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Vulnerability Analysis Of Civil Works Focused On The Geological-Geotechnical State In The El Plateado Sector Of The City Of Loja.

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Abstract **-** The assessment of geological-geotechnical vulnerability in urban areas represents a critical challenge for the development of safe infrastructure. In this study, we focus on the El Plateado sector of Loja, Ecuador, implementing a methodology that integrates geophysical, geomechanical, and geographic information system (GIS) techniques to comprehensively characterize ground susceptibility. Our research applied Electrical Resistivity Tomography (ERT) to diagnose subsurface conditions, complemented by geomechanical Atterberg boundary testing and triaxial testing to determine fundamental geotechnical properties. The analysis considered critical variables such as lithology, proximity to mass movements, and building typology to generate a spatial vulnerability model. The results showed a complex stratigraphy of sands, silts, and clays, with subsurface saturation at approximately 10m depth. Geotechnical characterization revealed high plasticity SP-CH and low plasticity SP-ML soils, with mechanical properties of moderate consistency. However, local geological factors suggest the need to implement improvement strategies before any construction intervention. Vulnerability zoning yielded a vulnerability index above 70%, which implies significant restrictions for urban development and demands detailed geotechnical studies before future interventions. Our work aims to contribute to local geological knowledge and offer a replicable methodology for territorial vulnerability assessments.

Keywords**:** Geotechnical vulnerability - Electrical Resistivity Tomography – Geomechanics - Geographic Information Systems . Risk Assessment.

1. Introduction

Geological vulnerability is a critical factor in the development of civil infrastructure, representing a fundamental scientific challenge in the assessment of territorial risks. Mass movements, as dynamic geomorphological processes, generate significant transformations in the landscape and compromise the stability of engineering works, constituting one of the geological phenomena with the greatest socio-economic impact at a global level. [1]

In the regional geological context of the El Plateado sector in Loja, the geotectonic complexity shows a marked susceptibility to gravitational instability processes. The interaction of multiple geological, hydroclimatic, and anthropic variables configures a scenario of high geomechanical fragility that demands a rigorous scientific characterization. [2]

The conditioning factors of geological instability include lithological characteristics, topographic slopes, hydroclimatic regimes, neotectonic activity, and anthropic intervention processes. Progressive urbanization in areas of high geological susceptibility exponentially increases the potential risk scenarios, justifying the need for systematic investigations to understand and mitigate geological hazards.[3]

The main objective of this research was to develop a comprehensive geological-geotechnical assessment of the El Plateado sector, through the implementation of advanced scientific methodologies to quantitatively characterize territorial vulnerability. The aim was to generate technical-scientific knowledge that would contribute to the understanding of the mechanisms of geological instability and guide territorial planning processes.

The methodological strategy combined geophysical and geomechanical techniques and geographic information systems, constituting a multidisciplinary approach that allows a holistic approach to the research problem. Electrical Resistivity Tomography (ERT), geomechanical testing, and geospatial modeling represent high-resolution scientific tools for the characterization of geological vulnerability.[4]

The results obtained are intended to contribute to regional geoscientific knowledge, providing a frame of reference for the assessment of geological risks and guiding territorial intervention strategies based on rigorous scientific evidence. The research was methodologically structured in four chapters that systematically address the physical, theoretical, methodological, and analytical dimensions of the research problem. [5]

The scientific relevance of this study lies in its capacity to generate technical information that transcends descriptive characterization, allowing for a comprehensive understanding of the mechanisms of geological instability and their implications for sustainable infrastructure development. [6]

2. Methodology

The methodological approach implemented in this study on the geological-geotechnical vulnerability of the El Plateado sector in Loja reflects a comprehensive and multidisciplinary scientific approach. The research team applied advanced geomechanical techniques, meticulously characterizing the physical and mechanical properties of the soils through laboratory tests such as Atterberg limits and triaxial tests. [7]

In addition, they employed state-of-the-art geophysical methods, using Electrical Resistivity Tomography (ERT) to analyze in detail the composition and structures of the subsoil, with special emphasis on the identification of saturated zones. In addition, the researchers used geographic information system (GIS) tools to integrate information collected in the field, including surveys of the local population and building damage assessments. This geospatial database enabled the generation of a high-resolution vulnerability map, considering critical variables such as lithology, proximity to mass movements, and building typology. The confluence of these methodological approaches provides a comprehensive scientific view of the problem, establishing a solid frame of reference for understanding the geological instability mechanisms affecting the study sector.

