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A Case Study of a Macro-Landslide in the High Mountain Areas of the Ecuadorian Andes: "La Cría" at the Azuay Province (Ecuador)

Francisco Javier Torrijo [1], Santiago Álvarez [2] and Julio Garzón-Roca [3,*]

[1] Department of Geotechnical Engineering, Research Centre for Architecture, Heritage and Management for Sustainable Development (PEGASO), Universitat Politècnica de València, Camino de Vera s/n, 46022 Valencia, Spain; fratorec@trr.upv.es
[2] Secretaría Nacional de Gestión de Riesgos CZ6, Simón Bolívar, Cuenca 010111, Ecuador; santiago.alvarez@gestionderiesgos.gob.ec
[3] Department of Geodynamics, Stratigraphy and Paleontology, Faculty of Geology, Complutense University of Madrid, 28040 Madrid, Spain
* Correspondence: julgarzo@ucm.es

Abstract: Large landslides, known as macro-landslides, pose a significant threat to the safety and stability of communities living in mountainous areas. In this work, an evaluation of a macro-landslide that occurred in the La Cría community (Azuay province, Ecuador) is conducted. This macro-landslide covered an extensive area of approximately 443 hectares and affected a population that is mainly dedicated to agriculture. Historically, a landslide was already identified in the area in the 1973 geological map. However, there has recently been a significant increase in the speed of the landslide, causing damage to infrastructure and homes, and directly affecting 97 homes of various structural typologies. The study area is characterised by its geological instability, influenced by the presence of reservoirs for agriculture. In addition, the community of La Cría within the landslide has experienced considerable population growth. The study conducted combines the use of a landslide susceptibility map with a multicriteria analysis (which considers the interactions of geological, hydrological and land use) and a stability evaluation based on limit equilibrium methods. The results show that most of the territory assessed, approximately 55%, presents with a very high susceptibility to landslides, and reveal that the geology and the interactions between local geology and water resource management are needed to prevent and mitigate the risks associated with mass movements in the area.

Keywords: macro-landslide; stability; threat; Andes; hazard; risk

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1. Introduction

Landslides represent an important danger in many regions of the world [1,2]. Their destructive potential usually includes both damage to infrastructure and life losses. Large landslides can also lead to the abandonment of inhabited centres [3]. Many variables interact in the triggering and development of landslides, including geological, geotechnical and environmental ones; uncontrolled urbanism may also affect slopes, while inappropriate agricultural practices and poor or inexistent hazard management strategies may result in increasing vulnerability to landslides. The combination of all those factors increases the occurrence and severity of landslides worldwide [4].

Landslide hazard is often described as landslide susceptibility [5]. However, hazard should be understood as the predisposition of an area to landslides or earth flows due to factors such as geology, topography, vegetation, hydrology and human activity [6]. On the other hand, susceptibility only indicates the area that may be affected by a landslide and neglects the period in which it could occur. However, landslide susceptibility is a powerful

tool to identify the most suitable areas for urban and infrastructure development. Comparing the location of proposed development areas with the respective landslide susceptibility levels can help establish the suitability of land uses as well as propose appropriate mitigation measures. Conducting a comprehensive macro-landslide assessment is therefore critical as it provides essential data to guide effective planning and decision-making [7,8]. Susceptibility studies can also be paired with the identification of vulnerabilities, so future investment initiatives can be created to avoid, eradicate or significantly reduce any potential risk.

Landslides can have different dimensions. A macro-landslide is considered to occur when the magnitude of the affected area and the volume of the material displaced is significant, generally reaching more than one million cubic metres and covering areas greater than one square kilometre [9]. These characteristics contrast markedly with smaller-scale landslides, which typically involve volumes of displaced material on the order of hundreds to thousands of cubic metres and areas smaller than one square kilometre [10]. Apart from seismic forces [11], macro-landslides are mainly triggered by the presence of surface water on slopes. Heavy rainfall increases the water content of the soil, eventually resulting in soil saturation. This reduces cohesion and increases pore pressures and soil unit weight, all of which reduce the safety factor of the slope. This may lead to the loss of stability and ultimately cause the slope to collapse [12]. Poor water management in agricultural areas can further aggravate such situations, increasing the velocity and likelihood of landslides [7,13]. A notable example of this dynamic is the La Josefina landslide in Ecuador in March 1993. In this case, high rainfall and poor land and water management contributed to the instability of the soil, resulting in a devastating landslide that caused both the loss of life and destruction of homes, along with the damming of the Paute River [1]. The tragedy is said to have left between 100 and 150 dead and missing and around 7000 people affected. However, there has never been an exact number of casualties. Another example of this dynamic is the landslide in La Conchita, California, which occurred on 10 January 2005. In this case, heavy rains and inadequate land and water management contributed to the instability of the land, resulting in a devastating landslide that caused both the loss of life and destruction of homes [2]. In this case, 10 people lost their lives and more than two dozen houses were buried. These events clearly illustrate how the combination of natural conditions and inadequate management practices can significantly exacerbate landslide risks.

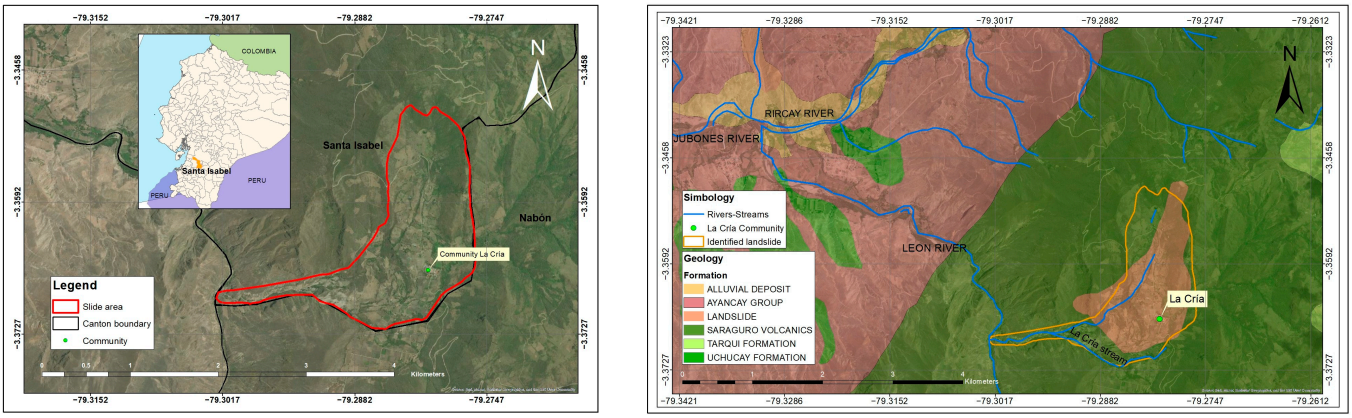
In this study, an assessment of a macro-landslide that has been observed since June 2022 at the La Cría community (Ecuador) was carried out by combining a 1:25,000 scale landslide susceptibility map with a multicriteria analysis and a stability evaluation. The landslide susceptibility maps incorporated information about geology, geomorphology, topography and land uses in a way that helped in assessing the landslide hazard in the study area. An Integrated Territorial Analysis System criterion was used to assign weighted values to each factor considered. A complementary analysis was then conducted using a geotechnical evaluation of the stability of the landslide profile using the limit equilibrium model. This model was built from the geotechnical information provided by previous investigations and field works and considered the seismic action, the water table and the presence of the La Cría community [14]. Finally, a comparison between both methodologies was conducted by analysing critical sections of the landslide profile, linking the weighted values obtained in the susceptibility map with the safety factors calculated through the geotechnical modelling. The importance of integrating susceptibility studies with geotechnical assessments has been highlighted in numerous investigations. For example, several studies have highlighted that landslide susceptibility maps not only serve as diagnostic tools, but also form the basis for developing comprehensive mitigation plans adapted to local conditions. Furthermore, the inclusion of detailed case studies, such as the La Josefina and La Conchita landslides, highlights the need for a multidisciplinary approach that considers climatic, geological and anthropogenic factors. Recent research supports combining susceptibility analyses with vulnerability and exposure assessments

to address risks in a holistic manner [15,16]. These approaches aim to minimise potential damages and increase the resilience of communities at risk.

2. Geographical and Geological Background

The study area is located between the border of the canton of Santa Isabel and the canton of Nabón, Ecuador. The community La Cría is delimited to the north by the municipality of Abdón Calderón, to the south and east by the municipality of El Progreso, and to the west by the municipalities of Sumaypamba and San Sebastián de Yúluc. Although this community belongs to the canton of Santa Isabel, the study area includes part of the canton of Nabón in the province of Azuay (Figure 1a). This community consists of about 250 people.

The community of La Cría is in a very dry subtropical climate, with altitudes ranging between 1300 and 1900 metres above sea level (average altitude 1729 m). Annual average temperatures are between 16 and 22 °C. In terms of annual precipitation, according to Cañadas [17], this region experiences an average between 300 mm and 500 mm; the area has a low annual rainfall due to its location in the Jubones Desert, a predominantly mountainous arid region. This desert extends along the Jubones River valley, characterised by its dry climate and sparse vegetation.



(**a**) (**b**)

Figure 1. La Cría community: (**a**) Location map and (**b**) Lithological map (original scale 1:25,000) [18].

Data from MAGAP [19] indicate that soils in the study area are formed from colluvial slope deposits with slopes of medium size. The soils show a mostly clayey texture and have a structure consisting of angular blocks. The pH is slightly alkaline, with moderate levels of organic matter and a high cation exchange capacity. A distinctive feature of these soils is the presence of friction faces and cracks in the first 50 cm of depth.

In the study area, the predominant rock formations are of volcanic origin, although outcrops of Upper Cretaceous sediments, as well as Mio-Pliocene and Pleistocene sediments are also observed. Figure 1b shows a lithological map of the region; note that although the geology shown does not directly affect the identified landslide, it was used to develop the mass movement susceptibility map. The most important geological features are as follows:

- Landslide Deposits (Des): This is the accumulation of material that occurs when rocks or soil collapse from a slope and are deposited at the base. As pointed out by Chacón et al. [20], these deposits represent an important geological risk in landslide-prone areas. The La Cría community sits on these materials, with medium to steep slopes (12 to 70%), where its relative slope gradient ranges from 50 to more than 200 m and its slopes are long with predominantly mixed or irregular shapes [19].
- Tarqui Formation (PT): The formation is described as a uniform sequence of pyroclastic material (white and red-coloured acid tuffs as well as agglomerates) that is highly

weathered and has a significant presence of kaolinite. In addition, lava flows of andesitic composition were identified [19].

