DESIGN FOR RESILIENT PERFORMANCE OF HYDRAULIC STRUCTURES

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ABSTRACT

Hydropower is the most efficient form of renewable energy that harnesses the power of flowing water to generate electricity. It is a clean, reliable, and sustainable source of long-lasting electricity generation. It is considered one of the most widely used and reliable renewable energy sources globally with the smallest amount of greenhouse gas emissions. Many countries count on hydropower to meet their electricity demand, contributing to energy security and reduced dependence on fossil fuels. Hydropower is a significant source of renewable energy in Bhutan, and hydraulic spillway facilities play a crucial role in ensuring the safety and efficient operation of these power plants. Investigating the design and performance of these spillway facilities is crucial for increasing their service life and reducing repair maintenance costs. Understanding the factors influencing their performance is essential for designing and rehabilitating hydraulic structures. The investigation was carried out to examine the design and performance of the hydraulic spillway facilities at the Kurichhu Hydropower Plant in Bhutan, focusing on parameters such as Froude number, conjugate depths, and the level of conjugate depth. The investigation involves data collection and analysis of flood events. Gumbel's method is used for flood frequency analysis to obtain peak flood discharge corresponding to different return periods based on recent inflow data sets. Additionally, calculations are conducted to determine the necessary gate openings at various discharges to maintain the constant upstream water surface elevation at the full reservoir level. With this, the flow velocity required to protect the spillway facilities from damage during multi-gate operations is determined. The study reveals that the height of the gate opening mainly influences the flow velocity, and the number of gate openings influences the amount of discharge. Small opening gate height was found with high crest velocity due to a higher pressure head difference. Moreover, the evaluation of hydraulic parameters indicated that the chosen spillway design and stilling basin geometry are adequate to guarantee a long-lasting safe structural performance with some rehabilitation. The additional concrete strengthening construction materials and modification in hydraulic structure i.e. a baffle wall and chute are suggested to improve the performance of the spillway and stilling basin.

***Keywords**: Kurichu hydropower, flood frequency, spillway, gate operation, flow velocity, stilling basin.*

1. INTRODUCTION

The gated spillway operation plays a vital role in managing river catchment flow and preventing floods in the dams and reservoirs. These gates control the release of excess water during extreme events, mitigating the overflow risk and protecting downstream areas. The safe release of excess water through dams and reservoirs is essential. Several studies concerning gate operation strategies have been carried out for safe operation to reduce the risk of structural damage, Salehi (2022). The multi-stage gate operation was tested to minimize the associated flood damage for different flood events, indicating the importance of flood forecasting data. Unver et al. (1990) developed a real-time optimal flood operation methodology and model for reservoir systems. The model establishes a non-linear flood routing method for the safe release of flood from the reservoir, tested in the case study of Lake Travis on the Lower Colorado River in Texas with adequate flood results. Sun (2018) carried out a real-time operation risk analysis based on the stochastic optimization method. The method was implemented to evaluate operational risk analysis for decision-making in the Daduhe River basin flood-controlled system with higher reliability. Karaboga et al. (2008) proposed a fuzzy logic controller design to increase accuracy and efficient solutions for dam and reservoir operations during extreme flood events. Focusing on the importance of flood events over the controlling spillway gated structure.

Several spillway surfaces and stilling basins have been affected due to inappropriate gate regulation strategies. The guidelines developed for gate regulation over the gated spillway are still lacking to reduce the risk of damage to the hydraulic structure. This paper mainly focuses on the design of the resilient performance of a gated spillway in Kurichhu Hydropower Plant in Bhutan. The key objectives of the study for defining the safety assessment of the spillway and stilling basin are :

- To evaluate the different return periods of flood events (HQT) and define the project's Probable Maximum Flood (PMF).
- Re-assessment of the spillway capacity and stilling basin length sufficiency, based on the recent hydrological data sets.
- To define the safe gate regulation strategy at a constant maximum reservoir level (MRL) during the flood event.
- Suggest appropriate application of construction materials for reducing the damage risk.

2. MATERIALS AND METHODS

2.1 Area of Interest

The Kurichhu Hydropower Plant (60MW) study area of Druk Green Power Corporation (DGPC) lies in eastern Bhutan in Gyalpozhing, Mongar, DGPC (2021). The project has a mean annual energy generation of 400 GWh, a design flow rate of 212 m^3/s, and a net head of 32m. The headworks of the dam site consist of five operational gated spillways as shown in Figure 1, DGPC (2021).

