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QUANTITATIVE ANALYSIS OF THE VULNERABILITY OF EXPOSED ELEMENTS IN THE SERRA PELADA REGION, BARRA DO TURVO, BRAZIL

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ABSTRACT

Vulnerability is a major factor in the analysis of landslide risks and is essential for predicting the consequences of such events. In this case study, we quantitatively assessed vulnerability in the rural area of Barra do Turvo, located in the Serra Pelada mountain range, Brazil. It is a landslide-prone area with 144 households settled alongside the Régis Bittencourt highway. Therefore, we used an indicator-based methodology that considered both landslide intensity and resistance of exposed elements (buildings, large-scale structures, roadways, and local population). Results indicated that 93% of the buildings had a high level of vulnerability, while 90% of the local population had a moderate level, as did the large-scale structures and the highway. Rural roads, in turn, revealed high levels of vulnerability. This is relevant data for designing risk mitigation strategies. Based on this approach, we were also able to map the region. Conclusions include the potential for applying this approach in other regions and its relevance to decision-makers involved in land use planning and civil protection measures for risk mitigation.

Keywords: Landslides. Landslide intensity. Resistance of exposed elements. Risk management. Rural area.

ANÁLISE QUANTITATIVA DA VULNERABILIDADE DOS ELEMENTOS EXPOSTOS NA REGIÃO DE SERRA PELADA, BARRA DO TURVO, BRASIL

RESUMO

A vulnerabilidade desempenha um papel crucial nas análises de riscos associados aos deslizamentos de terra, sendo fundamental para uma previsão adequada das consequências desses eventos. Neste estudo de caso, foi realizada uma avaliação quantitativa da vulnerabilidade para a área rural de Barra do Turvo localizada na cadeia montanhosa da Serra Pelada-Brasil. A região propensa à deslizamentos de terra possui 144 agregados familiares que se estabeleceram nas margens da rodovia Régis Bittencourt. Por meio de uma metodologia baseada em indicadores, foi considerada a intensidade dos deslizamentos e a resistência dos elementos expostos, sendo estes: as edificações, obras de arte especiais, vias terrestres e a população local. Os resultados indicaram que 93% das edificações apresentam elevada vulnerabilidade, enquanto 90% da população local possuem moderada vulnerabilidade, assim como as obras de arte especiais e a rodovia. Já as estradas rurais indicaram alta vulnerabilidade. Destaca-se a importância deste conhecimento para planejar estratégias de mitigação de riscos. Através da aplicação desta abordagem, foi possível a produção do mapeamento para região. Como conclusões, salienta-se a possibilidade de aplicação em outras regiões, além do potencial de uso pelos gestores públicos no planejamento territorial e proteção civil, direcionando ações voltadas à redução de risco.

Palavras-chave: Deslizamentos de terra. Intensidade dos deslizamentos. Resistência dos elementos expostos. Gestão de risco. Área rural.

INTRODUCTION

Landslides pose a significant threat on a global scale (RONG et al., 2020). However, despite available records, the true impact of landslides is often underestimated due to a lack of proper data, particularly in rural areas. Rural communities often face challenges like poverty, poor access to basic services, and natural resource dependency (PANDEY and JHA, 2012). This condition increases their vulnerability to landslides, making them more likely to suffer the impact of such events. In Brazil, this is a topic of great concern (SMYTH and ROYLE, 2000), particularly in areas where landslides are more prevalent, such as coastal areas and inland areas in the Southeast (LACERDA, 2004).

The consequences of a landslide are closely related to its magnitude and the value and vulnerability of the exposed elements, also known as elements at risk (BELL and GLADE, 2004). However, reducing the magnitude of landslides is a very complex task. Therefore, in the context of disaster risk analysis, it is essential to focus on studying the exposure and vulnerability of communities and infrastructure (BIRKMANN et al., 2017).

In this study, we developed an indicator-based methodology to assess the vulnerability of buildings, infrastructure, and local population, measured regarding landslide intensity and resistance of exposed elements. We then applied this methodology to the rural area of Barra do Turvo, located in the Serra Pelada mountain range, Brazil. However, it is a methodology that may be suitable for other regions, particularly areas with limited historical data on landslides. Also, mapping physical vulnerability makes it possible to identify critical points and can be used by authorities to develop strategies to reduce the risk of landslides, thereby increasing the population's resilience.

