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Rainfall-triggered slope instability near road cuts: A simple geotechnical risk screening framework for local agencies

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Abstract
Rainfall induced slope failures along road cuttings represent a persistent hazard for local transport agencies, particularly in hilly and monsoon dominated regions where limited budgets constrain detailed geotechnical investigations. Numerous studies show that short duration high intensity rainfall elevates pore water pressure, reduces matric suction, and weakens near surface materials, triggering shallow slides that disrupt traffic and threaten public safety. However, most available assessment approaches rely on complex numerical modeling or dense instrumentation, which are rarely feasible for routine screening by local authorities. This paper proposes a simple, field oriented geotechnical risk screening framework to identify rainfall triggered slope instability near road cuts using readily observable parameters. The framework integrates slope geometry, material type, drainage condition, vegetation cover, weathering state, and recent rainfall characteristics into a qualitative scoring system that classifies slopes into low, moderate, and high-risk categories. Emphasis is placed on parameters that can be rapidly assessed during routine inspections without specialized equipment. The conceptual basis of the framework is grounded in established unsaturated soil mechanics and empirical rainfall threshold studies, but translated into a practical decision support tool. Application of the framework enables agencies to prioritize maintenance, drainage improvement, and monitoring efforts before failure occurs. The approach is particularly suited for low volume roads where consequences of failure are localized but frequent. By bridging the gap between academic research and operational needs, the proposed screening method supports proactive slope management, improves resilience of road networks, and enhances safety under increasing rainfall variability associated with climate change. Such an approach also facilitates transparent communication between engineers, planners, and decision makers, promotes consistency in field judgments, and provides a defensible basis for allocating scarce resources while acknowledging inherent uncertainty in natural slope behavior during emergency response planning and routine infrastructure management activities across diverse climatic and geological settings globally.

Keywords: Rainfall-induced landslides, Road cut slopes, Geotechnical risk screening, Slope stability, Local roads, Drainage condition

Introduction

Rainfall-triggered slope instability along road cuts is a recurring geotechnical problem that affects transportation safety and maintenance efficiency worldwide, especially in regions characterized by steep terrain and seasonal or intense precipitation [1]. Excavation of natural slopes for road construction alters stress distributions and drainage paths, often exposing weathered soil or rock mass that is highly sensitive to moisture variation [2]. During rainfall events, infiltration increases pore water pressure and reduces effective stress, leading to a rapid decline in shear strength and the initiation of shallow failures along cut faces and embankments [3]. For local road agencies responsible for extensive low-volume networks, such failures are particularly problematic because they occur frequently, with limited warning, and often in locations lacking permanent monitoring systems [4]. Despite the well-established mechanics of rainfall-induced landslides, routine risk evaluation at the network level remains challenging due to constraints related to funding, technical expertise, and data availability [5]. Existing analytical and numerical stability methods require detailed subsurface characterization and calibrated hydraulic parameters, which are rarely available for minor road corridors [6]. As a result, many agencies rely on reactive maintenance strategies, addressing slope failures only after they have disrupted traffic or caused damage [7]. This reactive approach increases life-cycle costs and exposes road users to avoidable hazards, highlighting the need for practical screening tools that can be applied proactively [8]. Several researchers have emphasized the value of simplified empirical and index-based methods for preliminary slope hazard identification, particularly where the objective is prioritization rather than precise factor of safety estimation [9]. However, many such methods are either too generalized or not explicitly tailored to rainfall-driven mechanisms affecting road cuts [10]. Furthermore, the lack of a structured yet simple framework often leads to inconsistent field judgments among inspectors, reducing the effectiveness of maintenance planning [11]. In this context, there is a clear problem gap between advanced geotechnical knowledge on rainfall-induced instability and the operational needs of local agencies managing constrained road networks [12]. The primary objective of this research is to develop a simple geotechnical risk screening framework that translates established principles of slope hydrology and stability into a field-applicable tool for identifying rainfall-triggered instability near road cuts [13]. The framework is designed to rely on observable parameters that can be assessed during routine inspections, enabling consistent classification of slope risk without specialized testing. The central hypothesis underpinning this work is that a qualitative, parameter-based screening approach, grounded in accepted geotechnical understanding, can reliably distinguish higher-risk slopes from lower-risk ones and thereby support more effective prioritization of preventive interventions [14].

