APPLICATION OF EMBANKMENT BREACHING MODEL TO SIMULATE DAM-BREAK FLOODS OF BARRIER LAKES

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ABSTRACT

Barrier lakes pose great threats to the downstream due to their vulnerability to breaching. During the emergency disposal of the Tangjiashan Barrier Lake and the “10.10” Baige Barrier Lake in China, an embankment breaching model previously developed based on the mechanism of breach erosion as observed in various laboratory or field tests and prototype cases, was applied to simulate the dam-break floods. According to the continuous accumulated and updated measured or conjectured data transmitted from the sites which both are quite inaccessible, the model was applied to simulate a large number of possible scenarios of the dam-break floods for both barrier lakes, specially to predict the flood peak outflow and hydrograph, and help to evaluate the severity of the threat to the downstream area. The simulation results provide basis for the emergency evacuation of the population at risk. After the emergency disposal, back analysis of the draining process of the Tangjiashan Barrier Lake was also conducted by using the embankment breaching model to reproduce the well-monitored outflow hydrograph obtained during the draining process. This paper summarizes the simulation of the dam-break floods of the two barrier lakes and the back analysis of the draining process of the Tangjiashan Barrier Lake.

Keywords: embankment breaching, barrier lakes, dam-break floods

1. INTRODUCTION

The barrier lake refers to the lake formed by large-scale landslides or mudslides blocking the river after the earthquake, rainfall and snowmelt, etc. The so-formed dam is a kind of natural embankment with soil and rock mixed together, which is mainly caused by rapid accumulation. The natural embankments are usually relatively loose and lack necessary flooding facilities. Therefore, the natural embankments are prone to breaching and most of the barrier lakes are short-lived lakes. With the rise of water level in the barrier lake, the natural embankment will either break due to overflowing or break due to piping, both resulting in secondary flood disaster.

At present, there are relatively few studies specifically focused on natural embankment breaching simulation, most of which are combined with the study on dam break of artificial embankments, or borrow the research results of artificial embankment failure simulation (e.g. Costa and Schuster, 1988; Zhou et al. 2019). The emergence and successful disposal of the Tangjiashan Barrier Lake in 2008 triggered a wave of simulation study on the dam break of barrier lakes (e.g. Wang et al. 2008; Zhu et al. 2008; Fu et al. 2010; Chen et al. 2015). In this paper application of an embankment breaching model previously developed to simulate the dam-break floods of two high-risk barrier lakes are summarized.

2. OVERVIEW OF THE TANGJIASHAN BARRIER LAKE AND THE “10.10” BAIGE BARRIER LAKE

2.1 The Tangjiashan Barrier Lake

On May 12, 2008, a devastating 8.0-magnitude earthquake occurred in Wenchuan, China. The earthquake induced a large-scale landslide at Tangjiashan, the right bank of the Tongkou River, about 4 km upstream of the Beichuan County. The landslide blocked the Tongkou River and formed the Tangjiashan Barrier Lake (CWRC, 2008).

The Tongkou River is 173 km long, with a watershed area of 4520 km^2 and an average annual flow of 118 m^3/s. The landslide-formed natural embankment is about 803 m long in the direction of the river (see Figure 1), 611 m wide in the transverse direction, 82 m - 124 m high, and $20.4\times10^6\ m^3$ in volume. The maximum capacity of the lake can reach $3.16\times10^8\ m^3$.

The Tangjiashan Barrier Lake is a high natural embankment with a large reservoir (i.e. the barrier lake). Once the embankment breached, it will directly threaten the lives and property of millions of people downstream. To relieve the threat, a 475 m long artificial channel was excavated rapidly across the crest of the embankment by June 1, 2008 to drain the lake. From 7:00 of June 7, the lake began to be drained via the channel. The channel keeps widening and deepening due to flow scour, and shows strong characteristics of headcut erosion. On June 10, 2008, the breaching flow via the drainage channel increased dramatically from 439 m^3/s at 2:30 to 6500 m^3/s at 12:30.

