Experimental study of outburst flood of moraine dam

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Abstract. The moraine dam breach often causes catastrophic floods, this paper designed a field prototype experiment in the Jialongcuo and explored the evolution of the breach floods. Through the analysis of the experiments, the following conclusions are drawn: 1) the process of breach flow can be divided into "initial growth type", "delayed growth type" and "surge type". The first two types can be attributed to the evolution of the breach, and the "surge type" is attributed to the surge caused by the collapse in the upstream. 2) Flow process varies in each stage at different discharge, mainly due to the difference in the rate of undercutting of the breach. 3) A peak discharge formula is proposed involving the erosion of the dam and the influence of the upstream lake catchment, which gives more accurate calculation than the previous formulas.

1. Introduction
Glacial lake outburst floods (GLOFs) occur frequently in alpine glacier zones [1], and global warming has caused more and more events to bring about large amount of property damage and human casualties in areas such as the Tibetan Plateau and the Cordillera system [2-3]. GLOFs are characterized by low frequency and high destructive power [4-7]. For example, on August 1, 2020, a cascading glacial lake outburst occurred in the upstream of the Chongduipu basin, with a total water volume of $3 \times 10^6$ m$^3$ within 24 hours. The flood scoured and hollowed out in the ditch of Nyalam county, causing the collapse of the original berms in the channel, the foundations of buildings were exposed, and the floodwater merged into the Boqu River and advanced toward Zhangmu town, and washed away the State Road 318 near the Quxiang Border Inspection Station, causing the interruption of traffic on State Road 318. The
sediment destroyed the Quxiang power station, causing a three-day power outage in the county of Nyalam.

The current researches are mainly focused on the theory of dam-break flow, dam-break model tests and numerical simulation. The theory is mainly concerned with the analytical solution of the shallow water equation to provide an accurate description of the flow. Xie (1982) derived the peak flow equation for various scenarios including instantaneous and gradual breaching [8]. Zhang (2001) improved the wave velocity and peak flow calculation formulas, and the case verification showed that the improved formulas can be applied to any occasions and the results are reasonable [9]. Zhao et al. (2010) improved the calculation formula of the positive and negative wave intersection method by adding an imaginary pressure on the wave crest, and applied the formula to the case when the water depth downstream was small [10]. Many scholars have conducted dam-break experiments. Jiang and Wu (2020) studied the dam-break process under the influence of initial water content, and found that the rise of initial water content can significantly increase the peak flow [11]. Liu et al. (2020) studied the dam-break process under the influence of trench bed slope and found that the peak flow decreased gradually as the slope increased [12]. Zhou et al. (2019) conducted experiments with variable incoming water flow and found that the peak flow increased with the upstream flow [13]. Wang et al. (2016) studied the dam-break process under different particle gradations, showing that the peak discharge decreased with the average particle size [14].

Numerical simulation is often used to predict the evolution of floods and invert the parameters of failure process [15]. Zhuang et al. (2020) used DAN3D and FLOW-3D software to simulate the formation and failure of the Yigong dam, and the peak flow at the inverse performance Tongmai Bridge was 130,000 m³/s, which matched with the observed values [16]. Wang et al. (2020) used DB-IWHR and 2D hydrodynamic coupling to simulate the breaching of the Baige landslide dam, and found that peak flow and peak arrival time were not sensitive to the breach spreading [17].

Although empirical formulas and numerical simulations are widely employed [18-22], there are few researches on breached dam experiments. Huang et al. (2014) studied the breaching process of the terminal moraine dam under different wave generation methods by flume experiments using materials from the Guangxie lake [23]; and Neupane (2020) studied the breaching process with considering the effects of particle gradation and water content [24]. Since dam-break experiments need to satisfy geometric similarity, gravity similarity, and material similarity [25], and it is almost impossible to fully simulate the physical and mechanical properties such as the soil structure of the terminal moraine dam indoors, the indoor tests cannot satisfy the material similarity conditions between the prototype and the model. This paper conducted field experiments in the Jiarong lake, under the condition of maintaining the dam body in situ, the flow process of the dam breakage is studied, and the experimental results can provide a scientific basis for the disaster prevention of GLOFs.