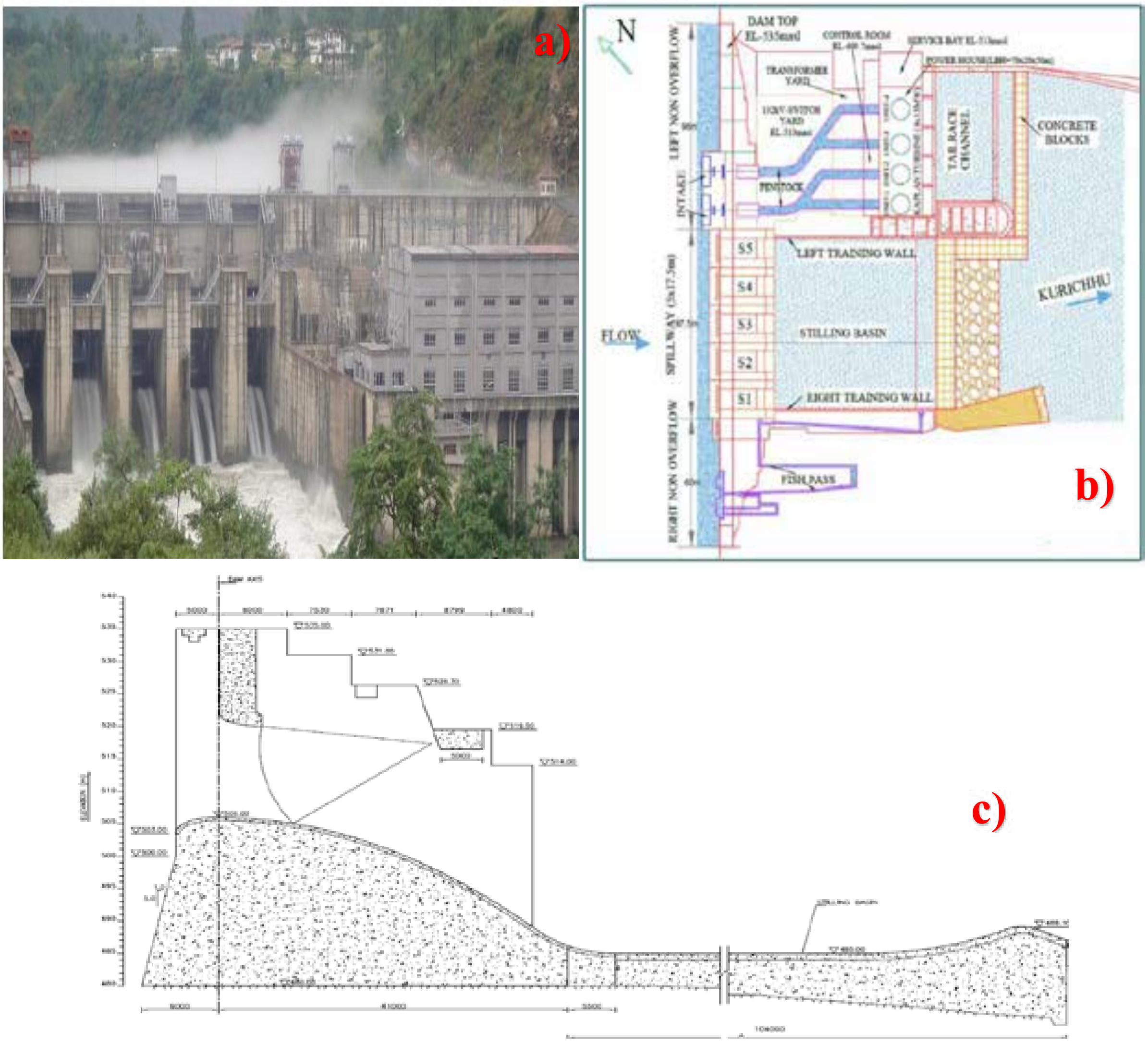


Figure 1 : Kurichhu Hydropower: (a) Project site, (b) Headworks plan view, and (c) Spillway section

2.2 Risks and Challenges During Gate Operation

The operation and maintenance inspection by DGPC in 2021 identified severe damage in the spillway and stilling basin due to abrasion as shown in Figure 2. The exposure of the reinforcement bar was observed, as a result of higher bed shear stress due to higher flow velocity. The main cause of damage was stated mainly due to unsafe asymmetrical gate regulation and the application of low-strength concrete surface construction materials.

