Risk assessment of Sichuan–Tibet Highway susceptible to debris flows at Suotong Basin, southeastern Tibet

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Abstract. The planned Sichuan–Tibet Highway will pass through many debris flow-prone areas. Suotong catchment with a drainage area of 38.03 km², a tributary of Parlung Zangbo River in the Bomi County of Tibet, has not experienced large-scale debris flows since 1991. Field survey and image interpretation show that glacial till in the catchment has volume of approximately 160 mm³ and is the primary source of loose materials for debris-flow reoccurrence. Once large glacial debris flows occur, they will cause harm to the highway. A comprehensive method including engineering geology, hydraulics, and computational mathematics is developed to quantitatively assess the debris-flow risk to the highway. The magnitude and peak discharge of glacial debris flows of a 100 year return period are calculated using empirical relationships in this region. The peak velocity at the outlet can reach 6.75 m/s, and the peak discharge is 6238 m³/s for such a return period. The Saint–Venant equations governing debris-flow movements are numerically solved by finite difference method. The simulated results are close to those by empirical methods. The hazard value at the alluvial fan is as high as 24.7 according to the numerical simulation. Two routing schemes (one goes through the tunnel and other pass the bridge) are compared with each other. Although the bridge scheme is cheaper than the tunnel scheme, the bridge’s section cannot fully discharge debris flows within the 100-year return period. Therefore, the tunnel scheme is safer and more strongly recommended than the bridge scheme.

1. Introduction
The road construction and operation practices in China show that highways routing through debris flow-prone areas are very important, because of the initial investment and the highway safety in the later stage (Cui & Lin, 2008). The 318 National Highway through the Parlung Zangbo Basin was repeatedly damaged by debris flows, and flash floods occurred at catchments or tributaries. For example, Guxiang catchment experienced several active periods of debris flows from 1953 to 1979, which destroyed the road many times (Shi et al., 1964; IMHE, 1999). In 2005, glacial debris flows occurred and destroyed the road again, causing the rerouting of road and rebuilding of one engineering
structure for protection in Guxiang. Glacial debris flows that occurred at the Peilong catchment destroyed the bridge across the catchment outlet and blocked Parlung Zangbo many times. The Yigong dam outburst flood in 2000 damaged the highway from Tongmai to Peilong, traveled downstream, and destroyed many buildings in India (IMHE, 1995; Zhu et al., 2000; Shang et al., 2003; Cheng & Wu, 2011; Delaney & Evans, 2015). Recent glacial debris flows in the Tianmo catchment after 2007 rushed across Parlung Zangbo, completely eroding the road on the other side of the river (Ge et al., 2014; Deng et al., 2017; Wei et al., 2018; Clarence et al., 2018).

The National Highway Network Planning from 2013 to 2030 intends to build the Sichuan–Tibet Expressway of which the G4218 reach belongs to the south part and pass through the Parlung Zangbo Basin. The influence of surrounding debris flows on the highway must be considered during the design stage. In the present work, we assessed the risk for the road crossing the dangerous section combined with route profile and calculation results to provide some suggestions for future design and construction. Suotong catchment, a typical catchment susceptible to debris flows, in the Parlung Basin is chosen as a case to evaluate the risk of debris flows to the expressway. The evaluation can be useful for the selection of alternative routes through the Suotong alluvial fan.

2. Study area

2.1. Geography

The Suotong catchment (N30°00'42"–30°05'37", E 95°16'48"–95°21'58") is located in the deep of Parlung Zangpo Canyon and belongs to Bomi County close to Suotong village (Fig. 1a). The catchment has a total channel length of c. 18.75 km, a channel gradient of 284.2‰, and a drainage area of 38.03 km². The elevation ranges from 2360 m to 5886 m. The main channel is a V-shaped valley with steep slopes on both sides with an average slope of 31.20°. The area of slope (>25°) was 26.57 km², accounting for 69.87% of the total area; the area of slope between 15° and 25° was 7.43 km², accounting for 19.54%; and the area of slope less than 15° was 4.03 km², accounting for 10.59%. Thus, the Suotong catchment is dominated by steep hillslopes, which are susceptible to rainfall and meltwater (Fig. 1b).

