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Theoretical Description of the Hydrodynamic Process after Barrier Lake Formation and Emergency Responses Implementation

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Abstract: Barrier lakes are secondary disasters with associated landslides and debris flow that can cause serious damage to the downstream populations and areas. Existing studies are lacking in comprehensive descriptions of the rescue process, where the main channel streamflow varies and topographic erosion develops, as well as engineering disposal performs. This paper aimed to theoretically investigate the formation and emergency responses to barrier lakes using on-the-spot investigation and calculus theory. The results showed that the formation of a barrier lake led to a sudden variation in the flow-change rate (normal to infinite). However, after implementing emergency measures, this rate returned to normal. The whole rescue process could be regarded as the accumulation of disposal effects. Volume changes in the main streams were expressed by a differential equation of the lake surface area and water level variations. In addition, a corresponding theoretical description of flow discharges was also given when engineering measures such as the excavation of diversion channels and engineering blasting were adopted. Specifically, the theoretical expressions of flow discharge were given respectively in the developing stage and breach stable stage after the excavation of diversion channels. The flow discharge through certain sections was also described theoretically when engineering blasting was chosen to widen and deepen the cross-section of the diversion channels. Overall, this paper mathematicizes and theorizes the existing emergency measures, which helps to better understand their implementation principles and application requirements.

Keywords: barrier lake; emergency response; calculus theory; diversion channel; engineering blasting

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1. Introduction

Barrier lakes usually form with natural phenomena such as earthquakes, rainfall and snow melting [1]. The large-scale landslides and debris flows that can be associated with these phenomena can obstruct the river valleys or riverbeds of the original river system, causing upstream flow to accumulate and then overflow. A barrier lake appears when this water-storage process reaches a certain level. Barrier dams refer to the above-mentioned loose deposits damming the original river systems [2,3]. Due to their diverse particle size distribution [4], barrier dams are easily affected by water pressure, seepage pressure, overflow, etc. Their overall stability and anti-erosion abilities are both weak, so the existing dams can break at any time. Modes of dam-breaking in barrier dams mainly include overtopping, piping, and slope failure, among which overtopping is the most common and prominent failure mode (Figure 1) [5]. The overtopping process can be described

as follows: the water level of the barrier lake gradually rises due to the water storage process. When the water level exceeds the dam height of the lowest part of the barrier dam, a breach will form as the dam is eroded continuously by water flow. Aggravation from headward and lateral erosion along the breach then gradually develops, which finally leads to slope instability and channel collapse. After a dam break happens, the resulting debris flow and flood disasters pose threats to the lives and property security of downstream populations [6]. Consequently, it is necessary to adopt immediate emergency measures before overtopping.

Figure 1. Failure modes of dams.

Many countries in the world have experienced frequent and numerous landslides (Figure 2a), such as Canada [7], China [8–10], Japan [11,12], Italy [13], New Zealand [14], and the United States [15]. Considering that dam breaks commonly submerge downstream populations in the lower reaches of rivers and cause tremendous losses [16,17], in the past few decades, many researchers have been engaged in the investigation of dam breaks and flood predictions. At present, field investigations, indoor experiments, and numerical simulations are all seen as effective research methods for studying barrier lakes [18–20]. In this paper, we studied existing research on barrier lakes and dam breaks from the last 20 years via cluster analysis using the Vos viewer software (Figure 2b).

Figure 2b shows that existing research on barrier lakes can be divided into four branches. First, starting with failure mechanisms [10,18], many studies focused on breach erosion, and then forecasted the peak discharge of the dam break [21,22]. For example, Jiang et al. [23] and Liu et al. [8] studied the effects of loose deposits and the downstream slope toes of natural dams on the formation process of debris flow and breach erosion characteristics. Gong et al. [22] systematically summarized numerous calculation formulas for the peak discharge of dam breaks. Notably, the Wenchuan earthquake of 2008 had triggered nearly 828 barrier dams, approximately 30% of which broke within one week after formation, threatening the safety of downstream populations and property [24]. Since then, research on barrier lakes has increased significantly. In these studies, scholars have tended to use numerical software to simulate the dam-break process and then carry out a risk analysis [25–28]. For instance, to simulate the evolution process of river blocking, Zhao et al. [25] and Wang et al. [26] chose the DEM-CFD and DDA-SPH software, respectively. Third, a series of studies were carried out on factors related to geomorphology [29], such as the material composition of the dam body, a risk assessment of dam breaks [13], a brief introduction to the dam-sliding process [30–32] and the evolution of the continuous sedimentary process [33], etc.

Figure 2. Localization and number of publications on barrier lakes, and the corresponding cluster analysis in the last 20 years. (Note: Different colors represent different research topics; the lines represent the co-citation relationship; the larger the node is, the more frequently the keywords appear in the research).