Figure 2 : Concrete abrasion over the spillway surface (a) stilling basin (b), DGPC (2021)

2.3 Flood Frequency Analysis

The statistical analysis was carried out to determine the flood flow events (HQT) associated with the return period, considering the recent hydrological data set from the nearest gauging stations of the Kurichhu River Dam site. The best-fit nonlinear equation of Gumbel's distribution was adopted to increase the accuracy of the flood events. The peak of the annual-daily discharge of 15-years of data set was considered from the year 2008 to 2022.

The adopted equations of Gumbel's distribution, Zelenhasic (1970) are:

$$\bar{X} = \frac{\sum X}{N} \ and \ \sigma_X = \sqrt{\frac{1}{(N-1)}\sum_{i=1}^{N}(X_i - \bar{X})^2} \quad (1)$$

$$T = \frac{(N+1)}{M} \quad (2)$$

$$Y_T = -\left[Ln.Ln.\left(\frac{T}{T-1}\right)\right] \quad (3)$$

$$K = \frac{Y_T - \overline{Y_n}}{S_n} \quad (4)$$

Where,

x = discharge value, N = number of samples, $\bar{X}$ = mean value and σ_X = standard deviation , T = return period , M = rank number , Y_T = reduced variate, $\overline{Y_n}$ = reduced mean and S_n = Reduced standard deviation

2.4 Flow rate

The equivalent discharge through the gated spillway was estimated considering an orifice flow as shown in Figure 3. The applied flow rate relation, USBR (1973) is represented below:

$$Q = \frac{2}{3} \cdot \sqrt{2 \cdot g} \cdot C \cdot L \cdot \left(H_1^{\frac{3}{2}} - H_2^{\frac{3}{2}} \right)$$

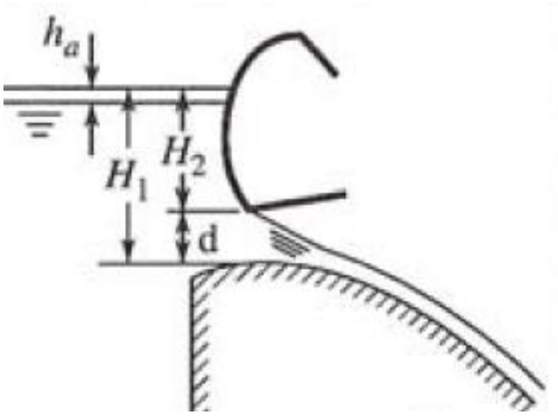


Figure 3 : Gated spillway

Where,

Q = total design discharge (m³/s), C = coefficient of discharge , L = width of spillway (m), g = acceleration due to gravity (m/s²), H_1 = upstream water head above the crest (m), H2 = upstream water head above the bottom of the gate (m)

2.5 Conjugate Depth and Jump Length

The hydraulic parameters were estimated through energy relations as illustrated in Figure 4. The jump height (Y2) due to the formation of the hydraulic jump in the stilling basin was evaluated through Belanger's equation, Chaudhry, (2008):

$$y_2 = \frac{y_1}{2} \cdot \left[\sqrt{1 + 8 \cdot {Fr_1}^2} - 1 \right] \qquad (6)$$

