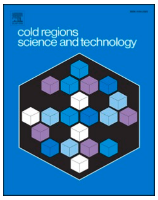
Cold Regions Science and Technology 228 (2024) 104315

Contents lists available at ScienceDirect

Cold Regions Science and Technology

journal homepage: www.elsevier.com/locate/coldregions



The breaching mechanism of moraine dams with buried ice: A Review

Yunying Mou [a,b], Huayong Chen [a,b,*], Tao Wang [a,b], Hechun Ruan [a,b], Xiao Li [a,b], Yunhan Yu [a,b], Yichen Zhou [a,b], Haoyang Meng [c]

[a] State Key Laboratory of Mountain Hazards and Engineering Resilience, Institute of Mountain Hazards and Environment, Chinese Academy of Sciences, Chengdu, 610299, Sichuan, China

[b] University of Chinese Academy of Sciences, Beijing, 101408, China

[c] School of Earth science and Engineering, Hebei University of Engineering, Handan, 056038, Hebei, China

ARTICLE INFO

Keywords:
Moraine dams
Buried ice
Breaching mechanisms
Breaching models
Phase change of ice

ABSTRACT

Moraine dams formed by the accumulation of loose glacial materials, typically exhibit poor consolidation properties and complex structure characteristics (especially with buried ice) which make them susceptible to failure. Influenced by global climate warming, the risk of moraine dam breaching is further exacerbated. This article summarizes the breaching modes, breaching mechanisms, and breaching numerical models of moraine dams, and analyzes several deficiencies: 1) The accuracy of long-term monitoring of moraine dams is relatively low, the dynamic monitoring for individual dam and its environment is insufficient; 2) Systematic research on how buried ice affects dam breaching is lacking, and a significant gap remains in the study of combined multiple breaching modes of moraine dams; 3) The predictive results of moraine dam breaching parameter models are quite unreliable, and physically-based mathematical models have not consider the influence of buried ice. Based on this, the article puts forward the following recommendations: 1) Enhance the understanding of climate change impacts on moraine dam breaching through long-term dynamic monitoring of moraine dams; 2) Focus on the erosion characteristics of materials, study the breaching process and mechanisms of ice-rich moraine dams under various breaching modes; 3) Reveal the response mechanism of moraine dams to temperature variations using numerical simulation techniques that couple thermal-stress modules and consider the phase change of ice, further revealing the breaching mechanisms of moraine dams containing buried ice.

1. Introduction

Moraine dams are natural barriers located at the terminus or sides of glaciers, which formed by the accumulation of glacial erosion and depositional activities (Yao et al., 2018). During the retreat of glacier, the particulate debris generated by glacial erosion separate from the ice mass accumulating at the forefront of the ice tongue and forming a moraine dam (Hewitt and Liu, 2013). The meltwater from upstream glacier gathers behind the dam, forming glacial moraine lake. Moraine dams are primarily distributed in the mid and low latitude mountainous glacial regions, such as the Cordillera mountain range in South America and the Tibetan Plateau in Asia (Agarwal et al., 2023; Ding et al., 2021; Veh et al., 2020; Xu et al., 1989; Zhang et al., 2015), directly connected to glaciers or situated at a distance. They typically consist of poorly sorted glacial till particles (Iribarren et al., 2014; Worni et al., 2012), and some of them contain buried ice (dead ice) (Fu et al., 2021; Worni et al., 2012). The buried ice usually exists within the dam in layers or as ice lenses (Xu et al., 1989), and its changes in quantity and form of buried ice increase complexities to soil strength (Eichel et al., 2018). In sub-zero temperatures, the dam remains in a frozen state, with its strength composed of both ice and soil particles, and the dam and its surrounding environment are in a stable condition. However, with ambient temperatures rising, the solid ice melts, leading to alterations in strength and internal moisture content, potentially compromising dam stability and increasing the risk of moraine dam breaching (li et al., 2011; Richardson and Reynolds, 2000; Wei et al., 2019; Zhao et al., 2022).

Over the past several decades, rising global temperatures have led to glacier retreat and a significant expansion of glacial lake (Agarwal et al., 2023; Hugonnet et al., 2021; Khadka et al., 2024; Shugar et al., 2020). In regions like the Himalayas, the Hindu Kush-Karakoram range, the Andes, and the European Alps, glacial lake outburst flood events have

---

[*] Corresponding author at: State Key Laboratory of Mountain Hazards and Engineering Resilience, Institute of Mountain Hazards and Environment, Chinese Academy of Sciences, Chengdu, 610299, Sichuan, China.

E-mail address: hychenimde2011@163.com (H. Chen).

https://doi.org/10.1016/j.coldregions.2024.104315
Received 23 May 2024; Received in revised form 27 July 2024; Accepted 5 September 2024
Available online 6 September 2024
0165-232X/© 2024 Published by Elsevier B.V.

become increasingly frequent (Fig. 1) (Wang and Zhang, 2013; Worni et al., 2012; Yao et al., 2012; Yao et al., 2014), posing a considerable threat to local lives and property. Further climate change is anticipated to expose millions worldwide to risks from glacial moraine dam failures (Taylor et al., 2023), which could severely constrain global economic development. Historical moraine dam failures have inflicted substantial socio-economic losses. In recent years, the frequency of moraine dam failures has risen in tandem with global temperature increases (Ding et al., 2021; Taylor et al., 2023). Considering the potential impacts of future climatic conditions, the instability of regional environments will elevate the significance of melting buried ice as a trigger for moraine dam breaching. Therefore, this study focuses on moraine dams containing buried ice, reviewing the current research both domestically and internationally across three main aspects: the breaching modes, the mechanisms underlying their failures, and breaching numerical models of moraine dams. Furthermore, recommendations for future research on moraine dam failures are provided.

2. The breaching modes of moraine dams

The breaching modes of moraine dams refer to failure form exhibited when dams breach (Clague and Evans, 2000). Similar to landslide dams, the breaching modes of moraine dams are characterized by overtopping failure, piping failure, slope instability failure, and combined multi-modal failures(Table 1 and Fig. 2) (Liu and Zhou, 2018). Liu et al. (2008) analyzed the outburst events of moraine dams in the Tibet and highlighted overtopping failure and piping failure, with the former being the primary mode. Currently, extensive researches have been conducted on the overtopping failure mode (Ruan et al., 2024; Ruan et al., 2021b). However, there is relatively less study on the piping failure triggered by the melting of buried ice and the multiple failure modes induced by various factors' coupling. Additionally, less attention is given to the temperature within dam and differences in materials under low and ambient temperature.

Table 1
The breaching modes of moraine dams, modified from (Liu et al., 2019).

Breaching modes	Triggers (Fig. 2a)	General breaching characteristics
Surge overtopping	Ice/snow/rock avalanche and landslide	Sudden destruction
Overflow overtopping	Glacier melting/heavy rainfall/ upstream flooding	Sudden or gradual destruction
Piping	Buried ice melting	Gradual destruction
Slope instability	Heavy rainfall/earthquakes	Gradual destruction
Multi-mode failure	Comprehensive action	Sudden or gradual destruction

2.1. Overtopping failure mode

The overtopping failure refers to the breaching mode where the water behind the dam overflows the crest and erodes the dam structure, leading to the dam's failure (Fig. 2b). Considering the characteristic of the overtopping flow, it can be categorized into two types: surge overtopping and overflow overtopping (Liu et al., 2019). Surge overtopping is generally caused by the collapse of glaciers or the sliding of lateral moraines (Fig. 3). The surges carry a substantial amount of energy in the form of waves, impacting the dam structure and resulting in instability and failure (Jiang et al., 2004a). On the one hand, surge waves deform the dam structure and erode the slope due to high-speed flow. When surge waves spill over the dam crest, it scours the crest and downstream slope, leading to overtopping failure and “slope” retrogressive erosion (Su et al., 2021). On the other hand, surge waves cause violent fluctuations in the water level in front of the dam, leading cyclical changes in pore water pressure within the dam, which reduces the dam's erosion resistance to some extent (Yang et al., 2021; Zhou et al., 2017). The scale of surge waves determine the amount of energy they carry, directly affecting the formation of the initial breach and the erosion rate (Lu et al., 2022). Typically, surge waves triggered by the source entering the lake are usually the largest in volume for the first wave, with subsequent waves gradually decreasing in volume. The initial wave that strikes the dam is the most likely to cause an instantaneous breach, leading to

