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The Geomechanical Behavior of Mine Waste Rock Slopes under Climate-Induced Stressors: A Global Perspective

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Abstract: Mine waste rock slopes are essential engineered structures in the mining sector, presenting significant geomechanical challenges due to their potential for catastrophic failure, which threatens both human safety and environmental integrity. Traditional stability analyses often fail to fully account for emerging stressors introduced by climate change, including stress redistribution, permafrost degradation, and hydrological shifts, all of which increasingly compromise slope integrity on a global scale. This paper adopts a global perspective, investigating key degradation mechanisms driven by evolving climatic conditions. These mechanisms include precipitation variability, which can trigger both immediate failure and progressive weakening; freeze-thaw cycles that alter structural integrity through pore pressure fluctuations and cumulative micro fracturing; thermal effects that cause long-term displacements and material weakening; biogeochemical alterations such as oxidation, leaching, and microbial activity that result in acid generation and metal mobilization; and wind erosion and drying cycles, which contribute to particle loosening and surface crust degradation. The paper also highlights advancements in monitoring technologies, such as InSAR and real-time piezometer systems, alongside modeling approaches like coupled hydro-mechanical simulations, which collectively enhance predictive capabilities for slope stability. Despite these developments, significant knowledge gaps persist, particularly concerning the long-term variability of geotechnical parameters under changing climatic conditions. The study emphasizes the urgent need for continued interdisciplinary research, improved scaling methodologies, and robust data integration frameworks to ensure the long-term stability and safety of mine waste rock slopes in the face of climate uncertainty.

Keywords: Climate, Slope Instability, Mine Waste Rock, Geomechanical, Hydro-Mechanical, Modeling.

INTRODUCTION

Mine waste rock slopes are essential engineered structures created from overburden and waste materials excavated during mining operations. In the mining sector, these slopes present substantial geomechanical challenges, as their failure can lead to catastrophic consequences for human safety and environmental integrity (Kolapo, *et al.*, 2022) Their stability is governed by a range of complex and interrelated geological, hydrological, and climatic factors, requiring detailed geological models that integrate structural geology, lithological variability, and hydrogeological conditions (Hoek, *et al.*, 2000). In addition to inherent geological variability, external influences such as weight distribution, groundwater movement, seismic activity, and weather variability significantly impact slope behavior, with stability coefficients varying widely under different environmental scenarios (Yang, *et al.*, 2024).

Climate change has emerged as a potent threat multiplier, introducing new stressors that traditional stability analyses often fail to fully account for. These include stress redistribution, permafrost degradation, and hydrological shifts, all of which can compromise slope integrity on a global scale (Krautblatter & Moore, 2014; *Physical Modelling of the Effect of Climate Change on Rock Slope Stability*, 2022). For example, climate-induced weathering processes systematically weaken rock structures by reducing their mechanical strength, underscoring the need to incorporate weathering effects into slope stability modeling (Liu *et al.*, 2024).

Among the most direct forms of climate-slope interaction is precipitation variability. High-intensity rainfall can trigger immediate slope failure, while prolonged rainfall contributes to progressive weakening of rock masses (Nguyen, *et al.*, 2022; Li, *et al.*, 2022). These hydrological changes significantly diminish rock mass strength, with empirical studies showing substantial reductions in stability indices following rainfall exposure (Tan, *et al.*, 2011). In colder climates, freeze-thaw cycles exacerbate degradation through volumetric expansion and contraction, resulting in progressive cracking and disintegration of both natural rock and engineered materials like concrete and cemented waste (Madera & Kruis, 2019; Dong *et al.*, 2018). Chemical weathering and acidic precipitation further accelerate material deterioration (Dabas, *et al.*, 2021), while increased precipitation frequency and variability

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amplify freeze-thaw damage, especially in marginally frozen terrains (Auld, *et al.*, 2006).

This paper adopts a global perspective on the interaction between climate change and mine waste rock slope stability. It investigates the key degradation mechanisms influenced by evolving climatic conditions and highlights critical research directions aimed at enhancing the resilience of mining infrastructure in a rapidly changing environmental context.

