

Geological-geotechnical risk mapping of gravitational mass movements in an urban area in Colombo, Brazil

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Case Study

Keywords

Susceptibility to landslides
Geoprocessing
Risk mapping

Abstract

This work presents a geological-geotechnical risk map of gravitational mass movements and a susceptibility map to shallow translational slides to Vila Nova community, located in the municipality of Colombo, Brazil. The first map was created through a qualitative mapping methodology and the second one was elaborated using a deterministic method of slope stability. An aerial photogrammetric survey with UAV technology was performed, as well as field reconnaissance, laboratory testing, and geoprocessing techniques. Seven slope failures were identified as well as a range of other evidences of instability associated with the predisposition of the terrain to erosive and gravitational movements linked to human intervention without urban planning and engineering techniques. Moreover, the qualitative and quantitative analyses pointed out that 13% to 9% of the study area, respectively, are in a very high-risk condition for landslides. Thus, the resulting cartographic products are presented as an important technical contribution for landslide risk management as well as land use planning for reducing the geotechnical problems faced on site.

1. Introduction

Among the natural disasters that most affect the Brazilian population, in the number of people, gravitational mass movements stand out. They are natural geological phenomena which can occur in any area of high slope on the occasion of, above all, intense and prolonged rains (Brasil, 2004). However, human intervention, especially those that do not consider the hydromechanical limitations of the physical environment, can also unbalance the system of forces existing inside the mass of soil, rock or debris, which keeps it in static equilibrium. This is due to the reduction of the shear resistance of the material or due to the increase in the shear stresses of a given potential failure surface, caused by internal (predisposing) or external (triggering) factors (Duncan et al., 2014).

Urban unregulated settlement in areas susceptible to landslides and without drainage infrastructure represent 39.5% and 35.5% of landslide records in Brazilian municipalities between 2013 and 2017, respectively (IBGE, 2017). The anthropic intervention that the most interfere in the triggering of slope ruptures are the execution of cuts and landfills with inadequate geometry and degree of compaction,

the deficiency of rainwater drainage systems and wastewater collections, the disposal of urban solid waste, and the removal of vegetation cover (Gerscovich, 2016).

Despite being complex and recurrent phenomena in nature, they can be minimized through preventive actions such as mapping, territorial planning, and monitoring in order to protect populations in risk areas.

The Federal Law 12,608 of 2012 (Brasil, 2012a) instituted the National Policy for Protection and Civil Defense (PNPDEC) in Brazil that covers prevention, mitigation, preparedness, response, and recovery actions aimed at protection and civil defense in terms of natural disasters. It delegated to the municipalities the task of promoting the identification and evaluation of susceptibilities, hazards, and vulnerabilities to disasters, in order to avoid or reduce their occurrences, resulting in the elaboration of cartographic products as a result/consequence.

The land geotechnical susceptibility map is the basic and essential technical product of the action plan required by PNPDEC for the cities. According to Prandini et al. (1995), geotechnical maps are a practical expression of geological knowledge applied to confront the problems posed by land use of slopes, seeking to understand the interaction between

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settlements and the physical environment as well as guiding preventive, corrective, or emergency measures when necessary. Geotechnical and hazard reconnaissance and the field and laboratory testing are applied in a qualitative criterion and/or mathematical modeling to correlate data and interpret physical phenomena resulting in digital geoprocessing works (Soeters & van Westen, 1996).

Analytical or numerical models of slope stability, based on deterministic methods, are the most widely way used to verify the safety of a slope in engineering approaches (Soeters & van Westen, 1996). They are especially employed in slope stabilization designs, for example.

However, to overcome the limitations imposed by the heterogeneity and anisotropy of soils and rocks involved in extensive mountainous areas, in addition to the limitations of deadlines and budgets, the analysis of slope stability based on qualitative methodologies, semi-empirical methods associated with geoprocessing techniques, has gained prominence in recent decades (Soeters & van Westen, 1996). These analyses, in general, lead to the identification and classification of weights of danger events in the field, deriving out of the study of the natural condition of the physical environment and the possible mechanisms that can generate instabilities (Ahrendt, 2005).

In this context, this work sought to identify the predisposing factors and signs of instability in terrain, translated into its susceptibility, as well as the pattern of the settlement and

its vulnerability, to analyze the risk of soil landslides in the Vila Nova community, in the municipality of Colombo, Brazil. Through this analysis, a geological-geotechnical risk map of gravitational mass movements was elaborated through a qualitative mapping methodology. Also, it aimed to understand the phenomenon of more recurrent instability in the study area and the geomechanical properties of the involved materials to elaborate a susceptibility map to shallow landslides through a deterministic method of slope stability analysis.

Such cartographic products can be used as technical tools to landslide risk management and land use planning in coping with the geotechnical problems faced on site.

