

Challenges In Landslide Prevention And Their Management Through Advanced Technologies

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Abstract— Landslides represent a critical natural hazard in the Republic of Armenia, significantly affecting infrastructure safety and long-term land use. This study investigates one of the most landslide-prone transport corridors—the Abovyan–Shorbulaq–Sovetashen bypass road—through field observations and engineering analysis, highlighting the consequences of inadequate geological and hydrogeological investigations. The results demonstrate that deep-seated, water-saturated clay layers, rather than surface slope geometry alone, are the primary drivers of progressive deformation and structural failure. The paper emphasizes the necessity of multidisciplinary site investigations and continuous monitoring prior to construction. Finally, the potential role of advanced technologies, including Building Information Modeling (BIM), artificial intelligence (AI), and modern sensing systems, is discussed as a pathway toward more effective landslide risk mitigation.

Keywords— Natural hazards, block movement, deformation, landslide, Natural hazards.

I. INTRODUCTION

The present study focuses on the investigation, analysis, and evaluation of landslide-prone areas within the Republic of Armenia, followed by conclusions derived in relation to the specific geo-environmental and climatic conditions of each site. The primary aim of this article is to emphasize a critical issue: before the construction of any building or infrastructure, it is essential to conduct comprehensive geological, hydrogeological, and multidisciplinary site investigations. The absence of such studies during the construction of the road segment discussed below has led to a number of structural and geotechnical challenges. This is particularly significant considering that landslide-susceptible zones in Armenia are predominantly composed of clay-rich, highly saturated natural soils, which inherently increase instability risks and complicate engineering decision-making. Understanding these factors is crucial for identifying effective and sustainable mitigation solutions.

Given that natural hazards—such as landslides, earthquakes, debris flows, and storms—pose threats to countries across the world, regardless of their level of development, our central mission is to present internationally relevant conclusions and recommendations that reflect the specificity of our regional conditions. Equally important is the exchange of knowledge and best practices with other countries, especially the adoption of advanced methodologies that have proven effective elsewhere. Such collaboration is particularly valuable when combined with the capabilities of artificial intelligence (AI) and the tools of Building Information Modeling (BIM).

In this context, we highlight the need for continuous monitoring systems, as their absence has often resulted in rushed and inadequate engineering decisions that undermine expected project outcomes.

It should also be noted that the challenges discussed in this study were further exacerbated by the technological limitations of the 1960s, when modern tools such as BIM, AI, and advanced sensing technologies did not yet exist [1].

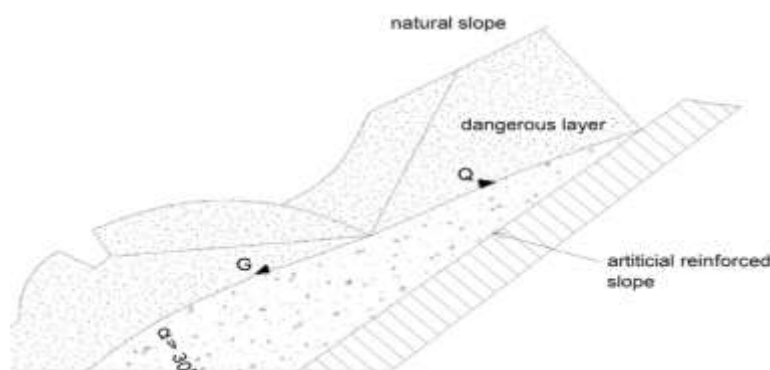
In this study, the primary object of investigation is one of the most landslide-prone corridors in the Republic of Armenia—the Abovyan–Shorbulaq–Sovetashen bypass road of Yerevan. Constructed in the 1960s during the Soviet era, this route was originally intended to connect the northern regions of the republic with the southern districts, thereby enabling freight transport without entering the capital city. However, over time the roadway has become completely impassable due to severe and progressive deformations, rendering unusable all buildings, engineering structures, utilities, and adjacent land parcels located on both sides of the corridor.

A technical overview of the site is presented below. In the initial 0–5 km section, starting from the town of Abovyan, one can easily observe the deteriorated condition of buildings, agricultural structures, and all surrounding infrastructure. Their continued use has become impractical and, in most cases, impossible. Field observations indicate that as the roadway underwent deformation and shifted leftward, the adjacent buildings were subjected to significant structural displacement. Several structures are partially situated on unstable slopes. It must be noted that in this segment the steep slopes and elevated terrain are located to the right of the built-up areas, where deep ravines are also present. Deformation cracks measuring 10 cm or more have developed in both the road surface and the adjacent structures, making access to the area hazardous. Early during the construction of these buildings, certain preventive measures—such as counterforts, retaining walls, and minor reinforcement works—were implemented. However, the cracks continued to expand, rendering these interventions ineffective and leading residents to discontinue repair activities.

