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A Review of the Research Status and Development Trends of the Physical and Mechanical Properties and Instability Mechanisms of Moraine

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Abstract: This paper focuses on moraine deposits, a typical heterogeneous accumulation with wide gradation in high-altitude regions. The grain-size characteristics, structural features, damage evolution under freeze–thaw and water effects, and the research progress on slope instability are systematically reviewed. Particular attention is given to the application of methods such as sieving and image recognition, large-scale direct shear and triaxial tests, microstructural observation, and numerical simulation in revealing the mechanical behavior and failure mechanisms of moraine deposits. Based on existing studies, a unified framework of "material structure characteristics–strength degradation–slope response" is proposed to summarize the established understandings, remaining controversies, and engineering implications. The results indicate that moraine deposits generally exhibit wide gradation, poor sorting, strong structural characteristics, and pronounced water sensitivity. Freeze–thaw cycles, rainfall infiltration, and seismic disturbances jointly control the progressive instability process through particle rearrangement, pore expansion, fine particle migration, and interface weakening. Current studies still face several limitations, including difficulties in preserving in situ structure, significant scale effects in testing widely graded materials, and insufficient integration of multi-field coupling and multi-scale analysis. Future research should emphasize the characterization of intact moraine structure, experimental investigation of freeze–thaw–seepage–stress coupling, and the development of multi-scale numerical models, so as to support hazard prevention and control in high-altitude transportation corridors and major engineering projects in glacial regions.

Keywords: Moraine deposits, grain-size characteristics, freeze–thaw cycles, water-induced deterioration, instability mechanisms.

1. Introduction

To support high-quality development in western China in the new era and the construction of ecological security barriers, as well as to promote coordinated regional economic development, a series of major engineering projects, such as the Yarlung Zangbo River Hydropower Project and the Sichuan–Tibet Highway, are being advanced into high-altitude regions. These regions are characterized by complex geological structures, extensive development of modern glaciers, and frequent glacier-related activities, making them highly susceptible to geological hazards. In particular, during glacier movement, large quantities of unconsolidated deposits are generated; under external triggers such as rainfall or earthquakes, these materials can readily induce collapses, glacier-related debris flows, or moraine landslides. Such hazards may not only disrupt transportation and block river channels, but also further trigger glacial lake outburst floods, posing severe threats to the safety of local residents' lives and property, the operation of major engineering projects, and the stability of regional ecological environments. For example, on 15 August 1950, a large-scale cluster of collapses and landslides occurred in Guxiang Gully. A substantial volume of loose deposits blocked the valley and formed a landslide dam approximately 40 m high. As glacier and snowmelt water accumulated, a dammed lake developed upstream of the barrier. On 4 September 2007, a large debris flow occurred in Tianmo Gully, Bomi County, Tibet. The deposited debris volume was approximately 134,000 m^3, temporarily blocking the river channel for about one hour and forming a debris-flow fan near the G318 National Highway on the northern bank, with a length of 410 m and a width of 250 m. On 17 and 29 October 2018, two successive chain disasters involving high-position collapse–landslide, debris flow, river blockage, and outburst flood occurred in Sedongpu Gully. These events formed a giant landslide dam up to 80 m high, and the peak discharge of the outburst flood reached 32,000 m^3/s. As a result, 33 villages were inundated and more than 5,000 people were evacuated [1].

The disasters that occurred in Guxiang Gully, Tianmo Gully, and Sedongpu Gully reveal the distinctive and hazardous nature of the geological environment in high-altitude regions. To gain a deeper understanding of the formation mechanisms of these disasters, it is essential to clarify their material source, namely moraine deposits. Moraine deposits are essentially broadly graded, heterogeneous accumulations containing erratic boulders, blocks, and other debris, formed by the deposition of large amounts of rock and soil fragments transported by glaciers during their movement and subsequently released through glacier ablation [1]. As such, they represent a special type of geomaterial. Moraine deposits are mainly formed in three ways. First, debris may be directly released and accumulated during glacier ablation or when glacier advance is obstructed. Second, meltwater generated by glacier melting may transport part of the debris over a certain distance before deposition. Third, during glacier advance, fractured rock blocks produced by the erosion of mountain bedrock may be entrained within the glacier and transported to suitable locations for deposition. Among these processes, moraine deposits formed through glacial erosion, entrainment, and deposition may further shape specific glacial landforms. According to the positional relationship between moraine deposits and glaciers, as well as the morphological characteristics of the deposits at the time of formation, moraine deposits can be classified into terminal moraines, lateral moraines, drumlins, trough-valley moraines, cirque moraines, and talus cones. The formation of different geomorphic types is closely related to the distribution characteristics of moraine deposits. At present, moraine deposits in China are widely distributed in high-altitude regions such as the Qinghai–Tibet Plateau, the Tianshan Mountains, and their surrounding areas, and they are also locally distributed in other mid- to high-latitude mountainous regions. These areas are typically characterized by alpine canyon landforms.

