Hydraulic model experiment of energy dissipation on the horizontal and USBR II stilling basin

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Abstract. Flow conditions on overflow systems can result in construction failure, mainly due to the high flow energy. Stilling basin at downstream of the spillway is useful for reducing flow energy. It can reduce the destructive force of water flow. Controlling the hydraulic jump is an important part that includes the jump's energy, length, and height. The physical hydraulic model was carried out with several series, by making a series of bottom lowering of horizontal and USBR II stilling basin. The experimental study is expected to represent flow behavior in the overflow system regarding flow conditions and energy dissipation. Based on the analytical calculation of flow velocity, the amount of flow energy that occurs at each control point is calculated. The control points are the starting point of the spillway, the chute way toe, and flow depth after the hydraulic jump. The energy loss can be calculated for each control point, while the efficiency of energy dissipation on stilling basin is calculated at the downstream flow depth after the hydraulic jump. Velocity calculated by dividing discharge per unit width by water depth which is based on the flow depth measurement data in the hydraulic model.

keywords: energy dissipation, spillway, stilling basin

1. Introduction

Hydraulic jumps are very useful as energy dissipators in supercritical flows. This energy attenuation is useful for preventing erosion that may occur in spillways, steep channels, sluice gates, by reducing the flow velocity in the protected layer to a point where the flow no longer has the ability to erode the bottom of the channel downstream. The hydraulic jump used as an energy dissipator usually covers part or all of the channel and is called a stilling basin. The bottom of the stilling basin is levelled to resist erosion. Aeration plays a main role in energy dissipation in open channel flows with supercritical and fully turbulent conditions. With the same water rate, higher air concentration involves lower friction head losses. This reduction has been quantified using the Manning roughness coefficient [6]. In general, it is rare for a stilling basin to be designed to withstand the entire length of the free jump, as this would be...
very expensive. For this reason, equipment to control the jump is usually installed in the stilling basin. The main purpose of this controller is to shorten the interval between jumps, thereby reducing the size and cost of the stilling basin. Control has several advantages, such as improving the function of the stilling basin, stabilizing the jump movement, and in some cases, also increasing the safety factor [2].

Dam have been built and researched with physical models to ensure that the hydraulic flow conditions that occur are following the plan and can be operated properly. This physical model test was carried out because of the uncertainty factor on the system's overall performance. Each hydraulic structure had a different value for the use limitation [3][5].

Various types of recommended stilling basin used for outlets. For any stilling basin, appurtenances play an important role in reducing the energy of flowing water [9]. Investigating screens as an energy dissipator at the downstream side of small hydraulic structures was already conducted. The results covered a range of Froude numbers between 2.5 and 8.5, screen porosity of 40% and 50%, and gaps of double screens between 1 and 5 cm. According to the experimental results, the screens have more energy loss than free hydraulic jumps, and the amount of energy dissipation increases with the increase of the Froude number. The double screen with a porosity of 40% has the best performance based on computing energy dissipation through screens compared to free hydraulic jump. The presented method is mostly useful for weak and medium jumps, not strong ones in dam weirs. This method is generally suggested for regime transformation in the conveyance channels at the drops, basins entrance, and settling basins [7].

An adverse slope surface at the end stilling basin was also investigated. It is caused to increase energy dissipation and stability of the hydraulic jump. The values of turbulent dissipation in USBR II stilling basin with end adverse slope show that maximum turbulent dissipation occurs at 20-30% start of stilling basin that if this point of view caused to the efficiency of them is increasing [1]. Some numerical modelling was also conducted to investigate the performance of USBR III of the smooth and stepped spillways. The basin flow structure was investigated for both smooth chute and stepped chute cases at two slopes. When a stepped chute is considered, the flow is continuously fed with turbulence throughout the spillway chute. The turbulence generated via impingement is smaller than for a smooth chute. The steps cause an even higher decay of the maximum velocity within the basin, possibly because the inlet flow is more turbulent than a smooth chute. This decrease is for smaller Froude numbers. Also, baffle blocks promote maximum velocity decay. The acceleration zone immediately downstream of the basin entrance is more significant in the profile when the jet impacts baffle blocks [10].

