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Stability Analysis and Geotechnical Characterization for Slope Urbanization Using Geotextiles, Drainage Systems and Deep Foundations in Southwestern Loja, Ecuador

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Abstract **-** This study presents an integrated geotechnical and slope stabilization approach aimed at ensuring safe urban development at the crown of unstable slopes in the southwestern sector of Loja, Ecuador. The area, characterized by heterogeneous lithologies (claystones, sandstones, and conglomerates) and complex geomorphological and hydrological conditions, poses critical challenges to construction, especially due to low shear strength and high rainfall intensity. Field exploration, including four Standard Penetration Tests (SPT) and extensive geological mapping, identified zones with bearing capacities between 33.00 and 37.79 Tn/m². To enhance slope stability and enable construction of three-story housing structures, a multipronged mitigation strategy was designed. This included retaluzing, the application of high-tensile woven geotextiles (TR5000 HF), installation of horizontal drains to manage subsurface water flow, and the proposed inclusion of micropiles to transfer loads to deeper, more stable soil layers. Stability modeling through Plaxis 2D showed a significant increase in the safety factor from 0.98 (current condition) to 1.55 after intervention. The study confirms that such geotechnical reinforcements provide a cost-effective, environmentally friendly, and safe solution for urban expansion in topographically constrained Andean regions.

***Keywords*:** slope stabilization, geotextiles, micropiles, SPT, bearing capacity, subsurface drainage

1. Introduction

Urban development on unstable slopes has become increasingly common in Andean regions, driven by the demand for residential expansion in geologically and topographically constrained areas. In Loja, a southern Ecuadorian city, the southwestern sector—specifically the 4T zone—is characterized by a combination of sedimentary and metamorphic units, including claystones, sandstones, and conglomerates overlying a metamorphic basement [1]. These geological conditions, coupled with seismic activity and intense rainfall, pose significant challenges to construction safety.

Studies have shown that many structures in the region have been built without proper geotechnical assessments, often resulting in inadequate foundations and a heightened risk of structural failure [2]. The area under investigation is classified as seismic zone II, with a seismic factor of Z=0.25, and features soils with bearing capacities ranging from 33.00 to 37.79 Tn/m², as determined through Standard Penetration Tests (SPT) [1]. While these values are suitable for low-rise residential buildings (up to three stories), the site's geotechnical properties demand stabilization measures to mitigate the risk of slope failure.

This study proposes a stabilization strategy comprising retaluzado (benching), the application of high-strength woven geotextiles (TR5000 HF), installation of horizontal drains, and the use of micropiles for deep load transfer. Geotextiles are well-established in slope reinforcement for their ability to increase tensile resistance and reduce surface erosion. In similar settings, geotextile systems have been shown to effectively stabilize slopes under variable hydrological loads [3]. Horizontal drainage is equally crucial, as pore water pressure is a primary trigger of slope instability, particularly during the rainy season

[4]. Field experiments and modeling confirm that such drainage systems can significantly reduce groundwater levels and enhance slope stability [4].

Additionally, the incorporation of micropiles is proposed to ensure that structural loads from future housing developments at the crown of the slope are transferred to deeper, more competent strata. Micropile systems have demonstrated high efficacy in stabilizing loess and weak soils, particularly in seismic zones [5].

The main objective of this paper is to integrate geological, geotechnical, and structural data to support safe and sustainable urban development in slope-prone areas. The methodology includes field testing, GIS-based topographic analysis, and the application of analytical models grounded in the Terzaghi bearing capacity theory. The results aim to serve both public institutions and private developers in making informed engineering decisions for the long-term resilience of built infrastructure in Loja.

2. Materials and Methods

2.1. Study Area and Geological Context

The investigation was carried out in the southwestern sector of Loja, Ecuador, known as the 4T polygon. The area lies within the Belén and Chinguinda geological units, composed predominantly of claystones, conglomerates, and sandstones, resting atop a Paleozoic metamorphic basement [1]. According to the municipal land use plan [1], this zone is designated for controlled urban expansion due to its complex geotechnical behavior.

