Process Analysis and Prediction of a Multi-stage Landslide Dam Failure

Shuang-shuang Wu1, Xin-li Hu*, 1, Peng Xia1, Chang Liu1, Jianchuan Wu2
(1Faculty of engineering, China university of geosciences (Wuhan), Wuhan, Hubei, China, 430074
2Chengdu Engineering Corporation, Ltd, Chengdu, Sichuan 610072, PR China)

Co-author and Corresponding author (*): Xinli Hu

ORCID: https://orcid.org/0000-0002-4529-1898

E-mail: huxinli@cug.edu.cn

TEL: 13907152610

Abstract: The studies of mechanism and calculated model of the earth-fill dam and landslide dam have a significant impact on the prediction and risk assessment for dam failure. The present study selected the event of a multi-stage landslide dam failure in southwestern China as a case study. Based on a mathematic model that can consider the failure mechanism, the key parameter can be obtained by back analysis, the twice failure processes can be displayed as well. It indicates that the second landslide dam cannot break under natural conditions, i.e. the landslide dam failure needs manual intervention, which is consistent with the actual situation. Because the landslide would occur again in different cumulated volumes in the future, the dam failure is predicted using the same model. The result illustrates that the maximal flow comes up to 20,000-60,000 m³/s after the dam failure and the failure would occur in a short day. The analysis and prediction provide an improved insight into the landslide dam failure process and risk control.
Keywords: Landslide dam, Dam failure, Failure mechanism, Mathematical model

1. Introduction

China is a country that is prone to natural disasters and is also a country in which hydropower projects have developed significantly. Landslide dams due to earthquakes and geological hazards are frequently reported. The accumulation of the landslide dam along the flow direction is generally long. Its geometrical characteristics, material composition, and other aspects are significantly different from those of artificial dams, and the dam breaching process is different from that of artificial earth and rock dams (Chen et al., 2019). The risk of landslide dam failure is much higher than artificial earth and rock dams, and in the event of a dam failure will pose a significant threat to the safety of people's lives and property downstream (Fan et al., 2020).

In the mechanism of landslide dam failure, through a series of physical model tests (Zhang et al., 2010; Jiang et al., 2016) and some field test data (Niu et al., 2009 and 2010), it was found that the erosive effect of water flow was shown as surface scouring. The slope angle of the dam body along the river direction also gradually decreased underwater flow, which is different from the “scarp” erosion of the viscous earth dam under the action of water flow in the dam overtopping. The centrifugal model test conducted by Nanjing Institute of Water Resources Science (NIWRS) found the phenomenon of coarse gravel accumulation at the outlet of the flume during the flume collapse, which slowed down the development of the flume (Zhao et al., 2016).

In the study of mathematical modeling of dam failure, it is divided into three categories (Wu et al., 2011). The first category is parametric models, which are generally based on a regression analysis of real dam failure cases and calculate dam failure-related parameters based on empirical formulas (Froehlich et al., 2016). It is often used for rapid prediction and evaluation of damage caused by dam failure. The second category is the accurate mathematical models based on the mechanism of collapse, which has developed rapidly in recent years (Kesserwani et al., 2014). It can currently be used only for simulation of overtopping and collapse processes in homogeneous dams or landslide dams. The third category is the simplified mathematical models based on break mechanisms (Chen et al., 2019). It assumes that the shape of the breaching section (rectangle, inverted trapezoid or triangle, etc.) remains unchanged during the breaching process. The breaching development process is calculated using water shear stress and critical shear stress of the dam material or a dam material erosion formula. The breaching flow is calculated by the weir flow (diffuse breaching) or orifice flow (permeable breaching) formula. The simplified mathematical model is used in this study because of its ability to consider the mechanism of collapse and its fast analytic speed.

Cristofano, 1965 established the first mathematical model of homogeneous dam overtopping, and later proposed a series of mathematical models to simulate earth and rock dam failure, the most widely used of which was the model developed by Freed and Breach, 1988. In recent years, relevant research institutes in China have researched the mathematical model system of soil and rock dam breaches, such as the NHRI-DB series of dam breaches of the Nanjing Academy of Water Sciences and the DB-IWHR series of dam breaches of
Chinese Academy of Water Sciences (Chen et al., 2019). These models focus on overtopping and infiltration damage, and simulate the flushing of dam material by assuming routing morphology, using different flow and erosion formulas, and analyzing the lateral extension and longitudinal undercutting. Although this type of model considers the failure mechanism of earth and stone dams, it is still difficult to truly consider the coupling of water and soil during the dam failure process.

