

Integrated Geotechnical and Groundwater Characterization, Static and Pseudo-Static Stability Analysis, and Evaluation of Proposed Mitigation Measures at the Kodari Landslide, Nepal

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Abstract: Landslide instability along Himalayan highway corridors reflects interactions among geological conditions, groundwater, rainfall infiltration, slope geometry, and human modification. The Kodari landslide at chainage 113+000 of the Araniko Highway (NH34), Sindhupalchok, Nepal, repeatedly disrupts highway access and threatens infrastructure and cross-border connectivity. This study integrates engineering-geological mapping, geotechnical testing and drilling, electrical resistivity tomography (ERT), hydrogeological interpretation, and limit-equilibrium modelling for static and pseudo-static stability analysis. Investigations covered approximately 75,000 m², including two boreholes, 15 portable dynamic cone penetration tests, 12 infiltration tests, laboratory soil testing, and ERT profiles along and across the slope. Deposits comprise coarse gravel and boulder-mixed soil, with gravel content of 80.91–81.66% and fines of 1.87–2.05% in large-particle samples. Direct-shear tests indicate cohesion of 0.00–1.94 kPa and friction angles of 28.09–31.78°. ERT identifies saturated or water-bearing zones and localized comparatively competent materials. Proposed stabilization measures, including soil nails/rock bolts, earth anchors, vertical drainage wells, horizontal drains, and a mechanically stabilized earth (MSE) wall, increase the static factor of safety (FOS) to approximately 1.5. However, pseudo-static FOS remains 1.034–1.04 under a horizontal seismic coefficient of 0.2, indicating reduced stability under seismic loading. The result emphasizes groundwater management and further seismic verification for effective mitigation design.

Keywords: *Landslide, Geotechnical characterization, Groundwater, Electrical resistivity tomography, Static stability, Pseudo-static analysis.*

Introduction

Landslides along Himalayan Road along river corridors arise from interactions among geological structure, weathering, slope geometry, rainfall infiltration, groundwater flow, seismic loading, and human modification (Cruden & Varnes 1996). Road cuts can alter the natural stress field, interrupt drainage, remove toe support, and create new failure surfaces. During monsoon periods, infiltration and concentrated runoff may increase pore-water pressure and reduce effective

stress, while earthquakes can impose additional inertial forces on slopes already close to limiting equilibrium (Dahal et al., 2024).

The Kodari section of the Araniko Highway is an important transport corridor facilitating cross-border trade between Nepal and China which pass through the mountainous terrain of Sindhupalchok District, Nepal. The investigated landslide has experienced recurring instability, with potential consequences for road access, nearby infrastructure, public safety, and cross-border movement (Ojha et al., 2026, Tiwari et al., 2024).

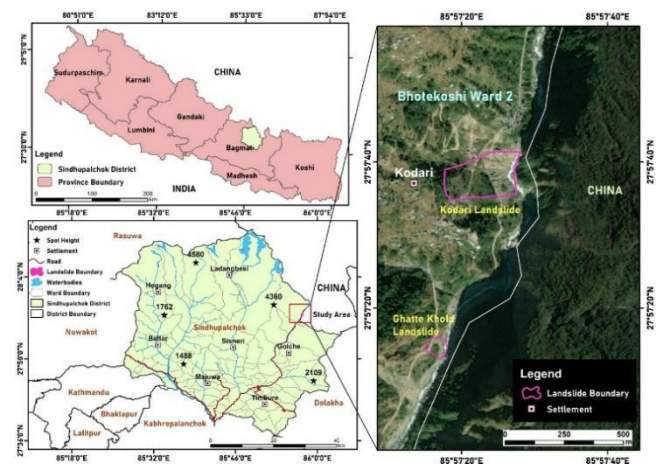


Figure 1, Location map of the Kodari Landslide along the Araniko Highway.

A reliable stabilization strategy requires an engineering ground model supported by complementary datasets rather than a single factor-of-safety value. Boreholes and laboratory tests provide direct information on material properties but sample only a limited volume of ground. Electrical resistivity tomography (ERT) provides spatially continuous indirect evidence of subsurface contrasts (Mahato et. al 2026), although resistivity is non-unique and must be interpreted alongside borehole, geomorphological, and

hydrogeological observations. Slope-stability modelling can then test the implications of the interpreted ground model, if geometry, groundwater conditions, material parameters, and reinforcement assumptions are documented.

This paper synthesizes the available Kodari investigation report to (i) characterize the geological and geotechnical conditions, (ii) examine groundwater-related evidence and hydraulic variability, (iii) integrate ERT interpretations with borehole and laboratory information, (iv) summarize reported static and pseudo-static stability results, and (v) identify design verification and monitoring requirements. The study is a case-based engineering assessment; the interpretations are constrained by the data and model outputs available in the project report.

