**Escuela Superior Politécnica del Litoral**

**Facultad de Ingeniería en Ciencias de la Tierra**

# INVESTIGACIONES GEOFÍSICAS PARA LA CARACTERIZACIÓN DE LA ZONA DE DESLIZAMIENTOS, PUNGALAPAMPA-PUNINHUAYCO-ALAO, CHIMBORAZO, ECUADOR

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## Resumen

La construcción de carreteras implica procedimientos de relleno y excavación, permitiendo que los taludes sean susceptibles a factores geológicos, hidrológicos y geomorfológicos, aumentando el riesgo de inestabilidad y amenazando la infraestructura vial como a las comunidades aledañas. La provincia de Chimborazo en Ecuador, debido a su ubicación geográfica, diversa topografía con estratos de suelo estructuralmente complejos y variaciones en la estratigrafía del subsuelo requieren de investigaciones detalladas enfocadas en geofísica y ensayos de suelo in situ. Este estudio tiene como objetivo evaluar la estabilidad del talud mediante la correlación de ensayos de geofísica y ensayos de suelo para la generación de medidas de estabilidad del talud. La metodología aplicada se basa en el análisis de condiciones superficiales, aplicación de exploración geofísica, caracterización geotécnica, análisis y estrategias de estabilidad del talud. En la caracterización del talud se realizaron tres calicatas alteradas donde se determinó que geológicamente existen materiales meta-volcánicos, gravas y coluviales. Mediante la correlación de ensayos de geofísica se definió que en el centro del talud los valores de resistividad aparente más críticos (90-140 Ω·m) corresponden a depósitos coluviales. Para la estabilidad se propone terracear la superficie del talud con zanjas de coronación en cada nivel debido a la presencia de ojos de agua y en las zonas más críticas colocar malla de contención sobre la vegetación. Se determinó la existencia de agua (ojos de agua) en el talud, como factor detonante de la inestabilidad. Estas estrategias sirven como base para los tomadores de decisiones en el mejoramiento de la conexión vial y desarrollo socioeconómico en comunidades rurales andinas.

**Palabras Clave:** Resistividad eléctrica, método electromagnético transitorio, perfiles estratigráficos, deslizamientos y peligros.

## Abstract

Road construction involves filling and excavation procedures, leaving slopes susceptible to geological, hydrological and geomorphological factors, increasing the risk of instability and threatening road infrastructure and surrounding communities. The Chimborazo Province in Ecuador, due to its geographic location, diverse topography with structurally complex soil strata and variations in subsurface stratigraphy, requires detailed investigations focused on geophysics and in situ soil testing. This study assesses slope stability by correlating geophysical and soil tests to generate slope stability measurements. The applied methodology is based on the analysis of surface conditions, application of geophysical exploration, geotechnical characterisation, analysis and slope stability strategies. In the characterisation of the slope, three altered test pits were made where it was determined that there are metavolcanic materials, gravel and colluvial geologically. By correlating geophysical tests, it was determined that in the centre of the slope, the most critical apparent resistivity values (90-140 Ω m) correspond to colluvial deposits. For stability, it is proposed to terrace the slope surface with crown ditches at each level due to the presence of water holes and, in the most critical areas, to place reinforcement mesh over the vegetation. The existence of seepage zones on the slope was determined as a triggering factor for instability. These strategies serve as a basis for decision-makers in improving road connections and socioeconomic development in Andean rural communities.

Keywords: Electrical resistivity, transient electromagnetic method, stratigraphic profiles, landslides and hazards.

## INFORMACIÓN GENERAL DEL PROYECTO

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| **Título del Artículo en español** | Investigaciones Geofísicas Para La Caracterización De La Zona De Deslizamientos, Pungalapampa-Puninhuayco-Alao, Chimborazo, Ecuador |
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| **Objetivo General** | El estudio tiene como objetivo evaluar la estabilidad del deslizamiento ubicado en la vía Pungalapampa-Puninhuayco-Alao (Chimborazo) mediante la integración de TGE, TDEM y ensayos geotécnicos como calicatas para la formulación de estrategias de sostenimiento del talud. |
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# Geophysical investigations for the characterisation of the landslide zone, Pungalapampa-Puninhuayco-Alao, Chimborazo, Ecuador.

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**ABSTRACT**

Road construction involves filling and excavation procedures, leaving slopes susceptible to geological, hydrological and geomorphological factors, increasing the risk of instability and threatening road infrastructure and surrounding communities. The Chimborazo Province in Ecuador, due to its geographic location, diverse topography with structurally complex soil strata and variations in subsurface stratigraphy, requires detailed investigations focused on geophysics and in situ soil testing. This study assesses slope stability by correlating geophysical and soil tests to generate slope stability measurements. The applied methodology is based on the analysis of surface conditions, application of geophysical exploration, geotechnical characterisation, analysis and slope stability strategies. In the characterisation of the slope, three altered test pits were made where it was determined that there are metavolcanic materials, gravel and colluvial geologically. By correlating geophysical tests, it was determined that in the centre of the slope, the most critical apparent resistivity values (90-140 Ω m) correspond to colluvial deposits. For stability, it is proposed to terrace the slope surface with crown ditches at each level due to the presence of water holes and, in the most critical areas, to place reinforcement mesh over the vegetation. The existence of seepage zones on the slope was determined as a triggering factor for instability. These strategies serve as a basis for decision-makers in improving road connections and socioeconomic development in Andean rural communities.

## 1 INTRODUCTION

In many cases, landslides are due to increased and expanded settlements in dangerous areas of high vulnerability or inadequate land use due to a lack of planning [1]. Implementing techniques to reduce geological risks and vulnerability is essential to determine disaster prevention and mitigation strategies [2].

Between 1990 and 2015, landslides were found to be responsible for 1.30% of deaths worldwide. According to the World Meteorological Organization (WMO), these phenomena are responsible for 10% of disasters in Latin America and 12% of human deaths in the region [3].