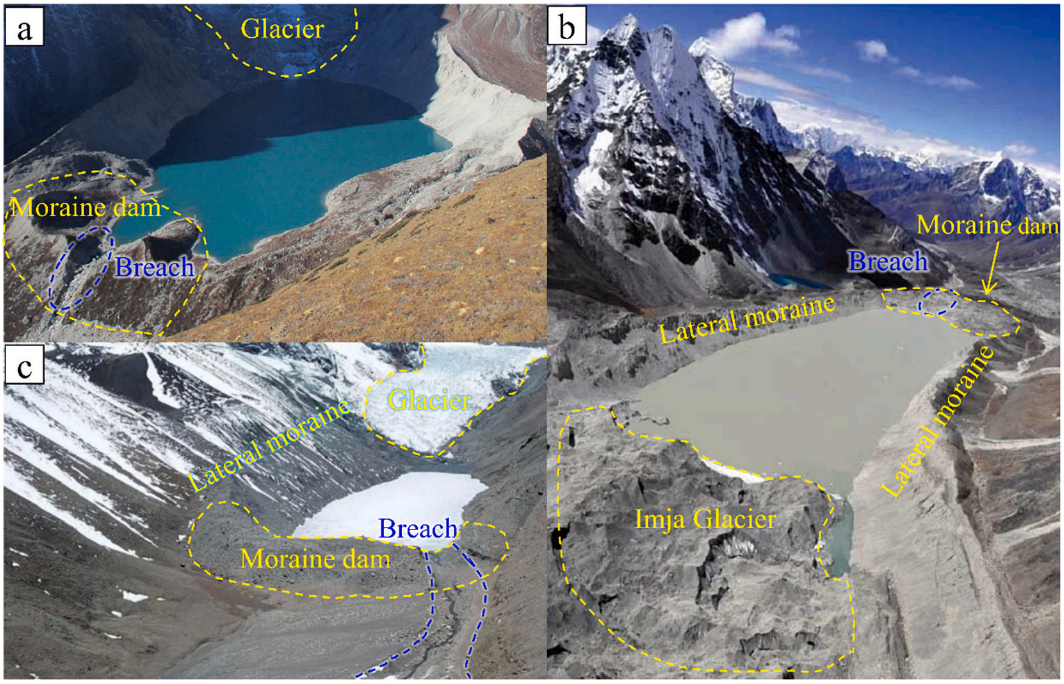


Fig. 1. Cases of moraine dams breaching. (a) The Jialongco moraine dam, located in Nyalam country, Tibet. It breached in 2002. (b) The Imja Tsho lake, located in the eastern Nepal Himalayas, experienced a breaching on August 4th, 1985. (c) The Rejieco moraine dam, characterized by a glacial lake directly connected to the glacier and tensional crevasses on the glacier surface, breached in 1992. Pictures modified from Allen et al. (2022), Kafle (2018),and Liu et al. (2019), respectively.

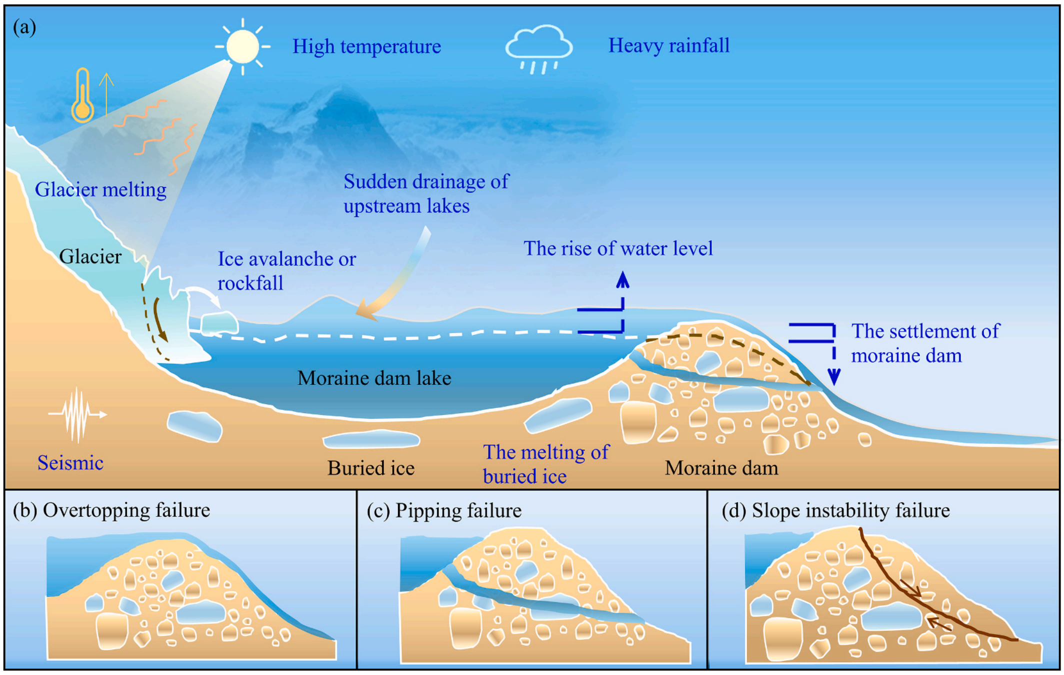


Fig. 2. Breaching triggers and modes of moraine dams.

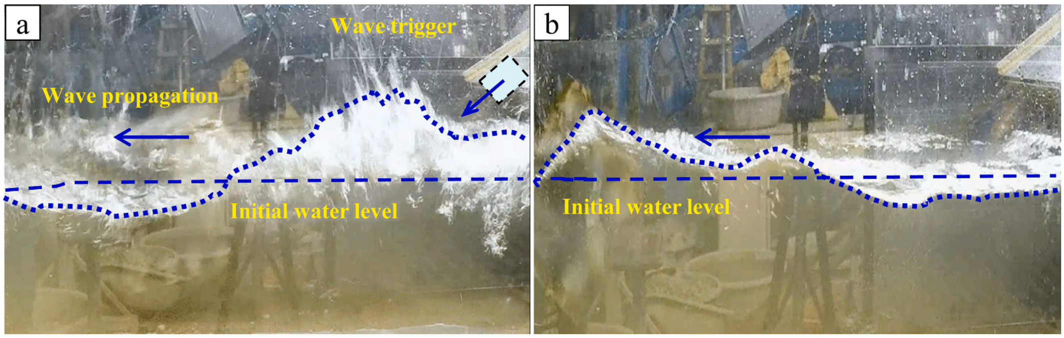


Fig. 3. Wave trigger slides into the lake and causes surge waves.

catastrophic destruction (Wolper et al., 2021; Xue et al., 2019).

Overflow overtopping primarily occurs due to intense glacial melting, heavy upstream rainfall, floods, and the inflow of debris into the lake, resulting in a rapid rise in water levels. During this period, the velocity and flow rate at the regular overflow outlet experience a significant surge. The flow velocity reflects the hydrodynamic conditions of the fluid. The greater the velocity, the stronger the erosive action on the dam, and the more intense the turbulent action and sediment transport capacity(Dou, 1999; Wang et al., 2022). Consequently, this process is prone to intense downward cutting erosion, potentially resulting in partial or total dam failure. Additionally, under high-temperature conditions, the melting of buried ice within the dam can result in dam settlement or the formation of cracks, providing favorable conditions for the breach. Currently, field studies have observed the settlement of dam crests in moraine dams (Sawagaki et al., 2012) and have a qualitatively understood the correlation between the rate of dam crest settlement and the amount of ice within the dam (Tonkin et al., 2016). However, the interaction among environmental temperature, material heat transfer mechanisms, and ice melting remains unclear and necessitates further study.

2.2. Piping failure mode

Piping refers to fine particles loss through the pores formed by the skeleton of coarse particles under the drive of seepage flow, and eventually forming a permeable channel within the dam body (Liao et al., 2023). Piping failure is a common mode of destruction for glacial moraine dams (Fig. 2c), which initially manifests as the stable seepage flow. Whether seepage develops into piping and causes damage is influenced by hydrodynamic conditions, mechanical factors, and the inherent properties of the soil materials (Yin et al., 2021). When these three factors reach a state of equilibrium, with minimal movement of fine particles without affecting the structural framework, and stable hydrodynamic and mechanical conditions, the dam can maintain stable seepage flow (Luo et al., 2011). If any of these factors change, the balance may be disrupted. Currently, scholars have conducted extensive research on the critical conditions for the formation of seepage in dam bodies under ambient temperature environments, as well as the conventional factors that influence seepage (Shi et al., 2014). However, less consideration has been given to situations where materials contain ice and the coupled effects of dam seepage and temperature fields. In permafrost research, Zhang et al. (2016) pointed out that seepage can deepen the melting depth and deformation of permafrost. Furthermore, under seepage, the melting process of permafrost accompanies changes in the temperature and fluid velocity fields (Patton et al., 2021; Shi et al., 2017). Permafrost melting further promotes the development of seepage channels until the seepage strain accumulates to a critical state (Fig. 4). For dam bodies containing buried ice, under the coupled action of water, heat, and force multi-field, there will be a mutual promotion between seepage and the melting of buried ice. The water seepage action is further enhanced, weakening the dam structure and stability until reaching critical failure conditions.

2.3. *Slope instability failure mode*

The upstream and downstream slopes of a hazardous moraine dams are relatively steep, and when subjected to heavy rainfall, earthquakes, and surge waves, they are prone to instability and causing damage to the dam structure (Fig. 2d). At this time, the dam is susceptible to failure under static/dynamic water pressure. Additionally, the melting of buried ice leads to deformation of the dam body and the formation of cracks, accelerating the entry of water into the interior of the dam, further deteriorating the slope strength and reducing the slope's ability. Hubbard et al. (2005) concluded that climate warming is the primary cause of reduced stability in moraine dams through the measurement and simulation of the dam's shear strength parameters. Moreover, due to the saturation of local areas of the dam by meltwater from buried ice, the dam slopes are prone to shallow surface sliding, which also affects the overall stability of the dam structure.

2.4. *Multi-modal failure*

The breaching of moraine dams is influenced by multiple factors and results from interactions among climatic condition, topography, and the dam's characteristics. The breaching mechanisms are complex and often involving a combination of modes with one mode predominating (Liu and Zhou, 2018). Moraine dams typically exhibit conditions conducive to significant breach disasters prior to failure (Sun et al., 2014). These conditions include the long-term stable expansion of glacial lakes, the development of crevasses in the ice tongue with steep slopes, the dam's large slope gradient coupled with the presence of buried ice, and so on, until a relatively routine disturbance triggers the breaching of the moraine dam (Clague and Evans, 2000). Furthermore, as one of the factors influencing dam breaching, climatic conditions affect both the moraine dam and its surrounding environment. For example, increasing temperatures can destabilize both the ice tongue and the dam, resulting in breaching and destruction due to surge overtopping and piping. The Guangxieco moraine dam, the Ceringmaco moraine dam, and the Yindapuco moraine dam have all experienced the combined effects of ice avalanches and buried ice melts, resulting in both surge overtopping and piping failure modes (Chang et al., 2017; Liu et al., 2019). However, research on the coupled multi-mode failure of moraine dams is still in its early stages. Hence, there is a need for more systematic research to elucidate the complex mechanisms of breaching in glacial moraine dams.

