

Analysis of the Hydraulic Jump Characteristics in a Stilling Basin to Avoid Dam Failure

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Abstract

Flooding may occur due to dam failure at downstream of the spillway. Stilling basin of the spillway plays an important role in reducing turbulence generated by hydraulic jumps. It can avoid flooding and local scouring as well. Therefore, this study aims to analyze hydraulic jump characteristics experimentally. Two series of structures namely initial (S_0) and final (S_1) were tested. The S_0 model is the United States Bureau of Reclamation (USBR) III type, while S_1 is set the adverse slope of 1:2 at the downstream and lowering the bottom elevation of the channel by 4 m. Measurements were taken on the length of hydraulic jumps, water level and high speed before-after hydraulic jumps at various return periods discharges (Q) of 2, 5, 10, 25, 50, 100 and 1000 years. It is found that at S_1 , the jump is submerged, causing the relative hydraulic jump height $(y_2 - y_1)/y_1$ to be 40-90% higher than S_0 . Furthermore, the compression of more than 50% of the hydraulic jump length ratio (L_j/y_2) was indicated at S_1 . In addition, the energy dissipation efficiency (ϵ_t) obtained for each discharge at S_1 ranged from 58-84% (good absorption). On the other hand, at S_0 , the ϵ_t produced was around 70-89% (Q_2 - Q_{50}) and <45% (Q_{100} and Q_{1000}). It can be concluded that the modification of USBR III can reduce the vulnerability of the bottom and downstream parts of the stilling basin. It is expected that the potential flood disaster due to the stilling basin failure of the dam can be eliminated. These results may be used as recommendation to the disaster management strategies, such as improving dam safety guidelines, informing emergency response plans, or guiding infrastructure design to withstand hydraulic forces.

Keywords: energy dissipation; hydraulic jump; physical model; stilling basin; USBR III.

Introduction

Part of the most important complementary structure of the dam is the stilling basin. Damage to this structure such as erosion can cause building failure and damage along the river downstream of the dam. Hence, the selection of a safe design is compulsory.

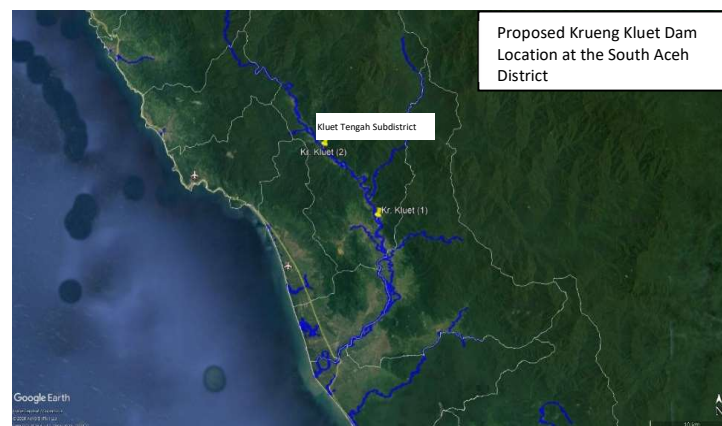


Figure 1. Location of the Proposed Krueng Kluet Dam Construction



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Design of the Krueng Kluet Dam is one of the alternatives efforts for optimizing water resources in Aceh Province. This proposed dam is located at the coordinates $03^{\circ} 13' 7.71'' - 03^{\circ} 17' 40.76''$ NL and $97^{\circ} 23' 1.60'' - 97^{\circ} 19' 29.22''$ EL. Administratively, the proposed study area will be constructed in the Gampong Lawe Melang and Gampong Sarah Baru, Manggamat City, Central Kluet District, South Aceh District, Aceh Province, as shown in Figure 1.

Before the dam constructed, it has to be designed thoroughly. Design alternatives that are usually carried out are analytical studies, numerical and physical models of the dam and its supporting structures in accordance with field condition. A stilling basin is one of the main structures that designed as an energy absorber due to flood flow over the spillway. This building utilizes the formation of hydraulic jumps in its energy dissipation principle. The energy absorber planned is a stilling basin utilizing a hydraulic jump on the absorption principle. Without proper planning, the jumps due to the change in supercritical to subcritical flow can create eddies that can erode the bottom and downstream of the dam (Emiroglu et al., 2011; Kitamura et al., 2017; Mesbahi et al., 2017; Zulfan, 2017). It can occur if large energy from upstream is not dissipated properly, leading to erosion on the banks and bottom of the river downstream of the dam. Many dams worldwide deal with hydraulic jumps and regulation of energy dissipation (Arief, 2018; Yadav et al., 2017).

