

Numerical Simulation of Dam Failure Process Based on Flow-3D

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Abstract. The process of a dam breach is very complex, and the resulting flood can pose a great threat to the personal and property safety of downstream residents. By using numerical analysis to simulate and analyze the sensitivity of parameters in the breach process of a large dam, it is of great significance for the formulation of emergency plans and rescue plans downstream of the dammed lake. Taking the Tangjiashan landslide dammed lake as an example, a three-dimensional numerical model of the Tangjiashan landslide dam was established based on the elevation data obtained from satellite remote sensing measurements using Autodesk Civil3D software. The Flow-3D software was used to simulate the dam breach process, and the rationality of the model was verified by comparing it with the measured breach flow rate on site. The sensitivity analysis of parameters showed that the initial breach water level had a significant impact on the breach process. Excavating the spillway channel can effectively lower the water level in the dammed lake during the breach, thereby reducing the peak flow rate of the breach and is an effective solution to control hazard losses.

Keywords. Barrier Dam; Flow-3d; Peak flow; Breach development; Numerical simulation

1. Introduction

A barrier lake is a deposited body formed by landslides, collapses, and debris flows that block river channels and valleys under certain geological and geomorphological conditions due to factors such as earthquakes and heavy rainfall^[1]. Barrier lakes, as a type of special earth and stone dam, are widely distributed globally and can lead to significant disasters. Investigations have shown^[2] that over 90% of barrier lakes are formed by landslides, collapses, and debris flows caused by earthquakes or precipitation, approximately 8% are formed by volcanic eruptions, and about 2% are formed by other triggering factors such as logging, river incision, and artificial excavation. Some barrier lakes are formed under the joint action of multiple factors. Due to their special geometric features and material composition, barrier lakes are prone to breach under the constant erosion of upstream water flow. Investigations have shown^[1,3] that the breach rate of barrier lakes within 1 day of their formation is approximately 27%, 50% of barrier lakes breach within 10 days of formation, and 90% breach within 1 year of formation. Global data on breached barrier lakes indicate that

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the breach modes of barrier lakes mainly include channelized erosion, overtopping, and slope instability^[4]. Research indicates^[3] that overtopping is the main breach mode of barrier lakes because they lack spillways and other flood discharge facilities. As upstream water increases, the water level rises, and the flow spills over the crest, constantly scouring the crest and slope of the dam. This reduces the elevation and volume of the barrier lake and accelerates its destruction, ultimately leading to a sudden breach.

The existing research on the Tangjiashan barrier lake did not simulate the dam-break process with actual terrain, and the numerical model used constrained the development of the breach, which could not describe the complexity of the breach development more realistically. In this study, aiming at the key issues in simulating the dam-break process of barrier lakes, a three-dimensional numerical model of the Tangjiashan barrier lake was established based on the terrain data obtained by satellite remote sensing and the simplified model of the barrier lake. The Flow-3D software was used to simulate the overtopping failure process of the Tangjiashan barrier lake, and a sensitivity analysis of the starting breach water level was conducted. The study provides technical reference for the formulation of emergency plans and countermeasures for barrier lakes in the future.

2. General Tangjiashan Barrier Lake

The Tangjiashan Barrier Lake is a dam formed during the 2008 "5.12" Wenchuan earthquake, which posed a significant threat to downstream areas. The plan view of the dam is rectangular, with a length of about 803 meters and a width of about 611 meters. The height of the dam on the left and right sides is about 90 meters and 124 meters, respectively. The total volume of the dam is about $2.03 \times 10^8 \text{ m}^3$, and the top of the dam is about 300 meters wide with undulating terrain. The upstream slope of the dam is about 200 meters long with a slope ratio of about 1:4, and the downstream slope of the dam is about 300 meters long with a slope ratio of about 1:2.4^[5]. The Tangjiashan Barrier Lake is composed of broken gravel and Cambrian quartz sandstone from the original mountain. In order to quickly reduce and eliminate the danger of the Tangjiashan Barrier Lake collapsing, excavation, diversion and discharge channels were constructed to drain the water. On June 7th, the lake water began to overflow, and the water level of the barrier lake reached about 740.3 meters. At around 6 a.m. on June 10th, the water level reached 742.10 meters, and the peak flow rate was about 6,500 m^3/s at 12:30 p.m. On June 11th, the water level of the lake dropped from 743.23 meters to below 715 meters, and the corresponding storage capacity of the lake water decreased from $2.466 \times 10^9 \text{ m}^3$ to less than $0.86 \times 10^9 \text{ m}^3$.