In the Andean countries, landslides have been frequent due to their complex morphology, geographic location and geodynamics associated with the margin of the active tectonic plate. Added to this is the influence of various hydrometeorological processes, such as the phenomena of "La Niña" and "El Niño", also known as El Niño-Southern Oscillation (ENSO) [1]. For example, in Colombia, approximately 32,000 landslides have been recorded between 1900 and 2016, with rain being the most common triggering factor, at 90%. Similarly, increases in the frequency of landslides have been observed in other Andean countries, including Ecuador, with these massive landslides being the main cause of deaths from natural disasters [4].

Generally, the characterisation and identification of the boundary of a landslide is carried out by drilling (direct method), a viable but expensive approach accompanied by subsequent monitoring of deformation and displacement [5]. In contrast, geophysical applications represent non–destructive methods that offer significant advantages over conventional techniques [6]. These methods reduce the risk of contaminant dispersion, improve understanding of subsurface geometry and enable cost reduction [7].

Geophysical methods are based on the interpretation of contrasts of specific physical properties of the subsoil (e.g., dielectric constant, electrical conductivity and density) [8].

The choice of the appropriate geophysical method depends on the physical property to which it responds, which determines and limits the range of possible applications [9]. The most common research fields in geophysics focus on permafrost mapping [10], determining the thickness of sediments on slopes [11], block fields and alluvial fans.

Increasingly, they are focusing on exploring landslides' depth and internal structures [12].

The success of geophysical methods depends on a detectable contrast in the physical properties of the lithological units [13], the depth and resolution of interest [7], geophysical calibration using geological or geotechnical data [14], the signal-to-noise ratio and the cost of the exploration campaign [15].

The contrasts identified could be local anomalies within the landslide caused by the rugged topography and, as a result, could be of little or no interest [16]. Geophysical methods have developed considerably over the last 20 years thanks to technological progress, the availability of cheaper electronic computing components, the development of portable equipment and the inclusion of new software in data processing, which allows obtaining 2D and 3D images of the subsoil [17].

Most landslide studies apply geophysical techniques to obtain accurate and reliable results of heterogeneous landslide structures [17, 18]. Currently, Electrical Resistivity Tomography (ERT) is the most widely used geophysical method, particularly in identifying water infiltration, which is one of the causes of the triggering or reactivation of ground movements [16]. Some investigations have applied the Transient Electromagnetic Method (TEM) or TDEM in landslides, for example [19], combining electrical methods with TDEM to detect the geomorphological conditions of the slope in the Langhe-Piemonte region (Italy).

Other authors, such as M. Schmutz [20], offer the joint inversion of TDEM data and Direct Current (DC) soundings when applied to the Super Sauze earth flow (France). Furthermore, Li et al. [21] evaluated the advantage of TDEM in Sichuan Province (China) for detecting seepage pathway systems in debris landslides.

Ecuador is located at the interaction of the Nazca oceanic plate convergence (South American and Caribbean continental plates), resulting in the uplift of the Andean mountains, active volcanism, geological faults, and a high probability of landslides occurring [22]. Landslides in this region occur due to the high elevations and steep slopes [23].

Significant population growth has been observed, creating the need to create new spaces for urban development, causing deforestation and using hillsides as construction land [23]. The most important landslides are: "La Josefina" (Azuay province) in March 1993, "Gulag-Marianza" (Azuay province) in March 2022, and the most recent one in Alausí (Chimborazo province) in March 2023 [24].

According to Hack [13], 75% of the tertiary network in the country is in a state of deterioration, 68% of the areas are located more than five hours away, and only 16% of the Agricultural Production Units (UPA) receive technical assistance for the development of their productive activities [25]. These factors contribute to increasing the vulnerability of rural areas, negatively affecting their capacity to respond and assist in the face of natural disasters such as landslides [26].

In the province of Chimborazo, landslides have forced the change of the route of several roads, such as Alausí, Guamote, Pallatanga and Chunchi [12]. On March 26, 2023, a landslide occurred in Alausí (south of the Chimborazo province), a city with 42,823 inhabitants, representing 10.6% of the province of Chimborazo. The landslide caused 43 deaths, 1,034 victims, 163 homes affected, and 57 houses destroyed [27].

This case was taken as a comparison analysis with the present study since similar studies were carried out, such as the collection of topographic data to obtain detailed information on the landslide, geological and geophysical prospecting tests such as ERT to identify the lithology of the study area [28].

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This case was taken as a comparison analysis with the present study since similar studies were carried out, such as the collection of topographic data to obtain detailed information on the landslide, geological and geophysical prospecting tests such as ERT to identify the lithology of the study area [28]. The slope under study is located 30 km from Riobamba, Chimborazo. On April 23, 2023, a landslide occurred due to heavy rainfall in the area and runoff from crops located on the crown of the slope, making it unstable and hindering mobility and access to the affected areas.

This research uses electrical and electromagnetic (EM) geophysical methods to characterise a landslide in the central Andean zone of Ecuador. Specifically, a combination of Vertical Electrical Soundings (VES), ERT and TDEM is used. In addition, sampling of altered soil from the landslide was carried out to correlate with geophysical data.

In this context, the research question arises: How does integrating VES, ERT, TDEM, and soil studies allow the characterisation of the landslide zone to contribute to decision–making and risk management? The study aims to evaluate the stability of the landslide located on the Pungalapampa–Puninhuayco–Alao Road (Chimborazo) by integrating ERT, TDEM and geotechnical tests such as test pits for the formulation of slope support strategies.

## 2 MATERIALS AND METHODS

### 2.1 Study area

The study area is in the province of Chimborazo, a rural parish of Pungalá located approximately 30 km from the city of Riobamba (capital of the province). The site is characterised by steep slopes ranging from 30–50°, inclined towards the Alao River micro–basin (Figure 1). The altitude varies from 2,680 to 4,440 m above sea level [29].

The access roads to the communities are paved and gravelled, where the predominant products of the area are transported, such as potatoes, corn, beans, vegetables, barley, wheat, mellocos (andean tuber) and oca. The lithology of the site is composed of tuffs, clays, silts, andesites, agglomerates and basaltic rocks [30].