2. Materials and methods

2.1. Characteristics of the study area

The community of Vila Nova is in the Roça Grande neighborhood, in Colombo County, Metropolitan Region of Curitiba, state of Paraná, and covers 48,500 m² in a densely occupied valley with approximately 300 houses. It is bordered by the streets Rio Araguaia, Rio Iguaçu, Rio Guaporé, Rio Grande do Norte, and Santa Bárbara (Figure 1).

It is based on the sub-unit morphosculpture of Curitiba Plateau and in the region where the rocks are surfaced

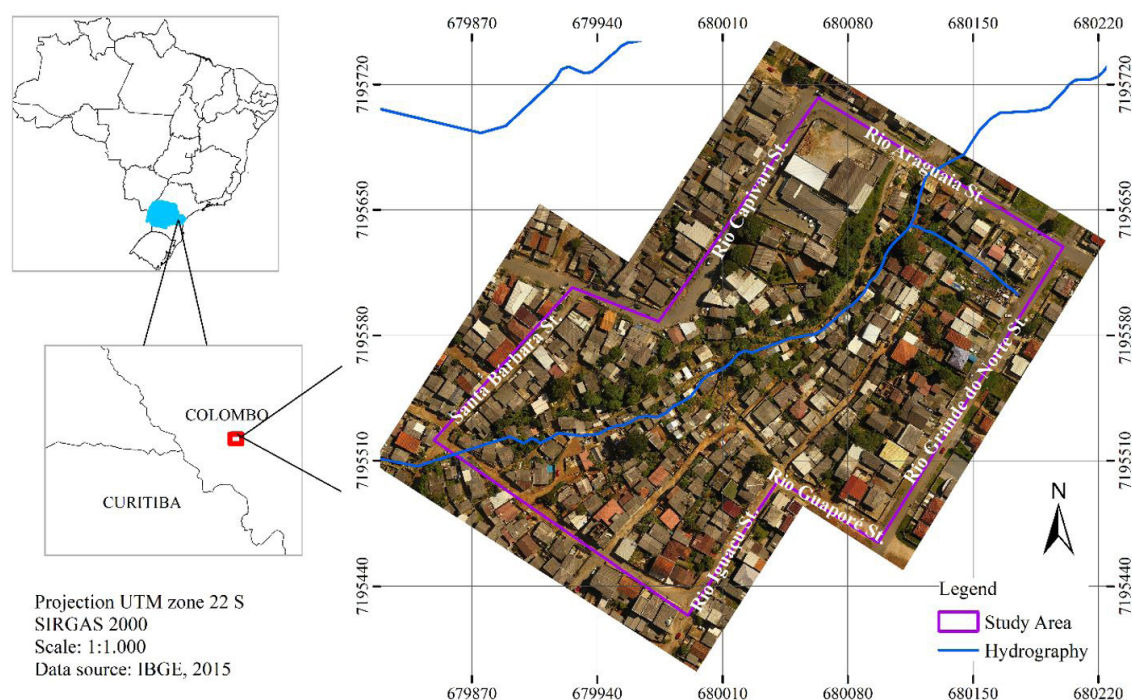


Figure 1. Location map of Vila Nova community, in Colombo, State of Paraná, Brazil.

and the residual soils of the crystalline basement of the Curitiba Sedimentary Basin, the Atuba Complex, are formed (IAT, 2000, 2005). There are mainly gneiss and migmatite, but also paragneiss, quartzite, quartz schist, mica schist, amphibolite and gneiss granite (Salamuni, 1998).

The studied area is located on one of the possible geological faults mapped by Salamuni (1998), geomorphological failures that occur, in general, towards NE-SW and NW-SE.

At the bottom of the valley, it permeates a stream of low flow water in times of drought and high flow in times of floods. It belongs to the Manjolo Cabeceira hydrographic sub-basin, which is part of the Atuba River basin, from Alto Iguaçu (IAT, 2000).

2.2. Topographic survey of the study area

The technique of aerial photogrammetry with Unmanned Aerial Vehicle (UAV) technology was used to perform the

topographic survey of the study area. Through this technique, it was possible to obtain the terrain coordinates to generate the 3D terrain model with a density of 350 points/m², as well as a high-resolution orthoimage with a 4 cm spatial resolution. The UAV equipment used was the Phantom 4 model developed and manufactured by the Chinese company SZ DJI Technology Co., Ltd. The flight was carried out under favorable weather conditions at an approximate height of 70 m AGL (Above Ground Level) and in VLOS (Visual Line Of Sight) mode (Figure 2).