By June 11, the water level of the barrier lake had dropped from a maximum of 743.23 m to below 715 m, and the corresponding water storage volume had dropped from $246.6\times10^8\ m^3$ to within $0.86\times10^8\ m^3$. The newly formed river channel has the capacity to pass through a 200-year flood, and the danger of Tangjiashan Barrier Lake has been successfully removed. The evolution of the drainage channel in the natural embankment can be considered as a certain process of breach erosion in an embankment.

Figure 1. Aerial view of the Tangjiashan Barrier Embankment (CWRC, 2008).

2.2 The“10.10” Baige Barrier Lake

On October 10, 2018 a massive landslide blocked the Jinsha River (a nickname for part of the upper reach of the Yangtze River) and formed a barrier lake (named the “10.10” Baige Barrier Lake, see Figure 2). The barrier embankment is about 15 km downstream of the Poluo Village and about 54 km upstream of the Yebatan Hydropower Station. The embankment along the river is about 2 km long, 450 m - 700 m wide and 61m - 100 m high. The elevation of the embankment is high on the left side (altitude 3005 m) and low on the right side (altitude 2931.4 m). The estimated volume of the embankment is about $25\times10^6\ m^3$.

The “10.10” Baige Barrier Lake began to flow from about 18:00 of October 12. The corresponding water storage capacity was about $2.9\times10^8\ m^3$ when the water level reached its highest point. At 1:00 of October 13, the flow significantly increased, marked the beginning of the actual breaching process. At 6:00 of October 13, the breaching flow reached its maximum value of 10000 m^3/s, after which the flow gradually decreased, and at 14:30 of October 13, it basically returned to the base flow. The on-site breaching flow is calculated based on the measurement process of the water level in front of the embankment (temporary measuring station) and the water level-lake capacity curve of the barrier lake. From October 13 to 15, the hydrological stations downstream of the barrier lake successively peaked and declined, and the danger situation of the “10.10” Baige Barrier Lake was basically lifted, without any casualties. The emergency response work achieved victory.

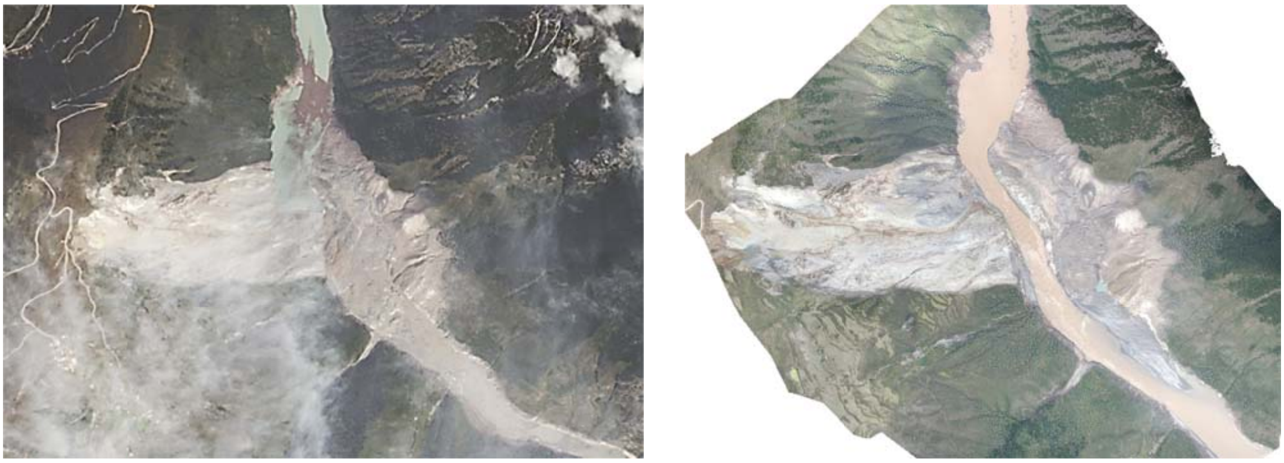

Figure 2 Photos of the “10.10” Baige Barrier Embankment before and after breaching (CWRC, 2019).

