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Hydraulic jump and energy dissipation with stepped weir

Azmeri Azmeri[1], Hairul Basri[2], Alfiansyah Yulianur[1], Ziana Ziana[1], Faris Zahran Jemi[3], Ridha Aulia Rahmah[1]

[1] Syiah Kuala University, Faculty of Engineering, Civil Engineering Department, Jl. Tgk. Syeh Abdul Rauf No. 7, Darussalam – Banda Aceh 23111, Indonesia

[2] Syiah Kuala University, Faculty of Agriculture, Department of Soil Science, Banda Aceh, Indonesia

[3] Syiah Kuala University, Faculty of Engineering, Department of Electrical Engineering, Banda Aceh, Indonesia

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Abstract: Energy dissipator functions to dissipate the river-flow energy to avoid longitudinal damage to the downstream river morphology. An optimal energy dissipator planning is essential to fulfilling safe specifications regarding flow behavior. This study aims to determine the variation of energy dissipators and evaluate its effect on the hydraulic jump and energy dissipation. For this purpose, a physical model was carried out on the existing weir condition (two steps). It was also carried out on four stepped-weir variations, i.e., three-step, three-step with additional baffle blocks at the end sills, four-step, and six-step. Dimensional analysis was employed to correlate the different parameters that affect the studied phenomenon. The study shows a three-step jump shows a significantly higher Lj/y_1 ratio, which is an advantage to hydraulic jumps' compaction. The comparison of energy dissipation in all weir variations shows that the three-stepped weir has wasted more energy than other types. The energy dissipation increase of the three-step type is 20.41% higher than the existing type's energy dissipation and much higher than other types. The dimensions of the energy dissipation basin are the ratio of the width and height of the stairs (l/h) of the three-step type (2.50). Therefore, this type is more optimal to reduce the cavitation risk, which damages the river structure and downstream area.

Keywords: energy dissipation, hydraulic jump, physical model, stepped weir

INTRODUCTION

A weir is a water structure that functions to raise the river's water level and divert the water flow into a channel. Dams create an energy head difference between the upstream and downstream of the weir, causing flow change from supercritical to subcritical and leads to hydraulic jumps [Tiwari, Goel 2016]. A hydraulic jump is a rapidly varied flow [Aksoy, Dogan 2019], which occurs in areas where the slope changes from steep to gentle. This condition is commonly found in flood structures such as flood drain tunnels, spillway and floodgates [Elnikhely 2018].

A hydraulic jump is the most widely used parameter to dissipate excess energy due to heavy flow exiting the spillway [Chanson 2009]. Hydraulic jumps are used as energy dissipation in hydraulic structures as well as rising water level. Barani [2005] studied energy dissipation on a variety of different stepped spillway shapes. Wüthrich and Chanson [2014] investigated the equation to calculate energy dissipation on stepped spillways. However, it remains widely understood that the hydraulic jump stilling basin is not an efficient energy dissipator. Also, water structures with high discharge and high water heads can be damaged by high velocity and high hydrodynamic pressure fluctuations near the bottom of the stilling basin [Bejestan, Neisi 2009].

Hydraulic jumps cause turbulent flows around the water structure, which has a significant impact on sediment particles' movement. The flow changes cause formations of scour holes due to the high flow velocity. Erosive local scours at the bottom is one of the main concerns of hydraulic engineers because it can cause structural [ABBASPOUR *et al.* 2016] and downstream morphology damage [ABDEL *et al.* 2018]. Thus, it is necessary to equip this location with stilling basin. The basin functions as a river-flow energy reducer to avoid longitudinal damage to the downstream river morphology. An optimal energy dissipator (stilling basin) planning is required to fulfill the flow behavior's specification.

