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The hydraulics analysis of the USBR stilling basin type of a dam under multiple flow discharge scenarios (A case study of Temef Dam, East Nusa Tenggara, Indonesia)

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Abstract. Temef Dam was built to meet the needs of water supply and irrigation. Climate change and dam construction exaggerate security issues related to water resources. One important part of dam construction is the stilling basin, which can dissipate the energy from the discharge of the spillway and preserve the dam from flooding and degradation. The purpose of this study was to determine the most appropriate USBR stilling basin type under multiple flow discharge scenarios. The analysis involved 1) determining the designed flood hydrograph and 2) hydraulic analysis to select the USBR stilling basin. The study results showed that 1) analysis of the designed flood hydrograph for a 100-year return period up to the PMF showed values from 890 m³/second to 4300 m³/second and 2) the appropriate stilling basin is a USBR Type II. The results also presented detailed hydraulic structure calculations (stilling basin length = 47 m, stilling basin wall height = 15 m, steep channel blocks = 14 pieces, and indentation blocks = 9 pieces). This study is very useful because the right design will be able to ensure the smooth operation of the dam and prevent the dam from damage.

1. Introduction
Climate change occurrences change the amount and intensity of precipitation, disturb the hydrological cycle, and influence a dam project [1]. Due to climate change impact, the flood concept is revisited, where the revamped flows frequently surpass the permissible design flows. Lack of natural disasters impacts understanding, dam is at high risk for failure due to inadequate current storage and spill capability [2]. In dam management, the excess discharge is generated by a spillway from an elevated tank to a stilling basin for waste dissipation before it flows back into the water. Optimized conception of Spillway-stilling (downstream) flow systems minimize river scouring and management of litter degradation [3].

Temef Dam construction in Timor Tengah Selatan Regency, NTT, is based on the lack of raw water availability during the area's dry season. The construction of the Temef Dam is planned to be able to accommodate 77 million cubic meters of water, which will later become a source of raw water to irrigate 10,000 hectares of irrigated land. In its planning, the safety aspects for both the structure itself and the dam's environment become important to be considered. The hydraulic aspect is one of the keys to achieving this safety. Extremely swift and uncontrolled water flow that overflows from the spillway can be dangerous for the river environment downstream. Large deviations of water levels between being dammed upstream and flowing downstream of the dam can result in high water flow velocities.
Therefore, there is a need for water attenuation when water overflows from the overflow structure to safeguard the environment from the effects of water flowing downstream of the river.

At the Temef Dam the deviation between the upstream and downstream of the dam is 50 m with a $Q_{100 \text{ Outflow}} = 785.567 \text{ m}^3/\text{sec}$ and $Q_{1000 \text{ Outflow}} = 1143.688 \text{ m}^3/\text{sec}$. The difference between high elevation and large discharge requires damping by way of a stilling basin.

Stilling basins commonly used in Indonesia dams are USBR I, USBR II, USBR III and USBR IV types. According to the book Embankment Type Dams written by Dr. Suyono Sosrodarsono in 1977, the type of stilling basin for a dam is determined by two main parameters: the Froude number (Fr) and the unit discharge ($q$) from the overflow runoff. Establishing the dimensions of a stilling basin includes establishing the stilling basin’s height, the length of the stilling basin, and the damping block, all of which are regulated in the book according to the type of the stilling basin.

Recent developments in the construction of a dam show that the dam’s capacity to withstand flooding is very important so that the operation of the dam can run smoothly, which can prevent the occurrence of a dam break which is very dangerous in the surrounding environment [4]. Stilling basin USBR type II is quite effective in dampening the energy arising from the end of the spillway. This is indicated by jumping hydraulics going for the design discharge $Q_{100\text{th}}$ and $Q_{1000\text{th}}$ is still in the stilling basin [5]. The experimental findings revealed that the energy dissipation improved with the application of the pendulum sill. It was discovered the pendulum sill’s optimal position is in the first half of the hydraulic jump [6]. Several previous researchers have researched the stilling basin design. What distinguishes this study from previous studies, in addition to the study location, is that in this study, designed safety controls were added through $Q_{1000}$ and $Q_{PMF}$. The purpose of this study was to determine the most appropriate USBR stilling basin type under multiple flow discharge scenarios.

2. Methodology

2.1. Study location

Timor Tengah Selatan Regency has an area of 3,947 km$^2$, of which 44.93 km$^2$ are rice fields. This Regency has a population of 465,970 people divided among 32 sub-regencies and 266 villages. Topographically, This regency covers upland or mountainous areas up to 2000 meters above sea level (masl) and lowlands or coastal areas. The study location is shown in Figure 1.