3. INTRODUCTION OF THE EMBANKMENT BREACHING MODEL

The embankment breaching model (BRESZHU) is previously developed based on the mechanism of breach erosion as observed in various laboratory or field tests and prototype cases (Zhu, 2006; Zhu et al., 2008). The model mainly simulates the coupling process of embankment failure, such as reservoir water balance, embankment-breaching flow change, embankment-breaching morphology development and embankment body erosion. The breaching of the embankment in the model is a two-phase interaction process of water and soil (i.e. the embankment material). On the one hand, the filling material of the embankment is washed away by the flow, the breach is continuously widened, the elevation of the bottom of the breach is decreasing, and the corresponding breach section is expanding; on the other hand, due to the development of the breach, the flood flow of the embankment breach is constantly changing. The failure rate of embankment mainly depends on the reservoir capacity, anti-scour performance and geometric characteristics of the embankment, etc.

According to the characteristics of the embankment failure development, the whole embankment breaching process can be divided into four stages, i.e. the beginning of the embankment failure → the formation of the headcut → headcut erosion dominated breaching → the break through of the embankment body → continuous widening of the breach. The breaching flow is calculated with a broad-crested weir formula. For the breach shear erosion, the expression for the erosion rate of cohesive soil is applied. The headcut erosion is simulated with a 2D module based on mechanical mechanism. For details readers are referred to Zhu (2006) and Zhu et al. (2015).

The main difference between barrier embankment and artificial embankment is that the material grading of barrier embankment is wider and looser, and the embankment body along the river is thicker. However, in terms of failure, the barrier embankment and artificial embankment still have similar failure process and hydraulic characteristics, and similar failure mechanism as well. Since the embankment body is thicker along the river, the characteristics of headcut erosion of the failure of the barrier embankment are more prominent.

4. MODEL APPLICATIONS DURING THE EMERGENCY RESPONSE PHASE

After the danger of the two barrier lakes occurred, the Yangtze River Flood Protection and Drought Relief Headquarters (YRFPDRH) initiated emergency response in a timely manner. On the one hand, they actively organized the on-site emergency monitoring in the front, and at the same time, organized as well the rolling calculation and analysis of the risk of breaching floods of the barrier lake under different working conditions overnight. According to the result of consultation of the YRFPDRH, combined with the continuous accumulated and updated measured or inferred data transmitted from the sites of the two barrier lakes which both are quite inaccessible, the embankment breaching model was applied to rolling simulation of a large number of possible scenarios of the dam-break floods for both barrier lakes. The model predicts some key information, including the flood peak outflow and hydrograph, helps evaluate the severity of the threat to the downstream area, and provides an important basis for the emergency evacuation of the population at risk in advance.

More than 100 working conditions have been calculated for the two barrier lakes. In the following, only the “10.10” Baige Barrier Lake is taken as an example to introduce the calculation results of several of the working conditions.

From October 10 to 13, simulation of about 50 possible scenarios of the embankment breach flood of the “10.10” Baige Barrier Lake was conducted. Because of the susceptibility of the natural embankment, it may break before the water reaches the embankment crest. Assuming different breaching water level (corresponding to different lake capacity), different breaching duration and different breach size, and calculate the embankment breaching flood respectively. Table 1 gives the calculation conditions for some of the scenarios and the corresponding calculated flood peak, and Figure 3 shows the calculation results of the breach flood for these scenarios.

As introduced above, for the “10.10” Baige Barrier Lake, the real breaching began at 1:00 on October 13, when the lake held about 2.9×10^8 m^3 of water. At 6:00 on October 13, the breach flow reached a maximum of 10000 m^3/s, after which the flow gradually decreased. It can be seen from Table 1 and Figure 3 that the measured flood peak is within the calculation result range of the several assumed working conditions, and the difference is not that big. For the formulation of the emergency evacuation plan, it is necessary to estimate the flood peak in advance, which should be safe but not too exaggerated.

It can also be seen from Table 1 and Figure 3 that with the extension of the breach duration, the flood peak decreases rapidly. When the size of the breach increases, the flood peak increases sharply.

Table 1. Calculation conditions and calculation results of the flood peak of the “10.10” Baige Barrier Lake.

