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Stress testing analysis of exposure threats of mountain bridges to glacier hazards: insights from Peilong Glacier, southeastern Tibet

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Climate warming is a significant driver of the increased frequency of glacier cascading hazards in the mountain cryosphere, particularly in the Tibetan Plateau. The region has been experiencing a rapid warming trend, with temperatures rising at a rate of 0.25-0.35°C per decade, which is nearly double the global average warming rate of approximately 0.15°C per decade. The cascading hazards induced by climate warming pose significant threats to the bridge infrastructures. Based on Peilong glacier in Southeastern Tibet, this study conducts a comprehensive stress testing analysis of glacier hazards, integrating remote sensing data with physical-based numerical modelling. Utilizing long-term meteorological records and debris-ice rheological modelling, the research elucidates the volume and thickness of unstable mass sources. A simulation program is employed to analyse multi-scenario hazard dynamics, predicting runout distances, velocities, and deposition patterns. By quantifying deposition distributions along river courses under various glacier detachment scenarios, the study assesses the potential size of barrier dams, thereby establishing a robust foundation for quantitative risk assessment.
Keywords: Peilong glacier; Stress testing; glacier hazard chain; Bridge.

1. Introduction

The Tibetan Plateau, recognized as Earth's largest and most fragile glacierized water tower, supports the needs of over a billion people (Immerzeel et al., 2020). Over the past sixty years, the plateau has undergone significant warming at a rate of 0.015℃/year, with Southeastern Tibet an ever more pronounced increase of 0.032℃/year (An et al., 2021). This change will induce growing glacier landslide cascading hazards, and acceleration and detachment of substantial debris-ice sediments that were previously stable. These hazards, known as glacier landslide cascading hazards, are characterized by a sequence of inter-linked processes: ice-melting, glacier landslides, ice-rock avalanches, and glacier debris flows (Mani et al., 2023). Such hazards are very large ($>10^6$ m^3) and can severely endanger the mountain ecosystem, infrastructures, and human settlements.

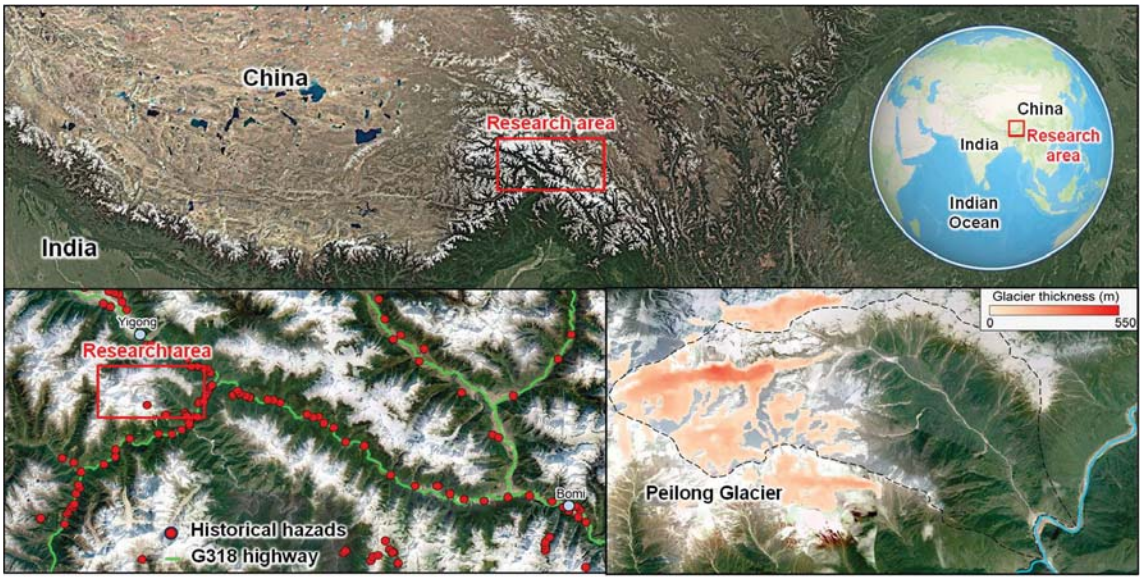

Fig. 1. Research area and historical hazards (e.g., landslide, debris flow and glacier collapses) in Southeastern Tibet.

