Analysis on the Influence of Hydraulic Behavior in Stilling Basin towards the Scour Depth at the Downstream Spillway of Krueng Kluet Dam

Azmeri
Department of Civil Engineering, Universitas Syiah Kuala, Banda Aceh, Indonesia
azmeri@usk.ac.id (corresponding author)

Raisha Athqa
Department of Civil Engineering, Universitas Syiah Kuala, Banda Aceh, Indonesia
raishaathqa2000@gmail.com

Alfiansyah Yulianur
Department of Civil Engineering, Universitas Syiah Kuala, Banda Aceh, Indonesia
fian_7anur@yahoo.com

Received: 7 March 2025 | Revised: 29 March 2025 and 17 April 2025 | Accepted: 19 April 2025

ABSTRACT

Changing the water flow leads to significant fluctuations in the water levels of the spillway, resulting in substantial energy changes as the water passes through and risking its stability. Consequently, spillway design must include the design of a stilling basin as an energy reducer to decrease the effects of scour. The primary objective of this research is to explain the influence of the hydraulic behavior in the stilling basin on the depth of scour downstream of the spillway structure. The study was conducted using the replica of the Krueng Kluet Dam spillway at the Dr. Masimin Hydrotechnic Physical Model Laboratory within the Faculty of Engineering, Syiah Kuala University, Indonesia. A dimensional analysis design methodology was deployed to examine the correlation between hydraulic parameters, including Froude number, hydraulic jump characteristics, energy dissipation efficiency, and scour depth. The research results show a direct relationship between discharge and both Froude number and hydraulic jump magnitude, resulting in corresponding scour depth. In addition, a higher discharge corresponds to a reduced energy dissipation efficiency, which contributes to increased scour depth. An anomaly observed in the efficiency-scour depth relationship is attributed to the generation of thin flow and its significant impact on the baffle block.

Keywords-Froude number; hydraulic jump; energy dissipation efficiency; scour depth; dimensional analysis design

I. INTRODUCTION

A dam is a hydraulic structure with a spillway to protect its crest from overtopping during flood events [1]. The energy dissipation capacity of a spillway plays a crucial role in mitigating the risk of flow erosion downstream of hydraulic structures. In general, supercritical flow in the stilling basin is followed by a hydraulic jump, which is expected to transition to a subcritical state towards the end of the structure [2]. If this transition fails, there is a risk of scour due to the sustained high flow velocity. Therefore, it is important that this area be equipped with an energy absorber to prevent the scouring of the downstream riverbed. The significant depth of scour poses a serious threat to the stability of the foundation, increasing the potential for damage or failure of the spillway structure, as exemplified by the incident at Oroville Dam in Northern California [3]. Given the severity of downstream scour, numerous researchers have studied the phenomenon with the goal of identifying the influencing variables and developing effective solutions to address the problem [4]. Any change in river morphology upstream of a dam can affect downstream flow due to hydraulic jumps. The change in flow characteristics is closely related to river cross-section, Froude number (F_r), hydraulic jumps, and energy dissipation efficiency [5, 6]. These parameters are crucial for the adaptation of river morphology and the construction of energy-absorbing structures. In order to address the potential for the scour of the downstream riverbed, careful design for energy dissipation is important, along with specific conditions and flow behavior [7]. Hydraulic behavior, characterized by the magnitude of the Froude number and the length of the hydraulic jump within the energy reducer, is carefully adjusted to achieve the safest design against downstream scouring [8]. The primary objective of this research was to explain the influence of hydraulic behavior in stilling basins on the depth of scour downstream of the spillway structure. A solution to this challenge involves examining the correlation between hydraulic parameters in the stilling basin and the depth of scour through a dimensional analysis design along with an in-depth study of the flow hydraulic behavior [9]. Based on studies aimed at elucidating the influence of Froude number on scour depth through dimensional analysis [1, 4, 9-11], the complexity of manipulating laboratory experimental data is effectively addressed by employing dimensional analysis techniques and organizing non-dimensional variables into groups [9]. Dimensional analysis was utilized to determine the relevance of multiple equations to yield a new equation. The observational results indicate a general trend in which increased scour correlates with an increase in Froude number. At the same time, authors in [12] observed the hydraulic jump within a physical model and showed that the relative length of the hydraulic jump (L_j/y_1) tends to increase with an increasing Froude number before the jump (F_{r1}), as a discharge parameter. Authors in [10, 13, 14] highlighted the effect of energy dissipation efficiency on scour depth. Their results suggest a positive correlation between discharge magnitude and energy dissipation efficiency, with a concomitant decrease in scour depth.