3. The breaching mechanism of moraine dams

Moraine dam breaching is a complex phenomenon involving the interaction between water and soil, as well as between continuous and discontinuous media. To comprehensively understand the mechanisms and influencing factors of moraine dam breaching, scholars have conducted extensive field monitoring and model experimental studies. Additionally, relatively mature research findings exist on the breaching of landslide dams, which can provide guidance for investigating the breaching mechanisms of moraine dam. This section, based on a summary of research related to moraine and landslide dams, identifies potential avenues for future research on moraine dams by leveraging existing knowledge.

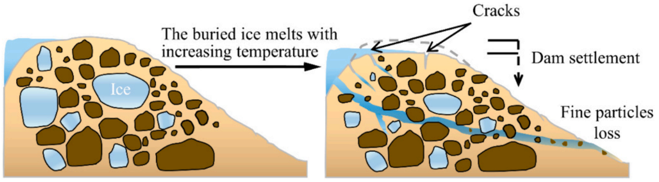


Fig. 4. The impact of buried ice melting on moraine dams.

3.1. *In situ detection and monitoring of moraine dams*

In situ detection can contribute to understanding physical phenomena and processes. In the 1970s, countries such as Nepal, China, and Canada conducted numerous field scientific expeditions to moraine dams in various regions(Clague and Evans, 2000; Liu et al., 2016; Xu et al., 1989). These expeditions generated comprehensive summaries on the formation, development, breaching morphology, and characteristics of moraine dams, providing valuable insights into the breaching mechanisms of moraine dams. In recent years, the distribution of multi-year buried ice within moraine dams has become crucial for assessing the risk of dam breaching due to rising temperature (Eichel et al., 2018). Modern geophysical probing technologies, such as two-dimensional electrical resistivity tomography (ERT) and two-dimensional seismic refraction tomography (SRT), exploit differences in the resistivity values and refractive properties to discern the material composition and distribution of the surveyed cross-section (Loke, 2001). These techniques are currently widely used for detection of subsurface material composition and structure. Dahal et al. (2018) used the ERT method to detect the spatial distribution of buried ice within the Imja moraine dam, revealing its heterogeneous characteristics (Fig. 5). Hauck et al. (2008) combined ERT and SRT technologies to quantify the content of water, ice, air, and rock debris in loose materials. However, limitations in interpretation techniques, necessitate further field validation to enhance the accuracy of the result. Furthermore, the variation of internal ice within the dam is an indispensable factor in the breaching process. Some scholars reflect the changes in the internal buried ice by the overall settlement deformation of the dam (Tonkin et al., 2016), or predict the melting situation of the buried ice within the dam by monitoring and simulating the temperature field(Zhang et al., 2024). However, there are currently no published results regarding equipment for detecting changes in buried ice within the dam.

The transition of a moraine dam from a stable to an unstable state, culminating in breaching, is a process of risk accumulation. A breach occurs when the accumulated risk surpasses the safety threshold of the moraine dam. Long-term monitoring of the moraine dam and its environmental system is instrumental in elucidating the mechanisms of moraine dam breaching and enhancing understanding of this phenomenon. Fujita et al. (2009) elucidated changes in lake area, water depth, and the height of the Imja moraine dam through on-site investigations and interpretation of multi-temporal ASTER imagery. Sawagaki et al. (2012) monitored glacier movement, ground subsidence, and changes in slope gradient using multi-temporal remote sensing images. Additionally, numerous scholars have conducted research on the regional changes in glacial lakes and glacier areas using multi-source remote sensing interpretation (Liu et al., 2020; Wang et al., 2015; Zhang et al., 2015). In summary, the rapid expansion of glacial lakes and the weakening stability of moraine dams pose an increased risk of dam breaches (Bajracharya and Mool, 2009). Moreover, changes in the physical conditions within the dam can profoundly affect its stability. Wang et al. (2023a) and Wang et al. (2018) conducted long-term monitoring of soil temperature, moisture, and heat flux at different depths within the Longbasaba Moraine Dam in the Himalayas (Fig. 6). They analyzed the thermomechanical and hydrodynamic effects on the stability of the moraine dam and pointed out that the annual residual heat will lead to further deterioration of permafrost, gradually reducing the stability of

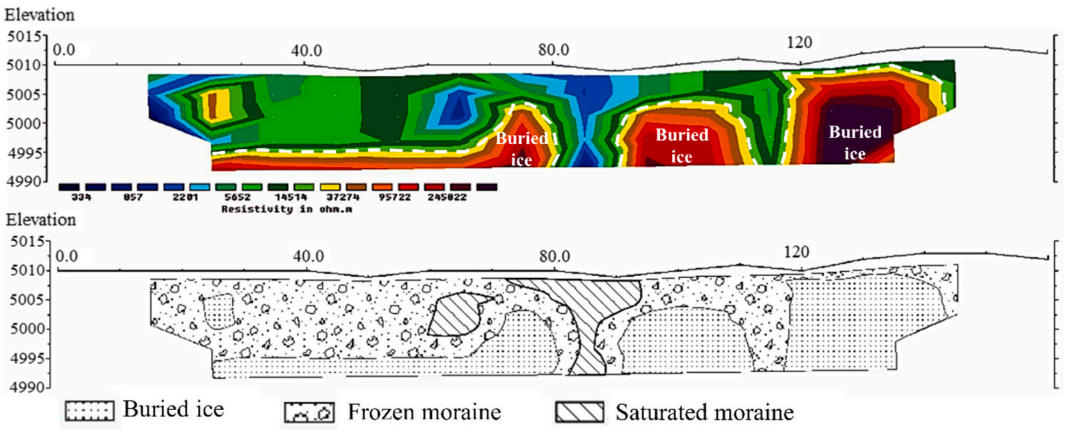


Fig. 5. The ERT conducted at the moraine dam of the Imja Glacier in eastern Nepal confirmed the existence and spatial distribution pattern of buried ice. The electrical resistivity's values of subsurface materials are classified as saturated moraine (<5000 Ωm), frozen moraine (5000 Ωm to 20,000 Ωm) and buried ice (>20,000 Ωm). The upper figure shows the distribution of resistivity values along a profile of the moraine dam; the lower figure presents the geological structure profile inferred from the resistivity values. Figure is modified from Dahal et al. (2018).

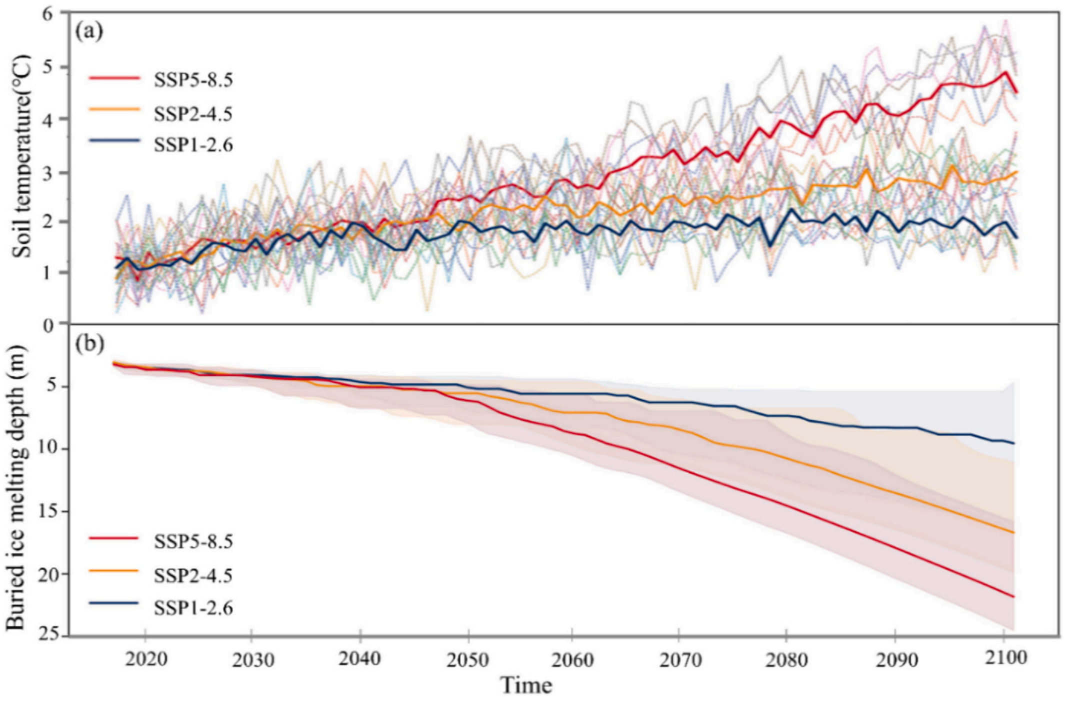


Fig. 6. (a) Annual mean soil temperature at a depth of 0.1 m inside the dam under future scenarios (SSP1–2.6, SSP2–4.5, SSP5–8.5). Solid lines indicate the mean temperature from all climate models. Dashed lines indicate soil temperatures from individual models. (b) Maximum depths of buried ice melting under future scenarios. Solid lines indicate the mean depth for each scenario. Shadings indicate the ranges from the different climate models. Figure is modified from Wang et al. (2023a).

the moraine dam.

