Proceedings of CONF-FMCE 2026 Symposium: Smart City and Infrastructure Engineering
DOI: 10.54254/2755-2721/2026.CH37631

Safety and Resilience in Slope Engineering Design for New Buildings under Extreme Rainstorm Climates

Shijia Xu

Department of Civil Engineering, Hong Kong Chu Hai College, Hong Kong, China
233301201@student.chuhai.edu.hk

Abstract. The safety of construction slopes holds significant importance in engineering and architecture, with the lack of resilience against extreme weather conditions being particularly critical. This paper systematically examines the fundamental flaws in traditional design theories regarding the limitations of compression-shear stress paths and the assumption of constant soil parameters. It delves into the systemic vulnerabilities in resilience across the entire lifecycle caused by operational supervision gaps and post-event regulatory gaps in the current construction system. Additionally, it reveals the consequences of mechanistic isolation between structural support and ecological protection, as well as the oversimplified engineering approach resulting from outdated drainage system standards, through real-world disaster case studies. Based on this, this article proposes a theoretical revision direction for constructing a tension shear fluid-solid coupling unsaturated soil mechanics system, explores a differentiated zoning control mechanism based on quantitative risk analysis (QRA), and integrates digital Bayesian pre-evaluation methods with on-site observations. The research aims to provide rigorous theoretical support for the disaster-resistant design of high-risk building slope engineering, and promote the transformation of slope engineering from static defense to a dynamic resilience management paradigm throughout its lifecycle.

Keywords: building slope, Safety resilience, Fluid structure coupling, Quantitative Risk Analysis (QRA), Bayesian update

1. Introduction

The stability of building slope engineering is a prerequisite for ensuring the safety of urban infrastructure and residents' lives and property in mountainous and hilly areas. In recent years, due to the frequent occurrence of extreme hydrometeorological events and the sharp increase in sudden heavy rainfall, there have even been catastrophic landslides of newly built building slopes and cut soil slopes that exceed current design safety standards at the national level. Such sudden instability events not only expose the vulnerability of engineering entities in resisting hydrological loads beyond the benchmark, but also deeply reflect the systematic lack of safety resilience in the current building slope geotechnical design standards and specifications system. The traditional slope design paradigm highly relies on static load assumptions and deterministic parameter inputs, and its theoretical core fails to truly depict the loss of unsaturated soil matric suction induced by extreme

© 2026 The Authors. This is an open access article distributed under the terms of the Creative Commons Attribution License 4.0 (https://creativecommons.org/licenses/by/4.0/).

DOI: 10.54254/2755-2721/2026.CH37631

rainfall, the accumulation of microstructural damage, and the complex fluid-structure coupling response mechanism of Hydro-Mechanical (HM). In engineering practice, the management inertia of "emphasizing initial design and neglecting long-term supervision" and the singular approach of "emphasizing rigid support and gentle ecology" further exacerbate the vulnerability of slope rock and soil mass to disasters under extreme weather conditions.

In response to the systemic deficiencies mentioned above, it is urgent to re-examine and reconstruct the logical framework of slope safety design from the dual perspectives of the origin of geotechnical mechanics and engineering lifecycle management. Therefore, this article aims to systematically deconstruct the mechanical limitations of the current slope design theory and specification system, and propose a resilience enhancement strategy based on fluid-structure coupling, Bayesian reliability update, and quantitative risk analysis (QRA) by combining typical engineering disasters and experimental cases, in order to provide rigorous theoretical support and technical paradigms for disaster-resistant design of high-risk slope engineering.

2. Theoretical level lack of security resilience and mechanism deconstruction

2.1. The constitutive mismatch between classical compression shear soil mechanics and tensile shear failure

The mechanical foundation of current slope safety design is deeply rooted in classical geotechnical theory, especially the Terzaghi effective stress principle and saturated soil drainage consolidation theory [1]. However, the establishment of the classical soil mechanics theoretical framework is mainly based on foundation loading engineering, and its core mechanical logic is to predict the stability process of soil under external loading conditions, including compression, shear stress, deformation, porosity reduction, and moisture content reduction, accompanied by soil skeleton compaction and increased shear strength. Directly applying this set of constitutive logic based on "compression shear stability" to the analysis of slope instability and failure results in fundamental mechanical constitutive misalignment. The essence of slope instability in excavation and construction is a typical external unloading process. With the formation of the free surface, the internal stress of the slope is redistributed, and the surface soil gradually breaks away from the compressive shear state and enters the tensile shear stress path. During this type of evolution process, the soil will inevitably undergo tensile deformation, resulting in a sharp increase in internal porosity; In the face of an extreme rainstorm, rainwater will rapidly infiltrate along the microcracks, leading to the rise of water saturation of the soil mass, rapid failure of matrix suction, and then causing a sharp decline of shear strength parameters. This rational generalization that equates the compression shear soil mechanics with the tension shear soil mechanics will eventually lead to the fact that the current specifications can not accurately describe the real mechanical mechanism of the expansion of microcracks, strain softening, and nonlinear degradation in the slope during rainstorm infiltration, thus constituting the most fundamental theoretical source of the loss of safety toughness in slope design.