Methodology

The investigation covered approximately 75,000 m² and combined topographic and geomorphological mapping, engineering-geological observations, two boreholes, infiltration tests at 12 locations, laboratory testing, electrical resistivity tomography (ERT), and limit-equilibrium slope-stability modelling using GeoStudio-based analyses. Laboratory testing included particle-size distribution, moisture content, specific gravity, density, Atterberg limits, and direct-shear testing. ERT sections were interpreted alongside borehole logs and field observations to identify contrasting subsurface zones. Existing and proposed mitigation conditions were assessed using the strength parameters and groundwater assumptions reported in the investigation documents.

Limit-equilibrium analyses were undertaken in GeoStudio using the geometry, material parameters, and groundwater interpretation adopted in the project report. The reported results include existing-condition stability, a proposed mitigated static case, and a pseudo-static case using a horizontal seismic coefficient of 0.2. The mitigation concept includes surface and subsurface drainage, vertical drainage wells, horizontal drains, soil nails or rock bolts, permanent earth anchors, retaining structures, a mechanically stabilized earth (MSE) wall, and associated slope/road-interface measures. The values presented here are reported model outputs; they should not be interpreted as an independent re-analysis because complete model files, all boundary conditions, and sensitivity results were not available for this manuscript.

Results

Engineering-geological mapping and borehole descriptions indicate a heterogeneous landslide mass containing silty gravel, silty sand, cobbly and bouldery deposits, and weathered to highly weathered rock. In-situ soil classification at 32 locations predominantly identified GM (silty gravel), while laboratory samples

included SM, SP-SM, GP-GM, GW-GM, and GW classifications. Borehole descriptions record alternating silty-sand matrix and cobble-boulder-sized gneiss; core-loss intervals in BH2 indicate localized fractured or weak zones.

Large-particle-size testing at three locations measured gravel fractions of 80.91–81.66% and fines contents of 1.87–2.05%, reported as cobbly gravel (GP). Across 12 laboratory samples, natural moisture content ranged from 3.48% to 21.74%, specific gravity from 2.66 to 2.69, bulk density from 1.70 to 2.33 g/cm³, and dry density from 1.54 to 2.05 g/cm³. Direct-shear tests yielded apparent cohesion of 0.00–1.94 kPa and friction angles of 28.09–31.78°. The low measured cohesion indicates that stability is strongly dependent on frictional resistance, confinement, material structure, and pore-water conditions. Infiltration coefficients were generally 0.0001–0.0006 cm/s, with localized values reaching approximately 0.0065 cm/s. This spread indicates that near-surface hydraulic response is not uniform across the landslide.

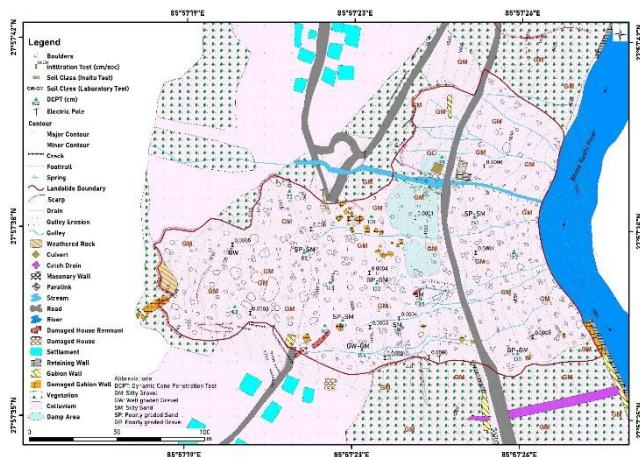


Figure 2, Engineering Geological map of the Kodari Landslide (113+000 km) along Araniko Highway

ERT profiles were interpreted to contain low-resistivity zones potentially associated with saturated or water-bearing material and localized weak zones. Higher resistivity in parts of the cross-slope profile was interpreted as potentially representing more compacted material or competent rock.

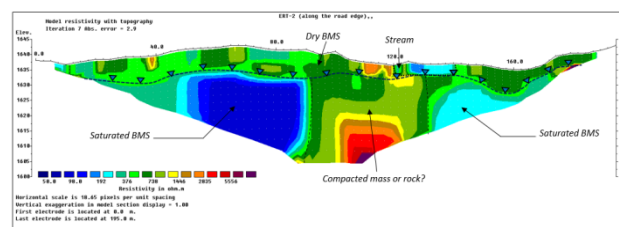


Figure 3, Electrical Resistivity Tomogram across the Kodari Landslide.