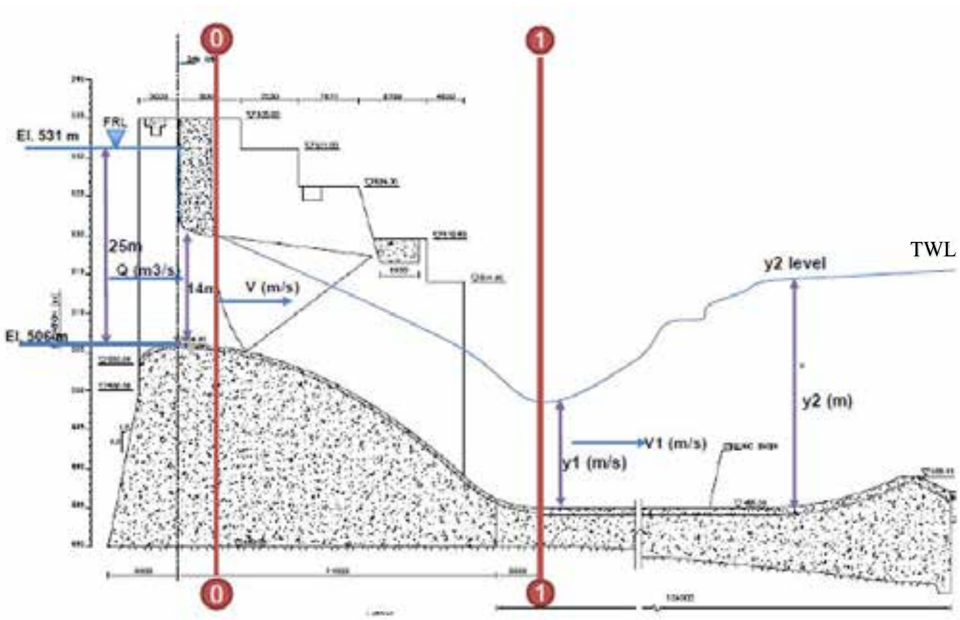


Figure 4: Spillway and Stilling basin configuration

Where, Y_1 and Y_2 are the conjugate depth, $Fr_1 = \frac{V_1}{\sqrt{gY_1}}$ is the Froude number.

The jump length was estimated with different empirical relations as presented in the tabular formatted in Table 1, for design sufficiency evaluation of the existing Kurichhu project stilling basin.

Table 1 : Jump length relation, Peterka (1978)

S.N	Name	Empirical relation
1	Rouse	$L = 2.5 \cdot y_1 \cdot \left(\sqrt{1 + 8 \cdot Fr_1{}^2} - 1\right)$
2	Smetana	$L = 3 \cdot y_1 \cdot \left(\sqrt{1 + 8 \cdot Fr_1{}^2} - 3\right)$
3	Safranez	$L = 5.9 \cdot y_1 \cdot Fr_1$
4	Einwatcher	$L = 8.3 \cdot y_1 \cdot (Fr_1 - 1)$
5	Woycicki	$L = (y_2 - y_1) \cdot \left(8 - 0.5 \cdot \frac{y_2}{y_1}\right)$
6	Chertusov	$L = 10.3 \cdot y_1 \cdot (Fr_1 - 1)^{0.81}$
7	Pavlovsky	$L = \left\{2.5 \left[1.9 \cdot \left(\frac{y_2}{y_1} - 1\right)\right]\right\} \cdot y_1$
8	Sienchi	$L = 5 \cdot (y_2 - y_1)$

The tailwater level (TWL) at 160m downstream side of the dam was evaluated through the cross-section profile using the HEC-RAS model. The rating curve representing downstream water levels for different flow is presented in Figure 5.

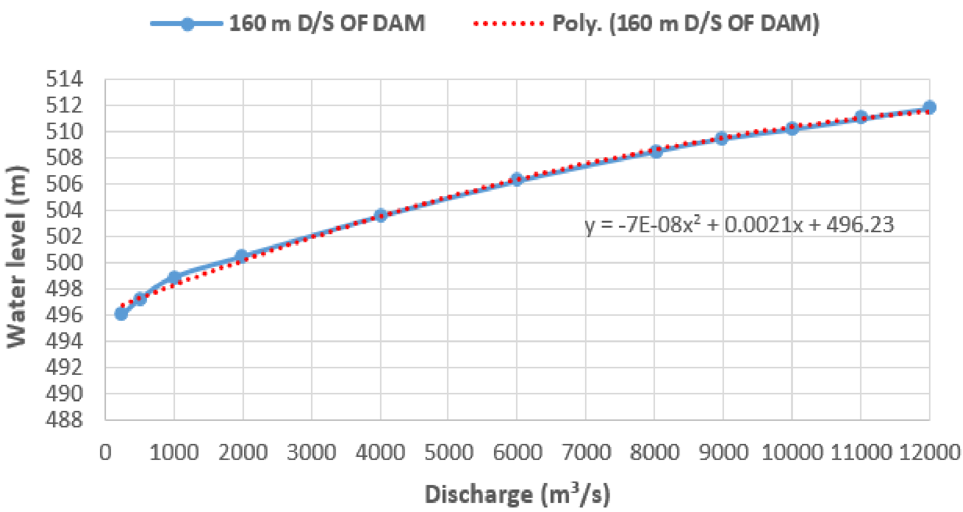


Figure 5 : Downstream rating curve

3. RESULTS AND DISCUSSIONS

3.1 Hydrologcial analysis

The hydrological analysis is crucial to check the capacity of the spillway. The water level fluctuation due to unexpected flood events might impact the built hydraulic structures. The spillway capacity should be checked against different return period of flood event. The flood frequency analysis was carried out to evaluate the different flood events using best-fit Gumbel's distribution which has been plotted in Figure 6. The 15-years data set of annual-daily discharge from the gauging station of Kurichhu River was implemented for flood frequency analysis.