Methods for assessing vulnerability

Vulnerability is a word with a wide range of meanings since it has been used in multiple research fields (THYWISSEN, 2006). From a natural sciences and engineering point of view, vulnerability is defined as the degree of loss of an element or set of elements exposed to a landslide threat of a particular type and intensity. It is expressed on a scale that ranges from 0 (no loss) to 1 (total loss) (UNDRO, 1991). For buildings and infrastructure, the loss is determined by the extent of damage relative to the overall value of the structures. In the case of the population, it represents the probability that a specific life (the element at risk) will be lost, considering that the individuals are affected by the landslide (LI et al., 2010).

Assessing vulnerability makes it possible to identify the buildings, infrastructure, and communities most likely affected by landslides. However, it has to deal with a wide range of scenarios, given the considerable variation in potential damage levels and other factors such as volume and velocity, not to mention the availability or non-availability of historical data (CARDINALI et al., 2002).

In the literature, there is no standardized methodology for measuring the vulnerability of elements exposed to different types and magnitudes of landslides (GLADE and CROZIER, 2005). Typically, it is assessed in terms of vulnerability curves, damage matrices, and vulnerability indicators (KAPPES et al., 2012).

Vulnerability curves are mostly specific, displaying the interaction between the hazard intensity and the type of element at risk and providing quantitative data (COROMINAS et al., 2014). Damage matrices are qualitative methods consisting of ranked intensities and scaled damage levels, and they often rely on expert assessment or empirical data (PAPATHOMA-KOHLE et al., 2017). Both have the drawback of generalizing other factors that also impact vulnerability (KAPPES et al., 2012).

The third approach is vulnerability indicators, which reflect the capacity of a system to provide information on vulnerability and its resilience to withstand the impact of a hazard (BIRKMANN, 2006). It has the advantage of being simple and flexible, which makes it easy to use in different scenarios and by different users. The only challenge is selecting the indicators carefully and obtaining, standardizing, and evaluating the required data (KAPPES et al., 2012). Thus, in this research, indicators were employed as variables.

Previous studies that employed the same methodology for assessing vulnerability

Uzielli et al. (2008) presented a method for quantitatively assessing physical vulnerability scenarios that links the damage potential of a hazard to the exposed elements' capacity to deal with it. Thus, vulnerability is calculated as the product of the landslide intensity and the resistance of the elements at risk, with variables defined in ranges from 0 to 1, according to literature-based or user-defined criteria.

Li et al. (2010) presented a quantifying method that relies on two variables. The first (intensity) is related to the hazard, and the second (resistance) is related to the element. Intensity is calculated based on the velocity and depth of the landslide debris or the landslide-induced deformation of structures. Resistance is calculated both for structures and for persons. For structures, it is calculated according to the structure type, number of floors, and maintenance condition. For persons, it is based on education and the age of the population.