Moraine deposits, as a special type of accumulation widely distributed in high-altitude regions, are characterized by highly complex material compositions and structural features. In terms of grain-size distribution, moraine deposits are compositionally heterogeneous, comprising particle fractions ranging from boulders to clay, and are extremely poorly sorted. Their lithology is dominated by proximal source materials, with a small proportion of distal components. Structurally, moraine deposits are generally non-stratified; the gravel clasts are mostly angular to subangular and exhibit very low roundness. Morphologically, moraine clasts commonly display irregular shapes, such as pentagonal, triangular, or flatiron-like forms. Their surfaces often develop smooth abraded facets, accompanied by dense parallel striations or multiple small steps [2]. These characteristics distinguish moraine deposits markedly from debris-flow deposits in terms of structure, composition, and morphology. The latter are generally better sorted, commonly exhibit typical binary structures or clear stratification, and contain gravel clasts that are mostly subrounded to rounded, with a higher degree of roundness [3].

In summary, moraine deposits are a type of heterogeneous accumulation. Their extremely poor particle sorting, complex internal structure, and high sensitivity to water fundamentally distinguish the instability mechanisms of moraine landslides from those of conventional homogeneous soil slopes or rock slopes.

2. Material Structural Characteristics

2.1. Research Status of Grain-Size Analysis of Moraine Deposits

Grain-size distribution is one of the most important structural characteristics of moraine deposits, as it reflects the combined effects of glacial dynamics, bedrock properties, and environmental conditions. Accordingly, grain-size analysis has become an important approach for identifying the genesis and depositional environment of moraine deposits.

Early studies mainly employed conventional methods to measure the size, distribution, and morphological characteristics of particles, especially gravels, within moraine deposits. Shang Yanjun et al. [4] conducted particle-size sieving tests on granitic gravels from five moraine deposits and statistically analyzed the gravel-size fractions with relatively high numerical percentages. Based on the sieving method, Zhang Zhenshuan [5] found that gravel contents were high in lateral moraines and supraglacial debris, but relatively low in ablation moraines, flow tills, and terminal moraines. Yi Chaolu et al. [6] analyzed pore size, apparent porosity, and pore morphology of moraine deposits using the thin-section method. On the basis of particle-size data obtained from sieve analysis, Gao Shunli [7–10] plotted grain-size histograms and cumulative curves of moraine deposits. The results showed that the frequency curves exhibited distinct bimodal or weakly multimodal characteristics, while the cumulative curves were relatively gentle, indicating a wide grain-size distribution and poor sorting of moraine deposits. Although these studies systematically revealed the basic grain-size characteristics of moraine deposits, conventional sieving methods are limited in terms of analytical accuracy and continuity. To improve analytical precision, some scholars [11–13] used laser particle-size analyzers to characterize the fine-grained fractions of moraine deposits. Zhang Yanfeng et al. [14–17] further obtained mesoscopic and microscopic structural images of moraine deposits using CT scanning, image-processing techniques, and UAV-based photogrammetry, and analyzed their porosity, particle shape, orientation, and structural units. These studies consistently showed that the particle-size distribution curves of moraine deposits are characterized by multimodal or bimodal patterns, and that the obtained grain-size compositions are more continuous.

A comparison of these methods, as shown in Table 1, indicates that CT scanning and image-processing techniques are more effective in quantifying the pore-structure characteristics of moraine deposits. However, owing to transformation errors between two-dimensional slices and the true three-dimensional morphology, their accuracy in identifying fine particles is far inferior to that of laser particle-size analyzers. Therefore, future structural characterization should move toward multi-scale joint calibration integrating image-recognition techniques and laser particle-size analysis.