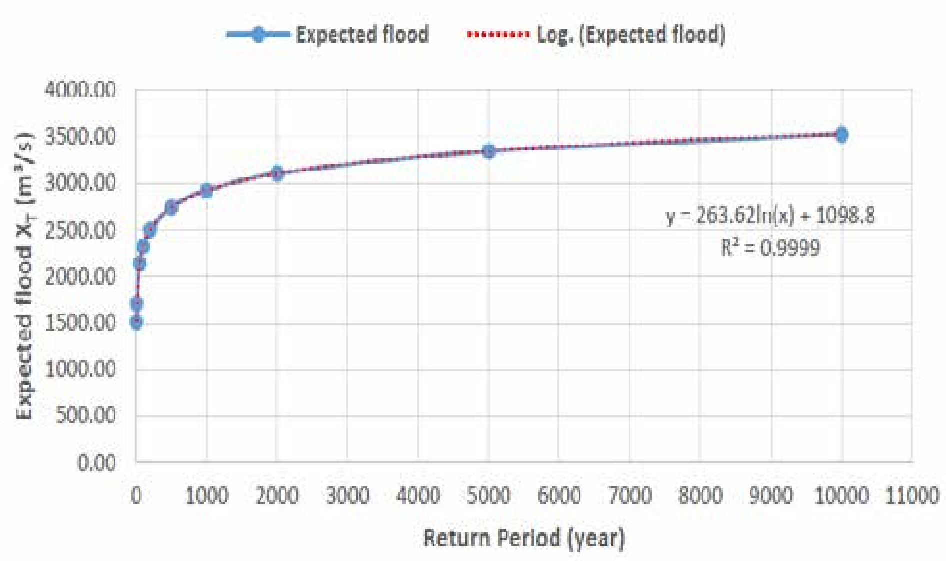


Figure 6 : Flood frequency curve and logarithmic regression equation

The obtained results through Gumbel's relation were plotted to build a logarithmic relation between the return period and expected flow rates. The results show the flood events versus return period adequately behave logarithmic form with R2 0.99. The results for 5, 10, 50, 100, 200, 500, 1000, 2000, 5000, and 10000 years flood events (HQT) flow rate have been listed in tabular format, Table 2:

Table 2 : Flow rate for different flood events (HQ_T)

Return Period (T) in years	Reduced variate (Y_T)	Frequency factor (K)	Expected flood (X_T) in m^3/s (HQ_T)
5	1.50	0.97	1510.62
10	2.26	1.71	1706.33
50	3.91	3.33	2137.03
100	4.61	4.01	2319.12
200	5.30	4.69	2500.54
500	6.22	5.59	2739.89
1000	6.91	6.27	2920.78
2000	7.61	6.95	3101.61
5000	8.52	7.85	3340.61
10000	9.22	8.53	3521.39

3.2 Re-assessment of the spillway and stilling basin capacity

The re-assessment of the spillway capacity was carried out against the adopted extreme event of 10000 years of the return period (HQ100000), considered as a Probable Maximum Flood (PMF). At a constant maximum reservoir level (MRL) of 531 masl in the full opening mode of all five gates, the spillway was able to pass the maximum flow of 9743 m3/s as estimated in Table 3 using the empirical relation of orifice flow. This implies the spillway was fully sufficient to pass the PMF with adopted HQ100000 of 3522 m^3/s.

Table 3 : Maximum spillway capacity

No. of gates operated	C	g (m/s^2)	L (m)	H_1 (m)	H_2 (m)	Design discharge (Q) in m^3/s
5	0.71	9.81	10.5	25	11	**9743.24**

The re-assessment of the as-built stilling basin length was carried out considering the maximum spilling discharge of 9743 m3/s. Table 1 listed jump length empirical relations were used to check the sufficiency length as presented in Table 4. The empirical relation of Sienchi was able to estimate a more or less similar length of the as-built stilling basin. However, the other resulted with higher basin length.