II. METHODOLOGY

A. Study Area

The objective of this study is to develop a downstream spillway replica of the Krueng Kluet Dam, which was constructed at the Hydrotechnical River and Coast Laboratory within the Civil Engineering Department at the Faculty of Engineering, Syiah Kuala University, Indonesia. The dam model was constructed at a non-distorting scale of 1:60 [3]. Figure 1 shows the specific observation areas. The research was carried out on a modification series, which is a series of changes to the original design of the physical model of the Krueng Kluet Dam [3]:

- The height of the stilling basin was reduced to a depth of 4 m to achieve a higher Thermal Work Limit (TWL).
- The length of the stilling basin was increased by 3.5 m and the riprap was increased by 0.5 m from the original design to increase energy dissipation.
- An additional height of the end was still in the form of an adverse slope as high as 5 m and a slope ratio of 1:2. This structure was designed to stabilize the hydraulic jump so that it remained within the stilling basin.
- Raising the walls of the stilling basin to a height of 0.3 m to prevent water runoff.

The Krueng Kluet Dam has a side channel spillway model, which has the potential to obstruct the flow, and the inner wall that bends will move away from the flow. This spillway model has a side channel with a trapezoidal/rectangular cross section located at the end of the regulating channel. The energy dissipation process results in the channel receiving hydrodynamic forces in the form of flow shock and vibration forces. Therefore, a spillway model with this geometric complexity and high hazard potential must be studied through implementing a detailed hydraulic-physical model [15]. The initial design is modified because it does not provide downstream safety [16, 17]. The optimal design obtained in the results is the novelty of this research. The observation results, evidenced in Figure 2, after each discharge, show a shift of riprap grains at Q10, Q25, Q50, Q100, and Q1000. This indicates that the riprap cannot reduce the energy, so it can endanger the riverbed downstream of the stilling basin of the spillway.

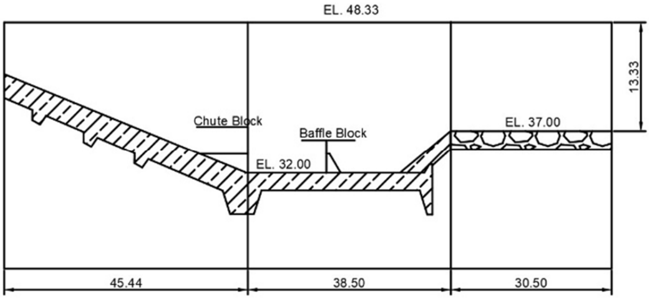

Fig. 1. The downstream spillway replica of the Krueng Kluet Dam.

Fig. 2. Riprap conditions of the initial design stilling basin before and after the discharge for the 100 year return period (Q_{100}).

B. Data Collection

The retrieval of velocity head data at the upstream jump (h_{v1}) and downstream jump (h_{v2}) can be performed once the values of y_1 and y_2 are determined. The measuring device employed was a pitot tube, depicted in Figure 3, positioned at the desired water level [18]. The experimental data were analyzed by measuring the height difference after the water in the pitot tube had been stabilized, which indicated the attainment of maximum velocity head. Water level data were collected through the gradual lowering of the iron tip of the point gauge until it reached the water level below it. The numerical value displayed on the tool is indicative of the water level elevation at a specific point [18-20]. Subsequently, the elevation at the base of the channel is determined by placing the tip of the iron point gauge at the designated point and meticulously recording the corresponding figures. Figure 4 portrays the areas of the physical models that require remediation.

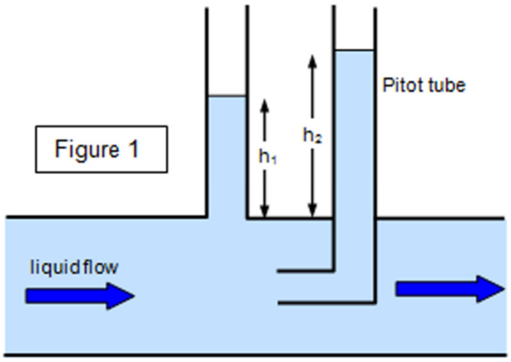

Fig. 3. Measurements on pitot tube.

Fig. 4. Scouring area.