The Keumala weir at the Krueng Baro River was built to fulfill the needs of irrigation water in Pidie District, Aceh Province, Indonesia. However, based on field observations, the downstream energy dissipator (stilling basin) has been damaged. This damage extends to the downstream area. Due to the changes and damages that have occurred, it is critical to conduct an on-site study immediately. Therefore, it is necessary to study the construction's hydraulic behavior to obtain the safest design. Many new types of energy dissipators can be modified; therefore, modifications need to be continuously carried out to dissipate energy [LI *et al.* 2015]. This study is focused on the relationship between the characteristics of hydraulic jumps and downstream energy dissipation and multi-story weir height change, number of weir steps, the slope of the downstream end sill, and the baffle block at the end sill. Stepped weir is widely applied in weir structures and river engineering. Moreover, stilling basins can be constructed as a low-cost energy dissipator [ABDEL *et al.* 2018]. Energy dissipation is compared to the Froude number, as well as the hydraulic jump length and height. This parameter is critical in the suitability of energy dissipating structures and the safety of downstream river morphology.

MATERIALS AND METHODS

EXPERIMENTAL WORK AND DIMENSIONAL ANALYSIS

The study was conducted in the Krueng Baro Irrigation scheme in the Krueng Baro River, Pidie District, Aceh Province, Indonesia. The primary water source was from the Krueng Baro River flow through Keumala weir at the coordinate of 5°13'10.2" E and 95°51'38.8" N.

EXPERIMENTAL SETUP

The experimental work was a stepped weir physical model test. At the upstream river model, a square rechbox was installed to measure the inflow discharge. The stepped weir model was designed according to the current field condition. Modifications of three-step, four-step, four-step with additional baffle blocks at the end sill, and six-step models were prepared.

A water pump and water pipe connect the upstream and downstream parts of the model. Measurements of water depth were carried out using a point gauge at four locations, i.e., upstream of the weir (y_1) and downstream of the weir (y_2). Hydraulic characteristics were observed using piezometers to monitor the head of velocity at the upstream and downstream weir [KIM *et al.* 2015]. The flow velocity was observed from the piezometer measurement by comparing the water level at the piezometer tube's foot (ΔH). The Froude number indicates the flow conditions as a ratio between flow velocity and propagation velocity [SULISTIONO, MAKRUP 2017]. The length of the hydraulic jump (Lj) was obtained through experimental measurements in the laboratory.

DIMENSIONAL ANALYSIS

This research was a physical test model. The model used a distortion ratio, with a different horizontal and vertical ratio: n_L = 200 and n_v = 50. From the vertical and horizontal ratio model, the discharge ratio was n_Q = 70711. The length of the prototype river (L_p) was 150 m, and we obtained geometric (length, width, area, and depth) and kinematics (time, velocity, flow) similarity, which was then applied to the model.

Testing of the physical model was carried out using three discharge variations having return periods q_2 of $2.83 \cdot 10^{-5}$ $m^3 \cdot s^{-1} \cdot m^{-1}$; q_{25} of $3.62 \cdot 10^{-5}$ $m^3 \cdot s^{-1} \cdot m^{-1}$; and q_{100} of $3.73 \cdot 10^{-5}$ $m^3 \cdot s^{-1} \cdot m^{-1}$. The resulting discharge is the outcome of hydrological analysis at the study location conducted by AZMERI *et al.* [2020].

The energy dissipation due to the hydraulic jump to the downstream of the stepped weir was influenced by several factors, including the stepped weir's geometric characteristics and the number of steps (n). The kinematic characteristics of the flow also affect it, such as velocity at the upstream and downstream of the hydraulic jump (V_1 and V_2), the hydraulic jump height at the upstream and downstream (y_1 and y_2), gravitational acceleration (g), and length of the hydraulic jump (Lj). With regards to the principles of dimensional analysis, the variables affecting energy dissipation (ΔE) through spillways can be formulated through the following dimensionless equation:

$$\frac{\Delta E}{L_j} = \frac{\Delta E}{y_1} = f\left(\frac{y_1}{y_2}, n, \mathrm{Fr}_1, \mathrm{Fr}_2\right)\frac{\Delta E}{Lj}$$

where Fr_1 and Fr_2 is the Froude number at the upstream and downstream of the hydraulic jump.

