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Influence of Accumulated Geotechnical Deterioration on Semi-Detailed Scale Landslide Phenomena: Cortinas Sector, Toledo, Colombia

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Abstract: In the initial investigations of hazard assessment for the Cortinas sector at a 1:25,000 scale, researchers validated the hypothesis that the terrain must be under specific magnitudes of conditioning factors for an instability event to occur, which does not depend only on certain critical thresholds of rainfall and earthquakes. This process was termed accumulated geotechnical deterioration (AGD). A larger-scale analysis of geotechnical criteria was conducted based on data obtained from direct exploration and geophysics, examining conditions prior to slope failure, immediately after failure, and several years later. The results showed that, indeed, the terrain experienced an increase in deterioration that, under the influence of a critical rainfall event, led to failure; however, the stability of the terrain later recovered to the point that failure did not occur under similar rainfall events. In accordance with this, a novel method of analysis is established herein at a 1:5000 scale, which uses AGD to predict instability events by calculating the safety factor derived from the application of the infinite slope formula in a GIS framework. By incorporating specific variables and field measurements, a better approximation for the prediction of an instability event can be achieved. This study identifies the innovative factors of this method and provides a baseline for future research.

Keywords: landslide; cumulative geotechnical deterioration; prediction; slope; hazard zoning

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Citation: Ballesteros, C.A.B.; Martínez-Graña, A.M.; Yenes, M. Influence of Accumulated Geotechnical Deterioration on Semi-Detailed Scale Landslide Phenomena: Cortinas Sector, Toledo, Colombia. *Appl. Sci.* **2024**, *14*, 11766. https://doi.org/10.3390/app142411766

Academic Editors: Sung-Min Kim and Jangwon Suh

Received: 28 October 2024
Revised: 29 November 2024
Accepted: 2 December 2024
Published: 17 December 2024

1. Introduction

For analyses of slope stability, especially in tropical zones with active geological processes, such as in the case of Colombia, and for the purpose of establishing a hazard zoning map and a prediction model, it is necessary to carry out a screening analysis using different scales such as regional (1:25,000), semi-detailed (1:5000), and detailed (1:2000), as proposed by the methodology used in the Colombian Geological Survey [1]. A smaller scale allows for covering a larger area, which can influence the analysis of a specific site and its surroundings without using more resources, provided that cartography has already been conducted. This approach relies on inputs such as geology, geomorphology, and vegetation cover, as discussed in the first article of this research [2]. It also serves as a starting point for the following phases. The 1:25,000 scale allows for a preliminary analysis of the projects. At the 1:5000 scale, a window of approach is obtained, focusing on more detail at a specific site where soil resistance parameters are already involved. These are understood as the conditioning factors and their correlation with the detonating factors, calculated through the safety factor, which determines the level of geotechnical hazard and, consequently, the potential failure of the analysis site. This scale is used for the analysis of project alternatives at the feasibility stage. Finally, the detailed 1:2000 scale uses specific topographic and geotechnical profiles involving, in addition to the safety factor, the probability of failure, the influence of rainfall infiltration, and deformation models. All of the above is applied to areas where a high hazard was identified at the previous scale and to moderate hazard areas flagged as high in the 1:25,000 scale, under the premise that the results of the analysis at each scale must be correlated since the method of analysis and its input variables differ in each case. The 1:2000 scale is used for the design and construction of engineering works.

In this study, we concentrate on the 1:5000 scale as a continuation of the first phase of the research, where a prediction methodology was established based on the concept of cumulative geotechnical deterioration AGD [2]. This, in turn, will serve as the basis for the next scale (1:2000), which will constitute the following article as the main innovative contribution of this research.

Based on the fact that existing methodologies focus on hazard zoning, the problem is oriented toward the need to improve the accuracy of landslide prediction by incorporating the concept of AGD as an innovative aspect in the application of these methodologies. This concept is based on the idea that for a slope to fail, deterioration of the conditioning factors—which differ from each daily manifestation of triggering factors—must occur. This makes it clear that terrain conditions, especially in slope deposits, are constantly changing.

The main objective of this paper is to use AGD to improve the 1:5000 semi-detailed scale analysis, improving the accuracy of Cortinas slope failure prediction as a continuation of the 1:25,000 scale analysis and as support for the 1:2000 detailed scale and future investigations.

The prediction proposal is summarized as follows: if changes in the magnitude of soil parameters can be measured and compared with pre-established failure scenarios from simulations, advance warnings of ground failure could be generated, i.e., the prediction. These measurements add value when taken directly and periodically over time.

Scientific research centers and consulting companies have mainly focused on defining hazard zoning to identify areas that are more susceptible to failure, which can affect different infrastructures within a country. Significant progress has been made in this regard, and today, there are several methodologies for this purpose. However, in terms of prediction, despite extensive study, it can be stated that the available models require further research to be more precise. This work focuses on defining "when" a potential mass removal event might occur [3].

The value of the present research lies in the existence of a geotechnical history specifically to the study area in Cortinas, as documented in [2], constituting a fundamental input for building a baseline for this investigation and future studies.

Geologically, the study area is located on the northeastern flank of the Eastern Cordillera of the Andes in Colombia. Observing the three-dimensional model of the available satellite images of the area reveals a high degree of complexity in terms of its stability, with the geoforms confirming this assessment. The first documented record dates back to 1990, when, according to local people and oil transportation engineers, there was a landslide similar to the one in 2021. Around 2015, during an extreme winter season, multiple regional landslides occurred. The largest recorded landslide in the area prompted one of the oil and gas companies operating in the sector to initiate an investigation process, indicating that, at present, progress is being made, with the possibility of reducing failures that interrupt gas transportation operations; however, no failure was recorded in the Cortinas field at that time. In January 2020, a failure was recorded in the gas transportation line in the Cortinas area (Slide D 2021) despite the fact that no extraordinary rainfall preceded the event to induce considerable movement of the slope. In 2021, the slope failure occurred "suddenly" following a rainfall event that was perhaps the most extreme in recorded history. Paradoxically, in the current year (2024), rainfall levels similar to those in 2021 occurred again but without generating significant slope displacements, as confirmed by topographic monitoring records. This paradox is precisely what creates uncertainty regarding how the failure mechanisms work in these contexts, particularly regarding what could have been predicted.

To reduce the uncertainty introduced by this paradox, in addition to the monitoring of triggering factors, we included, as a novel approach, the study of changes in the conditioning factors over time. Using the concept of AGD, we outline a path toward prediction, constituting a baseline for future research aimed at improving prediction accuracy. This is fundamental since it is necessary to be able to act in advance of landslides. In this way, an alert could be generated to save lives and/or infrastructure, as well as, for example, for hydrocarbon transportation companies to act by interrupting the flow and avoiding environmental and social impacts. As pointed out in the first article of this research [2], our main source of data corresponds to the information compiled through our own work covering 33 years of observation that constitute the history of the Cortinas sector and its surroundings, as well as the information from historical records of the Information System of Mass Movements (SIMMA) [4], Institute of Hydrology, Meteorology, and Environmental Studies (IDEAM), and Colombian Geological Service (SGC) [4] in relation to past landslides, rainfall, and earthquakes.

According to the literature, different methodologies are currently used for landslide prediction, such as probabilistic models focused on defining landslide susceptibility areas and statistical models of a subjective linear nature, similar to the probabilistic ones, which focus on pre-existing landslides [5]. However, these models are often unable to effectively represent complex landslide cases because the relationship between problems based on natural phenomena and their triggering factors is not always linear [6,7]. Additionally, they lack an exhaustive spatial analysis that allows evaluating the presence of spatial dependence or auto-correlation between global or local landslides [8,9], inducing important errors.

In contrast, methods based on spatial statistics focus on triggers and their thresholds aimed at defining areas of susceptibility, which are distorted by the AGD concept. Another method is automatic learning, which consists of an iterative process and gradual refinement. However, its main shortcomings include redundancy and multicollinearity as more factors are incorporated. Additionally, some of these automatic models are not capable of capturing local variations, while others depend on the absence of multicollinearity among explanatory variables and lack a probabilistic interpretation. Finally, hybrid or ensemble models focus more on predicting zones susceptible to mass movements rather than precisely when. Although these are recognized as the most advanced methods available, no technique fully encompasses all the characteristics required to establish itself as the ideal approach for this type of phenomenon [5]. The methods mentioned focus on the specific variation of triggering factors but fail to account for the deterioration of the conditioning factors over time; likewise, they are typically used at larger scales rather than at the scales of detail and design.

Given the above, there is a need to develop a proposal that integrates a baseline built from historical data, existing hazard zoning evaluation techniques, such as those mentioned above, and a series of variable values that indicate slope failure in advance. The variables would be validated through automatic simulations based on changes in real resistance parameters taken periodically in the field after critical events such as rainfall, earthquakes, or anthropic interventions. The proposal also includes the monitoring and interpretation of instrumentation installed in the area of interest. The goal is to improve the ability to predict when slope values may occur, enabling proactive actions to prevent disasters that could affect the operation of vital service lines or result in human tragedies. Knowing the weaknesses of the current prediction models, as well as the complexity and uncertainty of geological and geotechnical phenomena, it is necessary to enhance existing methods. As mentioned in the Unilibre article [5], advancing the way in which information is acquired and structured is crucial. This includes establishing a recurrent dependency between space and time (what we refer to as AGD) and reducing high correlations between independent variables.