Flow conditions on overflow systems can result in construction failure, mainly due to the high flow energy. The physical hydraulic model test was carried out with several studies by making a series of lowering the bottom of horizontal and USBR II stilling basins. It is conducted to know the best conditions of energy dissipation in the horizontal and USBR II stilling basin. The experimental study is expected to picture better flow behavior in the overflow system regarding flow conditions and energy dissipation. The final results of this study are expected to be used for a broader purpose.

2. Materials and Method
The research was conducted at the River Engineering Laboratory, Department of Water Resources Engineering, Faculty of Engineering, Universitas Brawijaya Malang, Indonesia. The research conducted with hydraulic physical model uses several laboratory facilities and equipment:

a. Hydraulic physical model with an open channel, equipped with an Ogee type overflow,
b. Chute way with a slope of 1:4,
c. The channel width, B = 40 cm,
d. Supply clean water discharge to the model using three water pumps,
e. Water reservoir to supply water to models equipped with a trash rack and a Rechbox flow meter,
f. Point Gauge, Pitot Tube, Waterpass, Measuring Glass, Bucket, Telemetry, and Stopwatch.
In this study, several variables were used to support the results of this study, as follows:

a. Dependent variable: Ogee Type Overflow
b. Independent variables: Discharge (Q), Froude Number (F), Depth of Flow \( y_1, y_2, y_3 \), and Hydraulic jump length \( L_j \)
c. Series Model are: (1) Seri 0 (original design: flat stilling basin and USBR I on the initial bottom elevation), Seri 1, 2, 3, 4, 5: Flat and USBR II with lowered bottom by 5 cm, 10 cm, 15 cm, 20 cm, and 25 cm.

Energy dissipator is USBR II, with the following planning conditions: \( Q = 15101.96 \text{ cm}^3/\text{s}, y_1 = 1.69 \text{ cm}, b = 40.00 \text{ cm}, A = 67.68 \text{ cm}^2, V = 223.15 \text{ cm/s}, Fr = 5.48, \) and \( y_2 = 12.29 \text{ cm} \)

The planning of the USBR II is as follows:

a. The length of the stilling basin, \( L = 4.16 \text{ y}_2 = 51.12 \text{ cm} \)
b. Chute Blocks:
   (i) Chute block height, \( h_1 = y_1 = 1.69 \text{ cm} \)
   (ii) Width of chute block, \( W_1 = y_1 = 1.69 \text{ cm} \)
   (iii) Distance between chute blocks, \( S_1 = y_1 = 1.69 \text{ cm} \)
   (iv) Distance of chute block to wall, \( 0.5 y_1 = 0.85 \text{ cm} \)
c. Edge Block
   (i) End block height, \( h_2 = 0.2 y_2 = 2.46 \text{ cm} \)
   (ii) Width of end block, \( W_2 = 0.15 y_2 = 1.84 \text{ cm} \)
   (iii) Distance between blocks, \( S_2 = 0.15 y_2 = 1.84 \text{ cm} \)
   (iv) Thickness of upper end block, \( 0.02 y_2 = 0.25 \text{ cm} \)

A hydraulic jump occurs when a supercritical flow must change to a subcritical flow. There is a sudden rise in the water level and a large energy loss in the hydraulic jump. Large turbulent eddies are formed at the beginning of the jump. These eddies draw energy from the mainstream, and the eddies are broken up into smaller parts as they flow downstream. In a hydraulic jump, the basic component that affects the energy calculation is the momentum equation [4].

\[
P_1 - P_2 = \rho g (V_1 - V_2) \quad (1)
\]

\[
\left( \frac{1}{2} \rho g y_1^2 - \frac{1}{2} \rho g y_2^2 \right) B = \rho V_1 y_1 (V_1 - V_2) \quad (2)
\]

\[
(y_1 - y_2)(y_1 + y_2) = \frac{2V_1 y_1}{g} (V_2 - V_1) \quad (3)
\]

