Dam breach analysis for the Hongshiyan barrier lake

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Abstract. This paper presents a hyperbolic erosion rate model and a calculating circular slip surface method of lateral enlargement, and obtain a numerical analysis method of the relative stability dam-breach flood analysis. This paper develops a DB-IWHR procedure based on this principle, preparing a dam breach flood procedure is simple, easy to understand and use program in Excel 2010 spreadsheet. This improves this program, and writes a flood regulation calculation program, forming a complete program of dam breach flood and flood regulation. This paper calculates Hongshiyan barrier lake breach flood flow and the reservoirs downstream impacts.

1. Introduction
A magnitude-6.5 earthquake struck Ludian County in Yunnan Province, causing landslides on mountains along both banks of a river to form a barrier lake. The collapse of the barrier lake will lead to huge dam breach discharge. This not only floods the banks of the reservoir area, causing damage to the upstream area of the reservoir. Moreover, naturally accumulated landslide dams are prone to uncontrolled dam breach under the effect of reservoir water osmosis or flooding scouring, which is extremely harmful. However, there are currently two medium-sized hydropower stations built downstream of the barrier lake. Therefore, it is necessary to analyze the flood flow when the dam is broken and the impact on the downstream reservoir dam. The US Bureau of Reclamation reports that when the dam breach warning exceeds 90 minutes, the loss of life is 0.02%. When the warning time is less than 15 minutes, the loss of life is 50%. Consequently, it is urgent to establish a dam breach model to predict dam breach parameters, including the width, height and flood hydrograph [1].

Inducing factors of natural disasters such as earthquakes, rainfall, volcanic eruptions, act on the slopes of river valleys to cause landslides, collapses, and blocked valleys, thus forming a barrier lake. Since the landslide dam is naturally piled up without dedicated drainage channel. Under the influence of the continuous water coming from the river, the reservoir water level in the barrier lake rises rapidly. This not only floods the two banks of the reservoir area, causing damage to the upstream area. What’s worse, the naturally accumulated landslide dam is prone to uncontrolled dam breach under the effect of reservoir water osmosis or flooding scouring, which is extremely harmful. The dam breaches have occurred in the damaged lakes formed by earthquakes before, such as the Ningxia Haiyuan Earthquake in 1920, Minjiang Diexi Earthquake in 1933, the Tibet Medog Earthquake in 1950, and the Taiwan
Nantou Earthquake in 1999. In the meanwhile, the number of deaths caused by the flood collapse is no less than the number of direct deaths caused by the earthquake\textsuperscript{1-2}. The 5.12 Wenchuan earthquake in 2008 formed the Tangjiashan dammed lake, directly endangering more than 1.3 million people in the downstream area of Mianyang and Suining\textsuperscript{3}. The Hongshiyan dammed lake formed by the 8.03 Ludian earthquake in 2014 inundated Mianyang and posed direct threat to the safety of the Tianhuaban hydropower station on the main stream of the Niulan River\textsuperscript{4}. As a result, exploring the dam breach flood flow of the barrier lake and the impact on the downstream reservoir dam has practical and application significance for the emergency rescue of the dammed lake.

During the dam breach, the water flow continuously washes the breach. The physics-based model generally calculates the scouring through the sediment transport formula, and then continuously calculates the dam scouring process through time iteration. By studying the existing numerical simulations, it can be found that different models have chosen different sediment transport formulas according to the adaptation conditions. For example, the BREACH model uses the Smart modified Meyer-Peter and Muller sediment formula\textsuperscript{3}; the BEED model adopts the Einstein-Brown sediment formula\textsuperscript{4}; the Englund-Hensen sediment formula\textsuperscript{5} is applied in the MIKE11 model. Observing such sediment formulas, they all use the erosion equation in which the erosion rate is exponential with the shear stress, but the differences in the research methods lead to different formulas. In 2014, the Chinese Academy of Water Sciences developed a new IWHR DB model for the dam breach calculation program. It proposed the use of a hyperbolic model of erosion and successfully simulated the dam breach process of the Tangjiashan dammed lake\textsuperscript{6}.