C. *Dimensional Analysis Design*

The resolution of hydraulic problems can be achieved through the application of a dimensional analysis approach, a mathematical technique that provides fundamental insights into observed phenomena. However, studies examining energy dissipation downstream of spillways have been lacking quantitative rigor. This method posits that these phenomena can be described by dimensional equations comprising variables that influence them [21]. The Langhaar method was selected due to its efficacy in organizing parameters and generating dimensionless numbers, which can be used to derive additional dimensionless quantities [22]. A dimensional analysis was conducted to evaluate the applicability of various equations in generating a new one. A number of flow parameters have been proposed by previous researchers for inclusion in the equation for the maximum scour depth [21, 22]. The objective of this study is to ascertain the scour depth ratio (ds) influenced by the Froude number (Fr), hydraulic jump length (Lj), and energy dissipation efficiency under submerged flow conditions. The parameters, shown in Table I, are:

- Independent variable: depth of water flow in upstream jump (y_1)
- Dependent variables: scour depth (d_s), initial velocity of the jump (v_1), length of hydraulic jump (L_j)
- Other variables: gravity acceleration (g), energy dissipation efficiency (ε_t)

TABLE I. DIMENSIONAL ANALYSIS PARAMETER

Parameter	d_s	L_j	F_{r1}	ε_t	y_1
M	0	0	0	0	0
L	1	1	0	0	1
T	0	0	0	0	0
Notation	k_1	k_2	k_3	k_4	k_5

Subsequently, the parameters were subjected to differentiation to generate a dimensional analysis. An empirical equation was derived to describe the fundamental configuration of the phenomenon under examination. The present study implemented the Langhaar matrix method in its dimensional analysis. In this system of measurement, *M* is the dimensional unit of mass (kg), *L* is the dimensional unit of length (m), and *T* is the dimensional unit of time (s). The fundamental quantity in matrix notation is $M = 1$, representing the length, and there are $m = 5$ variables, resulting in the formation of $m - M = 5 - 1 = 4$ dimensionless numbers. The calculation is:

$$k_1 + k_2 + k_5 = 0 \rightarrow L \qquad (1)$$

$$k_5 = - k_1 - k_2 \qquad (2)$$

Subsequently, the values in this equation were transferred to determine the dimensionless numbers with the Langhaar matrix, yielding a value of 1. The y_1 variable was selected as the recurring variable. The values and results of these operations are presented in Tables II and III, respectively.

TABLE II. DIMENSIONLESS NUMBER SETTING

Parameter	d_s	L_j	F_{r1}	ε_t	y_1
Notation	k_1	k_2	k_3	k_4	k_5
π_1	1	0	0	0	–1
π_2	0	1	0	0	–1
π_3	0	0	1	0	0
π_4	0	0	0	1	0

TABLE III. DIMENSIONLESS NUMBER RESULT

Dimensionless Numbers	**Description**
$\pi_1 = \frac{d_s}{y_1}$	Ratio of scour depth to flow depth upstream of hydraulic jump
$\pi_2 = \frac{L_j}{y_1}$	Ratio of hydraulic jump length to flow depth upstream of the hydraulic jump
$\pi_3 = F_{r1}$	Froude number upstream of the hydraulic jump
$\pi_4 = \varepsilon_t$	Efficiency of energy dissipation

The dimensionless numbers obtained serve as a basis for the analysis of the data from physical hydraulic model tests [9, 18]. The initial analysis yielded a graphical representation of the relationship between the dimensionless numbers. Subsequently, an equation closely aligned with the results of the hydraulic physical tests was formulated.

III. RESULTS AND DISCUSSION

The observation results demonstrate that, in the modified series, the position of the riprap remains constant, as shown in Figure 5. This finding suggests that the energy transmitted downstream of the dam has been adequately damped, thereby reducing the risk of damage to that area compared to the initial series.

Fig. 5. Riprap conditions of the modified design stilling basin before and after the discharge for the 100 year return period (Q_{100}).

Table IV provides an analysis of the data from the physical hydraulic model tests. The preliminary analysis yielded a graphical representation of the relationship between dimensionless numbers, paving the way for the formulation of an equation that closely approximates the results of hydraulic physical tests. The underlying mechanism of scour depth involves the flow velocity of water surpassing the sediment grains constituting the base material of the channel. This observation suggests that the presence of these minerals may be a contributing factor to the observed discrepancy, prompting the subsequent shift, movement, and migration of sediment grains within the reservoir [6, 20]. The measurement of scour depth was derived from variations in discharge.