Meanwhile, from the continuity equation:

\[
g = V_1 y_1 = V_2 y_2 \quad (4)
\]

By combining the equations above, then:

\[
(y_1 + y_2) = \frac{2V_1^2}{g} \frac{y_1}{y_2} \quad (5)
\]

\[
\frac{y_2}{y_1} \left(1 + \frac{y_2}{y_1}\right) = 2F_i^2 \quad (6)
\]

By simplifying the above equation, we get the equation:

\[
\frac{y_2}{y_1} = \frac{1}{2} \left( \sqrt{1 + 8F_i^2} - 1 \right) \quad (7)
\]
Where \( y_1 \) and \( y_2 \) are the water depth before and after the jump and \( F_1 \) is the Froude number of the first cross section before the jump. For supercritical flow in a horizontal rectangular channel, the flow energy will be dissipated by the channel friction resistance, causing a decrease in velocity and an increase in height in the direction of flow.

There are several different types of hydraulic jumps that occur on a flat bottom. Following research conducted by the United States Bureau of Reclamation, these hydraulic jumps can be distinguished based on the Froude number \( F_1 \) flow [2][5]:

1. Critical flow, for \( F_1 = 1 \) critical flow occurs so that no jump can be formed.
2. Waves jump, for \( F_1 = 1 \) to \( F_1 = 1.7 \) waves occur on the water's surface.
3. The jump is weak, for \( F_1 = 1.7 \) to \( F_1 = 2.5 \) a series of waves are formed on the surface of the jump, but the surface of the water downstream remains smooth. The overall velocity is uniform, and the energy loss is small.
4. Oscillating jump, for \( F_1 = 2.5 \) to \( F_1 = 4.5 \), there is an oscillating burst accompanying the base of the jump moving to the surface and back again without a certain period. Each oscillation produces a large irregular wave and causes unlimited damage to the embankment.
5. Steady jump, for \( F_1 = 4.5 \) to \( F_1 = 9 \), the ends of the downstream surface will roll, and the point where the burst velocity is high tends to separate from the flow. Generally, these two things occur on the same vertical surface. The depth of the water below does not so influence movements and jumps that occur. The hydraulic jump is perfectly balanced, and its characteristics are the best. Energy dissipation by 45% - 70%.
6. Strong jump, for \( F > 9 \) and greater, the high burst velocity will separate the blowing roll waves from the jump surface, generating waves downstream. If the surface is rough, it will affect the waves that occur. Jumping movements are rare but effective as energy dissipation can reach up to 85%.

Some of the basic properties of hydraulic jumps in a rectangular channel with a horizontal bottom can be described as follows [2]:

The energy loss in the jump is equal to the difference in specific energy before and after the jump. The amount of energy loss is:

\[
\Delta E = E_1 - E_2 = \frac{(y_2 - y_1)^3}{4y_1y_2}
\]  

(8)

The ratio between the specific energy after the jump to before the jump is defined as the jump efficiency. So the magnitude of the stepping efficiency is:

\[
\frac{E_2}{E_1} = \frac{\left(8F_1^2 + 1\right)^{3/2} - 4F_1^2 + 1}{8F_1^2 \left(2 + F_1^2\right)}
\]

(9)

This equation shows that the jump efficiency is a dimensionless function and only depends on the Froude number of the flow after the jump. The relative loss is equal to \( 1 - E_2/E_1 \), this quantity is also a dimensionless function of Froude's number. The jump height can be defined as the difference between the depth after and before the jump.

\[
y_j = y_2 - y_1
\]

(10)

The length of the hydraulic jump is the distance between the front surface of the hydraulic jump to a point on the surface of the wave roll that immediately goes downstream. The jump length is difficult to determine theoretically but has been investigated experimentally by several hydraulics experts.