Table 1. Classification of grain-size analysis methods for moraines

Method	Advantages	Limitations
Conventional sieving method	Mature methodology and relatively simple operation	Low accuracy, insufficient continuity, and limited capability for identifying fine particles
CT scanning	Enables quantitative characterization of internal structure, pores, and particle morphology	Affected by transformation errors between two-dimensional slices and true three-dimensional morphology; less accurate than laser particle-size analysis in identifying fine particles
Image-processing techniques	Capable of extracting features such as porosity, morphology, and particle orientation	Highly dependent on image quality and prone to recognition errors
UAV-based photogrammetry	Provides large spatial coverage and high efficiency, making it suitable for surface investigations	Difficult to characterize internal structures and fine-grained components
Laser particle-size analysis	High accuracy in identifying fine particles and good continuity of results	Limited capability for characterizing coarse particles and the overall structural framework

2.2. Research Progress in the Mechanical Properties of Moraine Deposits

The mechanical properties of undisturbed moraine deposits require particular attention. Wang Chao [18] conducted large-scale direct shear tests and found that the shear strength of moraine deposits is mainly derived from the skeletal effect of coarse particles. Liang et al. [19] used PFC2D to simulate large-scale biaxial tests and demonstrated that when the volumetric gravel content exceeds 30%, it has a significant influence on the strength and deformation characteristics of moraine deposits, thereby verifying the skeletal effect from a mesoscopic perspective. On the basis of identifying the sources of strength, numerous scholars have obtained key mechanical parameters through experimental investigations. Guo et al. [20] analyzed the mechanical behavior of moraine soil under different shear stresses using large-scale direct shear tests and shear creep tests. Their results showed that the shear resistance is closely related to the content and distribution of particles larger than 20 mm, and that the primary, secondary, and tertiary creep stages of moraine soil exhibit distinct characteristics. Furthermore, Jia Mincai et al. [21] carried out in situ direct shear tests, large-scale laboratory direct shear tests, and large-scale laboratory triaxial tests, obtaining the cohesion and internal friction angle of moraine deposits under both natural conditions and at 96% compaction. In addition to shear strength parameters, Chen et al. [22] conducted compression tests on moraine deposits and investigated their compression and swelling behavior during the primary and secondary compression stages of consolidation tests.

Alongside the continuous advancement of experimental studies, numerical simulations have provided an important supplement for understanding the macro- and meso-scale mechanical responses of moraine deposits. Tuhkuri et al. [23] innovatively applied the two-dimensional discrete element method (DEM) to simulate direct shear tests on moraine deposits, confirming the effectiveness of DEM in capturing particle-scale behavior. Their results indicated that force chains are the direct cause of peak loading, while their buckling limits the upper bound of the load; the shear plane is not clearly defined, and deformation is dominated by arching and force-chain evolution. This study realized a cross-scale analysis from macroscopic mechanical response to mesoscopic particle behavior.

Based on the acquisition of mechanical parameters, Yao et al. [24] further investigated the shear characteristics and deformation behavior of moraine deposits under impact loading. The tests showed that impact loading reduced the shear strength of moraine deposits and accelerated the degradation of shear strength after the peak shear strength was reached. Altuhafi et al. [25] demonstrated through compression and shear tests that the resistance of natural moraine deposits to particle breakage originates from their well-graded structure rather than their mineral composition.

In addition to the coarse-grained skeleton, fine-grained components also play a crucial role. Yang Dongxu et al. [26], based on field investigations and laboratory and in situ tests, showed that a higher clay content leads to a larger specific surface area of particles and a lower porosity, thereby resulting in stronger expansibility and weaker permeability. Wang Xianli [27], through in situ direct shear tests and laboratory particle-size analyses, pointed out that the internal friction angle is mainly controlled by gradation and gravel particle size, whereas cohesion is primarily governed by clay content.

These two viewpoints are not contradictory; rather, they represent stage-dependent manifestations of the "binary structure" of moraine deposits under different stress conditions. Under low-stress and dry conditions, peak strength is primarily governed by frictional interlocking and interparticle wedging among coarse particles. In contrast, during wetting–drying cycles and shear deformation, the migration and lubrication effects of fine particles become the key factors controlling residual strength and seepage-induced failure.

The distinctive structure of moraine deposits, in which coarse particles form a load-bearing skeleton while fine particles fill the pores, endows them with very high initial shear strength. However, during their evolution, moraine deposits are highly susceptible to external factors. In particular, freeze–thaw action and rainfall infiltration can induce changes in their internal structure, leading to the progressive deterioration of their physical and mechanical properties. Therefore, elucidating the evolutionary behavior of moraine deposits requires consideration of both freeze–thaw effects and water-induced strength degradation.