2. Study Area

The study area corresponds to one of the multiple landslides that occurred in August 2021 (previously defined in [2]), located in the Troya–Cortinas area of the Samoré district of the municipality of Toledo (Department of Santander, Toledo, Colombia). This landslide, denominated as D or Troya landslide, has an area of approximately 13 hectares, a length of 562 m, a width of 275 m, and a difference in elevation that varies between 617 and

477 m.a.s.l. (Figure 1). This landslide was selected because it has the largest amount of data and is the one that caused the greatest damage to road, electricity, gas, and oil pipeline infrastructure.

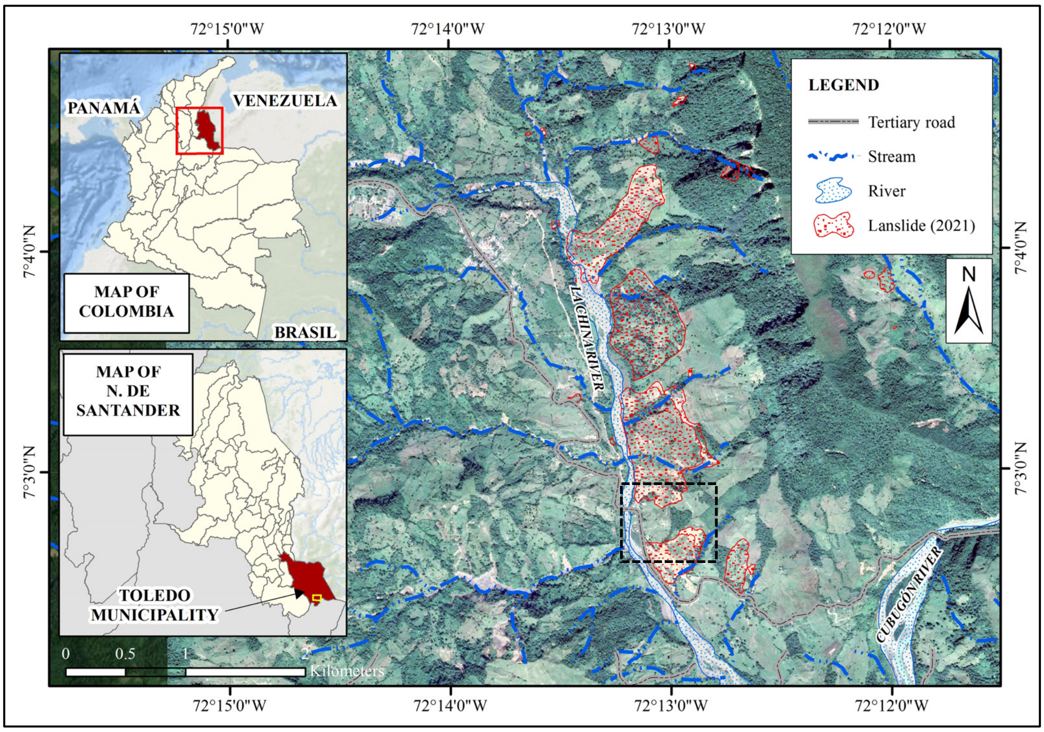

Figure 1. Study area location. The black box indicates the slip studied. Red box indicate department of Norte de Santander and yellow box shows Toledo municipality.

3. Background

The study area (Troya–Cortinas) lacks documentation of geotechnical behavior or initial studies related to the construction of its existing infrastructure, which includes roads, houses, an oil pipeline (1985), and a gas pipeline (2011) (Figure 2). Historically, it has suffered landslides, including a massive one in 1990 and others in 2013 and 2017. In 2015, extreme rainfall caused more than 50 instability sites, affecting infrastructure and agricultural activity, although the Cortinas slope did not show significant instability that year.

Private consulting firms conducted hazard, vulnerability, and risk (HVR) studies, cataloging the area as highly hazardous at the 1:100,000 and 1:5000 scales [10,11]. However, models at a scale of 1:2000 indicated an apparent low level of hazard, suggesting that no stabilization works were necessary. Despite this, landslides occurred that led to the failure of the pipeline, raising doubts about the effectiveness of current methodologies and the need to further investigate the causes of these phenomena, which underlies the rationale for this research.

In 2021, a landslide occurred (Figures 2 and 3) that generated a fault in the oil and gas lines that cross the sector, where an escarpment was generated in the upper part, and the material was deposited in the lower part of the slope.

The following diagram (Figure 4) conceptually shows the dynamics of the landslide that occurred, taking into account the topography before and after the event.

At present, it is believed that the soils on the slope have changed compared to the conditions that existed prior to the landslide, and the vegetation has also been re-established. Proof of this can be seen in the following images (Figure 5).

Figure 2. Slip sector, 2021.

Figure 3. Aerial view of the landslide in 2021.

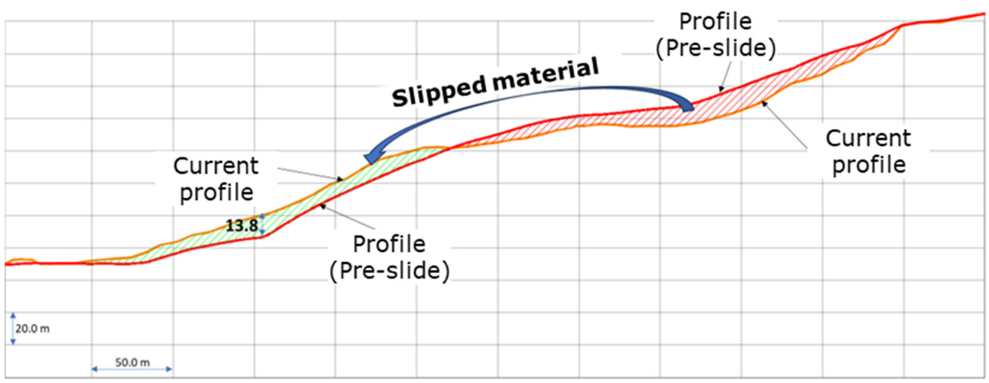

Figure 4. Slip conditions in 2021.

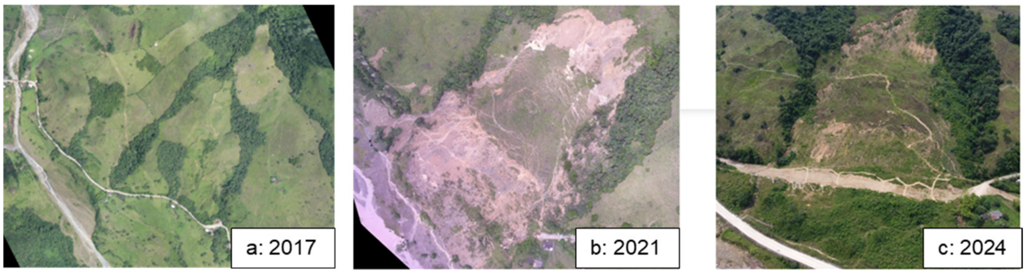

Figure 5. Drone images of the study area in 2017 (**a**), 2021 (**b**), and 2024 (**c**).

4. Hazard Analysis Methods

Evaluation of the hazard level at a scale of 1:5000 was carried out based on the Methodological Guide for Hazard, Vulnerability, and Risk Studies for Movements of Mass of the Colombian Geological Service [10]. Deterministic models were used for this evaluation, which, according to Crhirtofer [4], "are mathematical models where the same inputs will invariably produce the same outputs, not contemplating the existence of chance or the principle of uncertainty".

To evaluate the hazards, basic cartography of the analysis area at a scale of 1:5000 was required. From this, thematic cartography was generated, including geological cartography based on engineering geology units, geomorphological cartography detailing geomorphological elements, and land cover and land use cartography.

From the described topics, a geological–geotechnical model was established, in which a basic geotechnical exploration was required to characterize the geomechanical properties of subsoil materials, such as standard penetration tests (SPTs), geophysical tests, and sampling for laboratory tests, obtaining the spatial distribution of soil thicknesses, the position of the water table, and the seismic acceleration. With this, the safety factors in different soil cells or "columns" were determined using limit equilibrium methods to find their spatial distribution. In this procedure, safety is the determining factor for establishing the level of danger.

Figure 6 presents the methodology for establishing mass movement hazard zoning at a scale of 1:5000.

- Low hazard level:

  Factors of safety in the slope stability analysis are greater than 1.5.

- Medium hazard level:

  Factors of safety in the slope stability analysis are between 1.1 and 1.5.

- High hazard level:

  Safety factors in the slope stability analysis are less than 1.1.

4.1. Conditioning Factors

Conditioning factors are the elements or conditions that influence, modify, or affect the magnitude and behavior of geotechnical hazards at a given site or region. These factors are not necessarily the direct causes of a hazard but have a determining role in its development or intensity. These definitions were taken from the SGC-2016 methodological guide [11], which can be consulted for more information.

