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An experiment of energy dissipation on USBR IV stilling basin – Alternative in modification

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Abstract: Previous researchers have been widely studied the equation for calculating the energy dissipation in USBR Type IV, applied in the stilling basin structure as an energy dissipator. However, inefficient energy dissipating basins are commonly found in the field due to the large discharge and high water head, potentially damaging the bottom of the energy dissipating basin and its downstream river. Therefore, an energy dissipator plan fulfilling the safe specifications for the flow behaviour that occurred is required. This study aimed to determine the variation of the energy dissipators and evaluate their effect on the hydraulic jump and energy dissipation. For this purpose, a physical model was undertaken on the USBR Type IV spillway system. The novelty of this experiment showed that combination and modification dissipation features, such as floor elevation, end threshold and riprap lengthening, could effectively dissipate the impact of energy downstream. The final series exhibited a significantly higher L_j/y_1 ratio, a favourable condition due to the compaction of the hydraulic jump. There was also a significant increase in the downstream tailwater depth (y_2) during the jump formation. Therefore, the final series energy dissipator was better in the stilling basin design for hydraulic jump stability and compaction. The increase in energy dissipation for the final series type was the highest (98.4%) in Q_2 and the lowest (84.8%) in Q_{10} compared to the original series. Therefore, this type can better reduce the cavitation risk damaging to the structure and downstream of the river.

Keywords: energy dissipation, hydraulic jump, stilling basin, USBR Type IV

INTRODUCTION

A spillway is a structure constructed near a dam site to discharge excess water from the reservoir to the downstream of the channel. Spillways are provided for all dams as a safety measure against overtopping, possible damage, and construction failure [Chao-chao *et al.* 2015]. The spillway was hydro-dynamically optimised and safe to withstand the high velocity of the energy falling from the reservoir water surface to the downstream (tailwater). Hence, a control structure to dissipate excess energy at the end of the spillway channel is necessary [Kazemi *et al.* 2016].

Turbulent flow around the water structure is due to hydraulic jump, which significantly impacts the movement of sediment particles downstream and causes scouring due the high flow velocity. Erosive local scour at the bottom is one of the main concerns of hydraulic engineers because it can lead to structural [Abbaspour *et al.* 2016] and downstream rivers morphology damage [Abdel Aal *et al.* 2018]. Therefore, this location needs to be equipped with a stilling basin as an energy dissipator. The optimal energy dissipator planning is necessary to meet the specifications suited to the flow behaviour.

The difference in the head between the upstream and downstream of the weir is due to the dam. This difference changes the type of flow from supercritical to subcritical causing hydraulic jumps [Tiwari, Goel 2016]. Hydraulic jump parameters are mostly used to dissipate the high energy due to the heavy flow from the spillway [Chanson 2009]. Based on many studies, design engineers believed that the application of the U.S. Bureau of

Reclamation (USBR) stilling basin design criteria provides good performance [Sherry, Kem 2021]. The equation for calculating the energy dissipation in USBR Type IV has been widely applied by various previous researchers [Ali *et al.* 2010]. This type is widely applied in the structure of stilling basin as an energy dissipator [Abdel *et al.* 2018]. The water pressure profile provides a positive value to the floor level of the stilling basin. Besides, the pressure peaks at the bottom of the basin, floor beams, and end threshold. Froude number is a parameter for identifying the length and height of hydraulic jumps and the efficiency level of energy dissipation. This parameter is critical in the suitability of energy-dissipator construction and the river morphology safety downstream. However, regardless of the conditions, inefficient energy dissipator basins are commonly found in the field. This condition is due to the large discharge and high water head that potentially damage the bottom of the energy dissipator basin and downstream [Bejestan, Neisi 2009].

Turbulent flow around the water structure is due to hydraulic jump, which significantly impacts the movement of sediment particles downstream and causes scouring due the high flow velocity. Erosive local scour at the bottom is one of the main concerns of hydraulic engineers because it can lead to structural [Abbaspour *et al.* 2016] and downstream rivers morphology damage [Abdel Aal *et al.* 2018]. Therefore, this location needs to be equipped with a stilling basin as an energy dissipator. The optimal energy dissipator planning is necessary to meet the specifications suited to the flow behaviour.