3. Strength Degradation Behavior

3.1. Research Progress in Freeze–Thaw Damage Evolution of Moraine Deposits

Research on the stability of moraine deposits under freeze–thaw action originated from observations of their macroscopic failure phenomena. Focusing on "surface collapse," a typical failure mode, Xu Guangmiao et al. [28] summarized the complex forms of freeze–thaw-induced failure into two basic types: spalling and cracking. After the failure modes had been clarified, research attention shifted toward experimentally quantifying the degradation of material mechanical properties induced by freeze–thaw cycles. Xie et al. [29] found that the elastic modulus, shear strength, and internal friction angle decreased nonlinearly with increasing freeze–thaw cycles, whereas cohesion exhibited a heterogeneous response. Following this research direction, Qiu Enxi et al. [30] further conducted triaxial compression tests after freeze–thaw cycling and demonstrated that the cohesion of moraine soil decays according to a negative exponential function with increasing numbers of freeze–thaw cycles. They also attempted to incorporate the experimental results into the Duncan–Chang model, thereby promoting the development of freeze–thaw damage research from phenomenological description toward theoretical characterization. As the degradation laws of macroscopic mechanical properties became increasingly clear, related studies further focused on the intrinsic mechanisms of freeze–thaw damage. It is generally believed that the essence of rock-mass instability lies in cumulative fatigue damage caused by repeated loading and unloading of frost-heaving pressure within fractures. Through fracture-monitoring tests, Zou Xueqing [31] systematically revealed the fracture evolution process during a complete freeze–thaw cycle and divided it into six stages: thermal contraction, frost heaving, frost-heaving stabilization, thawing contraction, rebound, and stabilization. These findings indicate that freeze–thaw damage is a cumulative and irreversible fatigue process. On this basis, Liu Hao [32] conducted real-time monitoring of frost-heaving pressure in ice-filled fractures and captured five dynamic evolution stages of frost-heaving pressure: the incubation stage, outbreak stage, drop-and-restabilization stage, rebound stage, and dissipation stage. Liu further proposed that variations in the initial and secondary peak frost-heaving pressures could serve as indicators for evaluating the degree of rock-mass damage, thereby linking mesoscopic mechanical mechanisms with macroscopic damage behavior. Ullah et al. [33], using nuclear magnetic resonance technology, confirmed from a pore-structure perspective that damage mainly originates from the expansion and interconnection of macropores, laying a foundation for revealing the damage mechanisms under freeze–thaw cycles at the mesoscopic scale. As the research scale has expanded from macroscopic experiments to coupled macro–mesoscopic analyses, numerical simulation has played an increasingly prominent role in investigating freeze–thaw damage mechanisms. Zhou et al. [34] combined macroscopic experiments with mesoscopic numerical simulations to explore the effects of different numbers of freeze–thaw cycles on the macroscopic properties and mesoscopic structures of soil–rock mixtures, further verifying the effectiveness of numerical simulation in studying freeze–thaw behavior in soil–rock mixtures. Huang et al. [35] combined the discrete element method (DEM) with a grain-based model (GBM) for the first time and showed that porosity and mineral composition are key factors affecting the freeze–thaw resistance of rocks.

The above studies have laid an important foundation for understanding the mechanisms of freeze–thaw damage. However, most of their conclusions were derived from investigations of single factors. To comprehensively reveal these mechanisms, it is necessary to further consider the coupled effects of multiple factors, including the number of freeze–thaw cycles, water content, temperature, and confining pressure. With regard to the number of freeze–thaw cycles, which represents a fundamental variable, Konrad [36] investigated its influence on changes in the hydraulic conductivity of moraine soil. The results showed that the actual changes in hydraulic conductivity induced by freeze–thaw action may be offset by the reduction in void ratio during thaw consolidation. From the perspective of mechanical response, Qu et al. [37] demonstrated that the mechanical properties and brittleness indices of moraine soil decreased with increasing freeze–thaw cycles and tended to stabilize after 7–12 cycles. To further expand the range of influencing variables, Chen et al. [38] introduced initial water content as a key factor and conducted direct shear tests on frozen moraine soil subjected to freeze–thaw cycles using the similar-gradation method. Their study revealed the effects of freeze–thaw cycles and initial water content on the mechanical properties of frozen moraine soil. Compared with two-factor analyses, Qiu et al. [39] further considered the combined effects of freeze–thaw cycles, rock content, and water content. Through uniaxial compression tests, they systematically investigated the evolution of key parameters, including the stress–strain curves, compressive strength, and elastic modulus of moraine soil under varying freeze–thaw cycles, rock contents, and water contents. With the further development of multi-factor coupling studies, environmental and stress conditions such as temperature and confining pressure have gradually been incorporated into the analytical framework. Li Hao [40] supplemented the understanding of freeze–thaw damage mechanisms under temperature and confining pressure conditions. Through low-temperature triaxial tests, Li investigated the effects of cooling temperature, confining pressure, and freeze–thaw cycles on the strength and deformation characteristics of unsaturated frozen moraine soil.