Historically, the population has developed its economic activities in agriculture and livestock. However, drought, primary production in small farms, poor road networks, lack of basic services, high levels of poverty, and lack of productive development have caused social problems such as migration [31]. The agricultural production generated in the sector serves to supply the markets of Riobamba. These activities are affected by mass movements, which mainly cover the main access routes, causing economic losses and human lives [30].

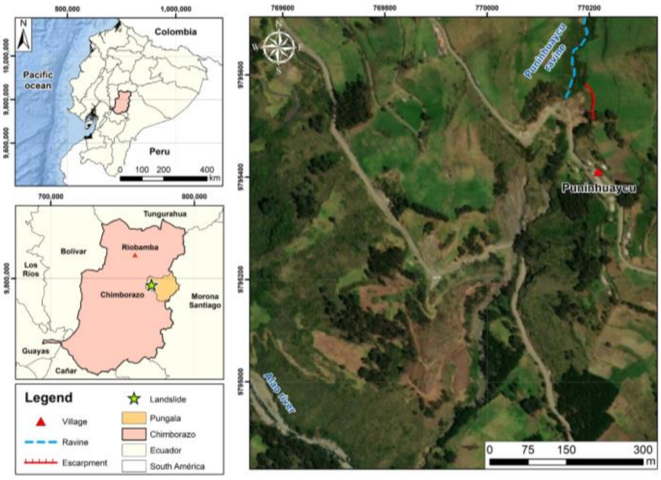


**Figure 1.** Location of the study area of the landslide scarp located in Puninhuayco, Chimborazo

## 2.2 Methods

The research uses a quantitative approach based on a case study, using a combination of non-destructive geophysical techniques, laboratory tests, and natural stability analysis of the terrain, which allowed slope stability strategies to be generated (Figure 2).

During the field activities, a technical visit was conducted to assess the main damages, impacts, and existing risks, and the main characteristics of the slope slide were identified. Subsequently, due to the terrain conditions, a topographic survey was carried out using a total station correlated with an orthophoto of the area.

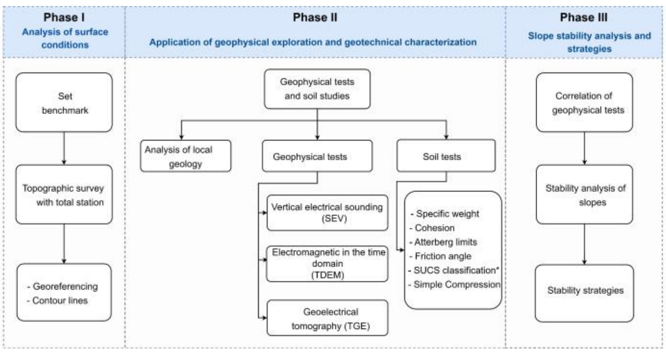


**Figure 2.** Methodological approach is divided into three phases of study. * Unified Soil Classification System (SUCS)

### 2.2.1 Phase I: Analysis of surface conditions

A visit was made to the study area to gather information, data and open interviews. Among the field activities, a preliminary assessment was made of the landslide that caused damage and risks. In addition, the topographic survey was carried out using the Leica FlexLine TS03 total station [32] to locate the coordinates that allowed the generation of plans and profiles using the AutoCAD software.

### 2.2.2 Phase II: Application of geophysical exploration and geotechnical characterisation

The local geology was surveyed, considering the sector's available base cartography and the main outcrops. This information, together with the results of Phase I, provided the input data for planning the geophysical exploration campaign, the geometry of the landslide and the structural conditions [32, 33, 34].

The electric current resistivity studies were carried out using the ABEM Terrameter SAS 1000 equipment, stainless steel electrodes and a 12V battery. The VES tests were performed using the Schlumberger configuration, and the data was processed in the freely available software IPI2win (version 3.06.16), with an error percentage of less than 7%.

The ABEM guideline geo brand tomograph, 21–output imaging cable and electrode cable junction, with the Wenner configuration, were used for the ERT test. Res2DInv software, version 4.10.3, was used for data processing, with an error of less than 3%.

Regarding the TDEM, the equipment used was the Walktem 2 from the ABEM guideline geo brand, with a 40x40 meter transmitter coil and a damping of 128 Ω·m. The test was performed at the top of the slope; the data was downloaded in gdb format and processed in the licensed software Aarhus Spia, version 3.8, with layer modelling.

Additionally, soil sampling was carried out to improve the interpretation of the geophysical results and the correlation with the physical properties of the soil. The following soil tests were developed: i) specific weight, ii) shear strength, iii) simple compression, iv) granulometry and v) Atterberg limits. For sampling, rectangular open pits approximately 50–60 cm deep were dug into the slope. Soil testing to determine physical properties was based on the American Society for Testing and Materials (ASTM) standard [37].

In the specific weight essay of the soil, a representative fraction of the samples was selected to apply the cylinder method and estimate the volume by measuring the dimensions and determining its weight. The unconsolidated–undrained methodology was used for the shear strength test, where the friction angle and cohesion were obtained–fundamental parameters in the study of bearing capacity, slope stability, and lateral pressures, among other infrastructures [34]. A uniaxial compression test was also conducted by applying a compressive force between two plates to a cylinder until it failed, determining the material's stress [35].

In the grain size analysis, the SUCS system was applied, which consists of observing and weighing the material from the sample that passes through the #200 sieve. When 50% of the sample's weight is retained on the mesh, it is defined as coarse material, and the second as fine material. Classification is important for analysing particle size and soil behaviour [36]. Then, the Casagrande Chart was used to determine the plastic limit, liquid limit, and plasticity index [37].

The geological correlation and geomechanical characterisation of the study area determined the properties of the materials and variations in the degree of saturation, resulting in a larger area and greater accuracy in the data [38].

It was decided to conduct three test pits in different slope areas, considering soil texture, topography, and other conditions. A horizontal area with little vegetation was selected for the geophysical tests, interfering with the current, noise, and movement [39]. The possible causes of soil sliding revolve around finding a factor of safety (fs) in two scenarios, as mentioned earlier [40].

