Study on the Surge Wave Induced by Glacier Avalanches and its Effects on Dam Failure Process

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In this article, experimental tests were conducted to study the characteristics of the surge wave and its effects on the failure process of a glacier dam. The results indicated that two obvious surges were monitored by pore pressure transducers (PPTs) when the blockage slid into water. The surge wave attenuated exponentially near the plunging location and then attenuated slowly when it propagated downstream. When the surge wave reached the glacier dam it climbed up along the dam and flew over. Sequential propagating surges exerting on the dam were one of the main factors causing the failure of the glacier dam. The failure mechanism of glacier dam triggered by the surge waves under different initial water supply conditions was primarily analyzed in this article.

Keywords: glacier avalanches, surge waves, GLOFs, glacier dam, dam failure

1. INTRODUCTION

Climate change and retreating of glaciers constitutes a major hazard in the high-mountain areas of the world. Many researches indicated that the size and number of the moraine-dammed lakes had increased dramatically in recent decades [Evans and Clague, 1994; Oerlemans, 1994; Chen et al., 2007; Watanabe et al., 2009; Bajracharya and Mool, 2010]. Usually, the moraine-dammed lakes with overflowing are in their critical status. Once an appropriate trigger is given, the moraine-dammed lakes are breached, leading to catastrophic Glacial Lake Outburst Floods (GLOFs) [Walder and Costa, 1996; Clague and Evans, 2000; Lipovsky et al., 2008; Allen et al., 2011]. Many factors result in the failure of a moraine dam in the high-mountain areas, such as surges induced by glacier avalanches, sudden rise of water level and overflowing of a moraine-dam due to intensive rainfall or retreating of glaciers, or embedded ice core melt in the moraines. Among the factors, the surge wave induced by glacier avalanches is the main factor that leads the failure of a moraine dam. Once a moraine-dammed lake is breached, outbursts of flood from the moraine-dammed lake seriously threaten the human life, public and private properties downstream [Clague and Evans, 1993; Walder and Driedger, 1995]. Studies have been carried out to investigate the characteristics of impulsive surges, peak discharge of GLOFs, and formation process of debris flows downstream along a gully [Cenderelli and Wohl, 2001; Fritz et al., 2004; Ahae-Ashtiani and Nik-Khah, 2008; Cui et al., 2010]. However, little attention has been paid to the characteristics of surge waves induced by ice avalanches and their effects on the failure mechanism of a moraine dam.

In this study, Impulsive surges were generated by the rigid sliding blockage with lower-density (Similar to the density of natural ice). For each experimental test, video cameras were employed to record the sliding process of rigid block along the flat plate and the failure process of the moraine dam. Pore pressure transducers (PPTs) were employed to record the variation of surge height and water level.
The characteristics of surge waves such as formation and propagation were studied. Discharges of glacial lake outburst flood under different initial conditions were compared. In addition, the failure process and mechanism of the glacier dam caused by surge waves was analyzed.

2. DESIGN AND FABRICATION OF SIMULATED EXPERIMENTS

Remote-sensing images and field investigation indicate that glacier dammed lakes are usually with elliptic or quasi-elliptic geometries such as Midui moraine lake and Cirenma moraine lake. Selecting a quasi-elliptic geometry in the experiment may more closely simulate the propagation of impulsive surge waves under natural conditions. The experimental set-up consisted of a sliding blockage, an inclined plate with adjustable slope, a dammed lake, and a downstream dam (Fig. 1). The blockage is about 0.4 m × 0.3 m × 0.2 m (Length × Width × Height) and the volume is about 0.24 m³. In order to simulate a surge generated by a glacier, the density of the sliding blockage was strictly controlled with that of the glacier, which was about 900 kg/m³ in the experiments. In order to obtain a sliding blockage with density similar to the natural ice, a blockage was made of sheet iron filled with light fluid materials (such as diesel and gasoline). The surge waves propagating downstream were monitored by the precise pore pressure transducers (PPTs) which were deployed along the moraine-dammed lake (P1-P6) as shown in Fig. 1.