TABLE IV. OBSERVATION RESULTS OF SCOUR DEPTH IN ALL DISCHARGE VARIATIONS

Return period	**Discharge**	**Independent variables**	**Dependent variables**			
		y_1	d_s	L_j	F_{r1}	y_1
		(m)	(m)	(m)		(m)
Q_2	514,677	0.480	5.769	26.260	8.949	0.536
Q_5	672,199	0.800	7.200	36.820	8.278	0.662
Q_{10}	807,464	1.490	9.060	41.720	6.345	0.723
Q_{25}	1018,503	2.150	10.380	48.320	5.655	0.724
Q_{50}	1210,775	1.610	11.700	54.660	4.805	0.631
Q_{100}	1495,660	1.430	11.530	59.700	6.132	0.8
Q_{1000}	1702,320	0.730	14.820	64.060	9.986	0.842

The relationships between the variables were systematically configured through dimensional analysis. The results of this study include several influential parameters and variables. Given the multitude of hydraulic variables involved, it is imperative to discern the dominant factor that will serve as the mathematical foundation for establishing an equation relevant to these hydraulic variables [6, 23].

A. The Correlation between Scour Depth and Froude Numbe

The relationship between the scour depth and Froude number is exhibitefd by comparing the Froude number at the upstream jump with the scour depth to water flow depth ratio at the same location ($\frac{d_s}{y_1}$), as detailed in Table V. A graphical representation was then produced based on the tabulated relationships to visually assess the precision of this correlation, as shown in Figure 6.

TABLE V. CORRELATION BETWEEN SCOUR DEPTH AND FROUDE NUMBER

Discharge	$\pi_1 = \frac{d_s}{y_1}$	$\pi_2 = F_{r1}$
Q_2	12.000	8.949
Q_5	9.000	8.278
Q_{10}	6.081	6.345
Q_{25}	4.828	5.655
Q_{50}	7.267	4.805
Q_{100}	8.063	6.132
Q_{1000}	20.301	9.986

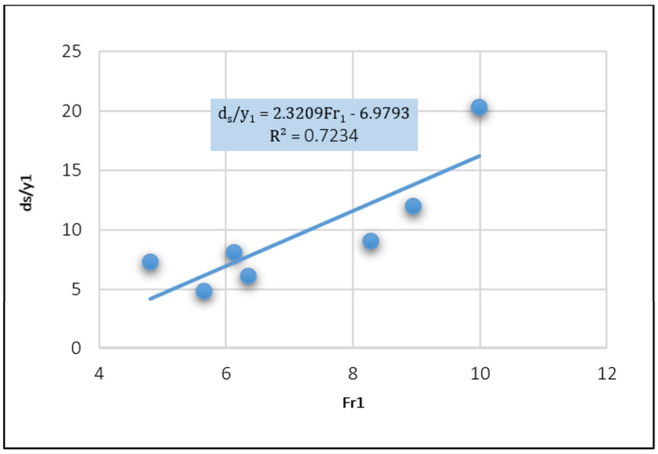

Fig. 6. Correlation between F_{r1} and $\frac{d_s}{y_1}$.

The turbulent flow induced by the high speed transports the grains of the material at the bottom of the scour hole further and wider. The analysis yielded a direct correlation, indicating that an increase in discharge resulted in concomitant increases in both the Froude number and the scour depth. This finding aligns with the results of other studies [1, 4, 6, 11]. It is important to acknowledge the difficulty in predicting scour depth downstream of spillways in specific hydraulic structures. Specifically, for flow discharges Q_2, Q_5, Q_{10}, Q_{25}, and Q_{50}, a decline in the Froude number was observed, primarily attributable to an increase in the depth of flow in the upstream jump (y_1). Conversely, a reduction in y1 during the maximum discharge flows of Q_{100} and Q_{1000} leads to an elevation in the

Froude number, thereby contributing to an increase in the scour depth ratio [24].

B. The Correlation between Scour Depth and Hydraulic Jump

The effect of scour depth on a hydraulic jump is described by contrasting the ratio of hydraulic jump length to the depth of flow upstream $(\frac{Lj}{y_1})$ with the ratio of scour depth to the depth of water flow upstream $\left(\frac{ds}{y_1}\right)$, as displayed in Table VI. Authors in [2] showed that the ratio of the hydraulic jump length to the depth of flow upstream (L_j /y_1) increased as the Froude number rose. As presented in Figure 7, an elevated discharge rate is associated with a greater ratio of the hydraulic jump length to the depth of flow upstream (L_j /y_1). This results in an increased ratio of scour depth to the depth of water flow upstream of the hydraulic jump (d_s /y_1). In the Krueng Kluet Dam, a hydraulic jump occurred before reaching its apron and concluded before entering the riprap for discharges Q_2, Q_5, Q_{10}, Q_{25}, and Q_{50}. In contrast, for discharges Q_{100} and Q_{1000}, the jump terminated in the riprap area. The observed discrepancy has been shown to contribute to an increase in scour depth formed at maximum discharges of Q_{100} and Q_{1000}.