The debris-flow formation region of the Suotong catchment is characterized by an elevation of more than 3300 m and steep terrain with a slope of 35°–40° in most cases. The longitudinal gradient of the channel is 378.2‰. There are glaciers and exposed bedrock in the upper reaches, which are steep and severely eroded, easily triggering rockfalls and avalanches. Since the neoglacialation, moraines existing below the snowline in the form of clastic cones, terminal moraines, and lateral moraines are distributed in the upstream glaciated valley. This area has become the main material source for glacial debris flows. The elevation of the passage region ranges from 2500 to 3300 m. The slopes on both sides are steep, and moraines are spread along the hillside on both sides. The surface forest vegetation is intact and relatively stable, so there are few materials participating in debris flows. There are residual deposit and slope wash in the region. Given the thin weathered material and its transport by the force of gravity, the material reserves mostly accumulate in the channel. In addition, the gradient of the channel in this region is steep, which is 190‰–260‰. Some landslide materials accumulate on both sides of the channel, and they can easily block the narrow channel. The elevation of the accumulation region is between 2500 and 2360 m. The maximum accumulation length is about 715 m, the width is about 1160 m, the area is about 0.43 km², and the average gradient is about 168.3‰. With the strong scour of surface runoff, the erosion of the accumulation section is obvious.

2.2. Hydrology and glaciers

The water supply of Suotong catchment mainly comes from rainfalls and melting water. Suotong catchment is located in the southeast of Tibetan Plateau and is heavily influenced by the Indian Monsoon. Water vapor travels upstream along the Yarlung Zangbo valley, crossing Puerto on the south of the Parlung Zangbo watershed and entering the area, bringing abundant precipitation. Given the influence of the maritime monsoon, the rainy season lasts for about 6 months (from late April to
According to the observation data of the Bomi meteorological station, the annual average temperature is 8.6°C and rainfall is 884.5 mm (Table 1). The annual rainfall is extremely uneven, in which the rainy season precipitation accounts for over 70% of the annual precipitation (Fig. 1c), and the maximum monthly rainfall is more than 20 times that of the minimum monthly rainfall. The precipitation is also affected by the altitude. With increasing altitude, the climate varies greatly from the catchment outlet to the summit. According to the observation data in the Guxiang catchment, which is close to the Suotong catchment, the vertical decline rate of air temperature is 0.6°C/100 m, the vertical increase rate of precipitation in summer is 80 mm/100 m, and the elevation of water vapor that condenses into rain in summer is about 4200 m. Remote sensing interpretation reveals that the glaciers in the Suotong catchment are mainly distributed in the glacial valley with elevation above 4000 m, including hanging glaciers and cirque glaciers, with an area of 7.99 km².

Figure 1. Location maps of the study area and sites. (a) The Parlung Zangbo Basin showing the location of the Suotong catchment; (b) topography of the Suotong catchment showing the location of glaciers; and (c) annual rainfall data near the Suotong catchment.
### Table 1. Meteorological data of the valley in Bomi.

| Elevation (m) | Average air temperature (°C) | Maximum air temperature (°C) | Minimum air temperature (°C) | Mean annual precipitation (mm) | Mean annual evaporation (mm) | Maximum daily precipitation (mm) |
|---------------|------------------------------|------------------------------|------------------------------|--------------------------------|----------------------------|-------------------------------|
| 2800          | 8.6                          | 30.4                         | −14.0                        | 884.5                          | 1434.5                     | 75.2                          |

2.3. **Debris-flow source**

The stratum in the Suotong catchment are mainly metamorphic rocks of the Carboniferous Period, such as gneisses, marble, and phyllite. The material sources are abundant and concentrated, and they are mainly distributed on both sides of the channel in the midstream and upstream. The material sources include slope material, slump mass, channel material, and moraine (Fig. 2).

![Figure 2](image-url). Distribution of loose material source in the Suotong catchment and the route schemes of the expressway.