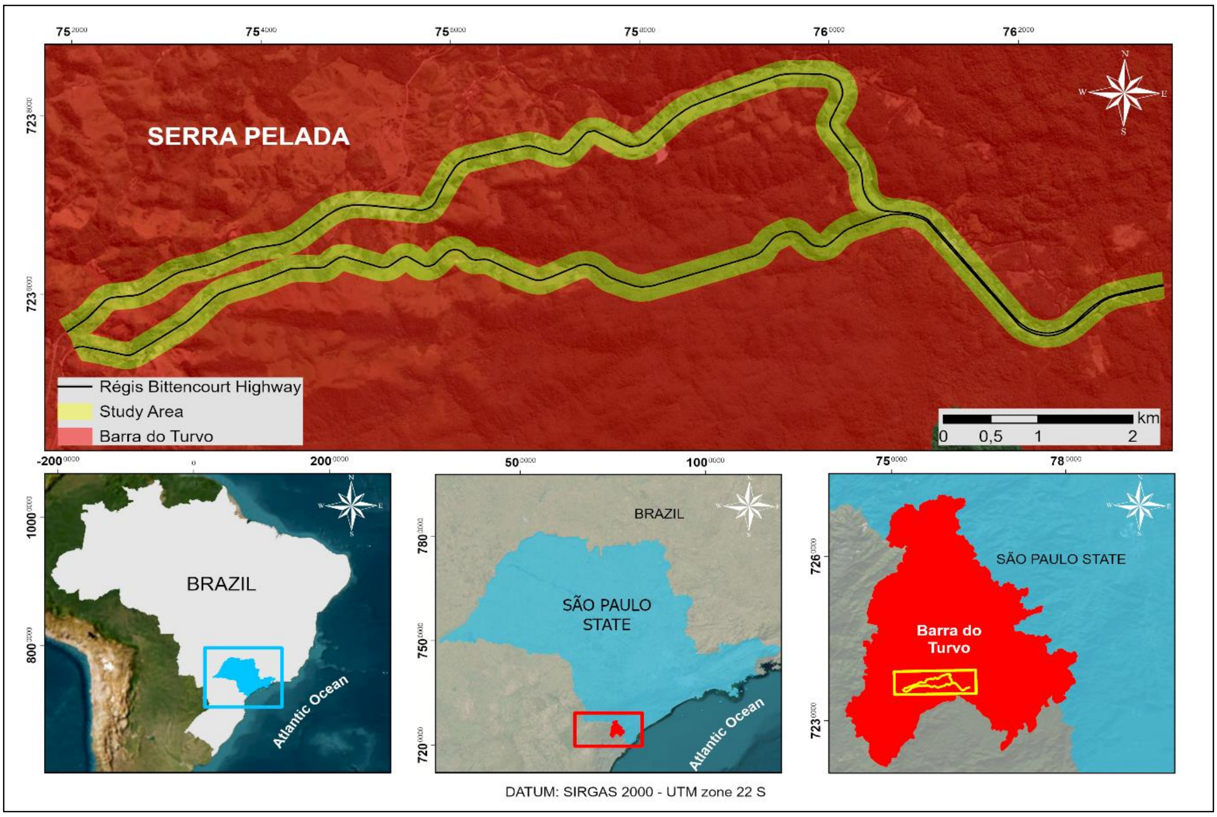
Peng et al. (2014) also presented a quantitative method for assessing vulnerability according to the landslide intensity and resistance of elements at risk. Here, intensity is estimated by considering aspects such as volume, velocity, sliding mass depth, and landslide height. For persons, resistance was calculated according to population density, age, education, and public investments. For public service utilities (communication, electricity, and water supply networks), roads, docks, and bridges, it was calculated based on the type of network, type of road (national, local, or rural), type of dock (cargo or passenger), and bridges' construction material (steel, concrete, brick, or stone). For buildings, it was based on structural typology, age, and number of floors.

Singh et al. (2019) presented a methodology for assessing the vulnerability of buildings in Uttarakhand, India, using an approach based on local indicators. It considers the landslide intensity as a function of velocity and volume and the resistance of buildings as a function of structural and non-structural elements. By applying a questionnaire to the local population, they identified fifteen indicators that could impact the vulnerability of buildings. They used the same equations proposed by Li et al. (2010) for resistance and vulnerability but also considered the distances between buildings and landslides.

STUDY AREA

The study area covers 7.3 km² of the Serra Pelada geological region, situated in Barra do Turvo (SP), in Southeast Brazil (Figure 1).

Figure 1 - Location and delimitation of the study area



Source: SIGRB, 2023. Compilation: The authors, 2023.

Serra Pelada belongs to the Serra do Mar escarpment, a section of the Atlantic Fold Belt. The morphostructural units in this area are supported by ancient crystalline rocks, both folded and faulted, resulting in rugged relief features (CBH-RB, 2019). With considerably long and steep slopes, along with deep and fairly narrow valleys, the area has an altitude range that extends from 100 to 200 meters in the lower areas (in contact with the Baixo Ribeira Tectonic Depression), to elevations that reach between 1,000 and 1,200 m in the highest sections. The average altitude ranges from 700 to 900 m (ROSS, 2002), with slope gradients ranging from 25° to 36° (SANTOS et al., 2018).

