

Geoengineering in Landslides Mitigation Experiences from Nepal Himalayas

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Abstract: The engineering geological diversity strongly influences landslide occurrences and road-slope stability. The Terai faces settlement, subsidence, and erosion in alluvial deposits, while the Siwalik is characterized by weak sedimentary rocks, differential weathering, and rainfall-induced failures. The Mahabharat Range experiences instability associated with steep terrain and fractured rock masses. In the Midland region, foliated metamorphic rocks, weathering, and groundwater contribute to shallow and deep-seated landslides. The Higher Himalaya is susceptible to rockfall, rockslides, and debris flows due to steep topography and fractured crystalline rocks.

These contrasting conditions require engineering geology-specific mitigation measures, including drainage improvement, slope regrading, rock bolts, retaining structures, bioengineering, and rockfall protection. Integrating engineering geological mapping, geotechnical investigation, stability analysis, and monitoring is essential for selecting effective and sustainable road-slope stabilization measures.

Keywords: Engineering geology, Landslides, Road-slope stability, Geological diversity, Slope failure mechanisms.

Introduction

Nepal's road network crosses a pronounced north-south range of geological and geomorphological settings, from the alluvial Terai to the steep, high-relief Himalaya. Active tectonics, folded and faulted rock sequences, contrasting lithologies, weathering, groundwater and intense monsoon rainfall interact to control slope performance. Road excavation can further destabilize slopes by removing toe support, exposing unfavorably oriented discontinuities and changing drainage pathways. Consequently, road-slope failures should be assessed as geological and hydrogeological processes—not simply as a function of slope angle. Effective mitigation begins with identifying the material, structure and failure mechanism at each site.

Geological division and typical engineering problems

Terai: alluvial settlement and river processes

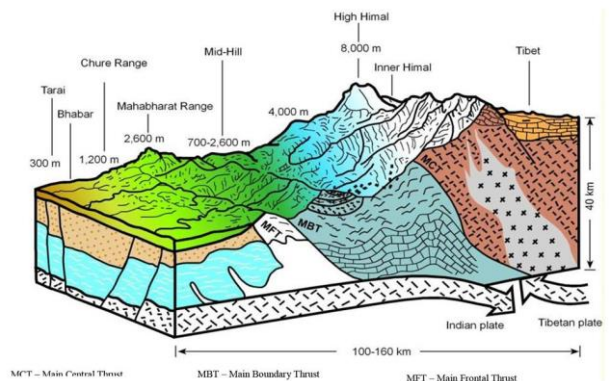


Figure 1. Conceptual south-north transect of Nepal's broad geological and terrain divisions (Modified after Hagen 1964).

The Terai is underlain largely by Quaternary alluvial deposits of gravel, sand, silt and clay. Variable layer thickness, compressible fine-grained soils, shallow groundwater, flooding, riverbank erosion and channel migration can affect embankments, bridge approaches and road foundations. Local settlement or subsidence may occur where compressible strata consolidate under loading or where groundwater changes contribute to ground-level movement. Investigation should establish stratigraphy, groundwater conditions and compressibility. Potential measures include foundation improvement where justified, staged construction or preload where appropriate, surface-water management, and protection against river erosion.

Siwalik:

The Siwalik (Chure) zone contains variable sequences of sandstone, mudstone, siltstone and conglomerate. Differences in cementation and weathering resistance create differential erosion; mudstone-rich beds may soften and lose strength when wet, while stronger sandstone beds can become unsupported. Siddhababa Area, Bhasu Bhir Area, Daunne Road section, Bankabbasa Road section area represents some typical failures include shallow slides, erosion gullies, bedding-slip of Siwalik related landslide and slope instability. This mainly includes controlled sliding, local wedge failures and rockfall. Road cuts may expose weak beds, rockfall or create seepage pathways. Mitigation may include suitable cut-slope geometry, crest and catch drains, lined side

drains, subsurface drainage, erosion protection, localized bolting or mesh where structurally warranted, and bioengineering for suitable shallow soil slopes. The treatment must match the observed failure mechanism.

Mahabharat Range:

The Mahabharat terrain includes folded, faulted and variably weathered sedimentary and metamorphic rocks, such as quartzite, phyllite, slate, schist and carbonate rocks. Steep relief, jointing, foliation, weathered rock–soil interfaces and river undercutting can produce planar or wedge sliding, toppling, rockfall and deeper landslides. Required assessments include discontinuity mapping, rock-mass characterization, groundwater observations and kinematic checks. Depending on the mechanism, measures may include drainage, scaling of unstable blocks, rock bolts, retaining or toe-support structures, gabions and erosion control. Typical slope failures along the Mugling–Narayanghat road illustrate the instability of highly weathered and fractured rock masses, characteristic of engineering geological problems in the Mahabharat Range.

Midland / Lesser Himalaya:

The Midland region commonly includes phyllite, slate, schist, quartzite, limestone, dolomite and associated metasedimentary rocks. Foliation, schistosity, joints and faults may form persistent weakness planes, especially where they dip toward a road cut. Weathered foliated rock can behave as a weak, closely layered mass; rainfall and groundwater can reduce shear resistance and reactivate old landslides. A key design step is to distinguish shallow excavation-related failure from deep-seated movement. Shallow failures may be addressed through drainage, regrading, localized reinforcement and erosion control. Deep-seated failures require subsurface investigation, slip-surface delineation, groundwater monitoring and stability analysis before considering horizontal drains, toe support or engineered reinforcement. Typical slope failures along the Mugling–Pokhara Highway illustrate the characteristic engineering geological challenges of the Mid-Hill region.

Higher Himalaya:

The Higher Himalaya contains high-grade metamorphic and crystalline rocks, including gneiss, schist, quartzite and migmatite, but intact rock strength alone does not determine stability. Persistent joints, faults, foliation, fractured zones and steep topography can control block release and large rock-slope failures. Rockfall, rockslides, debris flows and, at high elevations, snowmelt- or glacier-related processes may affect roads. Appropriate measures can include scaling, bolts or anchors, draped mesh, catch ditches, engineered rockfall barriers and drainage. Rockfall trajectory assessment is needed to size protective systems; large slope deformations require broader geomorphological assessment and monitoring.



Figure 2. Conceptual failure mechanisms commonly encountered in landslide and road cuts: weak interbeds, structurally controlled movement along foliation/joints, and rockfall.

Discussion

In context of Nepal, study approach for landslide mitigation must include a link between (i) engineering geological and geomorphological (ii) identification of lithology, weathering, discontinuities and groundwater, (iii) definition of the failure mechanism (iv) targeted investigation and analysis, and (v) selection of proportionate mitigation and monitoring. Depending on the site, investigation may include boreholes, trial pits, geophysical surveys, laboratory testing, kinematic analysis, limit-equilibrium or numerical modelling, and instrumentation. Drainage and erosion control are important across many zones, but reinforcement and protective structures must be designed for the specific mechanism and scale of movement.

Conclusion

Engineering Geological diversity is a primary control on landslide and road-slope stability in Nepal. Alluvial settlement and river processes may dominate in the Terai; weak, interbedded sedimentary rocks are important in the Siwalik; structurally complex and steep rock slopes characterize much of the Mahabharat and Midland terrain; and fractured high-relief rock masses and rockfall hazards are prominent in the Higher Himalaya. Case studies from the Siwalik, Midland and Higher Himalayan zones can therefore demonstrate how lithology, structure, weathering and groundwater lead to different failure mechanisms and mitigation needs. A site-specific engineering geological approach, integrated with geotechnical analysis, drainage management and monitoring, is essential for safe and sustainable road infrastructure.

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