- Ayancay Group (MPIY): The Ayancay Group is a sedimentary sequence formed by fluvial processes. It is composed of a series of strata including sandstones with inclusions of volcanic material, shales, siltstones and conglomerates. The thickness of these strata varies between 0.5 and 3 m, and they are characterised by their high instability [19].
- Saraguro Formation (OS): The Saraguro Formation is characterised by its composition of volcanic sequences and lava deposits, mainly of the andesitic and rhyolitic type, with a thickness exceeding 3000 m. It is organised into three distinct components: green andesitic tuffs, clastic tuffs and rhyolitic tuffs. It also has ignimbritic layers overlying the clastic and rhyolitic tuffs [19].

For a better understanding, the units can be arranged from the youngest to the oldest. In this case, the landslide deposits (Des) represent the most recent materials, followed by the Tarqui Formation (PT) and the Ayancay Group (MPIY), which contain Mio-Pliocene and Pleistocene sediments. Finally, the Saraguro Formation (OS) is the oldest material in the region, composed of volcanic sequences and lava deposits of an Upper Ordovician age. This sequence allows a better understanding of the geological evolution of the area and its relationship with the processes that contribute to the instability of the land.

As shown in Figure 1b, the community of La Cría is bordered by the ravine ("quebrada") of the same name, which flows into the León River to the southwest; León River flows into Jubones River to the north, and this river ends its course in the Pacific Ocean.

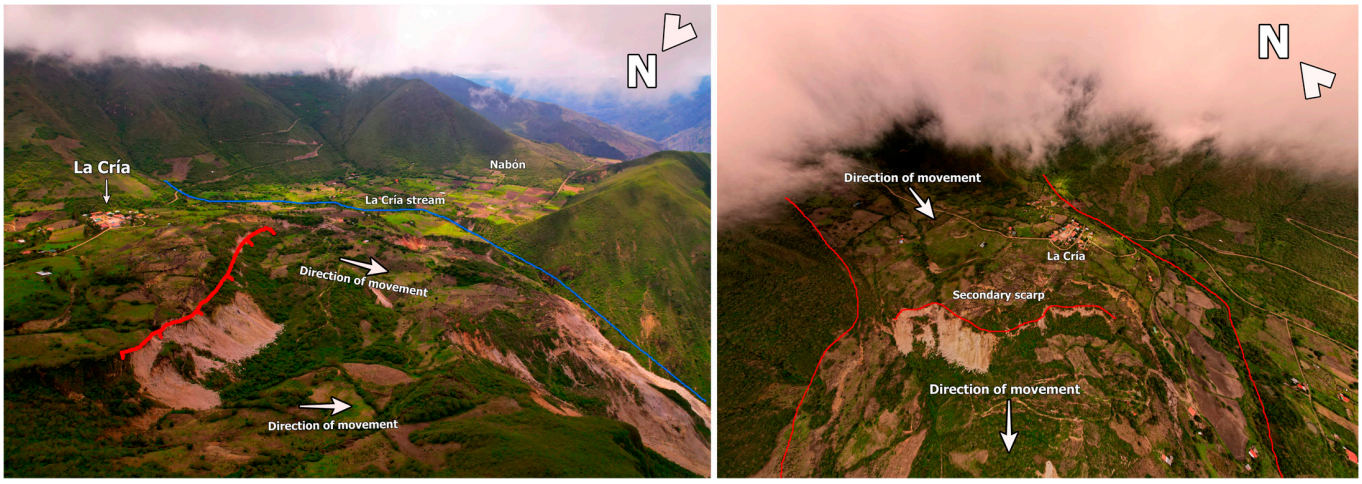
3. Problem Statement: Categorisation of the Event

The macro-landslide was identified in 1973 by researchers from the Universidad Central del Ecuador and was recorded in the Geological Map of Ecuador, produced by the Directorate General of Geology and Mines [20]. This is important because there is currently no concrete historical data on the original landslide. This data would have been very useful for understanding and mitigating the risks associated with the macro-landslide, as well as for proper land use planning [21–24]. Subsequently, the landslide reached a state of stability, although the exact year is unknown. The current landslide identified and analysed in this study (shown in orange in Figure 1) was reactivated in 2021 and is bounded by the La Cría stream. This was determined on the basis of several reports from residents of the La Cría community, as well as inspections carried out by technicians from the Santa Isabel GAD and the National Risk Management Secretariat. These inspections revealed the presence of numerous significant cracks and landslides in the La Cría community.

Since June 2022 [25,26], topographic monitoring has confirmed a significant increase in the speed of the landslide, directly affecting all the houses in the La Cría community, as well as roads, electrical infrastructure and sewerage systems (Figure 2).

The identified phenomenon of mass movement is complex, encompassing both rotational landslides and rock falls. It covers around 270.8 Ha. Regarding the classification of the recurrence sequence of the movement, according to Varnes categorisation [8], it can be identified as Regressive, which indicates that the regressive cracks expand in the opposite direction to the movement, particularly towards the centre of the La Cría Community.

From 12 January 2023 to May 2023, the Autonomous Decentralized Government (GAD) of Azuay Province conducted monitoring work with Real-Time Kinematic (RTK) topographic equipment—the Global Navigation Satellite System (GNSS). Sixteen mobile control points and one base point were set up. A total of 16 points were placed at different points of the identified landslide (Figure 3), 3 of which were placed in the Nabón canton to ensure their stability. Since January 2023, 10 measurements of the control points have been carried out, with a maximum displacement of 2.64 m/month between the months of January and April (with little rainfall). It was also observed that the points located in the canton of Nabón do not show any displacements.



(**a**) (**b**)

Figure 2. (**a**) The direction of the active macro-landslide affecting the community of La Cría; (**b**) The direction of the active macro-landslide and secondary scarp affecting the community of La Cría. The photos were taken by Santiago Álvarez, January 2023.

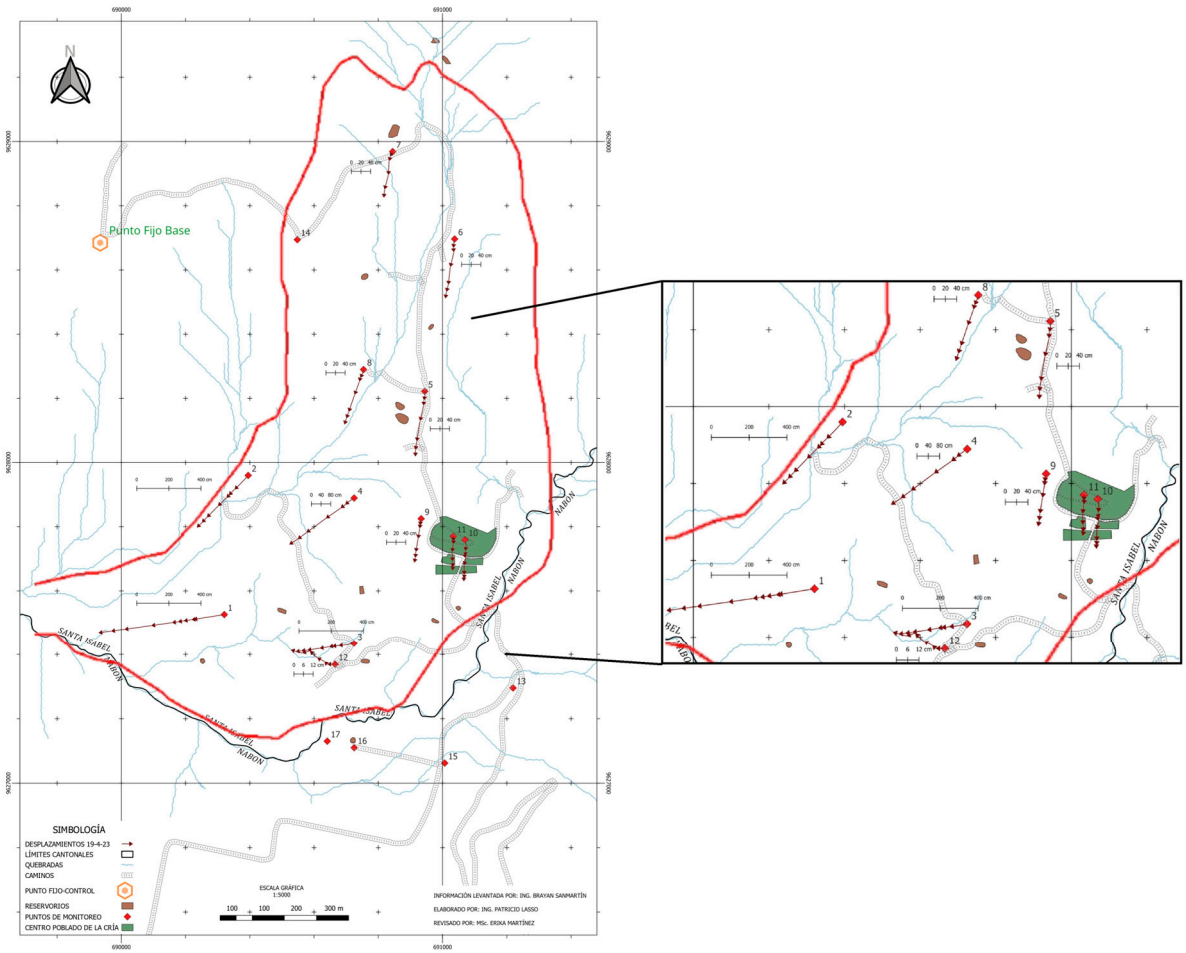


Figure 3. The control points installed by the Autonomous Decentralized Government (GAD) of Azuay Province [27].