Finally, there are also numerous case studies based on field data [34,35]: these studies have mainly recorded on-site processes from the formation of a barrier lake to a successful emergency response. Xu et al. [36] described the failure process, the emergency responses, and all efforts used to reduce the risk of the Yagu landslide on 20 March 2019. Song et al. [37] then outlined the successful disaster management of the July 2020 Shaziba landslide induced by heavy rainfall. Junichi and Naoki [38] noted that both tangible and intangible measures for debris flows were effectively implemented by the Sabo department of MLIT. Moreover, the authors noted that “landslide control works” such as drainage wells and drainage boring works are the most common methods to lower the groundwater level. Fan et al. [39] also considered the excavation of a spillway to be useful for dealing with the successive landsliding and damming of the Jinsha River in eastern Tibet. Moreover, many other existing emergency responses including engineering blasting, dam reinforcement and pump drainage were presented by Xu et al. [40].

It can be seen from the aforementioned literature review that barrier-lake research mainly focuses on formation and evolution processes, breach discharge predictions, analysis of geographical characteristics, and recordings of specific rescue processes. Undoubtedly, these areas of study have developed successfully and are indispensable in emergency rescue for barrier lakes. However, there are still no comprehensive theoretical analyses on the processes of barrier lakes from their initial formation to the emergency rescue of artificial breaches. The present research considers breach development, geographical characteristics, and some engineering measures for breaches, and seeks to explain the relevant physical processes and technologies in a scientific context, such as how to theoretically express the process whereby landslides dam a river. Then, for the existing emergency responses, our focus is mainly on how to adopt effective technical measures, such as the construction of diversion channels or engineering blasting, to immediately eliminate the risks of dam breaks. In other words, the present research provides a brief description of the rescue process and its technical measures but lacks relevant cause analyses, scientific explanations and theoretical descriptions. Therefore, it will be necessary to further enrich the technical theories to better understand their practical significance.

Overall, the main objective of the present study was to obtain the general corresponding theoretical description and scientific explanations for barrier lake formation and emergency response processes for barrier lakes. To be specific (Figure 3), this paper aims to (1) study the mainstream volume changes after emergency measures are implemented;

(2) analyze the technical principles of excavating a diversion channel and then give a theoretical description of flow variation; and (3) investigate the applicability of engineering blasting and obtain theoretical descriptions of flow discharges when the cross sections tend to be wide and deep. The main innovation of this research is its consideration of disaster occurrence as a differential process, and a rescue process as the accumulation of emergency response effects. This study not only provides a clear description of the development of the process from barrier lake formation, to artificial dam break, to normal river discharge, but also clarifies the implementation principles of emergency response measures, thereby providing some useful guidance and working ideas for the actual rescue processes.

Figure 3. The objectives of this research.

2. Materials and Methods

2.1. Tremendous Yigong Landslide

At 20:05 on 9 April 2000, a huge landslide occurred in zamnonggou, Yigong Township, Bomi County, Tibet Autonomous Region (94°53' E, 30°14' N) due to a rapid increase in temperatures, and the melting of glaciers. A trumpet-shaped natural dam with a length and width of approximately 2500 m, and a height of approximately 60–110 m completely blocked the Yigong Zangbu river. The area of this dam was 5 km² and its volume was approximately 300 million m³. Subsequently, the water level of Yigong Lake rose at a rate of approximately 0.5 m/day and showed an increasing trend. By 24 May, the measured inflow according to the ADCP method was 518 m³/s. At that time, the water level of the lake increased at a rate of about 1.0 m/day, and the storage capacity was nearly 1.07×10^9 m³. In addition, as the occurrence time of the Yigong landslide coincided with the peak period of ice and snow melt, the water level at the Yigong barrier lake rose continuously, with a maximum daily increase of more than 100 million m³. Overall, the scale and harm of the Yigong landslide were both large (ranking third in the world).

2.2. Emergency Responses of Yigong Landslide

More than 4000 residents were trapped near the upper reaches of Yigong lake, and a large amount of land was, or will be submerged. In addition, more than 70% of the dam material is composed of fine-grained soil. When overtopping occurs, the landslide dam is extremely easy to collapse. An overtopping collapse would cause tremendous damage to the downstream areas due to the presence of main communication trunk lines and people of all ethnic groups in the area. Therefore, urgent emergency response measures are necessary to prevent such a disaster. At present, there are numerous emergency response measures aimed at various categories of barrier lakes, especially engineering measures such as engineering blasting, excavating division channels or reinforcing landslide dams [40]. Among them, the excavation of division channels is the most common engineering measure (Figure 4). The emergency response to the Yigong landslide involved the excavation of diversion channels. Through scheme selection, it was determined that the lowest bottom elevation of the diversion channel was 25 m, while the excavation depth was 20 m. The

principles of this measure are to artificially induce the flow path by means of diversion channels with small cross sections such that the water body with a certain water head can erode the channel and carry sediments via potential energy. With an increasing flow velocity and flow discharge, the transport capacity of water flow also increases. Correspondingly, the diversion channel is deepened and widened gradually, leading to expanded cross sections. At this time, the flow discharge tends to increase significantly, which further enhances the transport capacity of the water flow and expands the cross sections of the diversion channels. This erosion process stops when the water flow reaches landslide mass with strong anti-erosion ability. Then eventually, a stable new channel forms.