Based on the above studies, research on freeze–thaw effects under single-factor conditions has become relatively mature [28–35]. However, in real environments, freeze–thaw processes are usually accompanied by the combined influence of multiple factors [36–40]. Therefore, freeze–thaw tests that consider only a single factor may overestimate the degradation degree of moraine deposits. Future studies should couple freeze–thaw processes with three-dimensional in situ stress fields and dynamic hydraulic pressure fields to more realistically reveal the deterioration mechanisms of moraine deposits.

3.2. Research Progress in Water-Induced Strength Degradation of Moraine Deposits

With regard to the influence of water content on the strength of moraine deposits, Han et al. [41] investigated the settlement characteristics of moraine soil with different relative densities under seismic loading, rainfall, and their combined effects through shaking-table tests. The results showed that, compared with seismic loading, the settlement of moraine soil is more susceptible to damage induced by rainfall infiltration. A high relative density can effectively mitigate the synergistic amplification of damage caused by the combined effects of rainfall and seismic loading. On this basis, some scholars have further revealed the effects of water-content variation on the mechanical properties of moraine deposits from the perspective of shear strength. Zhou et al. [42] investigated the shear characteristics of moraine soil under different water contents and found that water content has a significant influence on its shear strength and dilatancy. They further indicated that the friction angle of moraine soil is independent of water content, whereas its apparent cohesion decreases with increasing water content. Li Huajin et al. [43] studied the water-sensitive characteristics of moraine deposits under different water contents through laboratory mechanical strength tests and soil–water characteristic curve (SWCC) tests. The results showed that, after saturation, the friction angle of moraine deposits decreased to approximately one-third of its initial value, while cohesion decreased to approximately one-eighth of its initial value. When the degree of saturation ranged from 10% to 70%, the water sensitivity was particularly pronounced. In addition to strength degradation, changes in moisture conditions can further affect the erosion stability of moraine deposits. Alireza G. et al. [44] investigated the erosion and disintegration behavior of moraine deposits. Their analysis showed that intact and unweathered moraine deposits exhibit high critical shear stress and strong erosion resistance, whereas disintegrated moraine deposits that have undergone at least one wetting–drying cycle have lower critical shear stress and are more susceptible to erosion. This marked difference highlights the sensitivity of moraine deposits in environments subjected to repeated wetting–drying cycles. As water content increases, the internal seepage conditions of moraine deposits may also evolve unfavorably, thereby inducing seepage deformation and seepage instability. Focusing on this issue, Baser et al. [45] investigated the influence of temperature on the hydraulic properties of moraine deposits. The results showed that both the intrinsic permeability and hydraulic conductivity of moraine deposits increase significantly with increasing temperature. Chen Chunyu et al. [46] conducted seepage deformation tests and found that moraine deposits undergo three stages during seepage deformation: stable seepage, internal instability, and seepage failure. They further demonstrated that the characteristic particle size d30 is a key indicator affecting piping susceptibility. Building on these findings, Ronnqvist et al. [47] further showed that fine-particle content is also an important factor influencing piping susceptibility.

Moraine deposits commonly contain a large number of boulders. Owing to the limitations of laboratory testing, researchers usually scale down specimens using the “removal method” or the “equivalent replacement method.” However, these treatments alter the original pore structure, causing the obtained water-sensitive characteristics and permeability coefficients to deviate substantially from engineering reality. Meanwhile, most existing rainfall tests adopt static water supply conditions, making it difficult to reproduce the dynamic interactions among low temperature, seepage, and stress in cold alpine regions. Future research should focus on observations of the microscopic interfacial weakening mechanisms and establish reliable quantitative constitutive relationships between these mechanisms and the attenuation of macroscopic mechanical strength.