The recommended approach in planning the stilling basin for the Froude number \( 2.5 < Fr < 4.5 \) is to increase or decrease (but it is better to increase) the Froude number until it exceeds this magnitude. The Froude number can be increased by increasing the velocity \( V \) or decreasing the water depth, \( y \). The two are connected via the discharge per unit width \( q \), which can be added by reducing the structures' width (\( q = Q/B \)). If the approach is not possible, then two types of stilling basins can be used: (1) USBR type IV, equipped with a large front block that helps strengthen the eddies. (2) Baffle-block-type basin
(Donnelly and Blaisdell, 1954). The big drawback of this pool is that in this structure, anything that floats can get caught. It causes the pool to overflow, and the obstruction blocks break. Also, the manufacture of barrier blocks requires reinforced concrete [2][3][4][5].

For Froude numbers exceeding 4.5, the water jump can be steady, and energy dissipation can be achieved properly. Special USBR type III was developed for these numbers. If the use of barrier blocks and front blocks is not feasible (because the structure is made of masonry) the stilling basin must be designed as a jumping water pool with an end sill. This stilling basin will be long but shallow [2][4].

3. Results and Discussion

Based on the analytical calculation of flow velocity, the flow energy that occurs at each control point is calculated. The control points are the starting point of the initial energy on the spillway (E₀), energy on the chute way toe (E₁), and energy after the hydraulic jump (E₂). At the starting point of overflow, a critical depth (yc) and its critical energy are the same as initial energy (E₀=E₀). At the toe of the chute way occurs y₁, and the energy is E₁. And downstream after the jump, water depth is y₂, and the energy is E₂.

The values of E₀, E₁, and E₂ will determine the amount of energy loss (ΔE) and the efficiency of energy dissipation on stilling basin. The energy loss can be calculated for each control point, while the efficiency of energy dissipation on stilling basin is calculated at the downstream flow depth after the hydraulic jump (y₂). Based on the flow depth measurement data (yᵢ) in the hydraulic model, then the calculation of velocity is carried out based on analytical calculations, with the general equation that flow velocity is the discharge per unit width divided by the water depth, \( V = \frac{q}{y} \) (m/s).

![Figure 1. (a) Horizontal Apron (b) USBR Type II [5]](image)

![Figure 2. Average energy dissipation effectiveness (calculation)](image)
Based on the analytical calculations in Figure 2, the flat stilling basin has a higher average energy dissipation than USBR II for all model series. The energy attenuation of the flat stilling basin is in the range of 89% to almost 92%. At the same time, USBR II is in the range of 88% to almost 91%.

**Figure 3.** Effectiveness of energy dissipation in flat stilling basin ($V_{\text{calculation}}$)

Based on the analytical calculation of the velocity presented in Figure 3, the flat still has a decrease in average energy dissipation for the increase in discharge. The energy attenuation of the flat stilling basin decreases from 92% to almost 87%. For a flat stilling basin, the greater the flow through, the smaller the energy dissipation.

**Figure 4.** The effectiveness of energy dissipation in the USBR II ($V_{\text{calculation}}$)

Based on the analytical calculation of the velocity presented in Figure 4, the USBR II has a decrease in average energy dissipation for the increase in an overflow of discharge. The energy attenuation of the USBR II is decreased from almost 92% to get near to 86%. For the USBR II, the larger the flow rate, the lower the energy dissipation ability.
**Figure 5.** Effectiveness of energy dissipation at $Q_1 = 11.00$ l/s ($V_{\text{calculation}}$)

**Figure 6.** Effectiveness of energy dissipation at $Q_2 = 13.02$ l/s ($V_{\text{calculation}}$)

**Figure 7.** Effectiveness of energy dissipation at $Q_3 = 15.10$ l/s ($V_{\text{calculation}}$)
Figure 8. Effectiveness of energy dissipation at $Q_4 = 17.25$ l/s ($V_{\text{calculation}}$)

Figure 9. Effectiveness of energy dissipation at $Q_5 = 19.45$ l/s ($V_{\text{calculation}}$)