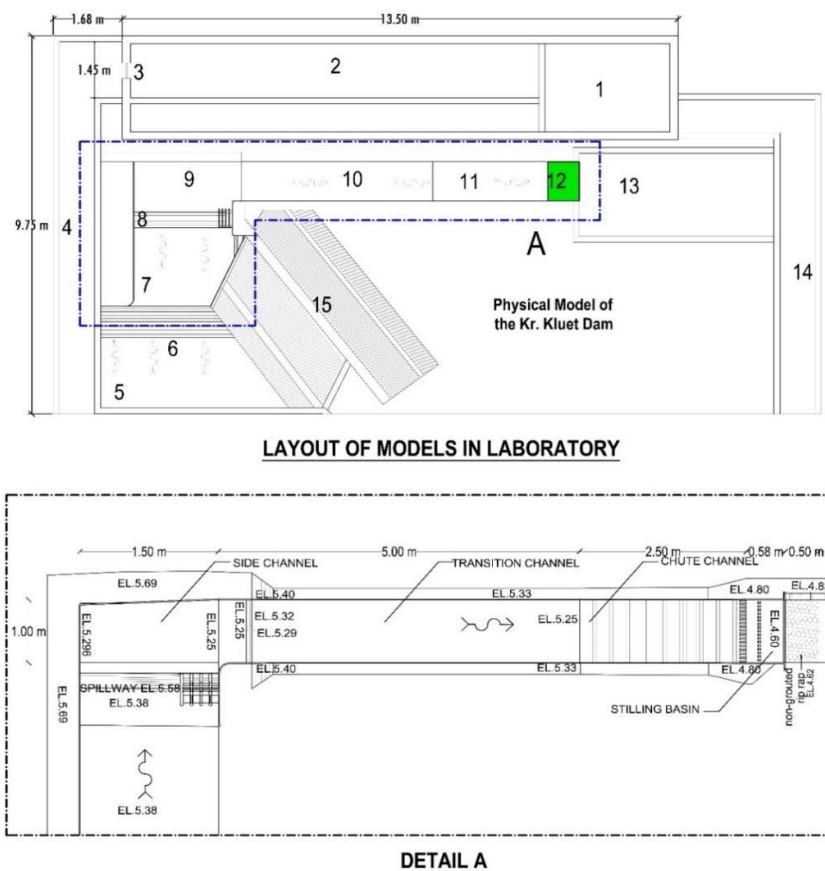


Figure 2. Layout of model and instrument positions

In which: 1) Lower Reservoir; 2) Upper Reservoir; 3) Rechbox; 4) Water Transmission Channel; 5) Sedation Pool; 6) Stagnation Pool; 7) Apron (Steering Channel); 8) Side Spillway; 9) Side Channel; 10) Transition Channel; 11) Chute Channel; 12) Stilling Basin and Riprap; 13) River Bed; 14) Drain Channel; 15) Bodies of Dam.

The type of energy dissipation is selected based on topographical conditions, as well as the working system such as hydraulic jump length, Froude numbers, and the energy dissipation efficiency. Various types of stilling basins have been studied by hydraulic experts, one of which is USBR TYPE III (Public Work Department, 1986). In this study, the type of USBR III stilling basin has been selected as part of the Krueng Kluet Dam main structures (Aceh Province Irrigation Service, 2017). However, this type of structure also does not guarantee stability against the effects of erosion and sedimentation for the various design flood discharge considered. Therefore, the characteristics of the hydraulic jumps, including the height and length of the jumps and the efficiency of energy dissipation that occurred in the stilling basin, should be identified using a physical model test. It aims to predict the phenomena that will occur in the structure and the surrounding environment based on the prototype to avoid the risk of failure and damage to construction from planning (Bari, 1993). This study aims to examine the characteristics of the hydraulic jumps generated in the stilling basin according to the plan, using the USBR III type of stilling basin as the initial series (S_0). Subsequently, the final series (S_1) was modified to obtain a safer stilling basin design. Stilling basin modifications have been done by some researchers previously, as it was called convergence wall stilling basin (Babaali et al., 2015), sluice stilling basin (Wang et al., 2016), and end adverse slope (Babaali et al., 2019, Eghlidi et al., 2020, Pourabdollah et al., 2022, Bantacut et al., 2022). This study assessed the characteristics of the hydraulics jumps to the modified USBR III stilling basin. The characteristics and patterns of the hydraulic jumps described are expected to be a reference in providing solutions for optimizing dam planning.