Modification of energy dissipators should be continuously conducted to create the optimal energy dissipation [Li *et al.* 2015]. Several modifications to energy dissipators and end sill have been conducted, such as using convergence wall [Babaali *et al.* 2015]; using end adverse slopes [Babaali *et al.* 2019]; and channel bed protection (a combination of six-legged concrete with riprap) [Ghaleh *et al.* 2020].

This study aimed to examine the characteristics of the hydraulic jump and downstream energy dissipation due to the changes from the initial series to the optimal series of stillingstilling basin design through a physical test model in the laboratory. The spillway physical test model aimed to evaluate the hydraulic behaviour before the physical construction was done. The hydraulic behaviour of energy dissipators was studied to obtain the safest optimal design for the downstream condition.

MATERIAL AND METHODS

EXPERIMENTAL SETUP

The experimental work was a physical spillway model test. The open-channel and spillway system used in this experiment was a channel installed in The River and Coastal Experiment Laboratory of Syiah Kuala University (Ind. Laboratorim Sungai dan Pantai Universitas Syiah Kuala), Indonesia. The inflow discharge upstream of the reservoir was controlled using a checkbox. The spillway model was designed based on the detailed engineering design prepared [DSDA 2020].

The upstream and downstream sides of the model were connected by the pump and water channel. The water level, velocity, and length of hydraulic jumps on each channel grid planned were measured. Data collection was conducted at three parts: the right, middle and left. The water level was measured using gauge points placed on the grid threads. The method of measuring water turbulence also uses a point gauge, based on the height and length of the hydraulic jump. Simultaneously, the velocity was measured by a piezometer [Kim *et al.* 2015]. The flow velocity was generated by comparing the water level at the foot of the piezometer tube (ΔH). The Froude number informed the flow conditions with a ratio between flow velocity and wave celerity [Sulistiono, Makrup 2017]. Besides, the hydraulic jump length (L_j) was measured from the start to the end of the jump station after determining the values of y_1 and y_2.

DIMENSIONAL ANALYSIS

This model used a non-distortion ratio, with a scale 1:30. There were obtained geometric (length, width. It obtained geometric (length, width, depth, and area) and kinematics (time, velocity, flow) similarity, which was then applied to the model. Physical model testing was conducted in seven discharge variations with return periods, namely Q_2, Q_5, Q_{10}, Q_{25}, Q_{50}, Q_{100}, and Q_{1000}, $0.66{\cdot}10^{-5}$, $0.86{\cdot}10^{-5}$, $0.99{\cdot}10^{-5}$, $1.18{\cdot}10^{-5}$, $1.30{\cdot}10^{-5}$, $1.44{\cdot}10^{-5}$, and $3.14{\cdot}10^{-5}$ $m^3{\cdot}s^{-1}{\cdot}m^{-1}$, respectively. The resulted discharge was the discharge from the hydrological analysis at the study location [DSDA 2020].

Several factors influence the energy dissipation due to hydraulic jumps to the downstream of the spillway, including the geometric characteristics of the spillway: the floor level of the stilling basin and the end sill. The flow kinematic characteristics, such as the upstream velocity and downstream hydraulic jump (v_1 and v_2, in $m{\cdot}s^{-1}$), hydraulic height of upstream and downstream jumping (y_1 and y_2, in m), gravitational acceleration (g, in $m{\cdot}s^{-2}$), and length of hydraulic jumping (L_j, in m), also contribute. Based on these principles of dimensional analysis, the variables affecting the energy dissipation (ΔE) through the spillway could be formulated in the following dimensionless equation [Azmeri *et al.* 2021].

$$\frac{\Delta E}{L_j} = \frac{\Delta E}{y_1} = f\left(\frac{y_1}{y_2},\ \mathrm{Fr}_1,\ \mathrm{Fr}_2\right) \tag{1}$$

where: Fr_1 and Fr_2 = Froude number upstream and downstream hydraulic jumps.

The design change from the original series to the final series was by decreasing the floor elevation of the stilling basin to 3 m below the riverbed, resulting in the ratio of the downstream slope from the stilling basin to the river with of 1: 2, and extending the rip rap to 30 m. The rip rap extension was intended to avoid scouring at the downstream riverbed.

