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Overtopping Risk Evaluation of Tabarak-Abad Dam based on Univariate and Bivariate Flood Frequency Analysis

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1. Introduction

Earth dams are destructed due to piping, overtopping, spillway erosion, etc. Among them, overtopping is one of the main causes of dam failure. Since design and performance of dams are always under the uncertainty and the potential of dam failure, it is essential to calculate the failure risk considering the uncertainties. In this study, the application of risk analysis for earth dam failure due to overtopping based on univariate and bivariate flood frequency analysis has been investigated using log-normal distribution for the Tabarak-Abad earth-fill dam. Considering Qp–V combinations (flood peak discharge - flood volume) for the joint return periods of 50, 100 and 200 years, the results of the bivariate flood frequency analysis have been proposed in the form of six inflow hydrographs. The overtopping risk has been evaluated based on the univariate flood frequency analysis for all hydrographs resulted from bivariate frequency analysis with different return periods and six initial depth of water in the reservoir, considering quantile of flood peak discharge, initial depth of water in the reservoir, and discharge coefficient of spillway as uncertain variables. Uncertainty analysis is conducted using Monte Carlo simulation method and Latin hypercube sampling technique.

2. Dam Risk Model

If a system is unable to perform expected tasks, the system will fail, and, accordingly, undesirable consequences will occur. Failure can be defined as the load (L) exceeding system resistance or capacity (R). Identifying load and resistance is a fundamental issue in risk analysis and it noticeably depends on the type of hydraulic structure and problem physics. The probability of failure is defined as P(L>R). Risk can also be represented as:

$$\alpha = \text{Risk} = P(Z < 0) \qquad (1)$$

where Z is performance function which can be defined as:

$$Z = R - L \ \ ; \ \ Z = \ln\left(\frac{R}{L}\right) \ \ ; \ \ Z = \left(\frac{R}{L}\right) - 1 \qquad (2)$$

2.1. Risk Modeling for Overtopping

Overtopping happens when the flood outlet cannot release water fast enough and water rises above the dam and spills over. In overtopping analysis, the maximum water height in the reservoir (H_{max}) and dam height (H_c) can be considered as the load and resistance of the system, respectively. Therefore, the overtopping probability with respect to the performance function can be expressed as follows:

$$Z_f = \ln\left(\frac{H_c}{H_{max}}\right) \qquad (3)$$

where Z_f is flood performance function and H_{max} is the highest water level during a flood event, calculated based on reservoir routing. Finally, the overtopping probability will be computed as:

$$\text{Risk} = 1 - \varphi\left(\frac{\mu_z}{\sigma_z}\right) = 1 - \varphi(\beta) \qquad (4)$$

in which β is the reliability index indicator and is defined as the mean ratio of the performance function (μ_z) to its standard deviation (σ_z). (Fig.1)

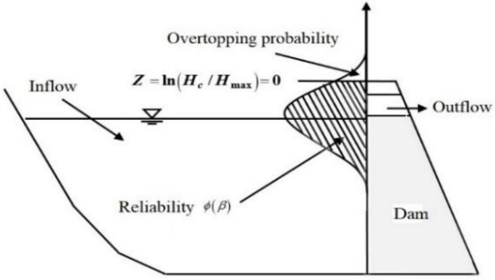

Figure 1. Schematic diagram of risk of overtopping for dam

3. Determination of Uncertainty Factors

The considered uncertain parameters in this study are as follows:

1. Quantile of flood peak discharge with Different return periods (Qp): Using flood frequency analysis, the values of mean and standard deviation of peak discharges for flood with 50, 100, 200-yr return period are presented in Table 1.

Table 1. Statistical parameters of peak discharges in different return periods

T (year)	Qp (m^3/s)	
	μ_{Qp}	σ_{Qp}
50	362.044	81.768
100	456.738	112.305
200	565.294	149.216

2. Initial water level (H_0): The mean and standard deviation of initial water depth were 50.1 (m) and 3.28 (m), respectively. In addition to that, five more depths (54, 58, 61, 64, and 66 m) have been assumed as the initial depths in order to consider the effect of changing initial water depth on the probability of overtopping.
3. Spillway discharge coefficient (C_d): Its mean and standard deviation has been determined 2.08 and 0.069, respectively based on the Tabarak-Abad Dam Technical Reports.

4. Bivariate Flood Frequency Analysis

In this study, six cases (V1-Q to V6-Q) with their corresponding characteristic values were assumed and the respective hydrographs were determined using the Aldama and Ramirez (1999) method. The appropriate relations of their method to generate desire hydrographs are:

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$$Q(t, Q_p, t_p, V) = \begin{cases} Q_p\left[3(\frac{t}{t_p})^2 - 2(\frac{t}{t_p})^3\right] & t \in [0, t_p] \\ Q_p\left[1 - \frac{3(t-t_p)^2}{(2\ VQ^{-1} - t_p)^2} + \frac{2(t-t_p)^3}{(2\ VQ^{-1} - t_p)^3}\right] & t \in [t_p, t_b] \\ 0 & t \in (-\infty, 0) \cup (t_b, \infty) \end{cases} \qquad (5)$$

where t_p and t_b are time to peak and base time of hydrograph, respectively and can be computed as follow:

$$t_p = \frac{2\ V}{3\ Q_p} \qquad t_b = 3\ t_p \qquad (6)$$

The resulted hydrographs using the above equations and the ranges of peak discharge obtained from the bivariate analysis with the related series of volumes are presented in Table 2.