3. The Process of Simulating Dam Failure

According to satellite remote sensing mapping, a three-dimensional solid model of the Tangjiashan barrier lake was established at a scale of 1:1 based on actual terrain. The model of the barrier lake was based on a simplified model of the dam and actual field measurements, taking into account the physical and mechanical characteristics of the dam material and its shape. A three-dimensional model capable of simulating the

overtopping and failure process of the barrier lake was established and imported into the Flow-3D software, as shown in Figure 1. In order to improve computational efficiency and avoid impacting the size of the study area, the computational model of the Tangjiashan barrier lake was set up in an area about 1100m long, 700m wide, and 150m high, including the range of the barrier lake. The grid was set up for the computational area, and in order to better observe the situation at the breach, a finer grid unit was used in the breach area, with a size of 2.5m × 2.5m × 2.5m, while the other grid units were set at 5m × 5m × 5m. The total effective grid was 3.9 million.

To eliminate the impact of the barrier lake's storage capacity and upstream inflow on the breach flow process, the upstream water level was strictly controlled. The boundary conditions in the model were set as follows: the upstream end was designated as a pressure boundary, the downstream outlet was designated as an outflow, the sides were designated as symmetrical, the bottom was set as a wall boundary, and the top boundary was set as a pressure boundary equivalent to atmospheric pressure.

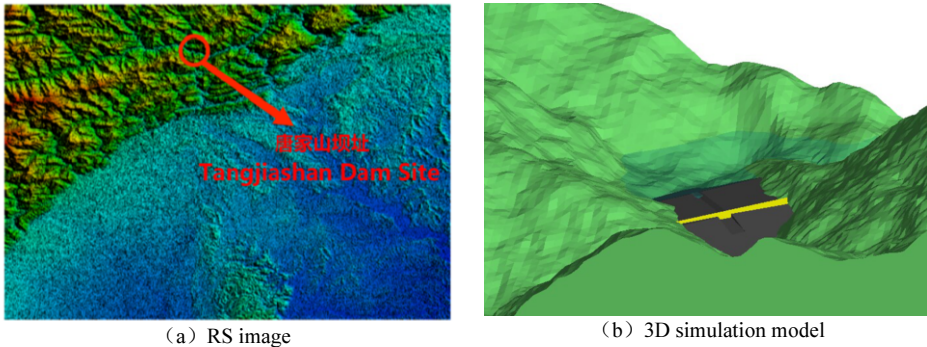


Fig. 1 RS image and 3D simulation model of the TanJiaShan barrier dam

Based on the grain size distribution curves obtained from the five selected boreholes on the Tangjiashan barrier lake^[6] (shown in Figure 2), the input parameters for the three-dimensional model were derived^[7]. The area of the barrier lake was set as a silt-sand model, with a dry bulk density of 2200kg/m³, a transport coefficient of 0.018, and a critical Froude number of 0.05. The other input parameters for the model are shown in Table 1.

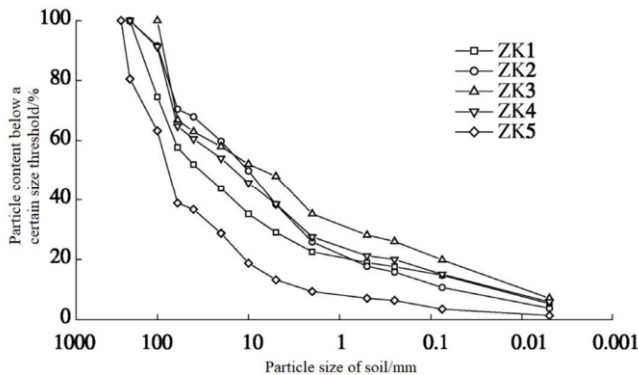


Fig. 2 Gradation curves of the TanJiaShan barrier dam

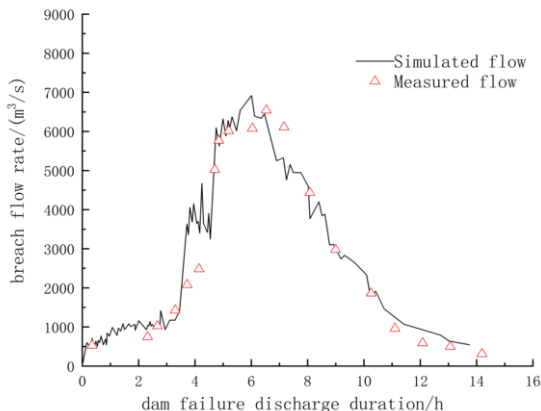
Tab. 1 Input parameters of sediment model

Diameter of sediment particles/mm	Angle of static friction/(°)	Percentage/%
0.005	21.0	13
0.08	21.0	10
0.72	20.5	19
3.6	22.0	10
7.2	22.0	8
10	22.0	27
37	31.0	13

4. Simulation Results Analysis

4.1. Comparison and Analysis of Simulation Results and Measured Data.

A flow monitoring section was set up at the breach of the Tangjiashan landslide dam, as shown in Figure 1 (b). The calculation results showed that the peak flow of 6937 m³/s was reached at 11:50 on June 10th, and the field measurement data showed that the peak flow was reached at the breach at 12:30 on June 10th. The difference between the Flow-3D simulation results and the actual peak flow was small, with a relative error of less than 15%. The time to reach the peak flow was 40 minutes earlier than the actual time, and the simulated peak flow was 7.05% larger than the measured value, while the simulated final width of the breach was 4.16% larger than the measured value. This indicates that the comparison between the measured and simulated peak flow and final breach width has verified the effectiveness and accuracy of the simulation using the field measurement data. The comparison between the measured and simulated data is shown in Table 2 and Figures 3 and 4.