According to field investigation and remote sensing interpretation, the total material source in the Suotong catchment is about $35806.4 \times 10^4 \text{ m}^3$, among which the material source participating in glacial debris flows is about $14322.5 \times 10^4 \text{ m}^3$. The slope material, slump mass, channel material, and moraine are about $7425.8 \times 10^4 \text{ m}^3$, $9892.0 \times 10^4 \text{ m}^3$, $2479.8 \times 10^4 \text{ m}^3$, and $16008.8 \times 10^4 \text{ m}^3$, respectively. Active volumes for these kinds of materials are about $2970.3 \times 10^4 \text{ m}^3$, $3956.8 \times 10^4 \text{ m}^3$, $991.9 \times 10^4 \text{ m}^3$, and $6403.5 \times 10^4 \text{ m}^3$ (Table 2).

### Table 2. Material source statistics of the Suotong catchment.

| Type               | Distribution                      | Static reserves (104 m$^3$) | Dynamic reserves (104 m$^3$) | Supply way | Supply condition                      |
|--------------------|----------------------------------|-----------------------------|------------------------------|------------|--------------------------------------|
| Slope material     | Upper and middle slope           | 7425.8                      | 2970.3                       | Slide      | Eroded by rainstorm and melting water |
| Slump mass         | Both sides of the channel        | 9892.0                      | 3956.8                       | Slide      | Induced by rainstorm and melting water |
| Channel material   | Channel                          | 2479.8                      | 991.9                        | Scour      | Eroded by flood and debris flows     |
2.4. Planned expressway

According to the plan of G4218 from Bomda Town to Nyingchi, there are two routes for constructing the way through the outlet of the Suotong catchment: Route K and Route F5. Route K passes through the Bitong tunnel in the form of a tunnel and then appears on the left hillside of the Suotong alluvial fan. It crosses the main channel (K317 + 370) of the Suotong catchment in the form of a bridge on the fan and then enters the hillside to the right of the fan. Route F5 passes through the channel of the Suotong catchment in the form of a tunnel (F5K315 + 343), which is connected to the Bitong tunnel, and continues to extend from the hillside on the right side of the Suotong accumulation fan in the form of a bridge (Fig. 2).

3. Methods

3.1. Parameter estimation

Debris flows in the Suotong catchment are triggered by rainfall and glacial melting. The catchment is located in the area with abundant temperate glaciers and large water supply by meltwater and precipitation, especially in the rainy season. The melt rate of glacier is fastest in July and August, and the meltwater in the rainy season accounts for more than 70% of the whole year. When the glacier area accounts for 10%–30% of the basin area, glacial meltwater plays an important role in the formation and change of runoff. Therefore, the combined effect of rainfall and glacial meltwater must be considered in the calculation of peak discharge of debris flows. We used the following formula to calculate the peak discharge of flood and debris flows, total transported material, velocity, impact force, and other parameters at different design frequencies (Table 3).

| Category of calculation | Calculation formula | Description of parameters |
|-------------------------|---------------------|----------------------------|
| Peak discharge          | \( Q_0 = 0.278 \varphi iF \) | \( Q_0 \) is the peak discharge of debris flows (m\(^3\)/s); \( Q_b \) is the peak discharge offlash flood (m\(^3\)/s); \( \varphi \) is peak runoff coefficient; \( i \) is the maximum average rainstorm intensity (mm/h); \( F \) is catchment area (km\(^2\)); \( d \) is the flood peak coefficient caused by glacier melt; \( F_i \) is the area of glacier and snow (km\(^2\)); \( \theta_b \) is the glacier slope (\(^o\)); \( H \) is rainfall (mm); \( \gamma_c \) is the density of debris flows (t/m\(^3\)); \( \gamma_w \) is the density of water (t/m\(^3\)); and \( \gamma_s \) is the density of solid material (t/m\(^3\)). |
| Flow velocity           | \( V_c = \frac{1}{n_c} H_c^{2/3} \frac{1}{c}^{1/3} \) | \( n_c \) is bed roughness of viscous debris flows; \( H_c \) is the mud depth (m); and \( I_c \) is channel gradient. |
| Total discharge         | \( Q_t = 0.26 T Q_c \) | \( Q_t \) is the total discharge (m\(^3\)); \( T \) is debris-flow duration (s); and \( Q_c \) is the volume of solid material (m\(^3\)). |
| Deposition              | \( d_c = 0.017 [V_r/(G^2 \ln r_c)]^{1/3} \) | \( d_c \) is the maximum deposition thickness of a debris flows (m); \( V_r \) is the
thickness maximum supply of material source (m³); and \( G \) is the gradient of the accumulation area.