RESULTS AND DISCUSSION

RESULTS OF ALL STEPPED WEIR VARIATIONS AND ALL DISCHARGES

A flow simulation of inflow and outflow discharge was employed to ensure the measurement accuracy of the model in this study. This simulation served as a model calibration to create an accurate discharge coefficient (C_d) as a flow variable. Furthermore, the water level accuracy was measured by a ruler in the smallest unit of millimeters. Piezometric calibration was performed through a simulation between measuring and checking the calculation results. The accuracy of this measuring tool is necessary to create the model condition per those of the prototype.

The hydraulic flow of the stepped weir is described and further analyzed in this section. Flow patterns of the stepped weir variations were analyzed for all water discharge conditions. Table 1 illustrates the sample results of all stepped weir variations and all discharges.

According to ALAM and TAUFIQ [2018], flow conditions during the physical model testing meets the requirements of good hydraulic conditions if the upstream flow velocity is less than 4 $m \cdot s^{-1}$, the Froude number of the subcritical flow is less than 0.4, and the ratio of spillway height (P) to upstream water level (H) is more than 1/5 ($P \geq H/5$). A good hydraulic spillway requires perfect flow conditions; therefore, the upstream and downstream

Table 1. Sample results of all stepped weir variations and all discharges

Parameter	Discharge	Variation of stepped				
		existing (2 stepped)	3 stepped	3 stepped with baffle block	4 stepped	6 stepped
y_2/y_1	q_2	1.3333	1.2414	1.2000	1.1563	1.1818
	q_{25}	1.4000	1.4333	1.3333	1.2500	1.2500
	q_{100}	1.3333	1.3235	1.3429	1.3333	1.2308
Lj/y_1	q_2	7.2222	6.7655	6.6000	6.4313	6.3636
	q_{25}	8.6000	8.5000	7.5455	6.6667	6.4167
	q_{100}	8.1818	8.0824	8.0571	7.8000	7.3846
$\Delta E/Lj$	q_2	0.0030	0.0017	0.0012	0.0008	0.0010
	q_{25}	0.0041	0.0047	0.0030	0.0018	0.0018
	q_{100}	0.0030	0.0028	0.0031	0.0030	0.0015
$\Delta E/y_1$	q_2	0.0069	0.0028	0.0017	0.0008	0.0013
	q_{25}	0.0114	0.0142	0.0069	0.0031	0.0031
	q_{100}	0.0069	0.0064	0.0075	0.0069	0.0025
y_1/y_2	q_2	0.7500	0.8056	0.8333	0.8649	0.8462
	q_{25}	0.7143	0.6977	0.7500	0.8000	0.8000
	q_{100}	0.7500	0.7556	0.7447	0.7500	0.8125
Fr	q_2	0.8165	0.7731	0.7454	0.6770	0.6195
	q_{25}	1.0954	1.0750	1.0050	0.9129	0.8607
	q_{100}	1.0636	1.0385	1.0048	0.9329	0.8573

Explanations: q_2 = 2.83·10^{-5} m^3·s^{-1}·m^{-1}; q_{25} = 3.62·10^{-5} m^3·s^{-1}·m^{-1}; and q_{100} = 3.73·10^{-5} m^3·s^{-1}·m^{-1}.
Source: own study.

water level difference shoud be greater than 2/3 of the water level above the spillway. Based on the calculation, this study's physical model has met the requirements for good hydraulic conditions.

According to Abdel Aal *et al.* [2018], the steps are small spillways that are small energy dissipators for the next steps; thus, decreasing the downstream velocity. A reduction of flow velocity leads to a decrease in the flow turbulence. A drop in the flow turbulence results in a reduction of kinetic energy and an increase in energy dissipation. Therefore, the weir cavitation risk can be reduced if the flow velocity is lower.

EFFECT OF DISCHARGE AND BREAKERS' NUMBER ON THE HYDRAULIC JUMP HEIGHT

The study shows the upstream (y_1) and the downstream (y_2) hydraulic jump flow depth. The flow depth was obtained from direct measurements on the model. Figure 1 shows the depth ratio, as well as the relationship between y_2/y_1 variations and the Froude numbers for different weir steps.