2.1. Geomechanics

Following the preparation of the geological map, the points where the test pits would be dug for the collection of representative samples were located. This activity was essential to ensure that laboratory tests were carried out on materials following the characteristics of the soil in the study sector. The pits were located at the coordinates x1: 695488, y1: 9559448 and x2: 695319, y2: 9559525, with a surface area of 1.5 m x 1.5 m and a depth of 2 m. The extracted samples were handled and transported strictly following the procedure described in ASTM D 4220 to preserve their properties. In the laboratory, the following geomechanical tests were carried out:

Atterberg limits: Following the standards NTE INEN 690, ASTM D 422, NTE INEN 691, and NTE INEN 692, the classification of soils was determined according to the unified system (SUCS), evaluating the granulometric distribution, liquid limit, and plastic limit.[8]

Unconsolidated Triaxial Test (UU): Using the ASTM D 2850-95 standard, the behavior of the soils was evaluated under confining stresses of 50 kPa, 100 kPa, and 200 kPa, without allowing changes in volume. This allowed the relationship between shear strength and normal stress to be established, determining the maximum strength of the material.[9]

2.2. Geophysics

Complementing the geomechanical analysis, the research team implemented Electrical Resistivity Tomography (ERT) geophysical techniques in the El Plateado sector. Two geophysical methods were applied: Schlumberger and Dipole-Dipole. In the field stage, three geophysical measurement lines were strategically located, considering the areas with evidence of infrastructure collapse and ground subsidence. These lines had the following characteristics:

- Line 1: 296 m long, with 74 electrodes spaced every 4 m, using the Schlumberger method. This section diagonally covered the area where a school is located.
- Line 2: 222 m long, with 74 electrodes every 3 m, using the Schlumberger and Dipole-Dipole methods. This line was parallel to the landslide slope at the back of the church.
- Line 3: 259 m long, with 74 electrodes every 3.5 m, also using the Schlumberger and Dipole-Dipole methods. This profile was diagonal to Virgilio Rodas Street, near a water tank.

In the cabinet stage, the data collected in the field were processed and analyzed using the RES2DINV software. This program solves the inverse problem, obtaining a distribution model of real subsurface resistivities from the apparent resistivity values, using an iterative adjustment that minimizes the error. The results of this geophysical analysis, correlated with the field lithological mapping, allowed for characterizing the subsurface composition and structures of the study area, identifying saturation zones and other relevant geological features for vulnerability assessment.[10]

2.3. GIS vulnerability mapping

Vulnerability was defined as the potential degree of damage or loss to exposed elements, quantifiable on a scale from 0 (no damage) to 1 (destruction). For this study, three main physical vulnerability variables were considered: distance to movements, type of construction, and type of lithology. For the distance-to-movement variable, a Digital Terrain Model (DTM) from SIGTIERRAS with a resolution of 0.1 m x 0.1 m was used. Using ArcGIS 10.8 software, a shadow map was generated that revealed the morphology of the terrain, and the distances to the movements identified were calculated. Five vulnerability categories were established, assigning the highest value (5) to infrastructures located less than 10 meters from the movement, and the lowest value (1) to those located more than 40 meters away.[11]

Vulnerability by building typology was determined through the creation of a geospatial database. Reference points taken in the field, survey information, and a georeferenced image from Google Earth were used. Each property was categorized according to its type of construction, assigning it a weight between 1 (least vulnerable) and 5 (most vulnerable).[12]

The lithological analysis was carried out by a detailed survey of the study area, collecting rock samples from available outcrops. Given the urban character of the area, the identification of rock types was challenging. Four lithological units were characterized: sandstones, interbedded clays and silts, calcareous shales, and micro conglomerates.