Figure 4. Typical engineering measures.

Apart from excavating a diversion channel, engineering blasting is also an effective way to form channels artificially (Figure 4). This measure is applicable to the following situations where: the composition of the landslides is complex, serious deposition occurs in the river bed, and/or the construction is difficult. For example, sometimes it is difficult to excavate a diversion channel when the landslides on both banks are relatively prone to collapse. Moreover, if large machinery is unable to enter the working location, only manual methods can be used; such methods do not meet the necessary requirements. In this context, engineering blasting is an effective method. For the disposal of the Yigong barrier dam, engineering blasting measures were also adopted on a small scale to clear up block stones in the diversion channels before the manual discharge process. At present, engineering measures have effectively reduced the peak flow and prolonged the discharge time. This emergency response process has therefore achieved major success, ensuring human security and minimizing disaster losses.

2.3. Calculus Application

The relevant calculus theory is described in Figure 5.

Figure 5a shows that when a rectangle is discretized into numerous small rectangles, after manual intervention, these rectangles can be recombined into a whole rectangle. Here the red area represents the area under the f curve, and can also be regarded as the area sum of countless small rectangles. The sum of the numerous small rectangles can be expressed by the Equation (1).

$$S_{\text{rectangles}} = \sum_{i=1}^n f(x_i) \Delta x \quad (1)$$

where n is the number of divided rectangles. When n is infinite, the sum area of countless rectangles was exactly equal to the area under the f curve, as shown in Equation (2).

$$S_{\text{curve}} = \lim_{n \rightarrow \infty} \sum_{i=1}^n f(x_i) \Delta x \quad (2)$$

Figure 5. The calculus theory in the research on barrier lakes. (a) The area segmentation in a rectangle and a f curve. (b) The area segmentation under the main channel streamflow curve of Yigong barrier lake.

Equation (2) describes how to calculate the area under a curve. In the emergency response process in Yigong ($94^{\circ}53' E$, $30^{\circ}14' N$), the main channel discharge curve was similar to the referred f curve. We make the hypothesis that emergency responses at different times contribute to the drainage of the barrier lake and to the normalization of the discharge (as shown in Figure 5b). The total response time T was divided into n short time periods, so there was $\Delta t = \frac{T}{n}$. The height of countless small rectangles was considered the main channel streamflow in different time periods. In this way, the area under the curve here equals the total increased amount of water $\Delta V_{\text{mainstream total}}$ in the whole emergency response process, as shown in Equation (3).

$$\Delta V_{\text{mainstream total}} = \lim_{n \rightarrow \infty} \sum_{n=1}^{\infty} [Q_{t_1} \cdot \Delta t + Q_{t_1 + \Delta t} \cdot \Delta t + Q_{t_1 + 2\Delta t} \cdot \Delta t + \dots + Q_{t_1 + (n-1)\Delta t} \cdot \Delta t] \quad (3)$$

Overall, it can be seen that the emergency response process is both differential and integral. To further express Equation (3), it is necessary to obtain the volume change in every short period of time. It can also be seen that Q_{t_1} , $Q_{t_1 + \Delta t}$ and $Q_{t_1 + (n-1)\Delta t}$ represent the main channel streamflow in different short time periods after a series of emergency response measures are adopted. Therefore, it is also useful to obtain a theoretical description of main

channel streamflow over time. In the following, we introduce theoretical descriptions of main channel streamflow for when the excavation of a division channel and engineering blasting are chosen to mitigate a barrier lake disaster.

3. Results and Analysis

3.1. Theoretical Analysis of Barrier Lake Formation

Based on the factors underlying the formation of the barrier lake, natural barrier lakes are classified into eight categories [15], landslide-dammed barrier lakes, ice-dammed barrier lakes [41], moraine-dammed barrier lakes, volcano-induced barrier lakes, river siltation-induced barrier lake, eolian sediment-induced barrier lake, current-induced barrier lakes, and organic barrier lakes. Among these types, landslide-dammed lakes are the most common (Figure 6). Costa and Schuster [15] further divided the damming types of such lakes into seven categories based on the landslide dams' relationship with the valley floor. The most common were the partial damming type (44%) and complete damming type (41%). However, regardless of the direction in which the river is dammed, a landslide will slide at a high speed as the huge height difference gives the landslide have a great potential energy.

Figure 6. Landslides damming the river.