RESULTS AND DISCUSSION

This section presents the hydraulic flow conditions from the spillway, which is further analysed. The flow patterns were analysed for all water discharge conditions. Table 1 shows data analysis results of flow patterns and energy dissipation efficiency for all flow variations and series.

Alam and Taufiq [2018] argued that criteria of good hydraulic conditions are as follows: if the upstream flow conditions are less than 4 $m{\cdot}s^{-1}$, the subcritical flow conditions with a Fr < 0.4, and the ratio of spillway height (P) to the

Table 1. Flow patterns for all discharge and series variations

Parameter	Discharge	Series type	
		original series	final series
y_2/y_1	Q_2	7.56	21.20
	Q_5	7.37	21.35
	Q_{10}	6.84	19.65
	Q_{25}	6.83	21.63
	Q_{50}	4.55	15.88
	Q_{100}	5.85	4.97
	Q_{1000}	2.87	2.53
L_j/y_1	Q_2	18.83	114.68
	Q_5	29.50	129.81
	Q_{10}	26.08	147.62
	Q_{25}	26.93	149.84
	Q_{50}	35.47	130.51
	Q_{100}	33.85	118.93
	Q_{1000}	27.95	53.15
$\Delta E/E_1$	Q_2	9.27	89.48
	Q_5	8.73	90.90
	Q_{10}	7.28	77.73
	Q_{25}	7.19	65.18
	Q_{50}	6.69	39.04
	Q_{100}	4.73	2.83
	Q_{1000}	0.40	0.35
Fr_1	Q_2	5.39	1.67
	Q_5	5.55	5.96
	Q_{10}	5.59	7.25
	Q_{25}	5.33	5.95
	Q_{50}	5.19	4.37
	Q_{100}	5.14	2.45
	Q_{1000}	3.22	3.45

Explanations: discharge with return periods Q_2, Q_5, Q_{10}, Q_{25}, Q_{50}, Q_{100}, Q_{1000} = $0.66{\cdot}10^{-5}$, $0.86{\cdot}10^{-5}$, $0.99{\cdot}10^{-5}$, $1.18{\cdot}10^{-5}$, $1.30{\cdot}10^{-5}$, $1.44{\cdot}10^{-5}$, and $3.14{\cdot}10^{-5}$ $m^3{\cdot}s^{-1}{\cdot}m^{-1}$, respectively, y_1, y_2 = hydraulic height of upstream and downstream jumping, L_j = length of hydraulic jumping, $\Delta E/E_1$ = energy dissipation towards the initial energy (relative energy loss), Fr_1 = Froude number upstream hydraulic jump.
Source: own study.

upstream water level (H) must be greater than 1/5 ($P \geq H/5$). Besides, good hydraulic conditions in the spillway are fulfilled, perfect flow conditions, when the difference in the gauge height of the upstream and downstream is greater than 2/3 the gauge height above the spillway [Azmeri *et al.* 2021]. Based on the flow conditions, the physical model testing in this study had met the requirements for good hydraulic conditions.

The USBR Type IV stilling basin application in this experiment had fulfilled the optimal design criteria for the Froude number conditions. It suited the water pressure profile that providing a positive value relative to the bottom height of the stilling basin along the stilling basin. Besides, the pressure peaked at the start of the basin, floor beams, and end threshold [Bejestan, Neisi 2009]. This physical model conformed to the tests conducted by USBR recommended for this type of design, i.e., vertical sidewalls compared trapezoid to ensure the proper performance of the hydraulic jump. The vertical sidewall design also eases the construction [Skutch 1997]. In addition, the elevation of the tailwater must be equal to or greater than 110% of the elevation of the full conjugation depth. The tailwater improves the jumping performance and reduces wave action. Hydraulic jump is very sensitive to the tailwater depth [Ali *et al.* 2010; USBR 1987].

The design criteria, especially in energy dissipators, were adequate freeboard on the sidewalls, hydraulic jumps in the stilling basin, optimal energy dissipation, and evenly distributed flow. As an illustration, in Q_{1000}, the quite long hydraulic jump occurred outside the stilling basin (Photo 1a), so it is necessary to modify the design to final series. The design change from the original series to the final series resulted in more optimal conditions (Photo 1b). The flow velocity was reduced, leading to a decrease in the flow turbulence. The decrease in flow turbulence decreases the kinetic energy and raises the energy dissipation. Hence, the scouring risk downstream of the river is lower.