### 2.2.3 Phase III: Application of geophysical exploration and geotechnical characterisation

In the third phase, the correlation of topographic, geophysical, geomechanical data, and in situ observations was conducted for the slope stability analysis. In the first stage, topographic profiles were obtained along the extent of the slope using AutoCAD software. In the two–dimensional slope analysis study, SLIDE software (version 5.014) was used, applying the limit equilibrium method to calculate slope stability, which is widely used in geotechnics and mining. The necessary data to analyse the slope in the software includes:

·Coordinates (x, y)

·Thicknesses of the strata

·Properties of the slope materials (specific weight, cohesion, and friction angle).

The soil properties were defined based on the geophysical and geological studies that have been carried out, which facilitate the determination of essential geotechnical parameters for the design of civil works [41]. In Ecuador, these calculations are based on geophysical methods, specifically seismic techniques that use surface waves and are correlated with tests such as triaxial compression, direct shear and soil properties [23].

The limit equilibrium method involves cuts made at the base of equilibrium, which must satisfy the equilibrium of forces and moments acting on individual blocks [42]. We must consider that the limit equilibrium method has certain limitations, as it does not consider deformations [43].

The calculation of the factor of safety (fs) in static conditions against the sliding of a force is based on the constant resistance of the materials used in the seismic analysis of slopes. The calculation of fs was evaluated using two methods:

·The static method assumes that the acting and resisting forces are equal along the failure surface, equivalent to a value of 1.50.

·The pseudo–static method involves the acceleration in rock for the design earthquake (z), obtained from the seismic zoning map of Ecuador, resulting from the seismic hazard study (10% exceedance in 50 years) with a value of 1.05 [44].

The fs results were reviewed based on the NEC [45] to generate slope strategies, considering that the higher the coefficient, the greater the safety, ensuring stability [46]. The strategies are crucial for conducting a detailed analysis and adapting to the specific conditions of the terrain and the project.

The possible methods that can be used to correct slope instability can be divided into two groups: protection methods, which aim to prevent potential alteration phenomena from developing in the surface zone of the slope, and stabilization or reinforcement methods, which involve actively intervening if these movements occur [47].

Water is one of the main factors affecting the slope, making it a primary issue for stability where various drainage systems exist, such as surface, underground or deep drainage systems [48]. Using vegetation is one of the most cost-effective measures and helps control soil erosion, as the roots act as anchors, preventing slope sliding [49], such as a protection and reinforcement system; there is a variety of techniques, such as geotextiles (unprotected surface) [50], shotcrete (unstable soils) [51], retaining mesh over vegetation (unstable soils) [52] or anchored wire mesh (colluvial soils and fractured rocks) [53].

## 3 RESULTADOS

### 3.1 Analysis of surface conditions

In Figure 3(a), the topography of the slope is presented, with a width of 40 m and a total length of approximately 35 m from the toe of the slope to the crest, forming an area of 1000 m².

The slope is rotational, facing SW, covering most of the roadway. The precipitation and high saturation from the crops at the crest of the slope create concentric and concave cracks in the direction of movement. In Figure 3(b), the natural conditions of the landslide around the entire slope are evident.

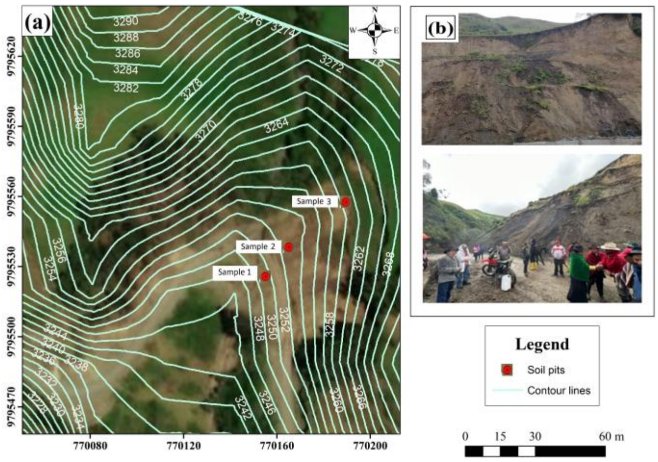


**Figure 3.** (a) Topographic map of the slope, (b) Photographs of the landslide that occurred on September 20, 2023

### 3.2 Geotechnical characterisation of the landslide

The geotechnical descriptions of the three test pits conducted at the base, centre, and crest of the slope, approximately 50 cm deep, were based on in situ observations and laboratory test results. These materials were classified according to SUCS and NEC–SE–GC (Ecuadorian Construction Code, Geotechnics and Foundations) and are detailed as follows:

·Sample S1: moist grey silty sand, classified as SUCS type SM–silty sand.

·Sample S2: silty sand material with weathered igneous rock gravel, subjected to saturation conditions and classified as SUCS type SM.

·Sample S3: classified as SUCS type SC–clayey sand, considered suitable for cultivation due to its high nutrient levels, with fine particles predominating.

About the local geology, outcrops of volcanic tuffs, metavolcanic rocks, and colluvial deposits with predominant material of sands and gravels were identified. Below, Table 1 presents the results obtained from the laboratory tests of the test pits conducted at the toe (sample S1), centre (sample S2), and crest of the slope (sample S3).

### 3.3 Results of applied geoelectric testing

In applying geophysical methods, six geoelectric tests were conducted throughout the study area (Figure 4). Three ERT tests with 8 m spacing at the toe of the slope (total length of 160 m), 2 m in the transverse direction (total length of 40 m), and 3 m parallel at the top of the slope (total length of 60 m). Two VES were conducted at AB/2 of 100 m at the toe of the slope and AB/2 of 14.70 m on the first terrace of the slope, with one TDEM test at the top of the slope.

