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Regional Variability in Geotechnical Properties and Slope Stability Mechanisms Across Climatic and Geological Zones of Nepal

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Abstract

Nepal's Himalayan terrain, characterized by extreme elevational gradients and heterogeneous lithology, presents region-specific challenges for slope stability and infrastructure resilience. This study evaluates the geotechnical properties of soils from five climatically distinct regions—Kathmandu Valley (subtropical urban basin), Pokhara (humid alluvial valley), Chitwan (forested sub-Himalayan tract), Mustang (arid trans-Himalayan zone), and Terai Plains (tropical lowland)—to establish predictive relationships between soil behavior, environmental factors, and slope failure mechanisms. Laboratory analyses, including triaxial shear testing under unsaturated conditions and advanced permeability profiling were paired with limit equilibrium stability modeling. Results demonstrate that moisture content ($R^2 = 0.87$, $p < 0.01$) and clay mineralogy dominate stability outcomes, with safety factors (FoS) ranging from 0.8 (Terai) to 2.5 (Mustang). A novel regional classification framework is proposed to guide slope management in Nepal's rapidly developing landscapes.

Keywords: *Geotechnical properties, Slope stability mechanisms, Climatic zones, Geological zones, Nepal Himalayas*

Introduction

The Himalayan arc, a product of ongoing continental collision between the Indian and Eurasian plates, hosts some of the world's most dynamic erosional and tectonic regimes (J. Lavé, 2001). Nepal, situated centrally within this orogen, experiences recurrent slope failures that claim over 300 lives annually and incur economic losses exceeding USD 10 million (D.N., 2012). While regional studies have addressed landslide inventories (Ranjan Kumar Dahal, 2008) and broad-scale susceptibility (Tiwari, 2021), critical gaps persist in linking microscale soil properties to macroscale slope behavior across Nepal's climatic gradients.

Existing geotechnical models often oversimplify Himalayan soils as homogeneous silty clays (Hasegawa, 2009), neglecting (i) the role of alluvial versus colluvial depositional histories, (ii) bioengineering effects of vegetation in sub-humid zones, and (iii) desiccation cracking dynamics in arid regions. For instance, Pokhara's alluvial fans—formed by Pleistocene glacial outburst floods (Anne Bernhardt, 2016)—exhibit spatially variable cementation, while Chitwan's Siwalik-derived soils show distinct laterization features (Gerrard, 1990). Such diversity necessitates a stratified analytical approach.

This study integrates field sampling across five bioclimatic zones (Figure 1) with advanced laboratory testing to achieve three objectives:

1. **Spatial variation quantification**: Quantify spatial variations in shear strength parameters (c', φ'), compressibility (compression index, Cc), and hydraulic conductivity across the five regions to establish baseline geotechnical property ranges.
2. **Region-specific correlations**: Develop region-specific correlations between plasticity indices, monsoon intensity, groundwater dynamics, and Factor of Safety (FoS) to establish predictive relationships for slope stability assessment.
3. **Decision matrix development**: Provide a thorough decision matrix for slope reinforcement methods (such as soil nailing, bioengineering techniques, and structural interventions) that is adapted to Nepal's geodiversity. This will allow practitioners to choose the best mitigation strategies according to local geotechnical features.