GLOBAL OVERVIEW OF MINE WASTE ROCK SLOPE INSTABILITY

Historical perspective and current global inventory of major slope failures

The global inventory of mine waste rock slope failures reveals critical patterns in geological and geographical factors contributing to instability across diverse environments from Atlantic Canada to Sri Lanka and mountainous mining regions (Igwe, *et al.*, 2023).

Slope failures exhibit clustering patterns reflecting topographic setting and geological substrate interactions. In Sri Lanka, over 80% of failures occur on slopes with angles of 25–45° and heights exceeding 5 meters (Yang, *et al.*, 2021). Atlantic Canada shows mass movements concentrated in higher relief areas, affecting infrastructure through topographic amplification and geological vulnerabilities (Spooner, *et al.*, 2013). Geological characteristics profoundly influence slope stability. Volcanic regions experience massive rock slope failures due to altered rock masses, resulting in catastrophic debris flows (Evans, *et al.*, 2006). Mining activities introduce complexity through stress field alterations, with repeated operations inducing progressive instability via crack evolution and shear slip development (Luo, *et al.*, 2024). Material composition determines failure mechanisms, where glaciomarine clays favor rotational slumps while friable rocks experience smaller-scale failures (Spooner, *et al.*, 2013). Recent developments combining satellite radar interferometry with finite element modeling provide unprecedented slope detection and characterization capabilities, enabling effective hazard mitigation (López-Vinielles, *et al.*, 2021). However, climate change may alter traditional risk patterns through increased precipitation intensity and extreme weather events (Spooner, *et al.*, 2013).

Differences across climatic zones (tropical, arid, permafrost, high-altitude regions)

Mine waste rock slope stability presents distinct challenges across different climatic zones, each requiring specialized management approaches. In tropical environments, intense rainfall and humidity accelerate weathering processes and increase landslide risks, while dense vegetation can both stabilize slopes and conceal underlying instability issues that complicate monitoring efforts (Alcántara-Ayala., 2025). Arid regions face different challenges, where water scarcity affects moisture regimes and increases dust and erosion problems, compounded by thermal expansion and contraction from temperature fluctuations that contribute to slope destabilization. Schrottn, *et al.*, (2024) and Krautblatter & Moore (2014) highlight that permafrost regions are especially vulnerable to climate change, as thawing permafrost destabilizes slopes and initiates rockfalls and debris flows. Additionally, Sengupta, *et al.*, (1990) emphasize that the unique dynamics of frozen ground necessitate specialized modeling techniques for accurate slope stability analysis. High-altitude environments face additional complications from seismic and geodynamic activity that exacerbates slope instability, as demonstrated by significant landslides at the Kumtor Goldmine, where glacial interactions with waste dumps create complex sliding and deformation risks (Torgoev & Toguzbaev, 2020). Despite these zone-specific challenges, all climatic environments share the fundamental need for robust monitoring systems and adaptive management strategies to effectively mitigate slope instability risks in mining operations.

A study by Liu *et al.*, systematically investigates how weathering over time degrades the mechanical properties of slope materials in open-pit mines, using laboratory testing, finite element modeling, and limit equilibrium methods to demonstrate the resulting reduction in slope stability and safety factors. The study reveals that both increased weathering time and slope height significantly reduce the safety factor of open-pit mine slopes, with slopes exceeding 90 m in height and a 47° angle falling below minimum safety standards after 28 days of weathering—indicating that steep angles should be avoided for long-term stability.