Change in the rate of the main channel streamflow when in the process of landslide damming the river can be expressed as:

$$\frac{\Delta Q_{\text{mainstream}}}{\Delta t} = \frac{Q_{\text{mainstream}_{\text{initial}}} - Q_{\text{mainstream}_{\text{final}}}}{\Delta t} \quad (4)$$

where $Q_{\text{mainstream}_{\text{initial}}}$ is the initial normal main channel flow of a river, and $Q_{\text{mainstream}_{\text{final}}}$ is the main channel flow when the landslides finally dams the river. After landslides dam the river, the downstream hydrological stations largely dry up, and the main channel streamflow approaches zero. The change rate of discharge in this process is large and can even be infinite. Then, a barrier lake forms and the water level continues to rise steadily. The danger of barrier-lake formation is mainly reflected in two aspects. The first is the basin water surface height in the barrier lake. If the crest elevation of the barrier dam is estimated to be relatively high, after overtopping occurs, the tremendous amounts of energy carried by the dam break will pose a great threat to the downstream residents. The second is the amount of water in the barrier lake. During the retaining process, assuming that the upstream inflow is expressed as $Q_{\text{in}}(t)$, then the theoretical description of increased water volume in the barrier lake is $\Delta V_{\text{barrier lake}} = \int_0^t Q_{\text{in}}(t)dt$. When an overtopping process appears without any intervention, the total amount of water in the barrier lake will be up to a maximum value.

For common landslide-dammed lakes, the barrier dam is mainly composed of loose deposits from both banks of the river. With an increasing water level, the head difference around the dam increases continuously, which then leads to a high seepage pressure. The possibility of piping and seepage then increases, further increasing the risks of a dam break. As a dam break poses serious threats to the downstream residents, it is necessary to adopt effective emergency measures.

3.2. Theoretical Description of Main-Stream Volume Variation

In the discharging process of Yigong barrier lake, eight hydrological stations were added to the existing hydrological stations (Gongde hydrological station, Yigongba front water level station and Tongmai hydrological station). The hydrological station and ADCP method were both used to monitor the upstream hydrological situation in real time. Due to data availability, after a series of emergency measures were adopted, the hydrological data for Yigong barrier lake in the Yarlung Zangbo River were considered to generalize an overall theoretical description of downstream volume variation and further express Equation (3).

An analysis of the relationship between the time, area, and water level is presented in Figure 7. By dividing the total studied time into some short time periods based on calculus theory, the relationship between time and barrier lake area in each time period can be expressed as a linear relationship with different slopes k_i . Water level showed a power function relation with time. When a series of emergency measures are taken, the increased water volume in the main channel becomes equal to the reduced water volume in the barrier lake. Therefore, the total main channel volume change is equal to the sum of the volume change of the barrier lake in every short time period, which can be expressed by Equation (5). Here, the area of the barrier lake at t is expressed as S_t while the water level over time is expressed as $H(t)$.

$$dV_{\text{mainstream}}(t) = S_t \cdot dH(t) \quad (5)$$

Figure 7. Relationship between the time, area, and water depth of the barrier lake.

When the total time T is divided into short time periods, the relationship of the piecewise linear functions between the barrier lake area and the studied time t can be described using Equation (6) to obtain the S_t :

$$S_t \begin{cases} S(0) + k_0 t & 0 \leq t < T_1 \\ S(T_{N-1}) + k_{N-1}(t - T_{N-1}) & T_{N-1} \leq t < T_N \\ S(T_N) + k_N(t - T_N) & T_N \leq t < T_{N+1} \end{cases} \quad (6)$$

where N is the number of finite time periods in measurable time length T ; k_i is a constant coefficient that is negative under a drainage state; the parameter k_N is the average value of k_i in a measurable time length; and $T_0=0$ and $T_N=T$ represent the starting point and ending point of the measurable time length, respectively. The interval from T_N to T_{N+1} indicates the time period to be estimated.

The relationship between water level H and time t is expressed using Equation (7).

$$H(t) = a_i(t - T_{i-1})^{b_i} + H(T_{i-1}) \quad T_{i-1} \leq t < T_i, \quad i = 1, \dots, n \quad (7)$$

where $H(0)$ represents the highest water level of the barrier lake; and a_i and b_i are constant coefficients.

By substituting the expressions of $S(t)$ and $H(t)$ into Equation (5) and then integrating them from T_i to T_{i+1} , the volume change can be expressed as.

$$V(T_{i+1}) - V(T_i) = \int_{T_i}^{T_{i+1}} dV(t) = \int_{T_i}^{T_{i+1}} S_t dH(t) = \frac{b_i a_i k_i}{b_i + 1} \Delta T_i^{b_i+1} + a_i S(T_i) \Delta T_i^{b_i} \quad (8)$$

From the highest water level in the barrier lake to normal main channel discharge, the calculated value of Equation (8) is negative, which represents the storage capacity loss of the barrier lake during the given time period (T_i to T_{i+1}).