Based on the analytical calculation of the velocity presented in Figures: 5, 6, 7, 8, and 9, the flat stilling basin has a better average energy dissipation than USBR II. The greater the height of flow from crest to bottom, the greater energy dissipation efficiency. For $Q = 11$ l/s, flat stilling basins have energy dissipation ranging from 90.5% to almost 92.5%. USBR II has energy dissipation ranging from 89.5% to approximately 92%. For $Q = 13.02$ l/s, flat stilling basins have energy dissipation ranging from 90% to 92%. USBR II has energy dissipation efficiency ranging from 89% to close to 93%. At the discharge of $Q = 13.02$ l/s and in the deepest bottom (series 5), the energy dissipation performance of USBR II is better than in the flat stilling basin. At a discharge of $Q = 15.10$ l/s, the flat stilling basin has energy dissipation ranging from 89% to approximate 92%. USBR II has energy dissipation ranging from 88.5% to get near 90.5%. For $Q = 17.25$ l/s, the flat stilling basin has energy dissipation ranging from 88% to almost 91%. USBR II has energy dissipation efficiency ranging from 87% to close 89.5%. At a discharge of $Q = 19.45$ l/s, the flat stilling basin has energy dissipation ranging from 87.5% to almost 90%. USBR II has energy dissipation ranging from 86.5% to almost 89%.
Figure 10. Average energy dissipation effectiveness ($V_{\text{observation}}$)

Based on the velocity measurements in the hydraulic model presented in Figure 10, the USBR II has a higher average energy dissipation than the flat stilling basin for several series models (Series 3, 4, 5). The energy attenuation of the flat stilling basin is in the range of 89% to almost 90%. At the same time, USBR II is in the range of 88% to almost 91%.

Figure 11. Effectiveness of energy dissipation in flat stilling basin ($V_{\text{observation}}$)

Based on the velocity measurements in the hydraulic model presented in Figure 11, the flat stilling basin has a decreased average energy dissipation for the flow rate increase. The energy attenuation of the flat stilling basin decreases from 92% to almost 86%. For a flat stilling basin, the greater the flow through, the smaller the energy dissipation efficiency.
Based on the velocity observations in the hydraulic model presented in Figure 12, the USBR II has decreased average energy dissipation for increased flow discharge. The energy attenuation of the USBR II decreases from 93% to almost 86%. For the USBR II, the larger the flow rate, the lower the energy dissipation ability.

Figure 13. Effectiveness of energy dissipation at $Q_1 = 11.00 \text{ l/s (}$V_\text{observation}$)$
Figure 14. Effectiveness of energy dissipation at $Q_2 = 13.02$ l/s ($V_{\text{observation}}$)

Figure 15. Effectiveness of energy dissipation at $Q_3 = 15.10$ l/s ($V_{\text{observation}}$)

Figure 16. Effectiveness of energy dissipation at $Q_4 = 17.25$ l/s ($V_{\text{observation}}$)
Based on the velocity measurements in the hydraulic model, presented in Figure: 13, 14, 15, 16, and 17, the flat stilling basin not always has a better average energy dissipation efficiency than USBR II. However, the greater the height of drop flow, the greater energy dissipation. At a flow rate \( Q = 11 \text{ l/s} \), a flat stilling basin has energy dissipation ranging from 90.5% to almost 92.5%. USBR II has energy dissipation ranging from 89.5% to almost 91.5%. At a flowrate \( Q = 13.02 \text{ l/s} \), the flat stilling basin has energy dissipation ranging from 90% to almost 91.5%. USBR II has energy dissipation ranging from 89% to almost 92.5%. At discharge \( Q = 13.1 \text{ l/s} \), at the highest depth of fall, USBR II has better reducing flow energy than flat stilling basin. At a discharge \( Q = 15.10 \text{ l/s} \), the USBR II has a better average energy dissipation than the flat stilling basin. Flat stilling basin has energy dissipation ranging from 88% to almost 90%, and USBR II has energy dissipation ranging from 88.5% to almost 90.5%. While at a discharge \( Q = 17.25 \text{ l/s} \), the flat stilling basin has a better average energy dissipation or is relatively the same as USBR II. A flat stilling basin has energy dissipation ranging from 88% to almost 90%. At the same time, USBR II has energy dissipation ranging from 87% to almost 90%. At a flowrate \( Q = 19.45 \text{ l/s} \), the USBR II has a better average energy dissipation than the flat stilling basin. Flat stilling basin has energy dissipation ranging from 86.5% to almost 88%, whereas USBR II has energy dissipation ranging from 87% to approximate 89%.