Repeated assessments conducted by engineering councils and expert commissions concluded that the primary driver of the slope displacement and roadway failure was likely the infiltration of water from the right-hand side of the slope. Based on this assumption, small drainage tunnels and channels were constructed beneath the roadbed. Nevertheless, shortly after reopening, recurring mass movements again displaced large volumes of soil, dragging nearby buildings downslope and once more causing the road to become impassable.

Our preliminary conclusion is that comprehensive geological and hydrogeological investigations were not carried out prior to the design and construction of the road and surrounding territories. Moreover, the road was largely built without removing the underlying clay layers, which are clearly present along the entire alignment. The gravitational force (G) acting on the clayey mass exceeded the resisting forces (Q), leading to instability. Additionally, the required slope stabilization and compliance with the natural angle of repose were not ensured (Fig. 1).

Fig.1 the road



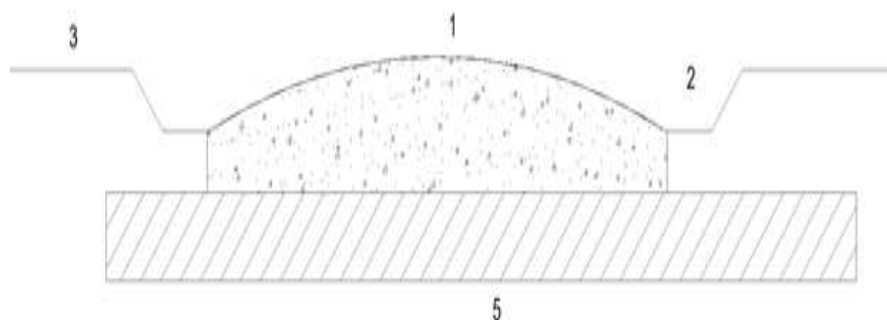
For the 5–9 km segment of the roadway, the following observations can be made. In contrast to the previous section, here the higher elevations are located on the left side of the alignment, while the right side transitions into a flat plain. Unlike the earlier segments, this portion does not exhibit a sharply rugged relief; rather, it is characterized by relatively level terrain with a gentle downward gradient. Surprisingly, however, the deformations are more pronounced and the road is entirely impassable, as evidenced also by the severe damage to utilities and infrastructure situated on both sides of the corridor. The extensive orchards adjacent to the road—located at a considerable distance—have also become unusable.

Whereas local traversal by foot or vehicle was still possible along the first two segments, the subsequent 9–13 km stretch has become completely inaccessible. This raises doubts about the previously stated assumption that the instability was primarily caused by slope-side water infiltration. In this area, the causes appear to be deeper and more complex. Field investigations reveal the presence of water-saturated, highly plastic layers resembling “floating” or “mud-flowing” strata. Given that Armenia is situated in an active seismic zone, expert assessments indicate that even minor seismic vibrations may gradually mobilize these underlying weak layers, causing them to shift. These deep-seated movements, in turn, disrupt and detach the overlying strata from the main geological formation [2].

Particularly noteworthy is the discovery of funnel-shaped subsidence depressions, 8–10 meters in diameter, along the section leading from the terminal part of the road toward Shorbulaq. In the forested portion of the area, the depressions display a distinct pattern of downward settlement, suggesting progressive subsidence.

Further examination of the adjacent Shorbulaq summer residential zone reveals that the buildings, internal roads, and engineering networks have undergone such extreme deformation that they defy logical structural behavior. The damage is so severe that the majority of residents have abandoned their homes, with only a few remaining due to lack of relocation options [3].

Fig.2 section view of road 1-road 2-water gutter 3-curb 4-curb



The intermediate conclusion derived from the investigation is that the unstable, water-saturated clay layers extend to significant depths, producing deformation patterns that transcend typical expert interpretations and exceed standard predictive models.

A particularly important fact must be noted: in the final segment of the road, just before Sovetashen, stands an archaeological museum situated on a hill composed of reddish

volcanic materials. These deposits, originating from past volcanic eruptions, have weathered into ash-like, highly lubricated material due to moisture infiltration.[4]

Remarkably, the same geotechnical characteristics continue into the adjacent area of the Sovetashen cemetery—one of Yerevan's long-established burial grounds. Despite being almost entirely flat, the cemetery terrain exhibits persistent and diverse deformations that have caused damage to burial plots, leading to both financial losses and emotional distress among families. This evidence strongly indicates that the entire region is unsuitable for any form of development, regardless of use.[5]

Practical Recommendations

1. The Technical and Economic Infeasibility of Standard Construction

Extensive field observations and geotechnical analyses unequivocally demonstrate that standard construction on such natural soils is neither technically nor economically reliable. The implementation of traditional buildings, continuous road networks, or rigid underground utilities on these specific substrata is inherently high-risk. This elevated risk profile is directly attributed to the extreme instability of the underlying clayey mass, which is highly susceptible to moisture-induced volume changes, plasticity variations, and catastrophic loss of shear strength when saturated.[6]