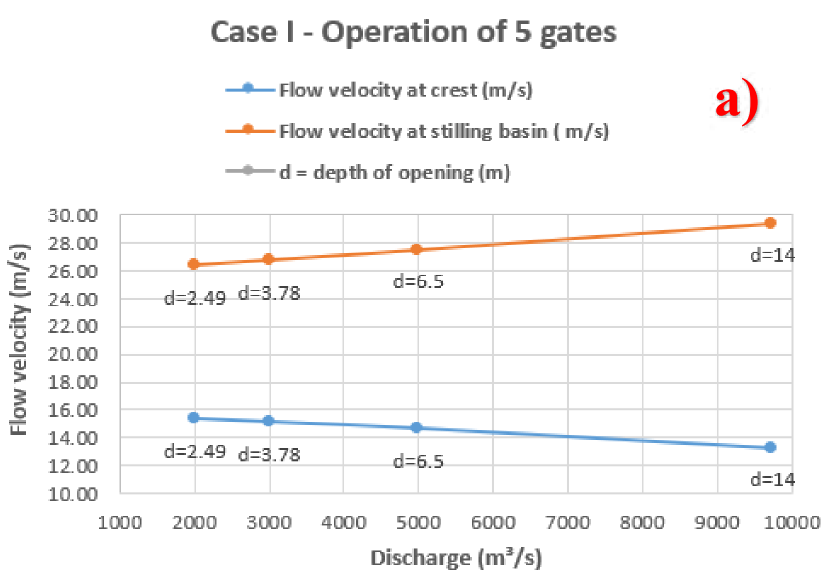
Table 4 : Stilling basin length sufficiency test

Sl. No.	Name of formula	Length (m)
1	Rouse	124.69
2	Smetana	125.90
3	Safranez	112.30
4	Einwatcher	123.79
5	Woycicki	103.54
6	Chertusov	120.31
7	Pavlovsky	98.90
8	Sienchi	104.10
9	**As-built designed length**	**104.00**

3.3 Gate operation case study

The four cases (i.e. Case-I : Operation of five gates, Case-II : Operation of four gates, Case-III : Operation of three gates, Case-IV :Operation of two gates) of operation strategies were built to assess the impact of gate operation over the crest surface as well as at the stilling basin. The flow velocities at the crest and stilling basin were evaluated for different gate opening heights with constant maximum reservoir level (MRL) of 531 masl.

The gate operation results of Figure 7 illustrated that the incremental opening height of the gate during higher flow reduces the flow velocity at the crest due to less pressure head difference (ΔH) and oppositely increases flow velocity at the stilling basin due to incremental flow rate over a fixed cross-section width of stilling basin. The maximum velocity of 29.37 m/s at the stilling basin was observed for higher flow rates during the full opening of 14m gate height, as illustrated in Figure 7. This implies the necessity of a plunge pool for dissipating energy in the stilling basin to avoid excessive erosion. The crest velocity decreases up to 12 m/s due to the higher opening of the gate, illustrating the advantages of higher openings.