In summary, the fundamental characteristics and changes of moraine dams have been synthesized through in-situ detection and monitoring. This work has provided a novel perspective for understanding the breaching mechanisms of moraine dams.Nonetheless, different moraine dams may exhibit variations in their breaching processes (Peng et al., 2023). Hence, more comprehensive and detailed on-site investigations and detection of moraine dams should be conducted. Furthermore, from a technical perspective, point-source and two-dimensional geophysical exploration techniques for internal structure detection have reached relatively mature stage. However, the detection of changes within the dam, particularly the variation of buried ice, still warrants enhanced investigation. Remote sensing technology offers unique advantages in monitoring glacial moraine dam breaching disasters (Liao, 2021). However, the accuracy of remote sensing data is greatly influenced by climatic conditions, and different periods of imagery and interpretation methods can affect the conclusions. At the same time, it is necessary to strengthen the integration of remote sensing methods with field observations to achieve real-time and continuous monitoring of moraine dams.

3.2. *Experimental study on the breaching mechanism of moraine dams*

Model experiments serve as a primary research tool for acquiring data that is challenging to obtain under natural conditions, enabling the study of physical processes (Ruan et al., 2023; Ruan et al., 2021a; Zhou et al., 2022a). Common methods for dam breaching experiments are flume tests and centrifuge tests. Flume experiments are simple and easy to conduct. Flume experiments have enabled scholars to investigate the effects of the dam's geometric shape, material composition, particle size distribution, reservoir capacity, and upstream inflow on the dam breaching process (Peng et al., 2020; Zhu et al., 2020). In general, smaller reservoir capacities, dam height-to-width ratios, and dam slopes result in less potential energy in the water body behind the dam, leading to weaker hydrodynamic conditions. Consequently, the breaching process tends to be more gradual, and the duration of breaching is prolonged (Cai et al., 2023; Yang et al., 2021; Zhou et al., 2021). The better the particle size distribution of the dam body and the more compact the material, the stronger the dam's resistance to erosion. Under equivalent hydraulic conditions, the peak breaching flow occurs later, and the peak flow rate is reduced (Shi et al., 2022; Yang et al., 2023; Zhao et al., 2018). Centrifuge tests address the limitation of flume model experiments in satisfying gravity similarity conditions, providing a reliable method for model experiment. Zhao et al. (2016) derived a calculation method for the flow of a rectangular thin-walled on dam under centrifugal fields, and further verified the breaching mechanism based on the breaching flow rate and the breach development process curve obtained from the experiments. Zhang et al. (2023) utilized the “space-time magnification” effect of the supergravity field generated by the high-speed rotation of the centrifuge test system to study the impact of dam height, downstream slope ratio, and dam material gradation on the overtopping breaching process of moraine dams. Additionally, the shaking table test system has been developed to study the breaching mechanisms of dams under different dynamic conditions (Shi et al., 2015). Novel testing systems，such as thermo-mechanical coupled test system, are also gradually being applied to study the performance of geotechnical materials and slope stability under freeze-thaw cycles (Wang et al., 2023b).

Additionally, certain scholars have investigated more nuanced aspects of the breaching process, including particle initiation and the evolution of the breach in longitudinal and transverse directions. Regarding particle initiation, the critical flow velocity or critical shear force is commonly employed to determine the initiation of particles (Dou, 1999; Qian and Wan, 1983; Zhang, 2012). However, obtaining these parameters in experiments is challenging. Yuan et al. (2019) determined the critical runoff depth for the initial initiation of non-cohesive sediment based on experiments. This parameter is easily measurable in experiments and has a relatively accurate and straightforward expression. Concerning the evolution of the breach, the rate of downstream erosion is primarily controlled by the difference between the shear stress of the water flow and the erosion resistance (Zhou et al., 2022b). The lateral expansion of the breach is predominantly governed by slope collapse, and the geotechnical engineering profession has widely adopted the analysis of slope failure through circular arc or planar sliding surfaces (Chen et al., 2015). As for the longitudinal evolution of the breach, Zhou et al. (2019) investigated the pattern of breach evolution in the longitudinal profile of a moraine dam under the influence of overtopping flow using flume experiments. They proposed a novel longitudinal evolution model for breaches, which considers the variation of soil erosion rate during the breaching process, making it more aligned with real conditions.

The above findings are mainly related to the research achievements of landslide dams, which offer some insights for the study of moraine dam breaching. However, moraine dams typically possess poor consolidation properties, with dam particles often displaying macroscopic characteristics of being unsorted, non-oriented, and poorly rounded (Lv et al., 2011). Additionally, moraine dams have a small width-to-height ratio, contain less cohesive material, and may include buried ice within them (Chen et al., 2022b). Consequently, there are distinct differences in breaching mechanisms between moraine dams and landslide dams, especially when buried ice is present within a moraine dam: previous research has shown that the quantity of ice contained within the dam can significantly affect the breaching flow (Chen et al., 2022a). The morphology and content of buried ice will alter the physical and mechanical properties of the dam materials (Li et al., 2022). In case where the volume of buried ice is relatively small, its lower density compared to soil particles facilitates its initiation under equivalent hydraulic conditions. Additionally, the initiation of ice can destabilize of the surrounding soil, accelerating the erosion of the dam body by water flow (Fig. 7a). If the volume of buried ice is large,under the continuous scouring action of water flow, buried ice may undergo local fracturing, and the accumulated fractured ice at the breach can affect the flow rate process (Worni et al., 2012) (Fig. 7b). Furthermore, temperature, by influencing the state of ice within the dam, can alter the dam's structure and internal physical environment. These changes make the dam more susceptible to piping failure. Therefore, temperature is also a crucial variable that cannot be overlooked in the experimental process of moraine dam breaching.

Presently, scholars have reached a consensus that the existence and melting of buried ice will impact the breaching of moraine dams. However, there have been no experiments studying the aforementioned scenarios. Firstly, moraine dams are often located in high-altitude uninhabited areas, where equipment transportation and field investigations are difficult to carry out. Thus, the reliable data that can be obtained to guide physical model experiments are limited (Zhang et al., 2024). Secondly, physical experiments generally difficult to simulate the real physical environment and state in which the moraine dam is situated, and can only simplify the other conditions by focusing on key issues, which causes the model tests to have differences from the actual situation. Lastly, in terms of experimental observation and measurement, there is a lack of observation technology that can quickly obtain the state of internal ice and the internal structure of the dam without destroying the dam.

4. The breaching numerical model of moraine dams

4.1. Breaching parameter models of moraine dams

Empirical models represent the simplest category of predictive models, comprising regression relationships derived from a series of data. Table 2 summarizes the commonly used empirical models for predicting breaching parameters. As shown in the table, the empirical models used in the early stages were structurally simple, often relying on predictions based on the dam's height, the volume of the moraine lake, or a combination of these two parameters (The volume of the lake can be derived from empirical equations or obtained through basin exploration (Westoby et al., 2014)). Although Such models can be quickly used for basic disaster assessments, their accuracy is constrained. In this paper, empirical models were employed to verify the breaching flow of four moraine dams that had already breached, and the resulting were quite dispersed (Table 2, Fig. 8).

This is due to the fact that, besides the parameters considered in the models, the dam's structure, composition, material properties, and the inducing factors of the breach all influence the breaching process (Westoby et al., 2014). There has been more research on particle composition and material properties in landslide dams, and detailed in Section 3.2. However, the parameterization of the dam structure is a key issue that needs to be resolved for both landslide dams and moraine dams. Additionally, for moraine dams, the amount of buried ice, the melting state of the buried ice, and the mode of breach all affect the magnitude of the peak flow. Studies have shown that the amount of ice contained in the dam significantly impact on the breaching. Chen et al. (2022a) concluded from simulations that as the ice content increases, the time to dam breach shortens, the peak time advances, and the peak flow increases. Moreover, the melting of ice changes the physical conditions of the dam (moisture content, temperature, heat flux, etc.) but also enlarges the pores of the dam, making it prone to seepage-induced breaching damage. Therefore, parameters such as ice content, particle

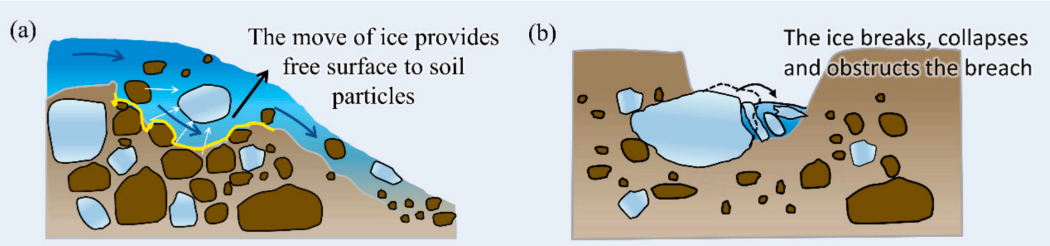


Fig. 7. The potential rule of ice in the breaching process. (a) It illustrates that the initiation of ice can provide a free surface for the nearby soil particles, which may accelerate the erosion rate of the dam. (b) It depicts that large blocks of ice may affect the breaching by breaking, collapsing, and plugging the breach during the breaching process.

Table 2
Parametric models and applications for predicting the peak discharge of moraine dam breaching.