Based on the results of calculations made from the results of running hydraulic model tests, it can be seen that the energy reduction that occurs always exceeds 88%. Thus, it means that the energy flow that occurs in the channel is less than 12% of the initial energy. This high dissipation rate is due to a stilling basin in which a hydraulic jump occurs.

The energy attenuation that occurs, based on the measurement data of flow depth \( y_i \) and flow velocity \( V_i \), shows that the attenuation of the flat stilling basin is better than the USBR II in Series 0 Series 1 at the same discharge. As for Series 2, Series 3, Series 4, and Series 5, the energy dissipation by the USBR II is better than the flat stilling basin. This phenomenon shows that with a higher difference in overflow height, the performance of the USBR II is better than the flat stilling basin.

However, this is not the case based on the depth measurement data \( y_i \) and the calculated velocity \( V_i \). The performance of the flat stilling basin is not always better than the USBR II. The difference in results between analytical calculations and measurements can be due to several things. One of the main differences is that the analytical calculation does not include any factors for air entrainment (natural aeration or self-aeration). In contrast, in the measurement in the model, this natural aeration process has occurred to affect the measurement results. One of the effects of natural aeration is that the depth of flow measurement will be higher than from analytical calculation.
In theoretical calculations, the depth and flow velocity at the overflow toe and the depth and flow velocity after the hydraulic jump will differ for each discharge and fall height. However, because the measurement conditions were carried out in the model tested in the laboratory on a small flume scale, the difference in the calculation and measurement was relatively small. Theoretically, the largest change in depth and flow velocity is due to the loss of energy due to channel roughness.

The depth and flow velocity at the upstream end of the USBR II will experience changes due to impact blocks on the chute way toe. The USBR II is also equipped with downstream impact blocks. These impact blocks disrupt the flow at the toe of the chute way channel and the downstream end of the USBR II, so that flow attenuation can take place properly along the stilling basin.

Figure 18. Observation of hydraulic jump behavior on USBR II
4. Conclusion

1. The condition of the depth, flow rate, and energy attenuation in the stilling basin is carried out by comparing the conditions of the flat stilling basin and USBR II. The depth of flow in the USBR II stilling basin experienced an increase in the water level at the toe of the chute way for all flow discharges. In USBR II, equipped with baffle blocks at the toe and end point of the stilling basin, the flow becomes more turbulent than the flat stilling basin that is not equipped with baffle blocks. Therefore, it is said that $y_1 \text{ USBR II} > y_1 \text{ flat stilling basin}$. The depth of flow after the hydraulic jump ($y_2$) was also higher in USBR II than in the flat stilling basin ($y_2 \text{ USBR II} > y_2 \text{ flat stilling basin}$). Velocity at the toe of chute way channel, $V_1 \text{ USBR II} < V_1 \text{ flat stilling basin}$, $V_2 \text{ USBR II} < V_2 \text{ flat stilling basin}$.

2. The flow reduction that occurs in hydraulic models always exceeds 88%. Thus, it means that the flow energy in the channel is less than 12% of the initial flow energy. Energy dissipation occurs in the energy dissipator in which a hydraulic jump occurs. Energy attenuation based on the measurement data of flow depth ($y_i$) and velocity ($V_i$), shows that the dissipation of flat stilling basin is better than USBR II in Series 0 and Series 1. Whereas for Series 2, Series 3, Series 4, and Series 5, the energy dissipation by USBR II is better than flat stilling basin. This phenomenon shows that on higher discharge with a higher difference in overflow height, the performance of the USBR II is better than a flat stilling basin.

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