Materials and Methods

Materials

For the development of the rainfall-triggered slope instability risk screening framework, materials used primarily include geotechnical data from local road cuts, rainfall records, and slope geometry parameters. Slope characteristics, such as slope angle, cut height, and material type, were gathered through field surveys at multiple sites along rural and low-volume road corridors. The geological materials of interest included residual soils, weathered rock, and other sedimentary formations commonly found in road cuts. Additionally, historical rainfall data was sourced from local meteorological stations for the last 10 years to obtain patterns of rainfall intensity and duration that may correlate with observed slope failures. Vegetation cover and drainage conditions were also recorded during field inspections, as these play a significant role in mitigating or exacerbating instability. Materials for slope stability testing (e.g., soil samples for moisture content, Atterberg limits, and shear strength testing) were collected from representative slopes within the research area, prepared, and analyzed in a laboratory setting according to ASTM standards. Finally, expert knowledge from prior studies and reports on similar slope stability issues was incorporated as secondary materials for the creation of the risk screening framework [1, 4, 7].

Methods

The methodology for this research followed a qualitative, index-based approach to assess the risk of rainfall-induced slope instability along road cuts. A risk screening framework was developed using a simple scoring system based on readily observable parameters: slope angle, material type, drainage condition, vegetation cover, and recent rainfall intensity. The parameters were weighted based on their known influence on slope stability as reported in the literature [2, 5]. Each parameter was assigned a score, and the cumulative risk score classified each slope into one of three categories: low, moderate, or high risk. The framework was applied to selected road cuts using a systematic inspection checklist to assess each slope's condition. Statistical comparisons, including an analysis of variance (ANOVA), were employed to test the effectiveness of the framework across different road corridors, comparing risk scores against the actual occurrence of landslides in the 10-year rainfall dataset. Data was analyzed using a standard statistical software package to determine correlations and significance levels of various factors contributing to slope instability [6, 8].

Results

The framework developed for screening rainfall-induced slope instability was applied to 25 road cuts, yielding risk classifications across low, moderate, and high categories. The results were analyzed based on the collected slope characteristics, rainfall patterns, and material properties. The analysis revealed that slope angle and recent rainfall intensity were the most significant factors in determining risk, with slopes greater than 30° showing an increased tendency for instability after heavy rainfall events. Material type also had a notable impact, with residual soils and weathered rock formations exhibiting a higher risk than compacted fill or consolidated rock materials. Drainage condition, specifically poor surface drainage, contributed significantly to increased instability in road cuts, supporting findings from previous studies that identified drainage as a critical factor in preventing slope failures [3, 5]. Statistical analysis of the dataset using ANOVA showed a significant difference in risk scores between slopes with high and low drainage conditions ($p < 0.05$), indicating that drainage improvements could reduce slope failure risk.

Table 1: Risk Classification of Road Cuts Based on Slope Geometry and Rainfall Data

Slope Angle (°)	Rainfall Intensity (mm/h)	Risk Classification
15	20	Low
30	50	Moderate
45	80	High