C. Correlation between Scour Depth and Hydraulic Jump

Discharge	$\pi_1 = \frac{d_s}{y_1}$	$\pi_2 = \frac{L_j}{y_1}$
Q_2	12.000	54.708
Q_5	9.000	46.025
Q_{10}	6.081	28.000
Q_{25}	4.828	22.474
Q_{50}	7.267	33.950
Q_{100}	8.063	41.748
Q_{1000}	20.301	87.753

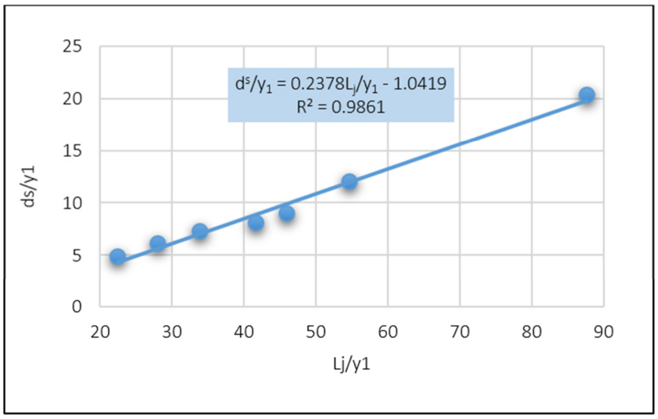

Fig. 7. Correlation between $\frac{d_s}{y_1}$ and $\frac{L_j}{y_1}$.

D. The Correlation between Hydraulic Jump and Energy Dissipation Efficiency

An energy dissipation analysis was performed to determine an efficient stilling pond design in a spillway structure to mitigate downstream river damage. This involves examining the relationship between the ratio of scour depth to the depth of water flow upstream of the hydraulic jump, $\left(\frac{d_s}{y_1}\right)$ and energy dissipation efficiency (ε_t), as illustrated in Table VII. The relationship between the energy dissipation efficiency and Froude number, evidenced in [16], indicates that higher Froude numbers correspond to greater scour depths. Figure 8 shows that the increase in $\frac{ds}{y_1}$ was influenced by the increase in $\frac{Fr1}{y_1}$. Building on these relationships, a higher energy dissipation efficiency (ε_t) leads to a greater $\frac{ds}{y_1}$. In the analysis of the influence of the energy dissipation efficiency on the ratio of scour depth to the depth of water flow upstream of hydraulic jump $\left(\frac{ds}{y_1}\right)$, the value for Q_{1000} was excluded. This exclusion is due to the exceptionally high flow velocity and the resulting thin flow formation at the maximum discharge Q_{1000}, which leads to an extremely large energy dissipation efficiency value. Table VII provides an analysis of the influence of energy dissipation efficiency (εt) on flow rates Q_2, Q_5, Q_{10}, Q_{25}, Q_{50} and Q_{100}.

E. Correlation between Hydraulic Jump and Energy Dissipation Efficiency

Discharge	$\pi_1 = \frac{d_s}{y_1}$	ε_t
Q_2	12.000	0.536
Q_5	9.000	0.662
Q_{10}	6.081	0.723
Q_{25}	4.828	0.724
Q_{50}	7.267	0.631
Q_{100}	8.063	0.800
Q_{1000}	20.301	0.842

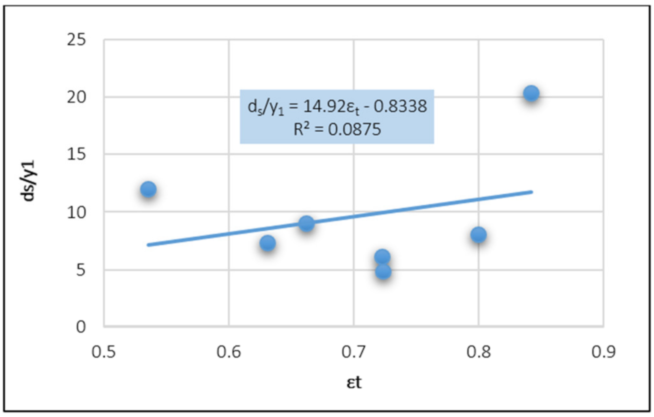

Fig. 8. Correlation between $\frac{d_s}{y_1}$ and ε_t.

