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CALCULATION OF DISCHARGE OF DEBRIS FLOWS CAUSED BY MORAINE-DAM FAILURE AT MIDUI GULLY, TIBET, CHINA*

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Abstract– Debris flows caused by moraine-dam failure are common on the Qinghai-Tibet Plateau in China. Peak discharges of debris flows should be predicted to evaluate the risk to people and property in valleys below the moraine dams. On the basis of the critical wave method, we have reduced a new series of formulas about the peak discharge of debris flow, including the peak discharge($Q^d_{\max}$)at the outlet of a failed moraine-dammed lake: $Q^d_{\max} = kq_m$ or $Q^d_{\max} = kQ_{\max}$, and the maximal height of the flow below the dam ($H^d_{\max}$): $H^d_{\max} = \eta k_H H_{\max}$. The calculated peak discharge agrees well with the estimate based on the field data at Midui Gully, Tibet. The critical wave method may be applicable to moraine dams in other areas, including the entire Qinghai-Tibet Plateau region and the European Alps.

Keywords– Debris flow, peak discharge, moraine-dam failure, Tibet

1. INTRODUCTION

Global and regional climate change during the twentieth century has impacted glacierized alpine environments. Glaciers have shrunk, accompanied in some cases by the formation of glacier- and moraine-dammed lakes. The sudden failure of some of the dams has generated large floods and debris flows in valleys below the dams.

Large floods and debris flows from glacier- and moraine-dammed lakes have been reported in high mountain regions around the world [1-14], and are especially common in the Qinghai-Tibet Plateau region of China. Thirteen lakes in Tibet have discharged at least 15 times since the 1930s [15-18]. Since 1826 thirty-five catastrophic glacier lake outbursts were registered in Western and Central Karakoram[19]. Potentially dangerous glacier- and moraine-dammed lakes are common in high mountains around the world, including the Himalaya-Karakoram [20, 21], the European Alps [22, 23], and the North American Cordillera [1, 24, 25].

Dam failure is a complex phenomenon that is controlled primarily by the form and material properties of the dam and by failure mechanism [26]. Direct measurements of flood discharge are virtually impossible, thus indirect methods are commonly used to estimate peak discharges. These methods include the determination of drawdown rates and measurements based on hydraulic formulae or channel surveys [12, 27]. A variety of empirical equations have been proposed, based on documented outburst floods from moraine-dammed lakes, to estimate peak discharges (Q_p) [26, 28, 29]. It is difficult to apply these methods to reliably estimate discharges of debris flows triggered by the breaching of moraine-dammed lakes. The main problems are: 1) some methods do not consider the entrained sediment; 2) many parameters required

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for the analysis must be estimated based on experience; consequently, these estimates are subject to considerable error; 3) it is difficult to obtain many parameters, even in the field.

The objectives of this paper are to: (1) describe the discharge process of debris flows caused by moraine-dam failure using the critical wave method; and (2) illustrate the use of the method with a case study in Tibet.

2. ESTIMATING PEAK DISCHARGE OF DEBRIS FLOWS USING THE CRITICAL WAVE METHOD

The critical wave method is widely used in China to calculate peak discharges of floods based on which East Water Conservancy College [30] has provided a series of equations. We use the critical wave method here to develop a new method of calculating the peak discharge of debris flows induced by moraine-dam failure.

a) Peak discharge of debris flow at the outlet

A debris flow is generated by the entrainment of large amounts of sediment in, and downstream of, the moraine dam. The peak discharge of the debris flow is determined by the volume of water released from the reservoir, the lake hypsometry, the height, width, structure, and texture of the moraine, downstream topography, and sediment availability in the valley below the dam [7, 26].

The sediment is considered in the calculation of flood discharge by using the critical wave method. Peak debris-flow discharge ($Q^d_{\max}$) is the sum of the water discharge and the entrained sediment as follows:

$$Q^d_{\max} = kq_m \qquad \text{(complete failure)} \tag{1}$$

$$Q^d_{\max} = kQ_{\max} \qquad \text{(partial failure)} \tag{2}$$

where q_m and $Q_{\max}$ are the peak discharge of the flood at the outlet, and k is imported as a new coefficient of debris flow discharge and is defined as:

$$k = 1 + \frac{\gamma_d - \gamma_w}{\gamma_s - \gamma_d} \tag{3}$$

where γ_d is the density of the debris flow (kN/m^3), γ_w is the density of water (10 kN/m^3), and γ_s is the density of solid grains in the debris flow (26.5-27.5 kN/m^3).