3. EXPERIMENTAL RESULTS AND ANALYSIS

3.1 Typical surge formation

When the blockage slid into the dammed lake at a relative high speed, the still water driven by moving blockage propagated forward and surges were formed at the same time (Fig. 2a-b). The surges formed due to the collapse between the still water and fast moving blockage was called the first surge or initial surge (Surge I, Fig. 2b). When the blockage immersed in water and kept moving forward, the empty space was formed behind it. The still water around the blockage filled in the empty space immediately and then mixed together. Another surge generated due to the collapse of the water was called the second surge (surge II) as shown in Fig. 2c-d. The measurement results of surge height demonstrated that the height of surge II even higher than that of surge I (Fig. 3). When the surges reached the moraine dam at some speed, it climbed up along the dam surface and overflow occurred.

3.2 The propagation of surge waves in the dammed lake

A series precise PPTs was employed to record the surge waves at different distances (P1-P6, Fig. 1). Based on the dimensional analysis, the variation of surge waves in different cases were analyzed as shown in Fig. 4. From Fig. 4 we know that with increasing the distance away from the plunging
point, the height of surge waves decreased due to viscosity of water. For different sliding angles, an obvious change existed at about $X/h_0 = 1.5$. If $X/h_0 < 1.5$, the surge height attenuated exponentially. On the contrary, if $X/h_0 > 1.5$, the surge height attenuated slowly because the energy transmission from the blockage to the water mass occurred only when it plunged into water. The still water mass which obtained the kinetic energy from the sliding blockage was confined in a limited region. However, no continuous kinetic energy was supplied to keep the water mass moving downstream after the blockage emerged into water. When the distance reached $1.5 H_0$ the wave height got to a small value and the residual energy kept the surge wave propagating downstream. In this process, energy dissipation in the water was so slight that the surge wave kept propagating downstream for a long time. In the experiment we estimated the surge wave speed by the two PPTs (P5-P6) near the glacier dam. The distance between the two PPTs was given and wave speed was estimated by measuring the time duration of the two PPTs ($v = 1.0 \text{ m/s}$). By assuming no energy dissipation occurred when the surge wave passed the dam, therefore the climb height can be calculated. Therefore, if the initial condition of overflow is considered, the elevation difference between the water level and the dam crest should be smaller than the value of the climbing height.

4. FAILURE PROCESS AND MECHANISM OF THE GLACIER DAM

4.1 The models of dam failure

Failure process of the moraine dam and flow discharge variation was investigated due to flow overtopping caused by surge waves. Two different initial conditions were considered in the experiments: without overflow (Case 1) and with overflow (Case 2).

The condition without overflow (Case 1) meant that the water level was lower than crest elevation of the glacier dam and no water flew over the dam. When the elevation difference was larger than the climb height of the surge wave, it reflected back toward the lake when approaching the moraine dam and no overflow occurred. On the contrary, if the elevation difference was smaller than the climb height, the surge wave climbed along the dam and overflow occurred. The characteristics of surge waves induced by ice avalanches were much different from those induced by rock avalanches. When the rock avalanches ($2.65 \text{ g/cm}^3$) slid into water it sank. The surge wave was not affected by the rock avalanches any more. The propagation of surge wave induced by ice avalanche was still affected by the ice avalanche when it came back to the water surface and kept vibrating because the ice density ($0.9 \text{ g/cm}^3$) is 0.9 times as bigger as that of water ($1.0 \text{ g/cm}^3$). Therefore, a series of propagating surges induced by ice avalanches overflowed the dam. The solid materials were initialized and transported by the intermittent flow. A gully was formed on the back of the glacier dam. The width of the gully was enlarged gradually due to the continuous erosion of the solid materials. Meanwhile, the overflow velocity was enlarged gradually when the down erosion rate was bigger than the falling speed of the water level. The water level fell gradually after large volume of water was released Fig. 5.

The condition with overflow (Case 2) meant that the water level was higher than the crest elevation of the glacier dam. Water from the moraine dammed lake flew over the dam and the fine solid materials at the bottom of the channel were initialized by the flow. The coarse materials were left to form armor layer which stopped further incision of the glacier dam. However, when a surge approached the dam,
Therefore, it was difficult to calculate the discharge passing through a certain cross-section. Fortunately, the discharge can be estimated by variation of water depth and water areas per unit time.