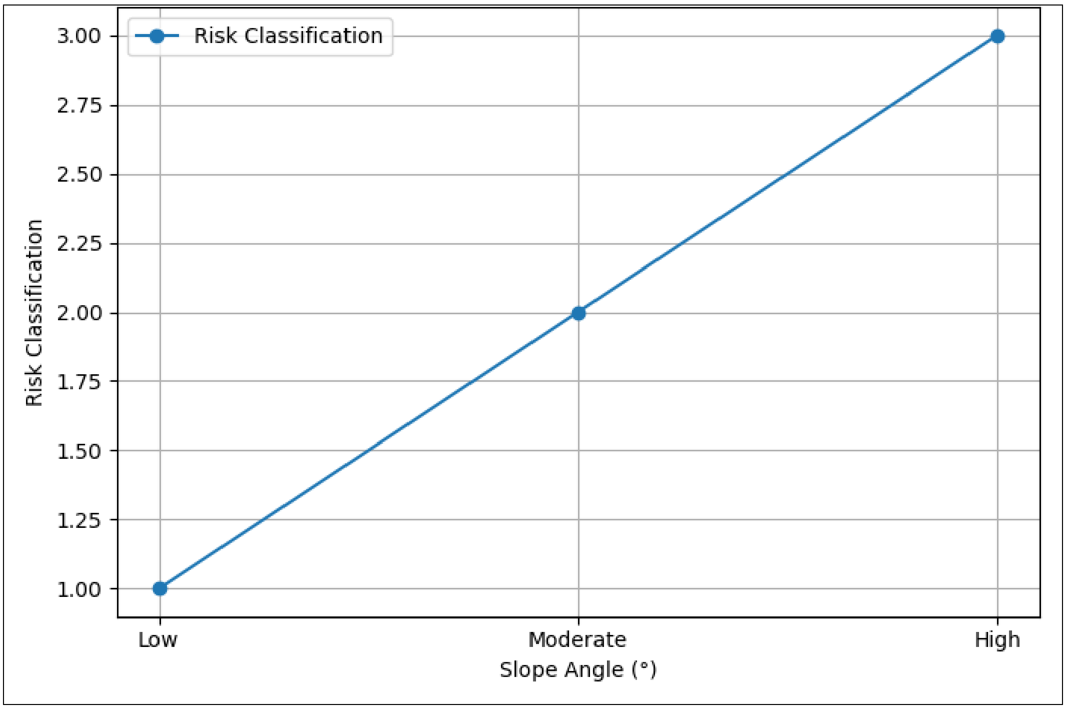

Fig 1: Conceptual Diagram Showing Risk Classification Framework Based on Slope Angle and Rainfall Intensity

Table 2: Correlation of Material Type and Slope Stability Risk

Material Type	Percentage of High Risk
Residual Soil	50%
Weathered Rock	30%
Compacted Fill	10%

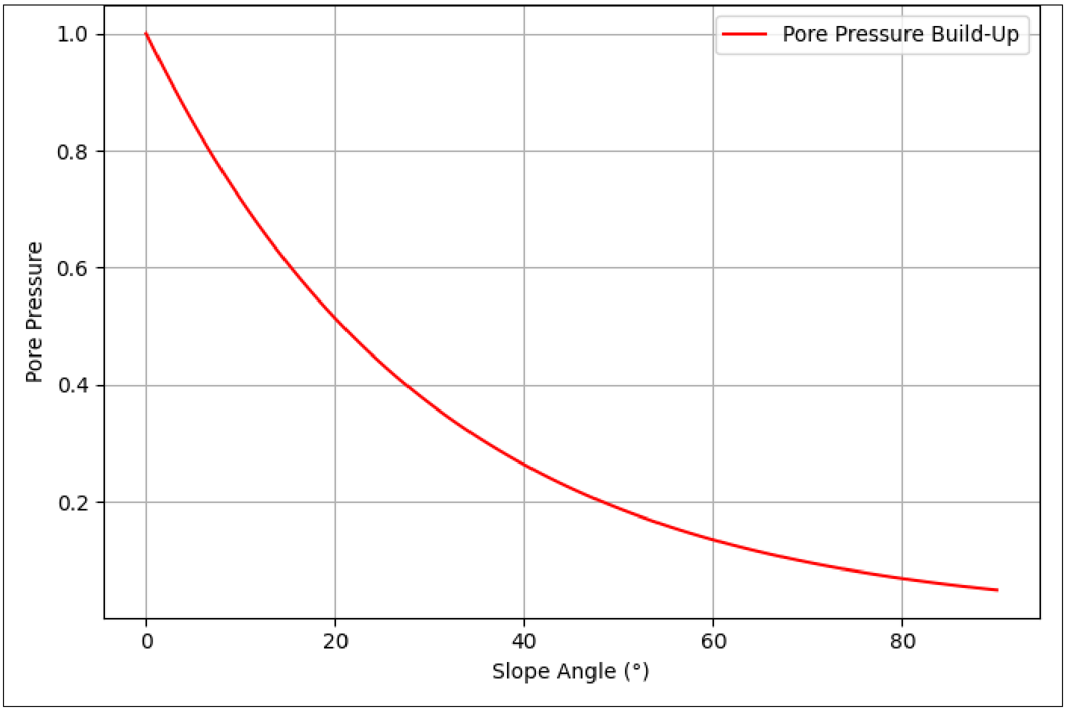

Fig 2: Rainfall-Triggered Slope Failure Mechanism in Residual Soils, Showing Pore Pressure Build-Up

Fig 3: These images depict the impact of rainfall-induced slope instability near road cuts, with one showing debris blocking a rural road during heavy rain, and the other highlighting a steep slope failure where a ruptured drainage pipe exacerbates soil erosion.