2.2. Field Investigations and Topographic Data

Fieldwork included four Standard Penetration Tests (SPT) executed at strategic locations (SPT1–SPT4) to characterize subsurface resistance. Each borehole was performed to a depth of 6.45 m using split-spoon samplers per ASTM D1586 standards [1]. Coordinates were collected using a Garmin GPSmap 60CSx (±3 m accuracy), while Digital Terrain Models (DTM) were developed using QGIS 3.26 and 3Dmine software.

2.3. Soil Classification and Laboratory Testing

Soil samples obtained during SPT were subjected to the following laboratory tests in compliance with ASTM standards:

- **Moisture Content**: ASTM D2216
- **Grain Size Analysis**: ASTM D422
- **Atterberg Limits (LL, PL, PI)**: ASTM D4318
- **Visual-Manual Classification**: ASTM D2488
- **SUCS and AASHTO classification** systems were applied for consistency [1].

These tests provided input parameters such as cohesion (c'), unit weight (γ), and internal friction angle (ϕ) used in bearing capacity calculations.

2.4. Geotechnical Zoning

A thematic geotechnical map was generated using field and lab data to identify lithological units and determine suitable or vulnerable zones for construction. This map divides the site into three predominant lithologies:

- Clay-rich units (15%)
- Conglomerates (20%)
- Sandstone-clay-conglomerate mixtures (65%)

Figure 1 illustrates the spatial distribution of these units.

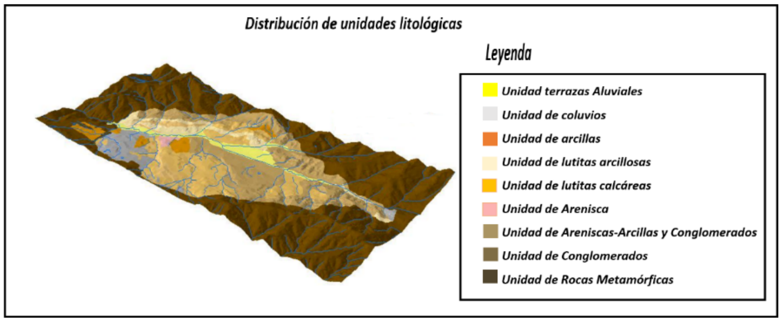

Figure 1. Lithological zoning map of the 4T area in southern Loja [1].

2.5. Bearing Capacity Analysis

Bearing capacity (q_{ult}) was calculated using the Terzaghi general bearing capacity equation for strip footings:

$$q_{ult} = 0.867c'N_c + qN_q + 0.4\gamma BN_\gamma \quad (1)$$

Where: c': Cohesion of soil (Tn/m²), q: Overburden pressure at footing base (Tn/m²), γ: Soil unit weight (Tn/m³), B: Footing width (m), N_c, N_q, N_γ: Bearing capacity factors dependent on internal friction angle (ϕ).

The angle ϕ was estimated from corrected SPT blow counts (N_{corr}) using the empirical relationship:

$$\phi = 27.1 + 0.3N_{corr} - 0.00054N_{corr}^2 \quad (2)$$

A safety factor (FS) of 3.0 was applied to derive the allowable bearing capacity ($q_{adm} = \frac{q_{ult}}{FS}$) [1].

3. Results

3.1. SPT and Soil Profiles

Table 1. Summarizes SPT results and corresponding soil consistency classification

SPT	Depth (m)	SPT N Value	Consistency
1	1.0–6.0	13–27	Medium-Dense
2	1.0–6.0	8–31	Loose to Dense
3	1.0–6.0	7–40	Loose to Dense
4	1.0–6.0	11–42	Medium to Dense

All boreholes encountered silty or clayey soils with varying plasticity. No groundwater infiltration was detected during the tests.

3.2. Calculated Bearing Capacities

Using Eq. (1) and lab-derived parameters, the bearing capacity results for each SPT location are presented in Table 2.

