Proceedings of the 10th International Conference on Civil Structural and Transportation Engineering (ICCSTE 2025)
July, 2025 | Imperial College London Conference Center, London, United Kingdom
Paper No. 247
DOI: 10.11159/iccste25.247

Slope Stability Analysis of the Slope Located On the E35 Pan-American Highway, Exit to Cuenca, Carigán Sector

Jose Luis Chavez Torres[1], Kunyong Zhang[2], Feng Tugen[3] and Dylan Manuel Cueva Castillo
[1-2-3]Hohai University
Nanjing 210024, China
[1-4]Department of Civil Engineering, Universidad Tecnica Particular de Loja
Loja 1101608, Ecuador
[1-2-3]Research Institute of Geotechnical Engineering, Hohai University
Nanjing 210024, China
[2-3]Key Laboratory of Ministry of Education for Geomechanics and Embankment Engineering,
Hohai University
Nanjing 210024, China

Abstract - This study analyses the stability of the slope located on the E35 Pan-American Highway, exit to Cuenca, Carigán sector, an area of importance for Ecuadorian road infrastructure. The research employed a quantitative methodology structured in systematic phases that included in situ evaluation, geotechnical zoning, topographic and geophysical survey, soil sampling, laboratory tests, hydrological studies, numerical modelling and profile analysis. The results showed safety factors of 0.41, 0.32, 1.21 and 0.95 for the different conditions evaluated, indicating instability in most of the scenarios analysed. The modelling showed that critical conditions such as the presence of a shallow water table, increased loading and seismic activity significantly reduce the factors of safety below the unit value established by the current regulations. It was determined that the composition of the soil, mainly clays and silts of high plasticity, contributes to the susceptibility of the slope to landslides, especially during periods of high rainfall. Sensitivity analyses revealed that the cohesion of the material and the angle of internal friction are determining parameters in the geomechanical behaviour of the slope. These findings suggest the need to implement mitigation measures such as drainage systems, equilibrium berms and retaining walls to guarantee the long-term stability of this important communication route and prevent potential landslides affecting the road infrastructure and the safety of users.

***Keywords*:** Slope stability - Factor of safety - Geotechnical analysis - Road infrastructure - Numerical modelling - Landslide mitigation.

1. Introduction

Landslides represent one of the most destructive geological processes affecting human populations, causing thousands of deaths and property damage worth tens of billions of dollars annually. Despite their impact, awareness of their importance is low. Studies indicate that approximately 90% of landslide losses could be avoided by early identification and appropriate preventive measures.[1]

Geotechnics, although relatively new as a structured technical discipline, is one of the fundamental branches of civil engineering because of its focus on the study of the hydraulic and mechanical properties of soil. This knowledge is essential for the design of everything from the foundations of complex structures to road works and their associated slopes.

Slope stability analysis is a geotechnical procedure to assess the safety of both natural and artificial formations by determining the factor of safety. This analysis integrates knowledge of civil engineering and geology, its main objective being to safeguard human lives and prevent significant material damage.

The present investigation focuses on the slope located on the E35 Pan-American Highway, exit to Cuenca, Carigán sector, where signs of instability have been observed that represent a risk for the road infrastructure and the surrounding houses. Methodologically, the study comprised a topographical survey, lithological characterisation, laboratory tests (moisture content, granulometry, Atterberg limits and triaxial tests), and a hydrological study of the area. The data obtained were analysed using specialised software (Geoslope and Midas) to determine the current stability conditions.[2]

During the investigation, the concern of the inhabitants of the sector became evident, who have observed the progressive deterioration of the slope without effective intervention by the competent authorities. This work seeks to provide viable technical solutions, including drainage systems for surface and subsurface water, as well as retaining structures to stabilise the slope.

The relevance of this study lies in its potential to guide technical decisions to protect critical road infrastructure and, above all, to safeguard the integrity and property of the inhabitants of this area of high geotechnical risk.

2. Methodology

This research implemented a quantitative methodology, structured in systematic phases oriented to the geotechnical analysis of the slope located on the E35 Pan-American Highway, Carigán sector. This methodological approach allowed the collection and processing of edaphological and geomechanical parameters for the precise determination of the safety factor through the analysis of variables such as rainfall, lithological stratigraphy and mechanical properties of the soil.[3]

The study started with the in situ assessment and geotechnical zoning through field reconnaissance, allowing the characterisation of the geomorphological conditions of the slope, road infrastructure and surrounding buildings. This assessment provided a preliminary qualitative categorisation of the physico-mechanical properties of the substrate and its construction implications, fundamental information for subsequent geotechnical modelling.[4]

The altimetric and planimetric representation of the terrain was obtained by topographic survey with Differential GPS, establishing a network of geodetic points in the crown of the slope and its zone of influence. Despite the accessibility restrictions derived from the steep slope and erosive processes on certain berms, it was possible to obtain sufficient data to generate contour lines with equidistances of 1-5m. The planialtimetric information was processed using specialised CAD software, allowing the generation of transverse and longitudinal profiles with a controlled vertical scale factor.