The graph shows that the depth ratio for q_2 discharge is relatively similar for all stepped weir types. The reason is that the q_2 discharge is too low; therefore, step variations' effect was not observable. However, for the q_{25} and q_{100} discharge, the depth ratio of water rises with the Froude number increase. According to Abdel Aal *et al.* [2018] and Altalib *et al.* [2019], the number of steps (N) and the discharge per unit width (q) can affect the depth ratio.

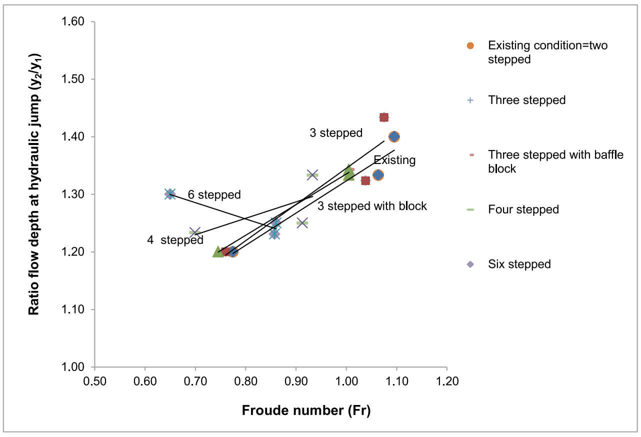

Fig. 1. Relationship between y_2/y_1 and Froude number for different weir steps; y_1 = the hydraulic jump height at the upstream, y_2 = the hydraulic jump height at the downstream; source: own study

After a hydraulic jump, the water level rises with the flow increase. The water level is up to 2 mm higher at a discharge of 3.73·10^{-5} m^3·s^{-1}·m^{-1} compared to a discharge of 3.62·10^{-5} m^3·s^{-1}·m^{-1} and 2.83·10^{-5} m^3·s^{-1}. The higher water level affects the upstream flow, thereby reducing the hydraulic jump size and length to a considerable extent [Kim *et al.* 2015]. As the downstream water level gets higher, the velocity decreases and reduces hydraulic jumps. Figure 1 shows the depth ratio according to the Froude numbers. The depth ratio refers to the ratio between water depth at the supercritical flow area and the post-hydraulic jump stabilization area. The depth ratio varies depending on the discharge volume. The Froude number shows a proportional relationship with the post-hydraulic jump water depth (y_2). The post-hydraulic jump water depth is similar since the amount of inflow is the same. The graph shows a similar slope pattern as the study conducted by KIM *et al.* [2015], except for the six-stepped weir type. This type has an inversed depth ratio slope compared to other types. This condition is not effective in reducing the hydraulic jump. In supercritical conditions, a Fr > 1, the depth ratio on the three-stepped weir type shows the greatest value, followed by the existing stepped weir type (two-stepped), three-stepped weir type with baffle blocks, and four-stepped weir type, from the perspective of y_2/y_1.

EFFECT OF DISCHARGE AND BREAKERS' NUMBER ON THE HYDRAULIC JUMP LENGTH

According to the Froude's number, the existing hydraulic jump length formula illustrates the relationship between the hydraulic jump length and the flow depth at the supercritical flow. This study compares the hydraulic jump length (Lj), the discharge variation, and the number of steps. Figure 2 shows the effect of discharge variations and the number of steps on the hydraulic jump length.