2. Experiment

The experimental site was selected in the Tibetan Boqu River basin of the Jialongzuo glacial lake. Figure 1 shows the grain composition of Jialongcuo moraine dam, and the density of dam is $2.11 \times 10^3$ kg/m³ that measured in lab with disturbed soil. The flume system is shown in Figure 2 (a), which consists of upstream lake area, dam body, downstream trench, water level meter and three cameras. The lake is 4 m long, 1.5 m wide and 1.5 m deep, and the dam top width, dam height and downstream slope of the
dam body are variables, detailed values are shown in Table 1, and the upstream slope of the dam is uniformly 1:1. The initial breach is preset in the middle of the dam, 0.2 m wide and 0.1 m deep (Figure 2 (b)). Dam formed by excavator, so the thin surface layer of dam is disturbed. But there is no disturbance inside dam during dam formation, it is under the natural condition during experiment.

The water feeding in all experiments are provide by 3 water pumps, one of them can provides flow about $0.5 \times 10^{-3}$ m$^3$/s, others can provides flow about $2.5 \times 10^{-3}$ m$^3$/s. In E-1, we used two water pumps, that can provide flow about $0.5 \times 10^{-3}$ m$^3$/s and $2.5 \times 10^{-3}$ m$^3$/s, respectively. In E-2, two water pumps that both can provide flow about $2.5 \times 10^{-3}$ m$^3$/s. In other experiment, one water pump which can provide flow about $2.5 \times 10^{-3}$ m$^3$/s. The changes in water level during the experiment were recorded once a second by a water level meter (RR-1840) at the bottom of the lake, and then the break discharge can be calculated by Eqs. 1 and 2. The calculated discharges were averaged once a minute to reduce the error caused by data fluctuations. During the experiment, no seepage from the dam was observed, so the effect of seepage was ignored during the dam breach. Three HD cameras (Sony FDR-AX60, GOPRO7, and Sony HDR-PJ820E) were located upstream of the storage area, on the shoulder side of the dam, and downstream of the dam to capture the evolution of the breach. 1# camera was used to record the changes in the upstream lake area during the breach, 2# camera was used to record the undercutting process of the breach, and 3# camera was used to record the spreading process of the breach and the downstream changes in the slope of the dam.

$$Q = V(t-1) - V(t) + Q_{in} \quad (1)$$

$$V(t) = 0.9H(t) + 7.2H(t)^2 \quad (2)$$

where $Q$ is the discharge at time $t$, $V(t-1)$ and $V(t)$ are the reservoir capacity at time $t-1$ and $t$, respectively, and $H(t)$ is the water level at time $t$.

| Table 1. experimental parameters |
|----------------------------------|
| **Experiment number** | **Inflow rate** $Q_{in}$ ($10^{-3}$ m$^3$/s) | **Dam top width** $W_D$ (m) | **Downstream slope of the dam** $\theta$ | **Dam height** $H_D$ (m) | **storage capacity** (m$^3$) |
|-------------------------|---------------------------------|-----------------|-----------------|----------------|-----------------|
| E-1                     | 3.0                             | 0.4             | 1:1             |                |                 |
| E-2                     | 5.0                             | 0.4             | 1:1             |                |                 |
| E-3                     | 2.5                             | 0.4             | 1:1             |                |                 |
| E-4                     | 2.5                             | 0.2             | 1:1             |                |                 |
| E-5                     | 2.5                             | 0.6             | 1:1             |                |                 |
| E-6                     | 2.5                             | 0.8             | 1:1             |                |                 |
| E-7                     | 2.5                             | 0.4             | 1:1             |                |                 |
| E-8                     | 2.5                             | 0.4             | 1:2             |                |                 |
|                         |                                 |                 |                 | 1              | 6.75            |
Figure 1. Particle size distribution of the moraine dams

Figure 2. Experimental equipment arrangement and initial breach morphology (all dimensions in the figure are in m)

3. Analysis of flow process
The flow process and the breach evolution process are complementary and mutually influencing. The undercutting and spreading of the breach provide space for the development of flow, and the hydrodynamic process of breach flow provides energy for the undercutting and spreading of the breach.
There are two types of undercutting in the "headcut erosion" process of breach development, the first type is “slope”, and the second type is “cliff”, where “slope” appears in experiments E-1, E-2 which has no surges and other experiment that with the effect of surge, “cliff” appears in other experiments without surge. “Slope” means there is a slope forms in breach at "headcut erosion" process, the gradient of breach is between 0 degree to 90 degree. While “cliff” means there is a wall that close to 90 degree in breach at "headcut erosion" process, the flow pattern likes to waterfall (Figure 3). The flow rate depends on the development of the breach and can be calculated by Eq. 3 [13].

\[ Q = \lambda B (H - Z)^{1.5} \]  

where \( \lambda \) is discharge coefficient, \( B \) is the width of the breach, \( H \) is the water surface elevation, \( Z \) is the bottom elevation of the breach, and \( H - Z \) is the water depth inside the breach.