According to the data of the predecessors and the dam breach of the Tangjiashan dammed lake, the Chinese Academy of Water Sciences proposes the hyperbolic scouring formula and develops the IWHR DB dam calculation model based on MS 2010\textsuperscript{8}. By improving the procedure, the inbound flow is changed from the original quantitative import to the introduction of the flood Hydrograph. A flood calculation program is written in the program to form a complete set of dam calculation and flood control procedures. This paper briefly introduces the numerical analysis method of dam breach proposed by Chen et al. (2014)\textsuperscript{8-9}, and studies the dam-breaching flood process of Hongshiyan dammed lake. Besides, the plan of dam breach flood for excavating 8m deep drainage channel proposed by the Earthquake Relief Headquarters is analyzed, and the impact on the downstream reservoirs is studied.

2. Numerical analysis model of dam breach
Since the introduction of the Cristofano model in 1965, the dam-breaching model has made significant progress in simulating dam breaches and subsequent flood forecasting. The model is mainly based on numerical methods of mathematical methods, parametric methods and physical mechanisms to establish a numerical model of dam breach. Typical examples are the Harris-Wagner model, the Brown-Rogers model, the Nogueira model, and the Fread model\textsuperscript{2-7}. These models use traction stress analysis and sediment transport theory to simulate the erosion of the water flow to the breach. The whole process of the Tangjiashan dammed lake collapse is an example of a completely recorded natural dam breach. Based on this engineering example, the research team develops the DB-IWHR dam breach model in view of the improvement of the aforementioned dam breach model. The theoretical framework of this model is briefly reviewed.

2.1 Water balance conditions
For earth-rock dams, when the storage capacity is large, the flood calculation is simplified into hydrological calculations. The hydrological calculation is based on the law of conservation of mass, and its mathematical expression is:
The breach outflow $O_b$ and the dam crest outflow $O_o$ are calculated with the flow over wide crested weirs formula. $O_{sp}$ is obtained from the design file.

The breach and dam crest flow can be calculated by the flow over wide crested weirs. However, the boundary conditions of the two are inconsistent, and the boundary of the outflow is changed with the dam breach process and the corresponding sediment erosion.

In general, for a channel with a rectangular cross section, the following formula is used:

$$Q = C_1 C_2 B (H - z)^{3/2}$$

(2)

Where $C_1$ is the flow coefficient, and the theoretical value is 1.7 m$^{1/2}$/s (Singh [10]). Based on numerous experiments, after considering the shape and contract effect of the crested weirs, Brater [11] suggests a range of $C_1$ values of 1.43–1.69m$^{1/2}$/s.

$C_2$ is the coefficient that considers the flooding of tail water and is expressed with the following empirical formula (eg, Fread [6]; Singh et al. [10]):

$$C_2 = 1.0 - 27.8(m - 0.67)^3$$

(3)

Fread and Singh suggest determination by the Manning formula of the steady flow in open channel, which in turn requires the input of the slope of the drainage channel. It has a great influence on the calculation accuracy, and it often happens that the calculation cannot be converged due to improper input of this value. As a result, Chen et al. [9] suggests directly inputting the waterhead drop coefficient $m$ of the drainage channel defined by the following formula.

$$m = \frac{h}{H - z}$$

(4)

When the water flow is a critical flow, the theoretical value of $m$ is 0.67. The actual calculation results show that when the value of $m$ ranges from 0.4 to 0.8, the difference of the corresponding flood flow rate does not exceed 15%. Therefore, the $m$ value can be determined by sensitivity analysis of the water level experience.

2.2 Erosion model

The scouring speed of the dam body under certain speed or shear stress is the most important parameter in the dam breach flooding analysis. Chen (2014) et al. [9] considers that soil stone has a certain yield strength for water flow erosion. When the flow rate of the water reaches the starting flow rate, that is, the critical shear stress is reached, the water flow begins its sediment transportation. Based on this, the following hyperbolic model is proposed:

$$\dot{z} = \Phi(\tau) = \frac{v}{a + bv}$$

(5)

Where $v$ is the shear stress after deducting the critical shear stress and can be calculated according to formula (5):

$$v = k(\tau - \tau_c)$$

(6)

$k$ is the unit transformation factor that allows $\dot{z}$ to approach $\dot{z}_{\text{crit}}$ during the working range of shear stress $\tau$. The hyperbola has a progressive line when $v$ is close to an infinite value, and its value is
It represents the largest possible scouring rate of the soil. Here, $k$ is taken as 100. $1/a$ represents the slope of the curve when $v$ is equal to zero.

The model is shown in Figure 1.

