction and critical flow conditions are reached.

4.2 Hidraulic Jump

Door opening sluice 1 = 6 cm (a1 = 6 cm) in section 1 with a discharge of 5802.82 cm^3/sec, as many as 1 point out of 7 measurement points or as much as 14.3% has a type of hydraulic jump that is choppy with a Froude number of 1.38. While the other 6 points are undefined hydraulic jumps or have a Froude number less than 1.00. In section 2, the discharge of 7381.01 cm3/sec has 3 types of hydraulic jumps, including: weak jumps at point 2 with a Froude number of 2.18, choppy jumps at point 3 with a Froude number of 1.23, and 5 other points have undefined hydraulic jumps. In section 3, the discharge of 9283.46 cm^3/sec has 3 types of hydraulic jumps, including: weak springing at point 2 with a Froude number of 2.12, choppy springing at points 3, 4, 5, and 6, and undefined hydraulic springing at points 1 and 7. In section 4, a discharge of 10081.32 cm^3/sec has 4 types of hydraulic springing, including: vibrating springboard at point 2 with a Froude number of 2.58, weak springboard at point 3 with a Froude number of 1.93, choppy springboard at points 4, 5, 6, 7, and undefined hydraulic springboard at point 1. In section 5, a discharge of 10999.9 cm^3/sec has 4 types of hydraulic springboard, including: Vibrating springboard at point 2 with a Froude number of 3.01, weak springboard at points 3 and 4, choppy springboard at points 5, 6, and 7, and undefined hydraulic springboard at point 1.

The sluice gate of door opening 1 = 9 cm (a1 = 9 cm) in section 1 with a discharge of 14995.46 cm^3/sec has 3 types of hydraulic jumps, including: weak jumps at points 2 and 3, choppy jumps at points 4, 5, 6, and 7, and undefined hydraulic jumps at point 1. In section 2, the discharge of 6830.59 cm^3/sec has 3 types of hydraulic jumps, including: weak jumps at points 2 and 3, choppy jumps at point 4 with a Froude number of 1.17, and undefined hydraulic jumps at points 1, 5, 6, and 7. In section 3, the discharge of 11221.5 cm^3/sec has 3 types of hydraulic jumps, including: weak jumps at points 2 and 3, choppy jumps at point 4 with a Froude number of 1.12, and undefined hydraulic jumps at points 1, 5, 6, and 7. In section 4, a discharge of 12270.46 cm^3/sec has 3 types of hydraulic jumps, including: weak jumps at points 2 and 3, choppy jumps at points 4, 5, 6, and 7, and undefined hydraulic jumps at point 1.

The sluice gate of door opening 1 = 12 cm (a1 = 12 cm) in each of the three sections has the same number of jumps and at the same point location. Each section, section 1 and section 2 with a discharge of 3940.55 cm^3/sec, section 3 with a discharge of 7937.99 had 3 types of hydraulic springing, including: Vibrating springboard at points 2 and 3, weak springboard at points 4, 5, 6, and 7, and undefined hydraulic springboard at point 1.

The sluice gate of door opening 2 = 12 cm (a2 = 12 cm) against door opening 1 = 6 cm (a1 = 6 cm) in section 1 with a discharge of 5802.82 cm^3/sec, has 4 types of hydraulic jumps, including: Vibrating jumps at points 10, 11, and 12, weak jumps at points 7, 8, and 9, choppy jumps at point 6, and undefined at points 1, 2, 3, 4, and 5. In section 2, the discharge of 7381.01 cm^3/sec has 3 types of hydraulic jumps, including: weak jumps at points 7 to 12, choppy jumps at point 6, and other points have undefined hydraulic jumps. In section 3 discharge 9283.46 cm^3/sec, section 4 discharge 10081.32 cm^3/sec, and section 5 discharge 10999.9 cm^3/sec each had the same number and type of springboards and at the same test points. Each of these sections had 2 types of hydraulic jumps, including: choppy stepping at points 6 to 12, and undefined hydraulic stepping at points 1 to 5.

Door opening 2 = 12 cm (a2 = 12 cm) against door opening 2 = 9 cm (a2 = 9 cm), respectively, section 2 with a discharge of 6830.59 cm^3/sec and section 4 with a discharge of 12.27046 cm^3/sec have the same number and type of hydraulic jumps and at the same point. Both have 4 types of hydraulic springboards, viz: Vibrating springboard at points 8 to 12, weak springboard at point 7, weak springboard at point 6, and undefined hydraulic springboard type at points 1 to 5. Whereas in section 3 with a discharge of 11221.5 cm^3/sec has 3 types of hydraulic springboard, including: Vibrating springboard at points 7 to 12, choppy springboard at point 6, and undefined hydraulic springboard type at points 1 to 5.