**Fig. 3** Comparison of calculated and measured breach hydrographs**Tab. 2** Comparison of peak flow of dam-break flow between simulation and recorded results

Time	Simulated flow m ³ /s	Measured flow m ³ /s	Relative error/%
11:30	6064	6065	-0.016
11:50	6937	6090	13.9
12:30	6150	6480	-5.1
13:00	5960	6190	-3.7

4.2. Sensitivity Analysis of Initial Breach Water Level Parameters

To further investigate the impact of model parameters on the Tangjiashan landslide dam failure process, the sensitivity analysis was conducted on the critical breach elevation, which is a key parameter affecting the peak breach discharge and the breach shape evolution^[8]. Two critical breach elevations, 745 m and 748 m, were simulated, and the relative errors were calculated and compared with the initial critical breach elevation of 742 m. The results of the sensitivity analysis on the critical breach elevation are shown in Table 3, and the breach discharge processes under different critical breach elevations are shown in Figure 4.

Tab. 3 Parameter Sensitivity Analysis of Different Starting Breach Water Levels

Starting Breach Water Levels/m	$Q_p/(m^3 \cdot s^{-1})$		B_f/m		T_p/h	
	Simulation results	Relative error/%	Simulation results	Relative error/%	Simulation results	Relative error/%
742	6937	-	150	-	5.83	-
745	7597	9.5	200.3	33.5	5.25	-9.9
748	8542	23.1	220.8	47.2	3.55	-39.1

Note: Q_p is peak breach flow rate; B_f is final breach bottom width; T_p is Time of peak breach flow rate

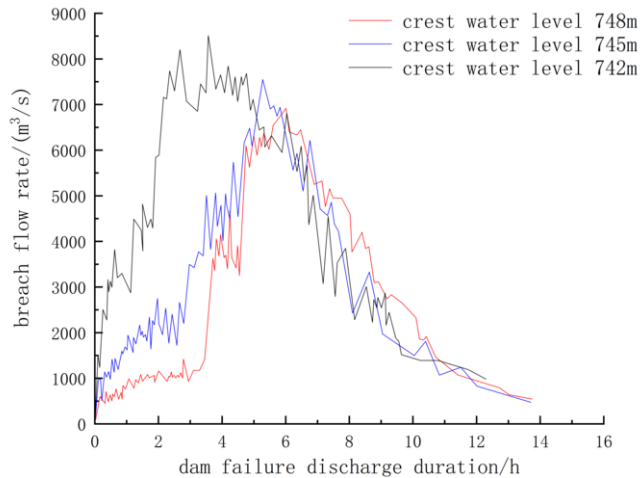


Fig. 4 Analysis of the impact of different upstream failure water levels on the flow rate through the breach

It was found from the simulation results that various parameters calculated in the dam breach simulation were sensitive to the initial breach water level, with breach bottom width being the most sensitive. As shown in Figure 4 and Table 3, when the initial breach water level increased from 742 m to 748 m, the corresponding peak breach discharge increased from 6937 m³/s to 8542 m³/s, an increase of 23.1%. The time to reach peak discharge also advanced from 5.83 hours to 3.55 hours, a 39.1% reduction, with a significant increase in downstream discharge. This indicates that accurate measurement of the initial breach water level is critical for simulating the dam breach process of the Tangjiashan barrier lake.

5. Conclusion

This article conducts an inverse analysis of the overtopping failure of the Tangjiashan landslide dam using numerical simulation methods. The calculated results are in good agreement with the measured data, indicating that the constructed numerical model can be used for the analysis of the overtopping failure of the Tangjiashan landslide dam. In order to explore the influence of model parameters on the dam-break process, a sensitivity analysis of important parameters is carried out. The sensitivity analysis of parameters shows that the initial breach water level has a significant impact on the dam-break process of the landslide dam. This simulation method has important guiding significance for the formulation of emergency plans for downstream rescue operations of landslide dams.

However, there are still some issues that need to be further explored and studied. In this study, natural pure water is used as the simulated flow for dam failure, and the change in water density caused by the erosion of sediment after the water flow hits the dam body is not considered during the simulation process. This may affect the movement trend of the water flow during the outflow process, and further research and improvement are needed in the future.

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