In particular, the 1543 km long Sichuan-Tibet railway and G318 National Highway will pass through Southeastern Tibet, where frequent glacier hazards occurred. In this region, numerous fast-moving mountain valley glaciers are distributed along the valley channels, exposing the area to high risks of glacier-related hazards. These potential glaciers pose significant threats to the construction and operational safety of the engineering project. In particular, the valley sediments in the Peilong catchment present imminent risks. The potential future glacier detachments, along with the possible volume of detached masses and the scale of barrier dams at various hazard spots, remain uncertain due to the lack of investigation. For example, the glacier landslide hazard chain at Yigong in 2000 blocked the river course and caused a dam-breaking flood that travelled more than 500 km with a peak discharge of 120,000 m^3/s.

Stress testing is a broad term encompassing a range of techniques employed to evaluate the resilience of a system to withstand extreme events. Conducting stress testing provides valuable insights into how a system performs under extreme conditions, allowing for effective risk management of potential weaknesses. Taking Peilong glacier as an example, this study presents a stress testing framework to quantify likely threats caused by glacier detachments to mountain bridges. Numerical simulation analysis is conducted to forecast possible damming. Multi-scenario physical-based simulations are conducted to reveal the consequences of glacier detachments and river damming, and to investigate key influence factors.

2. Research area

Fig. 1 shows that the location of the Peilong Glacier catchment, situated near Yigong County and the G318 Highway in Southeastern Tibet. The catchment covers 88.60 km^2 with its elevations ranging from 2000 to 5700 m above sea level (a.s.l.). Frequent glacier-related geohazards occurred at the upfront of the Peilong glacier including several massive glacier mass flows (Wang et al., 2021). Over nearly six decades of meteorological observations, a warming trend of approximately 0.25-0.35℃ per decade has been identified in this region. The average thickness and volume of sediments in the valley floor are approximately 300 m and 577×10^6 m^3, respectively (Fig. 1). These values were calculated using a glacier flow model based on the shallow-ice approximation (Millan et al., 2022).

3. Field investigation

We conducted field investigations to collect 3D topographic data, hydrological information and geo-material properties (Fig. 2). An unmanned aerial vehicle (UAV), DJI Mavic 2, was used to obtain the geometry and deposit deposition at the outlet of the catchmen. In-situ geo-material samples were collected. Sand cone tests using China ISO standard sand were conducted to obtain the density of geo-materials. The other physical properties of in-situ samples for a physically-based simulation model were determined as shown in Table 1.

