CHINESE GEOGRAPHICAL SCIENCE
Volume 14, Number 1, pp.39–47, 2004
Science Press, Beijing, China

CRITICAL HYDROLOGIC CONDITIONS FOR OVERFLOW BURST OF MORAINE LAKE

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ABSTRACT: Floodwater and debris flow caused by glacial lake burst is an important land process and a serious mountain disaster in glacial area of Xizang (Tibet) Autonomous Region, and the overflow burst is mainly caused by glacial landslide falling into moraine lake. On the premise that moraine lake is full, instantaneous burst in part of the lake bank happens, as flow velocity at burst mouth caused by overflow head is higher than threshold flow velocity of glacial till. Under some supposes, d_{90} and d_{10} of the glacial till in the bank were used as the threshold sizes of coarse and fine grains respectively. Thus, the formula of calculating threshold flow velocity of uniform sand was simplified, and threshold flow velocity of glacial till was calculated with the formula. Then, with synthesis formula calculating flow velocity of instantaneous part burst, flow velocity at overflow burst mouth was calculated, and calculation formula of critical height (H_0) of overflow head was derived. Overflow head was caused by volume and surge of glacial landslide falling into moraine lake, calculation formulas of ascendant height (H_1) of lake water surface and surge height (H_2) on burst mouth caused by glacial landslide falling into moraine lake were derived. To sum up, critical hydrologic conditions of moraine lake burst with overflow form are: the burst is inevitable as $H_1 > H_0$; the burst is possible as $H_1 < H_0$ and $(H_1+H_2) > H_0$; the burst is impossible as $(H_1+H_2) < H_0$. In the factors influencing the burst critical conditions, it is advantageous for the burst that scale of the lake is $10^5 m^2$ range; terminal glacial till is more fine and is even more uniform; the width of overflow mouth is even smaller than the length of the bank; the landslide has large scale and steep slip surface; and glacial end is close to the lake. With burst of Guangxiecuo Lake in Midui Valley of the Polongzangbu River in Xizang as an example, the burst critical conditions were tested.
KEY WORDS: moraine lake; terminal moraine bank; overflow burst; critical height of overflow head; glacial landslide; Guangxiecuo Lake

CLC number: P343; TV641 Document code: A Article ID: 1002-0063(2004)01-0039-09

1 OVERFLOW BURST OF MORAINE LAKE

Floodwater and debris flow caused by glacial lake burst is an important land process and a serious mountain disaster in glacial area. Glacial lakes with burst can divided into the glacier-obstructed lake (ice dam lake) and the terminal moraine lake (XU and FENG, 1988). Typical burst of ice dam lake happens in the modern glacier area of the upper reaches of the Keleqing River in Uygur Autonomous Region of Xinjiang (WANG, 1990). But most of burst glacial lakes are moraine lakes, which centralize in Xizang Plateau and Himalayas area. In Xizang Region, there are thousands of glacial lakes in high mountains, of which 1/4 are danger moraine lakes where bursts possibly happen. Now, 12 moraine lakes with burst are already investigated, which all happened since 1935. In direct causes of the bursts, most are glacial landslide or ice avalanche (be generally called glacial landslide in the following) falling into moraine lake. Floodwater caused by moraine lake burst and debris flow developed by the flood caused enormous disasters. The relevant main data are listed in Table 1 (LU *et al.*, 1999).

Bursts of the moraine lakes can be divided into two types. One is overflow burst which is caused by washing and down cutting of overflow head, as velocity of the overflow is higher than threshold flow velocity of glacial till and as descent speed of the lake water level is smaller than speed of down cutting. The overflow head is made by ascendant height of lake water level

Received date: 2003-06-06
Foundation term: Under the auspices of the Knowledge Innovation Program of Chinese Academy of Sciences (KZCX2-306)
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Table 1 Burst moraine lakes in Xizang Autonomous Region of China