No.	Corresponding lake storage ($10^8 m^3$)	Breach size	Breach duration (hr)	Calculated flood peak (m^3/s)
1	3.0	1/2 dam body	3	21600
2	3.0	1/2 dam body	6	15600
3	3.0	1/2 dam body	12	9500
4	3.0	1/3 dam body	3	9500
5	3.0	1/3 dam body	6	8500
6	3.0	1/3 dam body	12	6900

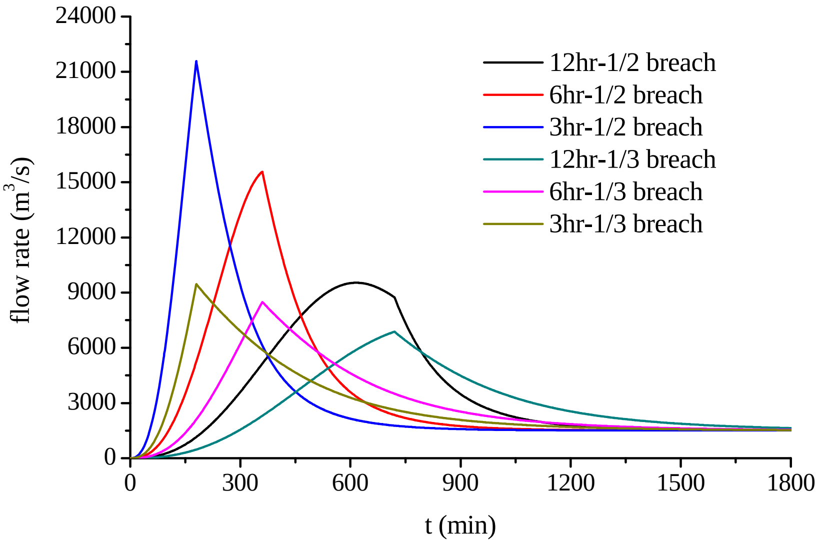

Figure 3. The breach flow rates of the “10.10” Baige Barrier Lake under different schemes for breaching of 3.0×10^8 m^3 lake storage.

5. MODEL APPLICATIONS TO THE BACK ANALYSIS

For the Tangjiashan Barrier Lake, to reduce the water volume of the barrier lake and the corresponding breaching flood peak, and consequently the flood risk to the downstream area, about one month later after its formation the lake was artificially breached by a manual excavated drainage channel. Just after the dangerous situation of the barrier lake was eliminated, the embankment breaching model is used to back analyze the drainage process of the barrier lake in time (CRSRI, 2008).

Since only the water level in front of the embankment and the discharge process are relatively complete in the observational data of the breaching process of the Tangjiashan Barrier Lake, in the model calculation the material parameter of the embankment is extrapolated by using the data of water level in front of the embankment, and then the material parameter is directly applied to the calculation of the development process of the drainage channel and the breaching flood, etc. In the calculation, the development process of the drainage channel section depends on the interaction between the breach flow and the embankment material, and the final opening width and the final bottom elevation of the drainage channel section are determined by the model calculation.

Figure 4 shows the calculated and measured water level in front of the embankment. It can be seen from the figure that the calculated value agrees well with the measured one. Figure 5 shows the model calculation results and measurements of the drainage flow process (i.e. the breaching flow process) of the Tangjiashan Barrier Lake. It can be seen from the figure that the calculated values of the model are in good agreement with the measurements as a whole, especially the flood peak flow, the peak time, and the discharge flow process after the peak appears. For example, the measured flood peak is 6500 m^3/s, while the calculated value is 6616 m^3/s, the difference between the two is 116 m^3/s, and the calculated value is 1.8% larger than the measured one.

In addition, it can be seen from Figure 5 that the flow rate measured in the early stage of the drainage process is slow to increase, while the calculated value of the model increases relatively fast. The reason is considered to be mainly due to the use of lead wire cages for protection after the excavation of the drainage channel. Therefore, its cross-section expanded slowly at the initial stage, and the corresponding flow increased slowly. Later with the enhancement of flow scouring ability, the channel cross-section expansion speed increased significantly after the surface protection of the drainage channel was gradually washed away, and the drainage flow also increased rapidly.

In general, the modeled results agree well with the available measurements, indicating that the embankment breaching model can be used to calculate and analyze the dam-break floods of barrier lakes.