The peak discharge of a flood induced by the failure of a landslide dam is related to water depths at the upper and lower ends of the outlet and to the shape and size of the outlet channel. Calculations using the critical wave method depend on the dam failure type: rapid complete failure, rapid partial failure, and gradual failure. The calculation methods for the first two types of failure follow.

Rapid complete failure: In 1892, A. Ritter proposed a formula for estimating peak flood discharge along a channel of rectangle cross-section during the failure of a dam [31]. The formula can be applied where the water at the downstream end of the outlet does not influence the outflow from the reservoir.

To analyze the flow during dam failure, we assume that 1) the gully gradient, i_0, equals zero; 2) the flow velocity at the upper and lower ends of the outlet before the dam failure is zero; and 3) the resistance, u^2/C^2R, is zero. The shape of the outflow channel is shown in Fig. 1. We express the flood width, B_x, in terms of the dam width, B, the flood height, H_x, and the water depth at the outlet before failure, H_1 as $B_x = B\times(H_x / H_1)^n$($n$ is a groove shape index; see Table 1). After the application of the feature line method of eigenfunction, the fluid kinetics equation and the continuity flow equation are solved [30, 31]. The flood is described by

$$h_x = [(2n+2)/(2n+3)]^2 H_1 \tag{4}$$

$$u = C = \sqrt{gH_1/(n+1)} \tag{5}$$

in which h_x is the maximum water level at the outlet and u is flow velocity. The peak discharge, q_m, is

$$q_m = \lambda B\sqrt{g}H_1^{3/2} \tag{6}$$

in which λ is a flow parameter ($\lambda = [1/(n+1)]^{3/2}\,[(2n+2)/2n+d]^{2n+3}$), B is the outlet width at complete failure (m), g is the acceleration of gravity, H_1 is the water depth at the dam before failure (m), n is the groove shape index, and u is the flow velocity (m/s).

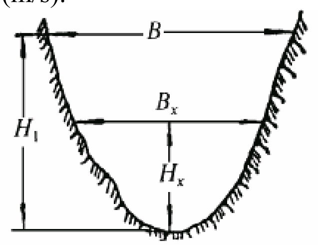


Fig. 1. Sketch of gully cross-section. B_x is the flood width after dam failure; B is the failure channel width; H_x is the flood height after dam failure; H_1 is the water depth at the dam before the failure

Table 1. Peak discharge parameters at complete failure

Section shape	Index of section shape, n	Maximum velocity, u	Maximum water height, h_l	Discharge parameter, λ	Applicable range, H_0/H_1(%)
Rectangle	0	$\sqrt{gH_1}$	$\frac{4}{9}H_1$	0.296	≤13.8
Wide parabola	1/2	$\sqrt{\frac{2}{3}gH_1}$	$\frac{9}{16}H_1$	0.173	≤17.3
Triangle	1	$\sqrt{\frac{1}{2}gH_1}$	$\frac{16}{25}H_1$	0.116	≤19.8
Closed parabola	2	$\sqrt{\frac{1}{2}gH_1}$	$\frac{36}{49}H_1$	0.065	≤22.7

In order to obtain a precise result, we must consider a range existing in the application which can be defined by the ratio of water level at the upside of the outlet, H_0,, to the water level at the upper end of the outlet before the dam failure, H_1, is less than a critical value (Table 1) [30, 31]:

$$H_0 / H_1 \leq [(2n+2)/1.8(2n+3)]^2 \tag{7}$$

Of course, if the ratio is larger than the critical value, the calculation precision will be low.

Rapid partial failure: In certain cases where failure may occur only at the top of the dam, the failure extends only along the dam axes and doesn't extend downwards. Figure 2 shows two cross-sections for hypothetical partial dam failures, in which b is the width of the outlet channel and a is the height of the dam remaining after failure. Using the critical wave method, we assume that (1) the gully gradient, i_0, = 0, (2) the resistance, u^2/C^2R, is zero, (3) the direction of water flow is perpendicular to the dam axis, and (4) the water of the reservoir holds still before the failure period. Figure 3 shows the propagation of the flood, where H_1 is the water depth at the dam before failure, and Z_1 and Z_0 are values of water level fall.