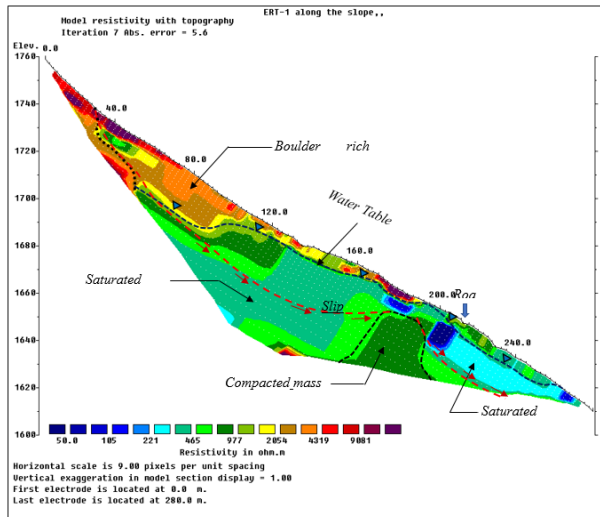


Figure 4, ERT profile along the Kodari landslide, as interpreted in the project investigation report.

The proposed combined mitigation model produced a reported static FOS of approximately 1.5. The concept combines water management with reinforcement and retaining measures rather than relying on a single structural intervention. The report also gives local post-mitigation FOS values of about 1.2 at the crown section and 1.9–2.0 along the MSE wall; these local values relate to different model sections and should not be treated as interchangeable with the overall reported FOS.

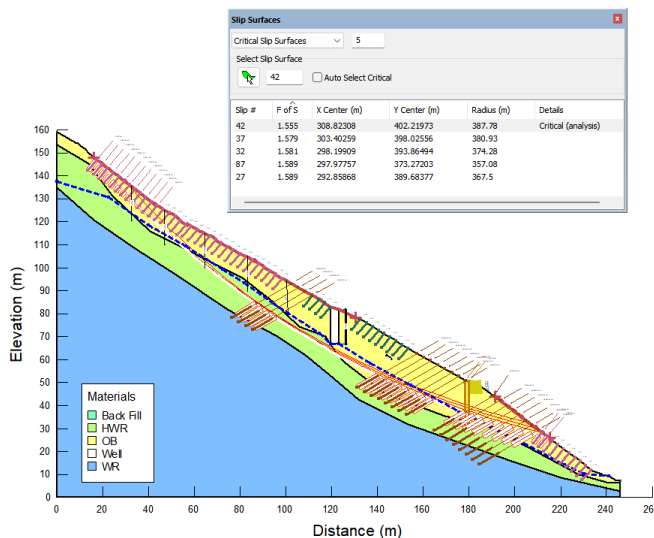


Figure 5, Reported post-mitigation static slope-stability model.

For the pseudo-static case using a horizontal seismic coefficient of 0.2, the reported FOS is approximately 1.034–1.04. This remains comparatively low and highlights the importance of verifying the seismic design basis, groundwater assumptions, reinforcement capacity, and possible compound failure mechanisms. A pseudo-static factor of safety is a simplified representation of seismic effects and does not replace a site-specific seismic hazard assessment or, where warranted, deformation-based analysis.

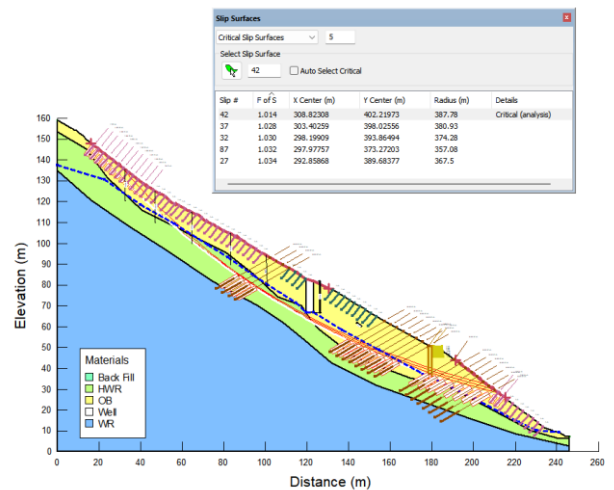


Figure 6, Reported post-mitigation pseudo-static stability model for a horizontal seismic coefficient of 0.2.

Conclusion

The Kodari landslide is characterized by heterogeneous colluvial and boulder-mixed deposits, predominantly granular soil with very low measured cohesion, variable infiltration, and ERT-indicated water-bearing zones. The integrated geotechnical and geophysical interpretation provides a basis for identifying weak or saturated materials and for developing a site-specific stabilization scheme. The proposed combination of reinforcement, retaining support, and surface/subsurface drainage improves the reported static FOS to about 1.5; however, the pseudo-static FOS of 1.034–1.04 under the adopted seismic coefficient indicates that further seismic design verification is warranted. Groundwater monitoring during and after the monsoon, confirmation of subsurface assumptions during construction, and performance monitoring after implementation are recommended. The reported groundwater level was interpreted from borehole and ERT information; the source report does not provide a quantified long-term piezometer time series.

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