4.1.1. Geomorphology

Landforms are the result of a combination of numerous factors, such as lithology, geological structures, tectonics, and climate, which, in turn, are closely related to denudation processes (erosion and mass movements). The geomorphological element was key to recognizing the detailed morphometry of the terrain, taking into account recommendations of the detailed analysis methodology [12]. The main objective was to identify and characterize the geo-shapes based on their morphogenesis, morphology, morphometry, and morphodynamics.

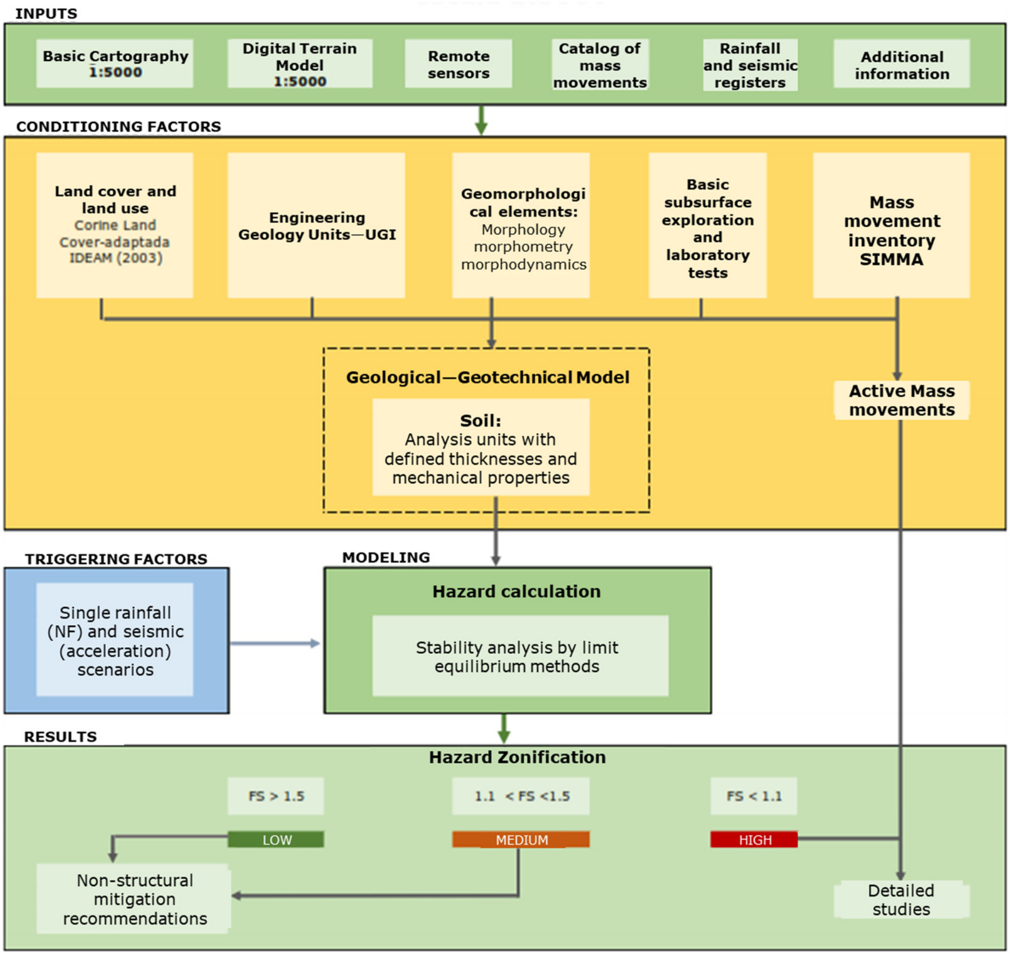

Figure 6. Basic mass movement hazard zoning at a scale of 1:5000 [10].

4.1.2. Land Cover and Land Use

Vegetation cover corresponds to the layer of natural vegetation covering the land surface, comprising a wide range of biomasses with different characteristics, ranging from grasslands to natural forests. Also included are induced or anthropic vegetation covers resulting from human action, such as crops.

4.1.3. Direct and Indirect Geotechnical Exploration and Laboratory Tests

Initially, based on the geological and geomorphological information and geomorphological conditions observed during a previous geotechnical reconnaissance and following the stipulations of the Methodological Guide for Hazard, Vulnerability, and Risk Studies for Movements in Mass, the geotechnical investigations were defined. These were developed by means of direct and indirect exploration with a field record that identified the location, type, and depth of the samples obtained, visual description of the samples, stratigraphic changes observed, conditions of the subsoil water level, and other parameters necessary for the geotechnical characterization.

For this, data such as SPT test records, soil resistivity values, 2D images of shear wave seismic tests, and re-strength tests were used (see Table 2). It is worth noting that for the above, information from the terrain was available at three different times, as follows: before the fault (2017), immediately after (two months later), and after the catastrophic fault (2023) that occurred in August 2021. The objective was to establish a correlation between the field and laboratory test data, with the deterioration of soil resistance over time and its post-failure recovery after the occurrence of landslides generated by extreme rainfall events [12].

4.1.4. Engineering Geology Units (UGIs)

The engineering geology map was elaborated by interpreting homogeneous surface geological units (GSUs). Super-surface geological units were defined as a set of materials that make up the ground surface to a specific depth related to the scale of work; these units were classified as rocks or soils, taking into account their genesis in four large groups: rocks, residual soils and saprolites, transported soils, and anthropic soils [13]. The UGS map at the 1:5000 scale was elaborated from a compilation of secondary information, primarily taking into account the geological plates at the 1:100,000 scale from the Colombian Geological Survey (SGC), the deposits mapped in the geomorphological map at the 1:25,000 scale, the geological map of the seismogeotechnical zonation, photointerpretation of aerial photographs, and inputs obtained from processing the digital terrain model (DEM). For the evaluation of the UGS, field exploration was carried out at sites identified as critical according to the hazard map elaborated in phase I (1:25,000). The evaluation followed the Generalized UGS Field Guide [1] and included descriptions and analyses of drill holes, apiques, laboratory tests (liquid limit, plastic limit, granulometry, and hydrometry), and analysis and interpretation of SEV, MASW, and refraction seismic data available in the study area. The global exploration campaigns include four boreholes executed in 2017, one in 2021, and three in 2023, for which the aforementioned tests were performed. A seismic refraction line and vertical electrical soundings were also executed in each year of analysis.

Each superficial geologic unit was subdivided according to the dominant geotechnical composition in each of the differentiated geologic formations, which allowed the separation of each superficial geologic unit into one or several homogeneous units.

With the information from these homogeneous zones, it was possible to develop a map of engineering geological units (UGIs), which formed the base input to generate the engineering geology map essential for the calculation of hazards at a scale of 1:5000. The EGU map was defined based on the analysis and correlation of the geotechnical parameters of cohesion, friction angle, and wet unit weight, obtained from the direct shear and unit weight laboratory tests, respectively.

4.2. Triggering Factors

4.2.1. Seism

As stipulated in the Methodological Guide for Hazard, Vulnerability, and Risk Studies for Movements in Mass, the seismic coefficient was determined based on the tables and calculations proposed by the Colombian seismic-resistant standard according to soil type classification and region. This included values for effective peak horizontal acceleration, the amplification coefficient for short periods of the spectrum, the importance coefficient, and the design seismic coefficient for pseudo-static slope analysis. The effect of seismic loading of 0.294 g was calculated and included as a horizontal inertial force, based on the horizontal acceleration coefficient in pseudo-static limit equilibrium analysis, for a return period of 100 years.

4.2.2. Precipitation

The rainfall triggering factor was evaluated at the basic study level (scale 1:5000) as a function of fluctuations in the water table. In landslides, the position of the water table is generally a conditioning factor for instability, as it increases pore pressure in the soil and decreases its shear strength. The variation in the water table is mainly related to long periods of rainfall, making this value directly linked to the models developed. According to studies and research, rainfall associated with a return period of 20 years is related to these instability phenomena, which is why this value was used to define the design rainfall.

The fluctuation in the water level was assigned following the process established in the Methodological Guide for Hazard, Vulnerability, and Risk Studies for Movements of

Mass. This guide relates to the variability of the depth of the water table as a function of the temporal variability of precipitation and establishes the proportion of infiltrated rainwater using the rainfall–runoff method of the Soil Conservation Service (SCS) of the United States Department of Agriculture [14]. This method calculates the amount of water from a storm (P) that becomes direct runoff (Pe). In this case, it was used to determine the amount of rainwater that does not become direct runoff (infiltrated rain), which was assumed to be the difference between the amount of total accumulated rainwater and the direct runoff rain. Evapotranspiration losses were disregarded in the calculations.

4.3. Determination of Basic Hazards

For the basic hazard zoning, the safety factor was determined for each work unit, which was defined by the mesh and the soil columns obtained. The calculation of the safety factor was based on the infinite slope method in each of the work cells. The safety factor equation, in this case, is expressed as follows [10]:

$$F.S. = \frac{C'b\sec(\propto) + \left[\gamma bh\cos(\alpha) - \gamma_w h_w b\cos^2(\alpha) - k\gamma bh\sin\alpha\right]\tan(\varnothing')}{\gamma bh\sin(\alpha) + K\gamma bh\cos(\alpha)} \quad (1)$$

C' and $\varnothing'$ are the strength parameters of the soil at the base of the soil column in terms of effective stresses.