Assuming the conservation of energy and the equilibrium of outside forces, the peak discharge of the flood resulting from partial failure is:

$$Q_{\max} = 2BH_1^{3/2}\sqrt{g}(1 - Z_1 / H)(1 - \sqrt{1 - Z_1 / H_1}) \quad (8)$$

where B is the outlet width at complete failure (m), H_1 is the water depth at the dam before failure (m), and Z_1 is the water-level fall after failure (m). B/b and a/H_1 are as follows:

$$B / b = \frac{\sqrt{2}}{3\sqrt{3}}[5 - 3\frac{Z_1}{H_1} - 4(1 - \frac{Z_1}{H_1})^{1/2} - \frac{a}{H_1}]^{3/2} /(1 - \frac{Z_1}{H_1})[1 - (1 - \frac{Z_1}{H_1})^{1/2}] \quad (9)$$

In the case of failures of landslide and moraine dams, B/b approaches infinity and Z_1/H_1 is near zero, thus

$$Q_{\max} = \frac{2\sqrt{2}}{3\sqrt{3}} b\sqrt{g}H_1^{3/2}(1 - \frac{a}{H_1})^{3/2} = 1.705bH_1^{3/2}(1 - a / H_1)^{3/2} \quad (10)$$

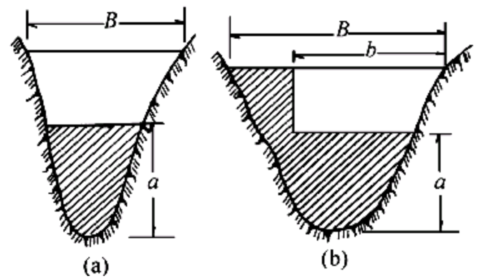


Fig. 2. Partial burst of a debris dam. B is the failure channel width; b is the width of the partial outlet; a is the height of the remaining dam

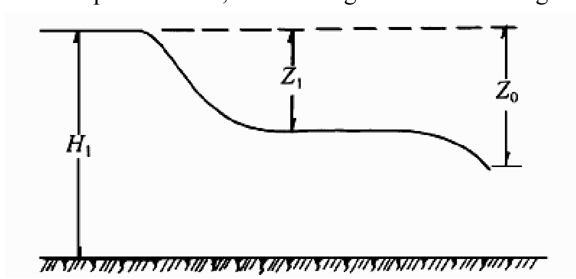


Fig. 3. Flow state of outburst flood. H_1 is the water depth at the dam before failure; Z_1 and Z_0 are values of water-level fall after dam failure

b) Peak discharge of debris flow below the dam

The flood extends downstream along the channel after the dam fails. The peak discharge is a function of the volume of water released from the reservoir, lake hypsometry, the height, width, structure, and texture of the dam, downstream topography, and downstream sediments.

Temporary blockages of large boulders or coarse woody debris can occur when a debris flow travels along a narrow channel with sharp bends. These blockages will influence the peak discharge of the debris flow.

The peak height of a debris flow ($H^d_{\max}$) at a point downstream of the moraine dam is related to the peak height of the flood, dam character, the quantity of solids exchanged along the path, and the gully shape, as follows:

$$H^d_{\max} = \eta k_H H_{\max} \quad (11)$$

where H_{max} is for the peak discharge of the flood at the outlet, η is imported as another new coefficient ranging from 1.0 to 3.0: 1.0-1.4 for low, 1.5-1.9 for medium, 2.0-2.5 for high and 2.6-3.0 for very high [32]. k_H is the peak discharge coefficient of the debris flow determined by the ratio of sediment in the debris flow and the gully shape

$$k_H = k \cdot k_G \tag{12}$$

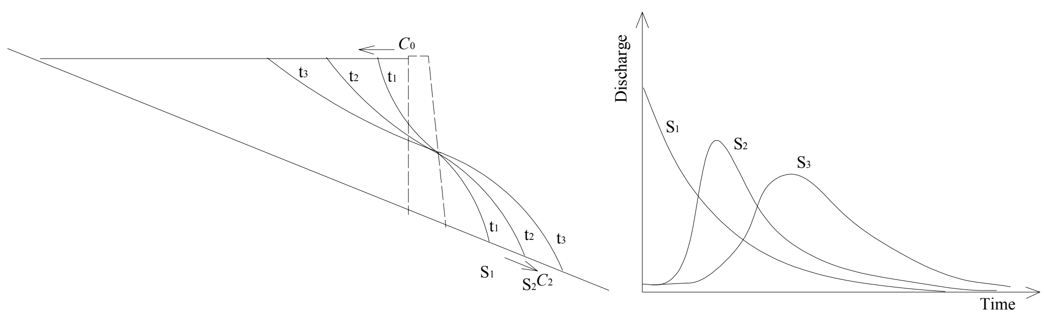
where k is fixed by Eq. (3) and, k_G is a parameter related to gully shape.