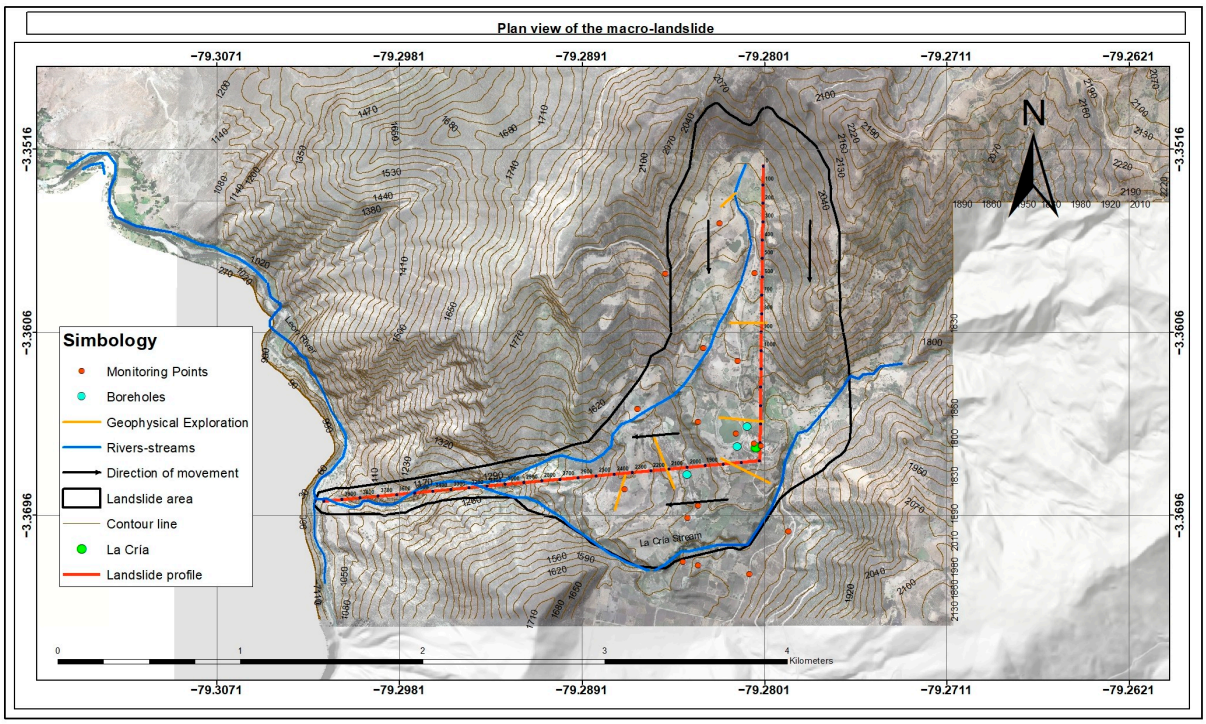
The speed of displacement has a considerable influence on the destructiveness of a landslide [28]. Thus, landslides that occur at an extremely fast speed often trigger catastrophes of a great magnitude, occasionally with a high number of casualties. In

contrast, landslides that occur at an extremely slow speed are practically imperceptible without the use of instruments and represent a relatively low risk for the loss of life. Although the La Cría landslide can be characterised as a slow landslide [29,30], the great area it covered makes the effects on human lives important, with the landslide even causing damage to structures and the potential for loss of life. Thus, within the affected area, there are approximately 97 dwellings that show advanced structural issues, with cracks in essential elements (e.g., beams and columns). Figure 4 shows the state of several of those dwellings; although having insisted that all these dwellings must be evacuated, many of them are still inhabited.

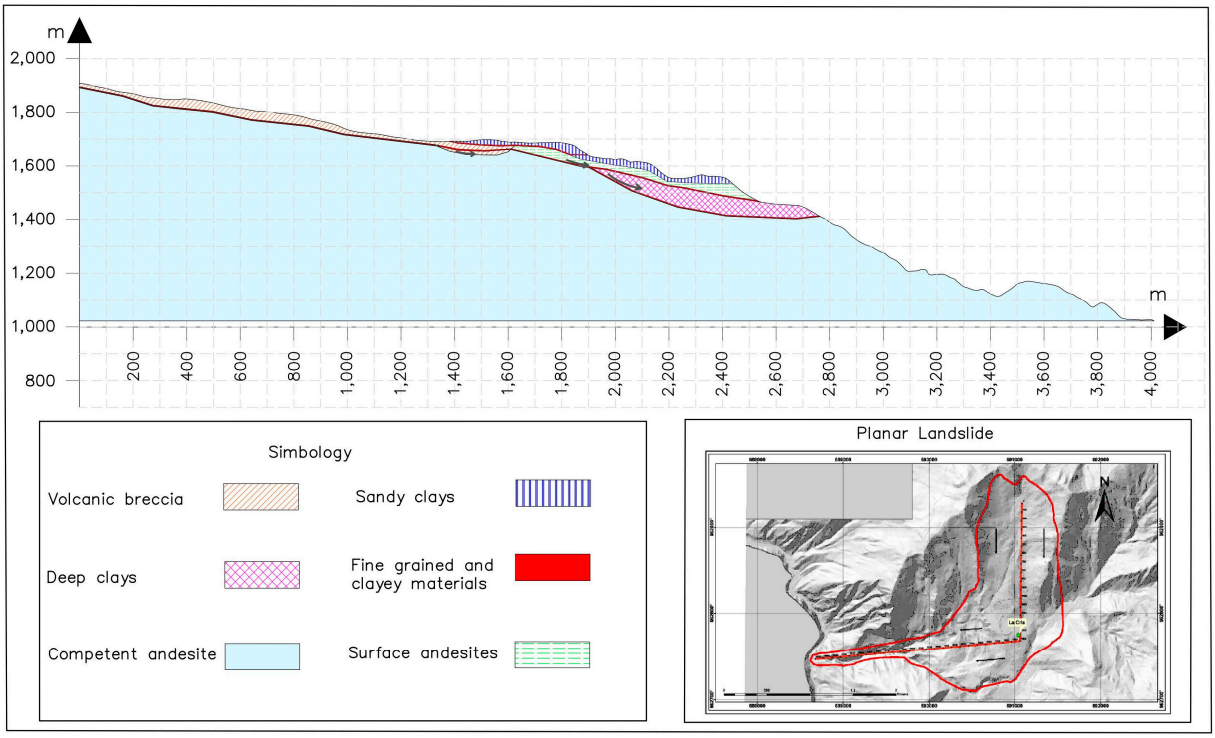


Figure 4. Photographic record of damage to houses in La Cría community, January–April (Geographic Coordinate System WGS 84). Photos taken by Santiago Álvarez, January 2023.

The delimitation of the macro-landslide was based on three sources (Figure 5a): contour lines obtained from a Digital Elevation Model-DEM [31], monitoring works by topographic equipment from the prefecture of Azuay, and on-site inspections carried out since January 2023. Based on that, it may be observed that there is a displacement in two directions, North–South and East–West, i.e., in the direction of the León River.



(**a**)



(**b**)

Figure 5. La Cría community macro-landslide: (**a**) plan view of macro-landslide and (**b**) geotechnical profile (depicted in red in (**a**)).

Figure 5b shows a geotechnical profile of the macro-slide. The geotechnical parameters are summarised in Table 1 and were taken from a study conducted by the Ecuadorian Department of Risk Management (SNGR) [32]. The parameters were estimated based on correlations established through the corrected number of N60 blows, laboratory tests and seismic velocities of geophysical tests. Within the geophysical surveys, six transversal lines to the landslide profile were performed, involving seismic refraction, ASW + REMI and Continuous Electrical Resistivity.

Table 1. Geomechanical parameters [25,32,33].

Material	Frictional Angle, φ′ (°)	Cohesion, c′ (KPa)	Description c′ y φ′	Specific Gravity (KN/m^3)
Sandy clays	7.5	33	By triaxial tests and correlations with N_{SPT}	18
Surface andesites	36	131	By Hoek Brown's criteria	19
Volcanic breccia	21.5	57	By Hoek Brown's criteria	19
Deep clays	25.5	317	By Hoek Brown's criteria	19
Fine-grained and clayey materials	16	128	By uniaxial compression, triaxial and direct shear tests.	18
Competent andesite	Material Competent			

From the results provided [25], three boreholes were drilled at specific locations. The first borehole was drilled near the centre of the La Cría community, reaching a depth of 36 m. The second borehole, with a depth of 24.20 m, was drilled in the lower part of the landslide. The third borehole was drilled in the upper part of the village, with a depth of 33 m.

According to the Ecuadorian Construction Standard NEC-15 [30], the study area is located in Seismic Zone II, characterised by a Peak Ground Acceleration (*PGA*) of 0.25 g and high seismic activity. This requires taking into account the seismic action by a pseudo-static analysis. The horizontal seismic coefficient k_h was obtained following Equation (1) [25,32]:

$$k_h = 0.6 \times PGA \times F_a \quad (1)$$

where F_a is an amplitude factor. Within the geophysical survey, six lines were identified where the average shear wave velocity in the first 30 m ($V_{s,30}$) was set, revealing velocities in a range between 360.74 m/s and 524.31 m/s. Those profiles correspond to a type C [25,32] ("Profiles of very dense soils or soft rocks"), so F_a was taken as equal to 1.3.

The lithology identified in the geotechnical profile (Figure 5b) corresponds exclusively to the identified landslide, including materials from the Alluvial Deposit and the Saraguro Formation. The alluvial deposit includes sandy clays, typical of sediments transported by mass removal processes, as well as layers of fine and clayey materials, reflecting the accumulation of sediments in unstable areas. At greater depths, deep clays can be identified, representing more compacted sediments associated with the prolonged accumulation processes in these areas. On the other hand, the Saraguro Formation provides volcanic materials such as shallow andesites and volcanic breccias associated with explosive deposits in this unit. In the deeper layers of the profile, competent andesites are prominent, corresponding to older consolidated volcanic deposits. It is important to note that this lithology is only associated with the landslide area, whereas the geological formations shown in Figure 1b cover the entire study area and reflect a greater geological diversity.

It should be noted that although seismic action was included in the stability analysis, no geologic faults were identified in the study area that could influence the acceleration of mass movements. This absence of relevant tectonic structures suggests that the stability of the ground is not compromised by planes of weakness associated with structural deformations. It was also verified that there is no historical record of significant seismic

activity in the area that could have acted as a triggering factor for the macro-landslide under study [28,31].