Generation of the Vulnerability Map:

To integrate these variables, the ArcGIS ModelBuilder tool was used, which allows the creation of spatial models using a flow diagram. The integration of the three thematic maps was carried out using the Weighted Overlay tool, applying a specific weighting formula:

$$VF = VL * 0.25 + VC * 0.25 + VM * 0.5 \quad (1)$$

Where VL represents lithological vulnerability, VC represents construction vulnerability, and VM represents vulnerability by distance to movement. This formula allows greater weight to be given to the distance to movement variable, which is considered more critical in determining total vulnerability.[13]

3. Results and Discussions

The lithological survey of the study area revealed a complex geological composition with four distinct lithological types, characterized by poorly graded sandstones with 1 mm thickness and creamy coloration, micro conglomerates with rounded clasts up to 6 cm, a significant 2.96-meter stratigraphic intercalation showing horizontal layering of cream-colored clays (0.002 mm), greyish siltstones (0.05 mm), and brown sandstones (1 mm), and calcareous shales with clayey matrix and grains smaller than 1/16 mm. These lithological variations, limited by urban environment constraints, indicate complex sedimentary processes with multiple depositional events, suggesting dynamic geological conditions that reflect significant environmental changes during rock formation. [14]

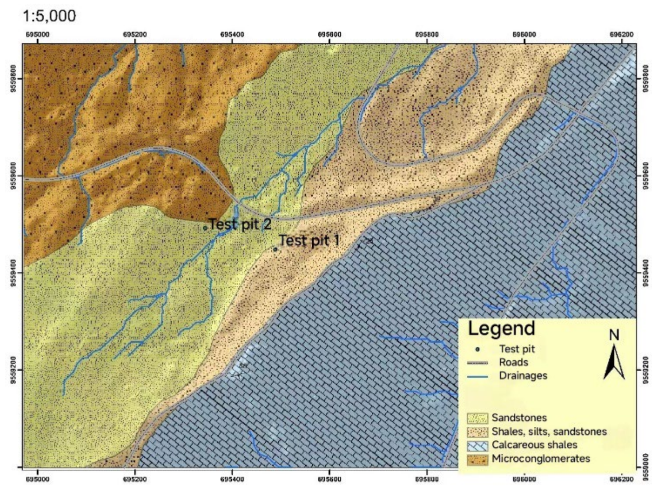


Fig 1. Lithological map

The mass movement study carried out through the integration of the Digital Terrain Model (DTM), field coordinates, and satellite images, revealed a main reputation movement of considerable magnitude in the Loja-Catamayo area, characterized by a high level of saturation and slow activity, which significantly impacts the road and surrounding infrastructure. In addition, 13 movements were identified in the 'El Plateado' neighborhood, whose urban nature limited the precision of their classification, resulting in the designation of 'undefined movements', with areas of influence varying between 376 m² and 3,831 m², in contrast to the reputation movement which covers 81,026 m². The methodological restrictions of the urban environment made it difficult to characterize these movements in detail, highlighting the geomorphological complexity of the region and the need for more in-depth investigations to fully understand the dynamics of landslides.[15]

Geomechanical analysis of the soils by Atterberg limits and granulometry revealed a complex composition of poorly graded granular soils (SP) with distinctive characteristics in the two test pits studied. Test pit 1 showed poorly graded sand with high plasticity (CH), characterized by a moisture content of 28%, liquid limit of 60%, plastic limit of 30%, and plasticity index of 29, indicating significant water-holding capacity and deformation potential. In contrast, test pit 2 presented a poorly graded sand with low plasticity silts (SP-ML), with a moisture content of 11%, liquid limit of 28%, plastic limit of 24%, and plasticity index of 4, showing a marked heterogeneity in soil composition. The predominance of silts and clays suggests that the stability of the ground will depend on critical factors such as the dip of the strata, the angle of internal friction, and pore pressure, aspects that will be determined by UU Triaxial tests, which highlight the geotechnical complexity of the study area.

Geomechanical tests in test pits 1 and 2 identified poorly graded granular soils (SP) with differentiated properties. Test pit 1 presented SP sand with high plasticity clays (CH) and 28% moisture, while test pit 2 revealed SP sand with low plasticity silts (ML) and 11% moisture. The results of the UU triaxial tests showed that both soils have friction angles above 20°, making them suitable for construction. However, external factors such as landslides, groundwater problems, and rainfall make the study area vulnerable, with a risk of collapse of the settled infrastructure, so construction is not recommended despite the favorable geomechanical properties of the soil.