**Table 1.** Results of geomechanical tests for obtaining physical properties

| Tests | | Sample $S_1$ | Sample $S_2$ | Sample $S_3$ |
|---|---|---|---|---|
| **Specific weight(kg/cm³)** | | 2.65 | 2.55 | 2.82 |
| **Moisture content (%)** | | 5.66 | 2.82 | 7.51 |
| **Cohesion (kPa)** | | 25.20 | 25.10 | 35.77 |
| **Atterberg limits** | Liquid limit (%) | 0.30 | 0.27 | 0.33 |
| | Plastic limit (%) | 0.21 | 0.20 | 0.13 |
| | Plasticity index (%) | 0.09 | 0.07 | 0.20 |
| | Flow index | 0.22 | – | 0.10 |
| | Toughness index | 0.41 | – | 2.03 |
| | Consistency index | 1 | 1 | 1 |
| **Friction angle (°)** | | 19.10 | 20.03 | 4.09 |
| **Sigma (kg/cm²)** | | – | 0.58 | 0.65 |
| **Qu max (kg/cm²)** | | | 0.65 | |
| **SUCS classification** | $D_{10}$ | 0.010 | 0.010 | 0.010 |
| | $D_{30}$ | 0.200 | 0.210 | 0.08 |
| | $D_{60}$ | 0.700 | 0.70 | 0.70 |
| | Cu | 70 | 70 | 70 |
| | Cc | 5.71 | 6.30 | 0.91 |
| | **SM:** Silty sands, sand–silt mixtures<br>**SC:** Clayey sands, sand–clay mixtures | | | |

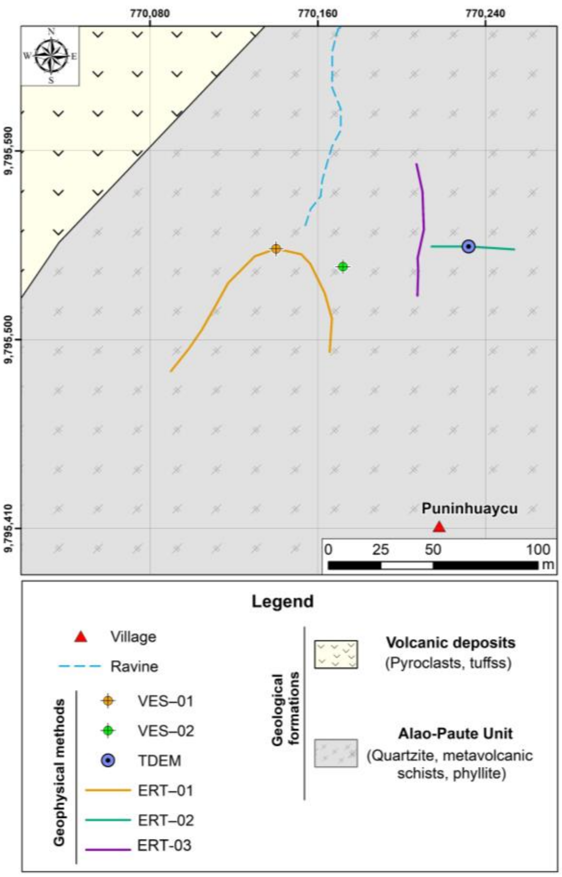


**Figure 4.** Geophysical test location map in the study area

3.3.1 Geoelectric Tomography 01

The ERT–01 reached a depth of 14 m, with a resistivity value ranging from 6.58 to 140 Ω·m (Figure 5). The first 2 meters of the profile show high resistivity values (> 85 Ω·m), corresponding to the granular fill/ballast material type IV that has been placed as a base for the roadway.

To the west of the profile, below a depth of 2 m, the high resistivity values represent layers of slightly wet rock fragments. Along with the profile, the orange hues are associated with changes in the compaction and saturation of the material (60–85 Ω·m). Low resistivity values (26–60 Ω·m) are observed in the central part of the profile, indicating the presence of wet metavolcanic material.

Meanwhile, the blue hue (< 23 Ω·m) represents the saturated material in the drainage pipe installed to evacuate water from Puninhuayco Creek. In the VES–01 (Figure 6), a surface layer of 0.50 m was identified, corresponding to a type IV fill made of granular material (gravel or fragmented rocks). The underlying layer, 2.20 m thick, shows higher resistivity (144 Ω·m), indicating the same type of material but more compacted due to lithostatic pressure. In the third layer, at a depth between 2.70 and 36.40 m, the resistivity drops to 38.10 Ω·m, indicating a higher moisture content in the metavolcanic materials of the area.

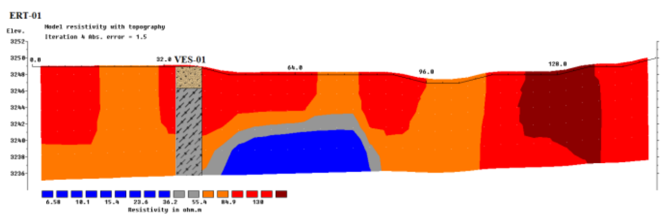


**Figure 5.** Correlation ERT–01 and VES–01 t the toe of the slope, with a length of 160 m

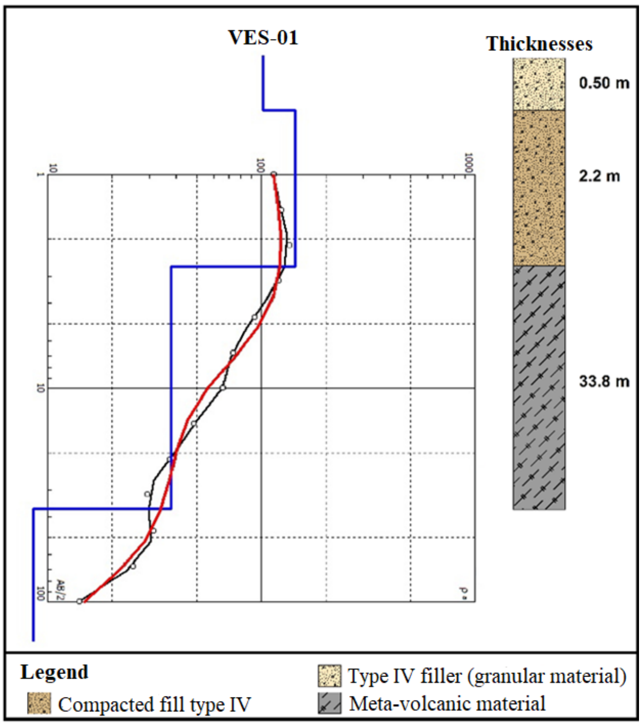


**Figure 6.** Electrical resistivity curve in the IPI2Win software with the representation of the stratigraphic column located at the toe of the slope

3.3.2 Geoelectric Tomography 02 and 03

The ERT–02 conducted at the top of the slope, in an E–W direction, reached an approximate depth of five meters, while the ERT–03, in a N–S direction, reached a depth of 8 meters (Figure 7). In the ERT–02, four layers of material with different saturation levels were identified. In the initial part of the profile, resistivity values ranging from 30–60 Ω·m were recorded, with a thickness of 4 m, corresponding to wet clays/silts.