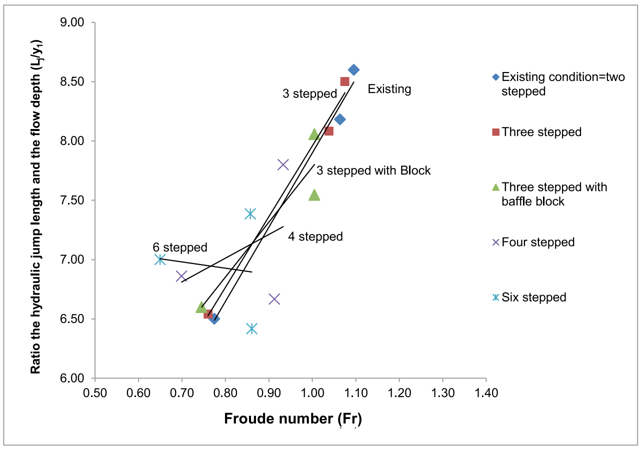

Fig. 2. Relationship between the hydraulic jump length ratio Lj/y_1 as a function of Froude number for variations of stepped weirs; source: own study

Several researchers have suggested formulas for hydraulic jump length. The Rajaratnam equation and the Bretz equation show that the hydraulic jump's length has a linear relationship with the Froude number [KIM *et al.* 2015]. This condition is in accordance with the results of this study. This study demonstrates that the Froude number is within the range of 0.7–1.2 and represents the lowest hydraulic jump length. The graph shows the same slope pattern as the study with stepped slope variations conducted by HUSAIN *et al.* [2010], as well as KIM *et al.* [2015], by comparing several equations from previous studies. If compared, the study results tend to be proportional to the Froude number, which indicates a similarity of results.

By comparing it with the Froude number, the relationship between the two factors is expressed in the graph, as shown in Figure 2. The graph describes the variation of the jump length ratio (Lj/y_1) with the Froude number. It indicates that hydraulic jumps in all types of stepped weir have higher Lj/y_1 with the increasing discharge, except for the six-stepped weir type, which has an inversed (negative) slope pattern. Hydraulic jumps in almost all types show the effect of energy release on reducing the jump length and the number of steps. A three-step jump shows a significantly higher Lj/y_1 ratio, which is an advantage to hydraulic jumps' compaction. This condition was primarily due to the significant increase in tailwater depth during the jump formation. Therefore, a three-stepped weir is considered a better dissipator in the design of stilling basins for hydraulic jump stability and compaction, followed by the existing stepped weir type (two-stepped), three-stepped weir with baffle blocks, and four-stepped weir, from the perspective of the hydraulic jump length.

EFFECT OF DISCHARGE AND BREAKERS' NUMBER ON ENERGY DISSIPATION

Figure 3 shows the effect of the number of steps on the extent of the energy dissipation. The relationship between the upstream Froude number (Fr) and the energy dissipation with the hydraulic jump length $\Delta E/Lj$ (Fig. 3a). The relationship between y_1/y_2 and energy dissipation with the upstream flow depth $\Delta E/y_1$ is presented in Figure 3b.

Figure 3a shows the relationship between the energy dissipation per unit hydraulic jump length ($\Delta E/Lj$) and the