![Figure 1. Study location](image-url)
2.2. Data collection
For this study, the data were utilized to analyze and determine the type of stilling basins and appropriate dimensions for them included hydrological analysis data, flood tracking data, and flow front profile data at the dam peak, side channel, and spillway.

3. Results and discussion

3.1. Flood routing
The system of operations of a dam requires studying the amounts of inflow and outflow and the maximum discharge that spills out when the reservoir water level exceeds normal levels or during floods. The maximum outflow is the value for planning the dimensions of the stilling basin. The outflow hydrograph of a reservoir can be analyzed based on the inflow hydrograph from hydrological analysis with the hydrologic routing method. The flood routing diagram is shown in Figure 2 [8]. The diagram shows the changing of inflow and outflow discharge with time. The maximum inflow discharge (889.61 m³/s) was reached after about 13 hours, while the maximum outflow (785.57 m³/s) was reached later than the maximum inflow discharge after about 15 hours.

![Figure 2. Flood routing diagram (Q100)](image)

3.2. Determining the stilling basin type
The process of determining the stilling basin type requires data on the characteristics of the water flow that will enter through the stilling basin. In this case, data on water characteristics from the chute way is required. The water flow characteristics include channel width, water depth, and flow rate (Q), which are described in Table 1 below:

Based on Table 1, the water depth's value downstream of the chute way (it is listed in the last row of depth h) is the same as the water depth upstream of the stilling basin. The following are the calculations for the Froude number (Fr) where formula for Manning corresponding to the Froude number Fr = v/(gd)^0.5 [9], and the unit discharge (q):

\[
V (Q_{100}) = \frac{(Q_{\text{outflow 100}})}{(b \cdot d_1)} = \frac{(785.57 \text{ m}^3/\text{sec})}{(30 \text{ m} \cdot 1.06 \text{ m})} = 24.70 \text{ m}^2/\text{sec}.
\]
The unit discharge \( q \) and Froude number \( Fr \) are defined as:

\[
\text{Unit discharge (q)} = \frac{(Q_{\text{outflow}} 100)}{b} = \frac{(785.57 \text{ m}^3/\text{sec})}{30 \text{ m}} = 26.186 \text{ m}^3/\text{sec/m.}
\]

\[
\text{Froude number (Fr)} = \frac{V}{\sqrt{g \cdot d_1}} = \frac{24.70}{\sqrt{9.8 \cdot 1.06}} = 7.66
\]

Unit discharge \( q = 26.186 \text{ m}^3/\text{sec} \) and Froude number \( Fr = 7.66 \) are the parameters to determine the appropriate stilling basin. Based on the above calculations, the determination of the stilling basin type is shown in Table 2.

### Table 1. Water flow characteristics

| Distance X (m) | Channel Width b (m) | Depth h (m) | Area A (m²) | Velocity V (m/sec) | Channel Base Z (m) | Water Level (m) |
|----------------|---------------------|-------------|-------------|-------------------|-------------------|-----------------|
| 0.0            | 30.00               | 5.86        | 1758.80     | 4.47              | 359.00            | 364.86          |
| 4.0            | 30.00               | 2.57        | 77.10       | 12.06             | 356.16            | 358.33          |
| 11.4           | 30.00               | 2.17        | 65.10       | 14.88             | 356.16            | 354.26          |
| 18.7           | 30.00               | 1.93        | 57.90       | 17.72             | 356.16            | 352.30          |
| 26.0           | 30.00               | 1.76        | 52.80       | 18.00             | 356.16            | 352.30          |
| 33.4           | 30.00               | 1.64        | 49.20       | 18.50             | 356.16            | 352.30          |
| 40.7           | 30.00               | 1.54        | 46.20       | 18.00             | 356.16            | 352.30          |
| 48.0           | 30.00               | 1.48        | 44.40       | 17.72             | 356.16            | 352.30          |
| 55.3           | 30.00               | 1.41        | 42.30       | 18.57             | 356.16            | 352.30          |
| 62.7           | 30.00               | 1.36        | 40.80       | 19.30             | 356.16            | 352.30          |
| 70.0           | 30.00               | 1.31        | 39.30       | 20.03             | 356.16            | 352.30          |
| 77.3           | 30.00               | 1.26        | 37.80       | 20.70             | 356.16            | 352.30          |
| 84.7           | 30.00               | 1.23        | 36.90       | 21.33             | 356.16            | 352.30          |
| 92.0           | 30.00               | 1.19        | 35.70       | 21.92             | 356.16            | 352.30          |
| 99.3           | 30.00               | 1.17        | 35.10       | 22.46             | 356.16            | 352.30          |
| 106.7          | 30.00               | 1.14        | 34.20       | 22.97             | 356.16            | 352.30          |
| 114.0          | 30.00               | 1.12        | 33.60       | 23.44             | 356.16            | 352.30          |
| 121.3          | 30.00               | 1.10        | 33.00       | 23.88             | 356.16            | 352.30          |
| 128.7          | 30.00               | 1.08        | 32.40       | 24.30             | 356.16            | 352.30          |
| 136.0          | 30.00               | 1.06        | 31.80       | 24.70             | 356.16            | 352.30          |