\[ \delta = \lambda \frac{g}{V_c} V_c^2 \sin^2 \alpha \]

\( \delta \) is the impact force of debris flows (Pa); \( g \) is the gravitational acceleration (m/s²), and \( g = 9.8 \text{ m/s}^2 \); \( \alpha \) is the included angle (°) between the force surface of the building and the direction of the impact force; \( \lambda \) is the building form factor, \( \lambda = 1 \) for circle, \( \lambda = 1.33 \) for rectangle, \( \lambda = 1.47 \) for square; \( F \) is the impact force of large stones (kN); \( \gamma \) is the kinetic energy reduction coefficient, and the positive impact is 0.3; \( V_s \) is the velocity (m/s) of the large rock, which is the same as the velocity of the debris flows; \( W \) is the weight of large rocks in debris-flow body (kN), and the size of large rocks is 5.0 m × 4.0 m × 4.0 m. \( C_1 \) and \( C_2 \) are elastic indexs of boulder and bridge pier, respectively, \( C_1 + C_2 = 0.0005 \text{ m/kN} \).

\[ \Delta H = \frac{V_c^2}{2g} \]

\( \Delta H \) is the height of debris flows.

\[ \Delta h = \frac{2V_c^2 B}{gR} \]

\( B \) is the width of the debris-flow surface (m), and \( R \) is the curvature radius of the stream center (m).

### 3.2. Numerical simulation

Methods of numerical simulation based on the Saint–Venant equations have been widely used to simulate the propagation of debris flows and determine their risks (Armanini et al. 2009; Chen et al. 2014). The two-dimensional Saint–Venant equations in a Cartesian coordinate are used to simulate debris-flow movement:

\[ \frac{\partial h}{\partial t} + \frac{\partial p}{\partial x} + \frac{\partial q}{\partial y} = 0 \quad (1) \]

\[ \frac{\partial p}{\partial t} + \frac{\partial}{\partial x} \left( \frac{p^2}{h} \right) + \frac{\partial}{\partial y} \left( \frac{pq}{h} \right) = -gh \frac{\partial (z_h + h)}{\partial x} - \tau_x \rho \quad (2) \]

\[ \frac{\partial q}{\partial t} + \frac{\partial}{\partial x} \left( \frac{pq}{h} \right) + \frac{\partial}{\partial y} \left( \frac{q^2}{h} \right) = -gh \frac{\partial (z_h + h)}{\partial y} - \tau_y \rho \quad (3) \]

where \( p = hu \) and \( q = hv \) are depth-averaged flow momentums along the x and y coordinates; \( u \) and \( v \) are x- and y- depth-averaged velocity components; \( h \) is the flow height; \( z_h \) is the elevation of base; \( g = 9.8 \text{ m/s}^2 \) is the gravity acceleration; and \( \rho \) is the bulk density of debris flows and is assumed as a constant. \( \tau_x \) and \( \tau_y \) are basal resistances along the x and y directions.