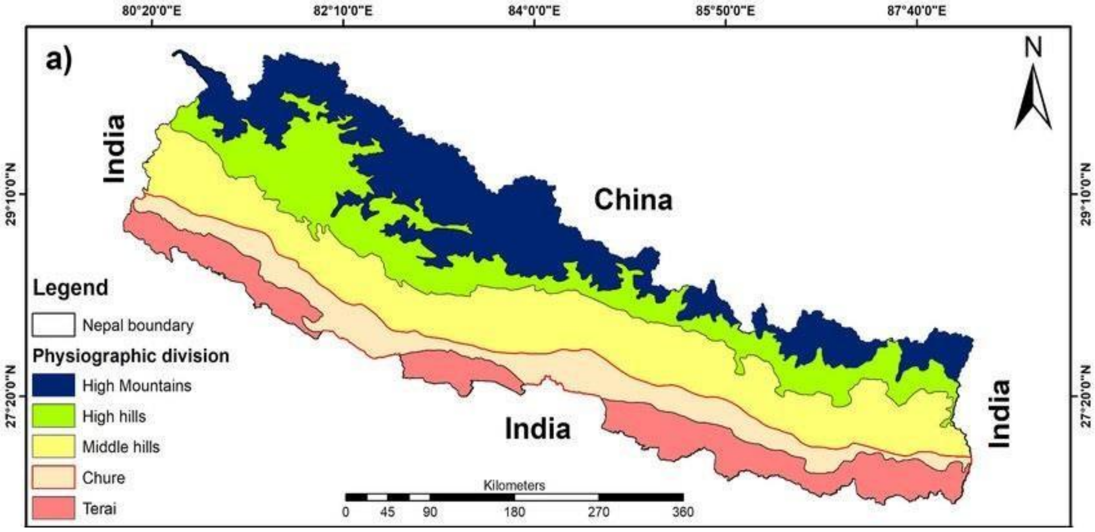

Figure 1: Bio-Climatic Regions of Nepal

Methodology

Site Selection and Sampling

Soil samples were collected during the pre-monsoon season (March-April 2023) from 15 undisturbed locations (3 per region) using ASTM D1587-08 thin-walled samplers to minimize sample disturbance. Sample depths ranged from 2 to 5 meters below ground surface, capturing the active slope zone. Sites were systematically chosen to represent dominant land use patterns, geological units, and bioclimatic characteristics specific to each region.

Table 1: Description of sampling locations, geological characteristics, and climatic conditions

Region	Coordinates	Geology	Land Use	Region
Kathmandu Valley	27°42'N, 85°18'E	Lacustrine clay/silt	Urban/residential	Kathmandu Valley
Pokhara	28°12'N, 83°59'E	Alluvial gravel-sand matrix	Agriculture/tourism	Pokhara
Chitwan	27°31'N, 84°20'E	Siwalik sandstone derived loam	Forest/agriculture	Chitwan
Mustang	28°48'N, 83°41'E	Colluvial scree with calcrete	Pastoral	Mustang
Terai Plains	26°54'N, 85°02'E	Gangetic silt-clay	Intensive farming	Terai Plains

Laboratory Characterization

Grain Size Distribution

After organic matter was removed by hydrogen peroxide (H_2O_2) treatment, the grain size distribution was measured by laser diffraction (Malvern Mastersizer 3000). Particle aggregation in clay-rich samples may cause this approach to underestimate clay fractions (<2µm), despite providing fast, high-resolution particle size data. Confirmation hydrometer study (ASTM D7928-21e1) was carried out when laser diffraction results seemed to be at odds with Atterberg limits.

Atterberg Limits

A Casagrande device with servo-controlled strain rates (ASTM D4318-17) was used to measure Atterberg limits in order to improve accuracy. To guarantee repeatability, samples with high plasticity (LL > 60%) were examined three times. This method's drawbacks include the possibility of losing fines during preparation and operator sensitivity when determining the liquid limit.

Shear Strength Testing

Consolidated undrained (CU) triaxial tests were used to determine shear strength parameters under confining pressures of 50, 100, 150, and 200 kPa (GDS Instruments EliteTriax apparatus), simulating common field stress states in slope systems. Using mid-plane transducers to continually monitor pore pressure, specimens were saturated until pore pressure parameter B value exceeded 0.95. Although results may underestimate long-term strength due to possible drainage during prolonged saturation periods, the CU testing approach was chosen because it accurately depicts fast shear during monsoon-induced failure. To reduce the impacts of pore pressure rate, strain rates were kept at 0.5% per minute.

Permeability Assessment

Hydraulic conductivity was assessed using flexible-wall permeameters (ASTM D5084-16) under hydraulic gradients of 5-15, replicating monsoon-induced groundwater flow intensities. Testing was conducted at both saturated and partial saturation states (using the osmotic suction method) to capture monsoon response. Limitation: saturated permeability may not fully represent in-situ behavior during partial saturation common in shallow slopes.