γ is the unit weight of the soil.

b is the width of the voussoir (cell width).

h is the height of the ground above the potential slip surface.

γ_w is the unit weight of water.

h_w is the height of the water table, determined from the water table corresponding to a 20-year return period of rainfall.

α is the angle of inclination of the failure surface.

k is the horizontal acceleration coefficient for a return period of 100 years.

The parameters C' and $\varnothing'$ should be the values assigned in geotechnical studies for the defined geotechnical unit. The depth of the failure surface is taken as the depth of the soil or the depth of the contact between two units of different mechanical behaviors. The angle α can be assumed as the angle of the ground surface in the cell (Figure 7).

Applying the equation, an analysis of random variables was carried out using the Monte Carlo method, which is a probabilistic model that can include an element of uncertainty or randomness in its prediction [15]. Testing 1000 simulations as an example to reduce the number of variables, it was decided to keep the slope parameter fixed, resulting in three models being carried out for three different slope values of the hillside. The aim was to analyze the behavior of the variation of parameters when there was a low, medium, and high slope, given that topographically, the hillside studied presents these three slope scenarios, and each one behaves in a different way. The results of these models yielded safety factors, which were tabulated and then plotted using a Gaussian bell (Figure 15) to observe the distribution of the data and the probability around a safety factor of less than 1.1. This is considered critical according to the SGC methodology for a scale of 1:5000 (Table 1) and is the warning criterion for the soil strength parameters and duration conditions reaching their limit due to the accumulated geotechnical deterioration for a specific slope and failure depth. The warning criteria were applied based on the "screening" of the different analysis scales where high threat levels were identified. When the safety factor falls below 1.1, an alert is generated. In this sense, it should be assumed that the resistant stress is decreasing in the face of a constant acting stress. In this way, the variation of parameters such as cohesion, friction angle, weight, and pore pressure determine how the resistant stress varies according to these parameters, which precisely define the concept of the AGD. RMR is a geomechanical classification used to characterize rock slopes.

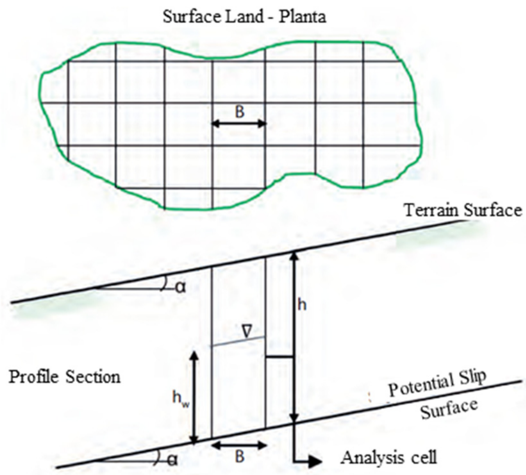

Figure 7. Parameters for basic hazard analysis, scale 1:5000 [10].

Table 1. Hazard level according to the SGC [10].

Hazard Level	Safety Factor	SMR	Color on the Map
High	<1.1	<40	Red
Medium	1.1–1.5	40–60	Yellow
Low	>1.5	>60	Green

The following flow chart (Figure 8) shows the application procedure for the infinite slope equation, incorporating randomness by means of the Monte Carlo method, and its use for possible prediction and the generation of warnings.

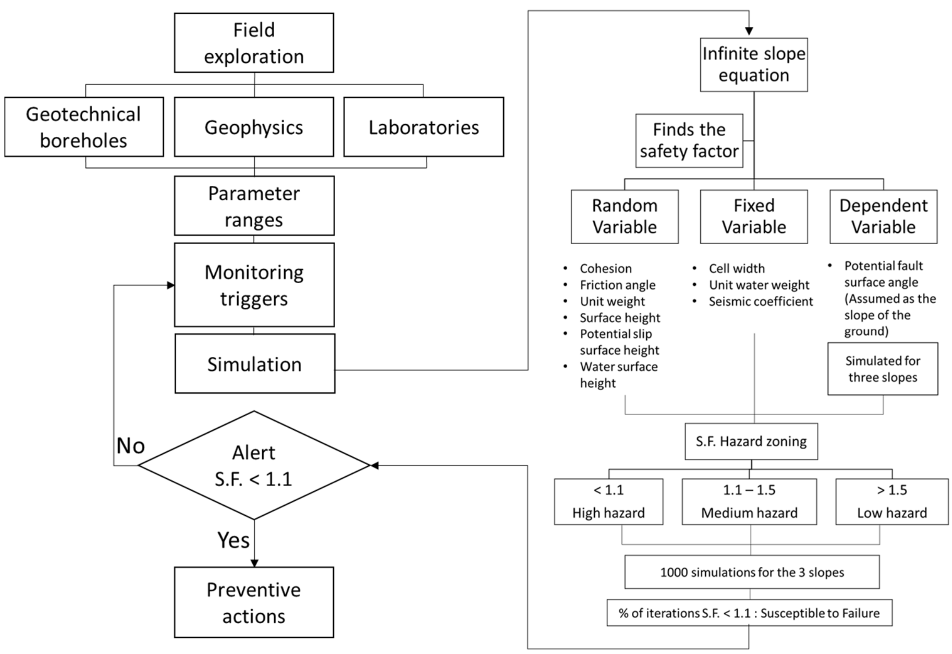

Figure 8. Monte Carlo simulation flowchart and application procedure.

5. Results in the Cortinas Sector

5.1. Conditioning Factors

The conditioning factors included an inventory of morphodynamic processes, a map of geological units, a map of geomorphological units, and land cover, ultimately leading to the creation of a map of superficial geotechnical units (UGS) (Figure 9).

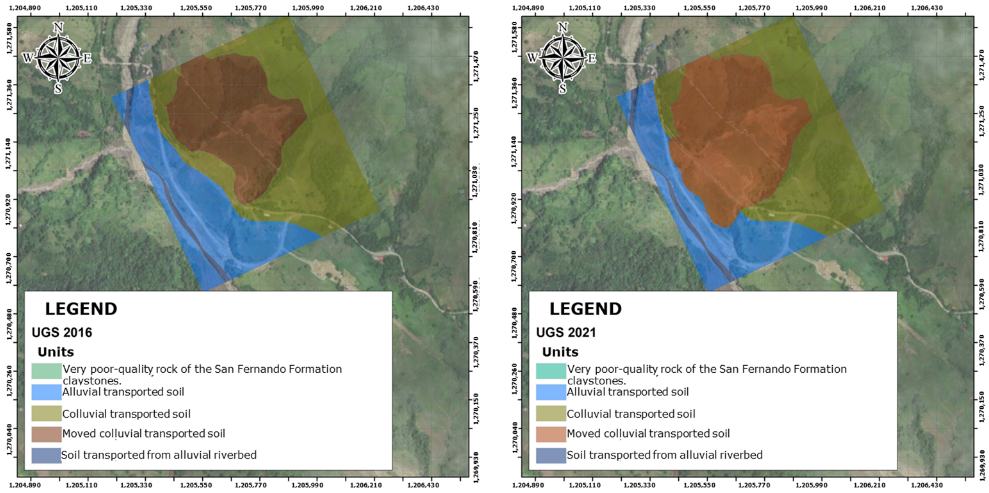

Figure 9. Geotechnical surface units before and after a landslide.

5.1.1. Slope Factor

The slope of the terrain was calculated from the DEMs taken by drone and converted into raster format to be further processed according to the methodology used (see Figure 10).

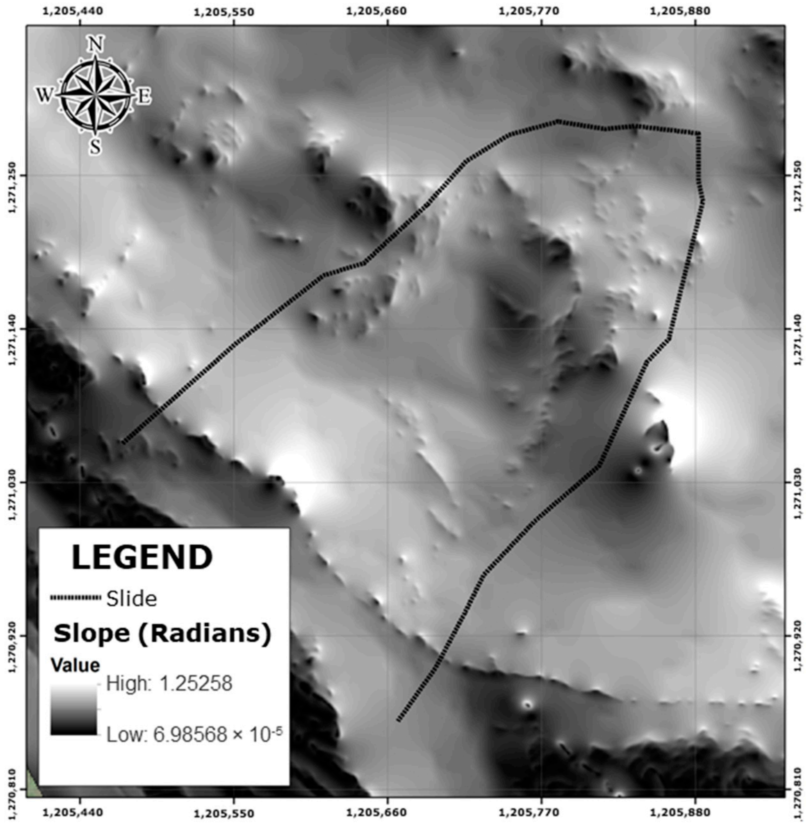

Figure 10. Slope map.

