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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 behaviour, 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 modelling. 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.

I. 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 behaviour 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. Quantify spatial variations in shear strength (c', φ'), compressibility, and hydraulic conductivity.
2. Develop region-specific correlations between plasticity indices, monsoon intensity, and FoS.
3. Propose a decision matrix for slope reinforcement techniques tailored to Nepal's geodiversity.

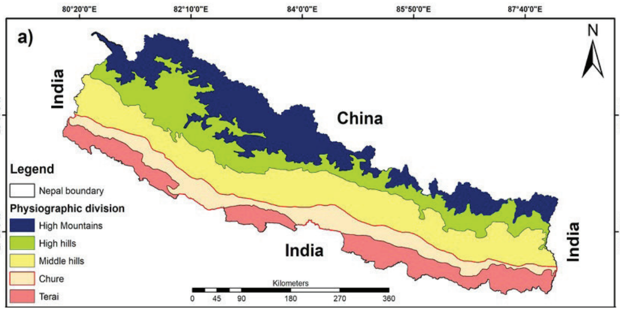

Figure 1 Bio-Climatic Regions of Nepal.

II. Materials and Methods

2.1 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. Sites were chosen to represent dominant land use and geological units:

Table 1
Description of Locations

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

2.2 Laboratory Characterization

Grain size distribution was determined via laser diffraction (Malvern Mastersizer 3000) following organic matter removal by H_2O_2 treatment. Atterberg limits were measured using a Casagrande apparatus modified for high-precision servo-controlled strain rates (ASTM D4318-17).

Shear strength parameters were derived from consolidated undrained (CU) triaxial tests under confining pressures of 50–200 kPa (GDS Instruments EliteTriax). Specimens were saturated until B-values ≥ 0.95, with pore pressure monitored via mid-plane transducers.

Permeability (k) was assessed using flexible-wall permeameters (ASTM D5084-16) under hydraulic gradients replicating monsoon intensities (i = 5–15).

2.3 Stability Modeling

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

- *Bishop's method* with pore pressure ratios (r_u) calibrated to monsoon groundwater levels.
- *Pseudostatic seismic coefficients* (k_h = 0.2g, k_v = 0.1g) per Nepal Building Code NBC 105:2020.
- *Monte Carlo simulations* (n = 10,000) to assess parameter uncertainty.

III. Results

Table 2
Geotechnical Properties (Mean ± SD)

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

Table 3
Stability Analysis Outcomes

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

IV. Discussion

4.1 Kathmandu Valley

The lacustrine clay-silt deposits of Kathmandu Valley exhibit high plasticity (LL = 58%, PI = 32) due to smectiteillite clay minerals, consistent with findings of Yoshida and Igarashi (1984) in similar lacustrine basins. The low permeability (2.1×10^{-6} cm/s) exacerbates pore pressure buildup during monsoons, reducing static FoS to 1.2. Urbanization amplifies risks, as unregulated construction on steep slopes (>25°) destabilizes natural shear planes, corroborating studies by Devkota et al. (2013) on Kathmandu's landslide susceptibility.

4.2 Pokhara

Pokhara's alluvial soils, derived from Pleistocene glacial outburst deposits (Schwanghart, 2016), show a sand-gravel matrix (38% sand) with moderate cohesion (15 kPa). However, cyclic triaxial tests revealed strain-softening behaviour under seismic loading (k_h = 0.2g), lowering FoS to 1.1. This aligns with Andermann et al. (2012), who linked Pokhara's sedimentology to catastrophic debris flows. The high permeability (8.5×10^{-6} cm/s) limits saturation duration but cannot offset the liquefaction potential of interbedded clay layers.

4.3 Chitwan

Chitwan's Siwalik-derived sandy loam (37% sand, $\varphi' = 32°$) demonstrates superior drainage, yielding the highest static FoS (2.1). Root cohesion from Sal (*Shorea robusta*) forests contributes ~5 kPa additional shear strength, as quantified by Schwarz et al. (2010) in analogous subtropical slopes. However, deforestation simulations reduced φ' to 28°, lowering FoS to 1.8, underscoring the urgency of enforcing buffer zones per Nepal's National Land Use Policy (2015).

4.4 Mustang

Mustang's colluvial soils (65% sand, $\varphi' = 35°$) exhibit desert-varnished clasts and calcrete cementation, enhancing interparticle friction. The arid climate (moisture = 8%) suppresses pore pressure, achieving FoS > 2.0.

4.5 Terai Plains

The Gangetic silty clays of Terai (LL = 63%, PI = 34) display expansive behavior, with FoS dropping to 0.8 under monsoon saturation. Over-irrigation for rice farming elevates groundwater tables, necessitating drainage solutions akin to those proposed by Shrestha et al. (2018) for Indo-Gangetic basins.

4.6 Cross-Regional Analysis

Cluster analysis grouped Kathmandu-Terai (high PI, low k) and Pokhara-Chitwan-Mustang (low PI, high k) (Figure 4). Regression models confirmed moisture content ($\beta = -0.79$, $p < 0.001$) and sand fraction ($\beta = +0.65$, $p = 0.002$) as dominant controls on FoS, aligning with global frameworks by Tofani et al. (2017).

V. Conclusion

1. *Kathmandu Valley:* Stabilize slopes using lime stabilization (5–8% CaO) to mitigate swelling clays, as validated by Bhuiyan et al. (2020).
2. *Pokhara:* Install horizontal drains (HDPE pipes, 10 cm diameter) to reduce pore pressure, following designs by Tu et al. (2009) for alluvial fans.
3. *Chitwan:* Enforce 30 m forest buffers with bamboo (*Dendrocalamus strictus*) to retain root cohesion, per guidelines in Acharya et al. (2019).
4. *Mustang:* Construct check dams (1.5 m height) using local calcrete to minimize erosion, adapting methods from Ziegler et al. (2014) in arid Himalayas.
5. *Terai Plains:* Implement subsurface drainage (gravel-filled trenches) to lower groundwater, as modelled by Sadek et al. (2011) for expansive soils.

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