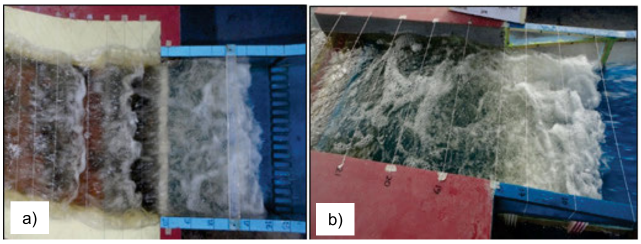

Photo 1. Hydraulic jump in energy dissipator at Q_{1000}: a) original series, b) final series (phot.: *A. Azmeri*)

- **Effect of discharge and series type on hydraulic jump length**

The modelling results show the flow depth before (y_1) and after (y_2) of the hydraulic jump. Figure 1 shows the variation of the water depth ratio y_2/y_1 and the Fr before the water jump for the original and final series.

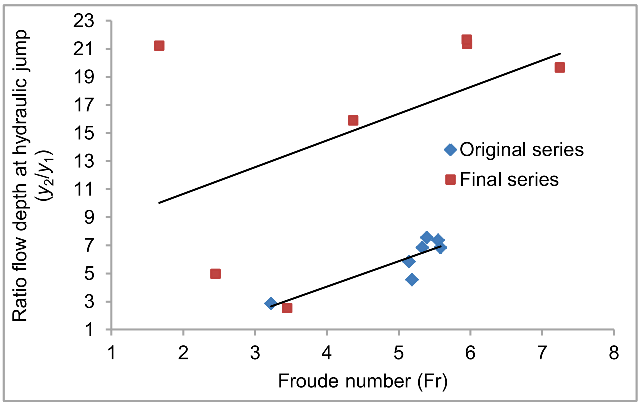

Fig. 1. The relationship between the Froude number and the water depth ratio (y_2/y_1); source: own study

The graph presents the ratio of the water depth of the discharge Q_2, Q_5, Q_{10}, Q_{25}, Q_{50}, Q_{100}, and Q_{1000} return periods to the Fr. The original series showed no improvement as the Fr increases. However, for the final series, the ratio of the water depth of discharge with the return period increased as the Fr increased. These findings agree with the research conducted by ABDEL AAL *et al.* [2018] and ALTALIB *et al.* [2019], revealing that the magnitude of flow rate affects the water depth ratio.

If the flow increased, the water level after the hydraulic jump also increased. This is in line with a study conducted by KIM *et al.* [2015], reporting that when the discharge rises, the water level in the downstream area is higher, decreasing speed and hydraulic jumps. Fr showed a proportional relationship with the depth of post hydraulic jump water (y_2). This finding means that because the amount of inflow is equal, the depth of the post-hydraulic jump water remains the same. The final series graph presented in Figure 1 shows a similar slope pattern as the study conducted by KIM *et al.* [2015], except for the original series. The original series showed no water depth ratio slope, and this condition was ineffective in lowering the hydraulic jump in terms of y_2/y_1.

The hydraulic jump length relates to the depth of supercritical water flow based on the Fr. This modelling compared the ratio of hydraulic jump length to the upstream flow height (L_j/y_1) to the flow and series variations. Figure 2 displays the effect of the discharge and series variations on L_j/y_1.

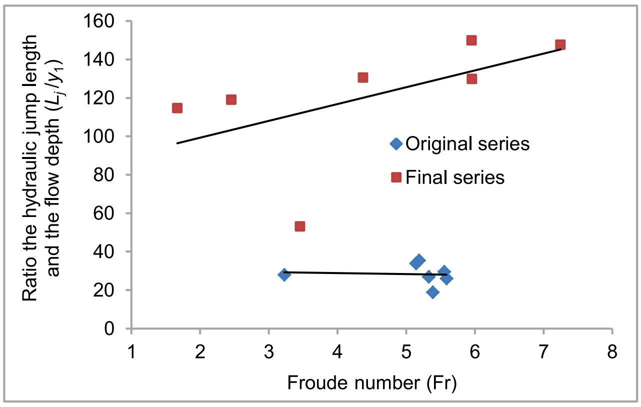

Fig. 2. The relationship between the Froude number and the jump length ratio (L_j/y_1); source: own study