2.2. Absolute strength masking of deterministic ratio safety factor method

The current slope design specifications generally adopt the limit equilibrium method (LEM) or finite element strength reduction method (SRM), defining the safety factor as the ratio of the average shear strength along the potential sliding surface to the actual applied sliding shear stress [1]. This single deterministic ratio safety factor method has significant flaws in both mathematical logic and

DOI: 10.54254/2755-2721/2026.CH37631

physical essence. Due to the relatively low absolute shear strength value (especially cohesion) of natural soil or artificially compacted fill, it is usually only a few thousand to tens of kilopascals. In engineering design, even if reinforcement measures such as adding anchor rods, anti-slip piles, or gravity retaining walls are used to achieve the minimum safety factor required by regulations, the absolute strength increase they can provide is still very limited in practical operation. This ratio-based evaluation system is prone to masking the low-quality properties of geotechnical materials themselves. In extreme rainstorms, the shear parameters of highly water-sensitive soil (such as residual soil and loess) will drop precipitously, or even drop sharply to the residual strength or close to zero, resulting in an extremely low toughness level of the slope when facing super standard rainfall, which is very easy to induce sudden brittle collapse.

2.3. Failure assuming constant strength parameters under wet-dry cycles

In conventional numerical calculations and engineering design models for slope stability, the shear strength parameters of soil (effective cohesion and effective internal friction angle) are usually simplified as constants that do not evolve over time or change with hydrological conditions. However, the surface rock and soil of building slopes that are exposed to the natural environment for a long time are difficult to protect from the alternating erosion of drought and rainfall. A large number of indoor triaxial shear tests and on-site in-situ tests have fully confirmed [2] that repeated wet-dry cycles can lead to significant nonlinear damage and degradation characteristics of geotechnical materials. Taking artificially compacted loess and loess slopes as an example, after experiencing the cycle of rainfall humidification and sunlight dehumidification, the expansion and contraction of hydrophilic minerals inside the soil lead to microstructure reorganization and crack development. Related experimental studies have shown that as the number of wet-dry cycles increases, the peak shear strength and deformation resistance of the soil sharply decrease; especially after 6 to 18 cycles, the strength parameters can decrease by more than 40% and eventually converge to an extremely low stable residual state [3]. The current conventional calculation model seriously lacks consideration of this dynamic deterioration mechanism of parameters driven by water content and dry-wet duration. It is not only unable to accurately capture the transient evolution of the uneven distribution of pore water pressure along the slope burial depth at the beginning of a rainstorm, but also causes the static numerical simulation results to be seriously divorced from the field reality, which significantly increases the actual safety reserve of the slope at the beginning of a rainstorm.

3. Resilience deficiency and case analysis of systems and the entire engineering cycle

3.1. Operation supervision gap and lagging review mechanism

In the traditional construction system, infrastructure slope and site leveling projects are often regarded as one-time projects attached to the main building, and there is a general tendency in the industry to prioritize initial design approval over long-term operation supervision. The slope safety review system has not been standardized and legalized. Often, after the initial review of design drawings and completion acceptance of the project, there is a lack of all-weather stress-strain and hydrological automated monitoring network coverage throughout its entire life cycle. During decades of service, due to changes in the surrounding terrain and landforms, blockages in underground drainage ditches, or hidden structural damage caused by long-term small-scale rainfall accumulation, it is often difficult to identify in a timely manner through routine visual inspections.

DOI: 10.54254/2755-2721/2026.CH37631

This fault, monitored during the operation period, makes the slope approach its mechanical critical state imperceptibly. Once encountering an extreme rainstorm beyond the design basis, the originally accumulated hidden diseases will be triggered instantly, leading to catastrophic collapse of the slope.