![Figure 3. Two forms of undercutting process](image)

In the first stage of breach evolution, the depth and width of the breach are unchanged. As the water level in front of the dam rises, \( H \) gradually increases, and the water volume in the lake reaches equilibrium when the breach flow reaches the inflow rate.

In the second stage, the breach width unchanged, but the depth increased gradually. When undercutting occurs, the breach depth increases to some extent. In this case, assuming that the rate of decrease of \( H \) is less than \( Z \), the depth of water in the breach continue to increase, resulting in a gradual increase in the flow (Figure 4). On the contrary, if the rate of reduction of \( H \) is equal to \( Z \), the flow of the breach remains unchanged, basically maintaining the convergence flow near (Figure 5). the rate of reduction of \( H \) is greater than \( Z \) only occurs in the case of surge, when the flow of the breach produces a sudden rise and fall (Figure 6). The first of these situations occurs in the “slope” form, the second situation occurs in the “cliff” form, the third situation occurs in the breach process that include surges.

In the third stage, due to the thinning of the breach caused by "headcut erosion", the undercutting rate of the breach is greater than that in the second stage, resulting in the maximum depth of water in the breach. In the undercutting process of the slope form, the discharge increases following the second stage until it reaches the peak flow. In the process with “cliff”, because the flow does not increase in the second stage, the flow changes abruptly and reaches a peak during the "fast" erosion. In the “slope” form of undercutting, when the slope stops developing, the thickness of the breach is larger than in the “cliff” form, so the undercutting rate of the outlet is smaller and the rate of change of the discharge is smaller.
In the fourth stage, since the undercutting and spreading of the breach no longer occurs, the breach flow gradually decline from the peak flow state to near the inflow rate.

4. Three types of flow processes
The process of routing evolution and flow appears in surge type and no-surge type, while no-surge type can be divided into the "initial growth type" and the "delayed growth type". As surge type is more complex, this paper begins to discuss from no-surge process.

4.1. "Initial growth" flow process
This type of flow curve is characterized by a step-by-step development after the start of the breach, and gradually reaches a peak, and then it goes through a period of gradual decline, and finally stabilizes near the catchment flow, which is different from the sudden increase and decrease of the lean and high type curve in the breach.

As mentioned earlier, stages 2 and 3 have the greatest influence on the flow process. In the initial growth flow process, the second stage of the "headcut erosion" process proceeds in the form of a slope, and under this condition, the flow curve shows a continuous increase from the beginning, and when the process enters the third stage, the "headcut erosion" develops beyond the outlet of the lake, the flow curve reaches a peak during the undercutting of the breach, and then gradually begins to fall back as the water level in front of the dam decreases. The evolution of the breach corresponding to this type of flow process has a “slope” form of undercutting.

![Initial growth type flow curve](image1.png)

**Figure 4.** “Initial growth” type flow curve (E-1 for experimental group times on the left, E-2 on the right)

4.2. "delayed growth" flow process
This type of flow curve is characterized by a gradual increase, and then it remains near the confluence flow, and then the breach flow changes abruptly and increases rapidly to the peak state, and finally it falls back rapidly, similar to the flow characteristics of coarse-grained dams.

The reason for this phenomenon is that the undercutting rate of the breach is small in the second stage, resulting in little change in the depth of the breach, and according to the water balance conditions, the breach flow is equal to the inflow rate. In the third stage, the breach rapidly undercuts as the “headcut erosion” develops to the outlet, and the rate of undercutting of the breach is much greater than the rate of decline of the water level in the lake, resulting in a rapid increase in the depth of water in the breach. In addition, the breach flow also increases rapidly, making the breach flow increase from the confluence.
flow to the peak state in a short time. In this evolution, the undercut of the breach is in the form of “cliff”.

![Flow Curve](image1.png)

**Figure 5.** “Delayed growth” type flow curve (E-4 for experimental group times on the left, E-7 on the right)

4.3. “Surge type” flow processes

This type of flow curve is generated because of the impact of the surge, when the surge comes, the discharge increases rapidly, thus leading to intense fluctuations with multiple peaks, as represented by experiments E-5 and E-6. In the E-6 group of experiments, a large collapse caused “collapse1” (figure 7) was generated in the upstream lake at 106 seconds after the outburst, and this collapsed body entered the lake, causing a rapid rise of water level and stimulating a surge. The curve in Figure 6 records this process, from the figure 6, the water level curve has a jumping between the 100s and 150s when the “collapse 1” occurred. Figure 7 shows six surges caused by “collapse 1”, This process lasts for about 20 seconds, and six surges spill out of the breach, five of which spill directly from the top of the dam, causing a jumping in the flow curve between the 120s and 180s (figure 8).