Authors in [1, 10, 13, 14] collectively indicate that a greater discharge results in a higher energy dissipation efficiency and a lower scour depth. This phenomenon is also evident in a broad spectrum of discharges. When excluding the Q_{1000} value from the analysis conducted in this study, the resulting graph, depicted in Figure 9, aligns with the patterns observed in the four aforementioned studies. However, the observed anomaly in the correlation between efficiency and scour depth is attributed to the thin flow generated and the pronounced impact on the baffle block. The phenomenon of thin flow has been demonstrated to possess the capacity to induce the occurrence of cavitation events at the base of stilling ponds. Prolonged cavitation has the potential to inflict substantial damage and even result in the complete failure of building structures. This underscores the importance of considering all factors, including extreme conditions, in hydraulic design and analysis. Side channel spillways provide pragmatic solutions for locations that are constrained by limited spatial availability and particular topographical conditions. However, this spillway configuration exhibits several drawbacks, including diminished flow efficiency, increased risk of downstream scouring, and augmented geometric complexity. These deficiencies necessitate thorough analysis through physical modeling or numerical simulations.

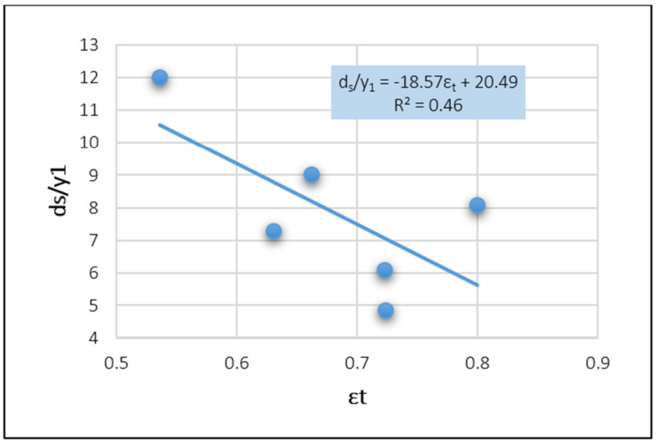

Fig. 9. Correlations between $\frac{d_s}{y_1}$ and ε_t (Q_2, Q_5, Q_{10}, Q_{25}, Q_{50}, and Q_{100}).

This study uses an experimental approach to examine the flow behavior and scour formation in a side channel spillway structure. The research introduces a novel contribution through a detailed experimental analysis of the influence of flood discharges, ranging from Q_{10} to Q_{1000}, on scour depth in a physical model of a side channel spillway. Furthermore, the study establishes an empirical relationship between flood discharge and scour depth downstream of the spillway, offering significant insights for the development of erosion protection strategies for downstream structural components. Despite the fact that numerous studies have been conducted on the hydraulic behavior of side channel spillways, a substantial gap remains in the extant literature concerning the quantification of downstream scour depth and the evaluation of protection systems, such as riprap [25, 26]. The current research aims to address this gap by providing empirical data, identifying critical scour zones, and proposing revised structural designs to enhance downstream safety. Accordingly, this study signifies a substantial contribution to the domain of hydraulic engineering and dam safety. It proffers theoretical advancements and practical guidance for the design and protection of spillways. Furthermore, the study focuses specifically on structural modifications, such as wall elevation adjustments and bed protection strategies. The optimal design outcomes derived from the experimental results further reinforce the novelty and practical significance of this research.

IV. CONCLUSIONS

The research results demonstrate a coefficient of determination (R^2) of 0.7234, formed by processing the Froude number (F_{r1}) with the ratio of scour depth to the depth of water flow upstream of the hydraulic jump $\left(\frac{ds}{y_1}\right)$. This indicates a substantial correlation, where an increase in discharge leads to higher Froude numbers, and subsequently, a greater scour depth. Furthermore, the hydraulic jump length ratio $(\frac{Lj}{y_1})$ increased with an increase in the Froude number (F_{r_1}). These relationships demonstrate that an elevated ratio of the hydraulic jump length to the depth of flow upstream $(\frac{\mathrm{Lj}}{y_1})$ influences the increase in the ratio of scour depth to the depth of water flow upstream $\left(\frac{ds}{y_1}\right)$. The analysis also reveals a relationship between the energy dissipation efficiency and Froude number, indicating that a higher Froude number corresponds to a greater scour depth. Moreover, the increase in $\frac{ds}{y_1}$ was influenced by the increase in $\frac{Fr1}{y_1}$. Building on these relationships, a higher value of εt leads to a greater $\frac{ds}{y_1}$. If the Q_{1000} value is excluded from the analysis, a greater energy dissipation efficiency will result in a smaller scour depth value. The noted anomaly in the relationship between the efficiency and scour depth is attributed to the thin flow generated and its significant impact on the baffle block. The results of this study can explain the influence of hydraulic behavior in the stilling basin on the scour depth downstream of the spillway. The spillway design, by integrating the design of a stilling basin as an energy reducer, can reduce the impact of scour downstream of the river.