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Table 1: The safety factors under different heights and weathering times at angle 45°

Slope Height (m)	0 Days	7 Days	14 Days	21 Days	28 Days
50	1.788	1.773	1.753	1.538	1.130
90	1.598	1.590	1.578	1.567	1.122
120	1.287	1.282	1.276	1.269	1.085

Table 2: The safety factors under different heights and weathering times at angle 47°

Slope Height (m)	0 Days	7 Days	14 Days	21 Days	28 Days
50	1.720	1.705	1.683	1.599	1.094
90	1.353	1.346	1.336	1.325	1.050
120	1.230	1.225	1.219	1.231	1.031

Table 1&2: Slope Stability Analysis of Open-Pit Mine Considering Weathering Effects (Liu, *et al.*, 2024)

Regulatory environments

Stewart (2010) explains that the European Union's Mine Waste Directive and Waste Framework Directive have established comprehensive waste hierarchies that prioritize reduction, reuse, and recycling, alongside strict permit requirements-transforming mining waste management practices across the region. Influenced by this European model, Yıldız, *et al*., (2024) note that countries like Turkey have adopted EU-compliant regulations that classify waste into hazardous and non-hazardous categories, thereby enhancing management and recovery efforts. The shift toward circular economy principles has reinforced the view of mining waste-particularly waste rock-as a valuable resource for recycling and construction applications (Plicanic, 2020). However, as waste rock is often stored in large engineered slopes, these regulatory frameworks also necessitate stricter geotechnical controls to ensure the long-term stability and environmental safety of mine waste rock slopes. Despite progress, challenges remain in developing harmonized end-of-waste criteria and overcoming regulatory barriers that impede effective waste management (Armistead & Babaahmadi, 2024). Overall, these regulatory developments represent a crucial shift toward sustainable mining practices that balance environmental protection and slope stability with resource recovery.

CLIMATE-INDUCED STRESSORS AND THEIR MECHANISMS

Freeze–Thaw Cycles

Freeze-thaw cycles create one of the most destructive forces affecting mine rock waste stability, as repeated freezing and thawing progressively weakens rock materials through pore pressure fluctuations that fundamentally alter their structural integrity. Research demonstrates that these cycles systematically reduce granite's mechanical properties, including uniaxial compressive strength and elastic modulus, while simultaneously increasing porosity and accelerating crack propagation (Qi, *et al.*, 2024; Wang, *et al.*, 2019). The physical transformation of pore structures during these cycles enhances permeability and groundwater transport, creating pathways that can destabilize mine slopes over time (Yu, *et al.*, 2021). As pore water pressure varies during freezing and thawing, soil microstructures undergo significant changes through particle rearrangement and consolidation, compounding stability issues (Wang, *et al.*, 2020). Given these cumulative degradation mechanisms, cold-region mining operations require robust monitoring and remediation strategies to effectively manage the risks posed by fluctuating pore pressures and freeze-thaw cycles (Zhao, *et al.*, 2024).

Uniaxial compression tests conducted by Qi, *et al*., (2024) demonstrated that freeze–thaw cycles have a more pronounced impact on the mechanical properties of granite than freezing temperature, significantly altering its stress–strain behavior. These cycles reduce both compressive strength and elastic modulus while producing a distinct four-stage deformation pattern. As shown in the diagram below, the uniaxial compressive strength of granite decreases by up to 60%, and the elastic modulus by 67.7%, after 120 freeze–thaw cycles. This degradation is attributed to the progressive development of internal fractures and increased porosity, which cause a downward and rightward shift in the stress–strain curves—reflecting cumulative damage and a pronounced strain-softening trend.