Morain lake	River or valley	County	Date	Area of lake before burst ($\times10^3m^3$)	Direct causes of burst	Disaster form	Others
Ta′acuo	Boqu River	Nyalam	1935-08-28	630	Glacial landslide, piping	Floodwater, debris flow	
Qiongbixiamacuo		Yadong	1940-07-10	200	Ice avalanche	Floodwater, debris flow	
Sangwangcuo	Nieruzangbu River	Kangmar	1954-07-16	5375	Glacial landslide	Debris flow(dilution)	Length of lake was 5.0km
Jilaicuo	Jilaipu Valley	Dinggyê	1964-09-21	525	Glacial landslide	Floodwater, debris flow	Height of front wall of glacial tongue was 10m
Longdacuo	Longda Valley	Gyirong	1964-08-25	491	Ice avalanche, glacial landslide	Floodwater, debris flow	Jilong River was obstructed and bursted
Damenlahecuo	Tangbulang Valley	Gongbo' gayamda	1964-09-26	189	Ice avalanche, glacial landslide	Floodwater, debris flow	①
Ayacuo	Kangqu River	Tingri	1968-08-15	420	Glacial landslide	Debris flow, floodwater	Successive bursts in 3 years
Pogecuo		Sog	1972-07-23	500	Ice avalanche, glacial landslide	Floodwater, debris flow (dilution)	Volume of the ice avalanche was $5.7\times10^6m^3$
Zharicuo		Lhozhag	1981-06-24	–	Ice avalanche, glacial landslide	Floodwater, debris flow	
Cirenmacuo	Zhangzangpu Valley	Zhangmu kuoan	1981-07-11	494	Ice avalanche, piping	Floodwater, debris flow	②
Jincuo		Dinggyê	1982-08-27	512	Ice avalanche	Floodwater, debris flow	
Guangxiecuo	Midui Valley	Bomi	1988-07-15	272	Ice avalanche, glacial landslide, piping	Debris flow (dilution), floodwater	

① Volume of the ice avalanche was $5\times10^6m^3$, shock downward to 500–600m, surge height was more then 10m, wide of terminal moraine dyke was 60m, top width and bottom width of burst mouth were 50m and 12m respectively; the Niyang River was stopped up.
② The lake length was1500m, width was 500m and depth was more than 35m; the top width, bottom width and depth of burst mouth were 230m, 40–60m and 50m respectively; the Boqu River was stopped up.

and surge height at burst mouth caused by glacial landslide falling into the lake. Other burst type is piping wreckage caused by melt of buried ice under terminal moraine. In 12 bursts of glacial lakes in Table 1, 9 bursts were the overflow bursts caused by glacial landslide, and other 3 bursts were made together by overflow and piping. Overflow burst is the research object of the paper.

Since the 1990s, the debris flow disaster caused by burst of moraine lake were investigated in China (YANG, 1983; LU and LI,1986; XU, 1987; LU *et al*., 1987; DENG, 1988; DING and LIU, 1992). Furthermore, dangerous degree of moraine lake was judged with scales and shapes of glacier, glacial lake and terminal moraine bank, and burst flood were calculated (XU and FENG, 1989; LUO and MAO, 1995; CHEN *et al*., 1996). After debris flow of moraine lake burst in Midui Valley of Bomi County in Xizang happened in 1988, the disaster situation, genesis and floodwater of the burst were investigated and studied (LI and YOU, 1992; CHEN,1993; ZHU *et al*., 1999; LI, 2001). Outside China, there are a few bursts of moraine lakes on high mountains, only burst forecast (KEPEMKONOV and KUPENSKAYA, 1985) with accumulated temperature was reported, but many researches were done on bursts of ice dam lake (PERCHANOK, 1980; YONG, 1985) at high latitude region. Besides, for bursts of landslide dams (ASANSA *et al*., 1991; FENG *et al*., 1994; WANG, 1995; LU *et al*., 2000; YAN *et al*., 2001) and earth dams (HUNT, 1984; XIE, 1993; WU *et al*., 1994; WU and GUO, 2000) of reservoirs in China and abroad, hydraulics principle of which is similar to burst of moraine lake, the key researches are the analysis of burst origin and establishment and improvement on calculating models of burst flood and its development to lower river, and experiment (KUANG, 1993) and calculation (TAKAHASHI and YAGI，1983) of overflow burst process are very few. Above studies on bursts of moraine lake, landslide dam and reservoir earth dam did not relate to critical overflow conditions. Study on the critical hydrologic conditions of overflow burst has obvious meaning for forecast of burst dam and controlling of burst disaster in the paper.