3.2. The gap in post-governance norms and the vicious cycle of "damage repair"

The focus of current geotechnical engineering design standards is highly concentrated on the initial excavation and support treatment of newly built slopes, while for residual slopes that have experienced local sliding damage and severe disturbance to overall structural integrity, there is a serious lack of specialized guidelines with a safety and resilience perspective for their reconstruction and repair design. In engineering practice, post-disaster slope treatment often adopts an emergency passive repair mode of "treating the head when the head hurts and treating the foot when the foot hurts", which fails to systematically upgrade the toughness of the slope after damage from the perspective of quantitative risk assessment (QRA) and deep reconstruction of geotechnical quality. This normative gap directly results in the repaired slope still retaining its original weak slip zones and infiltration channels. When faced with the impact of the next extreme hydrological event, these "sick in service" slopes are prone to more severe secondary instability, causing the engineering project to fall into an inefficient vicious cycle of "destruction emergency repair re destruction".

3.3. Warning of typical regional disaster cases

The current building slope regulations in China mainly rely on the height of the slope and the possible damage consequences in the classification of safety levels, and fail to fully consider the detailed management of relevant regulatory departments and the lack of post-construction governance regulations. The lack of such a refined grading design system has led to painful engineering lessons in extreme weather conditions. Taking the southeast coastal typhoon rainstorm-prone area as an example, under the extremely heavy rainfall brought by the super typhoon "Lichma" in 2019, Shiyang North Slope in Taishun County, Zhejiang Province, the pore water pressure of the slope increased sharply, and the effective stress decreased sharply. The fundamental reason is that the staff of the relevant departments lack awareness of protection and follow-up care. The quantitative risk assessment study shows that the instability probability of the slope under extreme rainstorm conditions is several times higher than that of conventional rainfall [4]. Due to management negligence, this consequence poses a very high risk to buildings and personnel at the foot of the slope. On the other hand, in the northwest Loess Plateau region, a high fill loess slope on a certain highway experienced multiple short-term heavy rainfall events [4]. Due to a lack of understanding of the basic concepts of loess and a single follow-up protection, rainwater quickly seeped along vertical joints, causing deep creep and sudden sliding and damage. The above real cases profoundly demonstrate that ignoring the importance of safety protection and the lack of a comprehensive design for specific soil mechanics degradation will inevitably lead to the loss of resilience and recovery of slopes in the face of extreme disasters.

DOI: 10.54254/2755-2721/2026.CH37631

4. Analysis of the shortcomings and effectiveness of the singularity of engineering design methods

4.1. Mechanical separation between rigid support and flexible ecological protection

The traditional design methods for building slope engineering are extremely singular, highly relying on pure mechanical rigid reinforcement systems such as reinforced concrete retaining walls, anti-slip piles, lattice beams with spray anchor support [5]. This design approach often completely separates the strong support of geotechnical structures from the ecological protection of surface vegetation, believing that vegetation only has the function of surface greening and slight erosion prevention. However, modern ecological geotechnical engineering research shows that rigid structures and flexible rock and soil often have significant deformation incompatibility under extreme rainstorms. When small plastic creep occurs inside the slope, the rigid panel is prone to cracking, forming hidden tensile cracks, providing an advantageous seepage channel for rainwater to directly reach the deep sliding zone, ultimately inducing sudden brittle failure.

4.2. Empirical study on the mechanical contribution of root soil composite structures

The defect of rigid support is undeniable. If the plant root system and reinforced concrete can be regarded as a whole, the root soil composite will significantly improve safety and toughness, providing sustainable development for building slope engineering. Firstly, when rainwater infiltrates the soil composite, the spatial network of plant roots within it will effectively form a solid skeleton anchoring structure for the soil, providing a shear strength influence of up to 27% for the composite soil [5]. As the plant roots gradually penetrate, the front, main, and rear roots of the root system will be sequentially pulled and yield through different stress points, thereby improving the tensile performance and shear toughness of a single rigid support. Its dense root network can also significantly reduce the pressure of rainwater and compensate for the key structural defects of rigid support.