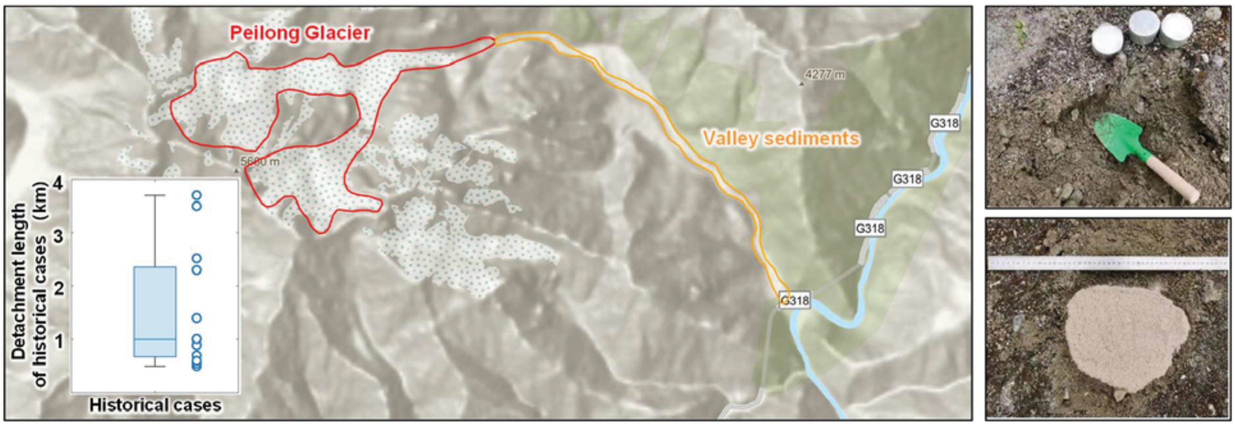

Fig. 2. Glacier thickness and field sampling in Peilong Glacier catchment.

Table 1. Simulation parameters

$\rho_s(kgm^{-1})$	d_{50} (mm)	$C_{v,channel}$	$C_{v,glacier}$	$\tau_c\ (Pa)$	$K_e\ (m^3Ns^{-1})$	C_{dep}
2700	10	0.5	0.65	50	1.5×10^{-7}	0.03

Note: ρ_s is the density of solid particle; d_{50} is particles sizes 50% finer; $C_{v,cha}$ and $C_{v,glacier}$ are the volumetric ratio of solid of deposits along valley channel and detached glacier valley geo-materials, respectively; τ_c is critical shearing stress; K_e and C_{dep} are erosion and deposition coefficients, respectively.

4. Simulation framework and model set-up

4.1. *Simulation model*

This study takes a cell-based integration simulation program, i.e., Erosion–Deposition Debris Flow Analysis program (EDDA) (Chen and Zhang, 2015; Shen et al., 2020), to conduct multi-scenario analysis on glacier cascading hazards in Peilong Catchment. The governing equations of mass flow dynamics are shown below:

$$\frac{\partial h}{\partial t}+\frac{\partial(hv_x)}{\partial x}+\frac{\partial(hv_y)}{\partial y}=i\left[C_{v*}+(1-C_{v*})s_b\right]+A\left[C_{vA}+(1-C_{vA})s_A\right] \tag{1}$$

$$\frac{\partial(C_v h)}{\partial t}+\frac{\partial(C_v h v_x)}{\partial x}+\frac{\partial(C_v h v_y)}{\partial y}=iC_{v*}+AC_{vA} \tag{2}$$

$$\frac{\partial v_x}{\partial t}+v_x\frac{\partial v_x}{\partial x}=g\left[-\mathrm{sgn}(v_x)S_{fx}-\frac{\partial(z_b+h)}{\partial x}\right]-v_x\frac{i\left[C_{v*}+(1-C_{v*})s_b\right]+A\left[C_{vA}+(1-C_{vA})s_A\right]}{h} \tag{3}$$

$$\frac{\partial v_y}{\partial t}+v_y\frac{\partial v_y}{\partial y}=g\left[-\mathrm{sgn}(v_y)S_{fy}-\frac{\partial(z_b+h)}{\partial y}\right]-v_y\frac{i\left[C_{v*}+(1-C_{v*})s_b\right]+A\left[C_{vA}+(1-C_{vA})s_A\right]}{h} \tag{4}$$

where the flow velocities along the x- and y-directions are represented as v_x and v_y, respectively; t and h are time and the flow depth; represents the erosion or deposition rate; z_b indicates the channel bed elevation; A the entrainment rate; g=9.81m/s^2 is the gravitational acceleration; C_V is the volumetric sediment concentration of the mass flow; C_{VA} and C_{V*} are the volume fractions of solids in the entrained materials and erodible channel bed, respectively; s_A and s_b are the saturation degrees in the entrained materials and the erodible bed, respectively; The $sgn(\cdot)$ represents a sgn function satisfying $sgn(x)=1(x>0)$, $sgn(x)=0(x=0)$ and $sgn(x)= -1(x<0)$, reflecting that the direction of resistance is opposite to the flow direction; S_{fx} and S_{fy} indicate the flow resistance slopes in the x- and y-directions. The viscosity and rheological properties of the flowing mass are characterized by the quadratic model. More details are presented in Chen and Zhang, (2015) and Shen et al., (2020).