2.3 Dam breach expansion model

The original dam-breaching model is often linked with wedges when considering the breach expansion. What is commonly used in geotechnical engineering is the more rigorous slope stability analysis method, such as the simplified Bishop method [12]. During the calculation, the critical slip surface is found by searching for possible slip surfaces, i.e., the safety factor $F$ is equal to the minimum value $F_m$. Therefore, this method is used to improve the sidewall stability analysis of the drainage channel. Then, through the corresponding program, the undercut depth of the slope is found when the safety factor $F_m$ is equal to 1. The entire calculation is implemented by STAB 2007 (Chen and Wang [13]), which program this paper also adopts.

In the calculation process, the width of the water surface is taken as the width of the breach. As the depth of the undercut increases, the safety of the breach slope gradually decreases. The simulated dam breach process is shown in Figure 2.

3. Flood analysis of the Hongshiyan dammed lake

3.1 Project Overview

The crest elevation of the Hongshiyan landslide dam is 1222m, the dam is 83-96m high, and the riverbed elevation is 1120m. The total volume of the landslide dam is about 12 million m$^3$. At a water level of 1222 m, the total storage capacity is 260 million m$^3$. The landslide dam No.1 is located 600m from the downstream of the Hongshiyan dam. The main building of the pivotal project in the downstream hydropower station is a RCC arch dam. Its maximum dam height is 107m, the dam crest elevation is 1076.8m, and the dam crest length is 159.87m. The storage capacity below the verified flood level of 1076.61m is 78.71 million m$^3$, and the storage capacity below the normal water level of
1071 m is 65.7 million m$^3$. The maximum discharge of the verified flood level is 5046 m$^3$/s, and it of the design flood level is 3152 m$^3$/s. The main building of the pivotal project in the downstream hydropower project No.2 is a concrete-faced rock fill dam. The maximum dam is 65m high, the dam crest elevation is 775m, and the dam crest length is 217.72m. The verified flood level is 774.37m, and the storage capacity below the verified flood level is 40.46 million m$^3$. The normal water storage level is 770m, and the storage capacity below the normal water storage level is 32.93 million m$^3$. The maximum discharge of the verified flood level is 6691 m$^3$/s, and it of the design flood level is 5744 m$^3$/s.

3.2 Brief plan and usage parameters

1. Analysis of the dam breach flood

The calculated input parameters used in this analysis are shown in Table 1. Because the grain size is similar to that of the Tangjiashan dammed lake, the same hydraulic and geotechnical indicators used in the Tangjiashan inversion process can be repeatedly used in this case. According to the urban flood control standards, flood that happens once in 20 years is simulated here.

Table 1 Dam breach flood analysis and calculation input parameter table

| Parameter name | Parameter symbol | input value | Parameter name | Parameter symbol | input value |
|----------------|-----------------|-------------|----------------|-----------------|-------------|
| The relationship curve between Reservoir and water level | $a_1$ | 0.041 | Erosion | Initial velocity | $V_c$ (m/s) | 2.70 |
| | $b_1$ | -1.907 | | Hyperbolic model erosion coefficient | $a_2$ | 1.1000 |
| | $c_1$ | 23.28 | | | $b_2$ | 0.0009 |
| Water level | $H_r$ | 1120.00 m | | | | |
| Lateral enlargement | | | Hydraulic parameters | discharge coefficient | $m_q$ | 0.36 |
| Initial width | $B_0$ (m) | 20.00 m | | submergence coefficient | $m$ | 0.80 |
| Final width | $B_{end}$ (m) | 180.00 m | | | | |
| Lateral inclination at start and end | $\alpha_1$ (°) | 144.00° | | Coefficient of lateral contraction | $n_b$ | 0.90 |
| | $\alpha_2$ (°) | 170.00° | | | | |

The structural form and characteristics of different excavation troughs are shown in Table 2.

Table 2 Structural form and characteristics of different excavation depth troughs table

| Item | Depth (m) | Elevation (m) | Width (m) | Discharge (m$^3$/s) |
|------|-----------|---------------|-----------|---------------------|
| No drainage channel | 0 | 1214 | | 215 |
| Excavate drainage channel | 8 | 1222 | 5 | 511 |

3.3 Calculation results of dam breach flood

1. Scheme without drainage channel

The calculation is performed with the DB-IWHR program. The relationship curve between the flow, the reservoir water level and the elevation of the drainage channel and time are shown in Figure 3(a), (b).
It can be seen from Figure 3 that when the no-drainage scheme is selected, the landslide dam reaches 8278 m$^3$/s after 7.26 hours with a total flood discharge of 348 million m$^3$. Table 3 lists the dam breach flood process and the flow changes clearly.