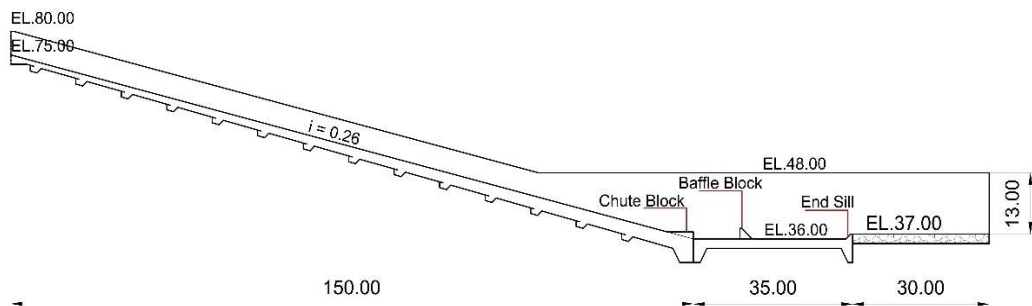


Figure 3. Sideways view design of S_0 stilling basin



Figure 4. S_0 stilling basin view on the physical model

Methods

Layout Model Test

The construction of the physical model of the Kr. Kluet Dam, with an undistorted scale of 1:60, was done at the River and Coast Laboratory of the Civil Engineering Department, Syiah Kuala University, Banda Aceh. The water circulation was an open cycle with a pumping system. Water discharge flow starts from the lower to the upper reservoir and flows through the outflow meter (rechbox). Rechbox is a square-shaped spillway with a thin sill (Triatmodjo, 1996). The outflow discharge was channelled to the model of the side spill system downstream of the dam, and measurements were done to collect primary data on the stilling basin. The layout of the test model and the position of instruments used to support research is shown in Figure 2. The physical model of the stilling basin was built based on the initial design as S_0 by Aceh Province Irrigation Service, 2017. In advance, stilling basin model of S_0 views are shown in the Figure 3 and Figure 4.

The modifications to S_1 are by lowering the elevation of the stilling basin by 4.0m, adding a length of 3.5 m to the stilling pool, and 0.5m of rip-rap from the design S_0 . In addition, at the end of the stilling basin, an end sill with an adverse slope of 5.0m and a slope ratio of 1:2 was added. The channel wall of the stilling basin was also elevated by 0.3m to prevent water runoff. Stilling basin model of S_1 views are illustrated in Figure 5 and Figure 6

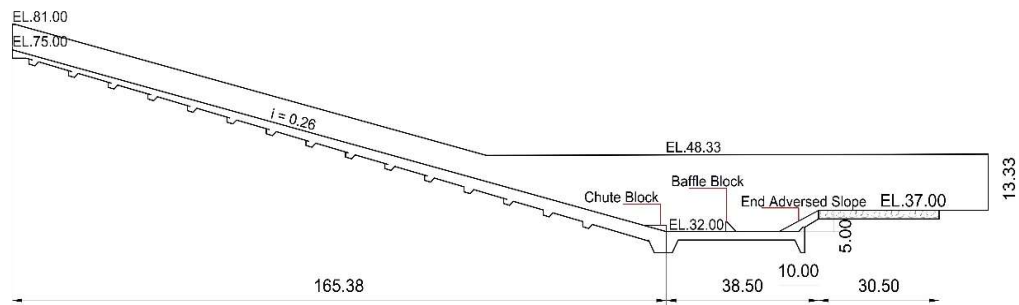


Figure 5. Sideways view design of S_1 stilling basin



Figure 6. S_1 stilling basin view on model

The variation of overflow discharge was equal to the return period discharge of 2, 5, 10, 25, 50, 100, and 1000 years (

Series	Design Discharge (Q) m ³ /s
Initial Series (S ₀)	Q ₂ = 514.7
Final Series (S ₁)	Q ₅ = 672.2
	Q ₁₀ = 807.5
	Q ₂₅ = 1018.5
	Q ₅₀ = 1210.8
	Q ₁₀₀ = 1495.7

). The testing takes place in an initial series (S₀) and then followed through with a final series (S₁).

Table 1. Testing Scenario

Series	Design Discharge (Q) m ³ /s
Initial Series (S ₀)	Q ₂ = 514.7
Final Series (S ₁)	Q ₅ = 672.2
	Q ₁₀ = 807.5
	Q ₂₅ = 1018.5
	Q ₅₀ = 1210.8
	Q ₁₀₀ = 1495.7

Primary data collection for hydraulic jump analysis includes the measurement of y_1 (water level before the jump), y_2 (water level after the jump), high speed upstream of the jump (h_{v1}), high speed downstream of the jump (h_{v2}), and the length of the hydraulic jump (L_j) on the left, middle and right side of the channel. Measurement of y_1 was done before the water level rise due to the hydraulic jump, while y_2 is measured when the water level after the hydraulic jump returns to stable, indicating that the hydraulic jump is no longer formed. The point gauge measured the water level, and the pitot tube measured the high speed. In addition, the initial and final positions of the jumps were recorded to determine L_j . Then water level measurements were recorded in some sections to illustrate the hydraulic jump on every variation scenario.