To generate the cartographic products, a GNSS (Global Navigation Satellite System) receiver was used to collect ground control and check points. Then, the SfM (Structure from Motion) technique was used to perform the bundle block adjustment to the image georeferencing, as well the dense cloud, digital surface model (DSM) and orthoimage generation. This whole process ensured the generation of cartographic products according to the Brazilian Accuracy Standards (PEC-A) for cadastral mapping. Also, in order

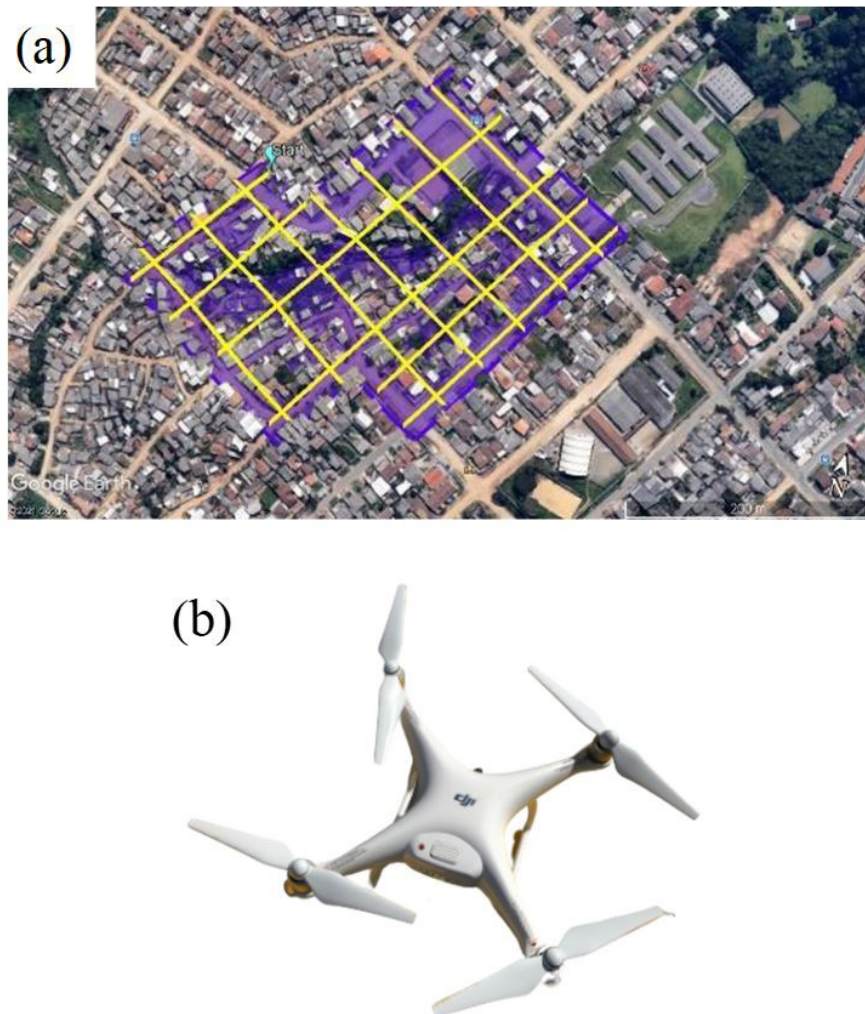


Figure 2. (a) crosshatch flight plan over the studied area; (b) UAV model DJI Phantom 4.

to generate precisely the Digital Terrain Model (DTM), the contour lines were extracted using 3D stereo compilation, due to the obstruction of the soil surface caused by the buildings and vegetation. The map projection adopted was the Universal Transverse Mercator (UTM), Zone 22 South, and horizontal datum SIRGAS2000. The altitudes were referenced to the ellipsoid of SIRGAS2000. All cartographic information was obtained by CEPAG (Geoinformation Applied Research Center of UFPR).

2.3. Qualitative landslide risk

The following methodology is based on the geological, geotechnical, and hydrological mapping and risk analysis manuals developed by the Brazilian Ministry of Cities (Brasil, 2018) and the Geological Service of Brazil (CPRM, 2018). Instructions from Soeters & van Westen (1996) are also used for the practice of landslides zoning.

2.3.1. Assessment of susceptibility, vulnerability, and risk

In the field zoning phase, a landslide inventory was made and the evaluation and classification of terrain susceptibility to the occurrence of landslides, followed criteria of the severity of evidence representing current or potential mass movements, as shown in Table 1. Through the steepness of the slopes, the danger mapping also followed topographical criteria. Based on the Law 6,766 of 1979 (Brasil, 1979) of land use urban zoning, areas whose inclination are greater than 30% (17°) cannot be urbanized, as this being the first topographical criterion. Ahrendt (2005) also identified that the landslides that took place in the residual soils of gneiss-migmatite and landfill in densely populated areas in the municipality of Campos do Jordão occurred more frequently in slopes steeper than 25°, once those of greater magnitude are among the slopes of 30° to 40°. Thus, it was defined that those areas with angles greater than 25° are more critical to the occurrence of landslides, which is the second topographic criterion, following the classification presented in Table 1.