![Flow Curve](image2.png)

**Figure 6.** “Surge type” flow curve (E-5 for experimental group times on the left, E-6 on the right)
Figure 7. Water level fluctuation caused by collapses at E-6 experiment

Figure 8. Six surges caused by “collapse 1” in E-6 experiment
4.4. Causes of the flow processes

4.4.1. Non-surge flow process

Figures 4 and 5 indicate that the change rate of discharge is different between the "initial growth" and "delayed growth", which can be expressed as

\[
\frac{dQ}{dt} = \lambda \left[ \gamma (H - Z)^{1.5} + \frac{3}{2} B(H - Z)^{0.5} \cdot \epsilon \right]
\] (4)

where \( \gamma \) is the spreading rate and \( \epsilon \) is the undercutting rate. As the spreading of breach is related to the undercutting, depending on whether the breach slope is damaged by tipping or shearing [26-27], there is a relationship between the spreading rate and the undercutting rate. Zhong et al (2018) proposed a model for the evolution of breach width applicable to different cohesive dams [28]

\[
\Delta B_t = \frac{n_{loc} \Delta z}{\sin \beta}
\] (5)

\[
\Delta B_b = n_{loc} \Delta z \left( \frac{1}{\sin \beta} - \frac{1}{\tan \beta} \right)
\] (6)

where \( \Delta B_t \) is the width of the top of the breach, \( \Delta B_b \) is the width of the bottom of the breach; \( n_{loc} \) is the location of the initial breach, which is 1 at the shoulder of the dam and 2 at the middle of the top. The breach in this paper is located in the middle, so the value is 2; \( \beta \) is the foot of the slope of the breach, which is 90 degrees in this paper, based on this there is the width of the top of the breach is equal to the width of the bottom of the breach, and the two at the same time divided by \( \Delta t \), and take the limit to have

\[
\gamma = 2 \epsilon
\] (7)

Substituting Eq. (7) into equation (4) can get follow equation

\[
\frac{dQ}{dt} = \lambda \left[ 2(H - Z)^{1.5} + B(H - Z)^{0.5} \right] \cdot \epsilon
\] (8)

From Eq. (8), the rate of change of flow is related to the depth of flow in the breach, the width of the breach and the undercutting erosion rate, and the undercutting rate of the breach is small and the breach does not widen before the "rapid" undercutting of the breach in the third stage. Since the undercutting rate has an effect on the depth of breach, the elevation \( Z \) at the bottom of the breach changes rapidly when the erosion rate is large. Since the depth of lake cannot change rapidly in a short time, a larger undercutting erosion rate must cause the increase of breach depth, so the rate of change of flow depends on the undercutting rate of the breach. For the "initial growth" flow process, because the undercutting rate has a large value in a period of time after the start of the breach, the rate of change of flow is also faster, which is expressed in the flow curve as a rapid increase in flow. For the second type of flow curve, the undercutting erosion rate is small for a period of time after the start of the breach, so the rate of change of flow is small, and when the "headcut erosion" develops to the outlet, the undercutting erosion rate increases sharply and the rate of change of flow increases sharply, making the flow curve jump at this moment.

4.4.2. Surge-type flow process
Surge type flow process does not meet the Eq. (8), the reason for the rise and fall of its flow is that when the surge comes, the current flow depth and velocity at the breach increases rapidly, resulting in an increase in the breach wander. If the surge is too large, its water flow depth, flow speed and wave height beyond the breach of the discharge capacity, the breach of water will be directly from the top of the dam overflow (Figure 8), when the breach flow will appear several times the amount of increase. To describe this instantaneous change in flow, we define a physical quantity $\zeta$ that describes the ratio of the flow amplification to the time interval between the two peaks before and after. $\zeta$ reflects the suddenness and rapidity of the flow change:

$$\zeta = \frac{Q_p}{Q_0 (T_{pi} - T_{pi-1})}$$

(9)