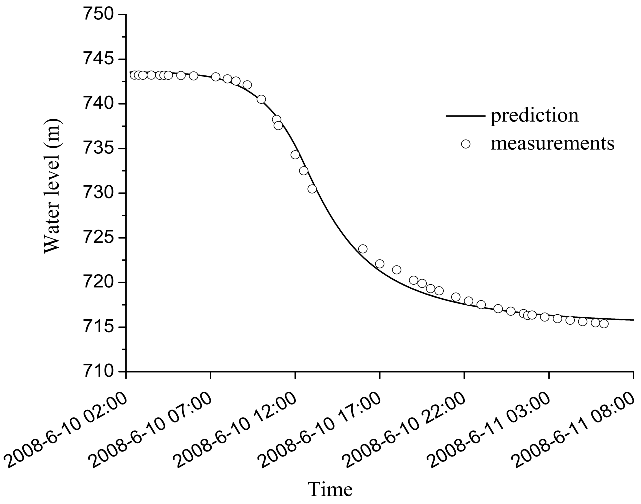

Figure 4. Comparisons of predicted and measured lake level for the Tangjiashan Barrier Lake.

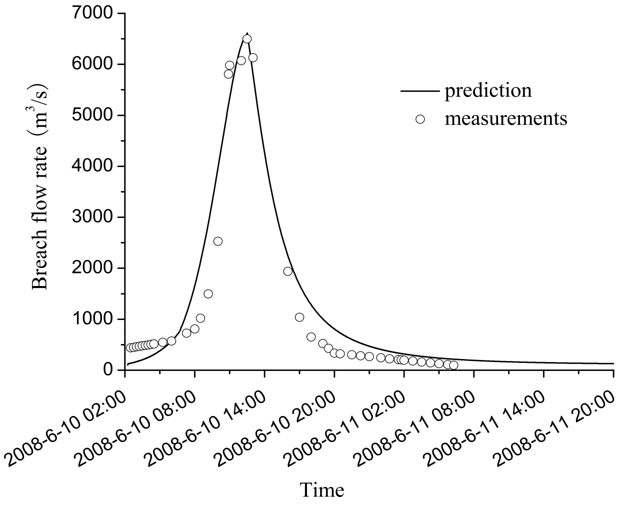

Figure 5. Comparisons of predicted and measured drainage flow rate for the Tangjiashan Barrier Lake.

6. CONCLUSIONS

After the formation of the Tangjiashan Barrier Lake and the“10.10” Baige Barrier Lake, according to the continuous accumulated and updated measured or inferred data transmitted from the sites of the two barrier lakes, an previously developed embankment breaching model was applied to simulate a large number of possible scenarios of the dam-break floods for both barrier lakes, providing important basis for the emergency evacuation of the population at risk. Later the model was also applied to back analyze the drainage process of the Tangjiashan Barrier Lake. The main conclusions and experience from the dam break flood calculation and back analysis are as follows.

(1) Non-engineering measures are the main means for emergency rescue and disposal of barrier lakes. Because the volume of the natural embankment body is often huge, and the embankment is usually remote, it is difficult for large machinery to reach and get to the embankment. Therefore, the emergency rescue of the barrier lake must first transfer personnel in dangerous areas as soon as possible, and strengthen monitoring and early warning. Of course, if conditions permit, supplemented with necessary engineering measures, e.g. trenching in the embankment and draining the lake proactively can effectively reduce the impact of the barrier lake.

(2) Model calculation shows that, the flood peak decreases rapidly with the extension of the breach duration; and the flood peak increases sharply with the expansion of the breach size.

(3)The most basic requirement for the calculation of dam break flood risk for the emergency treatment of barrier lakes is simple and fast. The simulation does not need to be overly refined, and it is usually based on constantly updated and accumulated data, step by step, rolling calculation, and gradually approaching the final process of dam break and breaching flood.

(4) Due to the lack of data and the urgency of time, many assumptions usually have to be adopted in the flood simulation and prediction during the emergency treatment of barrier lakes, so it is feasible to borrow the embankment breaching model at this time. In fact, the material grading of the barrier embankment is very wide, and there are even a lot of megaliths (e.g. in the Tangjiashan embankment). In fact, the general sediment transport formula cannot be applied at all, so the calculation assumptions are inevitable. However, in order to better understand and master the characteristics and mechanism of natural embankment failure, further research, especially experimental research, is still very meaningful.

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