Then, according to the principle of storage capacity balance, there is:

$$\Delta V(T) = (Q_{\text{mainstream}} - Q_{\text{in}}) \cdot \Delta T \quad (9)$$

A series of main channel streamflow values at discontinuous time points were obtained using Equations (8) and (9). The actual values are the same as those used both in Figure 7 and for obtaining the aforementioned k , a and b coefficients. The calculated values approach the actual values, as shown in Figure 8, indicating that the calculus theory is applicable when studying the volume changes of the barrier lake.

Figure 8. Comparison between the calculated main channel streamflows and actual values.

However, in an extrapolated time interval, if there is $T_N \leq t < T_{N+1}$, Equation (5) can be expressed as follows, after being integrated in a time period of 0– t .

$$\begin{aligned} V_{\text{mainstream change}} &= \left[\sum_{i=0}^N \frac{a_i b_i k_i}{b_i + 1} (T_{i+1}^{b_i+1} - T_i^{b_i+1}) + \int_T^t S(t) dH(t) \right] \\ &= \left\{ \sum_{i=0}^N \left[\frac{a_i b_i k_i}{b_i + 1} \Delta T_i^{b_i+1} + a_i S(T_i) \Delta T_i^{b_i} \right] + \frac{a_i b_i k_i}{b_i + 1} (t - T_i)^{b_i+1} + a_i S(T_i) (t - T_i)^{b_i} \right\} \end{aligned} \quad (10)$$

3.3. Theoretical Description of Emergency Measures

3.3.1. Excavation of Diversion Channels

To further express Equation (3), it is also necessary to obtain a theoretical description of the flow discharge when engineering measures are implemented. We previously noted that the dam breach process entails two important stages, including the developing stage and the stable stage. Accordingly, this section analyzed the main channel streamflow in the developing stage and stable stage of a dam breach based on calculus theory.

First, in the developing stage, the theoretical expression of main channel streamflow can be given via a time differential. Here, it is assumed that: (1) the barrier lake water is an ideal fluid that is incompressible and inviscid; (2) the breach shape forms and remains stable during time period T ; (3) the inflow momentum of tributaries is too small to consider, and the influence of rainfall and infiltration are both ignored; and (4) the bottom elevation, the headward erosion rate, and the lateral erosion rate of the breach change linearly during the given time period.

Taking the trapezoidal breach section as an example, the water level of the barrier lake is set as H . The initial water level of the division channels is H_0 and the bottom elevation is Z_s . The bottom width of the trapezoid is b and the slope is m . In addition, the water level of the barrier lake over time can be expressed as $dH(t)$. The bottom elevation of the division channel over time can be expressed as $dZ_s(t)$. The water level in the division channel during the discharge process is H' which can be expressed as:

$$H' = H_0 - \int H(t) - \int Z_s(t) \quad (11)$$

Then the area of the cross sections can be approximately expressed as,

$$A = (b + mH')H' = bH' + mH'^2 \quad (12)$$

$$\frac{dA}{dt} = b \frac{\partial H'}{\partial t} + H' \frac{\partial b}{\partial t} + 2mH' \frac{\partial H'}{\partial t} + H'^2 \frac{\partial m}{\partial t} \quad (13)$$

The flow velocity over time can be expressed as,

$$\frac{dv}{dt} = \frac{1}{2} \sqrt{2g} H'^{-\frac{1}{2}} = \frac{\sqrt{2g}}{2} \frac{\partial H'}{\partial t} \quad (14)$$

The varied flow discharge ΔQ can be expressed as:

$$\Delta Q = Q_{t_2} - Q_{t_1} = C_v \sqrt{2g} \left[b(t+\Delta t)H'(t+\Delta t)^{\frac{3}{2}} - b(t)H'(t)^{\frac{3}{2}} \right] + C_v \sqrt{2g} \left[m(t+\Delta t)H'(t+\Delta t)^{\frac{5}{2}} - m(t)H'(t)^{\frac{5}{2}} \right] \quad (15)$$

In practice, a correction coefficient is usually considered here, as shown in Equation (15). Parameter C_v is the correction coefficient of flow velocity, and the value generally fluctuates between 0.96 and 0.99.

Therefore,

$$\frac{\Delta Q}{\Delta t} = \frac{C_v \sqrt{2g} \left[b(t+\Delta t)H'(t+\Delta t)^{\frac{3}{2}} - b(t)H'(t)^{\frac{3}{2}} \right] + C_v \sqrt{2g} \left[m(t+\Delta t)H'(t+\Delta t)^{\frac{5}{2}} - m(t)H'(t)^{\frac{5}{2}} \right]}{\Delta t} \quad (16)$$

According to calculus theory, the differential can also be expressed simply from the perspective of the derivative, i.e.,

$$\frac{dy}{dx} = \lim_{\Delta x \rightarrow 0} \frac{\Delta y}{\Delta x} \quad (17)$$

In short periods of time, the change rate of the main channel discharge can be expressed as follows:

$$\frac{dQ}{dt} = C_v \sqrt{2g} \left[\frac{d \left(bH'^{\frac{3}{2}} \right) + d \left(mH'^{\frac{5}{2}} \right)}{dt} \right] \quad (18)$$