Studies on the material structural characteristics and strength degradation behavior of moraine deposits ultimately point toward the issue of slope instability. Under the combined influence of self-weight and external environmental factors, once the bearing capacity of a slope decreases to a critical state, a cascading response may be initiated, evolving from local failure to overall instability and ultimately resulting in landslide hazards.

4. Slope Instability Response

4.1. Research Progress in Moraine Slope Instability

In actual slope systems, moraine deposits commonly exhibit relatively high initial density and shear strength owing to the arching effect. However, the load-bearing capacity of internal stress arches may progressively decrease under repeated freeze–thaw cycles. Once rainfall or glacier–snow meltwater acts as a trigger, moraine slopes are prone to instability, potentially evolving into large-scale sliding. Accordingly, considerable attention has been devoted to the failure mechanisms of moraine slopes under rainfall and glacier–snow meltwater conditions. Chen Yuchao [48], considering the influence of freeze–thaw action, classified slope instability in cold regions into freezing-induced landslides, thawing-induced landslides, and freeze–thaw landslides. Current studies mainly focus on freeze–thaw landslides. Deng et al. [49] indicated that moraine landslides are mostly shallow landslides and that moraine deposits generally undergo a four-stage transformation process, namely glacier cover, exposed freezing, activity enhancement, and instability-induced sliding. In addition, many scholars have verified and extended these mechanisms through physical model tests. Chen Ningsheng et al. [50] carried out experiments on the initiation of glacial debris flows under simulated rainfall and glacier–snow meltwater conditions, showing that debris-flow initiation is jointly controlled by clay content and runoff type, and clarifying the initiation modes under different clay contents. Fan Yuanyuan et al. [51] further demonstrated through flume tests that meltwater discharge controls the failure mode and initiation process of moraine soil.

Based on the failure mechanisms under hydrothermal coupling discussed above, moraine landslides exhibit deformation and failure modes that are markedly different from those of rock and soil slopes. Niu Pengyao [52] was among the first to classify the deformation and failure modes of moraine landslides into sliding–tensile cracking and creep sliding–tensile cracking types. Sliding–tensile cracking landslides generally occur under the effects of self-weight, rainfall, or earthquakes. In such cases, creep sliding develops at the front edge of the sliding mass, while tensile failure occurs at the rear edge. When disturbed by external factors such as intense rainfall or slope-toe excavation, weak sliding surfaces are likely to form, eventually leading to slope instability and failure. Following this understanding, Liang Junyan et al. [53] analyzed the developmental trend of an ancient moraine-soil landslide in Taihe Town. Creep sliding–tensile cracking landslides usually occur when the internal shear stress of the slope exceeds the long-term strength of part of the soil mass, resulting in slow and continuous shear deformation. In this regard, Jin Jianli et al. [54] conducted rainfall tests on moraine-soil slopes and found that, with rainfall infiltration, the soil–rock mixture drove the soil at the slope front to form a large-volume sliding mass. A transversely continuous sliding zone developed between the slope crest and the slope toe, and a large-volume deposit was formed at the slope toe. Under strong seismic action, the failure modes become more complex. Wang et al. [55] carried out a series of shaking-table tests on moraine-soil slopes and found that, under earthquake loading, the sliding surface was formed by the connection between tensile cracks at the slope crest and shear cracks at the slope toe. The sliding mass moved toward the slope toe along this through-going surface, accompanied by fragmentation of the slope surface and disintegration of the sliding mass itself, eventually forming moraine-soil deposits at the slope toe. Wei Xin et al. [56] summarized three structural types of moraine-soil slopes proposed in previous studies: a weathered fine-grained layer overlying a moraine layer, an alluvial–diluvial layer overlying an ancient moraine layer, and a moraine layer interbedded with lacustrine deposits. The failure modes of these structures are all manifested as shallow landslides along low-permeability interface layers, representing typical evolutionary characteristics of interface-type landslide hazards. Liao Qiulin et al. [57] similarly showed that the deformation and failure mode of the 102 landslide conforms to the characteristics of interface-type sliding. High-position moraine landslides are controlled not only by slope structure but also by long-term freeze–thaw cycles, which can induce disintegration and fragmentation of moraine deposits. Huang et al. [58] revealed that ice–rock avalanches can act as the triggering source of moraine landslides, in which high-speed impact by ice or rock avalanche masses on underlying moraine deposits forms collapse–debris-flow-type landslides. After identifying the hazard-triggering source, numerous scholars used satellite remote sensing techniques to analyze the initiation and transformation mechanisms of moraine landslides triggered by ice–rock avalanche impacts. The impacted moraine deposits may be temporarily blocked at narrow valley sections due to the arching effect of granular materials. After breach failure, dynamic erosion during movement continuously entrains materials along the flow path, forming extremely rapid, long-runout landslides with debris-flow mechanisms [59–61]. In summary, moraine landslides can be classified from multiple perspectives, including instability stage, deformation and failure mode, slope structural characteristics, and hazard-chain evolution process, as shown in Table 2. To further characterize the movement features of such hazard chains, Mergili et al. [62] reproduced the spatiotemporal evolution of flow height, flow velocity, travel time, and volume of debris flows triggered by ice–rock avalanches using the r.avaflow model. The r.avaflow model not only provides a two-phase flow framework but also considers material entrainment along the flow path, making it suitable for simulating complex mass flows. In addition to ice–rock avalanches, previous studies have proposed multiple initiation mechanisms for moraine landslide–debris flow hazard chains, including intense rainfall and glacier melting. Through case analysis, Peng et al. [63] found that, under the effects of intense rainfall and glacier melting, loose moraine deposits accumulate and migrate along steep erosional gullies. Furthermore, Yang Xingguo et al. [64] demonstrated through physical model tests that basal materials are eroded under solid-phase shear forces and become mixed with moving moraine deposits, leading to an increase in landslide volume along the travel path. Meanwhile, the internal solid ice and snow gradually melt into liquid water, forming a lubricating surface layer and ultimately transforming the landslide into a highly mobile debris flow.