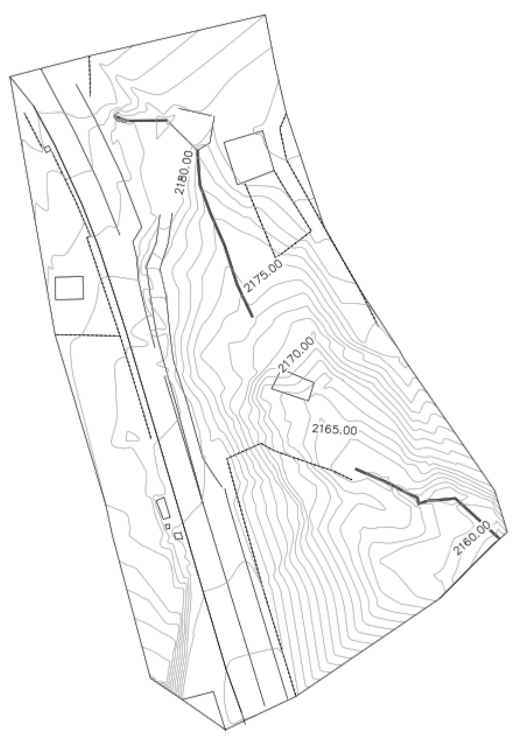

Fig 1. Topographical survey.

The geophysical component was developed using Electrical Resistivity Tomography (ERT) with a Dipole-Dipole configuration, with electrodes arranged along the foot of the slope with progressive spacing of two metres. This configuration was selected considering the required survey depth and the sensitivity of the array to vertical and horizontal discontinuities in the subsurface resistivity. A survey line of 144 metres perpendicular to the road axis was established with 21 nodes arranged every 5 metres, allowing a two-dimensional profile of the distribution of resistivity values at different depths to be obtained.[5]

Soil sampling was carried out in accordance with ASTM D421 standards, excavating a trench in the mid-slope of the slope for the extraction of undisturbed block samples. These samples were duly preserved with plastic material to conserve their natural humidity and transported to the laboratory under protocols that minimise alterations. The UTM coordinates of the sampling point were recorded to centimetre accuracy to ensure geospatial traceability.

In the laboratory, the samples were subjected to standardised geotechnical tests, including granulometric analysis (ASTM C 136-01), moisture content determination (ASTM D-2216), consistency limits (ASTM D 4318) and unconsolidated-undrained triaxial test (ASTM D 2850-82). These tests provided essential geotechnical parameters such as SUCS classification, cohesion, angle of internal friction and bulk density, fundamental inputs for the stability analysis. The hydrological study was based on INAMHI pluviometric data for the determination of maximum flood flows with return periods of 25 and 50 years. The Rational method was applied for the contributing micro-basins, in accordance with the guidelines established in the MOP-2003 Standard for drainage areas of less than 50 hectares, using records from meteorological stations near the study area. [6]

Finally, numerical modelling and geotechnical interpretation were carried out. The acting overloads were quantified, including the vehicular load on the Troncal de la Sierra E35 (categorised as an arterial corridor according to NEVI-12-MTOP) with an increased value of 3 Tn/m² and structural loads of single-family dwellings (2 KN/m² according to NEC-SE-CG). Four critical profiles were analysed under different geotechnical scenarios, considering circular failure surface and applying the Morgenstern-Price method for the calculation of the safety factor, selected for its suitability for the predominant cohesive soils in the slope stratigraphy.

3. Results

A sub-catchment area of 71.79 hectares and a maximum length of 908.59 metres was determined using ArcGIS. The average slope was calculated using the equidistance between contour lines and their lengths. The runoff flow was analysed using the rational method, which is essential for assessing the stability of the slope under study.