Door opening 2 = 12 cm (a2 = 12 cm) to door opening 3 = 12 cm (a3 = 12 cm), respectively, section 1 with a discharge of 3940.55 cm^3/sec and section 4 with a discharge of 7937.99 cm^3/sec have the same number and type of hydraulic jumps and at the same point. Both have 4 types of hydraulic jumps, viz: fixed jumps at points 9 to 12, vibrating jumps at points 7 and 8, choppy jumps at 6, and undefined hydraulic jump types at points 1 to 5. Whereas in section 2 with a discharge of 3940.55 cm^3/sec, it has 3 types of jumps, namely: fixed jumps at points 7 to 12, choppy jumps at point 6, and undefined hydraulic jump types at points 1 to 5.

V. Conclusions and Suggestions

5.1 Conclusions

Based on the results of the research and analyses that have been carried out on the flow through the sluice gate in the secondary channel, both with and without a wide sill, several

Jurnal Teknik Sipil
Vol. 2, No. 2, Desember 2024
e-ISSN: 3021-8705, p-ISSN: 3021-8713, Hal. 43-68

important conclusions can be drawn. The channel without a wide sill (channel 1) has 7 measurement points. From the research that has been done, it is found that this channel is found that the flow discharge greatly affects the flow characteristics that are relevant to the research conducted by (Martini et al., 2020). In sections with relatively small discharge, the flow tends to be subcritical when the water level is high. As the water level decreases and the flow velocity increases, there is a transition to supercritical flow. In contrast, in sections with larger discharges, the range of water levels that produce supercritical flow becomes wider, and at some points, the flow remains supercritical even when the water level increases again. An inverse relationship between water level and flow velocity was also observed, where a decrease in water level was always followed by an increase in flow velocity at each discharge.

The channel with the wide threshold (channel 2) has 12 measurement points. Analyses on this channel show a more consistent pattern. The decrease in water level consistently correlated with an increase in flow velocity, which in turn led to an increase in Froude number and the transition of flow from subcritical to supercritical. This pattern indicates that the presence of a wide sill exerts a uniform influence on the relationship between water level, flow velocity and Froude number, and facilitates the transition of flow from subcritical to supercritical. In other words, the wide sill modifies the characteristics of the flow passing through the sluice, creating a more linear relationship between the decrease in water level and the increase in velocity and Froude number.

The effect of door opening on the type of hydraulic springboard is also clearly observed. At door opening 1 of 6 cm (a1 = 6 cm), the hydraulic jumps formed tended to be dominated by choppy jumps with Froude numbers of around 1.00 to 1.70. Most of the measurement points under these conditions showed defined hydraulic surges (Froude number less than 1.00), especially at lower discharge rates. This indicates that at relatively small door openings, there is not enough flow to form a clear jump at some discharges. At door opening 1 (a1) of 9 cm, the dominant jump types were weak jumps and choppy jumps. Weak jumps generally occur at the initial points after the sluice (points 2 and 3), while choppy jumps occur at later points. This shows that with larger door openings, the flow has increased energy and is able to form stronger jumps. At door opening 1 (a1) of 12 cm, there was a shift in the type of jumps to vibrating jumps and weak jumps. Vibrating jumps were observed at points 2 and 3, followed by weak jumps at later points. This indicates that as the door opening gets larger, the flow energy gets higher and produces jumps with different characteristics.

Flow discharge also affects the type of stepping as in the study conducted by (Gao et al., 2024; Reece et al., 2024). Overall, the larger the flow rate, the higher the Froude number and the stronger the type of hydraulic jump (from choppy to weak, then to vibrating to steady). At small discharges, the analyses often result in a well-defined hydraulic jump (Froude < 1). This defined hydraulic jump means that the flow is still sub-critical at the study point.

5.2 Suggestions

Based on the analysis of the Froude number and the type of hydraulic jump that occurs in the flow through the sluice gate in the secondary channel with various variations of door opening and discharge, several suggestions are recommended for further research to complete the understanding and provide more comprehensive information, especially related to the variation of door opening in channel 2 and its relationship with energy dissipators:

1. This study used data of door opening 2 = 12 cm. For a more complete and representative analysis, future research is recommended to complete the data with other door opening 2 available in Sunik's (2001) research, namely 6 cm and 9 cm. By

Jurnal Teknik Sipil
Vol. 2, No. 2, Desember 2024
e-ISSN: 3021-8705, p-ISSN: 3021-8713, Hal. 43-68

completing this data, a more comprehensive comparison can be made on the effect of variations in door opening in channels with wide thresholds on hydraulic jump characteristics. This analysis will provide a deeper understanding of how the sill width modifies the effect of the door opening on the flow.