In this paper, the famous multiple landslide dam failure events in 2018 was taken as an example. Using a simplified mathematical model based on the failure mechanism, the overtopping flow and scale of the landslide multiple failure were inversed and calibrated. Moreover, the potential landslide dam was predicted and discussed. The results could inform the landslide and rever risk management and human intervention decisions, and provide an insight into the process and prediction of similar complex multi-stage instability landslide dams.

2. Methodology
In this study, the mathematical model of infiltration damage of soil and rock dams from NIWRS is used. The model proposes a numerical method to calculate the process of infiltration channel expansion and the development of the dam failure after the overtopping. It uses the pipe flow and weir flow formulas to calculate the process of flow changes during infiltration channel expansion and the dam failure after the overtopping. The calculations on the failure flow in the model are shown below and can be referenced in detail (Chen, 2012). Assuming that the initial permeation channel is circular, the velocity of the water flow in the permeation channel can be expressed as follows,

\[ v = \mu \sqrt{2gh} \]  

(1)

Where \( v \) denotes the flow rate, \( \mu \) denotes the flow rate coefficient, and take 0.97 here, \( h \) denotes the difference in water level at the point of escape from the upstream reservoir and infiltration channel.

Considering that the infiltration damage that could result in dam collapse, the flow through the infiltration channel can be expressed as,

\[ Q_b = vA = \pi R^2 \mu \sqrt{2gh} \]  

(2)

Where \( Q_b \) denotes the flow through permeable channels, \( A \) denotes the cross-sectional area of the permeable channel, \( R \) is the radius of the penetration channel.

With the expansion of the infiltration channel, the weir above the channel would collapse, resulting in dam overtopping and the water from the pipe flow to the weir flow. The weir width formula is applied to calculate the collapse flow.

\[ Q_w = mB\sqrt{2gh(H - H'_c)^2} + 2mB\sqrt{g} \tan \frac{\pi}{2} - \theta k(H - H'_c)^2 \]  

(3)

Where \( m \) denotes the flow coefficient, \( H \) is the reservoir level, and \( H'_c \) is the elevation of the breach bottom.
3. Study area

On Oct. 11th, 2018, a landslide in the right bank of a watershed in southwest China experienced a large-scale failure that blocked the river and formed a dam (hereinafter referred to as the #I dam). The dam lake began to naturally discharge the next day, and the full discharge was completed on the 13th. On Nov. 3th, the rear edge of the first landslide source area occurred failure and formed a dam again (hereinafter referred to as the #II dam), which was nearly 50 m higher than the highest point of the prior dam (according to Xu et al., 2018).

The scale of the #I dam is about 10 million m$^3$, the elevation of the dam top is 2,930 m, the dam height is 63 m, the reservoir capacity of the dam lake is 250 million m$^3$, and the maximum flow rate of the outfall flood is about 11,000 m$^3$/s, which has a huge flood impact on the downstream. After the dam overtopping, the residual accumulation on the left side of the riverbed is huge in scale, with a volume of 7~8 million m$^3$. The original river channel is narrow and the width of the overflow section is only 60~80 m. Moreover, the volume of a large number of dangerous cracking body at the rear edge of the landslide source was estimated at 2 million m$^3$ (Figure 1).

On Nov. 3th, the landslide collapsed again, blocking the overflow section of the #I dam. The volume of 1.5 to 2 million m$^3$, which is superimposed on the residual accumulation of the original riverbed to form the #II huge weir lake. The lowest and highest elevation of the dam top is 2,966 and 3,010 m, with a full storage capacity of 775 million m$^3$. After implementing manual intervention, the dam failed on the afternoon of Nov. 13th, with a maximum flow rate of about 33,900 m$^3$/s. A drainage channel of 800 m in length and 150~200 m in width was formed. After the dam collapse, there is still a huge dam body remaining on the left bank of the riverbed, with a high content of solitary blocks and a dense structure, estimating 800 m long, 150~250 m wide, and 20-120 m high, with a volume of about 8 million m$^3$ (Figure 2).