Then, the integral expression of the main channel discharge from 0 to t is as follows:

$$Q(t) = C_v \sqrt{2g} \int_0^t \left[d \left(bH'^{\frac{3}{2}} \right) + d \left(mH'^{\frac{5}{2}} \right) \right] \quad (19)$$

Second, in the stable stage, the dam-break process has almost ended, and the breach area remains unchanged. According to the Bernoulli's equation, there is:

$$\frac{p_0}{\gamma} + \frac{v_0^2}{2g} + H' = \frac{p_1}{\gamma} + \frac{v^2}{2g} \quad (20)$$

where p_0 represents atmospheric pressure on the surface of the barrier lake, p_1 represents atmospheric pressure on the side of the dam breach, v_0 represents the flow velocity in the barrier lake, v represents the flow velocity at the dam breach, H' indicates the height difference between barrier lake and dam breach, which equals to the water level of division channels. The atmospheric pressure on the lake surfaces equals to that of the dam breach, so there is $p_0 = p_1$, and the resulting flow velocity equals the well-known Torricelli's law.

According to the relationship between the flow discharge and velocity at the breach, as well as the breach width, a differential equation model can be established as:

$$dQ_b = W(H')v(H')dH' \quad (21)$$

Taking the bottom of the dam breach as the base line, the breach discharge at time t can be expressed as:

$$Q(t) = \int_0^{H'(t)} W(H')v(H')dH' = \int_0^{H'(t)} W(H')C_v\sqrt{2gH'}dH' \quad (22)$$

where H_d is the final breach height, as shown in Figure 9. According to the physical and geometric relations, there is:

$$W(H') = W_{\text{bottom}} + (W_{\text{top}} - W_{\text{bottom}}) \cdot \frac{H'}{H_d} \quad (23)$$

when $W_{\text{top}} = A \cdot W_{\text{bottom}}$, there is $W(H') = W_{\text{bottom}} + (A - 1) \cdot W_{\text{bottom}} \cdot \frac{H'}{H_d}$, where parameter A represents the ratio of W_{top} to W_{bottom} . The flow discharge can be expressed as:

$$Q(t) = \int_0^{H'(t)} \left[W_{\text{bottom}}C_v\sqrt{2gH'} + (A - 1)W_{\text{bottom}}C_v\sqrt{2gH'} \cdot \frac{H'}{H_d} \right] dH' \quad (24)$$

Figure 9. Breach shape after dam break.

After a dam break occurs, the breach can display different shapes. Overall, these shapes can be generalized into three categories. When $A \rightarrow \infty$, the final breach shape will be a triangle while the breach shape will be a rectangle or a trapezoid if $A = 1$ or $1 < A < \infty$.

3.3.2. Implementation of Engineering Blasting

Notably, the discharge capacity is relatively limited for natural diversion channels formed by water erosion. Due to continuously rising water levels and regular flood seasons, these overflow sections are not large enough to discharge increased water flow. To ameliorate this problem, blasting could be adopted to widen and deepen the overflow section. However, in this process, because of the uneven widths and depths of the channels, the velocity v and water depth h of the different depth-measuring verticals would not be the same.

Figure 10a shows the depth-measuring verticals of varying cross sections at a diversion channel. When engineering blasting is implemented, the shape of vertical cross sections along the flow direction will change. As shown in Figure 10b, the x -axis is assumed to be the flow direction. The y -axis and another red line are seen as two depth-measuring verticals. It is assumed that the flow velocity of two verticals are v_a and v_b , respectively. In addition, the water depths of two verticals are h_a and h_b , respectively. As the water depth of these two vertical lines are different, the parameters v_a and v_b represent different weights. The water depth of a differential unit dx is $h_a + (h_b - h_a)x/L_0$ while the flow velocity is $v_a + (v_b - v_a)x/L_0$, so the flow discharge over the length L_0 can be expressed as:

$$Q_{L_0} = \int_0^{L_0} [h_a + (h_b - h_a)x/L_0][v_a + (v_b - v_a)x/L_0]dx \quad (25)$$

Figure 10. Cont.

$$\Delta V_{\text{mainstream}_{\text{total}}} = \lim_{n \rightarrow \infty} \sum_{n=1}^{\infty} \left\{ \int_0^{H(t_1)} \left[W_{\text{bottom}} C_v \sqrt{2gH'} + (A-1) W_{\text{bottom}} C_v \sqrt{2gH' \cdot \frac{H'}{H_d}} \right] dH' \Delta t + \dots \right. \\ \left. \int_0^{H(t'')} \left[W_{\text{bottom}} C_v \sqrt{2gH'} + (A-1) W_{\text{bottom}} C_v \sqrt{2gH' \cdot \frac{H'}{H_d}} \right] dH' \right\} \quad (30)$$

Therefore, the whole rescue process in which the main channel streamflow varies from low to normal could be understood as the accumulation of emergency response effects in infinitely short time periods. It would be useful for future work to further establish a theoretical model of rapid response to dam breakage in the future, and also provide theoretical working principles for downstream disaster relief.