According to the critical wave method, a negative wave with velocity C_0 propagates upstream and a positive wave with velocity C_2 moves downstream (Fig. 4a). The attenuation of the flood wave is shown in Fig. 4b.

Assuming invariant flow, the peak height of the flood at the downstream side of the dam can be calculated by [33]

$$H_{\max} = H_{10}\left[1+\frac{4R^2(2n+1)H_1^{2n+1}}{n(n+1)^2 i_0 W^2}x\right]^{-\frac{1}{2n+1}} \tag{13}$$

where x is the distance from the dam to the calculation point (m), H_{max} is the peak flood height at x, H_{10} is the maximum water depth at the dam, R is an index related to the channel shape ($R = A/H^m$ where A is area and H is the height of cross-section), i_0 is the channel gradient, and W is the volume of the lake.



(a) (b)

Fig. 4. Graphs of a hypothetical flood at different sections downstream from the dam. (a) Development of flood wave with time. (b) Attenuation of the flood as it travels downstream from the breached dam (vertical and horizontal scales are dimensionless). S_1, site near the dam; S_2, mid-valley site; S_3, site distant from the dam. The total volume of the flood is the same at each of the three sites, but flood height decreases and flood period increases downvalley. Base flows increase downvalley due to inputs from tributary streams

3. PEAK DISCHARGE OF DEBRIS FLOW IN MIDUI GULLY

a) 1987 debris flow in Midui Gully, Tibet

Midui Gully is located at 29º23’8’’-32’0’’N latitude and 96º27’45’’-35’05’’E longitude, adjacent to the Sichuan-Tibet highway (Fig. 5). Its length from south to north is 16.5 km, its width from east to west is 11 km, and it has a basin area of 117.5 km^2. The altitude of the ridges around the drainage basin is over 5000 m. The drainage joins the Yupu River 94 km east of the Bomi county. The main channel of Midui extends from Guangxie Lake at 3820 m altitude north to the junction with the Yupu River at 3580 m. Generally, the discharge of Midui Gully ranges from 7 to 15 m^3/s in the rainy season, and from 1 to 3 m^3/s in the dry season.

Guangxie Lake is a moraine-dammed lake located in the middle part of the basin (Fig. 6). Before the moraine-dam failure, the shape of the lake was a rectangle 680m × 320m; the depth is about 10.24m on average. Owing to high temperature and heavy rainfall in 1988, it reached its highest water level in nearly 40 years. At 11 p.m. on July 15, the moraine dam failed and the lake emptied in 2.5 hours, with a total volume of 2.78 × 10^{6}m^3 [34-36]. Figure 7 shows the status of the lake in 2001. A viscous debris flow was formed by the mixing of sediment with flood water, which continued downstream to the main stream

(Yupu River), and gradually evolved into a dilute debris flow. The flow path was in places deeply incised and in others filled with sediment. The largest recorded flood in 100 years occurred over a distance of 100 km along the Yupu River immediately after the event, destroying 42 km of the highway. The direct economic loss was over US 0.7 million dollars, and the indirect economic losses were over US 12 million dollars.