4. Methodology

The methodology of this study combines a landslide susceptibility map at a scale of 1:25,000, based on a multicriteria analysis of geological, geomorphological, topographic and land-use data, with a geotechnical stability assessment using a limit equilibrium model. Critical sections of the La Cría landslide (Ecuador) will be analysed, relating susceptibility indices to safety factors for a comprehensive risk assessment.

4.1. Multicriteria Analysis

Multicriteria Analysis Method [16], also known as Heuristic, is based on the consideration of multiple criteria and variables in the study of landslides by Geographic Information Systems (GIS). This approach makes it easy by considering various factors that influence landslide susceptibility. The use of GIS helps in integrating, analysing and visualising complex geospatial data.

The GIS software ArcMap v.10.3.1 was used in this study, and slope, geology, land use and geomorphology were considered as the variables of the analysis. Each of these variables were classified into different categories or ranges, and a specific weight was assigned to each range (see Section 5.1). Different scales were used for the four variables considered, with each scale subjected to an appropriate resolution based on the data availability: geology and geomorphology 1:25,000; slopes 1:5000 (obtained from a DEM of the same scale), a higher resolution due to the well-known high impact that slope has on landslide hazard; land use scale 1:100,000, a lower resolution but enough for capturing general tendencies and useful for the analysis of this study, as changes in land uses have a gradual influence on landslide hazard [34].

The starting point of the analysis was a DEM of dimension 3 × 3 m and orthophotos of the study area [35]. The model was processed to obtain a series map of all the input variables necessary to produce the susceptibility and vulnerability maps. A polygon called "high impact zone" was defined, symbolising the approximate area affected in case of an adverse landslide event, i.e., an event in which all the material on the landslide profile is imminently displaced.

Figure 6a shows the slope map obtained from the DEM, where slopes are classified into three levels: level 1, gentle slopes ranging from 0° to 15° (represented by green); level 2, moderate slopes ranging from 16° to 30° (in yellow); and level 3, steep slopes greater than 30° (in red). It is worth noting that the ranges chosen are based on the stability observed in on-site inspections.

Figure 6b shows the geological map, where 5 formations were identified. The high impact zone is mostly composed of colluvial deposits, although the Saraguro Formation is also present. The existence of such deposits has significant implications for slope stability, as those materials are generally prone to instability due to their loose nature and lack of adequate consolidation [36]. The accumulation of loose material increases the susceptibility of the area to erosion and collapse, especially during extreme weather events or earthquakes. All in all, geological materials of the area, such as volcanic breccias, sandy clays, superficial andesites and fine materials, correspond to the colluvial deposit, while the Saraguro Formation consists of competent andesite (which is less prone to landslides).

Figure 6c shows the geomorphological map. Geomorphology provides information on the shape and structure of the terrain, as well as on the geomorphological processes that can influence soil stability [37]. A total of 22 morphological units were defined, with the high impact zone exhibiting terraced relief, sharp slopes and the presence of a colluvium. The presence of terraced relief and sharp slopes may increase the susceptibility to landslides by creating favourable conditions for water accumulation and soil erosion. Sharp slopes tend to be unstable due to the influence of gravity and erosion caused by water [8].

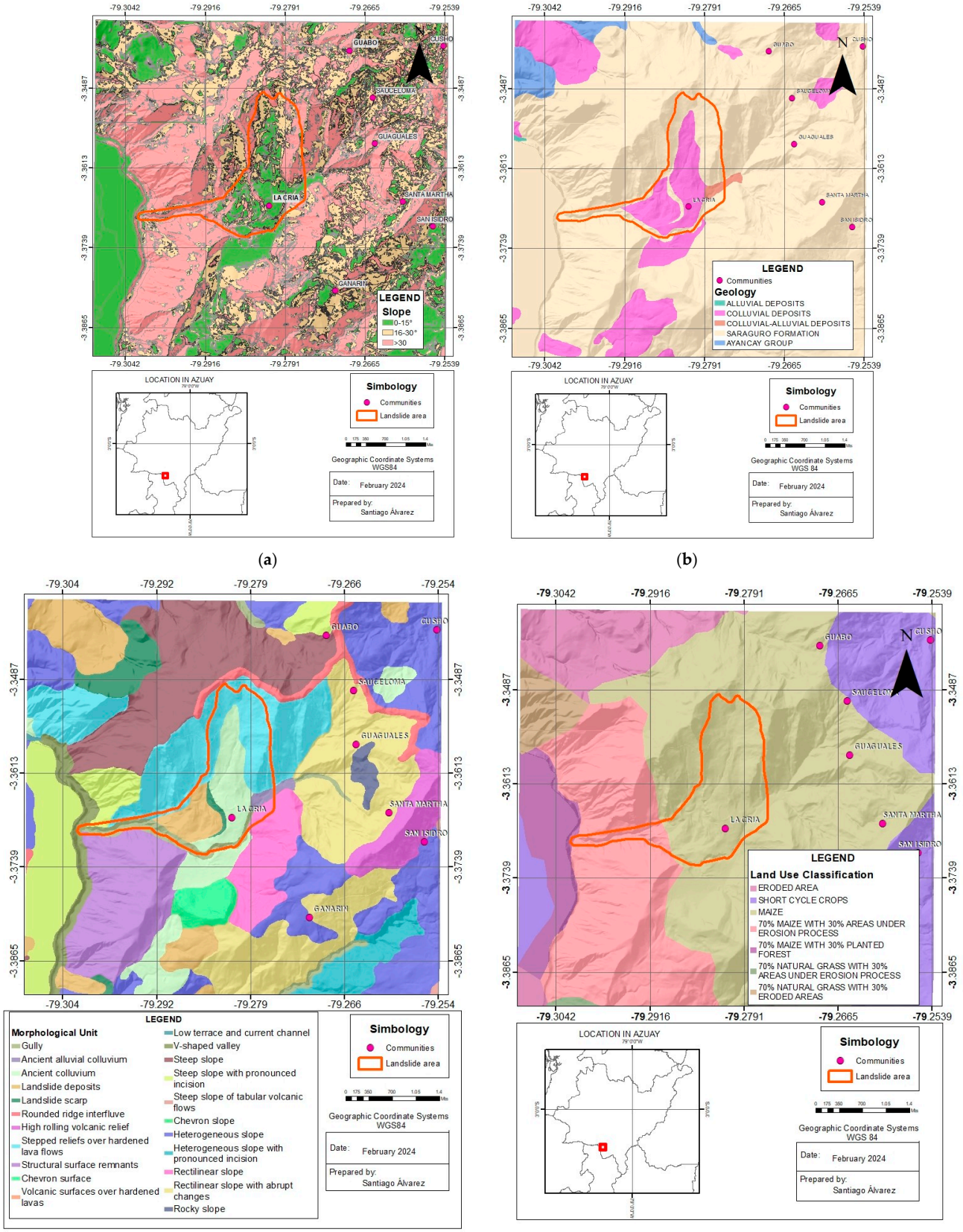
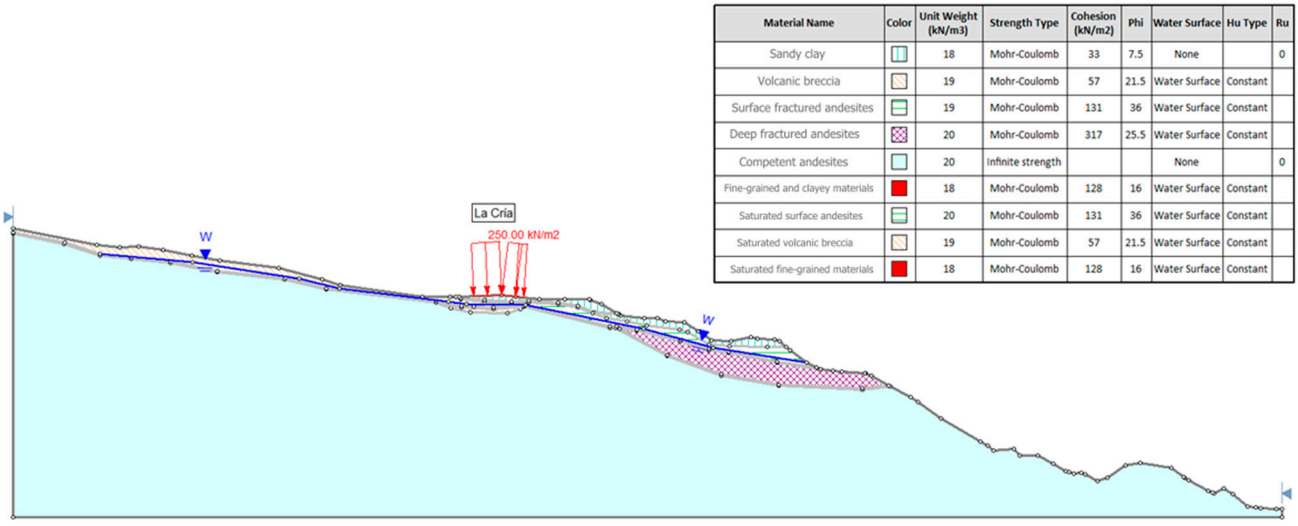


Figure 6. Variables considered for multicriteria analysis conducted in study area: (**a**) slope map; (**b**) lithological classification map; (**c**) geomorphological classification map; and (**d**) land use classification map.

Figure 6d shows the land uses map. A total of 6 units were defined, with the study area being mainly dedicated to agricultural activities. This can result in important implications on the stability of the surrounding slopes [38]. Removal of vegetation can lead to an increase in soil erosion and a decrease in soil cohesion, both increasing the susceptibility to landslides [39]. Agricultural practices, such as ploughing and irrigation, can modify soil structure and increase water infiltration, which in turn can weaken slopes and increase the risk of failure.

4.2. Limit Equilibrium Modelling

A limit equilibrium model of La Cría macro-landslide was carried out using software Slide v6 [40] (Figure 7). This software makes use of the slices method to solve the stability analysis problem. Mohr–Coulomb was set as failure criterion and the Morgerstein–Price method and the simplified Bishop and Janbu methods were used as solving algorithms. These simplified methods are widely used in geotechnical engineering due to their intuitive approach and their ability to capture the main failure mechanisms of a slope.