Stability Modeling

Slope stability was analyzed using SLIDE 6.0 (Rocscience), incorporating:

Bishop's Simplified Method

Analysis employed Bishop's method with pore pressure ratios (r_u) calibrated to measured monsoon groundwater levels at each site, ensuring realistic factor of safety calculations under saturated conditions.

Seismic Loading

Pseudostatic seismic coefficients (k_h = 0.2g, k_v = 0.1g) were applied per Nepal Building Code NBC 105:2020, representing anticipated earthquake ground accelerations for Himalayan zones.

Parameter Uncertainty Quantification

Monte Carlo simulations (n = 10,000 iterations) assessed parameter uncertainty, incorporating measured standard deviations of c', φ' values to generate confidence intervals around computed factors of safety. Model limitations include the assumption of plane failure geometry and the simplified representation of heterogeneous soil stratigraphy.

Results

Geotechnical Property Variations Across Regions

Significant regional variations in geotechnical properties were observed, reflecting differences in depositional history, weathering processes, and climatic influence. The key observations included:

Terai Plains

Exhibited the lowest permeability ($0.9 \pm 0.2 \times 10^{-2}$ cm/s) and the highest clay concentration (55%) because to the high organic matter content and Gangetic depositional systems. Low friction angle (16°) makes it susceptible to instability under rapid drawdown or seismic shaking, even with high cohesion (30 kPa).

Kathmandu Valley

Typical of lacustrine deposits, the soils had a low friction angle (18°), moderate cohesiveness, and an intermediate clay content (42%). Sensitivity to changes in moisture content, especially during monsoon seasons, is indicated by a high plasticity score (32%).

Pokhara

Alluvial deposits demonstrated reduced clay content (28%) and higher permeability 8.5 ± 1.1 $\times 10^{-6}$ cm/s, facilitating rapid drainage and limiting pore pressure buildup. Intermediate friction angle (25°) reflects coarser grain size distribution.

Chitwan

Soils exhibited transitional properties (18% clay, 37% sand) with enhanced friction angle (32°) due to laterization and cementation effects. Permeability (12.4 ± 1.5$\times 10^{-6}$ cm/s) supports good drainage despite high silt content.

Mustang

Colluvial soils showed lowest clay content (12%) and highest permeability (18.9 ± 2.2$\times 10^{-6}$ cm/s), reflecting sparse weathering and coarse particle distribution. Very low cohesion (5 kPa) and high friction angle (35°) typify angular colluvial material.

Table 2: Geotechnical properties across the five regions. Values represent means ± standard deviation (n=3 per region). Results indicate strong regional differentiation in shear strength and permeability characteristics.

Parameter	Kathmandu	Pokhara	Chitwan	Mustang	Terai
Clay (%)	42 ± 3.1	28 ± 2.8	18 ± 1.9	12 ± 1.5	55 ± 4.2
Silt (%)	38 ± 2.6	34 ± 2.1	45 ± 3.3	23 ± 1.8	32 ± 2.7
Sand (%)	20 ± 1.7	38 ± 3.2	37 ± 2.9	65 ± 4.1	13 ± 1.2
LL (%)	58 ± 2.3	49 ± 2.1	36 ± 1.8	31 ± 1.5	63 ± 2.9
PL (%)	26 ± 1.4	22 ± 1.2	19 ± 1.1	17 ± 0.9	29 ± 1.6
c' (kPa)	28 ± 1.8	15 ± 1.2	10 ± 0.9	5 ± 0.6	30 ± 2.1
φ' (°)	18 ± 1.1	25 ± 1.4	32 ± 1.7	35 ± 1.9	16 ± 0.8
k ($\times 10^{-6}$ cm/s)	2.1 ± 0.3	8.5 ± 1.1	12.4 ± 1.5	18.9 ± 2.2	0.9 ± 0.2

Slope Stability Analysis

Factor of Safety (FoS) calculations incorporating measured geotechnical parameters and bioclimatic variations revealed substantial regional differentiation:

Table 3: Slope stability analysis outcomes. Static FoS represents drained conditions; seismic FoS incorporates pseudostatic coefficients (k_h = 0.2g). Critical height indicates maximum stable slope height at 35° inclination.