### Table 2. Determining the stilling basin type

| USBR I | USBR II | USBR III | USBR IV |
|--------|---------|----------|---------|
| Criteria | q < 18.50 | Fr < 4.50 | q > 18.50 | Fr > 4.50 | q < 18.50 | Fr > 4.50 | q > 18.50 | 2.50 < Fr < 4.50 |
| Planned Value | 26.186 | 7.66 | 26.186 | 7.66 | 26.186 | 7.66 | 26.186 | 7.66 |
| Notes | Bad | Bad | Good | Good | Bad | Good | Good | Bad |
| Utilized | Not Utilized | Utilized | Not Utilized | Not Utilized |

Based on the unit discharge \( q \) value, the USBR stilling basin type II and IV met the criteria. However, based on the Froude number, the USBR stilling basin type II and III met the criteria. Thus, it can be concluded that the appropriate stilling basin following the calculation is the USBR type II stilling basin (Figure 3) because the type met both criteria unit discharge \( q \) and Froude number.
3.3. *Hydraulic analysis of the stilling basin*

The hydraulic analysis of the stilling basin was performed to determine the dimensions of the stilling basin. The basin dimensions (length, wall height, steep channel block, and channel block with indentation) were calculated based on Sosrodarsono and Takeda [10]. The following results were obtained:

Stilling basin length \((L)\) = 47 m  
Stilling basin wall height = 15 m  
Steep channel block:
  - Steep channel block width = 1.06 m  
  - Steep channel block height = 1.06 m  
  - Steep channel block distance = 1.06 m  
  - Number of steep channel blocks = 14 pieces  
Channel block with indentation:
  - Sill width with indentation = 1.64 m  
  - Sill height with indentation = 2.19 m  
  - Threshold distance with indentation = 1.64 m  
  - Width at the top of the indentation threshold = 0.22 m  
  - Number of thresholds with indentations = 9 pieces

The results showed that by using the above dimensions, the USBR Type II stilling basin can withstand the discharge conditions for \(Q_{1000}\) because the dimensions were designed based on the Froude number and discharge value.

3.4. *Safety control*

The safety control in the stilling basin design in this study utilized the discharges \(Q_{1000}\) and \(Q_{PMF}\). The safety control of the basin design is described in Table 3 below.

| Time Period | \(Q_{1000}\) | \(Q_{PMF}\) | Fr | q     | Remarks |
|------------|-------------|-------------|----|-------|---------|
| Control    | Fr > 4.50   | q > 18.5    |    |       | Safe    |

The Froude number of \(Q_{1000}\) (7.51) and \(Q_{PMF}\) (4.93) are higher than 4.50 (control value), so the stilling basin design is safe based on the Froude number. At the same time, the unit discharge value \(q\) of \(Q_{1000}\)
(38.12 m³/s/m) and $Q_{PMF}$ (137.08 m³/s/m) are higher than 18.5 m³/s/m (control value), so the stilling basin design is safe based on the unit discharge $q$ for $Q_{1000}$ and $Q_{PMF}$.

4. Conclusion
Due to climate change, the need for water supply and irrigation increases day by day. One important measure is building a dam designed to make sure the water supply in an area is sufficient for many purposes. This study performed one important step in designing Temef Dam in East Nusa Tenggara, specifically determining the most appropriate USBR stilling basin type in Temef Dam. For that purpose, the flood hydrograph for 100-year return period and hydraulic analysis were carried out in this study. Unit discharge value \( q = 26.186 \text{ m}^3\text{/s/m} \) and Froude Number \( Fr = 7.66 \) were obtained. The selected type of stilling basin was the USBR type II stilling basin. Based on hydraulic analysis, type II stilling basin design at the Temef Dam, including length, width, steep channel block details, and indentation threshold block details, was obtained. The design of the USBR type II stilling basin at Temef Dam is safe for a 1000-year return discharge \( Q_{1000} \) and PMF return discharge \( Q_{PMF} \) because based on the safety control values, Froude number \( Fr \) was higher than 4.50 and unit discharge value \( q \) was higher than 18.5.

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