Figure 2 shows that the L_j/y_1 of the hydraulic jumps in the two series have increased as the discharge increases. Many researchers have suggested a formula for hydraulic jump length. The Rajaratnam equation and the Bretz equation show that the hydraulic jump length has a linear relationship with the Fr and a steepness greater than 30° [KIM *et al.* 2015]. This agrees with this modelling results, where the Fr was in the range of 1.26–3.03 and represented the hydraulic jump length. Figure 2 reveals the same slope pattern as the research of HUSAIN *et al.* [2010], with slope variations. In terms of comparing the two models, the final series tended to provide proportional results with similar Fr results to the original series.

The final series exhibited a significantly higher L_j/y_1 ratio, indicating the advantage of hydraulic jump compaction due to the significant increase in tailwater depth (y_2) during the jump formation. Therefore, the final series energy dissipator was better in the stilling basin design for hydraulic jump stability and compaction than the original series in terms of a hydraulic jump length.

- **Effect of discharge and series type on energy dissipation**

The relationship between the upstream Froude number (Fr) and the energy dissipation towards the initial energy (relative energy loss) $\Delta E/E_1$ is presented in Figure 3.

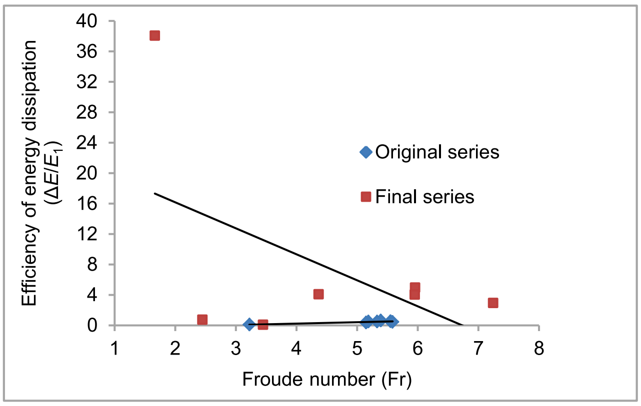

Fig. 3. The relationship between the Froude number and energy dissipation efficiency ($\Delta E/E_1$); source: own study

Figure 3 shows that when the Fr increases, $\Delta E/E_1$ decreases. It shows a similar slope pattern of energy dissipation in the final series to a study of ABDEL AAL *et al.* [2017]. The hydraulic results above are in the form of relative energy loss, meaning that it has a large energy release effect for the final series energy dissipator, yet this is not the case for the original series. The highest energy dissipation increase for the final series type was 98.39% in Q_2, and the lowest was 84.79% in Q_{10}, compared to the original series. The final series result was a hydraulic jump, illustrating the energy release effect as the advantage of the hydraulic jump compaction. Thus, the final series is more optimal in reducing the cavitation risk, damaging to the structure and downstream of the river.

CONCLUSIONS

The final series showed a significantly higher L_j/y_1 ratio, a favourable condition due to the hydraulic jump compaction. A significant increase also occurred in the downstream tailwater depth (y_2) during the jump formation. Thus, the final series energy dissipator was better in the stilling basin design for hydraulic jump stability and compaction. The increase in energy dissipation for the final series type was the highest (98.4%) in Q_2 and the lowest (84.8%) in Q_{10} compared to the original series. The final series generated an optimal model for energy reduction. The resulting hydraulic jump could provide a high energy release effect and benefit the downstream river stability. The implementation of the USBR Type IV stilling basin in this experiment conformed to the optimal design criteria for the Froude number conditions. It suits the water pressure profile, providing a positive value relative to the floor level of the stilling basin along the stilling basin. The design modification from the original series to the final series led to more optimal conditions. The decrease in flow turbulence decreased the kinetic energy and increased energy dissipation. Therefore, the reduction of cavitation risk in the spillway system can be overcome if the overflow velocity is low.

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