2. After completing the door opening data in channel 2, further research can directly compare the effect of variations in door opening (6, 9, and 12 cm) on hydraulic jump characteristics in channels with wide thresholds (channel 2) and without wide thresholds (channel 1). This comparison could include: comparison of Froude numbers, comparison of hydraulic jump types, and energy loss analysis.
3. Based on the Froude number and stepping type data obtained, further research could focus on the design and testing of different types of energy dissipators, such as sinks, blocks, or riprap. The effectiveness of energy dissipators can be evaluated based on their ability to dissipate flow energy and reduce scour potential.

VI. References

Ain, S. R., Abdullah, S. H., & Priyati, A. (2016). *Kajian Loncatan Hidrolik (Hydraulic Jump) pada Bukaan Pintu Air Saluran Irigasi Berbentuk Segi Empat Skala Laboratorium*.

Aji, Ign. S., & Darmadi, K. (2007). Penelitian Eksperimental Karakteristik Loncatan Hidrolik pada Pintu Air. *Majalah Ilmiah UKRIM*, *1*(12).

Ali, M. Y., Husaiman, & Nur, M. I. (2018). Karakteristik Aliran pada Bangunan Pelimpah Tipe Ogee. *Jurnal Teknik Hidro*, *11*(1), 72–82. https://doi.org/https://doi.org/10.26618/th.v11i1.2441

Amril Amril, Desty Anggita Tunggadewi, & Hari Hadi Santoso. (2017). Perancangan Sistem Monitoring Meter untuk Aplikasi Meter Orifice Menggunakan Perangkat Lunak PI ProcessBook. *Jurnal Ilmiah Giga*, *20*(2), 57–63. https://doi.org/https://doi.org/10.47313/jig.v20i2.553

Anggrahini. (1997). *Hidrolika Saluran Terbuka*. Citra Media.

Bahri, Z. (2012). Aplikasi Program Matlab pada Perhitungan Beda Tinggi Muka Air Terhadap Berat dan Sudut Kemiringan Pintu Air Otomatis Tipe Segiempat. *Bearing : Jurnal Penelitian Dan Kajian Teknik Sipil*, *2*(4). https://doi.org/https://jurnal.um-palembang.ac.id/berkalateknik/article/view/342

Budiarsyad, G., & Abdurrosyid, J. (2018). *Pengaruh Penempatan Baffle Blocks Tipe V Terhadap Reduksi Panjang Loncatan Air dan Energi Aliran Pada Pengalir Bendung Tipe Ogee* [Skripsi]. Universitas Muhammadiyah.

Chaudhry, M. H. (2013). *Applied Hydraulic Transients* (3rd ed.). Springer Science & Business Media.

Chow, V. Te. (1989). *Open-Channel Hydraulics*. McGraw-Hill Book Company Inc.

Doloksaribu, A., Paresa, J., & Para'pak, I. (2021). Kajian Pengaruh Tinggi Bukaan Pintu Air Terhadap Bilangan Froude Dibagian Hilir Saluran Primer. *Musamus Journal of Civil Engineering*, *4*(01), 36–44. https://doi.org/http://dx.doi.org/10.35724/mjce.v4i01.4009

Fahmiahsan, R., Mudjiatko, & Rinaldi. (2018). Fenomena Hidrolis pada Pintu Sorong. *Jom FTEKNIK*, *5*(1).

Gao, Y., Huang, F., & Wang, D. (2024). Evaluating Physical Controls on Conduit Flow Contribution to Spring Discharge. *Journal of Hydrology*, *630*(6), 130754. https://doi.org/https://doi.org/10.1016/j.jhydrol.2024.130754

Jurnal Teknik Sipil
Vol. 2, No. 2, Desember 2024
e-ISSN: 3021-8705, p-ISSN: 3021-8713, Hal. 43-68

Hazanah, M. (2023). *Studi Eksperimental Terhadap Distribusi Kecepatan Aliran pada Ambang Berpori dan Tertutup pada Flume* [Skripsi]. Program Studi Sarjana Teknik Sipil Fakultas Teknik.

Henderson, F. M. (1966). *Open Channel Flow*. Macmillan Publishing Co, Inc.

K. Subramanya. (1982). *Flow in Open Channels* (3rd ed., Vol. 1). Tata McGraw-Hill.

Kamiana, I. M. (2018). Aliran Seragam. In *HIDRAULIKA: Teknik Perhitungan pada Aliran Terbuka dan Tertutup*. Teknosain.