4.3. Standard lag and advantages of drainage system, seepage induced disasters

The current design standards for surface and underground drainage of building slopes are generally low, and the hydraulic calculation of the cross section of flood intercepting ditches and drop ditches is usually based on the historical static return period of rainstorms that occur once in many years. In the current frequent extreme rainstorm climate, the short-term strong rainfall far exceeds the historical extreme value. The hardened road surface and upper slope rapidly evolved into a huge concentrated catchment area, causing the drainage system, with severely insufficient design capacity, to instantly overflow and overflow. Even more deadly is that the surface drainage system of the slope often fails to be integrated with the deep anti-seepage and dewatering system inside the slope for joint design. The overflow water flows freely on the slope or along weak structural links such as shallow fully weathered layers and bedrock contact surfaces, resulting in strong dominant seepage and fluid-solid coupling. This process not only rapidly dissolves the stable matric suction inside the unsaturated soil, but also leads to a geometric increase in local pore water pressure [6]. The continuous accumulation of ultra-static pore water pressure promotes the rapid penetration of plastic strain bands from the shear outlet at the foot of the slope to the top of the slope, ultimately evolving into highly destructive overall liquefaction or deep sliding, becoming the most direct trigger for igniting modern slope landslide disasters.

DOI: 10.54254/2755-2721/2026.CH37631

5. Countermeasures and application cases for improving the safety and toughness of building slopes in extreme rainstorms

5.1. "Ecological mechanical" collaborative protection and anti-seepage design that combines rigidity and flexibility

In response to the lack of coordination between traditional rigid supports and flexible rock and soil media deformation, slope engineering design must transform towards a collaborative system that combines rigidity and flexibility. In deep anti-slip design, rigid structures such as anti-slip piles and geological anchor cables should be optimized to resist overall shear slip; In shallow tensile and slope protection, it is necessary to break the traditional mechanical solidification thinking and incorporate the mechanical contribution of the "root soil composite" into the quantitative design category. By explicitly introducing the additional cohesive force Δc provided by plant roots and the additional internal friction angle $\Delta \gamma$ into the limit equilibrium equation, effective suppression of surface tension cracks can be achieved. At the same time, relying on the canopy interception and root system network of ecological protection, an integrated anti-seepage and drainage network of "slope ecological hysteresis internal deep drainage" will be constructed to cut off the dominant seepage channels from the physical source, curb the hydraulic-mechanical (HM) fluid-solid coupling induced disasters, so as to significantly improve the impact resistance and resilience of the slope system in extreme rainstorms [7].

5.2. Differentiated zoning control based on quantitative risk analysis (QRA)

Faced with the excessive hydrological loads caused by climate extremes, it is difficult to achieve an effective balance between economic investment and life safety by continuing to use the "one size fits all" deterministic global reinforcement method. Therefore, it is necessary to comprehensively introduce and promote the mechanism of Quantitative Risk Analysis (QRA). Taking the years of slope safety risk management practice by the Geotechnical Engineering Office (GEO) in Hong Kong as a successful example, the disaster prevention perspective has been elevated from a single focus on "enhancing structural resistance" to "controlling expected losses from disasters" [8]. By introducing Monte Carlo simulation (MCS) to evaluate the spatial failure probability of the slope under extreme rainstorms at different return periods, and combining the prediction of the migration distance of sliding collapse mass and the vulnerability analysis of the bearing body (high-density residential buildings, trunk roads and lifeline projects along the slope), the annual expected death toll and economic loss are calculated quantitatively. On this basis, implement fine-grained differentiated zoning control and draw a landslide risk map. According to the socially and economically acceptable risk criteria (ALARP principle), priority treatment and funding allocation will be implemented for high-risk slopes, completely breaking the inefficient stalemate of traditional extensive disaster prevention [9].

5.3. Full lifecycle dynamic resilience management framework

To enhance the safety and resilience of building slopes, it is necessary to cross the traditional "one-time completion and termination" perspective in management systems and establish a dynamic management system for resilience throughout the entire lifecycle, covering front-end safety auditing, mid-range automatic monitoring, and back-end emergency response [10]. First, a specialized government slope safety regulatory agency should be established from top to bottom, and a regular

DOI: 10.54254/2755-2721/2026.CH37631

maintenance audit and statutory repair order issuance mechanism should be established through legislation to mandate slope owners to conduct regular assessments and reinforcement upgrades of hidden dangers in old and new slopes; In addition, it will vigorously promote the application of the Internet of Things and digital twin technology, and establish an open and transparent digital slope information system (SIS) [11]. Establish a high-precision multi-source data landslide warning model based on short-term heavy rainfall forecasts from meteorological departments. During extreme weather disaster periods, by issuing graded warning signals to the public and implementing community evacuation and road traffic control, the physical exposure of the carrier is comprehensively reduced. Through the dual efforts of engineering hard resistance and social soft resilience, the ultimate goal is to achieve long-term disaster prevention for building slopes throughout their entire lifecycle [12].