From an economic perspective, infrastructure built on such active landslide zones requires constant, capital-intensive remediation. The lifecycle costs associated with perpetual patching, structural underpinning, and utility rerouting rapidly eclipse initial construction budgets. Technically, traditional continuous foundations and rigid pavements are fundamentally incompatible with the immense, unpredictable lateral and vertical forces exerted by deep-seated, saturated clay movements. Therefore, avoidance of these hazard zones remains the primary and most effective strategy.[7]

2. Engineering Solutions for Unavoidable Construction

In geopolitical or urban planning scenarios where infrastructure routing through these hazardous zones is absolutely unavoidable, specialized and highly adaptive engineering solutions must be employed. To mitigate the catastrophic failure modes typical of these regions, we propose two integrated, non-traditional engineering approaches:[8]

a) Modular Roadways Constructed with "Floating Blocks"

To counteract the destructive forces of continuous ground movement, the road surface should not be poured as a monolithic or continuous ribbon. Instead, the road surface must be segmented into independent, floating concrete or heavily reinforced-concrete blocks.

- ***Deformation Management:*** It is critical to acknowledge that this method does not eliminate geological deformation entirely. The underlying earth will continue to shift. However, a modular approach allows severe differential settlement to be managed locally. When subsidence or heave occurs, individual blocks will articulate rather than shatter, enabling highly targeted, block-by-block restoration rather than total system replacement.
- ***Sub-base Engineering and Hydrodynamic Control:*** The success of the "floating block" system relies entirely on its foundational drainage. For this approach, the sub-base and preparatory layers must be fully constructed with a continuous, homogenous layer of coarse gravel (≥ 40 mm grain size). Utilizing an aggregate of this specific macroscopic scale creates a highly porous matrix that serves a dual purpose. First, it facilitates rapid, multi-directional drainage and significantly improves overall soil permeability. Second, it acts as a capillary break that strictly prevents water accumulation directly beneath the rigid pavement. By ensuring that water evacuates

the load-bearing strata swiftly, this aggregate layer significantly reduces hydrodynamic uplift forces and prevents the localized softening of the surrounding clay matrix.[9]

b) Implementation of Deep Structural Joints ("Deep Cuts")

Standard highway construction typically relies on superficial expansion joints to accommodate surface-level thermal expansion and contraction. Unlike these traditional surface joints, which are formed only in the final construction layer, we propose a fundamental redesign of joint geometry to address subsurface geological hazards.

- ***Excavation and Subgrade Preparation:*** We propose introducing deep structural joints immediately after the complete removal of the volatile clayey material. This must be carefully followed by the rigorous mechanical compaction of the underlying natural soil and the precise placement of the aforementioned coarse gravel layer.
- ***Interrupting Shear Failure Planes:*** The geotechnical rationale behind these "deep cuts" extends beyond mere flexibility. Such deep joints, penetrating entirely through the engineered sub-base and anchoring into the stabilized soil below, essentially act as physical geotechnical barriers. They are designed to help interrupt the continuity of subsurface sliding surfaces. By breaking the continuous shear planes that propagate through expansive clays, these deep structural joints effectively compartmentalize kinetic ground energy, thereby significantly reducing progressive, large-scale lateral displacement.[10]

Additional Considerations for Engineers and Researchers

We wish to draw attention to a critical observation regarding slope-related assumptions. Across all three sections of the road, the slopes adjacent to the corridor have been cited as a potential cause of the landslides. Conventionally, slope stability is assessed by comparing the downslope driving force (C) with the resisting force (F). When $C > F$, the mass inevitably tends to move towards lower elevations; otherwise, the slope remains stable.

However, despite this classical interpretation explaining the first two segments, the third segment presents a contradiction: it is a flat plain, yet the landslide processes here are more severe and more clearly expressed. This suggests that the slope itself is not the primary destabilizing factor in this area.

Thus, we conclude that the principal cause is likely deep-seated instability, where the weak layers lie at substantial depths and may possess anomalous, non-intuitive inclinations that are not visible at the surface. This warrants further investigation and foundational geotechnical analysis to determine long-term mitigation strategies.

Conclusion

The findings of this study allow us to draw the following key conclusions and recommendations:

- Prior to constructing buildings or infrastructure in landslide-prone zones, it is essential to conduct comprehensive and deep geological and hydrogeological investigations to fully assess subsurface conditions and instability risks.
- When construction is deemed necessary, the decision must be technically and economically justified, supported by detailed feasibility studies and risk assessments.
- Building foundations must be designed as continuous and uniformly distributed systems, ensuring uniform load transfer and minimizing differential settlement.
- Existing standards for determining the depth required to reach competent (firm) bearing strata should be revised and recalibrated, considering the presence of deep, unstable, water-saturated clay layers typical of the study area.

Furthermore, deformation (expansion) joints should not be limited to the surface pavement layer, as is commonly practiced in highway construction where asphalt or concrete layers are cut only 10–12 cm deep. Instead, joints must be constructed through the full depth of all pavement and sub-base layers, including the structural base. These joints must incorporate non-decaying, waterproof separating inserts between adjacent blocks to ensure their independence and to prevent the propagation of deformation across the structure.

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