4. Discussion

After landslides dam a river, a barrier lake forms, and the main channel largely dries up. The danger of a barrier lake disaster is then reflected in the upstream and downstream submergence, as shown in Figure 11. By implementing a series of emergency response measures, the main channel streamflow can then return to normal. This response process is similar to altering the external influencing factors of barrier dams so as to reduce losses due to water disasters. In this whole process, the flow discharge is clearly a prominent parameter. Thus, there are numerous models and formulas for predicting discharge variation and peak discharge [41–44]. Existing emergency measures are also used to immediately return the main channel streamflow to normal parameters [36,40,45]. Unlike previous studies, this research did not focus on obtaining a new model to more accurately predicts peak flow discharge compared with numerous existing models. In particular, a creative idea was put forward based on previous emergency response experiences. Specifically, this research tried to theorize and mathematicize the actual physical process, based on calculus theory that considers the rescue process as an accumulation and integral process of disposal effects, as shown in Equations (27)–(30). These kinds of integrals have not been referred to before and their importance is shown in three ways. Firstly, in a summary of the disaster disposal process, mathematical thought and scientific meaning are introduced to deepen the understanding of existing engineering rescue measures, that is, the rescue process is re-expressed in mathematical language. Secondly, some useful information can also be obtained from these mathematical equations, which in turn provides working ideas for the actual operation of emergency measures. Thirdly, the calculus theory here may provide theoretical references and mathematical expressions for establishing the emergency model for rapid responses to dam breakage in the future.

As for useful information obtained from these mathematical equations:

First, it can be seen from Equations (8) and (28) that the overtopping time of a barrier lake generally depends on the inflow discharge and storage capacity, and that the change in water volume can be reflected by the water level and lake surface area. We cannot prevent the formation of a barrier dam. However, if time permits, we can engage in effective artificial rescue measures such as excavating a diversion channel to induce the overtopping ahead of time. In this way, the water level and surface area of the barrier lake can both be reduced, thereby alleviating submergence upstream of the landslide dam. It can also be seen that monitoring the changes in water level and surface area is extremely important when estimating the main channel streamflow. Manual observations can be used in the initial stage; then when the requisite information is obtained, the water level recording instrument can also be selected. In short, the monitoring method should be simple and convenient, while also meeting the high precision requirements of hydrological monitoring accuracy. For example, when measuring a barrier lake area, the area is generally divided into several sections and measured separately [46]. In addition, when the downstream geographical conditions are not conducive to monitoring, the main channel streamflow changes can be described according to the relevant equations, as long as the barrier lake's

surface area and upstream water depth are known, as these values provide some references for the downstream emergency responses.

Figure 11. The sketch diagram of barrier lake disaster.

Second, the dam break process was considered as a process where dam materials were eroded by the overtopping flow [47]. The excavation of diversion channels prolongs the dam break time, and reduces the water level and upstream water storage capacity when the artificially induced overtopping occurs. As shown in Equations (19) and (29), at a developing stage, the main channel streamflow is mainly related to the erosion rate and elapsed time. Variation in the erosion rate is mainly reflected in the parameters m , b and H . The m value is small and it can be ignored. In addition, the derivative order of b and H is the same. To further verify the aforementioned analyses on the drainage and scouring process, a HEC-RAS method was adopted to model the dam-break process of the Baige landslides [48]. There are three reasons why another landslide was referenced here. Firstly, the excavation of a diversion channel was also used for this landslide to discharge the increased water flow. The demonstration of another artificial dam break process can confirm that the drainage and scouring process includes two stages and is related to time, breach width, and water depth (velocity). Secondly, the modelling results can qualitatively show the effect of b and H on flow discharge variation, and verify that the equations in this research can help to understand the artificial dam break process. Thirdly, it was used to indicate that combined with these mathematical descriptions and theoretical analyses, this research indeed can provide some working ideas for emergency responses to other dam-break disasters. The simulated working conditions were: the average elevation of the dam crest, 3001 m, and the bottom elevation of the diversion channel, 2953 m; in addition, the diversion channel had a top width of 42 m, a bottom width of 3 m, a maximum excavation depth of 15 m and a total length of 220 m; the simulated time period was from 11:00 on 12 November when the artificial diversion channel was fully penetrated to 20:00 on the 14th when the whole dam break process basically ended; the modelling initial water level was 2953 m while the final water level was 2905 m; and the final breach width was 150 m.