Debris flows consist of liquid slurry and coarse particles (Iverson, 1997). The liquid slurries are composed of water and fine particles. Furthermore, the rheology of liquid slurries can be described in the Bingham model (O’Brien et al. 1993). Meanwhile, frictional resistances of coarse particles are dominant during the motion of debris flows (Iverson, 1997). Therefore, the basal resistances of debris flows can be described as the sum of slurry stress and frictional stress of coarse particles:
\[ \tau_x = (1 - C_s) \left( \frac{p}{\sqrt{p^2 + q^2}} \frac{\tau_B + \eta}{\rho h^2} \right) + \frac{p}{\sqrt{p^2 + q^2}} C_g h \left( \frac{\rho_s - \rho_f}{\rho} \right) \tan(\psi) \]  
\[ \tau_y = (1 - C_s) \left( \frac{q}{\sqrt{p^2 + q^2}} \frac{\tau_B + 2\eta q}{\rho h^2} \right) + \frac{q}{\sqrt{p^2 + q^2}} C_g h \left( \frac{\rho_s - \rho_f}{\rho} \right) \tan(\psi) \]  

where \( C_s \) is the volume concentration of coarse particles; \( \tau_B \) and \( \eta \) are yield stress and dynamical viscosity of slurry, respectively; \( \psi \) is the frictional angle of solid particles; \( \rho_s = 2650 \text{ kg/m}^3 \) is the density of solid particle; and \( \rho_f \) is the density of slurry.

A finite difference scheme initially designed for simulating dam break flows is implemented to solve Equations (1)–(5) (Lin et al. 2011; Zhang et al. 2015). The gridded DEM with 5 m resolution is used to represent the geography and surface topology. The time step for the numerical simulation is 0.01 s. Three cases associated with frequencies of occurrence \( P = 1\% \), 0.5\%, and 0.33\% are simulated to determine the distribution of depositional height and covering area of debris flows. The initial conditions including flow velocity and flow depth are given at an initial cross section of 1.5 km upstream of the 318 national highway.

4. Debris-flow dynamic characteristics

4.1. Empirical estimation

Characteristic parameters of debris flows at Route K and Route F5 are shown in Table 4.

| Design route | Route F5 | Route K |
|--------------|----------|---------|
| Design frequency (%) | 0.33 | 0.5 | 1 | 0.33 | 0.5 | 1 |
| \( H_b \) (mm) | 168.76 | 160.15 | 144.65 | 168.76 | 160.15 | 144.65 |
| \( \gamma_c \) (t/m\(^2\)) | 2.30 | 2.10 | 2.00 | 2.30 | 2.10 | 2.00 |
| \( Q_0 \) (m\(^3\)/s) | 250.02 | 235.57 | 206.19 | 251.27 | 236.74 | 207.22 |
| \( Q_2 \) (m\(^3\)/s) | 208.54 | 200.02 | 184.69 | 208.54 | 200.02 | 184.69 |
| \( Q_C \) (m\(^3\)/s) | 12807.13 | 8110.33 | 6238.10 | 12806.48 | 8109.74 | 6237.23 |
| \( V_C \) (m/s) | 7.92 | 7.31 | 6.75 | 7.12 | 6.52 | 6.05 |
| \( Q_4 \) (104 m\(^3\)) | 2433.35 | 1540.96 | 115.24 | 2433.23 | 1540.85 | 1185.07 |
| \( Q_6 \) (104 m\(^3\)) | 1917.19 | 1027.31 | 718.33 | 1917.09 | 1027.23 | 718.23 |
| \( d_C \) (m) | 26.24 | 21.49 | 19.19 | 26.24 | 21.49 | 19.19 |
| \( \delta \) (kPa) | 212.08 | 164.96 | 133.95 | 171.40 | 131.23 | 107.61 |
| \( W \) (kN) | 5270.83 | 5270.83 | 5270.83 | 5270.83 | 5270.83 | 5270.83 |
| \( F \) (kN) | 7714.38 | 7120.22 | 6574.76 | 6935.15 | 6350.73 | 5892.93 |
| \( \Delta H \) (m) | 3.20 | 2.73 | 2.32 | 2.59 | 2.17 | 1.87 |
| \( \Delta h \) (m) | 2.80 | 2.39 | 2.04 | 3.25 | 2.72 | 2.34 |