2 MODEL OF CRITICAL OVERFLOW HEAD OF MORAINE LAKE BURST

With evaporation and seepage flow through terminal moraine bank, moraine lake keeps water budget to ice-snow melt water flowing into the lake, thus the lake is full usually. As ice-snow melt water increases in warm period, lake water is discharged through most low-lying area of moraine bank. It is premise of overflow burst that moraine lake is retained full. This is very different from burst of reservoir dam in which perennial water level is much lower than the dam top. Under the premise, if lake water level increases rapidly, which is caused by glacial landslide falling into the lake, then overflow head is formed. If height of the overflow head is enough, overflow velocity is greater than threshold flow velocity of sediment, then washing and down cutting to overflow mouth begin. If descent speed of lake water level caused by discharge is smaller than overflow speed of down cutting, then water head increases with down cutting, and flow velocity increases further. It leads to the washing and down cutting change fast to bottom of the bank. Thereupon, instantaneous burst to the bottom of dam at part section of terminal moraine lake happens. In a few conditions, because volume of the lake is too small or the bank is too thick, descent speed of the lake water level is greater than the speed of the down cutting. After arriving to some depth, because overflow velocity reduces to velocity stopping flow in this moment, the washing and down cutting stop, thus the burst does not arrive to the bottom. Therefore, the burst can happen at many times. Under above two conditions, bursts are generally called the instantaneous part burst. For analysis of critical hydrological conditions to the burst, it is first essential stage to inquire into height (H_0) of critical overflow head, that is, the head height being higher than overflow mouth and leading to start of washing and down cutting. The calculating process of the height can be divided into 3 stages.

2.1 Threshold Flow Velocity (V_c)

In calculating formulas of unitary threshold flow velocity V_c (m/s) of uniform sand, ZHANG Rui-jin's formula (ZHANG, 1998) conforms fairly to reality. The ZHANG's formula is:

$$V_c = (H/d)^{0.14}\{17.6\,[(\gamma s - \gamma)/\gamma]d + 0.000000605\,[(10+H)/d^{0.72}]\}^{0.5} \quad (1)$$

In the formula, H is water depth (m), d is grain size (m),γs andγ are proportions of sediment and water, generally being 2.65 and 1.0. Thus

$$V_c = (H/d)^{0.14}\{29.0d + 0.000000605[(10+H)/d^{0.72}]\}^{0.5} \quad (2)$$

In big bracket of the formula (2), the first term reflects gravity action and the second term reflects action of cohesive force. As the grain size d>2mm, the second term can be ignored, then the threshold velocity is positively correlated to the grain size:

$$V_c = 5.39H^{0.14}d^{0.36} \quad (3)$$

As the grain size $d < 0.02$mm, the first term can be ignored, then the threshold velocity is negatively correlated to the grain size:

$$V_c = 0.000778\,H^{0.14}(10+H)^{0.5}/d^{0.5} \quad (4)$$

Glacial terminal moraine is a mixture of coarse and fine grains resembling of non-uniform sand. Its starting problem is more complex than uniform sand. Grains of different sizes have different starting conditions (ZHANG, 1998). Today, a mature formula calculating the threshold velocity is not established, because 1) with influencing flow resistance, distribution of grain size influences average flow velocity and drag force; 2) the distribution also influences structure of bottom flow, which makes exposed coarse grain be easily started and hidden fine grain be hard started; 3) starting process of coarse and fine grains is an unsteady process. But under below similar supposes for complex conditions starting non-uniform sand, the threshold velocity of moraine lake burst can be approximately calculated with threshold velocity formula of uniform sand.

(1) The burst process is brief and can be assumed a steady process similarly.

(2) Moraine till has been poorer rounded than river sand. Even though the flow drag force increases and oneself stability increases, with offset between above two forces, starting of moraine till can approximately described with threshold model of river sediment.

(3) In comparison with uniform sand of same grain size, coarse grain is easily started and fine grain is hard started in non-uniform sand. Thus maximum size or average value between maximum size and bigger size fraction can be taken as threshold size of non-uniform sand. Therefore, threshold size used must be smaller one size fraction than reality while calculating threshold velocity of melange moraine till with borrowing uniform sand formula.

(4) Grain size curve of moraine till is generally bimodal or multi-modal. According to above principle of selecting threshold size, threshold size of coarse grain can similarly use d_{90}, which is the smaller one size fraction than maximum size and threshold size of fine grain can similarly use effective size d_{10}.