After the formation of the #II dam, the investigation found that a large number of landslide cracking bodies appeared on the rear edge of the slope surface, which can be divided into three subzones according to their location. The dangerous cracking body in the creeping stage is about 2.3 million m$^3$ in total. The stability of the landslide after twice failure may be unstable again due to the dangerous cracking body. The scraping residual in the trough is about 0.3 million m$^3$ of loose block debris, forming a total of about 2.6 million m$^3$ of landslide accumulation. The potential landslide failure plus residual accumulation on the river bed after the #II dam may block the river again. Meanwhile, the topography of the trough is conducive to the landslide accumulation concentrating in the river bed narrow drainage channel, again forming a large dam blockage lake.
4. Results and analysis

4.1. Parameter Inversion

Based on the above introduction and on-site investigation, the collapse of the dam caused by the landslide failure can be considered as seepage damage. Reverse calculation of the failure process of the #Ⅰ dam was conducted to determine relevant parameters.

The landslide occurred in the early morning of Oct. 11th, 2018. A dam was formed after the river was blocked. The natural discharge began at 17:15 the next day. It reached the balance of the inflow and outflow of the reservoir water, and the danger was relieved on the 13th. It took 72 hours for the dam break. A drainage channel with an upper width of about 200 m and a bottom width of about 60 m was formed in the dam body. Based on the image data, the inversion model of the dam-break calculation parameters is obtained as shown in Figure 3.

Due to the difference in the location of the initial infiltration channel, the inclination angle of the infiltration channel and its corresponding inversion calculation parameters are also different. When the inclination angle of the permeation channel of this landslide dam is taken as $\theta=1.9^\circ$, the flood peak flow is about 10,200 m$^3$/s, which is close to the actual peak flow of 11,000 m$^3$/s, and the width of the breach top is about 200 m, which is consistent with the fact (Figure 4). Therefore, when the inclination angle of the permeation channel is $\theta=1.9^\circ$, the calculation result is most consistent with the actual one.
4.2. Checking Calculation

After the first landslide, the rear edge cracked and destroyed at intervals of only 23 days, and the landslide collapsed to form the #II dam. According to the hydrological data measured upstream of the #II dam body after the dam break, the water level in front of the dam is 2907 m and the highest elevation of the dam top is 3020 m. The two landslide dam bodies are considered as the dam break calculation model (Figure 5), and the possibility of dam break is checked and analyzed.

According to the results of the first parameter inversion, the permeability channel $\theta=1.9^\circ$ is adopted to calculate the possibility of second dam failure. The theoretical calculation result shows that after $t=250$ h, the flow of the rupture is still equal to zero, and the width of the rupture has been maintained at 2.6 m. There is no dam collapse phenomenon, indicating that the secondary landslide dam body can not naturally collapse under the current actual conditions (Figure 6). With the heightening and extension of the second dam, the natural collapse cannot occur under the same inflow $Q=800$ m$^3$/s. Hence, manual intervention must be taken to dredge the dam and avoid dam collapse during flood season, which would bring greater security and economic losses.

After the artificial intervention, the #II dam body collapsed on the afternoon of Nov. 13th, 2018, and the maximum flow of the rupture flood was about 33,900 m$^3$/s, forming a discharge channel with a length of 800 m and a width of 150-200 m. This calculation can provide guidance and suggestions for the decision-making and risk assessment of implementing manual intervention for landslide dam failure.

![Figure 5 The #II dam breaching calculation model (a) along the riverbed, (b) perpendicular to the riverbed.](image-url)
4.3. Dam Failure Prediction

After the second dam break, the on-site investigation found that huge accumulation bodies remained on the left bank of the river bed, with a high content of solitary stones and dense structure. With the appearance of a new free surface at the rear edge of the landslide, the cracks recede and expand, and there is a risk of continuous cracking and collapse. The slope body gradually deforms under the action of its weight and the stability is extremely poor. Under the influence of rainfall, snowfall, melting water, and other complex factors, the cracking and destroying slope body may collapse again at any time. The dam shape due to the dangerous body on the right bank after the \#Ⅱ dam collapsed was simulated and calculated. The scale of the dam body formed after the dangerous bodies of different volumes slipped is shown in Table 1. The elevation of the township government upstream of the landslide is 2930 m. Considering the impact of immersion and other factors, the water level at the dam should not be higher than 2920 m. The dam breakage analysis was carried out. If the right bank dangerous body collapses by 0.5 to 3 million m$^3$, and the prior dam body of the river bed is not removed, the elevation of the dam top is about 2926 to 2955 m after the dam formation, which is higher than 2920 m. If the dangerous body slips during the flood season, a super large-scale dam will be formed in a short time, posing a significant threat to the lives and property of the people along the river downstream.