At approximately 11 m in length, a low resistivity zone (20–30 Ω·m) is observed due to the presence of material composed of saturated clays/silts. In the final part of the ERT–02, red colours represent areas of slightly moist colluvial deposits with intercalations of rock fragments (90–140 Ω·m). In the correlation of ERT–02 with TDEM–01, the presence of slightly moist and loosely compacted colluvial soils is evident, with resistivities ranging from 60–90 Ω·m. These soils predominate along the profile, with certain intercalations that vary based on the degree of saturation and compaction.

Regarding ERT–03 (Figure 7), to the west of the profile, a material composed of wet and friable clays/silts is observed, as identified during the field survey, in the first 2 meters of depth. Below, a layer of slightly moist and loosely compacted colluvial soils is present, with resistivities ranging from 60–90 Ω·m and an approximate thickness of 1 m. At depths greater than 4 m, the resistivities increase (> 90 Ω·m), corresponding to a layer of slightly moist colluvial deposits with intercalations of rock fragments.

On the eastern side, a thicker layer is shown with resistivities between 30–60 Ω·m, interpreted as wet clays/silts. In both profiles, it is evident how the degree of saturation varies with depth and the presence of fragments in specific areas.

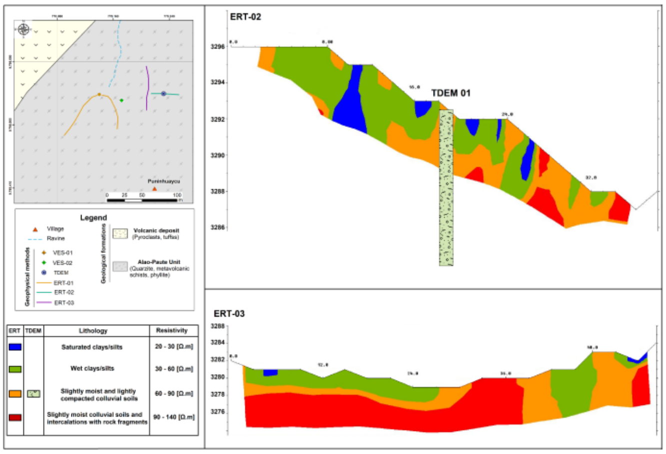


**Figure 7.** 2D geoelectric profiles conducted on the slope. ERT–02 located at the top of the slope, in a perpendicular direction with a length of 40 meters, correlated with TDEM–01, and ERT–03 in an E–W direction, with a length of 60 meters

3.3.3 1D Geophysical Tests Conducted on the Slope

The VES-02 carried out on the first terrace of the slope, reached a depth of 2 m, identifying two layers due to the small extension of the test (Figure 8). The first layer presents low resistivities compared to the test carried out on the main road due to the change of material, where the value of 73.3 Ω m corresponds to slightly humid and poorly compacted colluvial soils, evidenced in the field survey.

While the underlying layer presents higher resistivity values (345 Ω m) associated with colluvial soils with many dry rock fragments. In the upper part, in the electromagnetic profile with an approximate penetration depth of 91 m, three layers of colluvial soils with different degrees of saturation were identified (Figure 8). The first layer, with a thickness of 8.78 m, has a resistivity of 69.60 Ω m, corresponding to slightly moist and crumbly colluvial soil.

The second layer presents a slight variation in the resistivity value (54.80 Ω m) due to the moisture content present in the area, classifying it as humid and poorly consolidated colluvial soils. From 60 meters, the resistivity drops dramatically, with a value of 11.10 Ω m, relating it to a higher degree of saturation, corresponding to saturated colluvial deposits.

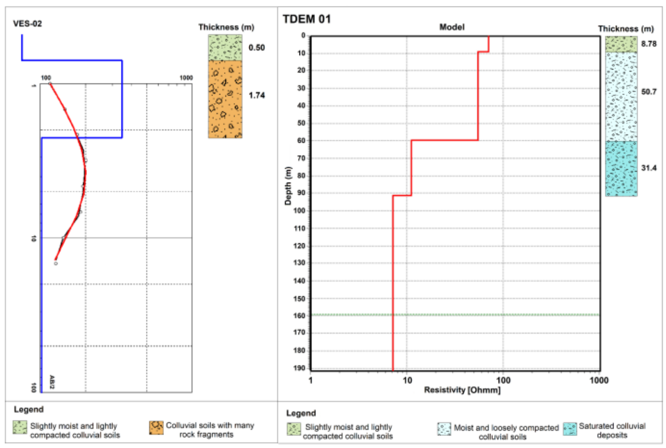


**Figure 8.** 1D tests performed on the slope. Vertical Electrical Sounding (VES-01) on the first terrace and TDEM-01 at the top of the slope

### 3.4 Stability analysis

The NEC [45] defines six soil profiles according to the shear wave velocity (Vs), soil moisture content (W) and other parameters (detailed in Table 2 of the Ecuadorian Standard for Construction Code Seismic Loads for Earthquake Resistant Design (NEC–SE–DS), part 1). To calculate the stability of the slope, computational tools were used where the surface of the landslide was analysed, using the limit equilibrium method, evaluating two conditions:

·Static condition, analysing the slope without any support element, movement of masses or any other type of landslides to observe the behaviour of the slope in an initial state, obtaining an fs of 0.993 (Figure 9a).