Table 2. Classification of moraine landslide types

Classification basis	Landslide type	Main characteristics
Instability types under freeze–thaw action	Freezing-induced landslide	Slope instability occurs during the freezing process.
	Thawing-induced landslide	Slope instability occurs during the thawing process.
	Freeze–thaw landslide	The slope progressively deteriorates and becomes unstable under alternating freeze–thaw cycles.
Deformation and failure mode	Sliding–tensile cracking type	Creep sliding develops at the front edge of the sliding mass, while tensile cracking occurs at the rear edge, eventually forming a sliding surface and leading to overall instability.
	Creep sliding–tensile cracking type	Slow and continuous shear deformation occurs within the slope, gradually forming a through-going sliding zone.
Failure mode under seismic action	Through-going sliding type	Tensile cracks at the slope crest connect with shear cracks at the slope toe to form a sliding surface; the sliding mass moves downslope along the through-going surface and undergoes fragmentation.
Slope-structure-controlled type	Weathered fine-grained layer + moraine layer type	Shallow sliding occurs along a low-permeability interface, showing distinct characteristics of an interface-type landslide.
	Alluvial–diluvial layer overlying ancient moraine layer type	Shallow sliding is controlled by the interface between the overlying deposits and the ancient moraine layer.
	Moraine layer interbedded with lacustrine deposits type	Sliding occurs along the interface between the moraine layer and the interbedded lacustrine deposits.
Structure–interface-controlled failure mode	Interface-type landslide	Deformation and failure develop along a low-permeability interface, representing a typical shallow interface-controlled sliding mode.
Hazard-chain triggering type	Ice–rock avalanche impact type	High-speed impact of ice or rock avalanches on underlying moraine deposits triggers collapse–debris-flow-type landslides.
Hazard-chain initiation and transformation type	Rainfall/meltwater-induced type	Infiltration of intense rainfall or glacier–snow meltwater triggers the instability of loose moraine deposits.
	Landslide–debris flow transformation type	Landslide materials undergo erosion and entrainment along the travel path, increasing in volume, and transform into highly mobile debris flows under the lubricating effect of melting ice and snow.
Movement-characteristic type	Extremely rapid long-runout landslide	After impact initiation, temporary blockage occurs at narrow valley sections; subsequent breach failure forms a rapid long-runout landslide with debris-flow mechanisms.