Region	Static FoS	Seismic FoS	Critical Height (m)	Failure Mode
Kathmandu	1.2	0.9	8.5	Rotational slump
Pokhara	1.5	1.1	12.2	Translational slide
Chitwan	2.1	1.8	18.7	Debris flow
Mustang	2.5	2.0	22.4	Rockfall
Terai	0.8	0.6	5.1	Mudflow

Regional Stability Patterns

Due to intrinsic instability, the Terai Plains showed the lowest factors of safety (static FoS = 0.8, seismic FoS = 0.6). Even in static settings, continuous instability is produced by a high clay concentration and a low friction angle. In this area, cautious slope management is required due to the critical height of only 5.1 m. Failure risk is increased by monsoon-induced rapid pore pressure rise, and mudflow is the usual failure mechanism.

Soils in the Kathmandu Valley showed only moderate stability (static FoS = 1.2), which was further weakened by seismic stress (FoS = 0.9). On natural slopes higher than 8.5 meters, stability is limited by the low friction angle (18°) and moderate cohesion (28 kPa). There are many rotational slump mechanisms, which are usually caused by monsoon infiltration into lacustrine clay that has dried out. Because of better drainage from increased permeability, Pokhara showed improved stability (static FoS = 1.5). In alluvial sequences with bedding planes and weak horizons, translational failures predominate. Vulnerability to mild earthquake shaking is indicated by a seismic FoS of 1.1.

Chitwan's high friction angle (32°) from laterized, cemented soils contributed to its outstanding stability (static FoS = 2.1). However, when pore pressure ratios above 0.6 during periods of strong monsoon, saturated debris flow failure becomes common. In comparison to other areas, the critical height of 18.7 m allows for steeper stable slopes. Because to its high friction angle and low cohesion dependence, Mustang earned the highest factors of safety (static FoS = 2.5, seismic FoS = 2.0). However, rather than planar sliding, rockfall and wedge failures are more common because of joining in colluvial material. Despite favorable FoS values, continued attention is necessary due to sparse vegetation and the quick weathering of calcrete.

Correlation Between Plasticity, Moisture, and Stability

All regions showed a strong inverse relationship between moisture content and factor of safety, according to statistical analysis ($R2 = 0.87$, $p < 0.01$). In clay-rich areas (Terai, Kathmandu), where the plasticity index is higher than 30%, this relationship is especially noticeable. Due to improved drainage capacity and decreased pore pressure deposition, Pokhara and Chitwan, which had lower plasticity indices (27% and 17%, respectively), demonstrated stronger stability resilience during simulated monsoon conditions.

Discussion

Regional Geotechnical Characterization and Depositional History

Fundamental variations in weathering regimes and depositional environments are reflected in the reported variances in geotechnical qualities. The Terai Plains are an example of contemporary Gangetic alluvial deposition with little oxidation; as a result, large levels of organic matter and iron-rich minerals improve cohesiveness and clay content while lowering the friction angle. Because of their montmorillonitic mineralogy, which is sensitive to changes in moisture, the lacustrine deposits in the Kathmandu Valley that were formed during late Pleistocene Lake phases have a moderate clay concentration and considerable flexibility. The coarser grain distributions and varied cementation seen in Pokhara's alluvial fans, which are derived from Pleistocene glacial outburst floods, result in moderate geotechnical qualities and regional stability variations.

The weathering of Siwalik sandstone combined with laterization processes typical of sub-Himalayan wooded zones is the source of Chitwan soils. An advantageous combination for slope stability is iron oxide buildup, which increases cementation and friction angle while decreasing flexibility. In contrast, there is very little chemical weathering in Mustang's arid colluvial deposits, which leads to angular grain particles, high friction angles, and little cohesiveness. It is impossible to overestimate the importance of mineralogy (clay type, iron oxide concentration, and degree of weathering): illite-rich Terai soils are very different from the kaolinite-montmorillonite combinations typical of the Kathmandu Valley.