Kim, Y., Choi, G., Park, H., & Byeon, S. (2015). Hydraulic Jump and Energy Dissipation with Sluice Gate. *Water*, *7*(9), 5115–5133. https://doi.org/http://dx.doi.org/10.3390/w7095115

Klaas, D. K. S. Y. (2010). The Characteristic of Critical Flow on Sluice Gate. *Dinamika TEKNIK SIPIL*, *10*(1). https://doi.org/https://doi.org/10.6084/m9.figshare.14532093.v1

Laishram, K., Devi, T. T., & Singh, N. B. (2022). Experimental Comparison of Hydraulic Jump Characteristics and Energy Dissipation Between Sluice Gate and Radial Gate. *Department of Civil Engineering, National Institute of Technology*, 207–218. https://doi.org/http://dx.doi.org/10.1007/978-981-19-0304-5_16

Laishram, K., Ngangbam, R., Kumar, P. A., & Devi, T. T. (2022). Numerical and Experimental Study on Energy Dissipation in Hydraulic Jump: A Comparison Between Horizontal and Sloping Rough Channel Bed. *Conference: 9th International Symposium on Hydraulic Structures*, 24–27. https://doi.org/http://dx.doi.org/10.26077/cb4c-fdc3

Laksitaningtyas, A., Legono, D., & Yulistiyanto, B. (2020). Karakteristik Kecepatan Aliran Di Dekat Dasar Pintu Peluapan Bawah (Sluice Gate). *Jurnal Teknik Pengairan*, *11*(1), 49–57. https://doi.org/https://doi.org/10.21776/ub.pengairan.2020.011.01.07

Lawtanius, A., Sunik, & Suswati, A. C. S. P. (2023). Pemodelan Nilai Koefisien Debit Pada Pintu Air. *Jurnal Teknik Sipil*, *1*(2), 44–63. https://doi.org/https://ejournal.widyakarya.ac.id/index.php/Sipil/article/view/65

Mandasari, W. (2018). *Pengaruh Debit Aliran Terhadap Tinggi dan Panjang Loncatan Hidrolik di Hilir Radial Gate pada Saluran Terbuka* [Skripsi]. Universitas Pendidikan Indonesia.

Martini, R. A. S., Bahri, Z., & Miranda, A. T. (2020). Pengaruh Debit Aliran Terhadap Sedimentasi di Sungai Lematang Kabupaten Lahat. *BEARING: Jurnal Penelitian Dan Kajian Teknik Sipil*, *6*(3), 188–193. https://doi.org/https://doi.org/10.32502/jbearing.2841202063

Mori, K. (2003). *Hidrologi untuk Pengairan* (Ir. S. Sosrodarsono, Ed.; 9th ed.). PT Abadi.

Mulyani, N., & Agustinus, E. (2022). Pengaruh Profitabilitas dan Non-Debt Tax Shield Terhadap Struktur Modal Pada Perusahaan Manufaktur Yang Terdaftar di BEI Periode 2016-2020. *JIMF (Jurnal Ilmiah Manajemen Forkamma)*, *5*(2). https://doi.org/https://doi.org/10.32493/frkm.v5i2.19529

Nurhaliza, Putra, Y. S., & Kushadiwijayanto, A. A. (2022). Studi Numerik Pola Aliran di Sekitar Pintu Air Menggunakan Pendekatan Komputasi Dinamika Fluida. *PRISMA FISIKA*, *10*(3), 241–250.

Nurjanah, R. A. D. (2014). Analisis Tinggi dan Panjang Loncat Air pada Bangunan Ukur Berbentuk Setengah Lingkaran. *Jurnal Teknik Sipil Dan Lingkungan*, *2*(3), 578–582. https://doi.org/https://doi.org/10.14710/jis.%v.%i.%Y.90-101

Jurnal Teknik Sipil
Vol. 2, No. 2, Desember 2024
e-ISSN: 3021-8705, p-ISSN: 3021-8713, Hal. 43-68

Nurnawaty, Rakhim, Abd., Safitri, M., & Muhaemina. (2021). Loncatan Hidrolik pada Hilir Pintu Sorong dengan dan Tanpa Ambang Akibat Variasi Tinggi Bukaan Pintu. *Jurnal Teknik Hidro*, *14*(1), 1–7. https://doi.org/https://doi.org/10.26618/th.v14i1.6010

Putranto, B. A., Rozi, K., & Utomo, M. S. K. T. S. (2014). Kajian Fenomena Separasi Aliran pada Pipa Sudden Contraction Menggunakan Metode Eksperimen dan Numerik. *Jurnal Teknik Mesin S-1, Vol. 2, No. 2, Tahun 2014* , *2*(2). https://doi.org/https://ejournal3.undip.ac.id/index.php/jtm/article/view/5534

Rachman, A., Yochanan, E., Samanlangi, A. I., & Purnomo, H. (2024). *Metode Penelitian Kuantitatif, Kualitatif, dan R&D* (1st ed., Vol. 1). CV Saba Jaya Publisher.