Material Name	Color	Unit Weight (kN/m3)	Strength Type	Cohesion (kN/m2)	Phi	Water Surface	Hu Type	Ru
Sandy clay		18	Mohr-Coulomb	33	7.5	None		0
Volcanic breccia		19	Mohr-Coulomb	57	21.5	Water Surface	Constant	
Surface fractured andesites		19	Mohr-Coulomb	131	36	Water Surface	Constant	
Deep fractured andesites		20	Mohr-Coulomb	317	25.5	Water Surface	Constant	
Competent andesites		20	Infinite strength			None		0
Fine-grained and clayey materials		18	Mohr-Coulomb	128	16	Water Surface	Constant	
Saturated surface andesites		20	Mohr-Coulomb	131	36	Water Surface	Constant	
Saturated volcanic breccia		19	Mohr-Coulomb	57	21.5	Water Surface	Constant	
Saturated fine-grained materials		18	Mohr-Coulomb	128	16	Water Surface	Constant	

Figure 7. The limit equilibrium model of the La Cría macro-landslide using the software Slide v6. The profile has a length of 4 km, an average slope of 22.4% and a difference in elevation of 712 m, while the cross-section represents the one shown in Figure 6. Note the water table and the representation of the dwellings (La Cría community) with a uniform load of 210 kN/m^2.

The geotechnical parameters given in Table 1 were used to define the characteristics of the ground materials involved in the landslide. Geotechnical parameters include cohesion, friction angle and unit weight. A topographic profile of the study area, provided in DXF format, was used as a reference for the landslide modelling. This profile provided information on the ground configuration and geomorphological features that influenced the generation and evolution of the landslide. The water table was also drawn in relation to the geophysical survey conducted. The seismic action was modelled following a pseudo-static approach, establishing the horizontal seismic coefficient k_h equal to that obtained in the previous section (0.195 g).

Existence of the La Cría community was also simulated in the model. In the landslide profile, within 500 m, there were approximately 70 dwellings, each one with an average building area of 100 m^2. So, a total built-up area of 7000 m^2 can be considered. Using a standard value of 15 kN/m^2 as the weight per square metre for residential dwellings, the total weight of the dwellings would be around 105,000 kN. Dividing this total weight by the length of the line gives a value about 210 kN/m^2. Conservatively within the modelling, a load of 250 kN/m^2 was used to represent the dwellings.

4.3. Multicriteria Analysis and Limit Equilibrium Models Comparison

The comparison between susceptibility mapping and software modelling is essential to complement and validate the results obtained from each tool in landslide analyses. While the susceptibility map is based on the identification of landslide conditioning and triggering factors through geological and topographical analyses [41], software modelling allows the simulation of the mechanical behaviour of landslides under various loading and geotechnical conditions [42]. By comparing the results of both tools, significant overlaps or discrepancies can be identified, providing a more complete and accurate understanding of the susceptibility and potential behaviour of landslides in the study area. Cross-validation between the two tools improves the reliability of the landslide assessment and helps identify critical areas more accurately and define more effective mitigation and risk management strategies [43]. Such comparison was carried out by drawing the modelled landslide profile within the susceptibility map.

5. Results

5.1. Results of Multicriteria Analysis and Susceptibility Map

Table 2 summarises the main variables considered for the multicriteria analysis, and the weights finally assigned to each category. An Integrated Territorial Analysis System criterion was used to assign weighted values to each factor in the preparation of the landslide susceptibility map. This process began with the identification of the relevant susceptibility factors, followed by an assessment of their relative importance in terms of their contribution to the landslide susceptibility. The weighted values assigned were calibrated by an iterative process to achieve a result where the outputted map matched the landslide identified in the study area. The weights therefore show the influence of each variable on the landslide susceptibility of the area under study.

Table 2. Variables, categories and weights used for multicriteria analysis.

Variable	Scale/Source	Category	Weight
Slope	1:5000 [18]	Inclination 0–15°	15
		Inclination 16–30°	30
		Inclination > 30°	60
Geology	1:25,000 [21]	Colluvial Deposit	70
		Ayancay Group	15
		Saraguro Formation	15
Geomorphology	1:25,000 [21]	V-shaped valley	5
		Heterogeneous/abrupt slope	20
		Ravine	35
		Landslide	60
Land use	1:100,000 [22]	Natural grass	20
		Short-cycle cultivation	60

All the weighted values were added together to obtain the landslide susceptibility map shown in Figure 8. This total weight has a maximum value of 250. Thus, a total weight value of above 180 was considered as high susceptibility (red in Figure 8); a total weight between 125 and 179, moderate susceptibility (yellow in Figure 8); a total weight between 100 and 124, moderate susceptibility (green in Figure 8); and a total weight lower than 100, moderate susceptibility (dark green in Figure 8). From a total study area of 3651 Ha, 2015 Ha corresponds to a very high susceptibility (55.19% of the total area), 1092 Ha corresponds to a high susceptibility (29.92%), 177 Ha corresponds to a medium susceptibility (4.85%) and 366 Ha corresponds to a low susceptibility (10.04%).

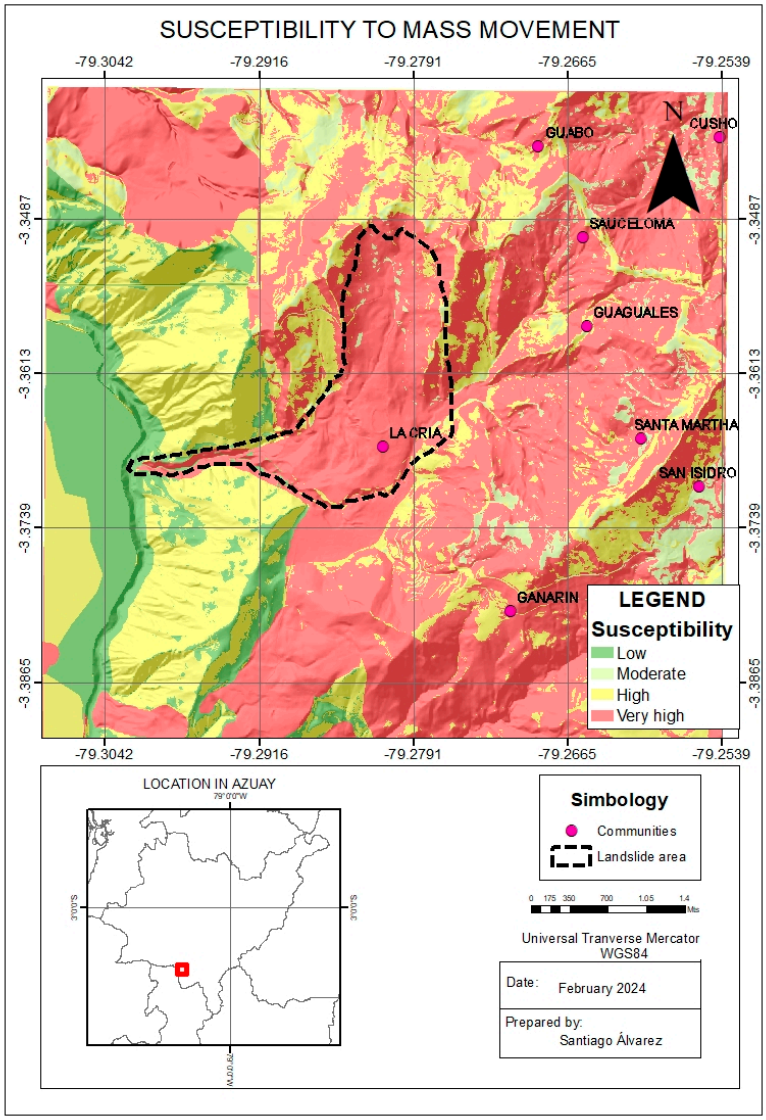


Figure 8. Mass movement susceptibility map of study area.

Although 443 hectares of the study area have been identified as landslide prone, it is important to note that 55.19% of the total area of 3651 hectares has a very high susceptibility to mass movements. This suggests that while the identified landslide is of immediate concern, there is a significant risk that other landslides could occur, especially if the identified landslide were to materialise in its entirety. Destabilisation of the surrounding areas could trigger further landslides, further increasing the risk to the community and the environment.

5.2. Limit Equilibrium Modelling

In a first static analysis without the seismic action, a safety factor of 0.789 was obtained using the simplified Bishop and Morgerstein–Price methods [44,45] (Figure 9a), while a slightly lower safety factor of 0.788 was obtained using the simplified Janbu method (Figure 9b). Neither methodology satisfies the standard NEC [25] minimum safety factor of 1.5 in this scenario. A second analysis was conducted for a failure surface adjusted to the one observed in the landslide profile, specifically in the deep clay stratum. Following this approach, a minimum safety factor of 2.115 was obtained (Figure 9c), significantly higher than the minimum safety factor of 1.5.