5.1.2. Subsurface Exploration

Geotechnical exploration for this scale was based on SPT boreholes and tests via direct exploration and seismic lines via indirect exploration. In 2017, four boreholes were carried out around the study area, while from the year 2021, there was a higher density of exploration due to several characterizations that were executed in the sector.

5.1.3. Laboratory Tests

Tables 2–4 list the results of the laboratory tests on samples obtained from boreholes in 2017, 2021, and 2023. Several tests were performed, but the sample with the least alteration was chosen since it is difficult to obtain unaltered samples for these materials. The relevant resistance parameters were obtained, including cohesion and friction angle, along with classifications such as unit weight, humidity, granulometry, and consistency limits.

Table 2. Laboratory tests performed.

Year	Borehole	Depth (m)	Laboratories
2017	S1	1.0–2.0 2.0–3.0	Granulometry, Atterberg limits, moisture content Direct shear consolidated drained
2021	S1	1.55–2.0	Granulometry, Atterberg limits, moisture content Direct shear consolidated drained
2023	S2	2.0–2.5 2.5–2.0	Direct shear consolidated drained Granulometry, Atterberg limits, moisture content

Table 3. Results of the laboratory classification tests.

Year	Borehole	Depth. (m)	% W	% Gravel	% Sand	% Fine	% L.L.	% P.L	% P.I.	Clasif. USCS
2017	S1	1.0–2.0	12.28	41.65	20.05	38.3	59.19	25.89	33.3	GC
2021	S1	1.55–2.0	20.5	25.7	19.9	54.4	35.00	18.00	17.00	CL
2023	S2	2.5–3.0	22.36	18.88	12.11	69.01	39.00	21.46	17.54	CL

Table 4. Results of the resistance laboratory tests.

Year	Borehole	Depth. (m)	Condition	Friction Angle (°)	Cohesion (kPa)	Unit Weight (kN/m^3)
2017	S1	2.0–3.0	Consolidated drained	25.10	20.20	19.90
2021	S1	1.55–2.0	Consolidated drained	21.30	12.10	17.10
2023	S2	2.0–2.5	Consolidated drained	20.86	16.00	18.30

5.2. Triggering Factors

5.2.1. Seism

The effective peak acceleration (Aa) given by the Colombian Seismic Resistant Construction Regulation NSR-10, which has a value of 0.294 g, was obtained.

5.2.2. Precipitation

The results used for the height of the water table, which was involved in Equation (1) and based on the behavior of the water table, electrical test results, and rainfall infiltration, are shown in Table 5.

Table 5. Parameters assigned to the colluvial unit in each scenario (see Equation (1)).

Year	C (kN/m^2)	$\varnothing$ (°)	γ (KN/m^3)	h	h_w	k
2017	20.20	25.10	19.90	3	0	0.294
2021	12.10	21.30	17.10	14.0	14	0.294
2023	16.00	20.86	18.30	14	2	0.294

5.3. Determination of Hazards

Based on the methodology described above, the analysis was carried out using the so-called homogeneous zones, which were based on the ground elevation model obtained from the flights and the surface geological units (GSUs) and correlated with the results of the geotechnical exploration (Figure 11).

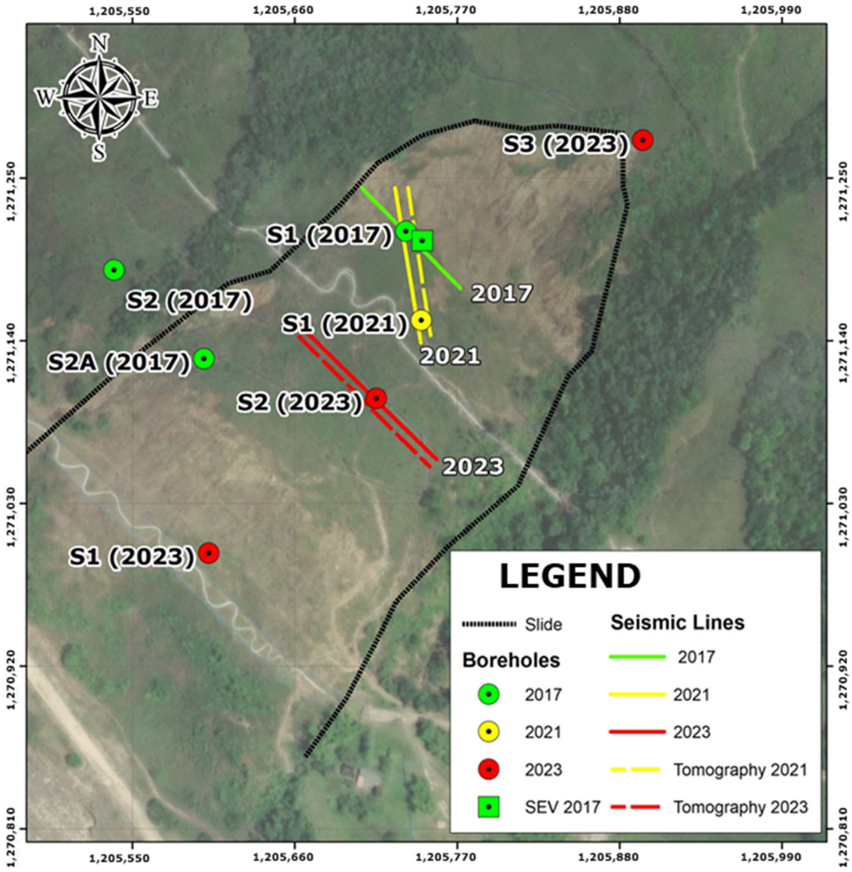

Figure 11. Geotechnical exploration map.

Likewise, parameters were assigned to each homogeneous zone according to the field tests, laboratory tests, phreatic levels, and rainfall and seismic analysis, as shown in Table 5.

Finally, the generation of maps was carried out using geographic information systems, where each variable adopted a raster format and was processed by means of map algebra, allowing the determination of the safety factor per pixel in each geological unit.

The above results (Figure 12) show that in 2017, there was a certain area with a high pellicle and medium hazard. In the analysis for 2021, when the landslide occurred, a high hazard level was obtained in a high percentage of the area studied, while in 2023, the hazard level decreased again to medium, with some high sections. Table 6 shows the percentages of each hazard classification for each year, according to the assigned parameters; these changes are mainly due to the decrease in resistance parameters and the increase in the height of the potential landslide surface. According to the results, the high hazard percentage for 2023 is slightly higher than that of 2017 (before the failure), given that the time has not been sufficient for its recovery; likewise, it is much lower than that of 2021 as soon as the failure occurred. The zones with the largest high-hazard area in these two years are reflected in the landslide escarpments, where, due to their high slopes, new landslides are expected to occur over time, in accordance with the results of the Monte Carlo simulations shown in Table 8.

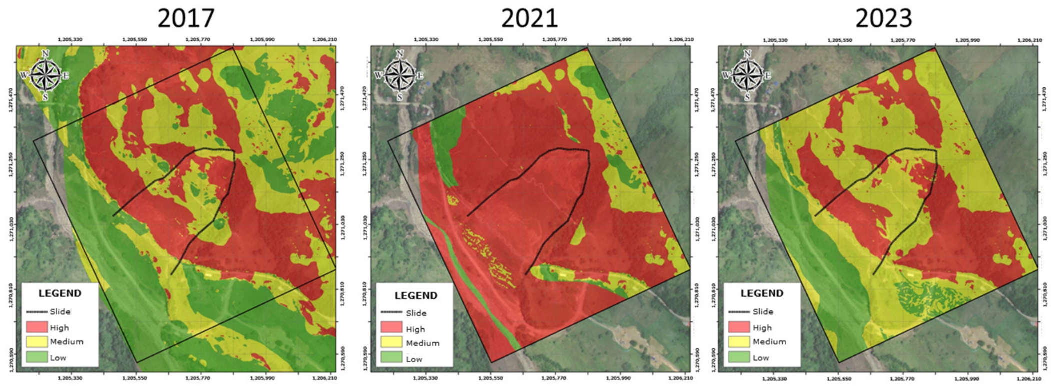

Figure 12. Hazard model at a 1:5000 scale in 2017, 2021, and 2023.

Table 6. Statistics of the simulations performed.

Year	% High Hazard Area	% Medium Hazard Area	% Low Hazard Area
2017	27	31	42
2021	80	12	8
2023	35	47	18

6. AGD at the 1:5000 Scale

The initial part of this research, which was part of the first article, described and presented the concept of AGD at a regional scale (1:25,000). It emphasized that, based on the hazard assessment model adopted from the SGC, the main conditioning factors taken into account are the deterioration of the geomorphology (slope and morphodynamics) and, particularly, the soil cover. These factors influenced the generation of landslides in the last year analyzed, as supported by the increase in areas of high susceptibility. Consequently, the deteriorating conditions could also be cataloged as a triggering factor, which should be studied in susceptibility and hazard analyses [2].