ACKNOWLEDGMENT

The authors greatly appreciate the help from the Universitas Syiah Kuala through the Magister's Tesis Research Incentive Grant No. 669.002/UN11/SPK/PNBP/2023 on May 4, 2023.

REFERENCES

[1] M. E.-S. El-Mahdy, "Experimental method to predict scour characteristics downstream of stepped spillway equipped with V-Notch end sill," *Alexandria Engineering Journal*, vol. 60, no. 5, pp. 4337–4346, Oct. 2021, https://doi.org/10.1016/j.aej.2021.03.018.

[2] N. B. Abdel-Mageed, A. Mobasher, M. A. Abdul-Muttalib, and M. H. Salih, "Review of The Energy Dissipation Over Stepped Weir," *Engineering Research Journal (Shoubra)*, vol. 42, no. 1, pp. 132–137, Oct. 2019, https://doi.org/10.21608/erjsh.2019.277199.

[3] E. Fatimah, A. Azmeri, Qurratul 'Aini, M. Fauzi, and M. Rizalihadi, "Analysis of the Hydraulic Jump Characteristics in a Stilling Basin to Avoid Dam Failure," *International Journal of Disaster Management*, vol. 6, no. 1, pp. 75–88, Jun. 2023, https://doi.org/10.24815/ijdm.v6i1.31990.

[4] E. A. Elnikhely, "Investigation and analysis of scour downstream of a spillway," *Ain Shams Engineering Journal*, vol. 9, no. 4, pp. 2275–2282, Dec. 2018, https://doi.org/10.1016/j.asej.2017.03.008.

[5] A. N. AlTalib, A. Y. Mohammed, and H. A. Hayawi, "Hydraulic jump and energy dissipation downstream stepped weir," *Flow Measurement and Instrumentation*, vol. 69, Oct. 2019, Art. no. 101616, https://doi.org/10.1016/j.flowmeasinst.2019.101616.

[6] G. M. Abdel Aal, M. Sobeah, E. Helal, and M. El-Fooly, "Improving energy dissipation on stepped spillways using breakers," *Ain Shams Engineering Journal*, vol. 9, no. 4, pp. 1887–1896, Dec. 2018, https://doi.org/10.1016/j.asej.2017.01.008.

[7] A. Azmeri, C. Ummah, F. Z. Jemi, I. Faudli, and Q. 'Aini B. Nasaiy, "Cross-waves and pulsating flows in the side-channel spillway - an

experimental approach," *Journal of Water and Land Development*, no. 56, pp. 51–57, 2023.

[8] A. Prayudi, M. Rizalihadi, and A. Fauzi, "Studi Gerusan pada Hilir Kolam Olak Model Fisik Bendungan Krueng Kluet," *Journal of The Civil Engineering Student*, vol. 4, no. 1, pp. 43–49, Apr. 2022, https://doi.org/10.24815/journalces.v4i1.19226.

[9] N. B. Rustiati, "Pemodelan Gerusan Dan Sedimentasi Pada Saluran Berbahan Dasar Non-Kohesif Dengan Aliran Tenggelam," Ph.D. dissertation, Universitas Brawijaya, Malang, Indonesia, 2017.

[10] A. Habib, M. Fahmy, and N. Taha, "Scour characteristics downstream converging spillways," *The Egyptian International Journal of Engineering Sciences and Technology*, vol. 19, no. 1, pp. 258–266, Jun. 2016, https://doi.org/10.21608/eijest.2016.97129.

[11] M. El-Gamal, O. Ragib, M. Sobeih, and S. El-Abd, "Experimental Study of Local Scour downstream Stilling Basins.," *Mansoura Engineering Journal*, vol. 27, no. 4, pp. 90–106, Oct. 2021, https://doi.org/10.21608/bfemu.2021.199415.

[12] Y. Kim, G. Choi, H. Park, and S. Byeon, "Hydraulic Jump and Energy Dissipation with Sluice Gate," *Water*, vol. 7, no. 9, pp. 5115–5133, Sep. 2015, https://doi.org/10.3390/w7095115.

[13] M. Hladík, M. Králík, J. Ouhel, V. Sýs, and M. Zukal, "Effect of Energy Dissipation on Scour Hole Development Downstream of the Chute," *IOP Conference Series: Earth and Environmental Science*, vol. 906, no. 1, Nov. 2021, Art. no. 012117, https://doi.org/10.1088/1755-1315/906/1/012117.