The climate is classified as humid subtropical with warm summer in the higher parts and humid subtropical with hot summer in the lower parts, according to the Köppen climate classification. It has a hot and humid season from September to March, with an average annual rainfall ranging from 1,500 mm to 2,000 mm and an average annual temperature of 21.5 °C (ROUSSELET-GADENNE, 2004).

These climate conditions, highly prone to heavy rainfall, plus the morphological characteristics of the region — where the middle and upper stretches of the Ribeira River and its tributaries flow through steep valleys with high slopes —create the perfect scenario for the potential occurrence of landslides and floods (DICKEL and BERRÍOS GODOY, 2016).

Barra do Turvo has 70% of its territory protected by conservation units (BIM, 2012). The study area covers a road reserve delimited as a 150 m stretch on either side of the 15 km of the Régis Bittencourt highway. This highway is the main corridor linking the most important economic centers in the Southeast to the South region of Brazil, with a high volume of users and goods transport (ICHIHARA, 2008). Since its construction, between 1957 and 1961, people have settled along the roadside and have built small villages. Nearly 60% of human occupation within the conservation units is confined to the highway's area of influence (CORTEZ et al., 2004).

With a population of 6,875 (IBGE, 2022), concentrated in rural areas, most people work in agriculture, livestock, and extractive activities (FRANÇA, 2005). The region has a medium level of human development, with a Human Development Index (HDI) of 0.641 and 13% of the population living in extreme poverty (IBGE, 2010).

The Serra do Mar is known for the occurrence of several landslides (NERY et al., 2015; CERRY et al., 2018), most often shallow translational slides (RIEDEL, 2010). The region's physical and socioeconomic environment, combined with the illegal occupation of the roadside, increases its vulnerability and directly influences the magnitude of the landslides' impact.

METHODS

We assessed the vulnerability of elements exposed to landslides in the study area according to the methodological flowchart in Figure 2.