·Pseudo–static conditions, the seismic hazard analysis in rock for a probability of exceedance of 10% in 50 years considered: soil type, seismic zone factor and soil amplification coefficient, resulting in an fs of 0.989 (Figure 9b).

It was determined that the landslide presents concentric and concave cracks in the direction of the displacement, which produces fragmentation into blocks, and the most critical points were identified.

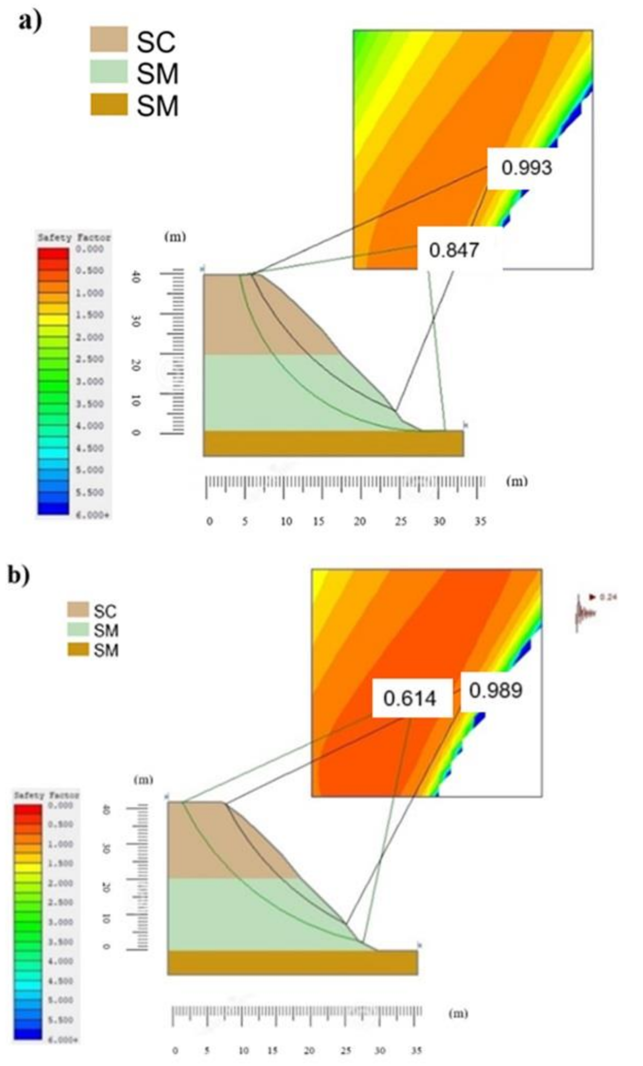


**Figure 9.** Calculation of the fs for the topographic profile a) static method b) pseudo–static method

3.4.1 Slope stability strategies

For the stability of an unstable slope, a surface treatment is necessary (Figure 10). One of the proposed strategies is to modify the geometry of the slope to reduce the forces that tend to the movement of masses and increase the resistance to shearing of the ground by increasing normal stresses [54]. As a result, the volume of unstable material will be reduced to prevent its mobilisation [55].

In addition, the profiling will begin from the top of the slope to control the runoff speed resulting from the crops found therein. Also, the top must be round to conserve moisture and plasticity characteristics, stimulate sufficient organic matter to cover the slope, and control erosion [56].

For the slope, the construction of three terraces will be contemplated, which will allow the elimination of irregularities and adaptation to the slopes [57], including intermediate berms, which are made in conjunction with the profiling, increasing the normal stresses and resistance at the base of the slope [58]. The function of berms is to facilitate the construction process, maintenance and intercept runoff [56].

Once the berms have been built, the crowning ditches will continue to control surface runoff and water erosion processes and avoid large volumes of infiltration [60]. The water coming from the crown of the slope is the result of irrigation from the crops, which infiltrate and accumulate, causing instability [60].

The geomembrane waterproofing is installed in areas where slow movements occur, and there is a need to control water infiltration. The proper placement of structures helps increase service life and reduce maintenance costs [62]. It should be installed over the excavated area, levelled and free of stones that could damage the geomembrane. Additionally, the pumping slopes should range between 4% and 6%, allowing for better drainage towards a concrete gutter at the base of the slope, which collects all the runoff water and directs it to an already constructed drainage system [63]. Finally, the entire slope will be covered with vegetation to prevent negative interaction between the civil works and the surrounding environment, thereby reducing the environmental impact [64]. It is easy to install because the maintenance costs are low compared to other processes [65].

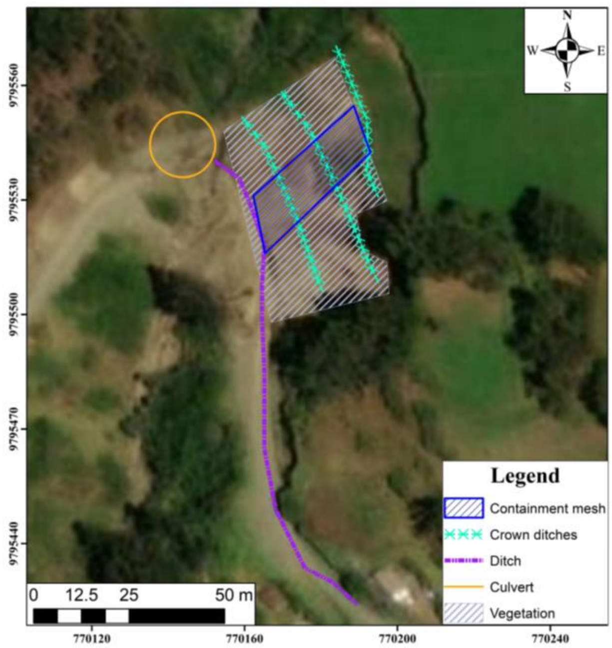


**Figure 10.** Location map with the proposal of stability strategies/measures based on in-situ conditions

## 4 DISCUSSION

This study provides a methodological approach that combines geophysical tests such as VES, ERT, and TDEM to obtain a 1D and 2D spatial view of the landslide. In addition to complementary studies of basic geomechanical tests on altered soil samples and slope stability analysis. The execution of a geophysical study is presented, with sampling points based on the nature of the slope and accessibility, which included: i) Combination of VES and ERT at the base of the slope, ii) Development of a VES in the body of the slope, iii) Combination of ERT and TDEM at the crown of the slope, where tension cracks were observed during the field visits. This methodology considers several authors' recommendations on applying two or more geophysical methods to reduce ambiguity in interpretation [32, 62, 63]. However, direct exploration methods such as drilling were not carried out [64] due to their limited spatial reach (1D), ground conditions (loose material, presence of water springs), and safety considerations.