The hydrological analysis of the sub-basin affecting the studied slope revealed an area of 71.79 hectares and a maximum length of 908.59 metres, calculated using ArcGIS. The mean slope, obtained from the altitudinal belt analysis, was 28.35%, a significant value that directly influences the runoff velocity. The calculated time of concentration was 6.16 minutes, while the precipitation intensity, determined using the INAMHI equation for La Argelia station M0033 with a return period of 100 years, reached 11.12 mm/h. Considering the characteristics of forest and semi-permeable vegetation of the soil, a runoff coefficient of 0.4 was established, fundamental parameters for the evaluation of the stability of the slope located on the E35 Pan-American Highway. [7]

The hydrological analysis of the slope located on the E35 Pan-American Highway, Carigán sector, revealed important characteristics of the sub-basin. An area of 71.79 hectares and a maximum length of 908.59 metres was determined using ArcGIS. The average slope was 28.35%, a significant value that directly influences the surface runoff velocity. With a calculated time of concentration of 6.16 minutes and using data from the INAMHI station La Argelia M0033 with a return period of 100 years, a rainfall intensity of 11.12 mm/h was obtained. Considering the characteristics of forest and semi-permeable vegetation of the soil, a runoff coefficient of 0.4 was established.

By applying the rational method, widely used to estimate maximum flows in drainage works without requiring extensive hydrometric data, a maximum flow of 11.12 m³/s was calculated for the sub-basin analysed.

The geotechnical study allowed the mechanical properties of the soil to be characterised. Electrical resistivity tomography, with a profile of 144 metres perpendicular to the road, identified two main strata: the first one of CL type up to a depth of 3.96 metres, and the second one composed of clay saturated with water up to 31.7 metres. Additionally, a water eye was detected between 118 and 124 metres in length. [8]

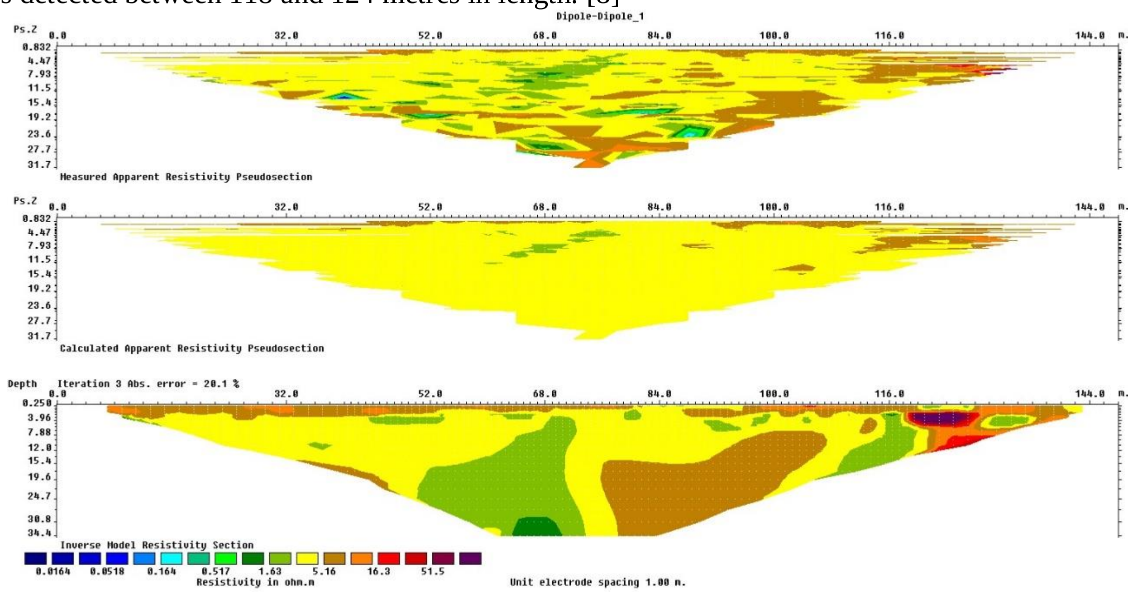

Fig 2. Electrical resistivity tomography results

Laboratory analyses classified the soil according to the Unified Soil Classification System (U.S.S.C.S) as SW/SP (well graded sand with gravel) and CL (clay). Atterberg limit tests showed, for the SW soil, a liquid limit of 43%, plastic limit of 26% and plasticity index of 17%, while the CL soil showed values of 30%, 16% and 14% respectively. These parameters are fundamental to evaluate the behaviour of the soil in the face of moisture changes and their influence on slope stability.[9]

The results of the triaxial test carried out on the CL type soil of the slope in the Carigán sector show a cohesion of 31.17 Tn/m² and a friction angle of 32.33°, with natural and dry densities of 3610 Tn/m³ and 3060 Tn/m³ respectively. These geotechnical parameters were introduced in the Slope software modelling, where 5 representative slope profiles were analysed using the Morgenstern-Price method under three different conditions: static in dry state, static with water table and pseudo-static considering seismic loads. The factors of safety obtained allow us to evaluate the stability of the slope on the E35 Pan-American Highway and to determine the most critical conditions that could compromise its structural integrity.