Data analysis

Parameters that influence the analysis of characteristics of hydraulic jumps are as follows:

- water level before (y_1) and after the jump (y_2) are obtained from measurements,
- the velocity before (v_1) and after the jump (v_2) are calculated using the following Eq. (1) (Triatmodjo, 1996)

$$v_i = \sqrt{2gh_{vi}} \quad (1)'$$

with, v_i = the velocity on the model (m/s); h_{vi} = high speed on the pitot tube (m); and g = gravity (m/s²). The illustrations of the y_1 , y_2 , v_1 , and v_2 positions are shown in Figure .

- hydraulic jump length (L_j) is obtained from measurements;
- Froude number (F_r) is calculated using the following Eq. (2) (Triatmodjo, 1996)

$$F_r = \frac{v}{\sqrt{gy}} \quad (2)'$$

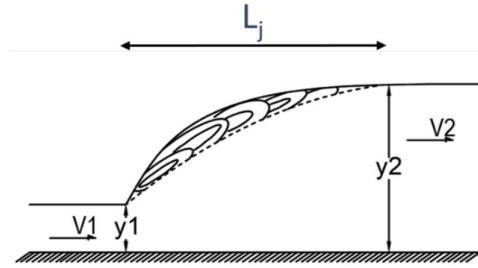


Figure 7. Illustration of the hydraulic jump parameters considered

- Dissipation efficiency (ϵ_t) for the submerged jump is calculated by the difference between the energy heights before (E_1) and after the jump (E_2) and normalized to E_1 , as follows ((Padulano et al., 2017)).

$$\text{Specific Energy, } E_i = y_i + \frac{V_i^2}{2g} \quad (3)'$$

$$\text{Dissipation efficiency, } \epsilon_t = \frac{E_1 - E_2}{E_1} \quad (4)'$$

Model Calibration

Calibration is done by calculating the magnitude of the relative error (taken 10%) that occurs between the water level above the spillway designed and measured. Calibrated data model (Table 1) shows a percentage of errors relatively below 10%, whereas an average fault is 5.1%. This indicates that a model is already verifiable and that a physical model test is feasible.

Table 1. Model Calibration Results

Description	Q_{designed} prototype (m ³ /s)	H_{designed} on Spillway Model (cm)	H_{measured} on Spillway Model (cm)	Relative error (%)
Q1000	1702.3	7.0	6.4	8.9
Q100	1495.7	6.4	5.9	8.4
Q50	1210.8	5.6	5.2	7.0
Q25	1018.5	5.0	4.8	3.7
Q10	807.5	4.3	4.1	3.9
Q5	672.2	3.8	3.7	2.0
Q2	514.7	3.2	3.1	1.8
Average relative error (%)				5.1

Results and Discussion

Visualization of each discharge's hydraulic jump for each series is described and documented as in the picture. Based on visualization can be identified the hydraulic jump formations and positions generated by every discharge on each model's series (Figure 8-Figure 16). Visualizing the water surface profile is the first step to conducting meaningful analysis and determining jump positions (Luo et al., 2021). The red line in the picture shows the length of hydraulic jump formations (L_j) on the left, center, and right channel. In the S_0 stilling basin, a stream is sweep-

out the basin, as seen by a thin flow on the stilling basin apron. This thin flow has been partly broken by the chute block on the upstream basin. Some others hit the baffle block and creating curved shards of water and pounding the bottom of the channel. Whereas the S_1 model creates the submerged jump formation. Next on series 0, the jumps that form in the basin are only at the flow of period discharge Q_2 , whereas Q_5 , Q_{10} , Q_{25} end at riprap and downstream for Q_{50} , Q_{100} , Q_{1000} . In addition to the S_1 model, the jump had ended before entering the rip-rap for Q_2 , 5, 10, 25, 50 and in the riprap area for the Q_{100} -1000 discharge.