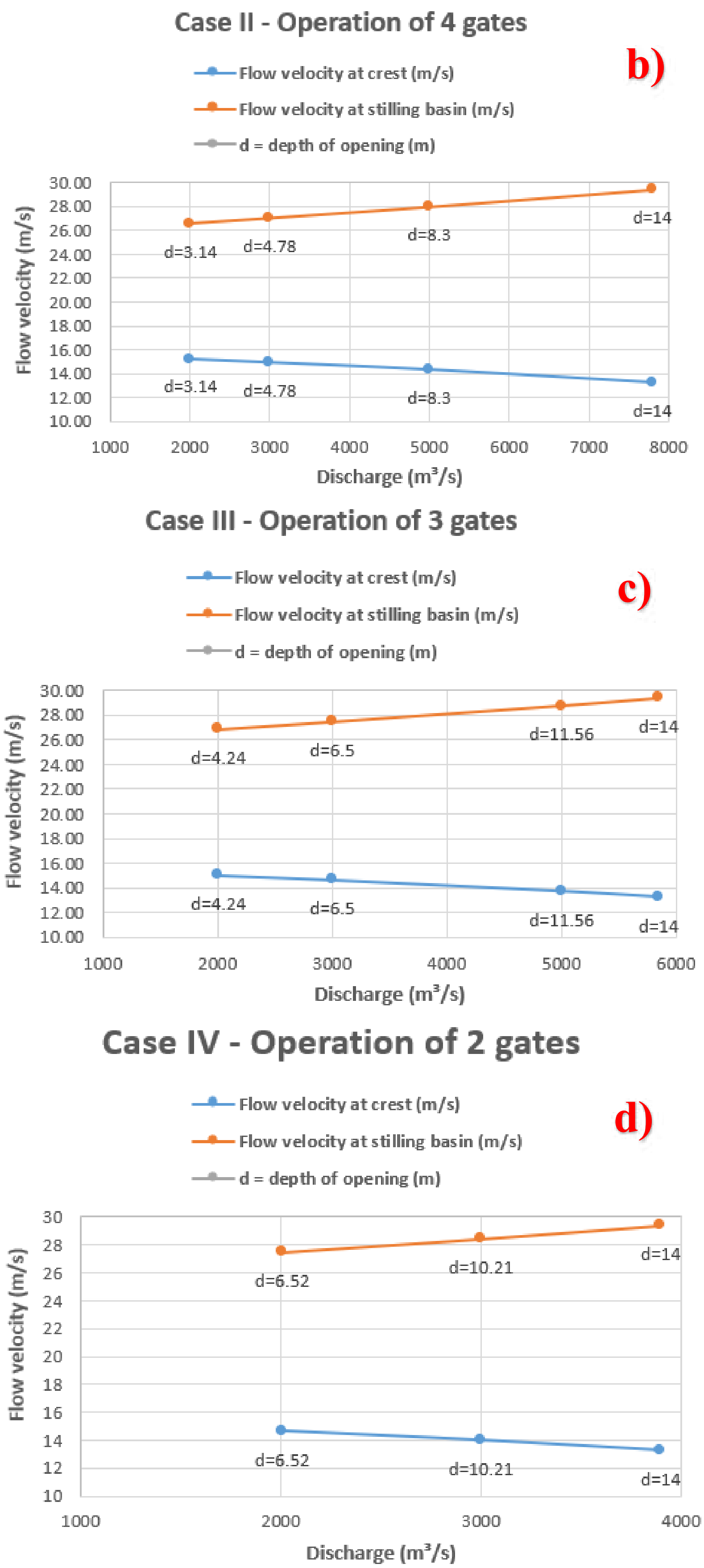


Figure 7 : Adopted gate opening strategies with sequential order

The flow velocities over the crest and at the stilling basin were found to be higher than the permissible flow velocity to cause possible damage, which were compared and distinguished according to the damage level suggested by Kermani (2013) in Table 5.

Table 5 : Possible level of damge based upon velocity and cavitaion index, Kermani (2013)

Level	Damage Risk	Flow Velocity (m/s)	Cavitation Index (σ)
1	No cavitation damage	V ≤ 5	σ > 1
2	Possible cavitation damage	5 < V ≤ 16	0.45 < σ ≤ 1
3	cavitation damage	16 < V ≤ 25	0.25 < σ ≤ 0.45
4	Serious damage	25 < V ≤ 40	0.17 < σ ≤ 0.25
5	Major damage	V > 40	σ ≤ 0.17

The maximum velocity at the crest was found to be 15.35 m/s at the minimum opening of 2.49 m of gate height indicating "possible cavitation damage" for flow velocity (5 < V ≤ 16). On the other hand, the maximum velocity at the stilling basin was found to be 29.37 m/s at a higher flow rate indicating "serious damage" for flow velocity (25 < V ≤ 40). The damage was observed due to the unsafe operation of the gate as a result of higher flow velocity.

3.4 Hydraulic design and construction materials

The abrasion damage due to higher flow velocities and granular flow can be highlighted to cause serious damage, based on the results and project information. The abrasion damage was mainly caused due to the poor quality concrete surface of spillway and stilling basin during higher flood events.

The design and performance can be improved by the application of steel lining, hard stone lining, and higher strength concrete on the surface of the spillway as illustrated in the design drawings, in Figure 8. Generally, epoxy resin is suitable to increase the strength of the concrete. In addition, the hydraulic design of end chute and baffle wall helps to reduce the higher flow velocity impact in the stilling basin, preventing serious damage. Moreover, the construction of a plunge pool in the stilling basin also helps to increase the dissipation efficiency ensuring less damage to the structure.