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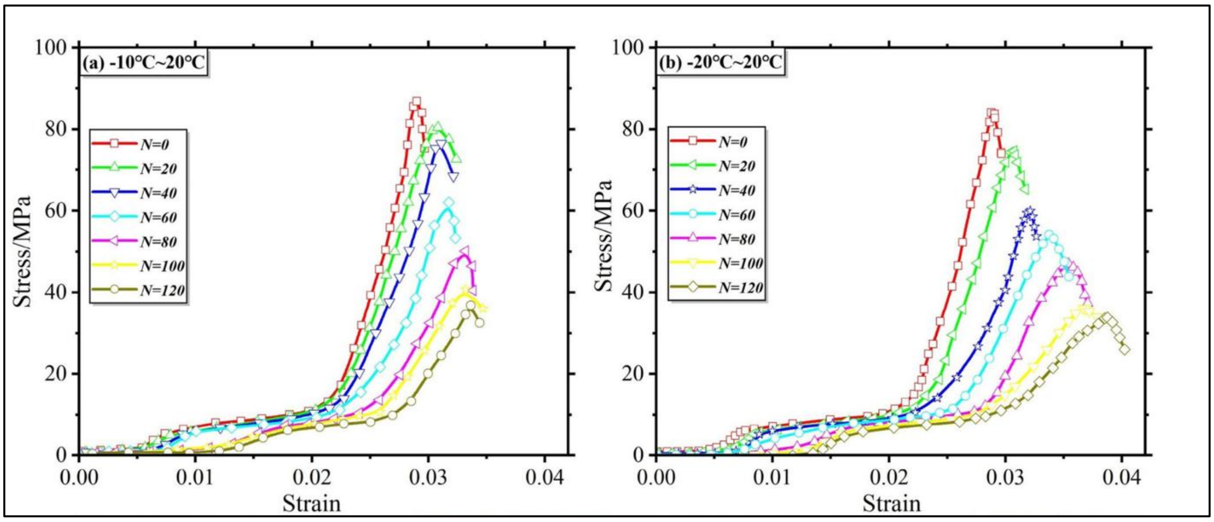

Fig. 1: Uniaxial compressive stress–strain curves and failure patterns of granite samples subjected to different freeze–thaw cycles.

Precipitation and Infiltration

The relationship between water ingress and pore pressure buildup in mine rock waste is primarily driven by geological and mechanical interactions, particularly in fault zones and karst collapse columns (KCCs). Water inrush events often occur due to the connection of cracks and the formation of water channels in the rock, exacerbated by mining activities that alter stress fields and increase permeability (Zhang, *et al.*, 2017) (Mu *et al.*, 2020). The mechanisms include the transition of seepage from pore flow to fracture flow, influenced by excavation depth and rock mechanical properties, which can lead to catastrophic failures if not managed (Liu, *et al.*, 2022; Li, *et al.*, 2017). Mitigation strategies involve monitoring pore water pressure and employing numerical models to predict water inrush risks, alongside reinforcing rock structures to withstand increased stress and prevent shear fractures that facilitate water ingress (Zhang, *et al.*, 2024; Mu, *et al.*, 2020). Understanding these mechanisms is crucial for developing effective prevention measures against water inrush disasters in mining operations

Thermal Effects

Temperature fluctuations create a relentless cycle of stress that gradually weakens mine waste rock slopes through repeated expansion and contraction, causing cumulative displacements that slowly push rock blocks out of stable positions (Bakun-Mazor, 2023). Thermomechanical weathering compounds this problem, as temperature variations generate thermal stresses reaching up to 18 GPa, driving crack propagation and systematically weakening rock integrity (Gage *et al.*, 2024). Ice-filled joints add complexity, as melting reduces shear strength and leaves slopes vulnerable to sudden failure (Physical Modelling of the Effect of Climate Change on Rock Slope Stability, 2022). Elevated temperatures also alter fundamental mechanical properties like friction angle and shear strength that are critical for slope stability (Raude, 2015). These thermal mechanisms create a complex web of degradation processes that demonstrate how climate change can profoundly undermine mining operations, requiring engineers to rethink their approaches to slope design and monitoring.

Biogeochemical Alteration

Mine waste rock slopes are subject to complex degradation processes driven by the interplay of oxidation, leaching, and microbial activity, which collectively contribute to significant environmental contamination. As exposed waste rock weathers on slope surfaces, acidophilic bacteria accelerate the oxidation of sulfide minerals, producing acidic drainage rich in heavy metals and forming secondary minerals that can either immobilize or further mobilize contaminants (Lu & Wang, 2012; Blowes, *et al.*, 2014; Ortiz-Castillo, *et al.*, 2021; Tam, *et al.*, 2024). The acidic conditions promote the leaching of metals such as iron, nickel, and copper, resulting in contaminated runoff that poses serious risks to surrounding ecosystems (Tam, *et al.*, 2024). Importantly, microbial communities within these slopes play dual roles-both enhancing metal release through bio-oxidation and contributing to bioremediation by transforming toxic metals into less harmful forms (Newsome & Falagán, 2021; Lu & Wang, 2012). This delicate balance between microbial mobilization and immobilization of metals highlights the need for

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continued research to inform the design, monitoring, and remediation of mine waste rock slopes in environmentally sensitive and geotechnically stable ways.