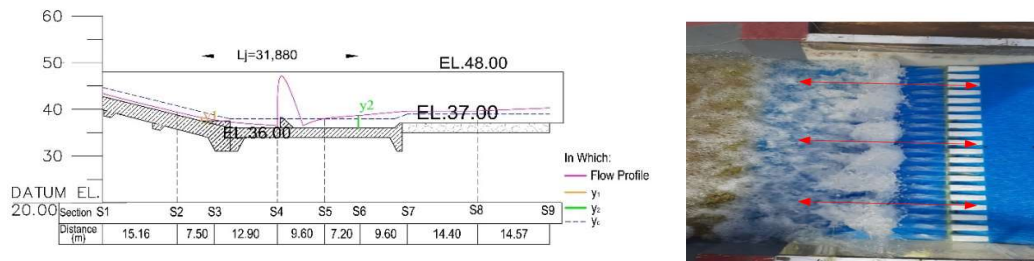


Figure 8. Visualization of S_0 model hydraulic jump on the Q_2 discharge

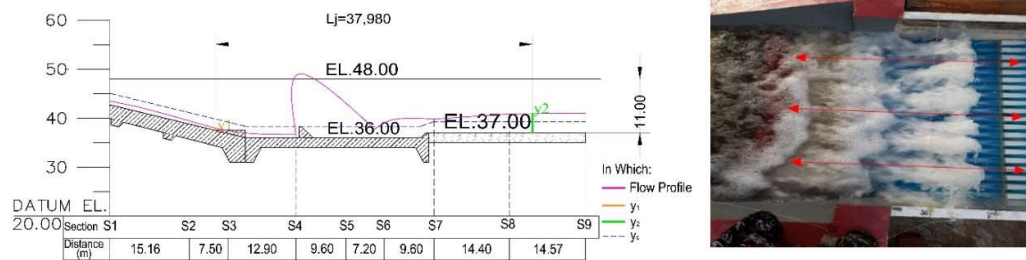


Figure 9. Visualization of S_0 model hydraulic jump on the Q_5 discharge

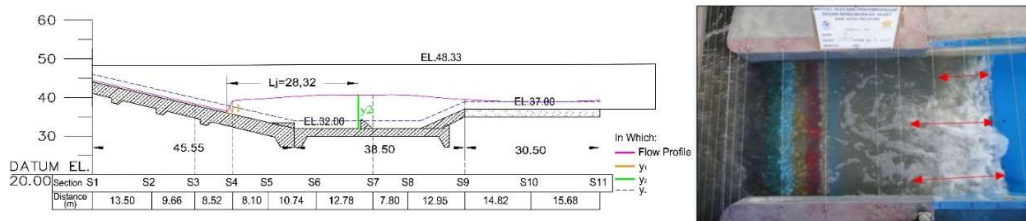


Figure 10. Visualization of S_1 model hydraulic jump on the Q_2 discharge

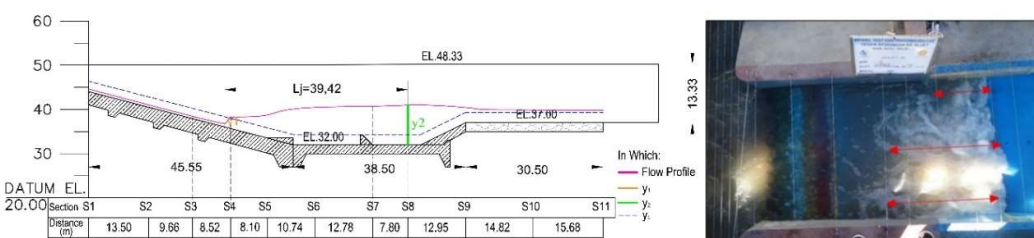


Figure 11. Visualization of S_1 model hydraulic jump on the Q5 discharge

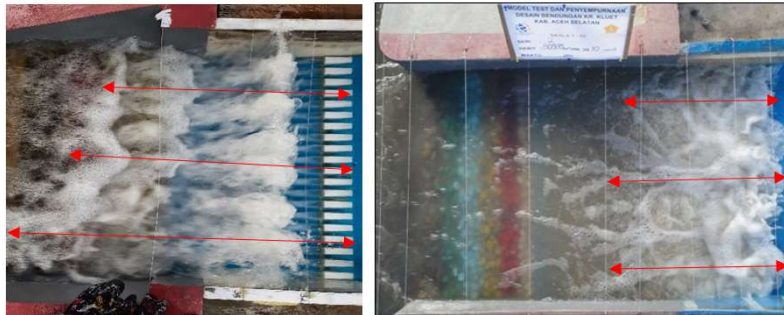


Figure12. Visualization of S_0 (left) and S_1 model (right) hydraulic jump on the Q10 discharge

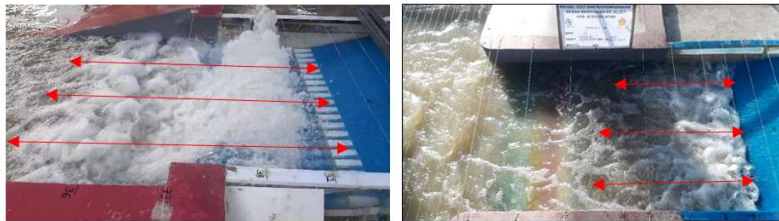


Figure 13. Visualization of S_0 (left) and S_1 model (right) hydraulic jump on the Q25 discharge

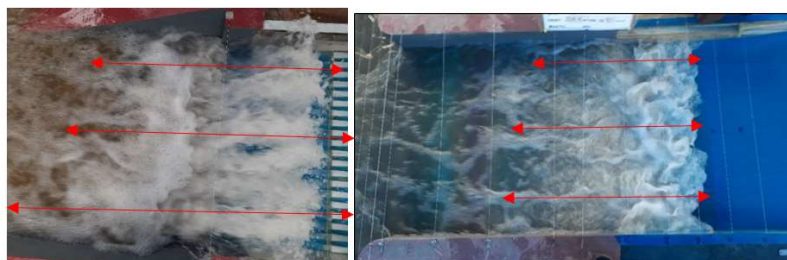


Figure 14. Visualization of S_0 (left) and S_1 model (right) hydraulic jump on the Q50 discharge