No.	Model expression	Guangxieco	Ranzeriaco	Zhangzangboco	Jilaipuco	Reference of formula
1	$Q_p = 0.063{P_E}^{0.42}$	7518.58	5231.70	21,432.22	28,817.65	(Costa and Schuster, 1988)
2	$Q_p = 0.0048V^{0.896}$	2846.56	1313.21	15,883.68	20,773.10	(Popov, 1991)
3	$Q_p = 0.72V^{0.53}$	1871.60	1184.33	5174.37	6064.55	
4	$Q_p = 0.0007V^{1.017}$	2499.20	1038.59	17,589.75	23,853.35	(Huggel et al., 2004)
5	$Q_p = 0.0045V^{0.66}$	80.48	45.52	285.55	347.96	(Walder and O'Connor, 1997)
6	$Q_p = 0.19(H_wV)^{0.47}$	2278.48	2377.68	10,388.19	12,175.35	
7	$Q_p = 46\left(V/10^6\right)^{0.66}$	90.21	51.02	320.05	390.01	(Walder and Costa, 1996)
8	$Q_p = 0.607V^{0.295}{h_b}^{1.24}$	1668.03	4200.37	6253.61	9289.02	(Froehlich, 1995)

Notes: (1) P_E: Potential energy of a lake (J); $P_E = H_d{\cdot}V{\cdot}\gamma_W$; H_d: Height of the moraine dam (m); V: Reservoir capacity of the glacial lake before breaching (m^3); γ_W: Specific weight of water, 9800 N/m^3; Hw: Lake water level above the breach; h_b: Ultimate height of the breach. (2) The data is sourced from Dang et al. (2019), Peng et al. (2023) and Costa and Schuster (1988).

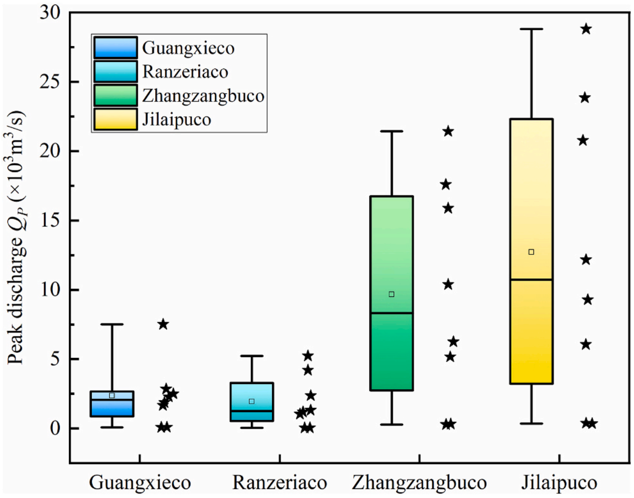


Fig. 8. The predictive results of parametric models for the peak flow of four breached moraine dams.

composition, and dam material properties should also be included in the peak flow prediction model.

For the overtopping breaching by a surge wave, there is a significant difference between a surge wave overtopping and a spillway overtopping. The overtopping by a surge wave has a strong instantaneous dynamic impact on the dam, and the surge wave may directly wash over the dam crest and erode the downstream area, thus affecting the subsequent breaching process. This differs significantly from overflow overtopping where the water continuously flows from upstream to downstream. Therefore, the parameter model for the peak flow of moraine dams should consider differences in parameter selection based on the mode of breach. Jiang et al. (2004b) proposed the critical hydraulic conditions for overtopping breaching, pointing out that the height of the surge wave will directly affect the dam breaching. Lu et al. (2022) provided a formula for calculating the surge wave height through flume experiments. Taking the parameter of surge wave height into the peak flow pre-diction model for the overtopping breaching by a surge wave in moraine dams makes the model more rational and its physical significance clearer.

4.2. *Breaching numerical models of moraine dams*

Breaching of moraine dams represents a complex water-soil coupled problem, which becomes even more intricate when buried ice is present. Numerical models, consider the movement of breaching flow, sediment transport, slope stability, and other processes, providing a better understanding of the breaching mechanisms. Numerical models are categorized into simplified and detailed mathematical models based on the degree of simplification. Currently, the simplified mathematical models applied to barrier dams include the DABA model (Chang and Zhang, 2010), DB-IWHR model (Chen et al., 2015; Wang et al., 2016), DB-NHRI model (Zhon et al., 2018; Zhong et al., 2017), and DL-BREACH model (Wu, 2013). These models simulate the breach process by setting up a coordinated evolution pattern for the breach in longitudinal and transverse directions and erosion formulas, using the broad-crested weir flow formula, and calculating iteratively under the set step size and termination conditions. They can reflect the breaching process of barrier dams to a certain extent and have the advantage of faster computation in rapidly simulating dam breaches. However, they still possess certain limitations in revealing the breaching mechanisms. For example, the relationship between the water head and dam width at the breach may not meet the conditions for using broad-crested weir flow throughout the entire process; erosion formula parameters often rely on empirical values; employing D_{50} to represent the particle size distribution characteristics of the dam ignores the wide gradation characteristics of the dam, thereby simplifying the treatment and impeding the accurate representation of flow characteristics and water-soil coupled actions during the breaching process.

Advancements in fluid dynamics, sediment dynamics, and digital simulation technology have led to the development of refined mathematical models for simulating dam breaching processes. These models, including one-dimensional, two-dimensional, and three-dimensional variants, as well as some relatively mature commercial software (HEC-RAS, BASEMENT, ANSYS-Fluent, and Flow-3D et al.), have been developed (Chen et al., 2019; Liu et al., 2022). Refined mathematical models primarily comprise three modules: a fluid dynamics module, a sediment transport module, and a breach morphology evolution module (Worni et al., 2012). These models employ the Saint-Venant equations, shallow water equations, and Navier-Stokes (N-S) equations, which are based on clear water or sediment-laden flow, to describe the dynamic characteristics of the breach flow. They use equilibrium and non-equilibrium sediment transport models to depict the erosion and sediment transport performance of the dam. Furthermore, they consider the impact of slope gravitational collapse mechanisms on the lateral expansion of the breach, enabling refined simulation of the dam breaching process. Currently, two-dimensional refined models have been widely applied in the simulation and study of moraine dam breaching (Worni et al., 2012; Zhou et al., 2019). However, the selection of governing equations for each module and the treatment of details will directly affect the accuracy of the simulation. For example, clear water dynamic models neglect the impact of sediment entering the flow on water density, viscosity, and subsequent erosion processes (Zhou et al., 2019). In contrast, sediment-laden flow models are more realistic. Additionally, existing models often assume that the sediment erosion process of the dam is uniform, giving less consideration to the spatial variation of basal shear stress, soil erosion, and bed surface erosion resistance (Chang and Zhang, 2010; Zhou et al., 2019).

Furthermore, existing research has shown that ice melting and ice form will significantly affect the shear behavior and strength characteristics of moraine soil (Li et al., 2022; Liu et al., 2024), which complicates the issue of moraine dam breaching as a multi-field coupling problem. In recent years, this issue has gradually gained the attention of researchers. Some scholars have conducted studies on the physical and mechanical properties of moraine soil under the effects of multi-field coupling. For cases where ice is relatively uniformly distributed within the soil pores, scholars often employ the continuum method to handle the thermo-mechanical coupling research of ice (Fisher et al., 2020; Zhan et al., 2018). But this type of modeling is not suitable for materials containing block ice.

For materials containing block ice, Liu et al. (2024) conducted an indoor triaxial study to investigate the response of moraine soil's strength characteristics to temperature changes and derived a relationship between the strength of moraine soil and temperature. Fu (2021) revealed that the melting of ice changes the material's internal friction angle and cohesion, thereby affecting the mechanical performance and behavior of the moraine soil. In addition, Wang et al. (2024) conducted a series of experimental-scale thermo-mechanical coupling simulations on ice-containing moraine soil under warming environment. They established a thermo-mechanical coupling framework considering the ice-water phase change and revealing the phased and nonlinear evolution characteristics of temperature, ice content, and permeability in the moraine soil system. Although relevant research is still relatively scarce, incorporating heat transfer and the thermal melting phase change of ice into existing models will fill the gap in the current modeling of moraine dam breaching and further reveal the hydro-thermal-mechanical breaching mechanism of moraine dams. The solution of moraine dam breaching is highly dependent on the solution methods and the development of computational capabilities. Commonly used discrete solution methods include the Finite Volume Method (FVM), Smoothed Particle Hydrodynamics (SPH), Discrete Element Method (DEM), and Distinct Element Analysis (DDA)(Chen et al., 2022b). Among them, the FVM is widely used in dam breaching simulation due to its stable and efficient solving capabilities, but it still struggles to handle large deformations of the grid. The SPH method uses a grid-free Lagrangian approach, which can better avoid grid distortion issues in large deformations and is suitable for numerical simulation of large-scale engineering problems, but it is computationally expensive when simulating multiphase flow calculations (Chen and Ge, 2021). The combined use of solution methods is indeed a wise idea. Marrone et al. (2016) developed a coupling method between SPH and FVM, where the introduction of SPH reduced the complexity of fluid-solid wall coupling, improving the accuracy and stability of the calculations. However, as the simulation scale increases and boundary conditions become more complex, new demands are placed on computational power. The use of large-scale parallel computing and GPU-accelerated computing technology can significantly enhance computational efficiency (Ge et al., 2013; Morikawa et al., 2020; Xiong et al., 2010). Moreover, selecting different discrete methods for material-based coupled solutions is a novel approach to simplifying calculations and improving computational efficiency.

The development of computational fluid dynamics and sediment dynamics has facilitated the emergence and application of breaching numerical models. Simplified mathematical models offer high computational efficiency, but excessive simplifications lead to limited model accuracy, hindering a comprehensive understanding of the breaching mechanisms. Refined models provide better simulation of the breaching process. Currently, two-dimensional models have become relatively mature and offer higher precision in simulations. However, existing models still struggle to handle issues such as the existence of ice within the dam body, the rupture of ice at the breach site, and the phase change of ice within the temperature field. Future research should fully consider the structural and material characteristics of moraine dams, coupling thermal-stress modules to reveal the interaction mechanisms between water, ice, and sediment during the dam breaching process. At the same time, updating algorithms and developing three-dimensional numerical models with GPU acceleration technology would enable more in-depth studies on processes and mechanisms of moraine dam breaching.