Wind Erosion/Drying Cycles

Another effect worth discussing is wind erosion and drying cycles which significantly contribute to particle loosening and crust weakening in mine waste rock slopes through a combination of mechanical degradation and changes in soil structure. The cyclic drying and wetting processes lead to a gradual deterioration of the physical and mechanical properties of rocks, including reductions in uniaxial compressive strength and elastic modulus, which can decrease by over 34% after multiple cycles (Yang, *et al.,* 2018). This degradation is attributed to mechanisms such as clay mineral swelling, microcrack evolution, and particle breakage, which collectively weaken the rock matrix (Zhang, *et al.*, 2021; Nihaaj, *et al.*, 2024). Additionally, the formation of surface crusts can alter the soil's response to erosive forces; while crusts may initially increase surface strength, they can also disrupt under wind action, leading to increased erosion (Singer & Shainberg, 2004). The interplay between these factors ultimately enhances slope instability, increasing the risk of sudden failures (Qin, *et al.*, 2018).

MONITORING AND MODELING ADVANCES

Monitoring Tools:

Modern mining operations have been revolutionized by advanced monitoring technologies that combine Interferometric Synthetic Aperture Radar (InSAR) and ground-based radar systems to provide real-time, sub-millimetric accuracy in detecting slope movements, even during harsh weather conditions (Atzeni, *et al.,* 2015). This technological combination captures both horizontal and vertical displacements simultaneously, giving engineers a complete three-dimensional picture of slope behavior (Maulana, *et al.,* 2023). When displacement data is integrated with Finite Element Modeling (FEM) systems, engineers can correlate real-world movements with rock mass mechanical properties, creating predictive models that forecast potential failures before they occur (Sertabipoglu, *et al.,* 2020). Enhanced slope unit analysis uses targeted geographical units to improve spatial analysis and identify unstable slopes with remarkable effectiveness (López-Vinielles, *et al.,* 2021). Real-world applications demonstrate these integrated approaches can successfully identify numerous unstable slopes and provide critical safety information for mining operations (López-Vinielles, *et al.,* 2021). Despite these advances, challenges remain in continuously validating data and integrating diverse information sources to maintain predictive accuracy. In research conducted by Maulana *et al.,* (2023) combined real-time ground-based radar for horizontal movements and satellite-based D-InSAR for vertical movements were complemented by finite element numerical modeling to understand the impact of these displacements on the rock mass's Young's modulus. This integrated approach provided a robust framework for slope stability assessment.

Real-time piezometer systems and satellite-based technologies have revolutionized the monitoring of mine waste rock slopes by enabling the creation of integrated early warning networks. Piezometers, which detect fluctuations in pore water pressure, are particularly valuable for signaling impending slope failures, as sudden increases often precede movement or collapse (Vaziri, *et al.*, 2010). When paired with inclinometers and temperature sensors, these instruments provide a layered understanding of subsurface and environmental conditions influencing slope stability, as demonstrated by Abeykoon, *et al.*, (2018).

Meanwhile, Synthetic Aperture Radar (SAR)-and more specifically Interferometric SAR (InSAR)-allows for continuous surface deformation monitoring across broad spatial scales. This technology captures both vertical and horizontal displacements, complementing ground-based data and enhancing the spatial resolution of slope movement detection (Chrzanowski & Wilkins, 2007; Maulana *et al.*, 2023). According to Guilhot *et al.*, (2021), integrating InSAR observations with ground instrumentation significantly improves the ability to detect early warning signs and refine displacement models.

The synergy between satellite imagery and real-time ground measurements supports the development of predictive models that inform risk management strategies. For instance, Maulana *et al.*, (2023) highlight how automated alert systems-triggered when piezometric or displacement thresholds are breached-allow for rapid, proactive interventions. Similarly, Chrzanowski and Wilkins emphasize the critical role of sensor integration in minimizing false alarms and improving decision-making accuracy.