Figure 15. Visualization of S_0 (left) and S_1 model (right) hydraulic jump on the Q100 discharge

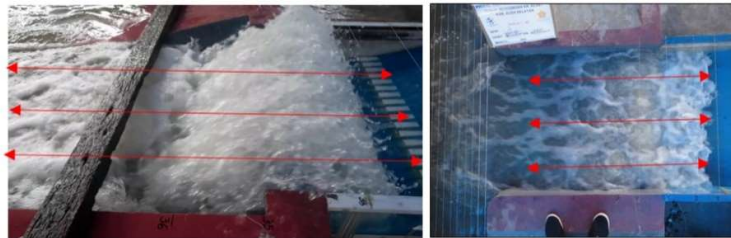


Figure 16. Visualization of S_0 (left) and S_1 model (right) hydraulic jump on the Q1000 discharge

Table 2. The calculation of the hydraulic jump parameter of the S_0 and S_1 model

Initial series (S_0)						
Description	Q (m ³ /s) (m ³ /d)	q (m ³ /s/m)	Fr ₁	(y ₂ -y ₁)/y ₁	L _j /y ₂	ε _t
Q2	514.7	5.719	7.157	2.488	10.627	0.871
Q5	672.2	7.469	8.993	3.643	14.554	0.797
Q10	807.5	8.972	7.226	2.157	11.820	0.782
Q25	1018.5	11.317	9.768	7.185	10.294	0.786
Q50	1210.8	13.453	7.831	5.628	8.996	0.703
Q100	1495.7	16.619	4.660	3.859	7.573	0.432
Q1000	1702.3	18.914	5.468	0.911	51.934	0.243
Final series (S_1)						
Description	Q (m ³ /s) (m ³ /d)	q (m ³ /d/m)	Fr ₁	(y ₂ -y ₁)/y ₁	L _j /y ₂	ε _t
Q2	514.7	5.719	8.949	16.458	3.134	0.536
Q5	672.2	7.469	8.278	10.100	4.146	0.662
Q10	807.5	8.972	6.345	4.551	5.044	0.723
Q25	1018.5	11.317	5.655	3.295	5.233	0.724

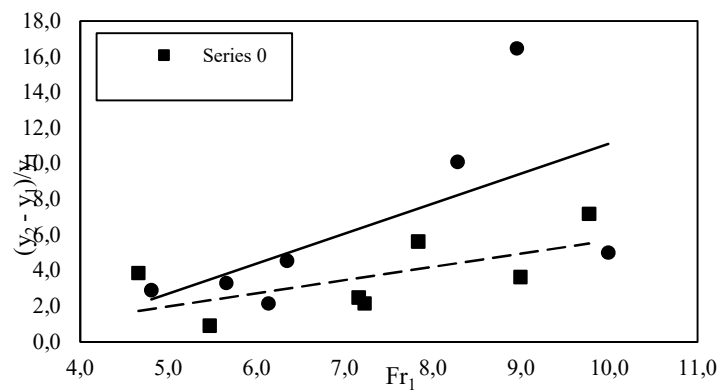
Q50	1210.8	13.453	4.805	2.901	8.704	0.631
Q100	1495.7	16.619	6.132	2.159	13.218	0.800
Q1000	1702.3	18.914	9.986	5.000	14.626	0.842

The analysis of the influential variables (

Table 2) was done on the S_0 model, followed by the S_1 . Before analysis, the entire model parameters were disassembled back onto the scale of the prototype. The impact of Froude Numbers before the jump (Fr_1) and flow discharges are discussed on non-dimensional parameters of hydraulic jumps as explained in each of the following subchapters.

Characteristics of hydraulic jump height

Figure 17 describes the characteristic pattern of jump height. The graph shows the trend of increasing relative jump height $((y_2 - y_1)/y_1)$ along with the increasing Froude number (Fr_1), reaching the upstream of hydraulic jump in both series of stilling basin models. This hydraulic jump characteristic is similar to the pattern shown by Jalil et



al., 2015. At $Fr_1 = 5$ and 9 , the $(y_2 - y_1)/y_1$ for S_0 is 2 and 5 , meanwhile it is 2.8 and 9.5 for S_1 model. This finding shows that the S_1 stilling basin model creates a jump 40-90% higher than that of the S_0 model.