6. Conclusion

Focusing on the design theory, specification system, and engineering practice of new building slope engineering in extreme rainstorm climate, this paper systematically analyzes the lack of safety toughness in the current system and puts forward cutting-edge countermeasures in combination with real disaster cases. The research value of this article lies in breaking the traditional thinking constraints of static deterministic design in slope engineering, and for the first time systematically integrating the mechanical mechanisms of tensile shear failure, the nonlinear degradation model of wet dry cycles, and the international frontier Bayesian reliability back analysis and QRA quantitative risk control. This provides a rigorous academic perspective and highly operational engineering guidance logic for the transformation of building slope engineering in high-risk mountainous areas and coastal rainy areas in China from "passive emergency disaster resistance" to "active resilience defense", which has important practical significance for ensuring urban public safety under extreme weather conditions.

References

[1] Yue, Z., & Xu, Q. (2014). The fundamental flaws and disaster consequences of current slope engineering safety design theory. *Journal of Geotechnical Engineering, 36*(9), 1601–1606. (in Chinese). https://doi.org/10.11779/CJGE201409005

[2] Wu, J. B., et al. (2022). Risk assessment of slope disasters induced by typhoon-rainfall in the southeast coastal area China: A case study of the Shiyang north slope. *Journal of Geomechanics, 28*(4), 583–595. (in Chinese). https://doi.org/10.12090/j.issn.1006-6616.2021168

[3] Chen, X., Chen, C., & Guo, Y. (2025). Long term stability study of abandoned soil slopes in ditches under wet dry cycles. *Journal of Water Resources and Water Engineering, 36*(1), 199–207. (in Chinese). https://doi.org/10.11705/j.issn.1672-643X2025.01.22

[4] Zhou, S., Bian, X., Li, W., et al. (2024). Nonlinear degradation study on the stability of Q2 loess slope in northern Shaanxi considering rainfall conditions. *Geological Science and Technology Bulletin, 43*(3), 218–226. (in Chinese). https://doi.org/10.19509/j.cnki.dzkq.tb20230432

[5] Luo, Y., Zhang, X., & Gao, Y. (2024). Stability of rainfall infiltration in root soil composite slopes under cold and arid environments. *Science, Technology and Engineering, 24*(24), 10500–10507. (in Chinese). https://doi.org/10.12404/j.issn.1671-1815.2306579

[6] Liu, X., Jie, H., Jiang, S., et al. (2023). Reliability analysis of slope stability observation information fused with historical rainfall. *Earth Science, 48*(5), 1865–1874. (in Chinese). https://doi.org/10.3799/dqkx.2022.327

[7] Guardiani, C., Soranzo, E., & Wu, W. (2022). Time-dependent reliability analysis of unsaturated slopes under rapid drawdown with intelligent surrogate models. *Acta Geotechnica, 17*(4), 1071–1096. https://doi.org/10.1007/s11440-021-01364-w

[8] Jiang, S., Liu, X., & Huang, J. (2022). Non-intrusive reliability analysis of unsaturated embankment slopes accounting for spatial variabilities of soil hydraulic and shear strength parameters. *Engineering with Computers,*

DOI: 10.54254/2755-2721/2026.CH37631

38, 1–14. https://doi.org/10.1007/s00366-020-01108-6

[9] Guo, Z. Y., Huang, Q. B., Liu, Y., et al. (2023). Model experimental study on the failure mechanisms of a loess-bedrock fill slope induced by rainfall. *Engineering Geology, 313*, Article 106979.

[10] Lian, B. Q., Wang, X. G., Zhan, H. B., et al. (2022). Creep mechanical and microstructural insights into the failure mechanism of loess landslides induced by dry-wet cycles in the Heifangtai platform, China. *Engineering Geology, 300*, Article 106589.

[11] Lu, Y., Chen, J., Huo, Z., et al. (2022). Analysis of the instability process of loess landslides under rainfall and excavation: Taking the Laomiao landslide in Yangchang Village, Changwu County, Guanzhong Region as an example. *Geological Science and Technology Bulletin, 41*(6), 95–104. (in Chinese).

[12] Zhao, H., Wang, D., Zhang, L., et al. (2017). Hong Kong landslide disaster prevention and reduction management system. *Journal of Glaciology and Geocryology [Glacier and Frozen Soil], 39*(3), 696–700. (in Chinese). https://doi.org/10.7522/j.issn.1000-0240.2017.0079