Rahayu, A. (2019). *Studi Bangkitan Loncat Air dengan Model Pintu Sorong dalam Fenomena Loncat Air pada Saluran Terbuka* [Skripsi]. Universitas Islam Indonesia.

Raju, K. G. R. (1986). *Aliran Melalui Saluran Terbuka* (Y. P. Pangaribuan, Trans.). Erlangga.

Rauf, R., & M., S. N. (2019). Analisis Perubahan Dasar Saluran Terbuka Akibat Variasi Debit pada Tingkat Aliran Kritis dan Super Kritis. *Jurnal Teknik Hidro*, *12*(1). https://doi.org/https://journal.unismuh.ac.id/index.php/hidro/article/view/2464

Reece, K., Dorrell, R. M., & Straub, K. M. (2024). Influence of Flow Discharge and Minibasin Shape on the Flow Behavior and Depositional Mechanics of Ponded Turbidity Currents. *GSA Bulletin*.

Rustiati, N. B., & Suciani, N. (2021). Kalibrasi Koefisien Debit Model Bukaan Pintu Sorong Pada Saluran Terbuka (Uji Laboratorium). *Jurnal Teknik Sipil MACCA*, *6*(1). https://doi.org/https://new.jurnal.untad.ac.id/index.php/renstra/article/view/404

Sahitua, A., Ashad, H., & Mallombasi, A. (2023). Kajian Energi Spesifik Terhadap Loncatan Air Akibat Variasi Tinggi Bukaan Pintu Sorong. *Innovative: Journal Of Social Science Research*, *3*(3). https://doi.org/https://j-innovative.org/index.php/Innovative/article/view/3693

Suhudi, & Pandawa, A. (2022). Analisis Energi Spesifik pada Saluran Terbuka dengan Penambahan Variasi Panjang Ambang Lebar. *Jurnal Qua Teknika*, *12*(1). https://doi.org/https://doi.org/10.35457/quateknika.v12i01.2106

Sujatmoko, B., Silia, N., & Mudjiatko. (2021). Pengaruh Parameter Aliran Terhadap Letak Awal Loncat Air Melalui Pintu Sorong Tegak (Sluice Gate). *Jurnal Teknik Sipil SENDI*, *2*(2), 57–66. https://doi.org/https://jim.teknokrat.ac.id/index.php/tekniksipil/article/view/1261/456

Sunik. (2001). *Simulasi Operasi Pintu pada Saluran Sekunder dengan Uji Model Fisik* [Tesis]. Universitas Brawijaya.

Sunik, Yoedono, B. S., & Kambu, H. F. (2020). Analisis Karakteristik Loncatan Hidraulik Melalui Pintu Sorong Menggunakan Baffle Block. *UKWK Institutional Repository*. https://doi.org/http://repository.ukwk.ac.id/handle/123456789/752

Tregaskis, C., Johnson, C., Cui, X., & Gray, J. M. N. T. (2022). Subcritical and supercritical granular flow around an obstacle on a rough inclined plane. *Cambridge University Press*, *933*(A25). https://doi.org/https://doi.org/10.1017/jfm.2021.1074

Ulfiana, D. (2018). *Studi Efektivitas Pola Pemasangan Baffled Block pada Peredam Energi dalam Mereduksi Energi Aliran* [Tesis]. Institut Teknologi Sepuluh Nopember.

Wigati, R., Subekti, & Prihatini, K. T. (2012). Analisis Pengaruh Kemiringan Dasar Saluran Terhadap Distribusi Kecepatan dan Debit Aliran pada Variasi Ambang Lebar. *Fondasi: Jurnal Teknik Sipil*, *1*(1). https://doi.org/https://dx.doi.org/10.36055/jft.v1i1.1998

Wulandari, L. K. (2020). *Penggunaan Bangunan bagi Ambang Lebar dengan Penambahan Pipa Melalui Uji Model Fisik* (1st ed.). Fream Litera Buana.

Zhang, W., Jia, X., & Wang, Y. (2024). Experimental Investigation of Hydraulic Characteristics for Open Channel Gates. *Water*, *16*(24).