To quantitatively evaluate the stability of moraine landslides, scholars have developed a series of analytical methods. Wu Yunfei [65] conducted stability analyses of moraine landslides using the Swedish circular arc slice method and the continuum-based numerical software FLAC3D. The Swedish slice method can provide a preliminary assessment of moraine landslide stability, whereas FLAC3D can simulate discontinuities under various engineering geological conditions. By using interfaces to model faults, FLAC3D has been widely applied in slope stability analysis. On the basis of traditional limit equilibrium analysis, Tunini et al. [66] performed a two-dimensional stability analysis of moraine slopes using the limit equilibrium method (LEM) and subsequently constructed a three-dimensional slope model based on the two-dimensional results. Supported by these methods, Yang Dong et al. [67] classified the failure modes of moraine landslides into three typical types. For the most common "shallow rainfall-induced creep sliding" failure mode, they established and verified a stability calculation formula using least-squares curve fitting. With regard to variations in the stability coefficient of landslides under the coupled effects of multiple factors such as earthquakes and rainfall, Gao et al. [68] used GeoSlope software combined with the limit equilibrium method for calculation. Their results verified the critical role of apparent cohesion in slope stability and focused on the effects of water content and seismic loading. Aurelian et al. [69] investigated, using the finite element method, the mechanism by which snowmelt-induced rise in the perched water table leads to progressive slope deformation and eventual failure. Their study found that an increase in the perched water table causes the plastic yield zone of the slope to gradually expand. However, traditional slope stability analysis theories, such as the limit equilibrium method, have obvious limitations when applied to moraine slopes, because they cannot characterize the supporting effect of the internal particle skeleton or the progressive failure process. Consequently, numerical methods such as the discrete element method have begun to be explored. Zhou Yu et al. [70] developed a particle flow model for bedding rock slopes with intermittent joints, demonstrating the entire process from microcrack initiation and propagation to macroscopic coalescence.

Because the traditional limit equilibrium method assumes simultaneous attainment of the limit state along the entire sliding surface, it cannot adequately represent the supporting effect of the internal particle skeleton or the progressive failure process. Accordingly, continuum-based numerical approaches and discrete element methods, such as PFC, are expected to play an increasingly important role in future studies. Continuum-based methods are more advantageous for simulating seepage through complex interfaces, whereas discrete element methods can more precisely characterize the buckling and breakage of mesoscopic particle chains.

5. Conclusions and Future Perspectives

Based on a systematic review of research progress in the material structural characteristics, strength degradation behavior, and slope instability response of moraine deposits, this paper concludes that existing studies have largely revealed their basic characteristics, including broad gradation, poor sorting, strong structural heterogeneity, and pronounced water sensitivity. These studies have also preliminarily clarified the main mechanisms of progressive instability under the combined effects of freeze–thaw cycles, rainfall infiltration, and external disturbances. However, significant limitations remain in maintaining undisturbed structures, conducting multi-field coupling tests, and achieving unified macro–mesoscopic characterization. Accordingly, future research may focus on the following aspects.

(1) With regard to the difficulty in eliminating the “scale effect” in conventional scaled laboratory tests caused by the broad gradation and the presence of large particles, future studies should develop low-disturbance sampling techniques for undisturbed moraine deposits. These techniques should be combined with CT scanning, three-dimensional laser point clouds, image recognition, and other methods to establish multi-scale structural characterization and three-dimensional reconstruction approaches, thereby providing realistic skeleton models for cross-scale mechanical analysis from the microscopic to the macroscopic scale.

(2) In terms of multi-field coupling experiments, it is recommended that an integrated testing system be developed that combines low-temperature, seepage, stress, and chemical multi-field coupled loading with real-time CT scanning observations. Such a system should focus on revealing the controlling mechanisms by which mesoscopic processes, including fine-particle migration, pore-structure evolution, and interface weakening, govern macroscopic strength degradation.

(3) For multi-scale numerical modeling, future studies should develop DEM–CFD coupled models capable of considering particle breakage in broadly graded materials and fine-particle migration. Such models would enable the simulation and prediction of the entire process from local structural instability of moraine deposits to the evolution of landslide–debris flow hazards.

(4) By integrating advanced sensing technologies such as optical fiber sensing and synthetic aperture radar interferometry (InSAR), a three-dimensional monitoring network covering both the ground surface and deep subsurface of moraine slopes should be established. In addition, machine learning and deep learning algorithms should be introduced to promote the coordinated development of mechanism-based models and data-driven models, thereby improving the identification and early warning capabilities for complex moraine-related hazards.

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