Discharge of the dam breach flow is calculated by

$$\frac{dV}{dt} = Q_1 - Q_2$$  \hspace{1cm} (1)

The difference form can be expressed as follows

$$\frac{\Delta V}{\Delta t} = Q_1 - Q_2$$  \hspace{1cm} (2)

Where \( V \) is the volume of glacial lake, \( t \) is time, \( Q_1 \), \( Q_2 \) was the incoming discharge and outlet discharge, respectively, \( \Delta V \) is the variation of water volume in time duration \( \Delta t \).

According to the relationship between the water level, size, and volume, the outlet discharge \( Q_2 \) is estimated by

$$Q_2 = \frac{(H_1 - H_2)(A_1 + A_2)}{2(t_2 - t_1)} + Q_1$$ \hspace{1cm} (3)

Where \( H_1, A_1 \) is the water depth and size of glacier lake at \( t_1 \), respectively; \( H_2, A_2 \) is the water level and size of glacier lake at \( t_2 \), respectively; With discharge \( Q_1 = 0.0001 \ m^3/s \). Without discharge \( Q_1 = 0.0 \ m^3/s \). The water area kept constant in the experiment, \( A_1 = A_2 = 7.46 \ m^2 \). The water depth of the dammed lake in the experiments was also measured by the PPTs.

Variation of flow discharges under different initial conditions was calculated by Eq. (3). The results indicated that peak discharge under the condition of Case 1 was only 0.01 \ m\(^3\)/s. However, peak discharge reached about 0.08 \ m\(^3\)/s under the condition of Case 2. It was explained as follows. For Case 1 the surge first flew over the dam from the lowest elevation and then ran down along the back surface of the dam when the kinetic energy was large enough. After the surge disappeared no discharge flew over the dam because the elevation of water level was still lower than that of the dam. When the intermittent flow passed the dam some of the particles were taken away from the dam. The dam was incised and a gully was formed gradually. So the flow discharge increased gradually (Fig. 8). On the contrary, for Case 2 water head increased when the surge arrived at the dam. The surge not only initialized the particles at the bottom, but also eroded and carried the solid materials at the both lateral sides due to the increase of the flow velocity. A large amount of solid materials were carried by the overflow, the dam breach developed very quickly. Therefore, the peak discharge was about 8 times as large as that in Case 1 (Fig. 9).

4.2 Flow discharge during the failure process of glacier dam

Generally, the glacier dams are composed of unconsolidated, poorly sorted mass of moraines. The dam breach developed quickly when the moraines were eroded by the flood. The water depth and velocity changed dramatically in this process.

water level and flow velocity increased suddenly. The armor layer was broken and coarse materials were also initialized when flow velocity was larger than the incipient velocity of sediment. Meanwhile, solid materials on both lateral sides of the breach were also initialized and carried downstream due to the sudden increase of water level. A large quantity of materials was eroded from the moraine dam and the breach developed quickly as shown in Fig. 6.

From the development of dam breach (Fig. 7), we know that it took about 170.0 s to develop the dam breach to reach 0.6 m (Channel width) under the condition of Case 1. However, it took only 20.0 s when the width of the breach developed to entire channel width under the condition of Case 2.

Fig. 6 The failure process of glacier dam with overflow (Case 2)

Fig. 7 The variation of the breach width
4.3 The failure mechanism under the two different conditions