These danger evidence and inclinations were then classified as low susceptibility (S1) to very high susceptibility (S4).

Regarding the diagnosis of the pattern of land use it was sought to define a classification criterion of how vulnerable to an extreme landslides event the constructions of Vila Nova are, as shown in Table 1. Also, the presence of vegetation, drainage system and anthropic interventions in the physical environment was observed. The analyzed areas were classified as low vulnerability (V1) to very high vulnerability (V4).

The consolidated and unconsolidated materials were recognized seeking to observe general geological-geotechnical aspects such as lithology, genesis (residual soil, landfill soil, etc.), and geomorphological features of the relief (Table 1).

At all the points analyzed in the field, its georeferenced position was plotted in the mosaic obtained by aerial photogrammetry.

The relationship between the landslide potential along the area (susceptibility) and the expected losses to life and property (vulnerability) by a landslide occur is expressed by the risk. Thus, empirical multiplications were performed between the degrees of susceptibility and vulnerability identified in each area, or pixel in the GIS environment, to determine its risk. This one was established to be higher than the highest degree of danger or consequence associated, a decision made on behalf of security, as also adopted in the work of the CPRM (2018). Hence, the four risk classes ranging from low (R1) to very high (R4) are the result of interactions between the degrees of susceptibility (S1 to S4) and vulnerability (V1 to V4). Table 2 shows the description of the risk classes employed.

2.4. Quantitative landslides susceptibility

The quantitative analysis of the susceptibility of the lands of Vila Nova to landslides were conducted deterministically using the Infinite Slope model, based on the Limit Equilibrium Method, coupled to the GIS environment, to calculate the safety factors of each pixel of the elaborated map. Conceptually,

Table 1. Aspects for risk classification of current and potential gravitational mass movements.

Geological/geomorphological diagnosis	Diagnosis of land use (vulnerability)	Diagnosis of evidence of mass movements (susceptibility)
Local geology (main lithology of rocks and genesis of unconsolidated materials, presence of geological structures, waste, etc.)	The material used (masonry, generally representing low and medium vulnerability, or wood, representing, in general, high and very high vulnerability)	Steps, subsidence, and fissures in the ground, retaining walls cracked or bowed, soil moistening by sewage/leaks deposition, trees tilted downhill (representing high susceptibility)
Local geomorphology (presence of steep slopes and/or poorly executed cuts and fills)	Constructive pattern and presence of visible structural damage	Presence of scars of movements (representing very high susceptibility)
	Local vegetation (presence and type)	Terrain slope greater than 17° (representing medium susceptibility)
	Inefficient/non-existent drainage or sewage system	Terrain slope greater than 25° (representing high susceptibility)

Table 2. Risk hierarchy criterion.

Risk intensity	Description
Low risk (R1)	Absence of unfavorable topography to stability and indications of gravitational mass movements. High level of building resistance. Maintaining the conditions of the land use, the possibility of destruction of buildings by landslides is low.
Medium risk (R2)	Meets the first topographic criterion (slope greater than 17°), but the terrain shows no indications or records of gravitational mass movements. High to the moderate level of resistance of the buildings. Maintaining the moderate conditions of the land use, the possibility of destruction of buildings by landslides is moderated.
High-risk (R3)	It meets all topographic criteria unfavorable to stability and presents indications of gravitational mass movements, although not intensely. High to the low level of resistance of buildings. Maintaining the moderate conditions of land use, the possibility of destruction of buildings by landslides of land is high.
Very high-risk (R4)	It meets all topographic criteria unfavorable to stability and the terrain presents intense indications or records of gravitational mass movements. High to the very low level of resistance of buildings. Maintaining the conditions of the land use, the possibility of destruction of buildings by landslides of land is very high.

the safety factor is defined as the relationship between the mobilized shear strength of the soil (τ_m) and the shear stress (τ) on a potential failure surface (Lambe & Whitman, 1969). In the Infinite Slope model, the failure surface is rectilinear and parallel to the surface of the ground, resembling shallow translational slides. Because it is a simple model of Limit Equilibrium, the implementation of Infinite Slope in a georeferenced computational environment is relatively simple, demanding few topographical and geotechnical parameters and facilitating the quantification of safety factors of extensive areas. In Equation 1 the mathematical formulation for calculating safety factors (SF) is presented using the Infinite Slope model.

$$SF = \frac{\tau_m}{\tau} = \frac{c' + (\gamma h \cos^2 \beta - \gamma_w h_w) \tan \phi'}{\gamma h \cos \beta \sin \beta} \quad (1)$$

Being c' the effective cohesive intercept of the soil, in kPa; γ the unit soil weight, in kN/m³; h the depth of the failure surface, in meters; β slope of the ground as well as of the failure surface, in degree; γ_w unit water weight, in kN/m³; h_w the depth of the groundwater table, in meters; and ϕ' the effective internal friction angle of the ground, in degree.