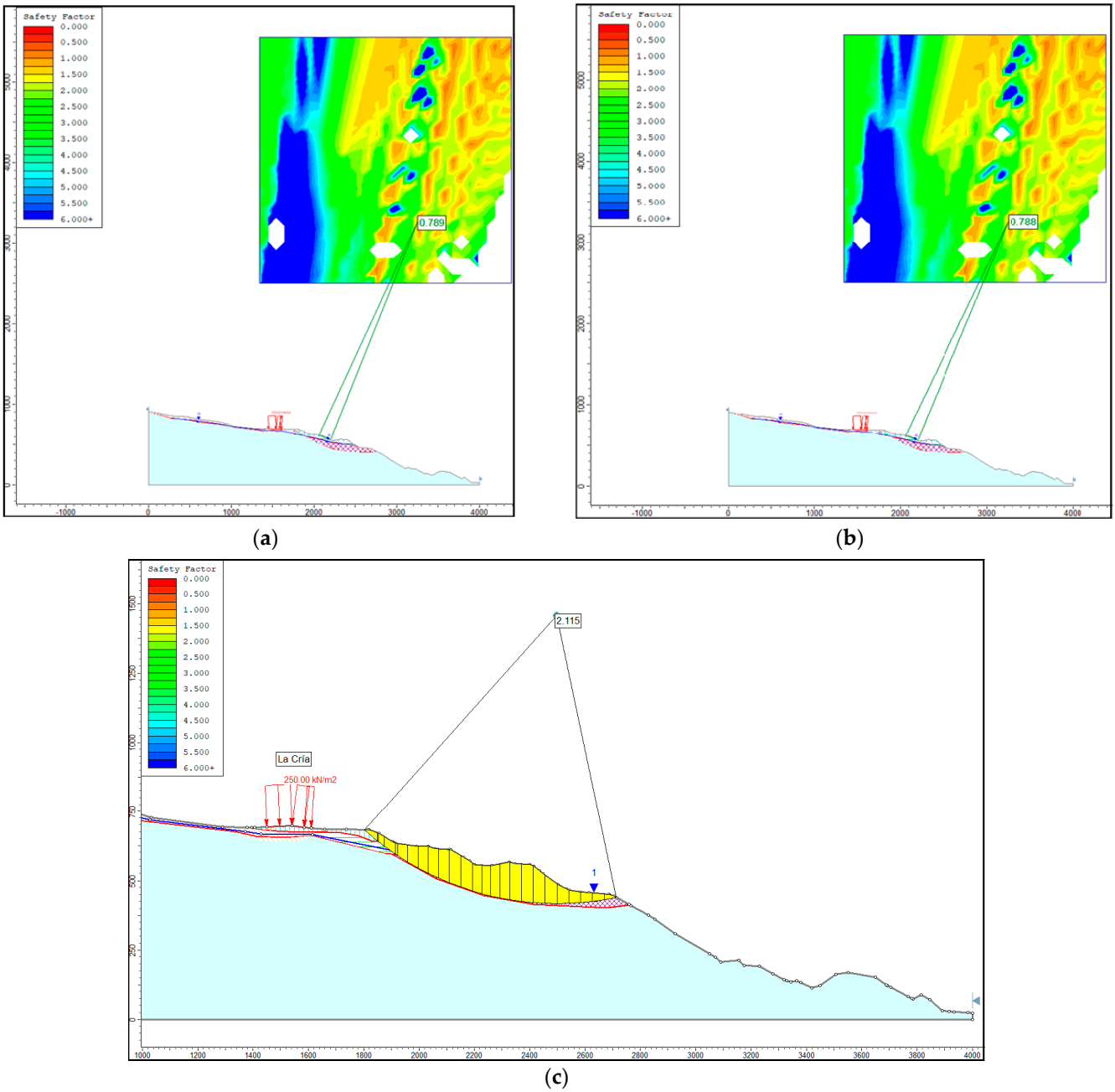
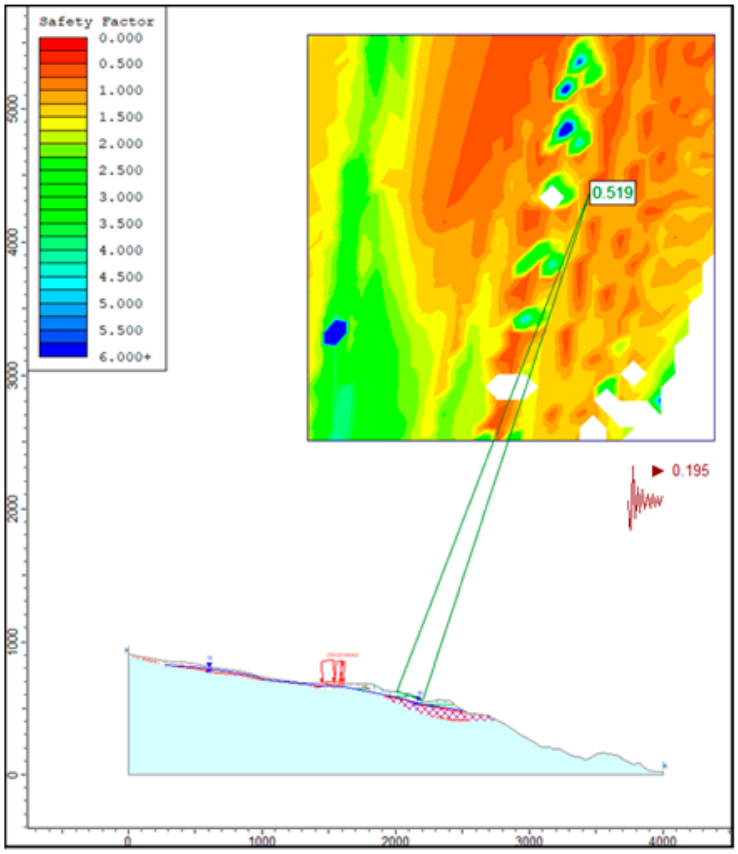


Figure 9. Stability analysis results without seismic action: (**a**) simplified Bishop and Morgerstein–Price methods; (**b**) simplified Janbu method; and (**c**) Morgerstein–Price method with failure surface adjusted to one identified on field.

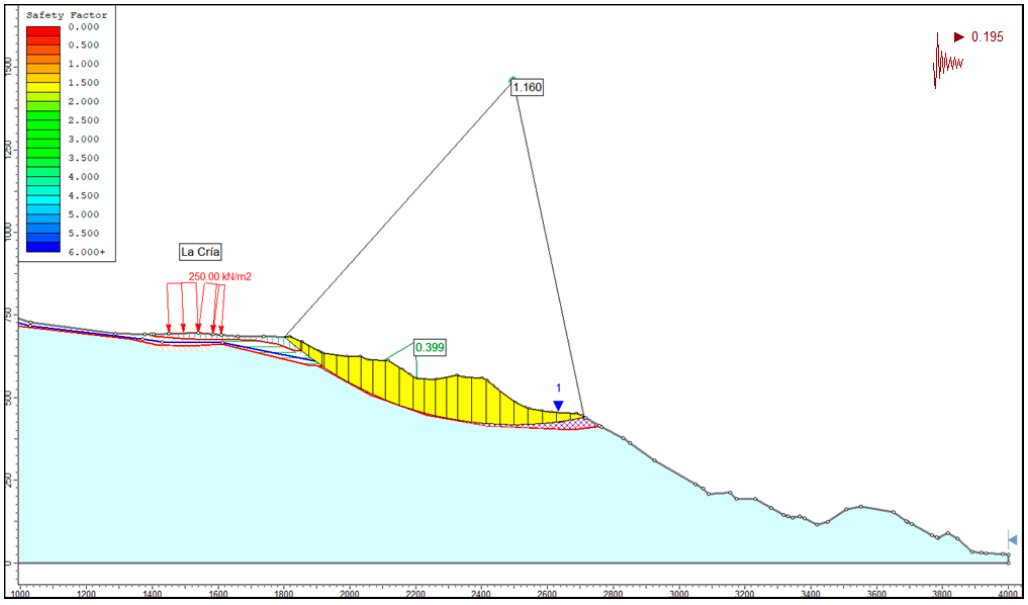
The higher safety factor obtained in the second approach can be attributed to the higher strength and stability of the deep clay stratum, which provides additional support in comparison to other less competent zones of the landslide. Such stability of the deep stratum may be due to several factors: overburden pressure, which increases the shear strength of the material; improved drainage conditions, which reduce the pore pressure and increase effective strength; consolidation effects, which can densify and strengthen the clays over time; and the reduced influence of external factors, such as climatic changes, surface erosion and human activities, which affect the deep strata less than the superficial layers.

A pseudo-static analysis was then conducted, introducing the seismic action. If the field-identified failure surface is neglected, a minimum safety factor of 0.5 was obtained for all methods (Figure 10a). No methodology meets the NEC [30] minimum safety factor

of 1.05. If the identified failure surface (deep clay stratum) is introduced, the minimum safety factor increases to 1.16 (Figure 10b), which is slightly higher than the minimum value of 1.05.



(**a**)

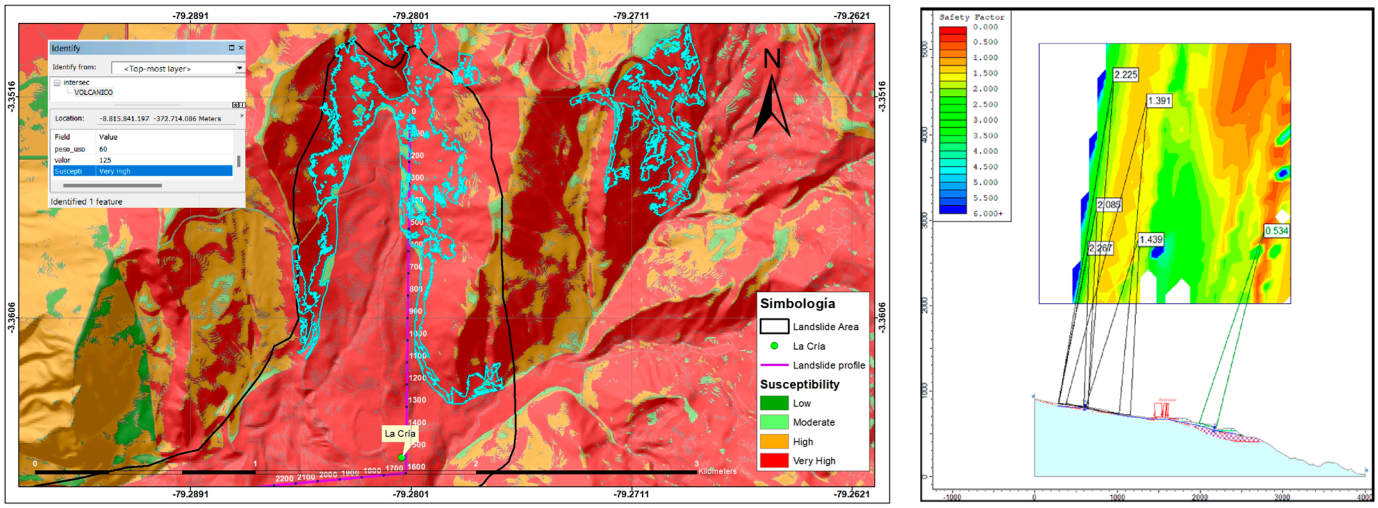


(**b**)

Figure 10. Stability analysis results with seismic action (pseudo-static stability analysis): (**a**) without failure surface adjusted to one identified on field and (**b**) with failure surface adjusted to one identified on field.