The stability analysis carried out with Slope software using the Morgenstern-Price method has made it possible to evaluate five critical profiles of the slope located on the E35 Pan-American Highway, Carigán sector. The results reveal an alarming situation of generalised instability in all the profiles analysed, with safety factors significantly below the minimum value of 1.5 established by the NEC-SE-CM regulations for major infrastructure works. [10]

Profile 1-1, located at the beginning of the road, presents a configuration of two layers (superficial CL on SW) under conditions of complete saturation according to the electrical resistivity tomography and subjected to a vehicular load of 3 tn/m². This profile exhibits an extremely low factor of safety of 0.41, indicating a high risk of failure. Profile 2-2, with similar stratigraphic configuration but with additional loads (vehicle load of 3 tn/m² and residential load of 2 tn/m²), shows the most critical factor of safety of all, at only 0.32, indicating the negative effect that the additional loads have on slope stability.

Profiles 3-3 and 4-4, also composed of CL (0-2m) and SW (>2m) soil layers and under saturated conditions, but with lower vehicle loads (1.5 tn/m²), show factors of safety of 1.21 and 0.95, respectively. Although slightly higher than the previous ones, they are still insufficient according to the applicable regulations, confirming the generalised condition of slope instability.

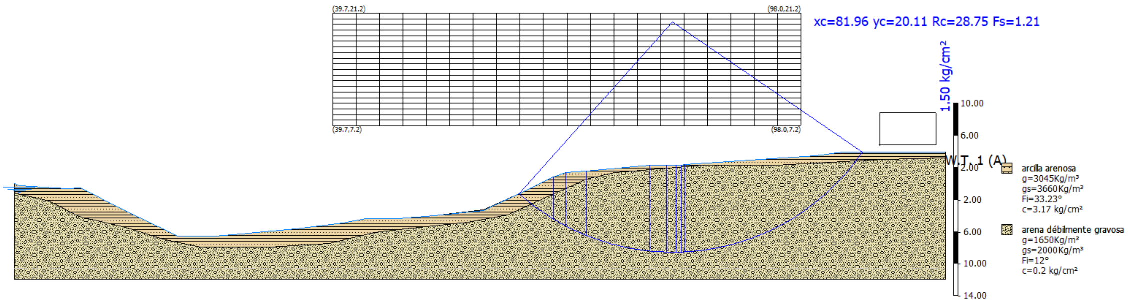

Fig 3. Profile with application of vehicular load, profile more tied up, unstable.

These results demonstrate that the combination of factors such as soil saturation, the presence of external loads (both vehicular and building loads) and the geotechnical properties obtained by triaxial testing (cohesion of 31.17 Tn/m² and friction angle of 32.33°) lead to a critical situation that requires immediate intervention through stabilisation works to ensure the safety of the road infrastructure and surrounding buildings.

4. Discussion

The slope stability analysis of the E35 Pan-American Highway, Carigán sector, showed a generalised critical condition with safety factors between 0.32 and 1.33, all lower than the regulatory minimum of 1.5 (NEC-SE-CM). Modelling by the Morgenstern-Price method on the four profiles revealed higher vulnerability under saturation and combined loading conditions, where profiles 1-1 and 2-2 presented the most alarming values (0.34-0.41). Electrical resistivity tomography identified persistent surface saturation (0-0.016m) and unfavourable stratigraphy (CL over SW), determining factors in the translational landslides observed in the field.

Linear regression analysis (R^2=0.763, 0.6541 and 0.5737) confirmed that the most critical condition corresponds to the combination of water table, external loads and seismic effects, with greater dispersion in these adverse conditions. The geotechnical parameters obtained (cohesion=31.17 Tn/m², friction angle=32.33°, densities of 3610 and 3060 Tn/m³) together with the low permeability of the superficial clayey stratum explain the deficiency of drainage, water retention and consequent instability, requiring immediate intervention to guarantee the safety of the road infrastructure and adjacent buildings.

5. Conclusions

The slope stability analysis in the Carigán sector, located at the exit to Cuenca from the E35 Pan-American Highway, has revealed a condition of generalised instability with considerably low safety factors, ranging between 0.32 and 1.21. These values are below the regulatory minimum of 1.5 established in the NEC-SE-CM, which confirms the susceptibility of the slope to geotechnical failure under different loading and saturation scenarios. The combination of cohesive soils of high plasticity and the presence of a shallow water table aggravates the problem, reducing the effective strength of the ground and increasing the risk of landslides.