2.4.1. Laboratory tests

The soil modeled in the calculation of safety factors is a landfill soil, quite recurrent on-site due to cut and landfill activities for laying the residences and opening accesses. To determine the residual resistance parameters of these soil, Direct Shear Tests were conducted using the reversal technique at vertical stresses of 25 kPa, 50 kPa, 100 kPa e 200 kPa in a residual soil collected on-site, since the collection in a landfill soil was hindered. It was sought to identify soil resistance under the condition of large deformations because it is possibly to be soils with pre-existing failures

or progressive internal failures, resulting in a minimum of shear resistance.

2.4.2. Map algebra in GIS environment

The elaboration of the geotechnical maps was conducted in ArcGIS 10.8 ESRI software. For calculation of safety factors, the map algebra presented below was carried out using the georeferenced terrain coordinates data obtained by aerial photogrammetry. For elaboration of the qualitative map, thematic maps as slope of the terrain were also necessary.

- Digital Elevation Model (DEM): terrain elevation raster surface with a spatial resolution of 0.5 m created through ArcToolbox's Topo to Raster interpolation using contour lines as input;
- Slope: slope raster surface created through the ArcToolbox's Slope tool using DEM as input;
- Safety factor variables: raster surfaces for each one of the input parameters involved in the formulation of safety factors (Equation 1) obtained through the ArcToolbox's Raster Calculator tool;
- Safety factor map: raster surface with the safety factor values for each cell of the geotechnical map using the ArcToolbox's Raster Calculator tool.

It has to be emphasized that the values of unit weight, cohesive intercept, friction angle, and depth of the rupture surface were kept constant; then, the inclination is the only spatially variable attribute.

3. Results

3.1. Geology and laboratory tests

During the field reconnaissance, it could be observed that the studied area is characterized by an intense heterogeneity of surface soils ranging from the residual soils of gneiss-

migmatite in different degrees of weathering to the alluvial soils in the stream bed that permeates the Vila Nova valley, through landfills with high presence of domestic solid waste and civil construction, coluvionar materials, and rocky outcrops. Along the slopes was verified the predominant occurrence of residual soils and landfill soils, as well as the second one was the most critical for stability and, then, used in the analysis of safety factors. Through the characterization tests conducted in the laboratory, the landfill soil was classified as a silty sandy clay, with natural moisture of 31.93% and a unit mass of grains of 2.52 g/cm³.

The sample of young residual soil tested using the reversal technique in the Direct Shear press has a unit natural weight around 17.5 kN/m³ and a degree of saturation around 95%. The tests were operated according to the requirements of BS 1377-7 (BSI, 1990). The sample was submerged in water before consolidation and the shearing speed was defined from parameters of consolidation as proposed by Gibson & Henkel (1954), allowing to perform the test in drained conditions. Was adopted a great displacement for the determination of the parameters of residual resistance, applying a deformation of 8% (4.8 mm) per shear cycle, to reach the stability of the curve without more variations of the shearing strength (Tchalenko, 1970; Advincula, 2016; Trevizolli, 2018).

The Mohr-Coulomb shear resistance envelope was obtained for the data from the tenth shear cycle performed in the test and is shown in Figure 3. Through it, were obtained the effective cohesive intercept of 12.7 kPa and the effective internal friction angle of 23° for the residual soil. In the analysis of safety factors, simulating a landfill soil, it was adopted a unit weight of 17 kN/m³, a cohesive intercept of 1.5 kPa and a friction angle of 22°. Those parameters were adopted based on interpretation of the results of the tests attended by the residual soil, on results of tests in landfill soils carried out in Campos do Jordão (Brazil) in the study

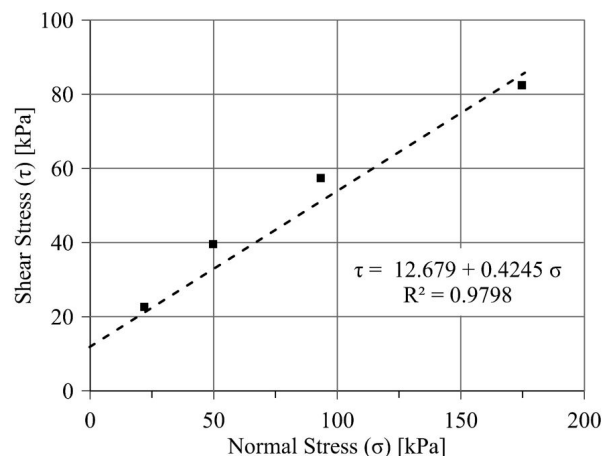


Figure 3. Mohr-Coulomb envelope for the tested residual soil under the condition of shear cycles and reversals.

of Ahrendt (2005), and on review of several references for different types of Brazilian tropical soils presented by Bressani et al. (2001). The input variables in the calculation of safety factors are presented in Table 3.