5. Conclusions

As the global temperature rising and the frequency of extreme climate events increases, the risk of moraine dams breaching will escalate further. Currently, scholars have reached a consensus on the breaching modes of moraine dams and possess a relatively comprehensive understanding of the conventional factors influencing dam breaching. In addition, scholars have recognized that the structure of moraine dams, as well as the morphology, distribution, and content of buried ice within them, will significantly impact dam breaching. However, research in these areas is still at an early stage. Therefore, based on the above review, three specific research recommendations are proposed:

(1) Improve the macroscopic understanding of moraine dam breaching through long-term monitoring of moraine dams. Moraine dam breaching results from accumulated risk surpassing safety thresholds. Long-term monitoring of moraine dams, topography, and the climate conditions aids in understanding the breaching mechanism of moraine dams from a macroscopic perspective, considering the climate, environment, and dam structure interactions. Therefore, maximizing the use of remote sensing technologies is essential to reflect the dynamic changes in moraine dams through multi-temporal remote sensing data analysis. Additionally, on-site investigations should utilize various monitoring equipment, including temperature, rainfall, heat flux, and displacement sensors, to monitor the dam and its surroundings. This comprehensive approach will reveal the dynamic mechanisms of dam change and breaching.

(2) Focus on the erosion characteristics of moraine materials, and study the breach process and mechanisms of moraine dams with buried ice. Given the unique material composition and structural characteristics of moraine dams, their breaching processes differ

from those of typical landslide dams. For instance, the resistance of ice to water erosion differs from that of soil particles; the size and location of buried ice also significantly affect the erosion and evolution. Consequently, future experimental research should consider the material properties and structural features of moraine dams, focusing on the materials' susceptibility to erosion. Additionally, it is also essential to recognize changes in dam structure with temperature and time, and to consider the combined effects of buried ice melting and erosion. Finally , the evolution of the breach and the changes in breaching flow during the breaching process of moraine dams under conditions of buried ice presence and melting will be study, the breach mechanism of moraine dams with buried ice will be revealed.

(3) Utilize numerical simulation techniques to further elucidate the response of moraine dam to temperature variations. Fluctuating ambient temperatures cause dynamic changes in the internal temperature of moraine dams, governed by heat transfer mechanisms. This significantly affects the ice form and trigger both macroscopic and microscopic changes in moraine dams. The macroscopic responses, such as dam settlement and local collapse, are relatively easy observed. However, the microscopic responses are less visible. Numerical simulation techniques incorporating thermal transfer modules can effectively study the mechanisms of these microscopic responses. Therefore, considering the interaction between ambient temperatures, the internal temperature of the dam, and ice phase change will be key issues for accurately simulating and predicting breaching in moraine dams containing ice, using existing numerical simulation technologies.

CRediT authorship contribution statement

Yunying Mou: Writing – original draft, Visualization, Resources. **Huayong Chen:** Writing – review & editing, Methodology, Funding acquisition. **Tao Wang:** Supervision, Methodology, Conceptualization. **Hechun Ruan:** Writing – original draft, Validation, Conceptualization. **Xiao Li:** Visualization, Supervision, Investigation. **Yunhan Yu:** Supervision, Resources. **Yichen Zhou:** Supervision, Resources. **Haoyang Meng:** Supervision, Resources.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this study.

Data availability

Data will be made available on request.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (Grant No. U20A20112, U21A2008), Science and Technology Program of Tibet Autonomous Region, China (Grant No. XZ202201ZY0011G), CAS Light of West China Program, the Science and Technology Research Program of Institute of Mountain Hazards and Environment, CAS (Grant No. IMHE-ZDRW-02).

References

Agarwal, V., Wyk, Van, de Vries, M., Haritashya, U.K., Garg, S., Kargel, J.S., Chen, Y.-J., Shugar, D.H., 2023. Long-term analysis of glaciers and glacier lakes in the Central and Eastern Himalaya. Sci. Total Environ. 898, 165598.

Allen, S.K., Sattar, A., King, O., Zhang, G., Bhattacharya, A., Yao, T., Bolch, T., 2022. Glacial lake outburst flood hazard under current and future conditions: worst-case scenarios in a transboundary Himalayan basin. Nat. Hazards Earth Syst. Sci. 22 (11), 3765–3785.

Bajracharya, S.R., Mool, P., 2009. Glaciers, glacial lakes and glacial lake outburst floods in the Mount Everest region, Nepal. Ann. Glaciol. 50 (53), 81–86.

Cai, Y., Yang, X., Zhou, Z., Zheng, D., Huang, W., Zhou, J., Zhang, Y., 2023. Barrier lake break mechanism with physical model. Adv. Eng. Sci. 55 (01), 150–160.

Chang, D.S., Zhang, L.M., 2010. Simulation of the erosion process of landslide dams due to overtopping considering variations in soil erodibility along depth. Nat. Hazards Earth Syst. Sci. 10 (4), 933–946.

Chang, M., Tang, C., Dou, X., 2017. Mechanism and hazards of typical glacial-lake burst in Southeastern Tibet. South-to-North Water Transf. Water Sci. Technol. 15 (06), 115–122.

Chen, F., Ge, W., 2021. A review of smoothed particle hydrodynamics family methods for multiphase flow. Chin. J. Theor. Appl. Mech. 53 (09), 2357–2373.

Chen, Z., Ma, L., Yu, S., Shujing, C., Zhou, X., Sun, P., Li, X., 2015. Back Analysis of the Draining Process of the Tangjiashan Barrier Lake. J. Hydraul. Eng. 141, 05014011.

Chen, S., Chen, Z., Zhong, Q., 2019. Progresses of studies on failure mechanism and numerical dam failure model of earth-rockfill dam and landslide dam. Water Res. Hydropower Eng. 50 (08), 27–36.

Chen, C., Li, H., Chen, J., Zhang, J., Zhang, L., Tang, X., 2022a. Overtopping and flood routing process of landslide dams consisted of ice-soil mixtures: a preliminary study. J. Hydrol. 604, 127252.

Chen, H., Ruan, H., Chen, J., Li, X., Yu, Y., 2022b. Review of Investigations on Hazard chains Triggered by River-Blocking Debris Flows and Dam-break Floods. Front. Earth Sci. 10, 16.

Clague, J., Evans, S., 2000. A review of catastrophic drainage of moraine-dammed lakes in British Columbia. Quat. Sci. Rev. 19, 1763–1783.

Costa, J.E., Schuster, R.L., 1988. The formation and failure of natural dams. Geol. Soc. Am. Bull. 100 (7), 1054–1068.

Dahal, P., Paudyal, K., Rajaure, S., 2018. Geophysical study on moraine dam of Imja Glacial Lake in Eastern Nepal using Electrical Resistivity Tomography Method. J. Nepal Geol. Soc. 55, 15–22.

Dang, C., Chu, N., Zhang, P., 2019. Computing method for discharges of debris flow induced by moraine-dammed lake outburst. J. Glaciol. Geocryol. 41 (01), 165–174.

Ding, Y., Mu, C., Wu, T., Hu, G., Zou, D., Wang, D., Li, W., Wu, X., 2021. Increasing cryospheric hazards in a warming climate. Earth Sci. Rev. 213, 103500.

Dou, G., 1999. Incipient Motion of Coarse and Fine Sediment. J. Sediment. Res. 6, 1–9.

Eichel, J., Draebing, D., Meyer, N., 2018. From active to stable: Paraglacial transition of Alpine lateral moraine slopes. Land Degrad. Dev. 29, 1–15.

Fisher, D.A., Lacelle, D., Pollard, W., 2020. A model of unfrozen water content and its transport in icy permafrost soils: Effects on ground ice content and permafrost stability. Permafr. Periglac. Process. 31 (1), 184–199.

Froehlich, D.C., 1995. Peak Outflow from Breached Embankment Dam. J. Water Resour. Plan. Manag. 121, 90–97.

Fu, Y., 2021. Effects of Short-Term Freeze-Thaw on the Shear Strength of Glacial Tills. University of Chinese Academy of Sciences, Chengdu, Sichuan.

Fu, Y., Jiang, Y., Jiao, W., 2021. Experimental study on the undrained shear behavior of glacial till in larger-scale triaxial testing. J. Lanzhou Univ.: Nat. Sci. 57 (02), 200–206.

Fujita, K., Sakai, A., Nuimura, T., Yamaguchi, S., Sharma, R., 2009. Recent changes in Imja Glacial Lake and its damming moraine in the Nepal Himalaya revealed by in situ surveys and multi-temporal ASTER imagery. Environ. Res. Lett. 4, 045205.

Ge, W., Xu, J., Xiong, Q., Wang, X., Chen, F., Wang, L., Hou, C., Xu, M., Li, J.H., 2013. Multi-scale Continuum-Particle simulation on CPU–GPU Hybrid Supercomputer. GPU Solutions to Multi-scale Problems in Science and Engineering. Lecture Notes in Earth System Sciences. Springer, Berlin, Heidelberg.

Hewitt, K., Liu, J., 2013. Ice-Dammed Lakes and Outburst Floods, Karakoram Himalaya: Historical Perspectives on Emerging Threats. Phys. Geogr. 31, 528–551.

Hubbard, B., Heald, A., Reynolds, J., Quincey, D., Richardson, S., Luyo, M., Portilla, N., Hambrey, M., 2005. Impact of a rock avalanche on a moraine-dammed proglacial lake: Laguna Safuna Alta, Cordillera Blanca. Peru. Earth Surf. Processes Landforms 30 (10), 1251–1264.

Huggel, C., Haeberli, W., Kääb, A., Bieri, D., Richardson, S., 2004. An assessment procedure for glacial hazards in the Swiss Alps. Canad. Geotech. J. - CAN GEOTECH J 41, 1068–1083.

Hugonnet, R., McNabb, R., Berthier, E., Menounos, B., Nuth, C., Girod, L., Farinotti, D., Huss, M., Dussaillant, I., Brun, F., Kääb, A., 2021. Accelerated global glacier mass loss in the early twenty-first century. NATURE 592, 726–731.