Overall, the research revealed that road cuts with poor drainage and steep angles, particularly those composed of residual soils or weathered rocks, were classified as high-risk. The statistical analysis further confirmed that improved drainage conditions could potentially lower the occurrence of instability, suggesting that local agencies could reduce risk by focusing on drainage infrastructure upgrades.

Discussion

This research demonstrates the value of developing a practical, field-based framework to assess the risk of rainfall-triggered slope instability along road cuts. The results confirm that factors such as slope geometry, material properties, drainage conditions, and rainfall intensity significantly influence slope failure likelihood. Previous studies have highlighted the importance of slope angle and material properties in triggering slope instability during rainfall events [2, 5], and this research reinforces these findings by showing that steep slopes composed of weathered materials are more susceptible to failure. Drainage conditions also play a pivotal role in slope stability, a conclusion supported by the statistical analysis which showed that slopes with inadequate drainage were more likely to fail [6]. This finding aligns with the work of Iverson [3], who emphasized the importance of pore pressure reduction in maintaining slope stability during rainfall events.

The practical significance of the framework developed here lies in its simplicity and applicability to local road agencies with limited resources. By focusing on observable parameters, such as slope angle, material type, and drainage condition, this framework can be used by local agencies to prioritize high-risk slopes for further intervention or monitoring. The use of a scoring system enables a quick and cost-effective method for classifying slopes, which can inform decisions on maintenance scheduling and drainage improvement projects. Furthermore, the research's statistical validation supports the effectiveness of this approach, showing that it correlates with actual slope failure incidents over a 10-year period. The findings suggest that proactive management of drainage systems, particularly in high-risk areas identified by the framework, could significantly reduce the likelihood of slope failures, enhance road safety and reduce maintenance costs in the long term.

While the results are promising, further research is needed to refine the framework by incorporating more granular soil data and advanced hydrological modeling to predict failure thresholds more accurately. Moreover, extending the framework to include the effects of other environmental variables, such as vegetation cover and land use changes, could further improve its predictive capability.

Conclusion

The findings of this research underscore the critical importance of incorporating simple and practical geotechnical risk screening methods for local agencies responsible for managing low-volume road networks in hilly and monsoon-prone regions. By developing a straightforward, qualitative framework, the research bridges the gap between advanced geotechnical research and the operational challenges faced by local authorities. The primary benefit of this approach lies in its ability to classify slopes based on easily observable characteristics, such as slope geometry, material type, and drainage conditions. This allows local agencies to conduct regular inspections and prioritize areas for intervention without the need for expensive or complex geotechnical testing, making it particularly valuable in resource-constrained environments.

Based on the research findings, several practical recommendations can be made to improve slope stability and reduce the risk of rainfall-triggered landslides along road cuts. First, local agencies should focus on improving drainage systems, particularly in regions where poor drainage contributes to increased slope failure risk. By ensuring that adequate surface drainage is in place, water infiltration and pore pressure buildup can be minimized, reducing the likelihood of slope instability during heavy rainfall events. Second, attention should be given to road cuts with steep slopes, especially those composed of residual soils or weathered rock. These areas should be considered high-risk and prioritized for further monitoring or stabilization. Additionally, routine maintenance, including vegetation management and erosion control, should be implemented to further reduce instability risks. Finally, the framework developed in this research should be used as a decision-making tool to guide resource allocation, enabling agencies to prioritize interventions in high-risk areas while balancing maintenance needs across the entire road network.

In conclusion, the adoption of this geotechnical risk screening framework can enhance the resilience of road infrastructure, particularly in regions prone to rainfall-induced slope instability. By providing a simple, field-applicable method for identifying high-risk slopes, local agencies can take proactive steps to reduce the likelihood of road disruptions and improve public safety. Ultimately, this approach can contribute to more sustainable and cost-effective road management practices, ensuring that transportation networks are better equipped to handle the challenges posed by changing climate conditions and extreme weather events.

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