Glacial lake outburst caused by small amplitude wave overflow

Baoliang Wang, Hongfei Wang, Zhenguo Yao
Yellow River Engineering Consulting Co., Ltd. Zhengzhou, Henan, 450003, China
*Corresponding author’s e-mail: wanghf@yrec.cn

Abstract. In this study, a series of glacial lake dam overflow experiments are conducted. In those experiments, the influence of surge scale on dam outburst was studied. According to the results of the experiment, the surge overflow is the direct trigger factor of the natural lake outburst, and the periodic return of the small amplitude surge is favorable to the formation of the dam outburst. The scale of the surge will affect the time required to form the break, and the shape of the outburst flood curve. The scour movement of the water in the dam back side will make the dam form a gully. The scour movement of the water in the back side will make the dam form a gully, when the gully developed to a certain extent, the interaction between the water flow and the bottom bed changed from shear action (friction resistance) to impact action, which greatly increased the erosion and destruction capacity of the water flow and formed a "headcut". The water flow constantly brushes the bottom of the "headcut" and produced retroactive erosion, make the break constantly expanded, eventually result in dam break.

1. Introduction
The number and size of glacial lakes are increasing all over the world due to the influence of climate warming[1-3], once these glacial lakes break up, it will pose a serious threat to the lives and property of the people downstream. Observation records show that several catastrophic dam-breaking events have occurred in recent years and unleashed devastating flood waves [4]. Notable examples include the outburst incidents of four large moraine dam between 1938 and 1950 in the Cordillera Blanca of Peru [5-6], among them, the most devastating event was the Cohup Lake outburst in 1941, which destroyed One-third of the city of Huaraz, and killed more than 6,000 people. In the Himalayan region, the recorded glacial lake outburst disaster has reached 33 times [7-11]. China is one of the countries with a large distribution of glacial lakes. The glacial lake outburst occurred mainly in the Himalayas in Tibet and the Tianshan Mountains in Xinjiang, and the resulting floods and mudslides caused serious damage in this area. For example, in August 2013, a glacial lake of nearly 10,000 cubic meters in Zhongyi Township, Jiali County, Tibet, its outburst triggered a debris flow and blocked the Harenqu River and formed a dammed lake, the debris flow dam burst three days later, destroying 40 km of roads along the river and killing two people [12].

According to the causes, glacial lake outburst can be divided into two types, one is caused by the melting of buried ice in the terminal moraine dam, the other is due to ice slides and the ice collapse into the lake increased the water level and generated wave superposition, thus, the water level through the spillway and the flow rate increased, resulting in a strong erosion led to the collapse of the dam, that is, overflow failure. After studying 20 cases of glacial lake outburst events which occurred in Nepal and Tibet (China), Ripendra Awal [13] found that 80% of Glacial lake outburst is induced by the erosion caused by surges triggered by of ice (snow) avalanches, and 10% is due to piping failure caused by the
melting of ice within the dam, and 10% is due to the seepage damage in the inner of the glacial dam. In recent years, the mechanism of glacial lake outburst has attracted the attention of scholars, most of their studies are mainly focused on the prediction of waves generated by landslide/rock avalanche [14-15]. A few scholars have studied the dam breaking by wave induced erosional incision [16-17]. However, the study on the outburst mechanism of moraine dam is still not sufficient. This study simulates different wave conditions through experiments, and explores its impact on the glacial lake outburst and the characteristics of glacial lake outburst flood.

2. Experimental design

2.1 Experimental materials
The composition of natural dam body has the characteristics of coarse and fine mixing, poor sorting and wide gradation and less viscous particles. To explore the influence of different wave scale on the natural dam outburst, sand particles with diameter of <20 mm and density of 1.44g/cm³ were selected as the natural dam material. The characteristic parameters are shown in Table 1, and the grading composition is shown in Figure 1.

![Figure 1 Gradation curve of particles at the burst of Midui ice lake](image)

Table 1 characteristic parameters of the particles used in the experiment

| Parameter | Dry density | Saturated density | characteristic particle size |
|-----------|-------------|-------------------|-----------------------------|
| Sample    | 1.46        | 1.87              | D₁₀ D₃₀ D₆₀ Cu Cc           |