Table. 1 Results of the scale of dam formed by the sliding of the dangerous cracking body on the right bank

| Engineering measures | Collapse volume (million m$^3$) | Dam top (m) | Engineering measures | Collapse volume (million m$^3$) | Dam top (m) |
|----------------------|---------------------------------|-------------|----------------------|---------------------------------|-------------|
|                      | 0.5                             | 2926        | Remove the residual   | 0.5                             | 2916        |
| None                 | 1                               | 2935        | landslide             | 1                               | 2922        |
|                      | 2                               | 2945        | deposit               | 2                               | 2931        |
|                      | 3                               | 2955        |                      | 3                               | 2937        |
From the above analysis, it can be concluded that the prior dam body must be removed. According to the proposed excavation plan, the collapse of the landslide after the excavation is predicted. Consider the two conditions of collapse of 2 and 3 million cubic meters of dangerous body volume respectively, and establish a dam-break calculation model (Figure 7).

According to the records, the 2-year and 20-year peak flood rates are 3,360 and 5,670 m³/s during the flood season, and the flow rate is 600 m³/s during the drought period. The calculation results are shown in Table 2. When the collapse volume is 2 million cubic meters and it occurs in the drought season, the peak flow of natural dam collapse is 6500 m³/s, the complete dam collapse duration is 58.7 h, the shape of the rupture is rectangular and the width is 53.5 m. During the 2-year flood period, the peak flow of natural dam break is 21,900 m³/s, the duration of complete dam break is 15.9 h, the shape of the rupture is inverted trapezoid, the upper and lower width are 114.8 and 75.5 m. During the 20-year flood period, the peak flow of natural dam break is 50,900 m³/s, the complete dam break lasts 12.1 h, and the shape of the rupture is inverted trapezoid, with an upper and lower width of 107.2 and 67.9 m.

When the collapse volume is 3 million cubic meters and it occurs during the drought season, the peak flow of natural dam collapse is 7,700 m³/s, the complete dam collapse duration is 65.9 h, the shape of the rupture is rectangular and the width is 59.3 m. During 2-year the flood period, the peak flow of natural dam break is 38,700 m³/s, the complete dam break lasts 17.4 h, the shape of the rupture is inverted trapezoid, the upper and lower width are 129.4 and 81.1 m. During the 20-year flood period, the peak flow of natural dam break is 56,800 m³/s, the complete dam break lasts 15.9 h, and the shape of the break is inverted trapezoid, with an upper and lower width of 129.6 and 90.3 m. To summarise, if the landslide collapses again during the flood period with a 2 or 3 million cubic meter, the peak flow after the dam failure is between 20,000 and 60,000 m³/s, and the dam break will occur in just one day. It is extremely hazardous to the lives and property of downstream residents. It is urgent to conduct landslide deformation monitoring and warning system, and carry out corresponding management work.

![Figure 7 Calculation model of the dam failure prediction](image-url)
Table 2 The calculation results of the dam failure prediction

| Computing conditions | 2 million cubic meter collapse | 3 million cubic meter collapse |
|----------------------|--------------------------------|--------------------------------|
|                      | Drought period | Flood period | Drought period | Flood period |
| The peak flow (10^3 m^3/s) | 6.5      | 21.9  | 50.9      | 7.7      | 38.7  | 56.8 |
| The duration (h)      | 58.7     | 15.9  | 12.1      | 65.9     | 17.4  | 13.4 |
| The top width (m)     | 53.5     | 114.8 | 107.2     | 59.3     | 129.4 | 129.6 |
| The bottom width (m)  | 53.5     | 75.5  | 67.9      | 59.3     | 81.1  | 90.3 |

5. Conclusions
In this study, a mathematical model based on the mechanism of dam break is used to perform inverse analysis and prediction of actual complex landslide dam collapse events. The conclusions are as follows:

(1) When the inclination of the infiltration channel is taken as θ = 1.9°, the inversion of the model parameters is most consistent with the actual dam breaching process of the #I dam.

(2) As the #II dam cannot be breached under natural conditions, manual intervention is required to unblock the dam to avoid greater safety and economic losses due to the breaching of the dam during the flood season.

(3) If the landslide collapses again, with a volume of 2~3 million cubic meters and occurs during flood season, the peak flow will be between 20,000~60,000 m3/s and the dam collapse will occur in just one day. The safety of downstream residents is extremely hazardous to life and property, and landslide deformation monitoring and early warning work are urgent to be done.

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