Where $Q_p$ is peak discharge $T_{pi}$ and $T_{pi-1}$ represent the moment of the next peak and the previous peak in the flow curve, respectively. For the process with only one peak, $T_{pi-1}$ is taken as 0. for the non-surge type flow process, there is only one peak and corresponding time, while the surge type often has more than one peak and corresponding time.

| Table 2. Comparison of $\zeta$ values for each group of sub-experiments |
|------------------|---|---|---|---|---|---|---|---|
| E-1  | E-2 | E-3 | E-4 | E-5 | E-6 | E-7 | E-8 |
| $\zeta_1$ | 0.0038 | 0.0046 | 0.0018 | 0.0015 | 0.0055 | 0.0352 | 0.0037 | 0.0046 |
| $\zeta_2$ | 0 | 0 | 0 | 0 | 0.0039 | 0.0099 | 0 | 0.0138 |
| $\zeta_3$ | 0 | 0 | 0 | 0 | 0.0068 | 0.069 | 0 | 0.0083 |

As seen in Table 2, the $\zeta$ values of the surge type are generally larger than those of the non-surge type. In Figure 6, the breached flow rate of the E-6 group suddenly increases about 8 times from $1.3 \times 10^{-3}$ m$^3$/s to $10.6 \times 10^{-3}$ m$^3$/s from 120s to 180s. The curve in Figure 7 shows that the water level in the lake rose by 289 mm in the same period, indicating that the flow process of surge type is more sudden and rapid compared with the non-surge type.

5. Non-surge type collapse peak flow calculation

Peak discharge of flow caused by surge wave is hard to predict due to intense randomness of the process. Comparison between "initial growth" and "delayed growth" indicates that the difference between the two types of flow process is reflected in the time of peak flow, from the peak form, both belong to the type of single peak, for this common point of both, from the peak for this common point of both, the flow process of the moraine lake outburst is discussed from the peak flow.

The dam breaching may be full or partial, and occurring instantaneously or gradually, according to the duration time. In our experimental situations, the moraine dams break gradually and the process is, long in time, which is also the case for natural dams. Many dams collapsed but remain in a certain depth, ready for further collapses; and the peak discharge occurs 30 minutes after the initial break. For the case of gradual outburst, Xie used an approximate mathematical model method to solve the formula for the peak flow of the outburst [8]

$$Q_p = \lambda g^{0.5} b_m H_0^{1.5}$$

(10)

where $b_m$ is the width of the breach gate, and $H_0$ is the maximum water depth upstream before the dam.
where and $b_m$ can be expressed as [29], respectively

$$
\begin{align*}
\lambda &= \frac{8m^{1.5}}{(1 + 2m)^{1.5}} \beta^{-1} \\
     b_m &= \frac{W \rho}{3E}
\end{align*}
$$

(11)

where $m$ is the index of river section shape, which can be obtained by checking the table [8]. In this paper, $m$ is 1 for rectangle section. $E$ is the square volume of the dam per meter length in $m^3$. $\beta$ is the coefficient, and is the percentage of the average volume sand content, which can be expressed respectively as

$$
\begin{align*}
\beta &= \frac{4m^2}{(1 + m)^2} \\
\rho &= \frac{KH}{100}, K = \phi W^{-0.577}
\end{align*}
$$

(12)

where $H$ is the height of the dam, $\phi$ is the coefficient related to the material and compactness of the dam. As the moraine dam is dense, $\phi$ is about 0.50 [8]. $W$ is the reservoir capacity.

From Eq. (10), the peak discharge takes into account the effects of the compactness of the dam material, the volume of the dam, the shape of the river valley section and the height of the dam. The breach flow rate of each experimental group was calculated using equation (10), and the results are shown in Table 3.

**Table 3. Theoretical values of sub-peak flow rate for each experimental group**

| Experiment number | $\lambda$ | $b_m$ | $H_0$ | Measured value $(m^3)$ | Theoretical value $(m^3)$ | Relative Error (%) |
|-------------------|----------|-------|-------|------------------------|--------------------------|-------------------|
| E-1               | 2.67     | 0.0038| 1     | 0.0041                 | 0.0314                   | 673.78            |
| E-2               | 2.67     | 0.0038| 1     | 0.0083                 | 0.0314                   | 278.84            |
| E-3               | 2.67     | 0.0044| 1     | 0.0033                 | 0.0365                   | 1001.81           |
| E-4               | 2.67     | 0.0038| 1     | 0.0062                 | 0.0314                   | 404.80            |
| E-7               | 2.67     | 0.0038| 1     | 0.0126                 | 0.0314                   | 161.53            |
| E-8               | 2.67     | 0.0038| 1     | 0.0062                 | 0.0297                   | 376.95            |