Under the above approximate suppose conditions, the calculating formula of the threshold velocity V_c of overflow burst of moraine lake is:

$$V_{c_1} = 5.39\,H^{0.14}\,d_{90}^{0.36} \quad (5)$$

$$V_{c_2} = 0.000778H^{0.14}(10+\mathrm{H})^{0.5}/d_{10}^{0.5} \quad (6)$$

For the burst of moraine lake, it is necessary that coarse and fine grains are all started, thus the threshold velocity must be the greater one of V_{c_1} and V_{c_2}:

$$V_c=\max(V_{c_1}, V_{c_2}) \quad (7)$$

2.2 Flow Velocity (V_b) at Burst Mouth

With overflow head as water depth in front of a dam, the flow velocity (V_b) (m/s) at burst mouth can be calculated by borrowing SCHOKLICCH's formula (The No. 3 Survey and Design Institute of Ministry of Railway, 1979) on instantaneous part burst to bottom:

$$V_b= 0.9\times10^{(0.3\,b/B)}(B/b)^{0.25}\,H_0^{\,0.5} \quad (8)$$

In the formula, B is the length of the dam. For moraine lake burst, B is the length (m) of terminal moraine dam obstructing the lake. b is the width of burst mouth in rectangle. For moraine lake burst, b is the width (m) of overflow. Section shape of burst mouth is generally an inverted trapezoidal, in which the width of the top is greater than that of the bottom. Thus, the average width of the top and bottom is suggested to be as b. H_0 is water depth in front of the dam. As start of overflow burst, H_0 is head (m) of over-bank water.

2.3 Height (H_0) of Critical Overflow Head of Moraine Lake Burst

For coarse grain, to unite formulas (5) and (8), thanks to $V_{c_1}=V_b$, to obtain:

$$5.39H^{0.14}d_{90}^{\,0.36} = 0.9\times10^{(0.3\,b/B)}(B/b)^{0.25}\,H_0^{\,0.5}$$

Because $H=H_0$, thus critical water head (H_{01}) (m) caused by over bank is:

$$H_{01}=144.3d_{90}/[10^{(0.833\,b/B)}(B/b)^{0.694}] \quad (9)$$

For fine grain, to unite formulas (6) and (8), thanks to $V_{c_2}=V_b$, to obtain:

$$0.000778H^{0.14}(10+H)^{0.5}/d_{10}^{\,0.5} = 0.9\times10^{(0.3b/B)}(B/b)^{0.25}\,H_0^{\,0.5}$$

Because $H=H_0$, thus critical water head (H_{02}) (m) caused by over bank is:

$$H_{02}/(10+H_{02})^{1.389} = 3.097\times10^{-9} / [10^{(0.833b/B)}d_{10}^{\,1.389}(B/b)^{0.694}] \quad (10)$$

Therefore, the critical overflow head (H_0) (m) of moraine lake burst is:

$$H_0=\max(H_{01}, H_{02}) \quad (11)$$

3 ASCENDANT MODEL OF MARAINE LAKE WATER LEVEL CAUSED BY GLACIAL LANDSLIDE

The total overflow head causing moraine lake burst come from volume and kinetic energy of glacial landslide falling into the lake. On the one hand, the glacial landslide submerged in lake water caused ascension of standing water level of the lake, thus relative stable overflow head is formed at overflow mouth. On the other hand, glacial landslide collides the lake surface, thus arouses surge. And the surge declines to overflow mouth and in a moment forms another overflow head to add on the risen lake water level.

3.1 Ascendant Height (H_1) of Standing Water Level Caused by Volume of Submerged Glacial Landslide

It is assumed that the volume of glacial landslide submerged in moraine lake is the C (m^3), the area of the lake water surface is A (m^2), the average gradient of lakeshore around the lake is the β (degree), the specific gravity of ice is γ_i, the ascendant value of the lake water level caused by glacial landslide in the lake is H_1 (m), the lake water area after the lake water level rising is A_1 (m^2), the lake surface is similar to a square, then

$$\gamma_i C = H_1[A + A_1 + (AA_1)^{0.5}]/3$$

$$A_1 = (A^{0.5}+2H_1\mathrm{ctg}\beta)^2$$

thus $\gamma_i C = H_1A + 2A^{0.5}H_1^2\mathrm{ctg}\beta + 4H_1^3\mathrm{ctg}^2\beta/3$