As verified in the field, the most recurrent depth of the landslides on-site is around 1 m depth in landfill soils on a predominantly plane rupture surface. Thus, it was adopted for the deterministic analysis, being model of Infinite Slope adequate for these failure conditions. The presence of a water table up to 1 m depth was not considered, as it was not found in outcrops on the slopes on-site inspections and, mainly, because the hydrogeological conditions of the substrate are not known through field tests. Nevertheless, soil resistance parameters were considered when it is close to saturation, a condition that can be achieved during the occurrence of rainfall events and/or by dumping/leaks of water and sewage pipes.

3.2. Landslides risk map – Qualitative analysis

During the field reconnaissance, held between October 2018 and December 2019, there was identified the presence of seven previous shallow landslides, which locality were classified as very high susceptibility (S4), and a range of other indications of instabilities, such as steps, subsidence, and fissures in the ground, retaining walls cracked or bowed, trees tilted downhill, disposal or leakage of water and sewage, localities classified as high susceptibility (S3), totaling 18 points analyzed.

The seven scars of shallow translational landslide were delimited to approximately 1 m depth, with mostly rectilinear shear surfaces parallel to the slope as well as with a considerably deformed and heterogeneous displaced mass. All of them were recorded in landfill soils, which denotes their high susceptibility to extreme events of slope instability, and in regions whose slope of the land is between 25° and 40°, corroborating the choice of classification of high danger areas (S3) to those steeper than 25°. It has to be emphasized that the recording of some of the movements was closely linked to a previous rainfall event.

It was observed that all the constructions in the discretized points are mostly built with wood, some in masonry, with precarious construction techniques, both infrastructure (foundation) and superstructure, some presenting structural damage. Thus, all were classified as very high vulnerability to landslide events. Figure 4 shows photographic records of two of the identified shallow translational slides and four records of indications of mass movements, as well as their

Table 3. Geotechnical parameters for stability analysis using the Infinite Slope method.

Depth of failure (<i>h</i>)	Unit natural weight (<i>γ</i>)	Cohesive intercept (<i>c'</i>)	Friction angle (<i>φ'</i>)
(m)	(kN/m ³)	(kPa)	(°)
1.0	17.0	1.5	22



Figure 4. (a) very high susceptibility (S4): translational landslide scar of approximately 1 m depth in landfill soil; (b) very high susceptibility (S4): translational landslide scar approximately 1 m depth in landfill soil; (c) high susceptibility (S3): steps on the ground; (d) high susceptibility (S3): retaining wall cracked and bowed; (e) high susceptibility (S3): subsidence and damping by sewage deposition; (f) high susceptibility (S3): tree tilted downhill.

susceptibility terrain classifications. Other pictures can be verified in Pontes (2019).

From the analysis of the interaction between the susceptibility of the terrain and the degrees of vulnerability to a sliding process, the risk levels to translational landslides of the study site in a GIS environment on a scale of 1:1000 were qualified. As a result, 13% of the community area of Vila Nova, that is, 6,086 m², is in a very high-risk area to occurrence and damages from a landslide event. In higher percentages, 19% is in a medium risk area and 68% in a site of low risk of occurrences and consequences of translational mass movements, as shown in Figure 5.

3.3. Landslide susceptibility map (safety factor map) – Quantitative analysis

The determination of quantitative susceptibility to shallow translational landslides in landfill soils in the

analyzed stretch of Vila Nova was based on the map of safety factors determined for this unconsolidated material with the resistance parameters and failure surfaces stipulated and presented in Table 3. It is important highlight that was assumed geological occurrence of the landfill soil throughout the length of the studied area.

The analysis resulted in a conjuncture in which 9% of the area, that is, 4,451 m², is in a scenario of very high susceptibility to shallow translational landslide ($FS \leq 1$), 17% in a scenario of high susceptibility, 16% in a context of medium susceptibility and 56% in an area of low susceptibility to the occurrence of movements, as shown in Figure 6.

It is noteworthy that the considerable percentage of areas whose safety factors are less than 1.0 can be attributed to the simplifications of the Infinite Slope method adopted, which does not consider, for example, unsaturated soil scenarios with suction (negative pore pressure) as a contributor in their shear resistance.