Figure 17. The relationship between the Froude number before the jump (Fr_1) and the relative height of the hydraulic jump resulted $((y_2 - y_1)/y_1)$

This can happen because the hydraulic jump formed by the S_1 stilling basin is more stable than S_0 , as shown in Figure 18. In S_0 stilling basin, there is a sweep-out basin flow, as seen by a thin stream on the stilling basin apron. This flow formation arises because the y_2 obtained is greater than the Tail Water Level ($TWL < y_2$) (Chow, 1988 dan Ulfiana, 2018). This flow condition causes an unstable hydraulic jump (pulsing wave). Sweepout or a hydraulic jump that occurs at the end of the stilling basin can cause excessive erosion and impair the structure as happened within the El-Guapo Dam, Venezuela (Environment Agency, 2022; USACE, 2019). The El Guapo Dam collapse destroyed settlements and plantations causing heavy losses. Unlike the case with the stilling basin S_1 , the decrease in the stilling basin and the addition of the adverse slope can increase the TWL so that $TWL > y_2$ and forms a submerged jump (Siuta, 2018). The elevation of water level due to backwater generated by this formation leads to a more stable hydraulic jump with a more significant increase in the water depth of the downstream jump.

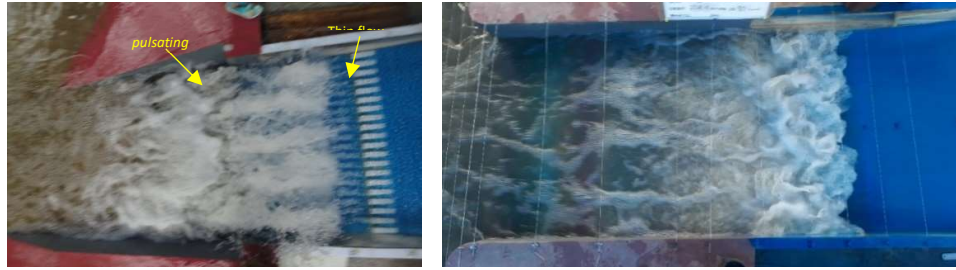


Figure 18. Typical example of the hydraulic jumps occurred in the stilling basin: S_0 (left) and S_1 (right) at Q50

Characteristics of hydraulic jump length

Figure 19 shows a linear relationship between the two parameters; the greater the unit discharge (q) flowing into the stilling basin, the higher the jump length ratio (L_j/y_2) in each S_0 and S_1 , as stated by Bejestan et al., 2017; Deshpande et al., 2015; dan Gandhi & Yadav, 2013. However, the average L_j/y_2 ratio for each q in S_1 is smaller than S_0 at the discharge of $5,719\text{m}^3/\text{d}/\text{m}$, $7,469\text{m}^3/\text{d}/\text{m}$, $8,972\text{m}^3/\text{d}/\text{m}$, $11,317\text{m}^3/\text{d}/\text{m}$, $13,453\text{m}^3/\text{d}/\text{m}$ and $18,914\text{m}^3/\text{d}/\text{m}$. If we look at the trendline graph, $q = 6\text{m}^3/\text{d}/\text{m}$ increase L_j every 1 m y_2 along 5.97m and 2.41m for S_0 and S_1 series, respectively. At $q = 18\text{m}^3/\text{d}/\text{m}$, $L_j = 27.92\text{m}$ (S_0) and 13.46m (S_1) for every 1 m y_2 .

This condition indicates compression of more than 50% of the hydraulic jump length in S_1 , as studied by Aini et al., 2022. The above analysis agrees with Babaali et al., 2019 stating that the end adverse slope can compress the hydraulic jump and stabilize the water jump to stay in the channel. Abbas et al., 2018 also mentioned that, the baffle block type in Series 1, is capable to reduce flow scattering through flow circulation and rotation vertically for the submerged hydraulic jump case. Hence, it can be concluded that the modified stilling basin investigated has less prone to damage downstream of the dam.

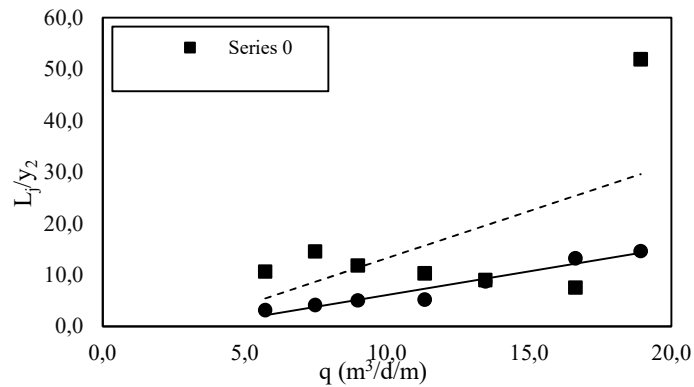


Figure 19. The relationship of unit discharge (q) and relative length of the hydraulic jump (L_j/y_2)