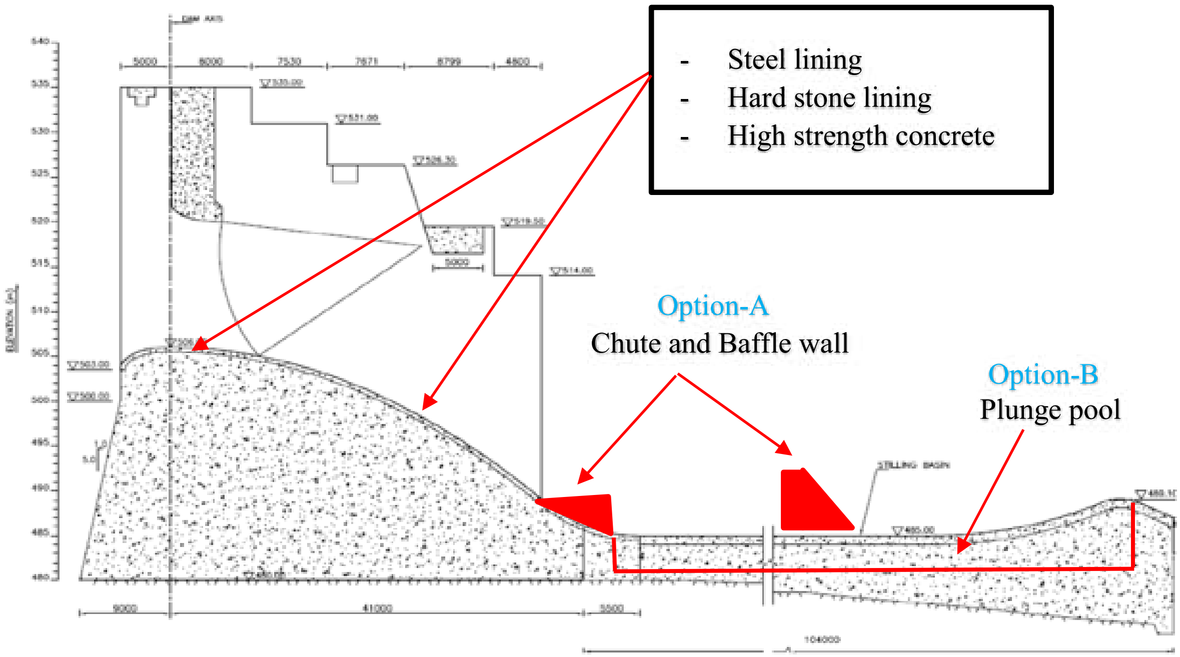


Figure 8 : Suggested improvement for increasing service life span

4. CONCLUSIONS

The following conclusions are drawn from the study:

- The adopted Probable Maximum Flood (PMF) with a return period of HQ10000 was able to pass through the as-build designed spillway and was found to be safe, for operational flood events till 10000 years.
- The flow velocity at the crest was found to be higher for the small opening due to the higher pressure head during the operation, higher opening of the gate was found to be suitable instead of a small opening with multiple gates during the flood events.

- The categorized risk of cavitation damage level during the small opening at the crest was found with “possible cavitation damage” for flow velocity ($5 < V \leq 16$). On the other hand, “serious damage” was identified at the stilling basing during the higher flood events for flow velocity ($25 < V \leq 40$).
- The site visual inspection damage after the flood events was found to be mainly due to unsafe gate operation and poor construction design. The lack of application of steel lining, hard stone lining and higher strength concrete were found in the construction design. The rehabilitation in design with appropriate construction materials and modification in hydraulic are suggested to dissipated energy with the application of a chute and baffle wall or plunge pool.

REFERENCES

Chaudhry, M. H. (2008). Open-channel flow. New York: Springer.

Karaboga, D., Bagis, A., & Haktanir, T. (2008). Controlling spillway gates of dams by using a fuzzy logic controller with optimum rule number. Applied Soft Computing, 8(1), 232-238.

Kermani, E. F., Barani, G. A., & Ghaeini-Hessaroeyeh, M. (2013). Investigation of cavitation damage levels on spillways. World Applied Sciences Journal, 21(1), 73-78.

Kurichhu Hydropower Plant. Druk Green Power Corporation Limited (DGPC). (2021). Operation and Maintenance Manual.

Peterka, A. J. (1978). Hydraulic design of stilling basins and energy dissi-pators (No. 25). United States Department of the Interior, Bureau of Reclamation.

Salehi, F., Najarchi, M., Najafizadeh, M. M., & Hezaveh, M. M. (2022). Multistage models for flood control by gated spillway: Application to Karkheh dam. Water, 14(5), 709.

Sun, Y., Zhu, F., Chen, J., & Li, J. (2018). Risk analysis for reservoir real-time optimal operation using the scenario tree-based stochastic optimization method. Water, 10(5), 606.

Unver, O. I., & Mays, L. W. (1990). Model for real-time optimal flood control operation of a reservoir system. Water resources management, 4, 21-46.

U.S. Bureau of Reclamation (USBR). (1973). Design of small dams, U.S. Government Printing Office, Washington, D.C.

Zelenhasic, E. F. (1970). Theoretical probability distributions for flood peaks. Hydrology papers, Colorado State University, Colorado.