2.2 Experimental equipment
In order to study the influence of impulsive wave on dam outburst under different conditions, a flume system is designed to simulate the dynamic process of natural dam outburst caused by wave, which mainly includes glass flume, wave trigger device and water collecting system, as is shown in figure 2. The development process of wave overtopping dam outburst and its hydraulic characteristics need to consider the action of wave, which is a complicated natural phenomenon, in view of the complexity of the dynamic process of the lake outburst, this experiment mainly uses the geometrical similarity simplification model to carry on the simulation research. The geometrical scale of the simulated experiment is 1:1000 based on the background of the outburst of the Guangxiecuo glacial moraine lake.
2.2.1 Glass Flume
In order to better study the influence of swell on dam collapse, the shape of moraine lake is reduced to a rectangular water tank of 450cm×50cm×50cm because of its various sizes and complex shapes, the glass sink is mainly composed of tempered glass, and the scale paper is pasted on the outside of the glass wall, so that the camera can record the wave height and the change of reservoir water level during the dam outburst. The dam body uses the trapezoid stacking, the slope of the face and back water surface uses the natural angle of repose, and does not carry on the extra pressure treatment, and so as to keep maintains the sand natural accumulation state as much as possible, among them, the dam is 20cm high, 50cm wide at the bottom and 5cm wide at the top, as shown in Figure 2.

![Figure 2 Schematic diagram of the experimental apparatus](image)

2.2.2 Surge Trigger Device
When the paddles enter the water in a different area and move at different speeds, they produce different waves at different heights, the volume of the paddle is negligible and different initial wave heights are triggered by adjusting the depth of the wood paddle entering the water. Among them, paddle A size: 40 cm × 40 cm × 1cm; paddle B size: 40 cm × 20 cm × 1cm; During the experiment, the top of the paddle is held at the same height as the water surface.

In order to compare the influence of wave on dam outburst under the small amplitude wave condition, a hand operated propeller that is small enough to be ignored is used to raise the waves. Its shape and size are shown in Figure 2, by adjusting the speed of the pulp to stimulate different initial wave height.

2.2.3 Water Collection Systems
The water collection system consists of water collection container and the electronic scale below it, as shown in Figure 2.

Among them, the size of the water collecting container is: 40cm×40 cm×40 cm, the inner wall is pasted scale. The water level of the water tank is recorded by the camera to calculate the real-time volume change, and the electronic scale is connected with the laptop computer through the data line, and the quality change of the water collecting container is recorded to obtain the flow process of the burst flood.

This experiment mainly studied the influence of different wave scale on Lake Outburst. Single factor experiment method was used to generate wave by different swell equipment. There were 12 groups in the experiment, as detailed in Table 2.

| Experiment arrangements               | Experiment number | EX1 | EX2 | EX3 | EX4 |
|--------------------------------------|-------------------|-----|-----|-----|-----|
| Paddle A                             | Paddle speed(m/s) | 0.1 | 0.3 | 0.5 | 0.7 |
| Paddle B                             | Experiment number | EX5 | EX6 | EX7 | EX8 |
|                                      | Paddle speed(m/s) | 0.1 | 0.3 | 0.5 | 0.7 |
| Hand-cranked propeller               | Experiment number | EX9 | EX10| EX11| EX12|
|                                      | Propeller speed(r/s) | 1   | 1.5 | 2.5 | 3.5 |
3. Experimental results and analysis

3.1 Experimental process and phenomena

Before the experiment, add water to the glass flume until 19cm, 1 cm lower than the top of the dam. Then the seepage of the dam is observed to ensure that the dam can withstand hydrostatic pressure without seepage failure and to ensure the reliability of the experimental results.

At the beginning of the experiment, the wave is triggered with paddle A, B or hand-cranked propeller. Taking paddle A as an example, when the propeller A moves at a certain speed, the work produced by the motion of paddle is converted to kinetic energy and the wave is triggered. For example, EX-2, the waves were triggered when the paddle moves and transmits rapidly. When the surge travels near the dam, it will climb along the upstream slope, causing disturbance to the soil at the contact point between the lower part of the surge and the upstream slope, as shown in Figure 3a. Finally, the wave overtops of the dam and scours away some of the sand on the top of the dam, reducing the height of the dam, which causes the dam to lower 2~5 mm. In general, although the first overtop of the surge will erode the dam top, it will not cause the dam to burst, as shown in Figure 3b. During the movement of water flow, the gully will be eroded and formed a steep ridge, and then a hydraulic drop will be formed at the steep bank, a rotational flow will appear at the bottom of the steep bank, a large shear stress will be generated by the rotational flow, and the shear stress will continue to erode the steep ridges and push it backward, as shown in figure 3c. After the steep ridge is pushed backward, the two sides form the steep surface. Due to the low strength and the saturation of the loose soil, the sliding force increases and the strength decreases, and the landslide damage occurs under the gravity action of the both sides of the gully (figure 3d).