Table 2. The peak discharges and correspondent volumes based on bivariate frequency analysis

T (year)	**Q_P (m^3/s)**	**V (MCM)**
50	345.5 - 856.44	10.94 – 31.57
100	433.3 – 1038.92	13.21 – 40.22
200	533.6 – 1210.73	15.33 – 48.96

5. Overtopping Risk Based on Univariate Flood Frequency

The probability of overtopping was calculated for various floods at 50, 100 and 200-year return periods by considering three uncertain variables as peak discharge, initial water level, and spillway discharge coefficient. All uncertain variables were assumed to be independent variables, while Monte-Carlo simulation (with a sample size of 20,000) and Latin hypercube sampling (with a sample size of 10,000) were applied for uncertainty analysis. Based on the results, by increasing the initial water level in each step, the probability of overtopping (in a constant return period) was raised for both uncertainty approaches adopted in this study. So that at the water level of 66 meters, overtopping risk for the dam is very high.

6. Overtopping Risk Based on Bivariate Flood Frequency

The overtopping risks due to different flood at 50, 100 and 200-year return periods in six initial water levels were evaluated by MCS and LHS uncertainty approaches. Overtopping risk have been increased with rising initial levels of water in the both adopted uncertainty methods. Figure 2 shows the trend of variation overtopping risks of V1-Q versus the initial depth of water for the joint return periods of 50,100 and 200. Also, the V1-Q hydrograph, which has the highest volume of flood, is associated with a higher risk in all water levels in comparison to other hydrographs.

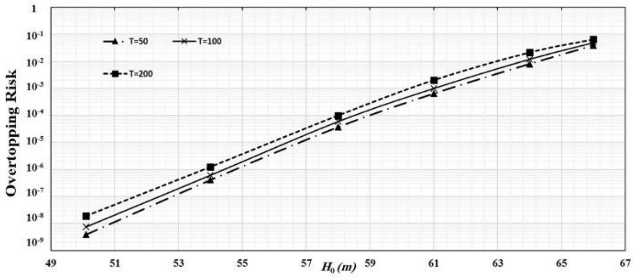

Figure 2. Overtopping risk of V1-Q based on MCS method

Figures 3 and 4 show the univariate and bivariate inflow hydrographs in conjunction with the correspondent overtopping risk for V6-Q and V2-Q. These figures demonstrate that the values of overtopping risks using univariate frequency analysis in both MCS (Figure 3) and LHS (Figure4) methods are less than the results of bivariate for all initial levels of water.

7. Conclusion

The comparison of univariate and bivariate flood frequency analysis within different periods indicates that bivariate flood frequency analysis method resulted in greater estimated overtopping risk values in all return periods which is accompanied with higher degree of risk. Also, the hydrographs with greater runoff volume (Q−V1 and Q−V2) have been produced greater risks rather than other inflow hydrographs. Moreover, to evaluate overtopping risk based on univariate and bivariate frequency analyses, the increasing trend of risk values for rising water level in the reservoir is more tangible than that of increasing return periods.

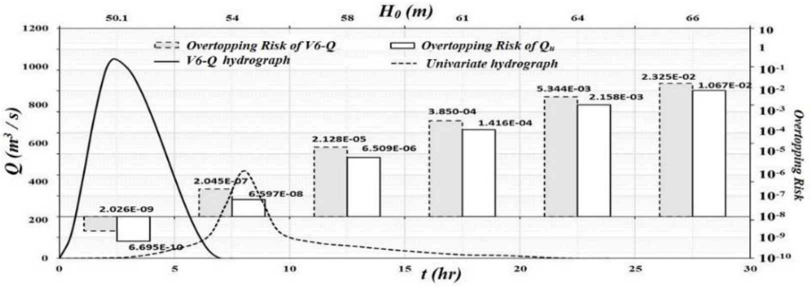

Figure 3. Overtopping risk of Qu and V6-Q and based on MCS method

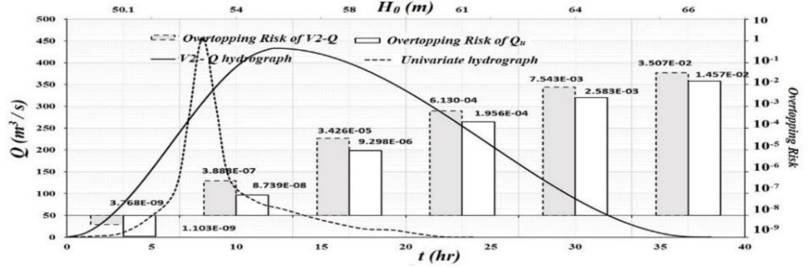

Figure 4. Overtopping risk of Qu and V2-Q and based on LHS method