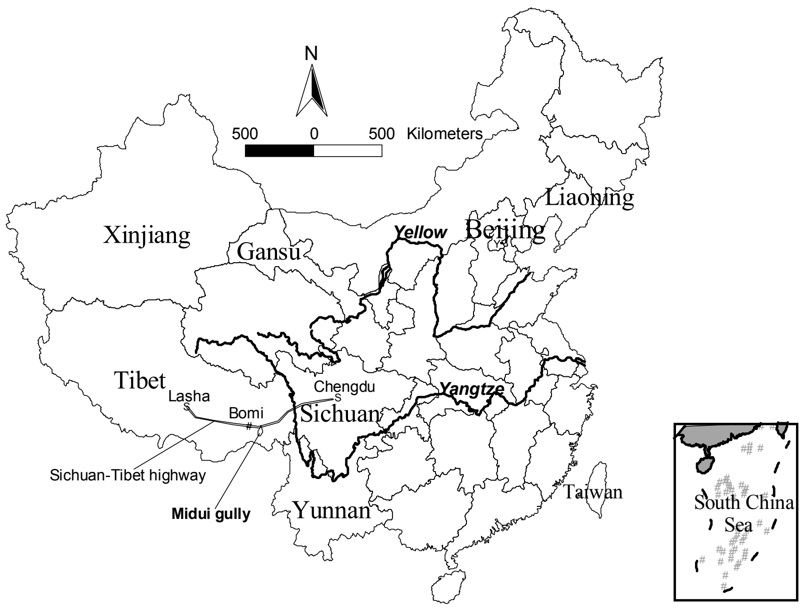


Fig. 5. Location of Midui Gully

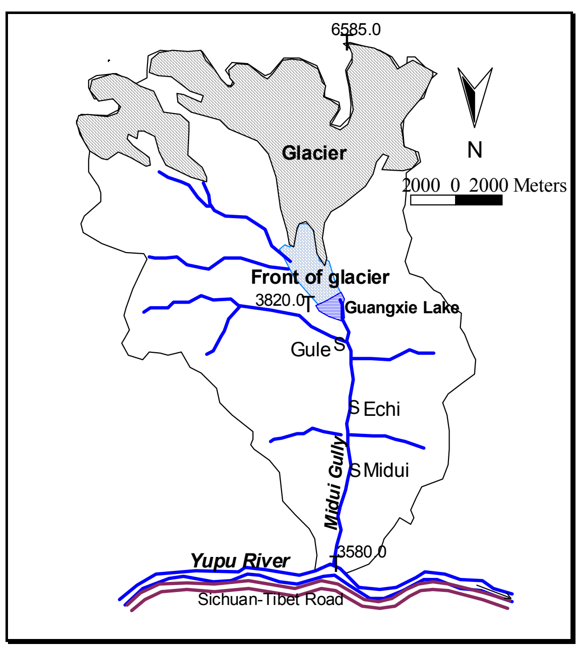


Fig. 6. Map of Midui Gully

Generally, post-flood channel surveys are widely used to estimate peak discharges of floods and debris flow. We have surveyed the drainage area and have sampled some sediment along the main channel. The particles bigger than 5cm have been eliminated from these soil samples. In order to calculate conveniently, the cross-section must be selected where the path of the channel is straight, and Fig. 8 shows the location of cross-sections along Midui Gully where field measurements were taken; Fig. 9 shows the longitudianl profile, and Fig. 10 shows cross-section profiles. Discharge estimates based on the field survey and hydraulic formulae are presented in Table 2.