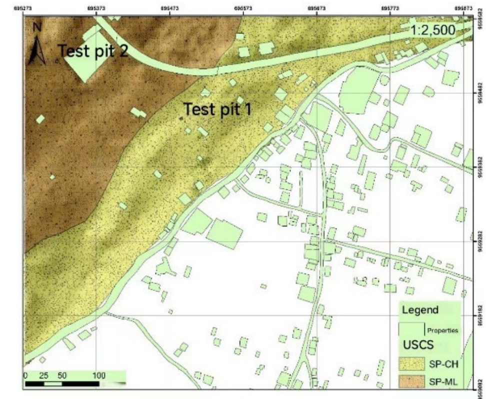


Fig 2. Geomechanical characterization

Geophysical profiles obtained by Schlumberger and Dipole-Dipole methods revealed a complex stratigraphy in the study area. The analysis of electrical resistivities allowed the identification and correlation of the different geological materials present. The low resistivity zones (0.3 to 13 Ohm-m) were interpreted as saturated materials, composed mainly of sands, silts, and clays. These wet zones were located at depths between 10 and 12 meters at different points along the profiles. Intermediate resistivities (12.3 to 143 Ohm-m) were associated with the presence of shales, which extended along the entire profile with thicknesses of approximately 30 meters.

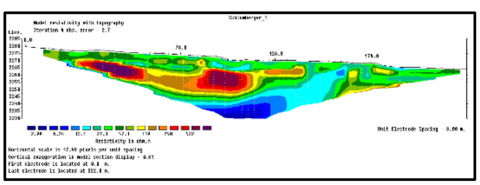


Fig 3. Interpretation L1 TRE, Schlumberger method

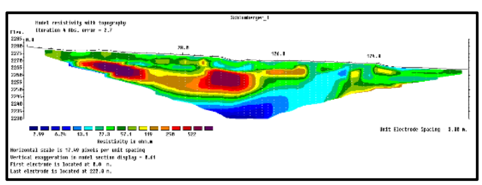


Fig 4. Interpretation L2 TRE, Schlumberger method

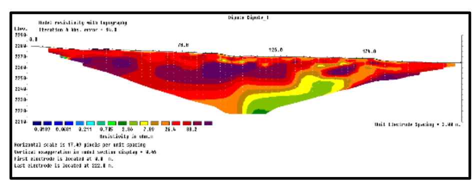
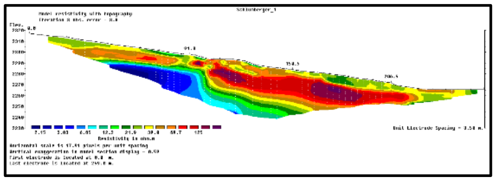


Fig 5. Interpretation L2 TRE, Dipole-Dipole method



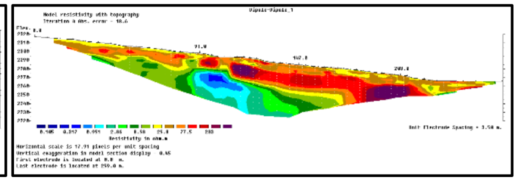


Fig 6. Interpretation L3 TRE, Schlumberger method Fig 7. Interpretation L3 TRE, Dipole-Dipole method

In addition, the high resistivity zones (119 to 1668 Ohm-m) corresponded to highly consolidated calcareous shales, identified in specific intervals with thicknesses of 8 to 15 meters. The profiles also showed evidence of discontinuities and movements in the layers, such as tilting and subsidence, particularly in line 3 obtained by the Dipole-Dipole method. This correlated with structural field measurements, which indicated a south-easterly direction of movement. These geophysical results, together with the previous lithological and geomechanical characterization, provide a comprehensive picture of the geological and geotechnical complexity of the study area.