As velocity variation can characterize the variation in water depth, it can be understood that initially, the amount of overflow is mainly affected by the water depth and flow-velocity fluctuations (Figure 12a). However, the overall variation in breach width b influences the flow capacity significantly. This is because the variation range of breach

width (0–150 m) is much greater than that of flow velocity (0–10 m/s) and water depth. Moreover, in the dam break process, the water-depth and flow-velocity distribution is relatively uniform (Figure 12b). It represents that the erosion characteristics are among the most prominent factors, and the shorter the time needed to begin lateral expansion, the more obvious the erosion, and the faster the discharge process will be. Therefore, the outlet of diversion channels should be set at a location that is easily to be eroded. The aim of this process is to rapidly form an effectively freed surface from the washed front, thereby accelerating the headward erosion process. Moreover, the longitudinal slope of the diversion channel from upstream to downstream should be gradually steepened in order to induce headward erosion. This slope should be located in a place with low terrain and fine particle composition as far as possible, so as to reduce the excavation quantity, lower the excavation difficulty, and to save the excavation time. In this way, the flow capacity can also be fulfilled. Furthermore, the slope of weak sections in the outlet of the diversion channels should be protected locally to avoid a slope collapse and channel blockage before the main channel streamflow increases to peak discharge. After a dam break occurs, a relatively spacious new channel is formed. Overall, this is a description of the developing stage and, combined with Equations (19) and (29), indicates that the varying relationships of H' and b with t are necessary when applying the two equations to actual situations. In fact, as the dam-break process is rapid, it is difficult to manually obtain the changes in breach width b for a continuous period of time. Numerical simulation software such as HEC-RAS can be used to provide successive data. At the same time, the continuous changes in water level can be monitored using an ultrasonic water level recorder. Therefore, numerical modelling is useful for verifying the mathematical descriptions when the monitoring instruments are not advanced enough.

Thirdly, Figure 12 also shows that when the breach width does not change, the dam-break process enters the stable stage. The flow velocity remains stable and the flow discharge should be related to time and water depth. In fact, it can be seen from Equations (24) and (30) that the amount of overflow is mainly related to the rising water levels in the channels. At present, the main channel discharge and flow velocity appears to have returned to normal, indicating that the risk level of the barrier lake is reduced. However, this trend does not mean that there are no concerns. In the past 100 years, there have been six barrier-lake disasters near Caoling [49]. Therefore, after the emergency responses are completed, we should continue to regularly monitor the residual landslides and flow discharges, so as to avoid a recurrence of barrier-lake disasters in the same locations.

Moreover, engineering blasting is an effective method for forming diversion channels, but has limitations in its applications. When the maximum depth of the diversion channel exceeds 2.3 m, the blasted rocks cannot be thrown out of the excavation boundary, so this method alone is not suitable to handle landslide dams. However, this measure can be used to widen and deepen the flowing cross sections. The present research determined the flow discharge variation during this process, as shown in Equations (26) and (27). This research is only suitable for short time periods without considering the erosion. However, it will be sufficient for analyzing the barrier lake formation and emergency response processes.

In short, there are few studies on the implementation mechanisms and evaluation benefits of artificial measures under different dam-break modes, so this research will help provide technical support for emergency responses to barrier lakes. How to actually carry out emergency responses presently depends primarily upon the on-site investigations and the judgment and experience of experts. However, it is difficult to fully understand the characteristics of landslide dams over a period of time due to complex disaster environments. Therefore, future studies will need to work on determining the dam-break mechanisms, understanding the characteristics of the breach flow, and developing effective emergency measures.

(a)

(b)

Figure 12. The modelling results of HEC-RAS. (a) The variation curve of breach width b and flow velocity v with time. (b) Water depth and velocity distribution after dam break.

5. Conclusions

This paper theoretically analyzed the formation of barrier lakes and emergency response processes. The main conclusions are as follows: (1) According to calculus theory, the overall process by which the main channel streamflow varies from abnormal to normal can be understood as the accumulation of emergency response effects over short time periods. In addition, to further express this view, the main channel volume changes during given time periods were described based on the area and water-level data, as well as the principle of storage capacity balance, all of which would also provide some references for the downstream emergency responses. (2) The excavation of division channels is an effective engineering measure. The variation process of dam breaches was divided into the developing stage and the stable stage. In the developing stage, a theoretical description of the mainstream flow discharge was obtained using the time differential. Moreover, in the stable stage, a description was also obtained using the differential water level. (3) The blasting principles and their applicable conditions were also analyzed. Further, the main channel streamflow was described for the process of blasting to widen and deepen the division sections.

These results are mainly related to changes in the main channel volume and flow discharge after implementing some rescue measures, which further indicate that the rescue process is an accumulation process of emergency response effects over short time periods.

Above all, this research will not only provide a theoretical basis for establishing a theoretical model of rapid responses to dam breaks, but also offer effective working ideas for downstream disaster relief. Moreover, this study will help to further improve the research on the systematic emergency responses to barrier lakes, the efficient engineering emergency measures, and the controllable risk analyses of drainage and scouring processes. Notably, this research aims to initially and innovatively re-express the rescue process in mathematical language. Due to the lack of data at this stage, verification is the next step.

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