In above formulas, the end term ($4H_1^3\mathrm{ctg}^2\beta/3$) is very small compared to the former two terms and can be omitted, and $\gamma_i = 0.9$, thus the formula is similarly:

$$H_1=[(A^2+7.2A^{0.5}C\mathrm{ctg}\beta)^{0.5}-A]/(4A^{0.5}\mathrm{ctg}\beta) \quad (12)$$

3.2 Surge Height (H_c) Collided by Glacial Landslide Filling into Moraine Lake

The surge height (H_c) relates to falling speed and completion of the landslide, area and water depth of the lake, and entanglement in water. Calculating the height H_c can borrow follow empirical formula (ZHENG and YANG, 1994):

$$H_c=D\cdot F^{0.7}(0.31+0.2\lg Q) \quad (13)$$

In the formula,

$$F=v/(g\cdot D)^{0.5}$$

$$Q=L\cdot h_1/D^2$$

In above formulas, H_c is stable maximum wave height (m); D is water depth of moraine lake and can be average value (m); v is colliding speed between landslide and water (m/s); g is gravity acceleration (9.8m/s^2); L is slip length, namely inclined length (m) from gravity center of the landslide to collided water surface. h_1 is thickness (m) of the landslide mass.

For glacial landslide falling moraine lake, assume

h_2 is height difference (m) between mass center of the landslide and lake water level, f is friction coefficient between glacial tongue and slop, α is gradient (degree) of slip surface (slope under the glacial tongue), h is height difference (m) between back end of the landslide and lake water level, thus can get the following formulas according to law of conservation of energy:

$$v=[\,2\,g\,h_2(1-f\cdot \mathrm{ctg}\alpha\,)]^{0.5} \quad (14)$$

$$h_2 = h/2+h_1/(2\cos\alpha\,) \quad (15)$$

While glacial tongue reaches to moraine lake surface and falls into the lake, because so-called "water pillow action", the glacial tongue is floated by melt water. Right now, friction coefficient f between glacial tongue and slope is 0 similarly, potential energy all changes to kinetic energy. Thus formula (14) can be simplified to:

$$v = (2g\cdot h_2)^{0.5} \quad (16)$$

3.3 Surge Height (H_2) at Burst Mouth by Declining

Based on empirical formula of Xintan landslide (ZHENG and YANG, 1994), without consideration of the change of water depth and complex condition of bank around lake, relation between declining of surge height along river and distance is a power function, namely surge height H_2 (m) at distance x (km) to hitting water point of landslide mass (central axis line) is:

$H_2 = 7.18x^{-0.91}$ (towards upper reaches) and

$H_2 = 13.2\,x^{-0.78}$ (towards lower rreaches).

Because water surface of moraine lake is horizontal, declining law of surge in the lake must be between laws towards upper reaches and towards lower reaches. By referring to observation data of Tangyanguang landslide surge in Zhexi Reservoir, it is obtained that calculation formula of surge height H_2 declining to overflow mouth of moraine lake is:

$$H_2 = 0.17\,H_c\cdot x^{-0.84} \quad (17)$$

In the formula, H is calculated with m, x is distance (km) to overflow mouth.

To verity above formulas (13) and (17), the observation data of Tangyanguang landslide surge in Zhexi Reservoir are used. The Tangyanguang landslide lies in right bank of gorge at upper reach and 1.5km away to the reservoir dam. In early period retaining water in the reservoir, front part of the landslide is submerged. The friction coefficient on the slip surface declines to 0.36 from 0.56. In 18:00 hours of March 6, 1961, the whole landslide along slip surface with a gradient of 34°–42° slipped into the reservoir with a depth more than 50m, and aroused surge with a height of 21m. The surge height was 2.5m while propagating to front of the dam and was 0.3–0.5m (ZHONG, 1994) while propagating to the upper reach of a distance of 15km. Average width, thickness and volume of the landslide mass were 185m, 20–30m and $1.40\times10^6\mathrm{m}^3$ separately. Inclined length of landslide mass over water level is 260m, height difference h between back end of the landslide and water surface is 120m. Accordingly, the water depth D equals 50m, the inclined length L to collided water surface from gravity center of the landslide equals 130m, the average thickness h_1 of the landslide mass equals 25m, the height difference between mass center of the landslide and the lake water surface h_2 equals 75.9m, the friction coefficient f on the slip surface equals 0.35, the gradient α of the slip surface equals 38°. Therefore we obtain:

Colliding speed between the landslide and lake water:

$$v=[\,2\times9.8\times75.9\times(1-0.35\times\cos38°)]^{0.5}=32.8(\mathrm{m/s})$$

Surge height:

$$H_c=50\times[32.8/(9.8\times50)^{0.5}]^{0.7}\times[0.31+0.2\times\lg(130\times25/50^2)]=21.9(\mathrm{m})$$

it is only 4.3% greater than observed value (21m).

