Slope Stability and Resilient Roads in the Himalayas: Nepal's Challenges and Initiatives

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Abstract: Road infrastructure underpins Nepal's socio-economic connectivity, yet the country's steep, tectonically active terrain makes roads highly vulnerable to landslides and slope failures. Geological fragility, intense monsoon precipitation, and unplanned excavation exacerbate risks, disrupting transport, trade, and access to services. Recent studies highlight the critical need for resilience-oriented planning. Advances in geospatial hazard mapping, slope stabilization techniques, including bioengineering, mechanical reinforcement, and drainage systems, and policy frameworks have improved risk management along major corridors such as Narayanghat–Mugling and BP Highways. A systems-oriented approach integrating geotechnical science, context-sensitive engineering, climate adaptation, and institutional coordination is essential for sustainable, resilient road networks in the Himalayas.

Keywords: ***Road transport infrastructures, Slope stability, Landslide vulnerability, Climate-resilient road network, Sustainable infrastructure development.***

Introduction

Road infrastructure forms the backbone of Nepal's socio-economic connectivity, providing mobility, enabling trade, supporting tourism, and ensuring access to health, education, and markets across remote mountainous regions. Given Nepal's rugged topography, where nearly 80% of the landmass is hilly and mountainous, road construction and maintenance are inherently complex and cost intensive. Slope instability, active tectonics, fragile geological formations, intense monsoon-driven hydrological cycles, and unplanned excavation practices make road corridors highly vulnerable to landslides and mass movement hazards (Dahal, 2014). The disruption of road networks has cascading impacts, including economic losses, market isolation, delays in essential services, and increased disaster risk for communities dependent on linear infrastructure.

This extended abstract synthesizes the status, challenges, and emerging initiatives to enhance slope stability and develop resilient road networks in Nepal, drawing upon empirical economic evidence, geospatial vulnerability assessments, and recent technical innovations including bioengineering, geo-hazard monitoring, and context-sensitive engineering. Recent studies, including Sharma et al. (2025), highlight that the Himalayan transport sector is at a critical juncture where resilience-oriented planning must be integrated as a core priority rather than a reactive response.

Geological and Climatic Drivers of Road Vulnerability

The Himalayan range is geologically young and tectonically active. Much of Nepal's hill road network passes through lithologically weak and highly weathered formations such as phyllites, shale, schist, and colluvial deposits, which are sensitive to saturation and disturbance. The steep slopes combined with high rates of monsoon precipitation induce frequent porewater pressure fluctuations, slope weakening, and landslide initiation. Moreover, climate change has intensified rainfall extremes, leading to higher frequency of rainfall-triggered failures observed notably along the Narayanghat–Mugling Highway (Khanal and Dahal, 2024), BP Highway, Arniko Highway, and Mid-Hill corridors.

Human interventions exacerbate natural susceptibility. Road construction often relies on cut-and-dump methods, inadequate drainage provisions, unsupported near-vertical cut slopes, and unmanaged spoil disposal, increasing the likelihood of slope failures. Sharma et al. (2025) showed that most failures along hill highways were directly linked to drainage-related deficiencies rather than inherent geological conditions alone. This underscores the importance of integrated slope-water-infrastructure interaction management in Himalayan engineering.

Socio-Economic Significance

Empirical macro-economic analyses indicate a unidirectional long-run causality from road infrastructure development to national economic growth. Expansion of paved road length and investment in transport infrastructure contributes significantly to agricultural commercialization, trade integration, tourism expansion, and rural livelihood improvement. Thus, sustaining reliable road networks is essential not only for physical accessibility but for national development outcomes.

However, recurrent landslide-induced disruptions impose substantial losses. Road closures during monsoon seasons increase transportation costs, impede supply chains, restrict mobility of labor and goods, and trigger safety risks. Ensuring slope stability and resilience is, therefore, not merely a technical issue, it is a national development necessity (Sharma et al., 2024).

Risk Mapping and Vulnerability Assessment Initiatives

Advancements in geospatial analytics have supported improved hazard assessments along transportation corridors. Multiple slope stability and landslide susceptibility studies using GIS-based multi-criteria models, remote sensing, and field inventory data have identified critical hotspots. Collaborations between the Department of Transport Infrastructure (DoTI), Department of Roads (DoR), Tribhuvan University, and international research partners have produced corridor-level vulnerability maps for the Narayanghat–Mugling, BP, and Mid-Hill highways. These assessments support proactive decision-making for slope protection design, alignment modification, and prioritized maintenance planning.

Sharma et al. (2025) emphasized integrating hydrological indices, rock mass parameters, slope geometry, and land use change dynamics for accurate susceptibility modeling. Their findings reinforce that risk mitigation strategies must be localized and geomorphologically contextual.

Engineering Approaches for Slope Mitigation

Nepal has increasingly adopted multi-disciplinary methods to enhance slope stability along road corridors. Combining vegetation with mechanical stabilization improves soil cohesion, controls erosion, and supports ecological restoration. Nepal has become a regional example in bioengineering applications in mid-Hill slopes. The use of rockfall barriers, flexible ring nets, wire-mesh drapery, geogrids, and ground anchors has expanded, particularly along critical high-risk corridors. Where slope stabilization is infeasible, tunnels and alignment shifts are being advanced, as seen in the Nagdhunga Tunnel, Mugling-Pokhara improvement projects, and Dharan–Chatara initiatives.

Longitudinal drains, sub-surface drainage, retaining walls with weep holes, and check-dam integration have proven particularly effective. Despite progress, challenges persist due to resource limitations, lack of continuous monitoring instrumentation, and fragmented institutional coordination.

Institutional and Policy Frameworks

The Ministry of Physical Infrastructure and Transport (MoPIT) and Department of Roads have recently introduced slope stabilization guidelines, disaster-resilient road construction standards, and periodic maintenance frameworks. The National Disaster Risk Reduction and Management Authority (NDRRMA) is integrating linear infrastructure risk management into provincial and local planning systems. However, sustainable success requires:

- Strengthening technical capacity at provincial and municipal levels.
- Integrating geotechnical risk assessments in feasibility and DPR stages.
- Ensuring maintenance budgets are protected and ring-fenced.
- Establishing corridor-level hazard monitoring and early warning systems.

Conclusion

Enhancing slope stability and resilience of road infrastructure in Nepal requires a systems-oriented approach grounded in geological understanding, climate adaptation, engineering innovation, and institutional coordination. The integration of geotechnical science, spatial risk assessment, context-sensitive engineering, and proactive policy frameworks offers a pathway toward a safer, reliable, and climate-resilient road network in the Himalayan region. These efforts support Nepal's broader objectives of regional accessibility, inclusive development, and disaster risk reduction.

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