[14] M. Karimi Chahartaghi, S. Nazari, and M. Solimani Babarsad, "Investigation of the impact of baffled-chute and divergence sidewall on the downstream scour pattern," *Ain Shams Engineering Journal*, vol. 12, no. 4, pp. 3543–3552, Dec. 2021, https://doi.org/10.1016/j.asej.2021.03.025.

[15] J. Lucas, N. Lutz, A. Lais, W. H. Hager, and R. M. Boes, "Side-Channel Flow: Physical Model Studies," *Journal of Hydraulic Engineering*, vol. 141, no. 9, Sep. 2015, Art. no. 05015003, https://doi.org/10.1061/(ASCE)HY.1943-7900.0001029.

[16] A. Y. Bantacut, A. Azmeri, F. Z. Jemi, Z. Ziana, and M. Muslem, "An experiment of energy dissipation on USBR IV stilling basin – Alternative in modification," *Journal of Water and Land Development*, vol. 4–6, no. 53, pp. 68–72, Jun. 2022, https://doi.org/10.24425/jwld.2022.140781.

[17] L. Prasetyorini, N. Anwar, and W. Wardoyo, "A physical hydraulic model test to solve the problem on spillway dam," *GEOMATE Journal*, vol. 19, no. 73, pp. 170–176, Nov. 2021.

[18] N. M. Ngoc and T. N. Thang, "A Study of an Empirical Sequent Depths Equation of the Hydraulic Jump in a Horizontal Trapezoidal Channel," *Engineering, Technology & Applied Science Research*, vol. 13, no. 6, pp. 12307–12313, Dec. 2023, https://doi.org/10.48084/etasr.6431.

[19] A. S. Kote and P. B. Nangare, "Hydraulic Model Investigation on Stepped Spillway's Plain and Slotted Roller Bucket," *Engineering, Technology & Applied Science Research*, vol. 9, no. 4, pp. 4419–4422, Aug. 2019, https://doi.org/10.48084/etasr.2837.

[20] S. M. Mousavimehr, O. A. Yamini, and M. R. Kavianpour, "Performance Assessment of Shockwaves of Chute Spillways in Large Dams," *Shock and Vibration*, vol. 2021, no. 1, 2021, Art. no. 6634086, https://doi.org/10.1155/2021/6634086.

[21] R. Rasooli and B. Cetin, "An Extended Langhaar's Solution for Two-Dimensional Entry Microchannel Flows with High-Order Slip," in *Mathematics Applied to Engineering, Modelling, and Social Issues*, F. T. Smith, H. Dutta, and J. N. Mordeson, Eds. Cham, Switzerland: Springer International Publishing, 2019, pp. 189–212.

[22] I. Rohani, D. Paroka, M. A. Thaha, and M. P. Hatta, "Dimensional Analysis of Compound Section in The Regulate Section Channel Model for Maintenance Main Channel," *IOP Conference Series: Earth and Environmental Science*, vol. 921, no. 1, Nov. 2021, Art. no. 012076, https://doi.org/10.1088/1755-1315/921/1/012076.

[23] D. Legono, R. Hambali, and D. S. Krisnayanti, "Experimental study on the side channel spillway and its impact on the jump, cross flow and energy dissipation," *Jurnal Teknologi (Sciences & Engineering)*, vol. 81, no. 6, Sep. 2019, https://doi.org/10.11113/jt.v81.13811.

[24] H. L. Tiwari and A. Goel, "Effect of impact wall on energy dissipation in stilling basin," *KSCE Journal of Civil Engineering*, vol. 20, no. 1, pp. 463–467, Jan. 2016, https://doi.org/10.1007/s12205-015-0292-5.

[25] R. S. J. Paksi, V. Dermawan, and U. Andawayanti, "Kajian Hidrolika Bangunan Pelimpah Samping (Side Channel Spillway) Bendungan Pomalaa Kabupaten Kolaka Provinsi Sulawesi Tenggara Dengan Uji Model Fisik 1:40,"*Jurnal Teknologi dan Rekayasa Sumber Daya Air*, vol. 1, no. 2, pp. 750–763, Jun. 2021, https://doi.org/10.21776/ub.jtresda.2021.001.02.34.

[26] Y. Huang, X. Zhou, J. Zhou, X. Yang, J. Zhang, and H. Li, "Physical model test of the influence of the spillway geometry on the scouring and breaching process of landslide-dammed lakes," *Arabian Journal of Geosciences*, vol. 15, no. 20, Oct. 2022, Art. no. 1610, https://doi.org/10.1007/s12517-022-10814-y.