One of the main challenges when conducting a geophysical survey in a landslide is determining the depth and lateral extent of the slip surface [65] due to the irregular topography, signal-to-noise ratio, and the instability of the ground, which can lead to difficulties in setting up electrodes and other measurement sensors. However, the proposed geophysical exploration strategy in the case study shows how the 1D geophysical surveys (Figure 7) exhibit a good correlation with the resistivities obtained from the 2D geophysical methods on the interpreted slip surface (Figures 4–6), identifying colluvial soils with varying degrees of saturation, reaching depths of approximately 91 meters (Figure 7).

Slopes that have remained stable for many years can fail due to topographic changes, seismic activity, groundwater flow, soil strength, geological faults, weathering, or anthropogenic and natural factors, modifying the slope's stability and triggering a landslide [60]. As in the article "Characterisation and geophysical evaluation of the recent 2023 Alausí landslide in the northern Andes of Ecuador" [28], where the contribution of geophysical surveys provides geological-geotechnical parameters for stability analysis, design, and slope reinforcement strategies [68]. In addition, it performs non-destructive evaluations, meaning that information about subsurface characteristics can be obtained without drilling, thereby reducing environmental impact. It identifies weak zones, such as landslides, to prevent and control disasters caused by mass movements. The costs are lower compared to other types of surveys and can be complemented with geological and geotechnical information. It helps identify groundwater and supports continuous monitoring over time of an unstable area [13].

A slope is composed of various materials (rock, soil, fill, or a combination of these), which may tend to slide due to the influence of gravitational forces, earthquakes, erosion, and other causes. These materials resist shear stress but do not sufficiently counteract the forces that tend to trigger mass movement [68]. Slopes that have remained stable for a long time can eventually fail for several reasons due to their geology; for example, in the case study, it was determined through the SUCS classification that the material is SM at the base and centre of the slope and SC at the crown. This indicates that silty sands are characteristic of having high nutrient levels, as they have more porous spaces (clay soils have larger pores than sandy soils), which allows them to absorb and retain water more efficiently. Additionally, it tends to contract and expand with changes in moisture content, making it prone to erosion [70]. Slopes that have remained stable for a long time can eventually fail for several reasons, including their geology. For example, in the case study, it was determined through the SUCS classification that the material at the base and centre of the slope is SM (silty sands), while SC (clayey sands) was identified at the crown. This indicates that silty sands have high nutrient levels, as they contain more porous spaces (clayey soil has larger pores than sandy soil), allowing easy water absorption and retention. In addition, it tends to contract and expand with changes in moisture content, making it prone to erosion [68]. Silty-sandy soils also have high nutrient levels and drain slowly, which causes them to expand and retain moisture, making them weak soils [71].

The geotechnical methods used in the article allowed for calculating the fs using static and pseudo–static methods to determine stability conditions, identify unstable areas, and quantify landslide risks. In the modelled cases, a fs greater than 1 is not achieved, indicating that the slope could experience some mass displacement, considering the presence of water on the slope caused by pore pressure due to the saturation level, which is the main factor to address. In addition to the suggested proposal, it was made to provide an immediate solution, even from an economic perspective.

## 5 CONCLUSIONS

The slope characteristics were determined through the characterization and correlation of geophysical and geotechnical tests. Geophysical methods, such as VES, ERT, and TDEM, were used to identify existing materials, including metavolcanic soils, clays/silts, and colluvial deposits.

The obtained results made it possible to determine that the slope is composed of SM and SC soils, which have high nutrient levels, making the soil fertile for the crops in the area. These soils are highly prone to erosion and drain slowly, which causes moisture retention and results in a weak soil structure.

The data obtained from the correlation between geotechnical and geophysical tests allowed for the determination of the material properties and variation in the saturation level of the slope, providing greater accuracy in the results as they cover a larger area.

The slope stability was designed under static and pseudo–static conditions based on limit equilibrium theory, determining the presence of concentric and concave cracks along the slope. The fs was more significant than one, which will depend on the slope's geometry and the geology that composes it. Some limitations affect the accuracy of the data obtained for the fs, which can lead to oversizing in the design.

Finally, the strategy for stabilization involves cutting the slope into terraces, including berms, to control the runoff speed caused by the crops located at the crown of the slope. This includes continuous crown trenches for each terrace and the installation of a geomembrane in areas with higher water infiltration. A gutter will be constructed at the base of the slope to collect water from the crown trenches, draining into the already constructed drainage system. Finally, the slope will be covered with vegetation to help prevent erosion and enhance stability.

The proposals were made from an economic and safety perspective, meaning the risk is imminent compared to any financial cost. However, failing to implement any intervention, despite the existing precedents, would leave the situation unresolved. These measures provide a provisional solution to stabilise the mass movement. The Pungalapampa community depends on planting and selling its products in Riobamba. Therefore, if a landslide were to occur on the slope, they would become isolated, as it is the only access route through the area. These situations are common in all Andean communities with similar conditions.

It is recommended that future investigations include complementary tests such as SPT (Standard Penetration Test) and refraction seismic surveys to further explore the characteristics of the study area in greater detail. Additionally, the design of retaining walls, anchors, and other civil works should be considered. It is also important to consider that Ecuador is highly seismic, so vulnerability maps should be developed, particularly for areas with surface runoff.

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