4.2. *Model set-up*

Considering that the length of the valley debris glacier significantly exceeds its width, the detached length of the glacier is used to quantify the multi-scenario glacier detachments. Fig. 2 shows that the detached lengths of historical glacier detachments worldwide range from 0.4 to 3.6 km, with a median of 1 km and an average of 1.5 km. We consider four scenarios, including 1-km, 2-km, and 3-km detached lengths (L_d), as well as the detachment of all sediments (Table 2). Fig. 2 shows the set-up of simulation model where orange and red curves represent the eroded channel material and valley glacier sediment, respectively. L_d represents the detached length of valley glacier, and the released source geo-materials are different for different L_d values in the multi-scenario analysis. The thickness and volume of glacier sediments are derived using remote sensing developed by Millan et al., (2022).

Table 2. Multi-scenario simulation design

Scenario	Detach length (km)	Detach sediment volume (m^3)
1	1	9.64×10^6
2	2	33.95×10^6
3	3	119.57×10^6
4	All sediments	577.03×10^6

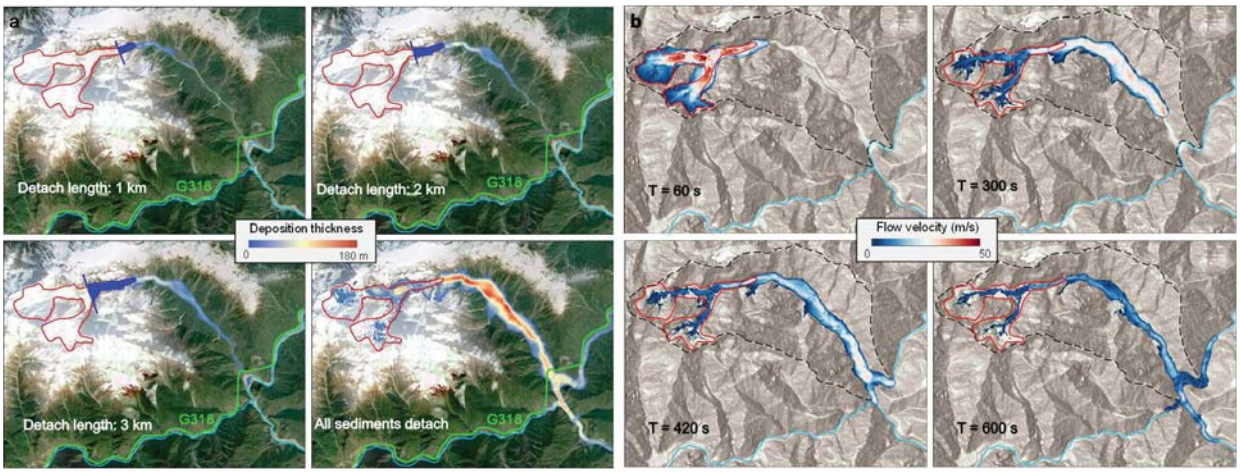

Fig. 3. Multi-scenario simulation (a) deposition thickness and (b) simulated flow velocity.

5. Simulation results

Multi-scenario simulation results are presented in Fig. 3. The modelling results are validated based on field deposition observations. Fig. 3b shows the flow velocity when all glacial sediments detached from the valley channel. The front velocity of the mass flow is about 40 m/s when sediment detached from a relatively steep slope. As the flowing mass enters the valley channel, its velocity gradually decreases to 25 m/s. The geo-material that flows into the river continues to travel along the river course at a speed of 5 m/s, ultimately forming a barrier dam (Fig. 3a). In the multi-scenario simulations, the entrainment volumes remain below 100 million m³. The primary reason for the relatively low velocities of the mass flows is the gentle slope of the valley channel.