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Nevertheless, ensuring data quality and system reliability remains a key challenge, particularly in geologically complex terrain where equipment durability, environmental variability, and sensor calibration can compromise long-term monitoring effectiveness (Binetti., 2024).

Modeling Approaches

Coupled hydro-mechanical modeling has emerged as a sophisticated and essential approach for evaluating the stability of mine waste rock slopes (Zhao, *et al.,* 2023). Software platforms such as FLAC, PLAXIS, and RS2 offer powerful simulation capabilities for capturing the intricate relationship between groundwater flow and soil or rock mechanical behavior. These tools are particularly effective in modeling transient slope responses to environmental triggers-such as intense rainfall events-which can rapidly alter pore water pressures and compromise slope integrity (Moradi, *et al.,* 2024).

Among these tools, FLAC's shear strength reduction technique has been highlighted as especially valuable, as it can automatically detect critical failure surfaces and simulate multiple failure mechanisms without requiring manual definition-streamlining the analysis process while improving reliability (Dawson & Roth, 2020). PLAXIS and FLAC are both well-regarded for their ability to simulate continuum mechanics and provide detailed insights into stress-strain relationships within saturated and unsaturated conditions (Castillo, *et al.,* 2025).

However, these fully coupled models often come with substantial computational costs. As Moradi, *et al.,* (2024) note, engineers are frequently forced to strike a balance between model fidelity and practical constraints. While simplified models may offer faster outputs, they often lack the precision required for sites experiencing dynamic hydrological changes.

Notably, RS2, though robust in many applications, may fall short in simulating the complex behavior of jointed or discontinuous rock masses, where the assumptions of continuum behavior become limiting. In such scenarios, distinct-element methods or discontinuum modeling approaches may be more appropriate (Eberhardt & Stead, 2011; Chen, *et al.,* 2016).

Given these variations, the selection of a modeling approach must be carefully tailored to the geological and hydrological characteristics of each site. Engineers must consider not only the accuracy and reliability of the chosen method, but also the computational efficiency, especially in high-stakes settings where slope failure poses significant environmental and safety risks (Jing, L., 2003).

Climate-Informed Geomechanical Modeling

Integrating machine learning with geomechanical modeling improves prediction of mine waste rock slope stability under climate-induced stressors by analyzing complex geomechanical data more accurately and efficiently. Geomechanical Integration of advanced finite element methods enable accurate representation of slope behavior under varying conditions by incorporating geological and geomechanical data. Hybrid ensemble methods combining multiple classifiers achieve high AUC values and significantly improved prediction accuracy (Sun, *et al.,* 2024; Qi & Tang, 2018). Despite promising advancements, challenges remain in capturing geological complexities and climate impacts, requiring continued research and model refinement Climate projection models are essential for predicting long-term stability of mine waste rock slopes under climate change, particularly assessing how precipitation and temperature variations influence geotechnical stability and waste cover system performance.

Climate Change Impacts: Increased temperatures destabilize slopes by affecting ice-filled joints in permafrost regions, while precipitation variability significantly impacts stability through rainfall intensity and frequency changes that reduce slope safety factors (Theocharis, *et al.,* 2022).

Methodological Approaches: Performance modeling requires evaluating extreme events and antecedent moisture conditions beyond average climate conditions for accurate net percolation and stability predictions. Statistical analyses of historical climate data capture precipitation variability effects on slope stability (O'Kane & Barbour, 2006).

Machine Learning Integration: Hybrid ensemble methods combining multiple classifiers with finite element geomechanical modeling achieve high accuracy rates (Karir, *et al.,* 2022; Sahoo, *et al.,* 2022; Sun, *et al.,* 2024; Qi & Tang, 2018). Tree-based models consistently outperform linear models using metrics like coefficient of determination and root mean square error (Karir, *et al.,* 2022; Sahoo, *et al.,* 2022).