For the semi-detailed scale of 1:5000, the focus of the present study, another evaluation model was used, which takes into account geotechnical parameters that, according to the AGD concept, continuously change in both deterioration and recovery. Using the expression for calculating the slip safety factor by the infinite slope method (see Equation (1)), some conditioning factor variables were defined based on the stiffness of the soil, expressed through N values from the SPT test and the shear wave velocity obtained from the MASW-2D seismic lines. Additionally, changes in soil moisture due to the effect of rainwater infiltration (wet front) were measured using soil resistivity tests, and strength parameters were determined through direct shear tests. Table 3 presents the changes in the mentioned parameters, obtained from laboratory tests on samples from the boreholes shown in Figure 11, with the advantage of having information on the scenarios before, immediately after, and following the catastrophic landslides that occurred in August 2021.

In 2017 (prior to the failure), all SPT tests indicated that the soils, up to a depth of approximately 4.0 to 5.0 m, were in a loose to very loose state and highly susceptible to sliding due to the deterioration accumulated over the previous 33 years, since the last catastrophic event in the study area. Underlying these materials, a slope deposit continues, but with apparent greater rigidity, which is consistent with the results of the seismic lines taken for this same date, given that for depths greater than 5.5 m, the shear wave velocity values increase. In 2021, immediately after the landslides, new boreholes were drilled, revealing colluvial deposits up to a depth of 9.0 m in a loose sub-surface state, as indicated by seismic line results with values below 300 and 205 m/s. These results show a more unfavorable condition regarding the stability of the slope compared to 2017. Approximately two years after the failure, additional drilling was performed, and field records indicated a noticeable recovery in the consistency of the soil, with the loose thickness having decreased, in accordance with the results of the geophysical exploration. A comparison of the changes in the borehole logs can be seen in Table 7.

Table 7. 2017, 2021, and 2023 borehole logs.

Depth. (m)	2017			2021	2023		
	S1	S2	S2A	S1	S1	S2	S3
	SPT-N						
0.5	2	2	2	RT	3	7	12
1	0	4	5	RT	4	5	15R
1.5	1	9	18	RT	RT	6	RT
2	2	17	20	RT	RT	7	RT
2.5	8	12	7	RT	RT	5	RT
3	8	9	11	RT	26	12	RT
3.5	3	12	11	RT	58	12	4
4	23R	9	15	RT	RT	14	9
4.5		10	34R	RT	RT	9	13
5		13		RT	RT	4	20
5.5		16		RT	RT	14	23
6		13		RT	RT	8	24R
6.5		16		RT	RT	9	RT
7		30R		RT	RT	9	RT
7.5				RT	RT	11	RT
8				RT	RT	13	RT
8.5				RT	RT	23	RT
9				RT	RT	14	RT
9.5				RT	RT	54R	20
10				RT	RT	RT	87R
10.5				RT	RT	RT	RT
11				RT	RT	RT	RT
11.5				RT	RT	RT	RT
12				RT	RT	RT	RT
12.5				RT	RT	RT	RT
13				RT	RT	RT	RT
13.5				RT	RT	RT	RT
14				RT	RT	RT	28
14.5				RT	RT	RT	70
15				RT	RT	RT	RT
15.5				RT	RT	RT	RT
16				RT	RT	RT	RT
16.5				RT	RT	RT	RT
17				RT	RT	RT	RT
17.5				RT	RT	RT	RT
18				RT	RT	RT	RT
18.5				RT	RT	RT	RT
19				RT	RT	RT	33
19.5				RT	RT	RT	RT
20				RT	RT	RT	RT
20.5				RT	RT	RT	RT
21				RT	RT	RT	RT
21.5				RT	RT	RT	RT
22				RT	RT	RT	RT
22.5				RT	RT	RT	RT
23				RT	RT	RT	RT
23.5				RT	RT	RT	RT
24				RT	RT	RT	RT
24.5				RT	RT	RT	RT
25				RT	RT	RT	RT

Colluvial Soil; Residual soil; RT, Rotary drilling; R, Percussion rejection.

In the same way, a comparison of the Vs values from the MASW-2D seismic line tests is shown in Figure 10. In 2017, at the surface level, such values started at 218 m/s. Following the landslide in 2021, these values reduced to 170 m/s, but by 2023, they had recovered to around 214 m/s, showing a significant recovery to conditions similar to those before the failure. In all cases, it should be noted that the values progressively increase with depth under similar conditions, from which it can be deduced that at these levels, there was no change in stiffness (see Figure 13).

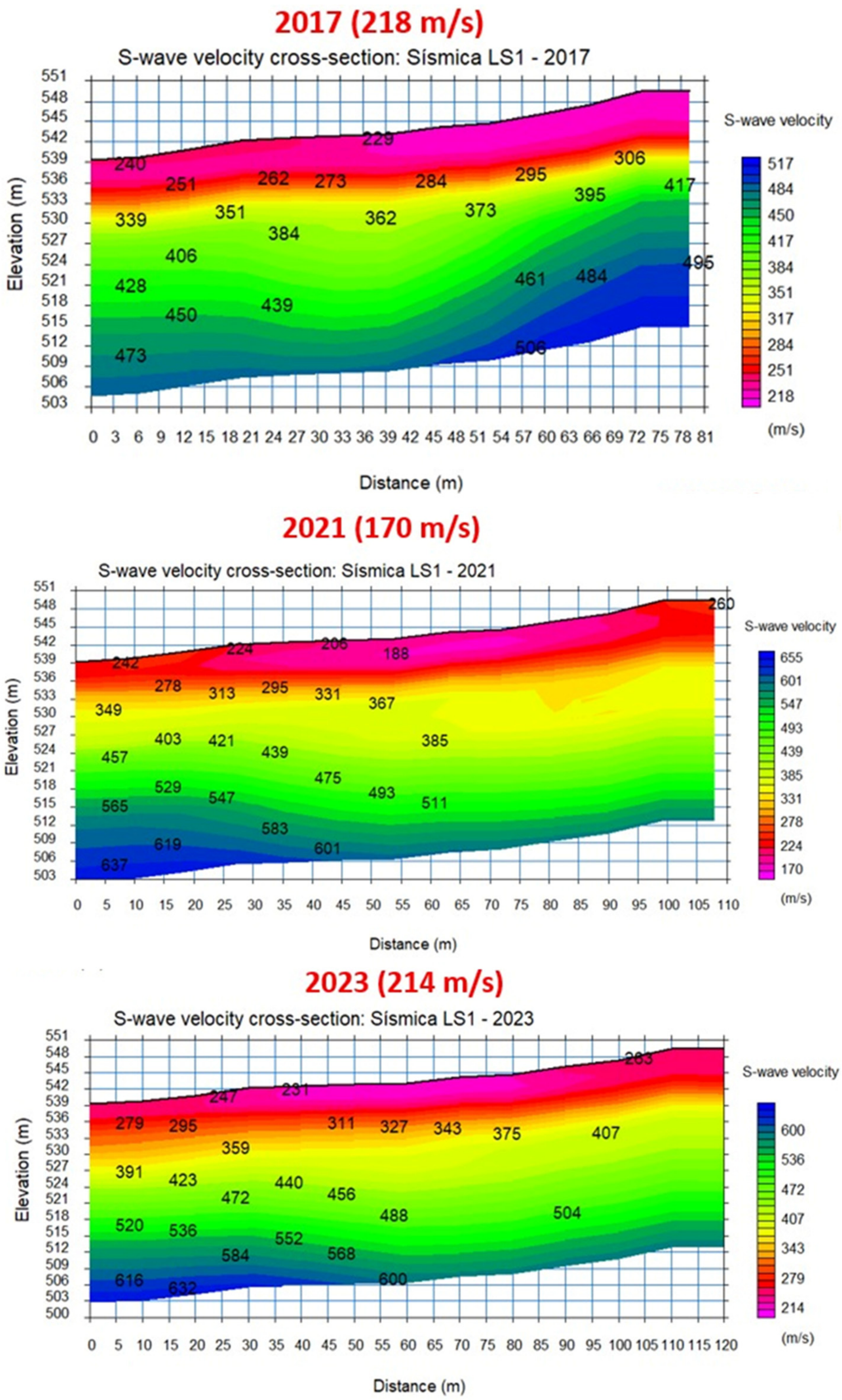

Figure 13. Seismic line test results for 2017, 2021, and 2023.

Regarding the soil resistivity tests (Figure 14), on the date immediately after the landslides, the data from the images of the results indicate a considerable increase in the saturation of the soil profile (40 Ω) compared to the scenarios before (294 Ω, 2017) and after the failure (140 Ω, 2021). The latter value indicates that the soil began drying via evaporation and percolation toward deeper mantles (2023). It should be noted that discontinuities were induced at depth due to a possible fracture zone associated with the influence of the large-magnitude landslides that occurred, which generated greater deterioration of the soil profile at depth, with the possibility of deeper faults occurring over time.