**(2) Scheme of excavating 8m drainage trough**

The drainage channelscheme is intended to be excavated to a depth of 8 m, with an inlet elevation of 1214 m and a bottom width of 5 m. The peak flow of the 8m drainage channelscheme is 7424 m$^3$/s, and the total flood discharge is 290 million m$^3$. The relationship curve between flow, reservoir water level, and discharge channel elevation and time is shown in Figure 4(a) and (b).

The calculation results show that the peak flow is reduced from 8278 m$^3$/s to 7244 m$^3$/s with the 8m drainage channel with the peak clipping rate of 11%. The total flood discharge decreases from 348 million m$^3$ to 290 million m$^3$ with a decrease of 20%. The total duration of flood discharge is reduced from 24h to 22h. In general, the calculation results prove that the excavating drainage channel has an obvious effect of slowing down the possibility of disasters in downstream areas. The characteristics of the above two schemes for dam breach floods are shown in Table 3.
Table 3 Calculation results of dam breach flood characteristics of each scheme

| Item                        | Depth (m) | Elevation (m) | Discharge (m³/s) | Time (h) | Volume (10⁸ m³) | Time (h) |
|-----------------------------|-----------|----------------|------------------|----------|-----------------|----------|
| No drainage channel         | 0         | 1222           | 8278             | 7.26     | 3.48            | 24       |
| Excavate drainage channel   | 8         | 1214           | 7424             | 6.88     | 2.91            | 22       |

Note: The natural runoff of 900 m³/s is considered in the calculation of dam breach.

3.4 Calculation results of flood control by No.1 hydropower station through dam breach flooding of excavating drainage channel

Due to the slight decline in the dam-breaching floods in the mountainous canyon-type rivers, the flood evolution process from the dammed lake to the No.1 hydropower station is not considered. It is assumed that the dam flood directly enters the No.1 reservoir. Figure 5 shows the relationship between the water level of the reservoir and the time. Figure 6 is the total discharge flow of the inflow flood from the middle hole, the surface hole and the dam crest. The relevant characteristic indicators are shown in Table 4.

![Figure 5 Relationship curve between discharge and time](image1)

![Figure 6 Total discharge flow from the middle hole, surface hole and dam crest of the inflow flood flow](image2)

Table 4 Characteristic data of No.1 reservoir flood control analysis

| Item                        | Critical water level(m) | High water level(m) | Inflow Discharge (m³/s) | Time (h) | Outflow Discharge (m³/s) | Time (h) |
|-----------------------------|-------------------------|---------------------|-------------------------|----------|--------------------------|----------|
| No.1 hydropower station     | 1020                    | 1078.25             | 7423.69                 | 6.88     | 6685.40                  | 8.5      |

From the above analysis, it can be seen that the flood peak flow of the reservoir is reduced by 738.30 m³/s and the highest water level is 1078.25 m, because the flood discharge of the dam breaches through the middle hole and the surface holes. This has exceeded the dam crest of the No.1 hydropower station by 1.45 m.

4. Conclusion

(1) With the 8m drainage trough, the peak flow is reduced from 8278 m³/s to 7424 m³/s with the peak clipping rate of 10%. The total flood discharge decreases from 348 million m³ to 290 million m³ with a decrease of 17%. The total duration of flood discharge is reduced from 24 hours to 22 hours. Excavating drainage troughs have the effect of slowing down possible downstream disasters.

(2) The flood peak flow of the landslide dam after being regulated is reduced from 7242.69 m³/s to 6685.40 m³/s after the storage of the No.1 hydropower station, and exceeds 1.45 m above the dam crest when reaching the highest water level of 1078.25 m.

(3) This paper adopts the DB-IWHR program independently developed by Chen et al. Taking advantage of the improved procedure by changing the inbound traffic from the original quantitative import to the flood hydrograph, the flood calculation is programmed into it. In this way, a complete set
of dam calculation and flood control procedures are formed. This program is applied in the Hongshiyan dammed lake, which is also adopted by the rescue headquarters.

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