5.3. Multicriteria Analysis and Limit Equilibrium Models Comparison

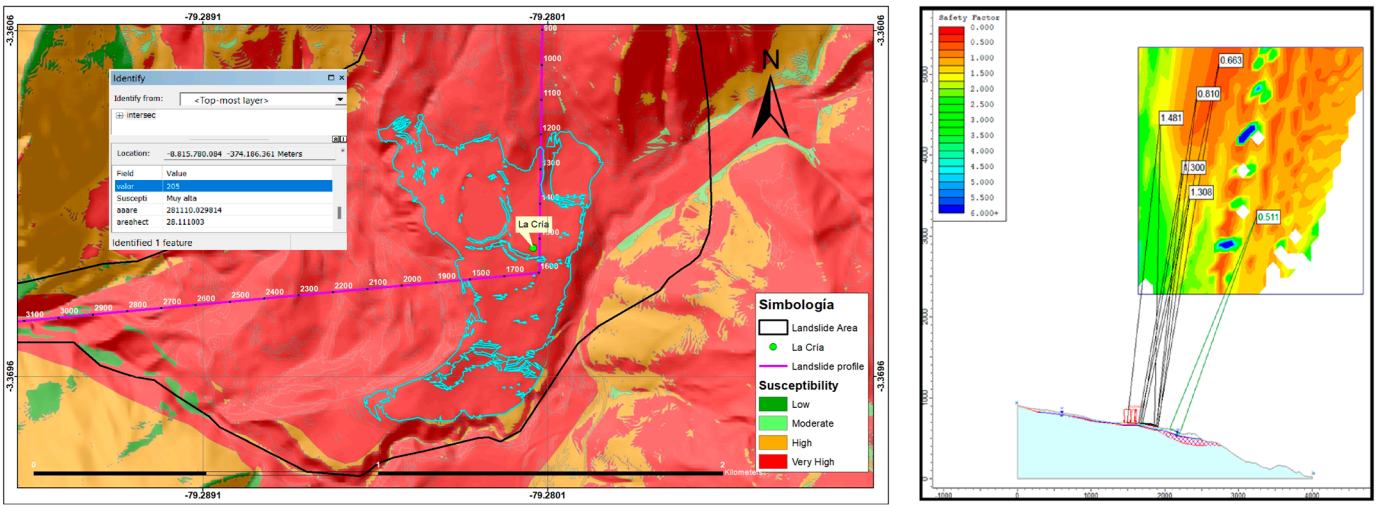
Figure 11a shows that, between the abscissae 0 and 1200 m, there is a polygon (marked in blue) with a total weighting value of 125 (sum of all the assigned weight values for each variable considered in the susceptibility map). Within these abscissae, Figure 11b shows that the limit equilibrium model following a pseudo-static analysis places the safety factor between 1.39 and 2.26.



(**a**) (**b**)

Figure 11. Multicriteria analysis and limit equilibrium model comparison: (**a**) 125-weighted polygon between 0 and 1200 m abscissae of landslide profile and (**b**) pseudo-static safety factors (Janbu method) between 0 and 1200 m abscissae of landslide profile.

Figure 12a shows that, between the abscissae 1200 and 1900 m, there is a polygon (marked with blue) with a weighting value of 205. Within these abscissae, Figure 12b shows that the limit equilibrium model following a pseudo-static analysis places safety factor between 0.63 and 1.48.

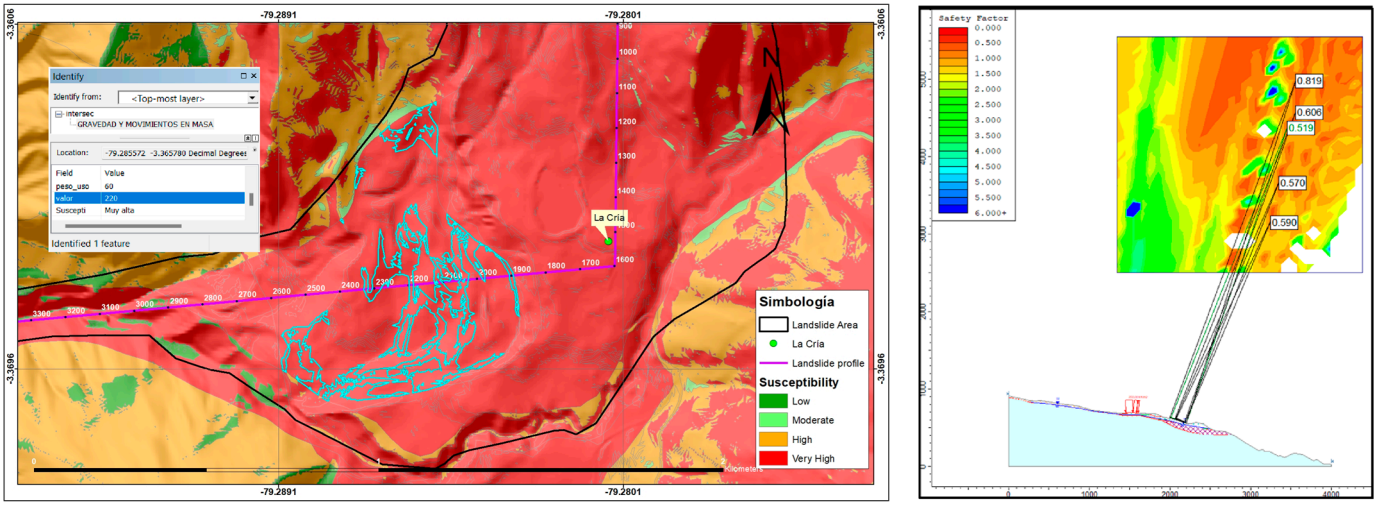


(**a**) (**b**)

Figure 12. Multicriteria analysis and limit equilibrium model comparison: (**a**) 205-weighted polygon between 0 and 1200 m abscissae of landslide profile and (**b**) pseudo-static safety factors (Janbu method) between 0 and 1200 m abscissae of landslide profile.

Figure 13a shows that, between the abscissae 2000 and 2300 m, there is a polygon (marked with blue) with a weighting value of 220. Within these abscissae, Figure 13b shows

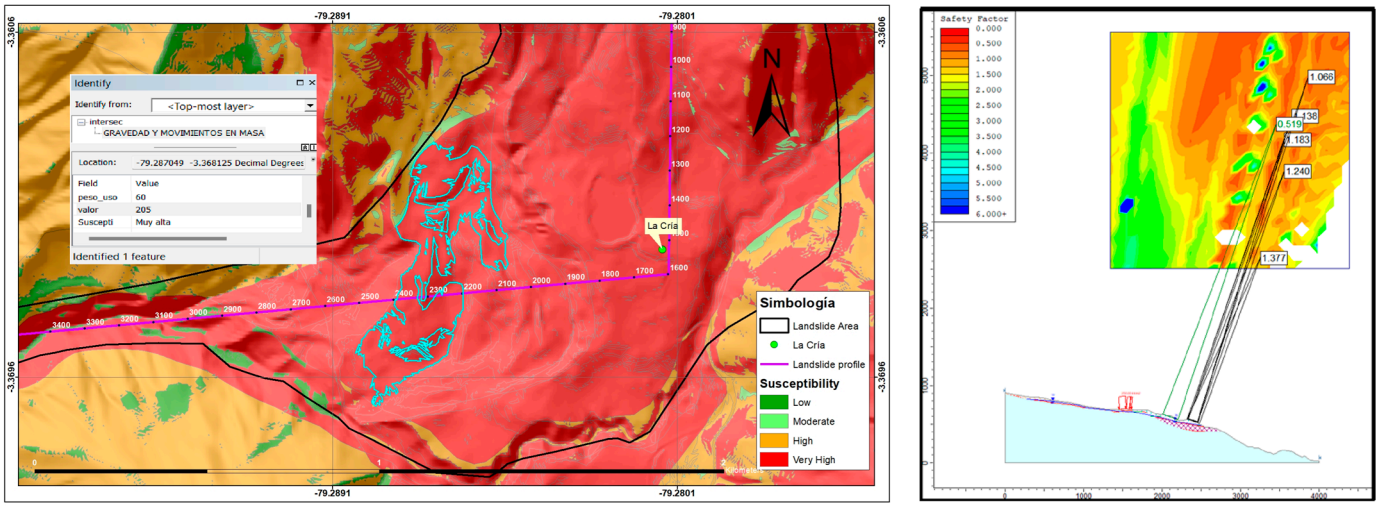
that the limit equilibrium model following a pseudo-static analysis places the safety factor between 0.519 and 0.819.



(**a**) (**b**)

Figure 13. Multicriteria analysis and limit equilibrium model comparison: (**a**) 220-weighted polygon between 0 and 1200 m abscissae of landslide profile and (**b**) pseudo-static safety factors (Janbu method) between 0 and 1200 m abscissae of landslide profile.

Figure 14a shows that, between the abscissae 2300 and 2400 m, there is a polygon (marked with blue) with a weighting value of 205. Within these abscissae, Figure 14b shows that the limit equilibrium model following a pseudo-static analysis places the safety factor between 1.06 and 1.37.

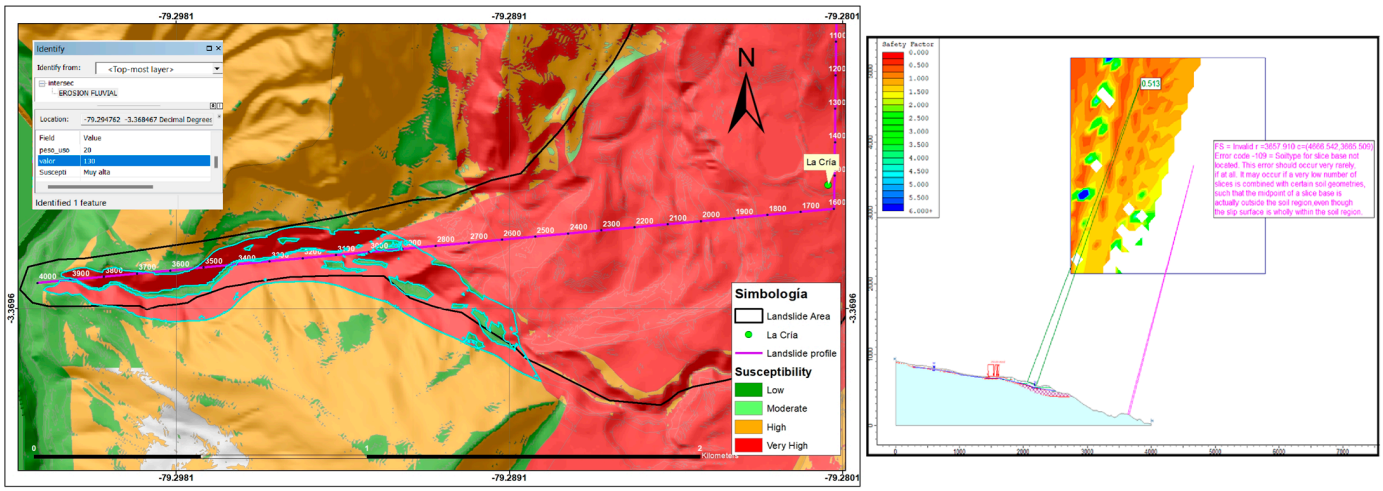


(**a**) (**b**)

Figure 14. Multicriteria analysis and limit equilibrium model comparison: (**a**) 205-weighted polygon between 0 and 1200 m abscissae of landslide profile and (**b**) pseudo-static safety factors (Janbu method) between 0 and 1200 m abscissae of landslide profile.