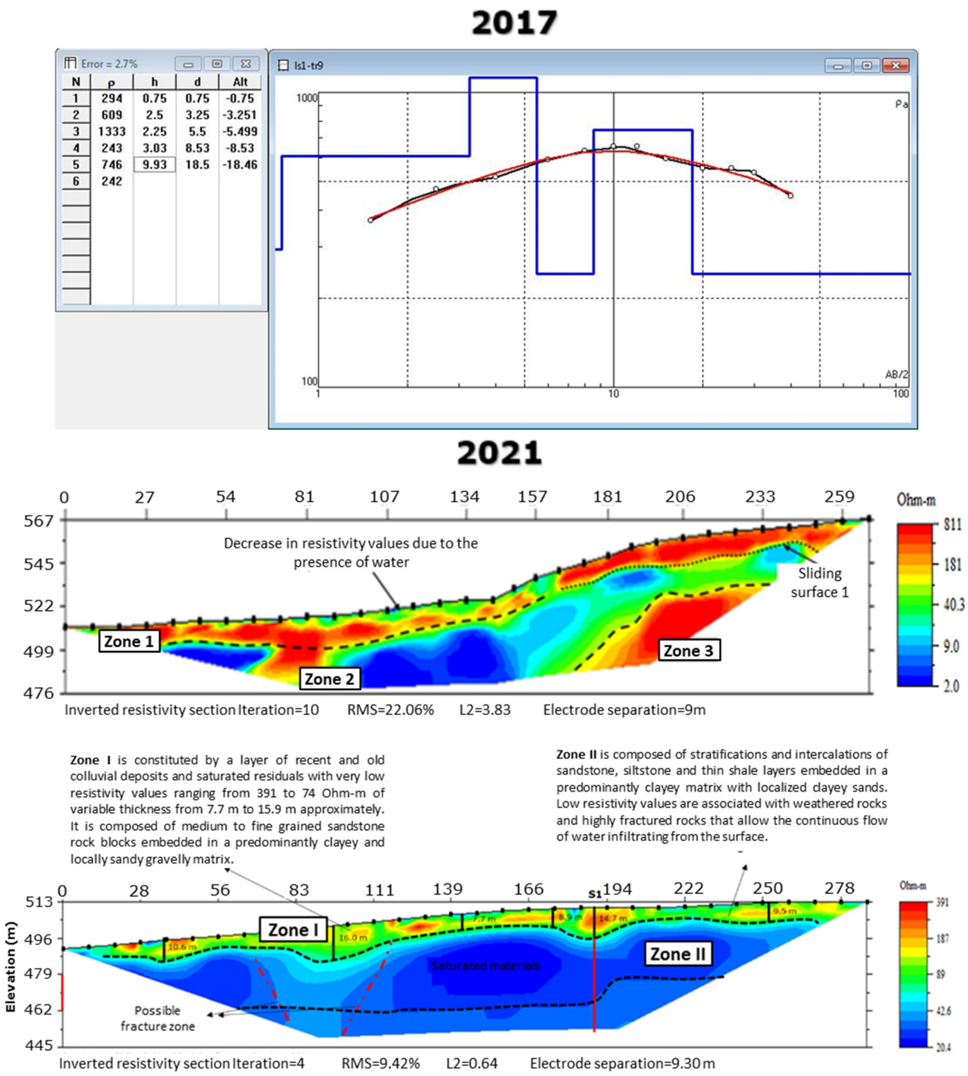

Figure 14. Resistivity test results for 2017, 2021, and 2023. Red dashed lines mean possible fracture zones. Red vertical line is borehole S1. Black dashed lines are soil stiffness zone changes.

The location of the assays, whose results are shown below, corresponds to the center of the geophysics line for the 2017 assay and the line plot for the 2021 and 2023 assays shown in Figure 11.

In the figure above, the first column of the 2017 table indicates the number of layers determined after processing (N). The second column (p) indicates the resistivity values in Ohm-m, the third column (h) represents the thickness of each layer, and the fourth and fifth columns (d and Alt) indicate the total height measured from the surface in meters. The 2021 and 2023 figures show the 2D resistivity plots in Ohm-m. As with the previous tests, it can be observed that although the soil in 2017 presented low consistency and was susceptible to failure, there was a greater decrease in resistance immediately after the landslide in 2021.

In contrast, a noticeable recovery of the resistance parameters was observed by 2023 (see Table 2). This is reflected in the hazard results shown in Figure 12.

AGD was evidenced when analyzing the four types of tests (number of blows, direct shear tests, seismic refraction lines, and resistivity) in the different periods. A redundant relationship was observed in the tendency to identify a decrease in soil consistency and increase in saturation at the time of failure, compared to their values before the failure, as well as a recovery of such consistency and a decrease in saturation sometime after the landslides occurred.

7. Proposal Toward Prediction

For the semi-detailed scale of work (1:5000), three scenarios were compared, corresponding to before, immediately after, and following the failure in 2021. Field data and tests (SPT), as well as indirect tests (seismic and geo-electrical), were collected to show how the conditioning factors varied over time. This comparison was considered necessary to evidence the changes defining the safety factors of the slope. The monitored parameters are those that are part of the expression for the calculation of the safety factor of the infinite slope method, namely, cohesion, friction, density, probable height of failure, and height of the water table with respect to the slope for the different slope gradient ranges. According to the AGD concept, these parameters will vary over time and influence the occurrence of the failure; for this reason, they were treated as random variables within the ranges of possible values. For example, the range of the friction angle was limited between 18° and 32°, based on multiple measurements. To understand its behavior, a range was defined to analyze greater sensitivity and variability for prediction purposes rather than relying solely on real data.

The following Table 8 defines the number of simulations and the probability of failure (F.S. < 1.1) for each range of low, medium, and high slopes.

Table 8. Statistics of the simulations performed.

Category of Slope Gradient	Value of Slope Used	No. of Simulations with F.S. < 1.1	Probability of Failure
Low	9°	280/1000	28.0
Medium	45°	754/1000	75.4
High	68°	935/1000	93.5

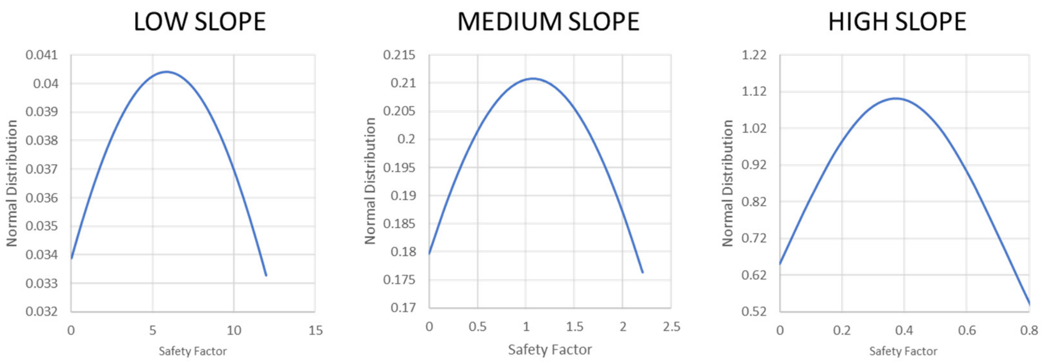

Figure 15. Gaussian bells and application of the infinite slope equation.

As shown in Figure 16, the GIS modeling of the S.F. formula using the infinite slope method for each slope scenario showed variation in the areas of each zonation category. This indicates that the greater the slope, the greater the probability of failure and the greater the area of the high landslide category.

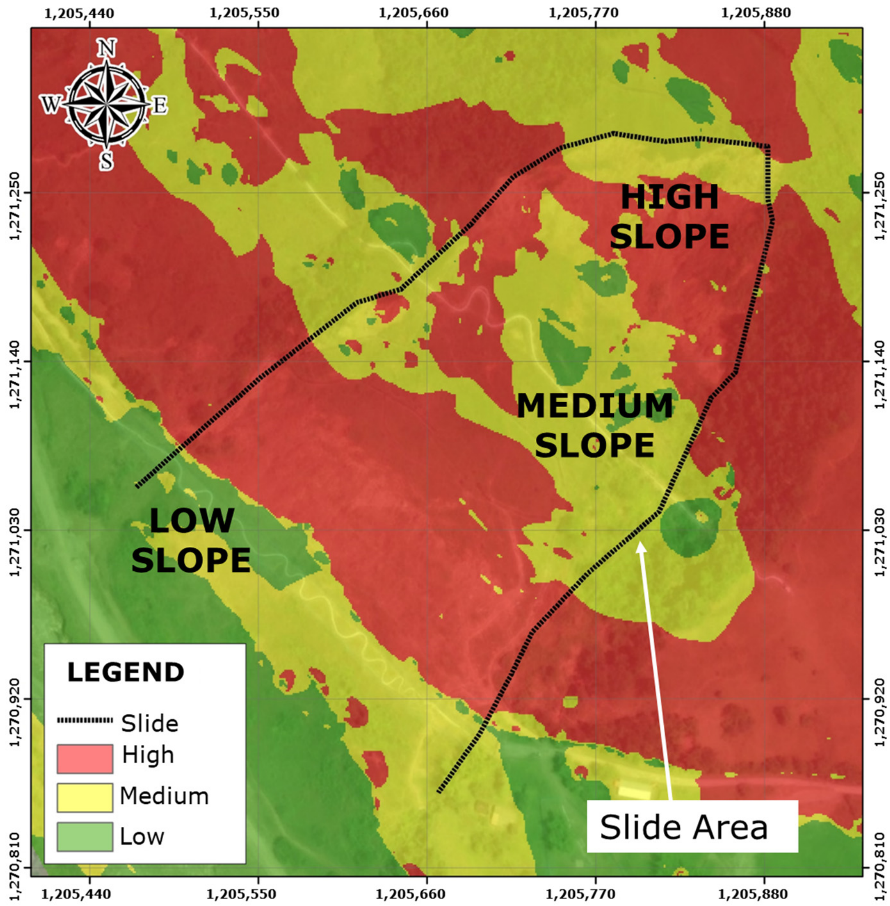

Figure 16. Variation in the results using the slope variation infinite slope method.