Fig. 7. The status of the Guangxie lake in 2001

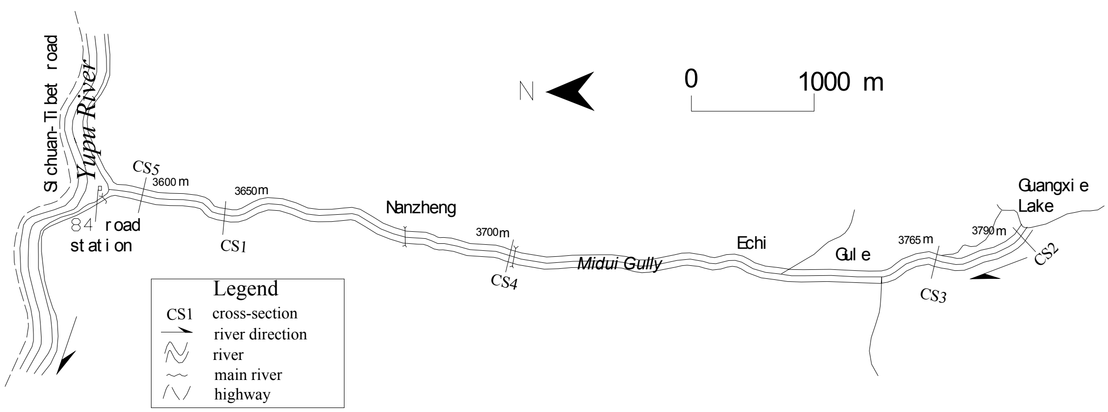


Fig. 8. Cross-sections along Midui Gully

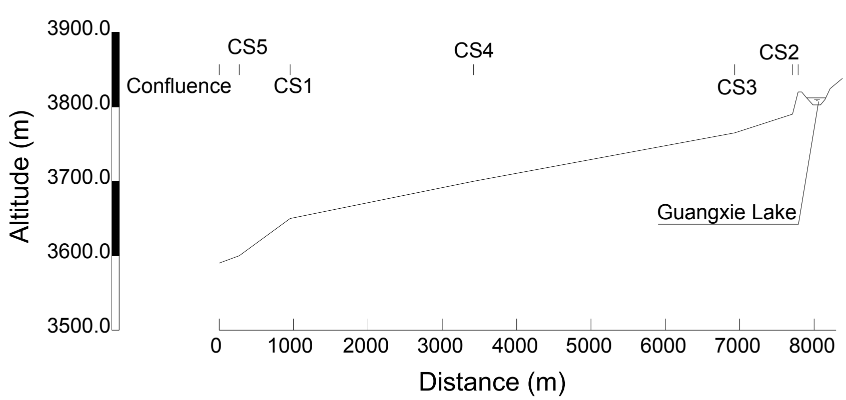


Fig. 9. Longitudinal profile of Midui Gully

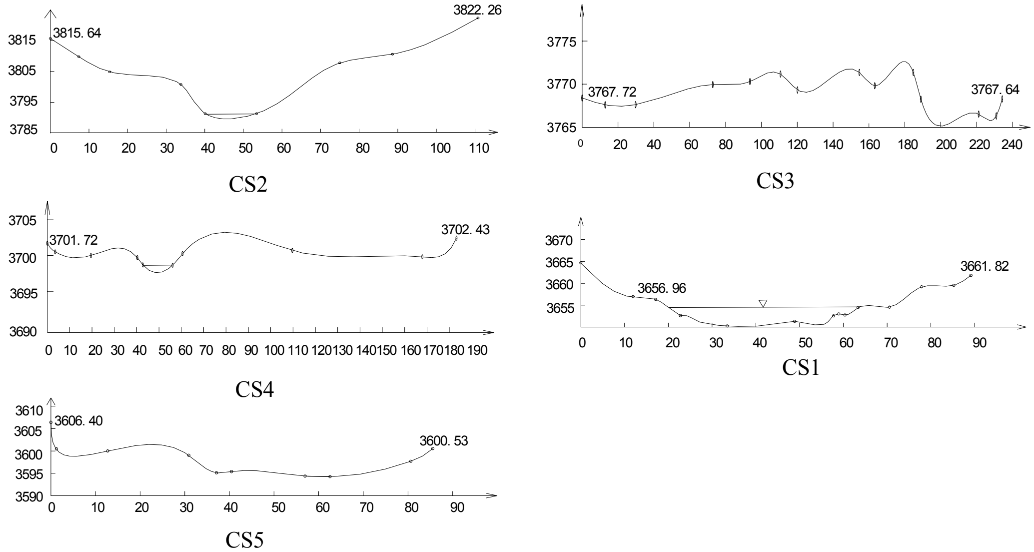


Fig. 10. Topographic profiles at cross-sections (see Fig. 8 of cross-section locations)

Table 2. Cross-section data and peak discharges

Section no.	Channel gradient (%)	Mannings *n* (1/nc)	Flow velocity (m/s)	Section area (m^2)	Discharge (m^3/s)
CS2	4.8	10.5	15.9	1556.0	2472.8
CS3	4.6	18.0	9.9	132.0	1312.1
CS4	0.9	18.5	3.4	321.0	1081.8
CS5	1.0	5.5	2.7	529.0	1438.0

Velocity trend lines and the peak discharge of the debris flow are shown in Fig. 11**.** Both velocity and peak discharge generally decrease downvalley from the dam. The peak discharge of the debris flow decreased from about 2470 m^3/s at the outlet to 1080 m^3/s at the Yupu River. Peak discharge and velocity may locally increase, however, due to differences in sediment availability and constrictions and bends along the path.

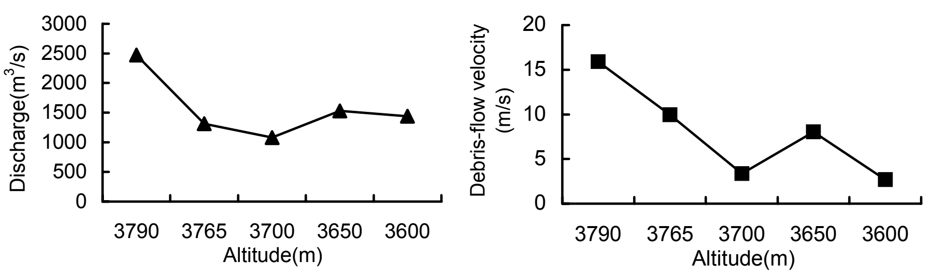


Fig. 11. Plot of debris-flow velocity and peak discharge along the flow path

b) Peak discharge estimates using the critical wave method

Peak discharge coefficients (k and k_G) are required to calculate the peak discharge of the debris flow using the critical wave method. k can be estimated from the size of grains remaining along the debris flow path, and k_G can be estimated from the channel shape.