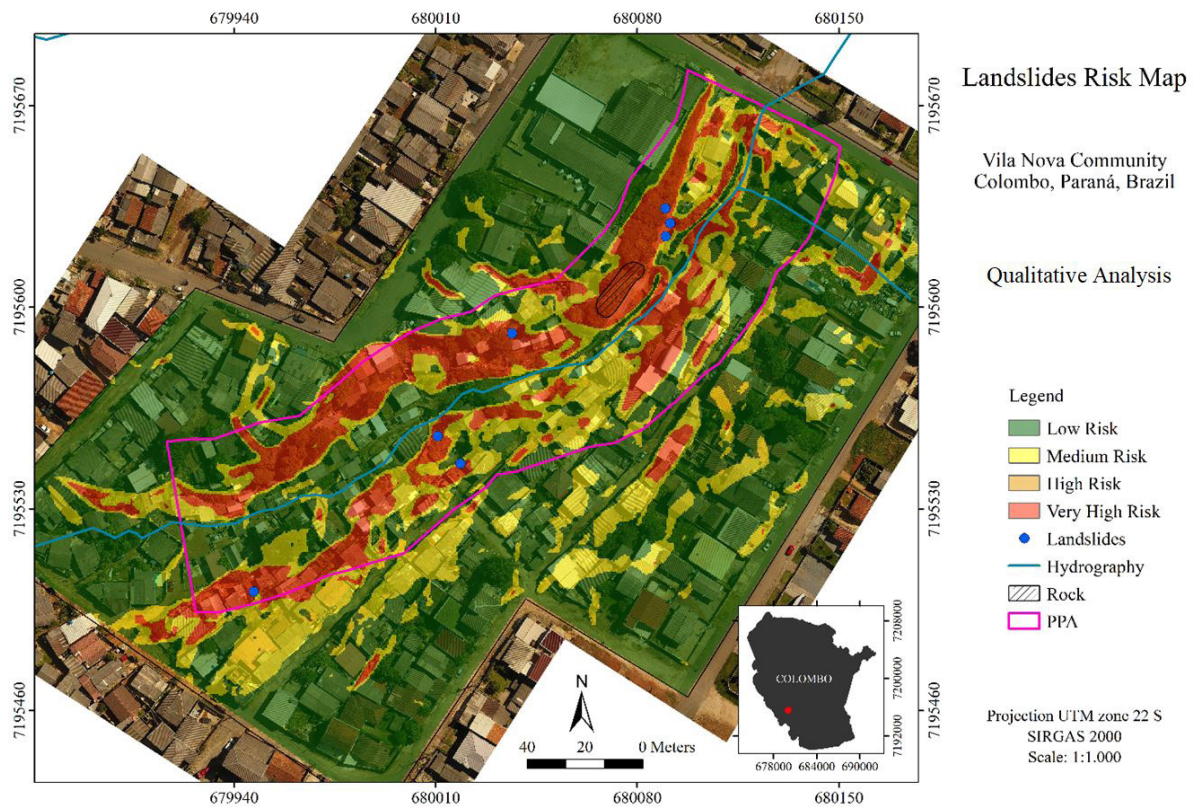


Figure 5. Landslides risk map of Vila Nova community – Qualitative analysis.