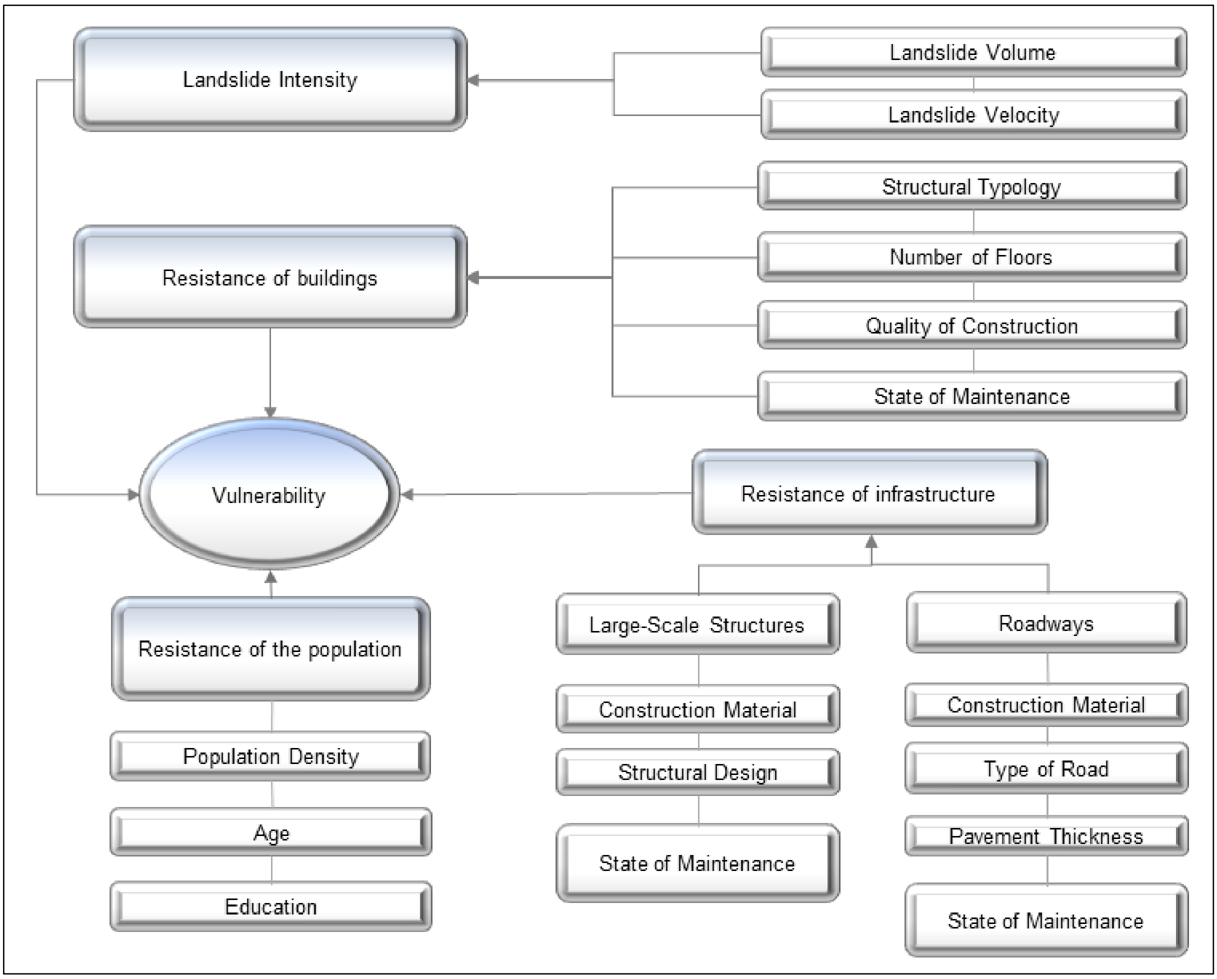
In our approach, we adapted the quantitative model proposed by Singh et al. (2019) — who, in turn, used an empirical equation applied by Li et al. (2010) —where vulnerability (*V*) is considered a function of the intensity (*I*) of the threat and the resistance capacity (*R*) of exposed elements to withstand it, as shown in Equation 1.

$$V = f(I,R) = \begin{cases} 2\frac{I^2}{R^2} & \frac{I}{R} \leq 0.5 \\ 1.0 - \frac{2(R-I)^2}{R^2} & 0.5 < \frac{I}{R} \leq 1.0 \\ 1.0 & \frac{I}{R} > 1.0 \end{cases} \quad (1)$$

Intensity (*I*) and resistance (*R*) are expressed in dimensionless terms with values from 0 to 1.

However, in the model proposed by Singh et al. (2019), vulnerability assessment is restricted to buildings only. Therefore, this study adapted this model to broaden the assessment's scope, covering infrastructure (such as Large-Scale Structures [LSS] and roads) and the local population. The methodology was then applied using Geographic Information Systems (GIS) to an area with a predominance of shallow translational slides.

Figure 2 - Methodological flowchart for assessing the vulnerability of elements at risk



Compilation: The authors, 2023.

Landslide intensity

Landslide intensity has been quantitatively determined according to a wide range of parameters, such as velocity, volume, depth, and area affected (OJEDA-MONCAYO et al., 2004). In this study, we defined intensity (I) as a function of landslide volume (V) and velocity (U) (CARDINALI et al., 2002), as shown in Equation 2.

$$I = f(V, U) \tag{2}$$

Parameters such as velocity and volume can be obtained using empirical, simplified analytical, or numerical simulation methods (LI et al., 2010). Given the lack of historical data on landslide intensity parameters in the study area, we used empirical estimations.

Initially, we used an image interpretation approach to make an inventory of Google Earth images (PSOMIADIS, 2020), which covered the period between 2012 and 2022. We also examined the reports provided by the highway concessionaire, Arteris S.A., which recorded the occurrence and location of landslides over the same period. We could identify the location, time, type, and number of landslides by matching the image interpretation with the concessionaire reports.