Iribarren, P., Mackintosh, A., Norton, K., 2014. Hazardous processes and events from glacier and permafrost areas: Lessons from the Chilean and Argentinean Andes. Earth Surf. Process. Landf. 40 (1), 2–21.

Jiang, Z.-X., Cui, P., Jiang, L.-W., 2004a. Critical hydrologic conditions for overflow burst of moraine lake. Chin. Geogr. Sci. 14, 39–47.

Jiang, Z.-X., Cui, P., Jiang, L.-W., 2004b. Critical hydrologic conditions for overflow burst of moraine lake. Chin. Geogr. Sci. 14 (1), 39–47.

Hauck, C., Bach, M., Hilbich, C., 2008. A Four-Phase Model to Quantify Subsurface Ice and Water Content in Permafrost Regions Based on Geophysical Data Sets. Proceedings ofthe 9th International Conference on Permafrost 2008 (Fairbanks, AK), pp. 675–680.

Kafle, J., 2018. Dynamic interaction between a two-phase submarine landslide and a fluid reservoir. MPhil Dissertation, School of Science. Kathmandu University, Kavre, Nepal.

Khadka, N., Chen, X., Liu, W., Gouli, M.R., Zhang, C., Shrestha, B., Sharma, S., 2024. Glacial lake outburst floods threaten China-Nepal connectivity: Synergistic study of remote sensing, GIS and hydrodynamic modeling with regional implications. Sci. Total Environ. 948, 174701.

Li, Z., He, Y., Song, L., Catto, N., Wang, Y., Shijin, W., Liu, H., Cao, W., Theakstone, W., Wang, S., Du, J., 2011. Climate and glacier change in southwestern China during the past several decades. Environ. Res. Lett. 6, 045404.

Li, C., Wang, R., Gu, D., Wang, J., Chen, X., Zhou, J., Liu, Z., 2022. Temperature and ice form effects on mechanical behaviors of ice-richmoraine soil of Tianmo valley nearby the Sichuan-Tibet Railway. Eng. Geol. 305, 106713.

Liao, X., 2021. Scientific and technological progress and development prospect of the earth observation in China in the past 20 years. National Remote Sens. Bull. 25 (01), 267–275.

Liao, Z., Chen, H., Zhu, S., Li, M., 2023. Research progress on the initiation and development mechanism. Pearl River 45 (03), 146–156.

Liu, J., Zhou, L., 2018. Research Progress on Moraine Dammed Lake Outburst Flood. Exploration Engineering (Rock and Soil Drilling and Tunneling) 45 (08), 44–50.

Liu, J., Cheng, Z., Li, Y., Su, P., 2008. Characteristics of Glacier-Lake Breaks in Tibet. J. Catastrophol. 23 (01), 55–60.

Liu, Z., Zhang, Y., Yu, X., Yuan, C., 2016. Unmanned surface vehicles: an overview of developments and challenges. Annu. Rev. Control. 41, 71–93.

Liu, J., Zhang, J., Gao, B., Li, Y., Li, M., Wujin, D., Zhou, L., 2019. An overview of glacial lake outburst flood in Tibet, China. J. Glaciol. Geocryol. 41 (06), 1135–1347.

Liu, M., Chen, N., Zhang, Y., Deng, M., 2020. Glacial Lake Inventory and Lake Outburst Flood/Debris Flow Hazard Assessment after the Gorkha Earthquake in the Bhote Koshi Basin, 12(2), p. 464.

Liu, J., Zhon, Q., Chen, L., Shan, Y., 2022. Review on the simulation Technologies of Breach Mechanism and Breaching Process of Landslide Dam. J. Disaster Preven. Mitigation Eng. 42 (03), 638–652.

Liu, Z., Wang, J., Cui, P., Yao, J., Wang, R., Liu, Z., 2024. Experimental study on response of strength characteristics of glacier tills to temperature in Southeastern Tibet. Earth Science—Journal of China University of Geoscience 1–15.

Loke, M. (2001) Tutorial: 2-D and 3-D Electrical Imaging surveys.

Lu, X., Zhou, G.G.D., Cui, K.F.E., Tang, H., Xie, Y., 2022. Overtopping volume of impulse waves in glacier lakes: Experimental and numerical investigation using rigid dams. Eng. Geol. 306, 106763.

Luo, Y., Su, B., Sheng, J., Zhan, M., 2011. New understandings on piping mechanism. Chin. J. Geotech. Eng. 33 (12), 1895–1902.

Lv, S., Wang, R., Hu, M., Shen, J., 2011. Current status, problems and future trends of the research on engineering properties of moraine soil. J. Eng. Geol. 6.

Marrone, S., Di Mascio, A., Le Touzé, D., 2016. Coupling of Smoothed Particle Hydrodynamics with Finite volume method for free-surface flows. J. Comput. Phys. 310, 161–180.

Morikawa, D., Senadheera, H., Asai, M., 2020. Explicit incompressible smoothed particle hydrodynamics in a multi-GPU environment for large-scale simulations. Comput. Part. Mech. 8, 493–510.

Patton, A., Rathburn, S., Capps, D., McGrath, D., Brown, R., 2021. Ongoing Landslide Deformation in Thawing Permafrost. Geophys. Res. Lett. 48 (16), e2021GL092959.

Peng, M., Wang, K., Zhang, G., Ma, C., Zhu, Y., 2020. Review of model experimental studies on break of landslide dams. J. Eng. Geol. 28 (05), 1007–1015.

Peng, M., Wang, X., Zhang, G., Veh, G., Sattar, A., Chen, W., Allen, S., 2023. Cascading hazards from two recent glacial lake outburst floods in the Nyainqêntanglha range, Tibetan Plateau. J. Hydrol. 626 (Part A), 130155.

Popov, N., 1991. Assessment of glacial debris flow hazard in the north TianShan Proceedings of the Soviet-China-Japan Symposium and Field Workshop on Natural Disasters, pp. 384–391.

Qian, N., Wan, Z., 1983. Mechanics of Sediment Transport. Science Press, BeiJing.

Richardson, S.D., Reynolds, J.M., 2000. Degradation of ice-cored moraine dams : implications for hazard development. IAHS-AISH publication 187–197.

Ruan, H., Chen, H., Li, Y., Chen, J., Li, H., 2021a. Study on the downcutting rate of a debris flow dam based on grain-size distribution. Geomorphology 391, 107891.

Ruan, H.C., Chen, H.Y., Wang, T., Chen, J.G., Li, H.B., 2021b. Modeling Flood Peak Discharge Caused by Overtopping failure of a Landslide Dam. Water 13 (7), 921.

Ruan, H., Chen, H., Chen, X., Zhao, W., Chen, J., Wang, T., Jiang, Y., Wang, X.a., Li, X., Li, X. and Yu, Y., 2023. Modeling of breaching parameters for debris flow dams. J. Mt. Sci. 20 (10), 2835–2851.

Ruan, H., Chen, H., Chen, X., Zhao, W., Chen, J., Wang, T., Li, X., Yang, Z., 2024. An investigation of discharge control in landslide dam failures utilizing flexible protecting nets. Eng. Fail. Anal. 159, 108134.

Sawagaki, T., Lamsal, D., Byers, A., Watanabe, T., 2012. Changes in surface morphology and glacial lake development of Chamlang South Glacier in the eastern Nepal Himalaya since 1964. Glob. Environ. Res. 16, 83–94.

Shi, Z., Liu, S., Peng, M., 2014. Research status and prospect of the seepage of landslide dam material. J. Eng. Geol. 22 (S1), 88–93.

Shi, Z., Wang, Y., Peng, M., Chen, J., Yuan, J., 2015. Characteristics of the landslide dams induced by the 2008 Wenchuan earthquake and dynamic behavior analysis using large-scale shaking table tests. Eng. Geol. 194, 25–37.

Shi, W., Liu, S., Zhang, H., 2017. Heat transfer in Frozen Soil based on Coupling Model of Water Flow and Heat Convection Conduction. Arid Zone Res. 34 (02).

Shi, Z., Zhang, G., Peng, M., Zhang, Q., Zhou, Y., Mingjun, Z., 2022. Experimental Investigation on the Breaching Process of Landslide Dams with Differing Materials under Different Inflow Conditions. Materials 15, 2029.

Shugar, D.H., Burr, A., Haritashya, U.K., Kargel, J.S., Watson, C.S., Kennedy, M.C., Bevington, A.R., Betts, R.A., Harrison, S., Strattman, K., 2020. Rapid worldwide growth of glacial lakes since 1990. Nat. Clim. Chang. 10 (10), 939–945.

Su, P., Liu, W., Li, H., Chen, Q., Liu, Y., Zhang, Y., 2021. Experimental study on the process of end-moraine dam failure in the middle Himalaya glacial lake: taking the Jialongcuo glacial lake end-moraine dam as an example. Chin. J. Geol. Hazard Control 32 (05), 18–28.

Sun, M., Liu, S., Yao, X., Li, L., 2014. The cause and potential hazard of glacial lake outburst flood occurred on July 5, 2013 in Jiali County. Tibet. J. Glaciol. Geocryol. 36 (01), 158–165.

Taylor, C., Robinson, T., Dunning, S., Carr, J., Westoby, M., 2023. Glacial lake outburst floods threaten millions globally. Nat. Commun. 14, 487.

Tonkin, T.N., Midgley, N.G., Cook, S.J., Graham, D.J., 2016. Ice-cored moraine degradation mapped and quantified using an unmanned aerial vehicle: a case study from a polythermal glacier in Svalbard. Geomorphology 258, 1–10.

Veh, G., Korup, O., Walz, A., 2020. Hazard from Himalayan glacier lake outburst floods. Proc. Natl. Acad. Sci. 117 (2), 907–912.