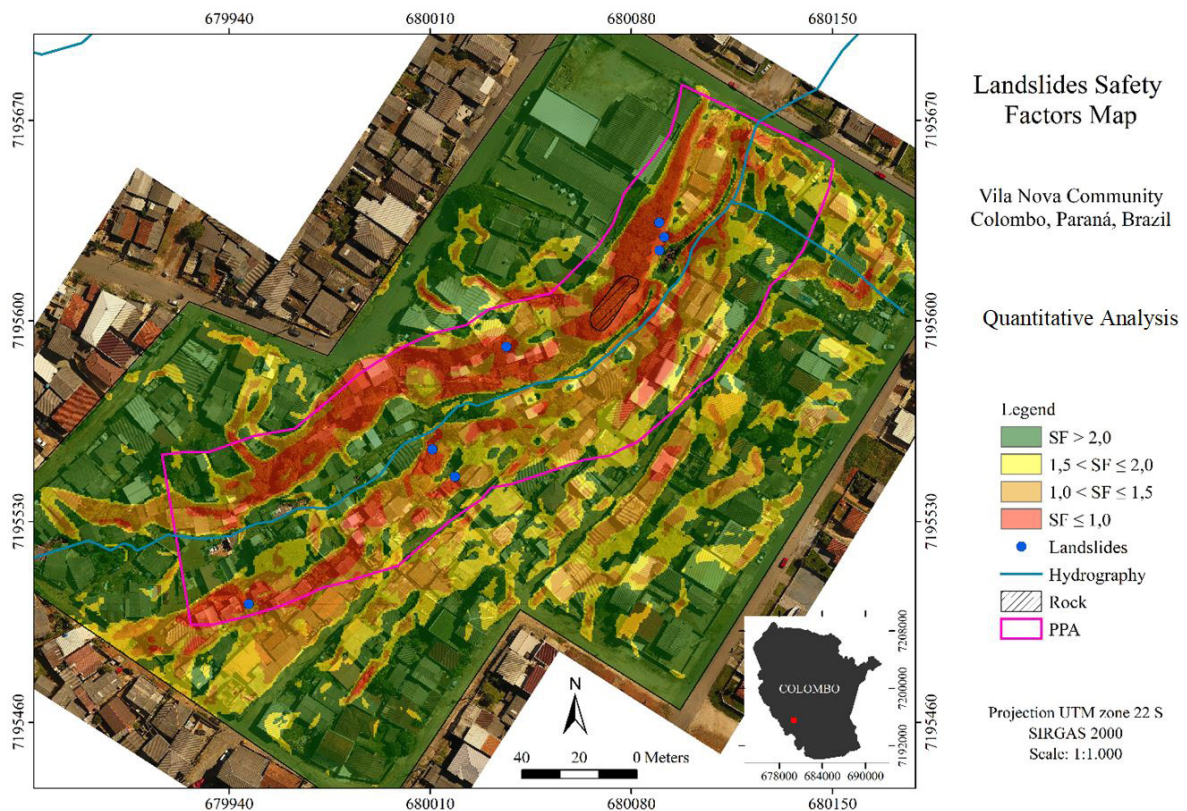


Figure 6. Landslide susceptibility (safety factors) map of Vila Nova community – Quantitative analysis.

4. Conclusions

The present work aimed to evaluate a section of the community of Vila Nova, in Colombo, Brazil, regarding its susceptibility and vulnerability to landslides, in order to identify regions and dwellings with higher risks of gravitational mass movements. The research culminated in the elaboration of a geological-geotechnical risk map, as well as a susceptibility map to shallow translational landslides.

Based on the two methodologies applied - qualitative and quantitative - about 11% of the study area covering approximately 50 residences is indicative of very high geotechnical risk of shallow translational landslides.

It was possible to observe that the high-risk areas in Vila Nova are associated with anthropic interventions without either urban planning or engineering techniques in steep slopes, since the records of landslides occurred in areas whose average slope is greater than 27° and in poorly executed cut and landfill soils. In addition to the landslide inventory, it was also pointed out the precariousness of the construction techniques of the residences, the intense clearing of the local vegetation, disposal of domestic solid waste along the slopes and the stream bed, the recurrent floods, the existence of irregular and damaged networks of water and sewage that can lead the soil to saturation and contribute to weakening the land as to the triggering of landslides.

It can be inferred that for the case analyzed, the application of a qualitative method was an efficient alternative for geological-geotechnical risk zoning due to the similarities found between the maps produced from the two methodologies. A qualitative method demands lower financial, time and computational resources, but can be well applied in conditions of urban and geotechnical precariousness exposed to naked eye in field reconnaissance. Nevertheless, it is important to highlight the relevance of quantitative analyses of landslides to perform a more accurate slope stability analysis, especially for time and spatial evaluations.

Regarding the topographic survey performed by aerial photogrammetry with UAV technology, it was possible to notice that this technique has advantages over conventional topography in conditions of time, financial and access limitations. Even though this technology allows a practical and fast survey, it is an indirect technique of obtaining the three-dimensional coordinates of the terrain. Therefore, all theoretical and practical aspects of photogrammetry must be followed for the production of cartographic products with accuracy compatible with the characteristics of the project.

Based on the geological-geotechnical analyses, hydraulically oriented studies about the stream channel, and socioeconomic exams, the residences in the most vulnerable locations should be reallocated to a safer place, and intervention works should be done on the land suitable for urbanization. Thus, the vulnerability would be eliminated and the hazard reduced. In addition, the Permanent Preservation Area (PPA),

meeting the Brazilian Forest Code - Law No. 12,651 (Brasil, 2012b), would be restored to preserve the natural ecosystem within the 30 m-length lane from the stream at the bottom of the Vila Nova valley – the very same most hazardous area based on the present study.

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Declaration of interest

The authors declare that there are no conflicting interests associated with this publication among them or other parties (people, support financial agencies, etc.). They confirm that the manuscript has been read and approved by all named authors and that there are no other people who satisfied the criteria for authorship but are not listed. There is no financial interest to report.

Authors' contributions

Carla Vieira Pontes: conceptualization, data curation, formal analysis, investigation, methodology, software, validation, visualization, writing – original draft. Roberta Bomfim Boszczowski: conceptualization, funding acquisition, supervision, writing – review & editing. Leonardo Ercolin Filho: data curation, writing – review & editing.

List of symbols and abbreviations

c'	Effective intercept cohesion
h	Vertical depth of rupture surface
h_w	Vertical depth of groundwater table
SF	Safety factor
β	Slope of the terrain as well as of the failure surface
γ	Unit soil weight
γ_w	Unit water weight
τ_m	Mobilized shear strength
τ	Shear stress
$\varnothing'$	Effective internal friction angle
CEPAG	Geoinformation Applied Research Center of UFPR
GECEO	Geotechnical Study Group of UFPR
PNPDEC	National Policy for Protection and Civil Defense (Brazil)
PPA	Permanent Prevention Area
UAV	Unmanned Aerial Vehicle
UFPR	Federal University of Paraná

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