The group of data associated with the subset of F.S. < 1.1 constitutes the values of the strength and saturation parameters, which, when compared with those obtained from periodic samples (monthly and especially in rainy seasons, according to the geotechnician's criteria) of the soil for triaxial tests, revealed that the unit weight and position of the water table would induce failure. Correlations with the SPT and the shear wave velocity (Vs), provided there is an agreement between them, would reduce uncertainty given the difficulty of sampling granular materials in slope deposits. Considering the uncertainty generated by resistance values in an unaltered sample, in order to generate an alert, these results can be validated by analyzing changes in humidity reflected in electrical tomographies, which can also show possible ground anomalies associated with discontinuities related to failure surfaces. Similarly, these results can be validated by comparing them with possible changes in stiffness values from seismic MASW-2D lines and the values of accumulated rainfall. The idea is to make use of the redundancy principle to reduce uncertainty. It should be noted that well-taken, -processed, and -interpreted geophysical data will serve as effective input for the hazard analysis, as shown in Section 6 (AGD) in this article.

8. Discussion

From the development of the present study, it was demonstrated in practice that AGD is indeed manifested and can be feasibly measured and monitored to determine changes in the magnitude of the resistance and saturation parameters of the soil that influence the safety factor to predict failure. This conclusion is validated by the fact that all explorations carried out (both direct and indirect) in the different scenarios showed that the deterioration of ground capacity is measurable and comparable. If a specific case is to be implemented, the geotechnical history must be available since computer programs rely on methods that use historical data to predict potential results based on certain scenarios [15]. Therefore, if such history does not exist, it must be constructed in order to apply it, as it was in this research at a scale of 1:5000. From this scale onward, periodic measurements must be taken and correlated with simulations of possible scenarios.

In comparison with geotechnical zoning methodologies, this research work differs because it establishes an applied prediction method based on the AGD concept, which should be applied and strengthened in future research. Most of the current prediction methodologies correspond to smaller scales (1:100,000 and 1:25,000) based on the identification of evidence of changes in geoform and vegetation cover, as proposed under the same AGD concept in the first article (scale 1:25,000). The present research contributes to better prediction because it contemplates greater detail through AGD measurements with direct and indirect tests at the 1:5000 scale that correlated and established interdependence with the results of other scales. Although the GSC 1:25,000 scale zonification methodology, the F.S. equation using the infinite slope method, the Monte Carlo method, and the direct and indirect tests are well known individually, the strength of this work lies in the systematic organization and interrelation between these methods, specifically oriented toward the measurement and monitoring of AGD.

As with all research, achieving greater certainty in evaluations requires a large amount of data, which is often unavailable. The advantage of this research is that to counteract this difficulty, it makes use of certain data in different scenarios that have already occurred, which allows the models to be calibrated. These scenarios include a fault that occurred three decades ago, conditions prior to the fault in 2017, immediately after the fault in 2021, and two years after the fault in 2023. It is important to keep in mind that faults are not only related to precipitation thresholds, as evidenced by the accumulated rainfall magnitudes (Table 9), which were similar to those in 2021, yet no landslides occurred during these occasions.

Table 9. Historical cumulative precipitation.

	Accumulated Precipitation (mm)			
Days	**26 August 2015**	**3 August 2021**	**30 May 2024**	**15 June 2024**
0–2	74.0	304.2	292.1	221.0
2–4	168.0	480.2	437.1	339.1
4–8	300.8	660.6	690.6	456.7
8–16	643.7	1152.8	1151.3	958.2
16–35	1154.5	2087.8	2113.5	1702.2
35–55	1744.7	2790.5	2803.9	2080.1

To complete this research, which, in the first article, was focused on a regional scale (1:25,000) and in the present document is based on a semi-detailed scale (1:5000), it was necessary to establish a method at a more detailed scale, such as 1:2000, which includes cross-sections of the slope in areas where the "sieving axis" resulted in a high hazard category. The perspective focused on the design of possible solutions that allow the operation of the infrastructures that operate in the study area and their functionality over time in the face of the constant AGD already identified, which will be the main topic for future research. The methodology established in this research should be defined under the same concept of AGD and its relationship with its prediction, which was the fundamental objective.

The analysis of these sections should include sudden rotational and translational failures by means of force analysis methods such as limit equilibrium. In the case of sliding, slow, reptation-type failures, while not involving significant travel distances, can still impact the integrity and operation of houses, roads, and transportation lines. These models should account for not only the S.F. but also for deformations and their relationship to the vulnerability of the exposed elements.

Consequently, the application of the AGD concept explains why the triggering events over the last 33 years led to the slope deposits being in a specific condition that caused failure in this particular scenario, while such failure had not occurred before. This is based on the premise that the terrain does not fail solely due to a rainfall or earthquake threshold but rather as a result of their prolonged influence. The proposal described in this research could be used in similar contexts, with the respective adjustments, to achieve better predictions—this being the primary objective of the present document, applicable to other cases of sudden rotational and translational failures.

Considering that this document intends to put forward a proposal and highlight the need to include AGD in prediction models, as well as provide evidence of the deterioration and periodic recovery of slope soil properties, there is currently a wealth of data to demonstrate the influence of AGD at different scales of work. However, there are no measured data from the method's application that allow for quantitative analysis or error estimation. This should be part of future stages of research.

9. Conclusions

The present work demonstrates the application of the landslide hazard methodology at three different times in the sector known as Cortinas (Colombia) (2017, 2021, and 2023), making it feasible to carry out this research and address the recurrence issue, which is a limitation of current methodologies. This method could be applied and extended to other case studies around the world, both in academic research and in geotechnical consulting. In the modeling performed for the three years mentioned, a high-hazard area of 27% of the study area was identified in 2017. In 2021, when the failure occurred, this area increased to 80%, and in 2023, it decreased to 35%.

The SGC hazard zoning models, the Factor of Safety by the Infinite Slope method in GIS, and the Monte Carlo simulation model were used to process the different data obtained during the exploration campaign for each epoch. These models enabled the comparative analysis of changes in the conditioning factors that determine stability in each scenario. The above approach is based on the concept of accumulated geotechnical deterioration (AGD), which was introduced at a regional scale of 1:25,000 in the first article of this research. It will also be part of the analysis for the detailed scale 1:2000, which is the subject of a third article.

This second part of this research reiterated the importance and necessity of analyzing the variability, randomness, and interdependence not only of the triggering factors but also of the conditioning factors under the concept of AGD.

In contrast to the 1:25,000 scale, where the factors to be analyzed for deterioration were changes in geomorphology and vegetation cover, for the evaluation of AGD at the 1:5000 scale, the relevant parameters define the safety factor.

In contrast, in order to apply the model, three types of slopes of different ranges, typical of the morphometry of the studied slope, were analyzed. Consequently, it is concluded that each time triggering actions occur, the variables for calculating the S.F. either deteriorate or recover, making the prediction of when these events will occur very complex. However, if AGD is considered, a better approximation can be achieved as long as periodic measurements, automatic simulations using AI, and the construction of big data—none of which are part of this stage of the research—are carried out.

In terms of stability, the condition of the terrain should not be visualized as a photograph (as is customary) but as a sequence of photos (like a video). Although conventional prediction methods can identify areas of high danger, moderate-risk areas may eventually deteriorate, increasing their risk and requiring intervention. This approach, based on the novel AGD concept and validated through geophysical anomalies and real-time monitoring reports, proposes a proactive model.

Author Contributions: Conceptualization, C.A.B.B., A.M.M.-G. and M.Y.; methodology, C.A.B.B., A.M.M.-G. and M.Y.; validation, A.M.M.-G. and M.Y.; formal analysis, C.A.B.B.; investigation, C.A.B.B.; resources, C.A.B.B.; data curation, C.A.B.B.; writing—original draft preparation, C.A.B.B.; writing—review and editing, A.M.M.-G. and M.Y.; visualization, C.A.B.B.; supervision, A.M.M.-G. and M.Y. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The data that support the findings of this study are available upon reasonable request from the authors.

Acknowledgments: The authors would like to thank the company E.D Ingeotecnia S.A.S for providing the data and financial resources for this research. They would also like to thank the gas transportation company PROMIORIENTE SA ESP for its constant willingness to allow the research to be carried out for the preparation of this article. The GEAPAGE (Environmental Geomorphology and Geological Heritage) research group of the University of Salamanca assisted in this research. They would also like to thank Engineer Pablo Salamanca for his support in editing, software, and data curation, as well as Engineer Jorge Jiménez for his immense support in the strategic direction, AGD conceptualization, and writing of the initial document.

Conflicts of Interest: The authors declare no conflicts of interest.

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