By comparing the failure characteristics of the glacier dam above, we know that the peak discharge and breach erosion rate in Case 1 was much different from that in Case 2. So what make this difference? When the failure process was analyzed in Case 1 the ‘headcut’ (in the adverse direction of water flow) was introduced by many researchers [Bennett et al., 2000; Flores-Cervantes et al., 2006; Wells et al., 2009; Zhu et al., 2011]. However, few studies have analyzed the mechanism of this phenomenon. The authors concluded the process in these reasons: (1) the flow velocity increased along the back surface of the glacier dam at the steep slope (the slope angle was equal to the critical angle of the solid material, 38°-42°). The erosion ability increased gradually due to the increase of flow velocity. (2) Unlike to the uniform materials, the glacier dam was formed by the solid materials with wide particle diameters (from clay to gravel). Increase of erosion ability resulted in more solid materials being initialized and carried downstream. The imbalance of flow erosion and wide particle sizes distribution often led to vertical drop in the gully (Headcut). When the impinging jet fell downstream the interaction between the flow and solid material was changed from friction to impact at the bottom which increased the dissipation of flow kinetic energy. The energy dissipation led to excessive erosion and vertical drop upstream migration. (3) When the ‘headcut’ migration reached the top of the dam, the water head increased immediately. The increase of flow discharge deepened and widened the gully gradually, which enhanced the failure process of glacier dam as shown in Fig. 10.

For Case 2 the elevation difference between the water level and dam crest was so small that the surge passed the dam at a high velocity. The solid materials were carried downstream and the dam elevation decreased. Meanwhile, with increasing the water head, more materials were carried and transported by the flow. The failure process developed much faster than the condition without overflow as shown in Fig. 11.

5. CONCLUSION AND DISCUSSION

5.1 Conclusion

In the experiments, the formation, propagation and attenuation of surge wave induced by ice avalanches was investigated. The failure process and mechanism caused by surge waves was also analyzed. Conclusions were drawn as follows:

1) Two obvious surge waves induced by the ice avalanches were measured by PPTs. The first one was induced by the high speed avalanches hitting on the still water. The second one was generated by the collapse of water when the avalanches emerged into water. The height of the second surge was 2 times larger than that of the first one which was triggered by the rectangular sliding blockage.
2) The attenuation speed of surge waves changed dramatically in its propagation direction. A turning point was found at about $X/h_0 = 1.5$. If $X/h_0 < 1.5$, the surge height attenuated exponentially. On the contrary, if $X/h_0 > 1.5$, the surge height attenuated slowly.

3) An initial small discharge provided flowing over the glacier dam enlarged the peak discharge obviously. Peak discharge almost reached about 0.08 m$^3$/s. However, peak discharge without stream flowing over the dam was only 0.01 m$^3$. The primary explanations for the enlargement of flood discharge during the failure process were given. The intermittent flow induced by surge waves, gully formation, 'headcut', dam failure is the main stages of dam failure without initial discharge. The 'headcut' was an important stage to dramatically widen the breach and enlarge discharge in this process. The mechanism of 'headcut' was also analyzed in detail. However, with initial discharge flowing over the glacier dam, a large amount of solid materials were transported when the surge waves approaching the dam. The glacier dam elevation decreased quickly. ‘headcut’ phenomenon was not obvious in the whole process.

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5.2 Discussion
Surge wave propagation and its effects on the downstream moraine dam is a very complicated problem. Here the authors have only presented the primary study results about this problem. Certain issues such as the initial surge height estimation, the dissipation of surge wave, dynamic pressure loads exerted on the glacier dam, the relationship between the pressure loads and dam stability, erosion rate of solid materials in the dam failure process, peak discharge prediction will require elucidation in future studies.

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NOTATION
The following symbols are used in this paper:

- $A_1$ = The water area at $t_1$ (m$^2$)
- $A_2$ = The water area at $t_2$ (m$^2$)
- $B$ = The width of the dam breach (m)
- $g$ = The acceleration due to gravity (m/s$^2$)
- $h_0$ = Initial water depth of the damaged lake (m)
- $H_0$ = Initial surge wave height (m)
- $H_1$ = The water depth at $t_1$ (m)
- $H_2$ = The water depth at $t_2$ (m)
- $Q_1$ = The incoming discharge (m$^3$/s)
- $Q_2$ = The outlet discharge (m$^3$/s)
- $Q_b$ = Discharge of the dam-break flow (m$^3$/s)
- $X$ = Distance away from the plunging location (m)
- $t$ = Release time (s)
- $V$ = Volume of glacial lake (m$^3$)
- $\Delta V$ = The variation of water volume in $\Delta t$ (m$^3$)
- $\Delta t$ = Time duration (s)

Greek letters

- $\alpha$ = Slope angle (°)

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