Table 3. Multi-scenario simulation results

Scenario	Runout distance (km)	River deposition thickness (m)	River deposition volume (m^3)
1	12.3	0	0
2	15.5	5	6900
3	16.6	13	0.37×10^6
4	26.3	108	269×10^6

Fig. 3a and Table 3 show the simulated final deposition thickness. The simulation results demonstrate the consequences of hazards occurring on the same scale as historical ones (Fig. 2). Results show that a small-scale detachment hazard ($L_d = 1$ km) results in no river deposits. Almost all detached mass remains in the valley channel. Similarly, when the detached lengths are 2 km and 3 km, there is no threat near the outlet of the Peilong gulley. A glacier detachment with 3-km detach length could lead to a deposition depth ranging from several meters to nearly 10 meters at the outlet of the valley. This result confirms why the old G318 Bridge was repeatedly washed away in history (Fig. 4). By contrast, a massive detachment of $L_d > 3$ km causes large-scale river damming. The new G318 bridge at the outlet of the valley, although able to withstand hazards when $L_d \leq 3$ km, our analysis indicates that the new G318 bridge would still be affected by glacier hazards in the extreme scenario (Fig. 4).

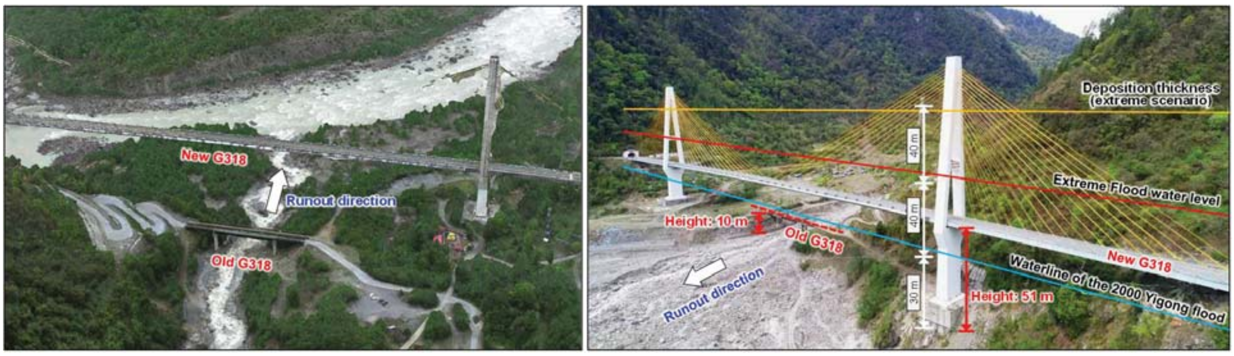

Fig.4. Simulated deposition thickness at the outlet of Peilong Gully.

6. Conclusions

Rapid-flowing valley glaciers pose significant concerns regarding their potential to infrastructures. Taking the Peilong Glacier as a case study, this research provides a quantitative framework to assess the threats arising from the detachment of large valley debris glaciers. This framework is developed through a combination of in-situ investigations, remote sensing, and a physical-based simulation analysis. Taking the Peilong Glacier as an example, this study investigates threats caused by glacier detachments. The results reveal that relatively small-scale sediment detachment (i.e L_d = 1-2 km) has limited impacts on the river course. By contrast, a massive detachment (L_d >3 km) can cause large-scale river damming and threaten the G318 bridge at the outlet of the valley. The study offers valuable insights into the consequences of glacier detachments, facilitating a more comprehensive assessment of consequences and their implications for infrastructure construction in the Himalayan region.

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