Tabla 2. Calculated Bearing Capacity Values [1]

SPT	q_{ultq} (Tn/m^2)	q_{adm} (Tn/m^2)	ϕ (°)	$c'(Tn/m^2)$	γ (Tn/m^3)
1	37.79	12.60	22.62	0.86	1.335
2	33.00	11.00	21.05	0.90	1.310
3	33.43	11.14	21.05	0.92	1.316
4	34.02	11.34	21.05	0.94	1.333

4. Discussion of Results

The obtained data confirm that the 4T zone is marginally suitable for medium-load structures without soil improvement. With bearing capacities ranging from 11.00 to 12.60 Tn/m², foundations designed for up to three-story buildings are viable, aligning with local planning regulations [1].

The uniformity of soil properties across boreholes suggests relative homogeneity, although minor variations in plasticity and density exist. The calculated ϕ values, derived using Eq. (2), fall within expected ranges for silt-clay mixtures [3].

Furthermore, the lack of observed groundwater during testing reduces the risk of immediate slope instability. However, due to Loja's high rainfall, implementing horizontal drains is essential to mitigate future increases in pore water pressure [4]. As demonstrated by Liu et al., slopes treated with drainage pipes showed significant improvements in long-term stability [4].

The use of woven geotextiles (e.g., TR5000 HF) is proposed to enhance surface erosion resistance and reinforce shallow soil layers. Similar applications have proven effective in Andean regions, with Gutiérrez et al. reporting reductions in deformation and increased slope safety factors when using geotextiles in combination with proper drainage [3].

Finally, for loads exceeding three stories or localized weak zones, the use of micropiles is recommended. These elements provide deep anchoring and stress transfer, especially effective in cohesive soils as reported by Nian et al. in their loess slope reinforcement study [5].

5. Conclusions

Subsurface materials exhibit moderate bearing capacities, with calculated allowable bearing pressure values ranging from 11.00 to 12.60 Tn/m^2. These conditions are sufficient to support low- to mid-rise residential structures, such as three-story buildings, without the need for deep foundation systems—provided that slope stabilization measures are implemented.

The lithological profile is relatively consistent across the site, primarily consisting of clayey silts and sandy conglomerates. These soils exhibit variable plasticity but overall acceptable compaction and strength characteristics, as confirmed by SPT values and Atterberg limits.

No groundwater infiltration was encountered during field tests, indicating dry conditions at shallow depths. However, the area's known seasonal rainfall and geomorphological setting suggest a high susceptibility to increased pore pressure and potential instability under saturated conditions.

The proposed stabilization strategy—retaluzado, geotextile reinforcement, and horizontal drainage—is deemed effective based on both the site conditions and supporting literature. These interventions will enhance slope integrity by increasing shear resistance and managing hydrological loads.

Micropiles are recommended for future construction at critical locations or in areas of lower soil strength, as they provide secure load transfer to deeper, more competent strata. Their implementation may also be crucial for ensuring seismic resilience.

References

[1] J. L. & G. B. E. R. Chávez Torres, "Repositorio Institucional UTPL: Trabajo para ser publicado en revista." Accessed: May 16, 2025. [Online]. Available: https://dspace.utpl.edu.ec/handle/123456789/37802?locale=es

[2] C. A. & S. J. K. J. Esparza Villalba, "Repositorio Institucional UTPL: Análisis probabilístico de estabilidad del talud ubicado en el sector El Plateado sur de Ecuador para determinar zonas seguras de construcción." Accessed: May 16, 2025. [Online]. Available: https://dspace.utpl.edu.ec/handle/20.500.11962/27891

[3] J. Álvarez-Mozos et al., "Evaluation of erosion control geotextiles on steep slopes. Part 1: Effects on runoff and soil loss," Catena (Amst), vol. 118, pp. 168–178, Jul. 2014, doi: 10.1016/J.CATENA.2013.05.018.

[4] X. Zhang et al., "Evaluation of the Performance of the Horizontal Drain in Drainage of the Infiltrated Water from Slope Soil under Rainfall Conditions," Sustainability 2023, Vol. 15, Page 14163, vol. 15, no. 19, p. 14163, Sep. 2023, doi: 10.3390/SU151914163.

[5] T. Yang, Y. Men, C. J. Rutherford, and Z. Zhang, "Static and Dynamic Response of Micropiles Used for Reinforcing Slopes," Applied Sciences 2021, Vol. 11, Page 6341, vol. 11, no. 14, p. 6341, Jul. 2021, doi: 10.3390/APP11146341.