Estimation of *k*: The clay content (< 0.005 mm) of debris flow is closely related to the concentration (γ_C) [37]. Empirically based, logarithmic relations exist between the concentration and the clay content for ordinary debris flows and viscous debris flows [37]

$$\gamma_C = -1.32\times10^3 x^{'7} - 5.13\times10^2 x^{'6} + 8.91\times10^2 x^{'5} - 55x^{'4} + 34.6x^{'3} - 67x^{'2} + 12.5x^{'} + 1.55 \quad \text{(debris flow, 153 samples)} \tag{14}$$

$$\gamma_C = \log\left[\frac{x^{'}+0.23}{|x^{'}-0.089|+0.1}\right] + e^{-20x^{'}-1} + 1.1 \quad \text{(viscous debris flow, 125 samples)} \tag{15}$$

where γ_C is the concentration of the debris flow and x' is the clay content.

We measured the clay contents of samples of the debris along the Midui Gully and calculated debris flow density from formulae (14) and (15) (Table 3). The clay content of the debris flow deposit gradually decreases downstream from the dam, indicating a decrease in density of the debris flow in that direction (Fig. 12). The peak discharge coefficient of the debris flow is illustrated in Fig. 13. It decreases downvalley, with localized increases in some reaches.

Table 3. Variation of debris-flow density

Section no.	Clay content (%)	Debris-flow density, r (t/m^3)	Coefficient of discharge, k
CS2	2.01	1.89	2.07
CS3	1.65	1.74	1.77
CS4	0.67	1.63	1.58
CS1	0.88	1.65	1.61
CS5	0.65	1.62	1.56

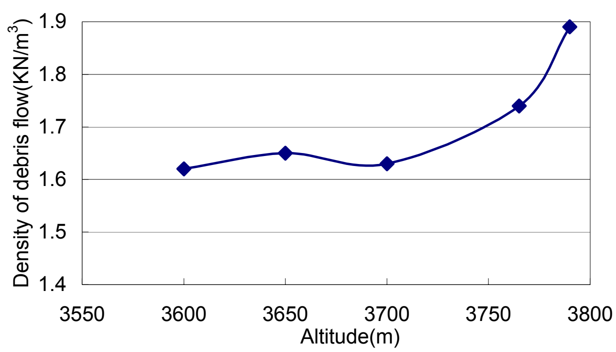


Fig. 12. Changes in debris-flow density along the flow path

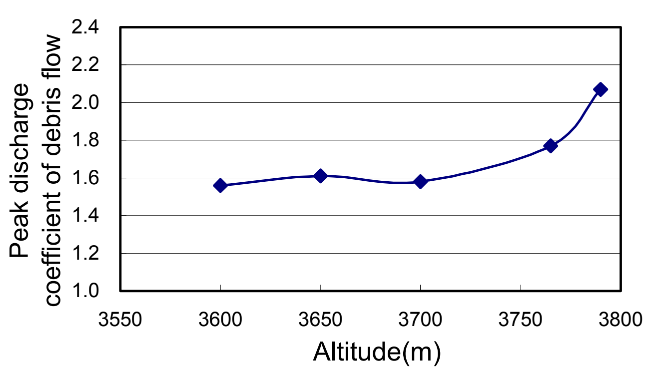


Fig. 13. Change in k along the debris-flow path

Estimation of k_G: k_G depends mainly on the geometry of the cross-section below the dam. Deposition will occur where the channel is wide (k_G is small), and temporary damming may occur at a bend or where the channel narrows (k_G. is large). k_G can be simplified as

$$k_G = (B_L/B_0)^{-1/2} \tag{16}$$

where B_L is the average width of the channel bed and B_0 is the average width of the outlet. In the case of Midui Gully, B_L is 120.1 m at the confluence of Midui Gully and Yupu River, and B_0 is 21.8m, thus k_G=0.43.

Peak discharge of debris flow: The width (b) of the gap in the moraine dam at Guangxie Lake is 21.8 m; the water level near the dam is 10 m, and the remaining dam height is 0 m. From equation (10), the maximum discharge of the outburst flood is 1175 m^3/s. k is 2.07 (Table 3), therefore the maximum discharge of the debris flow at the outlet, calculated from equation (2), is 2433 m^3/s. This value compares with the 2473 m^3/s estimated using field measurements.