![Figure 3 Different stages of dam-breaking caused by overtopping](image)

3.2 Analysis of influence of different experimental factors on dam break

3.2.1 Influence of surge scale on dam break

In laboratory situations, different scale of surges generated by different landslides can be simulated by adjusting the movement speed of different paddles (A and B), the advantage of using a paddle instead of a slider to create surge is that the effect of the rising water level caused by the volume of the slider can be eliminated. Theoretically, the larger the area of the paddle and the greater the velocity of its
motion, the larger the scale of the surge triggered. In order to study the influence of different wave scale on dam-break, 3 groups (EX1, EX2, EX3) of different moving speed of the same paddle, and 2 groups (EX3, EX6) of different paddles at the same moving speed were selected for comparison and analysis. Among them, the first wave heights of EX1, EX2, EX3 and EX6 were 20 mm, 30 mm, 40 mm and 20mm respectively. When the paddles are the same, the velocity of experiment 1 is not as big as that of EX2 and EX3, so the formed surge scale is smaller, so the burst formation takes more time, and the duration of periodic return surge is longer, as shown in Figure 6, the longest wave duration of EX1 is about 70 s, during which 8 waves overtopped and eroded the crest of the dam. As can be seen from Fig. 6, the initial curve fluctuates obviously and the amplitude attenuates gradually. At this stage, the embryonic form of the breach has been developing continuously, and eventually the discharge channel has been formed. In the later period due to the formation of the dam outburst, the surge wave dissipated, the overflow water cuts down and erodes the dam body, and the erosion rate is obviously accelerated. In order to analyze the role of wave in the process of outburst, T₀ is defined as the limit of wave termination time, of which 0~T₀ represents the burst formation stage (i.e. the wave stage), the T₀~Burst end indicates the stage of flood outburst. After T₀, the water level in the lake area decreased rapidly, and the slope of EX1, EX3 and EX6 curves increased, as shown in Figure 4. The greater the erosion of water to the dam crests, the greater the burst width and the faster the flood discharge rate, and therefore the steeper the curve. As can be seen from Figure 5, compared with EX2, EX3, the profile line of EX1 is denser, so the retrogressive erosion is slower; however, EX1 erosion degree is smaller, the flood outburst duration is long. In the case of the same speed, the area of the paddle used in EX 2 is larger than the EX 6, and the scale of the surge is larger, therefore, the wave time is shorter and the erosion of the burst is faster, as shown in Figure 4 and Figure 5.
Figure 5 Development of longitudinal breach bottom profiles
3.2.2 Influence of landslide into Lake on dam break
During the process of moving the paddle, the static water level of the lake will rise and the surge will be superimposed. In order to compare the influence of the scale of the surge to the dam break under the condition that the static water level is not changed, different scale of surges will be generated by changing the speed of the hand propeller. In this case, the lake water level will not rise significantly. The larger the rotation speed of the propeller, the more work the propeller does and the larger the wave scale formed. The EX11 and EX12 with 2.5 and 3.5 r/s are selected for comparative analysis. In addition, EX8 was selected for comparative analysis under the condition of static water level changing. It was found that the wave height triggered by hand-cranked propeller waves was low, but the wave lasted for a long time, as shown in Figure 6. Among them, EX11 and EX12 have 9 and 12 waves respectively, and the wave propagation duration $T_0$ is 73's and 91's respectively, both of which are much larger than the EX8 of the static water level changing condition. Compared with EX8, the first wave amplitude of EX11 and EX12 under the condition of constant water level is small, and erosion of dam crest is weaker, therefore, the breach is continuously developed under the action of subsequent periodic waves. Under the condition of constant water level, the scale of the surge is smaller, the erosion ability of the surge is weak and the wave energy dissipation is slow, so the amplitude of the first few waves changes little, until the late breach is formed, the wave amplitude decreases rapidly, as shown in Figure 8. When the static water level is constant, the dam surface profiles are denser than that when the static water level is changed, and the erosion degree of the surge is relatively uniform. The lateral erosion of the dam body is stronger under the static water level invariant condition, so the final width of the breach is larger than that under the change of the static water level.