Figure 15a shows that, between the abscissae 2600 and 4000 m, there is a polygon (marked with blue) with a weighting value of 130. For the safety factors at these abscissae, the software indicates an error, as shown in Figure 15b. This is caused by the existence of competent andesites in the profile, which were modelled as "infinite strength". This is

correct when compared to the strength of the rest of the materials, which are soil ones, but it makes it impossible to detect any failure across them.



(**a**) (**b**)

Figure 15. Multicriteria analysis and limit equilibrium model comparison: (**a**) 130-weighted polygon between 2600 and 4000 m abscissae of landslide profile and (**b**) pseudo-static safety factors (Janbu method) between 2600 and 4000 m abscissae of landslide profile.

Table 3 summarises the comparison conducted between the multicriteria analysis and limit equilibrium models at the five abscissae mentioned.

Table 3. Summary of multicriteria analysis and limit equilibrium model comparison.

Abscissa of the Landslide (m)	Safety Factors Range		Average Safety Factor	Susceptibility Map Total Weight
0–1200	1.39	2.26	1.825	125
1200–1900	0.63	1.48	1.055	205
2000–2300	0.519	0.82	0.669	220
2300–2400	1.06	1.37	1.215	205
2600–4000	Stable slope			130

It is evident that the safety factor has an inversely proportional relationship with the weighting value given by the susceptibility map. This is consistent with both the safety factor and the weighting value concepts. The landslide section between the abscissae at 2000–2300 m has the most unstable slope, with an average safety factor value of 0.669 and a weighting of 220. This coincides with the greatest area of susceptibility to mass movements in the macro-slide.

Regarding the variability observed in the range of safety factors for the different sections analysed, this may be put down to the slope geometry, as the steeper sections have inferior safety factors compared to the lower steep sections.

6. Discussion

When comparing the susceptibility map developed and the geotechnical models conducted, an inverse relationship between the weighted values of the variables used in the susceptibility map and the factors of safety obtained in the geotechnical modelling was found. This inverse relationship may not necessarily always be found though. There are situations where other factors, not weighted in the susceptibility map, can significantly influence the safety factors. For example, human interventions such as engineering works or drainage systems can alter the local stability conditions. Therefore, although the trend observed in this study suggests that the higher the weighted value, the lower the factor

of safety, it is crucial to consider that this is not an invariable rule and that all acting parameters must be considered for a comprehensive assessment of slope stability.

Generally speaking, the significant factors that contributed to landslides in Ecuador include the following:

- Heavy rainfall: the climate all over the country experiences two seasons; one of them has intense, fast and prolonged rainy periods, which increase soil saturation.
- Seismic activity: Ecuador is located along the Pacific Ring of Fire, an area prone to earthquakes, which are one common trigger of landslides [46].
- Volcanic activity: the so-called Volcanoes Avenue (named by A. Humbolt in the XIX century) has the presence of active volcanoes and recent soft sediments from their eruptions.
- Deforestation and land use: inappropriate or uncontrolled land use and deforestation practices exacerbate soil nudity and, consequently, the erosion of slopes.

In addition, the vulnerability in Ecuador must be considered to increase due to the size of the population, land use (deforestation) and urbanisation, with the last two being poorly controlled. All those issues drive a progressive risk increase [47–49].

According to [50], landslides are more prominent in the earth slide type (>50%) with a medium to large size, with deep to very deep failure surfaces (between 5 and 20 m and more than 20 m); a slow motion is reported in more than 65% of cases, with the same proportion for the trigger element (rainfall) and an important 10% for the human activity affecting infrastructural facilities and residential houses (75%). Even though these figures were gathered from European landslides, such characteristics can be applied to Ecuadorian landslides.

For this reason, the importance of having sector-specific and sector-adapted landslide susceptibility maps at a specific scale is based on the need to understand the particularities and risks inherent to each area. Since different geomorphological, geological, land use and climatic factors can influence the susceptibility of an area to landslides, detailed and contextualised maps are essential. These maps provide a sound basis for risk assessment and the implementation of appropriate and effective mitigation measures [48,51].

Within the identification of the essential parameters for the elaboration of susceptibility maps, the importance of precipitation in the susceptibility to landslides is revealed. Precipitation, especially in areas with high rainfall, can cause landslides by saturating the soil and increasing the pore pressure, which decreases the strength of the ground. However, in the context of this paper, this parameter was not considered due to the lack of rainfall stations close to the study area. The closest station is in the province of El Oro, 51 km southeast of the study area, which implies that the inclusion of precipitation data in the susceptibility map would not adequately reflect the reality of the study area. The absence of accurate local precipitation data limits the ability to accurately model the influence of this factor on the landslide susceptibility in the study area. This situation raises an important need for an adequate network of weather stations in landslide-prone areas around the country. The availability of accurate precipitation data would be essential for improving the accuracy of susceptibility maps and for better management of the landslide risk in these regions. Even though global precipitation models could have been used in the preparation of susceptibility maps, they were not used in this work due to the limited spatial resolution and local accuracy of such models, which may not adequately reflect the specific conditions of the study area. The absence of nearby meteorological stations prevents the validation and calibration of this global data, which reduces their relevance and accuracy for the detailed analysis of landslide susceptibility.

7. Conclusions

A macro-landslide that occurred at La Cría, Ecuador, was studied. Information was acquired both from previous geotechnical investigations and field studies involving site inspections. The macro-landslide was categorised as a complex phenomenon including rotational landslides and rock falls. It was determined that the landslide is regressive in

nature and extends towards the centre of the La Cría community. Rapidly expanding cracks and escarpments were identified, causing significant damage to all community houses and the surrounding infrastructure. Particularly, around 97 houses suffered a high degree of structural damage, causing the evacuation of 56 families.

A variety of mapping data was collected and analysed, including geological information, land use, geomorphology, historical earthquake records and a Digital Elevation Model. A landslide susceptibility map was prepared and calibrated to be optimally adjusted to the area under study. The distribution of susceptibility shows that most of the territory, approximately 55%, presents with a very high susceptibility to landslides. This is followed in proportion by high susceptibility, covering about 30% of the area, low susceptibility with close to 10%, and medium susceptibility, comprising nearly 5% of the territory. It is evident that most of the study area is exposed to a very high landslide hazard, which underlines the importance of this tool in risk assessment. This finding suggests that the La Cría community is in a highly vulnerable and high-risk location. This information is essential for local authorities in making decisions related to urban planning and risk management. It also highlights the need for a change in land use, given the hazard it implies for the safety and well-being of the population.

A limit equilibrium analysis of the macro-landslide was also conducted. Without considering the seismic action, the safety factor was about 0.78, which is clearly inferior to the minimum factor of 1.5 established by the Ecuadorian standard [30]. When the seismic action is considered by a pseudo-static analysis, a safety factor of 0.519 was obtained, a value which is also lower than the minimum established by the Ecuadorian standard, 1.05 [30]. These results indicate a notable instability in the landslide studied, which highlights the seriousness of the situation. It was also seen that the lowest safety factor obtained coincides with the location of the highest occurrence of cracks visualised (abscissa 2100 m).

The comparison between the landslide susceptibility map and the limit equilibrium analysis highlighted that the safety factor has an inversely proportional relationship with the added weighting value of the map, which agrees with the concepts of the safety factor and weighting values. From the analyses conducted, the most susceptible section reached an average safety factor of 0.669 and a total weight of 220, with this area having the greatest landslide susceptibility area with respect to the macro-slide. This data validation reveals a clear relationship between the safety factor and weighting values. This is significant, as it indicates that in situations where the necessary funding is not available to develop a specific geological–geotechnical study (a common reality in several regions of Ecuador), the elaboration of an adequate susceptibility map becomes a crucial tool for decision-makers. In this context, the community of La Cría is located on an active but stable landslide. This, combined with the area's high susceptibility to landslides, provides a strong enough reason to limit construction in the region.

The landslide analysis conducted in this work reveals that both the landslide susceptibility map and the limit equilibrium slope model point to the geology of the sector as the main conditioning factor for the occurrence of the current landslide. Most of the area is characterised by colluvial deposits, which suggests a predisposition to phenomena of this type. In addition, the main factor causing the landslide was identified as the presence of numerous water reservoirs in the area, which, lacking any type of waterproofing, have contributed to the over-saturation of the soil. This analysis highlights the importance of understanding the interactions between local geology and water resource management to prevent and mitigate the risks associated with mass movements. These findings can provide a solid basis for the formulation of risk management policies and strategies in areas vulnerable to similar landslides.

In conclusion, the study area will remain under continuous monitoring utilising the tools outlined in this paper. Furthermore, efforts are underway to develop protocols and guidelines for responding to landslides, aiming to mitigate their occurrence and minimise their impact on both people and infrastructure. This initiative is especially critical, as the study highlighted the absence of several key aspects, such as historical data. This is

important because there is currently a lack of concrete historical data regarding the original landslide. Studying this phenomenon can help fill critical knowledge gaps, enabling a better understanding of its causes, progression and long-term effects. Such insights are essential for designing effective prevention strategies and mitigating future risks to both people and infrastructure.

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