Surge height propagating to a distance of 1.5km:

$$H_2= 0.17\times21\times1.5^{-0.84}=2.54(\mathrm{m})$$

it is only 1.6% greater than observed value (2.5m).

Surge height propagating to a distance of 15km:

$$H_2=0.17\times21\times15^{-0.84}=0.367(\mathrm{m})$$

it is only 8.3% smaller than average observed value (0.4m).

Above results demonstrate that the formulas (13) and (17) can be used.

4 CRITICAL HYDROLOGIC CONDITIONS OF OVERFLOW BURST OF MORAINE LAKE AND THEIR CONTROLLING FACTORS

4.1 Critical Hydrologic Conditions of Overflow Burst of Moraine Lake

Ascendant height H_1 of standing water level caused by glacial landslide falling into moraine lake is relative stable for the lake with ordinary scale. If H_1 is greater than critical height H_0 of overflow head, then flow velocity at overflow mouth can reach the threshold flow velocity of sediment on terminal moraine bank, thus washing and down cutting happen and the moraine lake begin burst to mouth. Therefore, it is an ample condition of overflow burst of the lake that H_1 is greater than the H_0, namely if $H_1>H_0$, then the overflow burst is inevitable.

As $H_1<H_0$, but $(H_1+H_2)>H_0$, overflow burst of moraine lake is possible, because surge height H_2 propagating to overflow mouth disappears in a moment. Although the sum of H_2 and H_1 is greater than H_0, scour at a moment is not certainly to down cutting at overflow mouth.

As $(H_1+H_2)<H_0$, overflow burst of moraine lake is impossible.

To sum up, the critical hydrologic conditions of overflow burst of moraine lake are:

The burst is inevitable as $H_1>H_0$; the burst is possible as $H_1<H_0$ and $(H_1+H_2)>H_0$; the burst is impossible as $(H_1+H_2)<H_0$.

4.2 Main Factors Affecting Critical Hydrologic Conditions of Overflow Burst

4.2.1Terminal moraine bank

(1) In terminal moraine bank, if size distribution is not even, size fraction is more, coarse and fine grains are more chaotic and maximum grain size is bigger, then gravity of coarse grain and cohesive force of fine grain are bigger, threshold flow velocity needing by the grain is greater, overflow head needing by beginning down cutting is higher. Formula (6) shows that critical height of burst head is direct proportion to coarse grain size and is inverse relation to square radical sign of fine grain size.

(2) The ratio between width of overflow mouth and length of terminal moraine bank is N ($N=b/B$, and $0<N\leq 1$). The formula (5) shows that flow velocity V_b of burst mouth is a function of the ratio N, but the function is not monotonous increase or decrease. For formula (5), to get the first derivative of N and to command the derivative value equals 0, then $0.225\times 10^{0.3N}H_0^{0.5}N^{-0.25}(2.763-N^{-1})=0$.

Therefore, the N equals 0.362, namely as the b equals $0.362B$ the V_b is an extreme value. While the second derivative of formula (5) is a positive value as $b=0.362B$, it is shown that the V_b is a minimum value at that moment. That is, V_b increases with the increase of the N as $N>0.362$, and the V_b increases with decrease of the N as $N<0.362$. In statistical bursts of moraine lake in Xizang, N values are 0.069–0.280 and are all less than 0.362, thus flow velocity V_b at burst mouth is a decrease function of N. Therefore, relative width of burst mouth is smaller than length of the bank, then the flow velocity is bigger and the burst is more easy.

(3) Width of terminal moraine bank is bigger, then sediment discharge and total flow discharge needing by washing and down cutting are bigger, time of down cutting is more long. This is disadvantageous to the burst of smaller lake.