The study of physical vulnerability in the El Plateado sector of the city of Loja was carried out using a multivariate analysis that considered three fundamental variables: distance to movements, construction typology, and lithological units. The research involved exhaustive fieldwork that included the collection of information on 232 houses, using survey sheets and local cartography. Using ArcGIS 10.8 software and the NEAR tool, the distances between movements and infrastructure were calculated, subsequently transforming the information into a raster format and applying a reclassification into five vulnerability categories. The weighting of the variables was established considering 50% for distance to movement, 25% for construction typology, and 25% for lithology, which allowed for an integral and contextualized evaluation of the physical vulnerability of the territory.[16]

The results of the analysis revealed a critical vulnerability scenario in the study area, with more than 70% of the territory classified between very high and medium vulnerability. Specifically, 0.5% present very high vulnerability, 52.7% high, 17% medium, and 29.9% low vulnerability. Of the total of 31 hectares, 9.6 hectares correspond to the infrastructure zone, while 21.4 hectares are green areas not suitable for construction. The physical vulnerability map generated by ModelBuilder showed that the El Plateado sector constitutes a high-risk area for urban settlements, mainly due to factors such as proximity to movements, fragile construction typologies, and susceptible lithological characteristics. The conclusions of the study highlight the urgent need to implement preventive measures such as the correct channeling of streams, control of fluvial and wastewater, and improvement of sewage systems to mitigate the potential risks of structural collapse and ground displacements.[17]

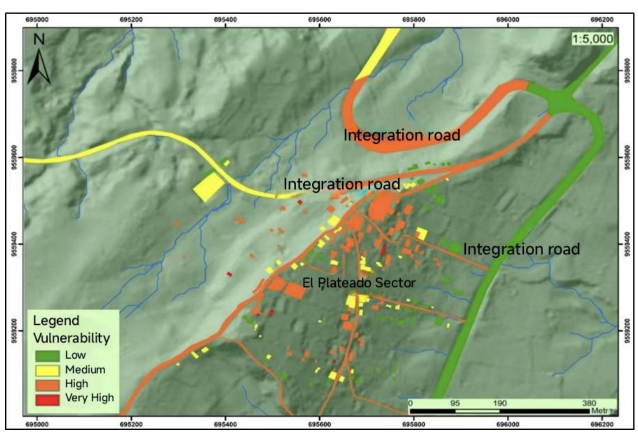


Fig 8. Vulnerability of buildings in the El Plateado sector of the city of Loja.

The geotechnical vulnerability of the El Plateado sector in the city of Loja is a complex phenomenon where multiple geological, geomechanical, and anthropogenic factors converge. The saturation of materials at a depth of 10 meters, confirmed by geophysical methods and previous research such as that of Jiménez (2016), reveals a surface deformation dynamic determined by the interaction between conditioning and triggering factors. The geomechanical properties of the soil, characterized by silts and saturated clays, generate a geologically unstable environment, while anthropogenic inputs, especially infrastructure intervention and vehicular traffic on the Loja-Catamayo road, act as catalysts that increase susceptibility to mass movements. The old drains, although imperceptible in the current topography, maintain their underground influence, generating saturation zones that systematically modify the mechanical behavior of the materials. This complex interrelationship suggests that vulnerability is not a static state, but a dynamic and evolving process that demands a holistic approach to geotechnical risk management and mitigation.[18]

4. Conclusion

The El Plateado sector of the city of Loja presents a critical geotechnical vulnerability, with more than 70% of the territory classified between very high and medium vulnerability. Geophysical, geomechanical, and mass movement analyses reveal a high-risk scenario for urban settlements.

The instability of the terrain is configured by a complex interaction of factors: saturation of materials at a depth of 10 meters, geomechanical properties of silts and clays, anthropic intervention, and the presence of underground drainage. Thirteen mass movements were identified, highlighting a reputation of 81,026 m² that significantly impacts the road infrastructure.

Geomechanical and geophysical studies revealed a complex stratigraphy with saturated materials, shales, and discontinuity zones, resulting in a dynamic and evolving territory that requires comprehensive risk management. Despite presenting favorable geomechanical characteristics, the area is not recommended for construction due to its high vulnerability.The multivariate methodology applied, considering the distance to movements, construction typology, and lithological units, allowed us to generate a physical vulnerability map that demonstrates the urgent need to implement preventive measures to mitigate and control geotechnical risks.

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