3.2.3 Flooding Characteristics of Different Surge Scales
In the case of different static water depths, it can be seen from the curve of flood flow process interpreted by the water collection system that the initial surge overflow forms a very large scale of sand carrying flood and forming an initial discharge $Q_0$. Take EX3 as an example, the $Q_0$ reaches 3000 cm$^3$/s, even greater than the later peak flow $Q_M$ (about 1800 cm$^3$/s), as shown in Figure 7. Comparing EX1, EX2, EX3 (or EX2 and EX6), it is found that the larger the surge scale, the larger the initial discharge $Q_0$, the two are positively correlated. This is because large surge scale will increase the erosion capacity of the first wave and increase the quality of the solid material, which is consistent with the erosion profile of the dam profile in Figure 5. When the breach of the dam body is formed, the water in the lake area drains downward through the breach, which in turn broadens the breach. At this time, the flood flow reaches a peak value of $Q_0$, and then gradually decreases as the lake level decreases, as shown in Figure 9. The larger the surge scale, the earlier the peak flow occurs, for example, the time required for EX3 is about 45s, occurs
approximately 5's after $T_0$ at the end of wave time (i.e., burst formation time), so the peak discharge appears in a small period of time after the dam break. It can be seen from Figure 7 that the magnitude of the peak discharge $Q_m$ is positively related to the scale of the surge, but since the reduction of storage capacity in the lake area affects the water potential energy, the peak discharge does not increase significantly. The flow curves of the flood in different surge scale are different, and the flood flow curves of EX2 and EX3 with large surge scale are sharp thin peak shape, while the smaller surge scale EX1 has a gentle peak shape.

Compared with experiments under different static water depth conditions, the first wave triggered by paddle is small in scale and cannot strongly wash the top of the dam. Therefore, the initial flow $Q_0$ is small and much smaller than the peak flow $Q_m$ of the flood, as shown in Figure 8. Similarly, the peak discharge appears in a short period of time after the formation of the breach, and the difference between $Q_m$ is not significant. But obviously, the peak discharge time of EX11 and EX12 under the condition of constant water level is about 20 s behind the EX8 when the static water level changes. This is related to $T_0$, and the $T_0$ of EX8 is less than EX11 and EX12, as shown in Figure 8. Due to the small scale triggered under the condition of constant static water level, the flood discharge curves are mostly having a gentle peak shape.

**Figure 7 Breach flow rate of dam**

**Figure 8 Breach flow rate of dam**

3.3 Mechanism of glacial lake outburst

Usually, the glacial lakes formed by the terminal moraine dam are in full state. The surges formed by the ice landslide may cause the overflow at the top of the dam (or sudden increase of the overflow). Once a large overflow is formed, the critical stability of the soil on the slope behind the dam may be changed, and the solid particles may start and transfer, thus forming a small flushing ditch, which leads to the continuous development of the dam burst. We believe that the main reasons for the formation of the steep bank behind the dam are: We believe that the main reasons for the formation of the scarps behind the dam are: (1) After the water body flows through the dam crest, the water flow accelerates along the dam back surface under the action of gravity, the velocity increases along the path, and the scour damage ability is enhanced. At the same time, affected by the particle size distribution and structure composition of the dam, the cutting speed is uneven along the path, the weak area after the dam will develop into a small pit, the water flow in the pit prone to vortex flow, and the Reynolds shear stress of the pit inner wall increases, make the particles in the pit inner wall edge more easily to start, and make the pits development rapidly; (2) When the pit develops to a certain extent, the main stream (the bottom flow may move along the wall of the headcut) moves away from the bottom bed and acts as a tongue flow on the downstream dam surface. The interaction between the water flow and the bottom bed changes from shear action (friction resistance) to impact action. The water continues to brush the edge of the pits, and the depth and range of pits is further enlarged to form a "headcut" (Figure 9(a)). With the development of the gully, the burst flow is constantly increasing, the water constantly brushes the bottom of the "headcut", at the same time, under the effect of the shear stress of the flow at the top
of the steep slope, the steep back wall continuous upstream (retrogressive erosion), the collapse of the mouth continues to expand (figure 9(b)), resulting in the dam body burst.

![Surge and climbing](image)

![Water depth](image)

(a) surge climbs and overtopping the dam           (b) Dam break process

Figure 9 Dam outburst process under the action of surge

4. conclusion

On the basis of field investigation, this paper explores the influence of different surge conditions on the natural dam outburst and its flood characteristics through self-made simple experimental device. Experimental result shows that:

In the event of dam overtopping outburst, the dam outburst usually occurs instantaneously. The periodic reversion of surge is favorable to the formation of outburst. The larger the scale of the surge, the shorter the time it takes to form a break, the more easily the dam collapses, and the resulting outburst flood curve is a sharp-thin type. The smaller the scale of the surge, the smaller the erosion degree of the dam, the longer the duration of the outburst flood, and the resulting outburst flood curve is gentle peak type.

After the water flow over the dam, under the action of gravity, the water flow accelerates along the downstream slope, the speed increases along the course, and the ability of erosion is enhanced. When the shear stress generated by the water movement exceeds the shear strength of the soil, a trench will be formed. With the development of the gully, the impact force of the water flow is much greater than the shear stress between the water flow and the bottom bed. At the same time, it is affected by the pulsating pressure of the water flow, which greatly increases the erosive and destructive capacity of the water flow, causes the bursting to expand continuously, and finally leads to the dam body bursting.

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