4.2.2 Moraine lake

(1) If the area A of moraine lake is bigger, as well as gradient β of the lake bank is smaller, then overflow height H_1 of the lake water level caused by glacial landslide of identical volume filling into the lake is smaller, the burst is not more easy. But if the scale of the lake is very small, then water level descends fast after beginning overflow washing, the overflow head at burst mouth can descend below critical head, thus down cutting will stop. This is not advantageous to the development of the burst.

(2) If the length of the lake is longer, namely distance x between entering water point of glacial landslide and overflow mouth is longer, then declining range of surge to the mouth is even bigger, the burst is not even more easy. As water depth D is bigger, then volume of the lake is also bigger and surge is also a little too big. This is advantageous to the burst.

(3) To sum up the advantageous and disadvantageous influences of the scale of the lake to the burst, we can have qualitative understanding that the lake of moderate scale (the area is $10^5 m^2$ range) is most advantageous to the burst. In Table 1, since 1935 in 11 moraine lakes with burst, areas of 10 lakes are $(189\times10^3-630\times10^3 m^2)$.

4.2.3 Glacial landslide

(1) Immersion volume of the landslide into lake water is bigger, then ascendant height H_1 of the lake water level is bigger, this is even more advantageous to the burst.

(2) Length, thickness and slope of the landslide are greater, then slip speed v and surge height H_c are greater, this is more advantageous to the burst.

(3) Distance between glacial tongue and moraine lake is shorter, even the tongue reaches to the lake already, then on the one hand the surge is higher, because slip speed is bigger as a result of smaller friction coefficient (even is 0) on slip surface; and on the other hand the surge is lower, because of short slip distance and smaller slip speed caused by low mass center. Therefore, smaller distance between the tongue and the lake is advantageous to the burst.

(4) If glacial tongue is more complete, then the landslide falls into the lake as a whole. This is advantageous to the burst. If the tongue is more break, then the landslide falls into the lake with dispersed ice avalanche in many times, thus the surge is relative low. This is disadvantageous to the burst.

5 A CASE—BURST OF GUANGXIECUO LAKE IN MIDUI VALLEY

The Polongzangbu River in southeast Xizang, is a first order tributary of the Yarlung Zangbo River, and guards the traffic thoroughfare of Sichuan–Xizang and Yunnan–Xizang. But mountain disasters of debris flow and landslide etc. are serious along the river, in which the debris flow caused by moraine lake burst in Midui Valley is the most serious. The Midui Valley is a first order branch valley in the south bank of the Polongzangbu River and lies at 94km away to Bomi Town southeastward. Its main runoff is fed by Gongza glacier. The Gongza glacier is a model oceanic glacier, and features frequent advancing and retreat, big motion range and fast motion speed. Thickness of the glacial tongue is 15m, the slope of glacier surface is about 6°. The tongue extends already into Guangxiecuo Lake. The Guangxiecuo Lake is a moraine lake, formed in the Little Ice Age of recent 500 years. Length, average width and average water depth of the lake are 680m, 400m and 10.2m separately. Height, length and top width of terminal moraine bank obstructing the lake are 45m, 320m and 30–80m separately. The grain size of the bank is mixture of gravel and clay, in which fine grain occupies 80%. Elevation of two overflow mouths in middle and west on the bank top are all 3818m, most height of the overflow head is about 0.5m. Because rich antecedent precipitation and rich ice-snow melt water in spring and summer, in 23:00 hours of July 15, 1988, the glacial tongue slipped into the lake. Volume and length of the landslide were $360\times10^3 m^3$ and 136m separately. As a result, water level rose 3m and more, bursting happened on the west end of the bank to bottom. Section shape of the burst mouth is an inverted trapezoidal, in which top width is 35.6m, bottom width is 8m and depth is 17.4m. Maximum flow discharge of the burst is $1538 m^3/s$. The burst floodwater drained along the lower course of the valley, thus washing and smuggling fossil glacial till at both banks, developing to dilution debris flow with a volumetric weight $1.53 t/m^3$. The floodwater and debris flow caused a huge disaster to 3 villages along the valley. The debris flow accumulated down at the entrance of the valley, blocked up the Polongzangbu River and formed a blocked lake. Then, burst happened in the blocked lake, the burst floodwater drained down along the river, caused a huge damage to 42km of Sichuan–Xizang highway. Traffic of the highway was suspended in a half year.