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Climate projection uncertainties and complex climatic-geotechnical interactions highlight the need for continued research and model refinement to enhance predictive reliability.

CONTROVERSIES, KNOWLEDGE GAPS, AND UNCERTAINTIES

Scaling laboratory results to accurately predict the real-world behavior of mine waste rock slopes under climate stress remains one of the most formidable challenges in geotechnical engineering (Vriens, *et al.*, 2020). This process demands a careful balance between the precision of controlled laboratory testing and the inherent unpredictability of natural systems. To bridge this gap, engineers have adopted several integrative strategies, with field monitoring emerging as a critical tool for validating and contextualizing lab-based findings. A notable example is the seismic monitoring network at Rochers de Valabres, which delivers continuous real-time data on slope deformations and environmental conditions, significantly advancing the understanding of rockfall mechanisms (Senfaute, *et al.*, 2007).

The use of advanced geotechnical instrumentation, such as electrical resistance tomography (ERT), further enhances subsurface characterization by enabling visualization of internal slope conditions. However, as Hughes, *et al.*, (2016) caution, interpreting such complex datasets across multiple spatial and temporal scales introduces significant analytical challenges. To integrate these data streams, engineers employ numerical modeling approaches that combine mechanical models with empirical field data to simulate the impacts of climate variability on slope stability. In parallel, bounding theoretical models offer conservative estimates of potential slope behavior, but must be empirically validated to reduce uncertainties and ensure practical relevance (Senfaute, *et al.*, 2007; Hughes, *et al.*, 2008; Pigford & Chambre, 1985).

Despite these advancements, critical knowledge gaps persist, especially concerning the variability of geotechnical parameters over time and their evolving relationship with environmental drivers. As Hughes, *et al.*, (2016) highlight, this variability complicates long-term predictions and undermines confidence in model outputs. The most pressing uncertainty lies in understanding the long-term effects of climate change on slope stability across diverse geological contexts. Krautblatter and Moore, (2014) emphasize that this dynamic interaction between climatic forcing and geological heterogeneity introduces considerable uncertainty into predictive models.

These ongoing challenges underscore the need for continued interdisciplinary research, improved scaling methodologies, and robust data integration frameworks to enhance our ability to predict slope responses in a changing climate and ensure the long-term stability and safety of mine waste rock facilities.

IMPLICATIONS FOR MINE DESIGN AND RISK MANAGEMENT

The mining industry is undergoing a profound transformation as climate resilience, advanced monitoring technologies, and environmental, social, and governance (ESG) considerations increasingly shape mine design and risk management in a world marked by uncertainty(Maybee, *et al.*, 2023). Climate-resilient design has become a core priority, with operations like the Ballarat Gold Mine illustrating how the integration of climate change projections into closure planning and the reinforcement of tailings storage facilities against extreme weather can significantly improve both operational resilience and community sustainability. These outcomes are achieved through early hazard identification and proactive design adjustments (Trotta & Ridgway, 2022).

One of the most significant methodological shifts is the transition from traditional deterministic safety factors to probabilistic approaches. Tools such as Monte Carlo simulations and risk-based design models offer more refined risk assessments, enabling optimized support strategies that balance safety and cost-effectiveness. This marks a departure from the often overly conservative factors of safety used in conventional underground construction (Amusin & Eisenberg, n.d.).

Simultaneously, real-time monitoring systems, powered by the Internet of Things (IoT) and machine learning algorithms, are revolutionizing proactive risk management. These technologies enable the continuous collection and analysis of operational data, allowing for immediate anomaly detection and response. As noted by Iwe, *et al.*, (2023), automated systems not only enhance operational efficiency and safety but also play a vital role in reducing the probability of environmental incidents. Barry, (2020) further emphasizes the growing role of automation in sustainable operations.

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Beyond technical innovation, ESG considerations have become pivotal in guiding mine design. The inclusion of environmental and social risks in early-stage planning is essential for meeting regulatory expectations and aligning with stakeholder values. Models like the Social Value Capital Decision Model support this integration, offering frameworks that capture broader community impacts (Nehring & Knights, 2024). At the same time, adherence to international benchmarks such as the Global Industry Standard on Tailings Management (GISTM) and Towards Sustainable Mining (TSM) ensures alignment with ethical investment criteria and operational transparency (Barry, 2020).