The results of the numerical modelling with the Morgenstern-Price method showed that the most critical condition occurs when the slope is completely saturated and subjected to external loads, such as vehicular traffic and nearby buildings. Profiles 1-1 and 2-2 presented the lowest stability values (0.41 and 0.32 respectively), indicating that the soil is not able to withstand the applied stresses without deformation or failure. In addition, the presence of a superficial layer of high plasticity clays increases water retention and reduces the drainage capacity of the soil, intensifying the effects of liquefaction and loss of shear strength.

The hydrological analysis revealed that the micro-watershed affecting slope stability has a high average slope of 28.35% and a rapid concentration of runoff with response times of 6.16 minutes. The combination of these conditions with heavy rainfall increases infiltration in the cohesive soils and contributes to an increase in the water table, a determining factor in the decrease of slope stability. This is confirmed by the results of the electrical resistivity tomography, which identified areas of surface saturation and the presence of a water table between 118 and 124 metres of the profile analysed.

References

[1] J. Chadwick, G. Thackray, S. Dorsch, and N. Glenn, "Landslide surveillance: New tools for an old problem," *Eos, Transactions American Geophysical Union*, vol. 86, no. 11, pp. 109–114, Mar. 2005, doi: 10.1029/2005EO110001.

[2] Miele, P., Di Napoli, M., Guerriero, L., Ramondini, M., Sellers, C., Annibali Corona, M., & Di Martire, D. (2021). Landslide Awareness System (LAwS) to increase the resilience and safety of transport infrastructure: The case study of Pan-American Highway (Cuenca–Ecuador). Remote Sensing, 13(8), 1564. https://doi.org/10.3390/rs13081564.

[3] M. F. Bravo-Zapata, E. Muñoz, P. Lapeña-Mañero, J. M. Montenegro-Cooper, and R. W. King, "Analysis of the Influence of Geomechanical Parameters and Geometry on Slope Stability in Granitic Residual Soils," *Applied Sciences*, vol. 12, no. 11, p. 5574, May 2022, doi: 10.3390/app12115574.

[4] A. Rosi, P. Vannocci, V. Tofani, G. Gigli, and N. Casagli, "Landslide Characterization Using Satellite Interferometry (PSI), Geotechnical Investigations and Numerical Modelling: The Case Study of Ricasoli Village (Italy)," *International Journal of Geosciences*, vol. 04, no. 05, pp. 904–918, 2013, doi: 10.4236/ijg.2013.45085.

[5] A. Sigdel and R. K. Adhikari, "Application of Electrical Resistivity Tomography (ERT) survey for investigation of the landslide: a case study from Taprang landslide, Kaski district, west-central Nepal," *Journal of Nepal Geological Society*, vol. 60, pp. 103–115, Sep. 2020, doi: 10.3126/jngs.v60i0.31261.

[6] M. Kinde, E. Getahun, and M. Jothimani, "Geotechnical and slope stability analysis in the landslide-prone area: A case study in Sawla – Laska road sector, Southern Ethiopia," *Sci Afr*, vol. 23, p. e02071, Mar. 2024, doi: 10.1016/j.sciaf.2024.e02071.

[7] C. J. Shepheard, P. J. Vardanega, E. A. Holcombe, and K. Michaelides, "Analysis of design choices for a slope stability scenario in the humid tropics," *Proceedings of the Institution of Civil Engineers - Engineering Sustainability*, vol. 171, no. 1, pp. 37–52, Feb. 2018, doi: 10.1680/jensu.16.00081.

[8] M. Maślakowski, S. Kowalczyk, R. Mieszkowski, and K. Józefiak, "Using Electrical Resistivity Tomography (ERT) as a tool in geotechnical investigation of the substrate of a highway," *Studia Quaternaria*, vol. 31, no. 2, pp. 83–89, Dec. 2014, doi: 10.2478/squa-2014-0008.

[9] E. Polidori, "Relationship Between the Atterberg Limits and Clay Content," *Soils and Foundations*, vol. 47, no. 5, pp. 887–896, Oct. 2007, doi: 10.3208/sandf.47.887.

[10] Morante, F., Aguilar, M., Ramírez, G., Blanco, R., Carrión, P., Briones, J., & Berrezueta, E. (2019). Evaluation of slope stability considering the preservation of the General Patrimonial Cemetery of Guayaquil, Ecuador. Geosciences, 9(3), 103. https://doi.org/10.3390/geosciences9030103.