Table 2 shows that the calculated discharges are much larger than the measurements, so some corrections to equation (10) are needed. Through the observation and analysis of experiments, we find that the peak discharge is also related to the sink flow rate, and the larger the sink flow rate is, the larger the peak flow rate will be. In addition, equation (10) does not consider the effect of the erosion resistance of the dam. Therefore, we refer to the method of Peng (2012) and consider a physical quantity that describes the erosion rate and controls the flow rate, and consider the effect of the lake catchment [30], and propose the following corrected equation for the peak discharge:

$$
Q_{\text{max}} = \left( \lambda g^{0.5} b_m H_0^{1.5} \frac{W_D}{H_D} \sin \theta \right)^{0.5} Q_m^{0.5}
$$

(13)
Equation (13) was used to calculate the collapse flow rate for each experimental group, and the results are shown in Table 4.

**Table 4. Theoretical values of sub-peak flow rates for each experimental group calculated by the improved empirical formula**

| Experiment number | $\lambda$ | $b_m$ | $H_0$ | $Q_{in}$ | $\frac{W_b}{H_0}\sin\theta$ | Measured value (m$^3$) | Theoretical value (m$^3$) | Relative Error (%) |
|-------------------|------------|-------|-------|----------|----------------------------|----------------------|-----------------------|-------------------|
| E-1               | 2.67       | 0.0038| 1     | 0.0030   | 0.2828                    | 0.0041              | 0.0052                | 3.04              |
| E-2               | 2.67       | 0.0038| 1     | 0.0050   | 0.2828                    | 0.0083              | 0.0067                | -34.87            |
| E-3               | 2.67       | 0.0044| 1     | 0.0025   | 0.1414                    | 0.0033              | 0.0036                | -12.59            |
| E-4               | 2.67       | 0.0038| 1     | 0.0025   | 0.2828                    | 0.0062              | 0.0047                | -38.64            |
| E-7               | 2.67       | 0.0038| 1     | 0.0025   | 0.2828                    | 0.0126              | 0.0047                | -68.21            |
| E-8               | 2.67       | 0.0038| 1     | 0.0025   | 0.1789                    | 0.0062              | 0.0036                | -56.15            |

6. Conclusion
In this paper, the flow process of the moraine dam breach under diffuse top breach conditions is studied through field flume experiments. The following conclusions can be obtained:

1) The breaching flow process can be divided into "initial growth type", "delayed growth type" and "surge type". In "initial growth type" process, the undercutting form of the rout is a slope, and the flow continues to rise from the beginning of the rout and gradually falls after reaching the peak. In the "delayed growth type" process, the undercutting form of the rout is a slope, and the flow continues to rise from the beginning of the rout and gradually falls after reaching the peak. In the "delayed growth type" process, the undercut form of the breach is a slope, and the flow starts to maintain after rising to the confluence flow, and then changes abruptly after a period of time, reaching a peak and then falls back quickly. The "surge type" flow process appears to fluctuate sharply and suddenly rise and fall.

2) "Initial growth type" and "delayed growth type" have different rate of change of flow, it is found that the rate of change of flow is mainly related to the width of the breach, the depth of water in the breach and the undercutting of the breach. The flow process of "surge type" is closely related to the size of the surge.

3) The breach of moraine dam is more often partial and a gradual process, based on which an improved formula is proposed, taking into account the erosion of the dam and the upstream lake catchment, and the improved formula can be better used for calculating the moraine dam.

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8. Appendices
Notations

\[ Q \] discharge of breach
V(t-1) reservoir capacity at time t-1
V(t) reservoir capacity at time t
H(t) water level at time t
Q_i inflow rate
W_D dam top width
θ downstream slope of the dam
H_D dam height
λ discharge coefficient
B width of the breach
H water surface elevation
Z bottom elevation of the breach
γ spreading rate
ε undercutting rate
ΔB_t width of the top of the breach
ΔB_b width of the bottom of the breach
n_loc location of the initial breach
Q_p peak discharge
T_{pi} moment of the next peak in the flow curve
T_{pi-1} moment of the previous peak in the flow curve
b_m width of the breach gate
H_0 maximum water depth upstream before the dam
m index of river section shape
E square volume of the dam per meter length
β undetermined coefficient
H height of the dam
φ coefficient related to the material and compactness of the dam

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