Despite these advances, the sector continues to face barriers to full integration, including regulatory complexity, cost concerns, and operational inertia. Achieving a balance between innovation and traditional practices remains a significant challenge-one that demands sustained collaboration and leadership across all levels of the mining industry.

FUTURE RESEARCH DIRECTIONS

The future of understanding mine waste rock slope behavior under climate stress hinges on bold and collaborative research initiatives capable of transcending disciplinary boundaries. Developing universal climate-slope response frameworks is considered the "holy grail" of this field, requiring predictive models that function across diverse climatic regimes and geological contexts. Such models must integrate the complex interactions between stress redistribution**,** permafrost degradation**,** and altered hydrology**,** ultimately enhancing hazard forecasting and risk management strategies (Krautblatter & Moore, 2014; Senfaute *et al.*, 2007).

The integration of multidisciplinary expertise offers a transformative opportunity. By combining geotechnical engineering**,** climate science**,** and artificial intelligence**,** researchers can unlock powerful new predictive capabilities. AI systems, for instance, can process and learn from vast datasets generated by field monitoring systems to identify subtle trends and failure precursors that traditional methods may overlook (Senfaute, *et al.*, 2007). Furthermore, collaborative projects involving multiple universities and research institutions are proving instrumental in overcoming the limitations of siloed approaches. As demonstrated by Hughes, *et al.*, (2008), such partnerships facilitate the development of robust modeling frameworks and monitoring technologies that no single entity could achieve independently.

A key enabler of this progress is the open sharing of mine-related geotechnical data**.** As Toll, (2022) argues, data-sharing platforms between academia, industry, and government can significantly accelerate innovation by allowing for model validation across broader datasets and by promoting the co-development of novel monitoring tools. In parallel, the establishment of global slope observatories-dedicated to long-term monitoring of slope behavior under changing climatic conditions-could generate invaluable empirical insights. These observatories would function not only as data collection hubs but also as international collaboration platforms to guide adaptive geotechnical infrastructure planning (Hughes *et al.*, 2008; Toll, 2022).

Despite these promising directions, substantial implementation challenges remain. Realizing global observatories and cross-sector collaborations requires considerable financial investment**,** data standardization**,** and international cooperation**.** Integrating diverse datasets involves addressing compatibility issues**,** methodological inconsistencies, and institutional resistance. Moreover, establishing effective data-sharing protocols requires complex negotiations between stakeholders with differing priorities and regulatory frameworks. As such, progress in this domain depends on unprecedented levels of global coordination, long-term commitment, and an open-science mindset across the mining and geotechnical research communities (Intrieri., 2021).

CONCLUSION

The stability of mine waste rock slopes is profoundly impacted by a complex interplay of geological, hydrological, and increasingly, climate-induced factors. The paper underscores that climate change acts as a significant threat multiplier, introducing new degradation mechanisms such as extreme precipitation, freeze-thaw cycles, thermal fluctuations, biogeochemical alterations, and drying/wetting cycles, which systematically weaken rock structures and increase instability risks. While significant progress has been made in monitoring technologies, including InSAR and real-time piezometers, and sophisticated modeling approaches like coupled hydro-mechanical models, challenges remain in accurately predicting long-term slope behavior due

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to the inherent variability of geotechnical parameters and the dynamic nature of climatic forcing. Addressing these complex challenges necessitates a paradigm shift towards climate-resilient mine design and risk management, integrating advanced monitoring, probabilistic risk assessments, and real-time data analysis. Future research must focus on developing universal climate-slope response frameworks, fostering multidisciplinary collaboration, and promoting open data sharing to bridge existing knowledge gaps. Ultimately, ensuring the long-term stability and environmental safety of mine waste rock facilities in a changing climate requires unprecedented levels of global coordination, sustained commitment, and an open-science mindset across the mining and geotechnical research communities.

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