Monsoon Hydrology and Pore Pressure Dynamics

The main cause of slope failures in all areas is monsoon-driven infiltration, which works by quickly increasing pore pressure and reducing stress. Groundwater response rates are directly controlled by the permeability range (0.9 to 18.9×10^{-2} cm/s). Shear strength is quickly undermined by strong positive pore pressures that occur in low-permeability locations (Terai: 0.9×10^{-1} cm/s). Because of joint saturation and accelerated weathering, high-permeability zones (Mustang: 18.9×10^{-1} cm/s) drain rapidly and maintain lower pore pressure ratios, but they are still vulnerable to rockfall.

The hydro-mechanical interaction in these soils is highlighted by the substantial moisture content-FoS correlation ($R^2 = 0.87$). While coarser, less plastic soils maintain comparatively consistent FoS values over moisture gradients, areas with higher clay content and plasticity index see exponential declines in FoS as saturation rises. This conclusion implies that rather than being applied consistently throughout Nepal, early monsoon warnings associated with rainfall thresholds should be calibrated regionally.

Seismic-Hydro Interactions and Cumulative Hazard

All locations had a 20–30% reduction in factors of safety due to seismic loading, with low-friction zones experiencing the worst deterioration (Terai FoS drop: 0.8–0.6). Our modeling predictions were validated by the 2015 Gorkha earthquake (Mw 7.8), which caused over 25,000 landslides concentrated in areas with FoS < 1.0 static values. Particular attention should be paid to combined hazard scenarios when monsoon saturation occurs either before or after seismic shaking since they may surpass design criteria in slopes that are now stable.

Implications for Slope Management and Reinforcement

Nepal is divided into five geotechnically and climatically diverse zones according to the suggested regional classification framework, each of which calls for different management strategies. This framework combines measured geotechnical parameters, geological substrate, and bioclimatic features (vegetation, rainfall) into a logical classification. Terai and Kathmandu are examples of zones with low FoS and high plasticity that need proactive reinforcing, such as improved drainage and structural methods like soil nailing and anchoring. Bioengineering integration (slope revegetation, debris flow barriers) combined with targeted drainage enhancement is beneficial for intermediate-stability zones (Pokhara, Chitwan). In order to reduce erosion, high-stability zones (Mustang) place a high priority on maintaining sparse natural vegetation and keeping an eye on specific weak zones.

Based on geotechnical zone categorization, slope height, and anticipated groundwater conditions, the decision matrix derived from these findings offers practitioners a methodical framework for choosing reinforcing techniques. This framework fills up the gaps that currently exist between general slope design guidelines and Nepalese characteristics unique to a given place.

Conclusion

Throughout Nepal's five main bioclimatic zones, this study demonstrates quantitative correlations between regional geotechnical characteristics, climatic gradients, and slope stability mechanisms. Key findings show that the main stability controllers are clay mineralogy and moisture content ($R^2 = 0.87$), with factors of safety ranging from favorable values (2.5 in Mustang) to critically low levels (0.8 in Terai). All three of the research's stated goals were effectively met: (1) quantifying the spatial differences in shear strength, compressibility, and hydraulic conductivity among the five regions; (2) creating region-specific correlations between factors of safety and plasticity indices and monsoon intensity; and (3) proposing a novel regional classification framework combined with a decision matrix for slope reinforcement techniques.

The innovative regional classification framework provides a methodical foundation for site-specific slope management in Nepal's quickly urbanizing landscapes by combining observed geotechnical properties with bioclimatic zonation (rainfall, temperature, vegetation). This paradigm goes beyond conventional homogenized methods, acknowledging that spatially calibrated engineering solutions are necessary for Himalayan soil products of various depositional and weathering regimes. By matching reinforcement techniques to geotechnical zone classification and slope-specific conditions, the slope reinforcement decision matrix operationalizes these findings and allows practitioners to allocate resources optimally toward the highest-risk regions (Terai, Kathmandu) while avoiding over-engineering in zones that are naturally stable (Mustang).

As monsoon strength forecasts rise under global warming scenarios, these findings have urgent implications for improving landslide hazard assessments, designing infrastructure in Himalayan terrain, and preparing for climate adaptation. To improve forecasts during periods of intense rainfall, future studies should use real-time piezometric monitoring networks, vegetative root reinforcement modeling, and three-dimensional slope geometry.

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