Walder, J., Costa, J., 1996. Outburst floods from glacier-dammed lakes: the effect of mode of lake drainage on flood magnitude. Earth Surf. Process. Landf. 21, 701–723.

Walder, J.S., O`Connor, J.E., 1997. Methods for predicting peak discharge of floods caused by failure of natural and constructed earthen dams. Water Resour. Res. 33 (10), 2337–2348.

Wang, S., Zhang, T., 2013. Glacial lakes change and current status in the central Chinese Himalayas from 1990 to 2010. J. Appl. Remote. Sens. 7, 073459.

Wang, S., Qin, D., Cun, d., 2015. Moraine-dammed lake distribution and outburst flood risk in the Chinese Himalaya. J. Glaciol. 61, 115–126.

Wang, L., Chen, Z., Wang, N., Sun, P., Yu, S., Li, S., Du, X., 2016. Modeling lateral enlargement in dam breaches using slope stability analysis based on circular slip mode. Eng. Geol. 209, 70–81.

Wang, X.I.N., Yang, C., Zhang, Y., Chai, K., Liu, S., Ding, Y., Wei, J., Zhang, Y., Han, Y., 2018. Monitoring and simulation of hydrothermal conditions indicating the deteriorating stability of a perennially frozen moraine dam in the Himalayas. J. Glaciol. 64 (245), 407–416.

Wang, L., Chen, Y., Zhan, Q., Wang, S., 2022. Critical incipient motion of slope soil under thin layer flow scouring. J. Civil Environ. Eng. 46 (02), 23–32.

Wang, J., Wang, X., Zhang, Y., Ran, W., Zhang, Y., Wei, J., Liu, Q., Lei, D., 2023a. Simulation of Freeze–Thaw and Melting of Buried Ice in Longbasaba Moraine Dam in the Central Himalayas Between 1959 and 2100 Using COMSOL Multiphysics. J. Geophys. Res. Earth 128 (3) e2022JF006848.

Wang, Y., Liu, X., Zhang, X., Cui, B., Wu, Y., 2023b. Dynamic response characteristics of moraine-soil slopes under the combined action of earthquakes and cryogenic freezing. Cold Reg. Sci. Technol. 211, 103854.

Wang, R., Li, C., Gu, D., Thaw, N.M.M., Wang, J., 2024. Strength criterion of ice-rich moraine soil considering the ice form and temperature based on thermal-mechanical triaxial tests. Cold Reg. Sci. Technol. 220, 104150.

Wei, Y., Wang, S., Liu, J., Zhou, L., 2019. Multi-Source Remote-Sensing monitoring of the Monsoonal Maritime Glaciers at Mt. Dagu, East Qinghai-Tibetan Plateau, China. IEEE Access 7, 48307–48317.

Westoby, M.J., Glasser, N.F., Brasington, J., Hambrey, M.J., Quincey, D.J., Reynolds, J. M., 2014. Modelling outburst floods from moraine-dammed glacial lakes. Earth Sci. Rev. 134, 137–159.

Wolper, J., Gao, M., Lüthi, M., Heller, V., Vieli, A., Jiang, C., Gaume, J., 2021. A glacier–ocean interaction model for tsunami genesis due to iceberg calving. Commun. Earth & Environ. 2, 130.

Worni, R., Stoffel, M., Huggel, C., Volz, C., Casteller, A., Luckman, B., 2012. Analysis and dynamic modeling of a moraine failure and glacier lake outburst flood at Ventisquero Negro, Patagonian Andes (Argentina). J. Hydrol. 444-445, 134–145.

Wu, W., 2013. Simplified Physically based Model of Earthen Embankment Breaching. J. Hydraul. Eng. 139, 837–851.

Xiong, Q., Li, B., Chen, F., ma, J., Ge, W. and Li, J.H., 2010. Direct numerical simulation of sub-grid structures in gas–solid flow—GPU implementation of macro-scale pseudo-particle modeling. Chem. Eng. Sci. 65, 5356–5365.

Xu, D., Liu, C., Feng, Q., 1989. Dangerous glacial lake and outburst features in XiZang Himalayas. Acta Geograph. Sin. 44 (3), 343–352.

Xue, H., Ma, Q., Diao, M., Jiang, L., 2019. Propagation characteristics of subaerial landslide-generated impulse waves. Environ. Fluid Mech. 19, 203–230.

Yang, J., Shi, Z., Zheng, H., Wang, Y., 2021. Seepage stability and dynamic response of landslide dam under earthquake. J. Eng. Geol. 31 (02), 574–583.

Yang, B., Miao, H., Yang, Z., Shen, Y., 2023. Experimental study on the influence of dry density and fine particle content on landslide dam break. Sci. Technol. Eng. 23 (01), 46–53.

Yao, T., Thompson, L., Yang, W., Yu, W., Gao, Y., Guo, X., Yang, X., Duan, K., Zhao, H., Xu, B., Pu, J., Lu, A., Xiang, Y., Kattel, D.B., Joswiak, D., 2012. Different glacier status with atmospheric circulations in Tibetan Plateau and surroundings. Nat. Clim. Chang. 2 (9), 663–667.

Yao, X., Liu, S., Sun, M., 2014. Study on the glacial lake outburst flood events in Tibet since the 20th century. J. Nat. Resour. 29 (08), 1377–1390.

Yao, X., Liu, S., Han, L., Sun, M., Zhao, L., 2018. Definition and classification system of glacial lake for inventory and hazards study. J. Geogr. Sci. 28 (2), 193–205.

Yin, Y., Cui, Y., Tang, Y., Liu, D., Lei, M., Chan, D., 2021. Solid–fluid sequentially coupled simulation of internal erosion of soils due to seepage. Granul. Matter 23 (20), 14.

Yuan, X., Zheng, N., Ye, F., Fu, W., 2019. Critical runoff depth estimation for incipient motion of non-cohesive sediment on loose soil slope under heavy rainfall. Geomat. Nat. Haz. Risk 10, 2330–2345.

Zhan, Y., Lu, Z., Yao, H., Xian, S., 2018. (2018) a coupled Thermo-Hydromechanical Model of Soil Slope in seasonally Frozen Regions under Freeze-Thaw Action. Adv. Civil Eng. 10, 7219826.

Zhang, H., 2012. A unified formula for incipient velocity of sediment. Shuili Xuebao 43 (12).

Zhang, G., Yao, T., Xie, H., Wang, W., Yang, W., 2015. An inventory of glacial lakes in the Third Pole region and their changes in response to global warming. Glob. Planet. Chang. 131, 148–157.

Zhang, M., Wen, Z., Xue, K., Chen, L., Li, D., Gao, Q., 2016. Temperature and deformation analysis on slope subgrade with rich moisture of Qinghai-Tibet railway in permafrost regions, 35, pp. 1677–1687.

Zhang, L., Zhong, Q., Yang, M., Peng, M., Liu, J., 2023. Centrifugal model tests on overtopping-induced breaching of landslide dams. Chin. J. Geotech. Eng. 45 (S1), 197–200.

Zhang, W., Wang, X., Ran, W., Wei, J., Liu, Q., 2024. Surface Deformation Detection of the Moraine Dam of the Longbasaba Lake inTibet of China based on PS-InSAR Technique and Associated Influencing Factors. Mountain Res. 42, 60–69.

Zhao, T., Chen, S., Wang, J., Zhong, Q., Fu, C., 2016. Centrifugal model tests overtopping failure of barrier dams. Chin. J. Geotech. Eng. 38 (11), 1965–1972.

Zhao, G., Jiang, Y., QIao, J., Meng, H., Yang, Z., 2018. Experimental investigation on overtopping failure of landslide dams with different conditions of compactness. Chin. J. Rock Mech. Eng. 37 (06), 1496–1505.

Zhao, H., Su, B., Lei, H., Zhang, T., Xiao, C., 2022. A new projection for glacier mass and runoff changes over High Mountain Asia. Sci. Bull. 68 (1), 43–47.

Zhon, Q., Chen, S., Deng, Z., 2018. Breach mechanism and numerical modeling of barrier dam due to overtopping failure. Scientia Sinica Technol. 48 (9), 959–968.

Zhong, Q., Chen, S., Cao, W., 2017. Numerical simulation of landslide dam breaching due to overtopping. Landslides 15, 1183–1192.

Zhou, Y., Yao, L., Ai, Z., Chen, M., 2017. Instability of moraine dams under the combined action of seismic forces and resonant hydrodynamic pressures. Chin. J. Rock Mech. Eng. 36 (07), 1726–1735.

Zhou, G.G.D., Zhou, M., Shrestha, M.S., Song, D., Choi, C.E., Cui, K.F.E., Peng, M., Shi, Z., Zhu, X., Chen, H., 2019. Experimental investigation on the longitudinal evolution of landslide dam breaching and outburst floods. Geomorphology 334, 29–43.

Zhou, M., Shi, Z., Zhou, G., Cui, K.F., Peng, M., 2021. Experimental Investigation of the Outburst Discharge of Landslide Dam Overtopping failure. Front. Earth Sci. 9, 766524.

Zhou, G.G.D., Li, S., Lu, X., Tang, H., 2022a. Large-scale landslide dam breach experiments: Overtopping and “overtopping and seepage” failures. Eng. Geol. 304, 106680.

Zhou, G.G.D., Lu, X., Xie, Y., Cui, K.F.E., Tang, H., 2022b. Mechanisms of the Non-Uniform Breach Morphology Evolution of Landslide Dams Composed of Unconsolidated Sediments During Overtopping Failure, 127(10), p. 28.

Zhu, X., Liu, B., Guo, J., Jiang, C., 2020. Summary of research on landslide dam break. Sci. Technol. Eng. 20 (21), 8440–8451.