Accordingly, parameters of the Guangxiecuo Lake were that, the area A was $272\ 000 m^2$, the water depth D was 10.2m, the distance x to overflow mouth from hitting water of glacial landslide was 680m, the average gradient of lakeshore around the lake β was 24. Parameters of the glacial landslide were that, the volume C was $360\ 000 m^3$, the inclined length L to collided water surface from center of gravity was 68m, the thickness h_1 was 15m, the height difference between mass center and lake water level h_2 was 14.6m, the friction coefficient f of slip bed was 0. Parameters of the terminal moraine bank were that, the length B was 320m, the average depth b of burst mouth was 21.8m, with 40mm as d_{90}, with 0.008mm as d_{10} according to size composition (ZHU *et al.*, 1999) of modern glacial till in Peilong Valley near the study area.

Therefore, based on formula (9), $H_{01}=144.3\times0.04 / [10^{(0.833\times21.8/320)} (320/21.8)^{0.694}]=0.785$m.

Based on formula(10), $H_{02}/(10+H_{02})^{1.389}=3.097\times10^{-9}/ [10^{(0.833\times21.8/320)}\ 0.000008^{1.389}\times(320/21.8)^{0.694}]=0.00506$, namely H_{02} is 0.126m.

Thus for burst of Guangxiecuo Lake, the height of critical overflow head $H_0=\max(0.785,0.126)= 0.785$m.

Based on formula (12), the ascendant height of lake water level caused by glacial landslide submerged in the lake $H_1= [(272000^2+ 7.2\ \mathrm{ctg}24°\times272000^{0.5}\times 360000)^{0.5}- 272000]/(4\ \mathrm{ctg}24°\times272000^{0.5}) =1.18$m.

Based on formula (15) further, the colliding speed of landslide and water $v=(2\times9.8\times14.6)^{0.5}= 16.9$ m/ s, and $F=16.9 /(9.8\times10.2)^{0.5} = 1.69$, $Q = 68\times15/10.2^2 = 9.80$. Thus, according to formula (13), the surge height at colliding water point $H_c=10.2\times1.69^{0.7}(0.31+ 0.2\times\lg 9.80)= 7.485$m.

Based on formula (17), the surge height at burst mouth $H_2= 0.17\times7.485\times0.68^{-0.84} =1.76$m.

Based on $H_1=1.18\text{m}>H_0=0.78$m and $(H_1+H_2) >>H_0$, it is determined that overflow burst of Guangxiecuo Lake is inevitable, whether there is piping or not caused by melt of buried ice under bank. The calculated H_0 value is greater than the observed overflow head (0.5m) while without burst, thus the value is reasonable. Calculated (H_1+H_2) value equals 2.94m, the value approximates to calculated ascendant value (3m or more) of water level in front of bank. This shows that above critical hydrologic conditions of overflow burst conforms to reality basically.

6 CONCLUSIONS

(1) Critical head (H_0) in formula (11) of overflow burst of moraine lake by combining threshold velocity

formula and flow velocity formula at burst mouth, ascendant height (H_1) formula (12) of lake water level caused by glacial landslide falling into the lake and surge height (H_2) formula (17) in overflow mouth, are tally with reality basically by test of example.

(2) Critical hydrologic conditions of overflow burst of moraine lake are that, the burst is inevitable as $H_1>H_0$, the burst is possible as $H_1<H_0$ and $(H_1+H_2)>H_0$, the burst is impossible as $(H_1+H_2)<H_0$.

(3) Main factors affecting critical conditions of the burst are mainly terminal moraine bank, moraine lake and glacial landslide. It is advantageous for the burst that, scale of the lake is $10^5 m^2$ range, size composition of terminal moraine bank is more fine and is even more uniform, width of overflow mouth is even smaller than length of the bank, the landslide has large scale and steep slip surface, and glacial end is close to the lake.

(4) This study is still initial because it has some supposes and simplifying. In the paper, stress release while glacial landslide broke off is not considered, impacting force of surge to the bank is not calculated because the surge is higher than overflow mouth, piping caused by increases of water head and filtration pressure and its overlap action to overflow burst are not discussed. In calculation, it is still need verification by experiments that d_{90} and d_{10} are used as threshold size of coarse and fine grains separately and width of burst mouth uses its average value of top and bottom widths. It needs further quantitative study for the qualitative advantageous conditions for the burst, that is, suitable scale of moraine lake and smaller distance between glacial end and the lake.

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