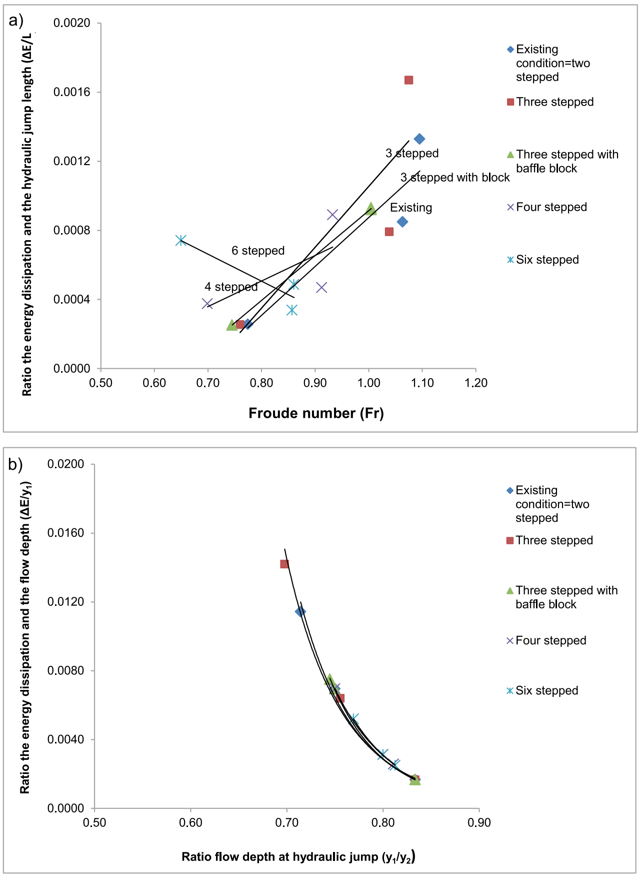

Fig. 3. Relationship between the Froude number and $\Delta E/Lj$ (a); the relationship between y_1/y_2 and $\Delta E/y_1$ (b), for different weir steps; source: own study

upstream Froude number. Based on the graph, $\Delta E/Lj$ increases as the Froude number rise. This condition is in accordance with the study by Kim *et al.* [2015]. The highest energy dissipation value is obtained at the three-stepped type, while the lowest value occurs at the four-stepped type. The six-stepped weir type shows an inverted (negative) slope pattern. The increase in energy dissipation at a three-stepped type is 20.41% higher than the existing step type's energy dissipation. Thus, based on this study, the best variant for energy release is the three-step type, from the perspective of energy dissipation per unit hydraulic jump length.

Figure 3b shows the relationship between y_1/y_2 and $\Delta E/y_1$ for variations of discharges and the number of steps. The graph shows a similar slope pattern as the study by Altalib *et al.* [2019]. The relationship between energy dissipation, the upstream depth of water ($\Delta E/y_1$), upstream hydraulic jump depth of water (y_1), downstream depth (y_2), and y_1/y_2 is illustrated. The graph shows that $\Delta E/y_1$ declines as y_1/y_2 rises. This situation occurs because the values of y_1 and y_2 converge, which causes a weakening of the hydraulic jump. Also, increasing y_1 means lowering Fr_1 and decreasing energy dissipation, as mentioned in the study by Altalib *et al.* [2019]. This figure indicates that the energy reduction in almost all stepped weir types as the discharge increases is relatively similar, except for the six-stepped weir type. The three-step jump shows significantly higher than other types. The increase reaches 19.47% for the three-step type, which is greater than the existing step-type at q_{25}, which is the largest percentage in this study.

The results obtained from this research are hydraulic jumps at the three-step jump shows the effect of energy release which is an advantage to hydraulic jumps' compaction. Therefore, this type is more optimal to reduce the cavitation risk, which damages the river structure and downstream area. The three-step jump shows at Figure 4.

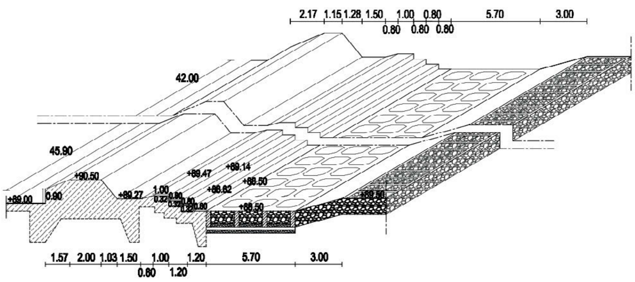

Fig. 4. Optimal model of 3 stepped weir; source: own study

CONCLUSIONS

Energy dissipation increases during hydraulic jumps formed downstream of the weir as the Froude number and length of hydraulic jumps rise. Meanwhile, energy dissipation declines when (y_1/y_2) rises. The highest energy dissipation value was obtained at the three-step type, while the lowest value occurred at the four-step type. The energy dissipation increase of the three-step type is 20.41% higher than the existing step type's energy dissipation and much higher than the other types. The dimensions of the energy dissipation basin are the ratio of the width and height of the stairs (l/h) of the three-stepped type (2.50). Hydraulic jumps in almost all types show the effect of energy release on reducing the jump length and the number of steps. The three-step jump shows a significantly higher Lj/y_1 ratio, which indicates advantages to hydraulic jumps' compaction.

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