Characteristics of energy dissipation efficiency

Figure 20 shows that there was no significant impact of Fr_1 on energy dissipation efficiency (ϵ_t) in the two stilling basin series unlike that obtained by Gupta et al., 2013. However, the efficiency at each discharge by the S_1 stilling basin is between 54-84%, indicating good absorption of 45-70% (Chow, 1988). In comparison, the absorption efficiency by S_0 stilling basin ranges from 70-89% (good absorption) at Q2-Q50 discharges and is below 45% at Q100 and Q1000 discharges. This condition indicates that S_0 stilling basin is not efficient in reducing energy at the maximum Fr_1 . Energy dissipators, as part of the main spillway, must be designed to withstand extreme flows to prevent structural failure. One of the failure cases that occurred was the Oroville dam, California which was triggered by extreme flows eroding and perforating the main spillway (Mallakpour et al., 2019; Vahedifard et al., 2017).

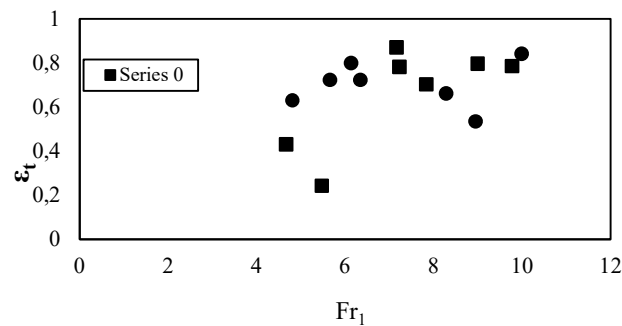


Figure 20. The relationship of Froude Number before the jump (Fr_1) and the energy dissipation efficiency (ϵ_t)

Although the efficiency of the S_0 stilling basin tends to be greater than S_1 , the hydraulic jump at S_0 is more susceptible to damage to the bottom of the stilling basin channel and the baffle block. The thin flow generated and a strong bump on the baffle block can lead to cavitation. This thin flow phenomenon is highly avoided in a plan as proposed by Basco 1969 dan Chow, 1988. Meanwhile, increasing the absorber of the baffle block by increasing the depth of the TWL can reduce the cavitation tendency in the structure while maintaining its effectiveness factor (FEMA, 2010).



Figure 21. The rip-rap of the S_0 model condition before and after flowing 100 years discharge (Q100)

In addition, the S_0 stilling pool does not provide security downstream of the structure. The observation results after the flow of each discharge in Figure 21 show a shift in the rip-rap grains at Q10, 25, 50, 100, and 1000 at S_0 . It indicates that the rip-rap could not reduce the residual energy generated in the absorption process by the stilling basin, which in turn endangers the riverbed downstream of the stilling basin of the spillway. While in S_1 , the position of the rip-rap grains does not move (Figure 22), indicating that the energy channelled downstream of the dam has been well absorbed.



Figure 21. The rip-rap of the S_1 model condition before and after flowing 100 years discharge (Q100)

Conclusions

This study evaluates the hydraulic jump in S_0 and S_1 stilling basins. The analysis shows that the S_1 model is more optimal than the S_0 . The hydraulic jump in the S_1 stilling basin is considered more stable, with the relative jump height $(y_2 - y_1)/y_1$ being 40-90% greater than S_0 . In addition, the hydraulic jump length ratio (L_j/y_2) of S_1 has been reduced by an average of more than 50% compared to S_0 . This reduction greatly affects the ability of the dam to overcome potential erosion disaster downstream of the structures. The absorption efficiency of S_1 is around 54-84% for each variation of discharge. While the S_0 model is inefficient in absorbing energy at maximum discharge (Q100 and Q1000). Even though the efficiency of S_1 is slightly smaller than S_0 , the hydraulic jump that occurred at S_0 is more susceptible to damage to the bottom of the stilling basin channel and the energy dissipation of the baffle block. In addition, the shift of the rip-rap grain of the S_0 stilling pool at Q10, 25, 50, 100, and 1000 indicates that the rip-rap can not reduce the residual energy generated in the absorption process. This condition can endanger the river downstream of the stilling basin of the spillway structure. This physical model test is very useful in the optimization method of planning a dam structure. Furthermore, the submerged jump factor against the baffle block at each discharge considered has been analyzed to assess the effectiveness of the building in dissipating energy. Therefore, the assessment of the hydraulic jump characteristics shows that modifying the USBR III stilling basin design can stabilize the hydraulic jump formed and dissipate energy better. Hence this modified type of stilling basin can be promoted as an alternative solution to eliminating the adverse impact of downstream dam failure. Hence, from these findings, it can be applied in disaster management strategies, such as improving Krueng Kluet dam safety guidelines, informing emergency response plans, or guiding infrastructure design to withstand hydraulic forces.

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