4.2. Numerical scenario simulation

The bulk density of debris flows in Suotong is evaluated as 2000 kg/m\(^3\), and the corresponding volumetric concentration \( C_s \) of coarse particles is 0.48. The dynamic viscosity, yield stress, and density of liquid slurry are 0.32 Pa.s, 43 Pa, and 1400 kg/m\(^3\), respectively. The frictional angle of coarse particles is estimated to be 16°. The results indicate that the maximum depositional heights associated with the frequencies of occurrence \( P = 1\% \), 0.5\%, and 0.33\% are 20.09, 22.29, and 27.02 m, respectively (Figs. 3–5). The hazard value at the alluvial fan is as high as 24.7 according to the numerical simulation. There is a risk of blocking river when the debris flows enter the Parlung Zangbo Basin (Figs. 3–5).
Figure 3. Distribution of depositional height and inundation area of debris flows with frequency of occurrence $P = 1\%$ for the Suotong catchment.

Figure 4. Distribution of depositional height and inundation area of debris flows with frequency of occurrence $P = 0.5\%$ for the Suotong catchment.
Figure 5. Distribution of depositional height and inundation area of debris flows with frequency of occurrence $P = 0.33\%$ for the Suotong catchment.

5. Route alternative
For Route K, the peak discharge is 12806.48 m$^3$/s and the average velocity is 7.12 m/s when $P$ is 0.33%; the peak discharge is 8109.74 m$^3$/s and the average velocity is 6.52 m/s when $P$ is 0.5%; the peak discharge is 6237.23 m$^3$/s and the average velocity is 6.05 m/s when $P$ is 1%. The depth of the bridge from the bottom of the channel is about 15.60 m, and the maximum flow area is about 760 m$^2$ (Fig. 6). The maximum discharges of the bridge opening are 5411 m$^3$/s ($P = 0.33\%$), 4955 m$^3$/s ($P = 0.5\%$), and 4598 m$^3$/s ($P = 1\%$), respectively, under different frequencies. All of these values are smaller than the calculated results. Once debris flows pass the bridge opening, they will overflow the channel and flood the accumulation fan. The lowest elevation of the area on the right side of the accumulation fan is about 74 m lower than the right bank of the channel, and the debris flows will flood the right side of the accumulation fan after overflowing the channel. Therefore, the bridge pier and bridge floor will be silted by such low-frequency large-scale debris flows.
Figure 6. Profile of Route K through the outlet of the Suotong catchment.

Route F5 passes through the bottom of the Suotong catchment in the form of a tunnel (Fig. 7). The depth of the channel at this point is approximately 13.2 m, and the maximum discharge is about 480 m$^3$. According to the velocity calculation results, the maximum discharge of the bridge opening is 3802 (P = 0.33%), 3509 (P = 0.5%), and 3240 m$^3$/s (P = 1%); these values are smaller than the calculation results as well. The route will pass through the tunnel with a buried depth of about 61.5 m, which cannot be influenced by debris flows.

Figure 7. Profile of Route F5 through the outlet of the Suotong catchment.

6. Conclusion

On the basis of the two designed routes of future G4218 threatened by debris flows from the Suotong catchment, the parameters such as discharge and velocity of debris flows at different frequencies are determined by field investigation, remote sensing interpretation, and empirical and numerical calculations. We then provide some suggestions for the selection of an appropriate route.
The total material source in the Suotong catchment is about 35806.4 $\times$ 104 m$^3$, among which the material source likely participating in glacial debris flows is about 14322.5 $\times$ 104 m$^3$. The moraine source accounts for 44.7% of the total, while the channel source only accounts for 6.9%.

The flowing area in the Suotong catchment is easy to block. Debris flows are mainly rainfall-induced glacial debris flows. The peak velocity at the outlet can reach 6.75 m/s, and the peak discharge is about 6238 m$^3$/s for the 100-year return period.

When low-frequency large-scale debris flows occur, the permissible discharge of the channel at the design point cannot bear the debris flows, and resultant overflow will occur. Given that Route F5 passes through the channel in the form of a tunnel, debris flows cannot influence the path. Hence, we recommend the Route F5 scheme.

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