At the confluence of the Midui Gully and Yupu River, R = 70, n = 1.1, η = 1.0, $H_{10} = H_1$ = 10 m, i_0 = 0.01, $W = 2.67\times10^6 m^3$, and x = 7600 m. From Eq. (13), the maximum height (H_{max}) is 6.5m. Moreover, k = 1.56, and k_G = 0.43, thus k_H = 0.78. From Eq. (11) $H^d_{\max}$ = 4.36 m, which is close to the survey value of 4.40m.

c) Estimation of peak discharge of debris flow using traditional methods

Peak flood discharges from glacier- and moraine-dammed lake outbursts are currently estimated in China using a formula developed by the Science and Research Institute of the Railway Ministry [36]

$$Q_{\max} = 0.27\sqrt{g}\left(\frac{L}{B}\right)^{\frac{1}{10}}\left(\frac{B}{b}\right)^{\frac{1}{3}b}\left(H - kh\right)^{\frac{3}{2}} \tag{17}$$

where B is the width of the dam, b is the width of the dam breach, H is the water depth near the dam, L is the lake length, h is the remnant dam height, and k is a coefficient.

The average width of the outlet when Guangxie Lake burst was 21.8 m, and the water depth near the dam was 10.0 m. From Eq. (17), the maximum flood discharge ($Q_{\max}$) is 1538 m^3/s.

Costa and Schuster [26] proposed another empirical equation for estimating peak discharge (Q_p), based on documented outburst floods from moraine-dammed lakes

$$Q_p = 0.0013PE^{0.60} \tag{18}$$

where PE is potential energy (J) which can be expressed as:

$$\mathrm{PE} = vgh \tag{19}$$

where v is water volume (m^3), g is the acceleration of gravity, and h is dam height (m).

The volume of the Guangxie Lake when it burst was 2.67×10^6 m^3 and the water depth near the dam was 10.0 m. The maximum discharge of the debris flow at the outlet, calculated from equation (18) is 9217 m^3/s.

d) Comparison of the critical wave and traditional methods

We use the peak discharge estimated from the field survey to validate results obtained using our new critical wave method, the formula developed by the Science and Research Institute of the Railway Ministry [36], and the empirical equation proposed by Costa and Schuster [26].

The peak discharge of the debris flow determined from field measurements at the outlet is 2473 m^3/s. The peak discharge estimated using the critical wave method is 2433 m^3/s, with an error of –1.6%. The peak discharge calculated from Eq. (17) is 1538 m^3/s, with an error of -37.8%. The peak discharge determined from Eq. (18) is 9217 m^3/s, with an error of +272.7%.

4. CONCLUSION

This paper provides a new method of discharge calculation for debris flows induced by the moraine-dam failure. The peak discharge can be directly computed if the path is straight and the gradient is low. If the path is irregular or sinuous, however, k_G must be estimated by analyzing the outlet and gully shapes.

With appropriate adjustments for sediment type, the density change curve for the Midui Gully outburst can be applied in these other areas, including the Himalaya- Karakoram, the European Alps, and the North American Cordillera, thus assisting in hazard mitigation.

It is impossible to acquire estimates of all important parameters required to predict debris-flow peak discharges, owing to the complexity of debris flow mechanics and the difficulty in conducting field surveys in high mountain areas. In this paper, two main parameters have been taken into account–the debris-flow density and the shape of the channel. The computational accuracy has been necessarily reduced because other parameters are not considered, even so, the method yields reasonable results.

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NOMENCLATURE

η	new coefficient	λ	flow parameter= $[1/(n+1)]^{3/2}\,[(2n+2)/2n+d]^{2n+3}$
a	height of the dam remaining after failur	A	area
b	width of the outlet channel	B	outlet width at complete failure
B_0	average width of the outlet	B_L	average width of the channel bed
B_x	flood width	C	flow velocity
C_0	a negative wave with velocity	C_2	a positive wave with velocity
g	acceleration of gravity	H	remnant dam height
H_0	water level at the upside of the outlet	H	height of cross-section
H_1	water depth at the dam before failure	H_{10}	maximum water depth at the dam
h_x	maximum water level at the outlet	H_x	flood height
H_{max}	peak height of the peak discharge of the flood	$H^d_{\max}$	peak height of a debris flow
i_0	channel gradient	K	coefficient of debris flow discharge
k_G	parameter related to gully shape	k_H	peak discharge coefficient of the debris flow
L	lake length	k_H	groove shape index
PE	potential energy	q_m	peak discharge of the flood at the outlet (complete failure)
Q_p	estimating peak discharge	$Q_{\max}$	peak discharge of the flood at the outlet (partial failure)
$Q^d_{\max}$	peak debris-flow discharge	γ_C	concentration of debris flow
γ_d	density of the debris flow	γ_s	density of solid grains in the debris flow
γ_w	density of water	R	an index related to channel shape, $R = A/H^m$
u	flow velocity	W	volume of lake
x	distance from the dam to the calculation point	x'	clay content of debris flow
Z_0	water level fall	Z_1	water-level fall after failure

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