The volume of a landslide is a crucial parameter, as it determines the distance covered, the extent of the affected area, and the elements at risk possibly affected (MICHEL et al., 2020). It can be estimated using the landslide's average depth and surface area, and it is common to use empirical equations that define the relationship between volume and area (GUZZETTI et al., 2009).

For the calculation of the average volume of landslides, we used two different methods to determine the volume that best reflected the landslides in the study area — which had relatively smaller volumes than, for instance, debris flows or rockslides, as they were shallow translational slides affecting a top layer of soil. Based on geometric information from the polygons obtained from the inventory, we used Equations 3 and 4, which rely, respectively, on the empirical equation by Guzzetti et al. (2009) and the estimated slip surface depth proposed by Dias et al. (2022).

$$V = 0.074A^{1.450} \tag{3}$$

$$V = Ah \tag{4}$$

A is the landslide surface area and h is the slip surface, using a value of 1.0 m. According to Dias et al. (2022), slip surface depths ranging from 0.7 to 2.0 m have been observed in the Serra do Mar due to lithology variances. Results of the mathematical modeling that considered h equal to 1.0 m for the average depth of the slip surface in different areas, were the ones that corresponded fairly accurately with volumes of the events that were measured.

Velocity is another key parameter for determining landslide intensity. There are several models in the literature for assessing the velocity of landslides. However, these models often require many detailed parameters, which were unavailable in the study area. We, therefore, used a method proposed by Marinelli et al. (2022), which consists of a simple morphometric methodology based on a spatialization of the Energy Line method, to determine the velocity of shallow landslides at a regional scale. We ran the calculation procedure proposed by the authors in the Matlab software (MathWorks, version R2020a) to obtain the maximum velocities of each polygon based on the Digital Elevation Model (DEM) of the polygons, the length and the maximum and minimum heights (taken as the top and base of the landslide).

Once the average volume and average velocity of the polygons had been calculated, we estimated the intensity of the landslides using the landslide intensity matrix proposed by Singh et al. (2018).

Resistance of exposed elements

Resistance is related to an element's capacity to withstand landslides of varied intensities without suffering substantial damage. For structures, such as buildings, roads, and LSS, this parameter represents their physical resistance to the landslide movements. For the local population, it represents their resistance and evacuation capacity (PENG et al., 2014). For the calculation of resistance (*R*), we used the equation proposed by Li et al. (2010), which considers resistance as a function of multiple factors, as shown in Equation 5:

$$R = \left(\prod_{i=1}^{n} \beta_i\right)^{1/n} \tag{5}$$

Where β_i represents the i-th value of $n \geq 1$ resistance factors (expressed in dimensionless terms), thus contributing to the definition of different categories. The estimated values were classified into the three categories proposed by Singh et al. (2019), *i.e.*, low (R ≤ 0.5), moderate (0.5 < R ≤ 0.9), and high (0.9 < R ≤ 1.0) levels of resistance.

Spatial mapping and resistance factors of buildings

Since there were no records of the buildings within the study area, we mapped them using the QGIS software with the Mapflow plugin, a tool for detecting and extracting buildings from satellite images fed by semantic segmentation and deep-learning techniques (HRISTOV et al., 2023).

A total of 144 buildings were identified. Then, we cataloged each building using the Google Street View tool, which provided 360-degree panoramic images of the mapped areas. We have included in the analysis some buildings that were not within the road reserve but were close enough to be directly affected by a landslide.

A wide range of factors are proposed in the literature for the resistance of buildings (SILVA and PEREIRA, 2014; PAPATHOMA-KÖHLE et al., 2017; SINGH et al., 2019). However, the available data will ultimately determine which factors will be selected. We considered four resistance factors based on our mapping and previous research into the physical vulnerability of buildings (LI et al., 2010; SINGH et al., 2019).

β_{st} is the resistance factor for the structural typology — related to the type of construction material; β_{nf} is the resistance factor for the number of floors — used as a proxy indicator for the type and depth of the foundation because data was unavailable; β_{qc} is the resistance factor for the quality of the construction — it assesses whether the building complies with building codes, particularly in risk-prone areas; and $\beta_{sm}$is the resistance factor for the state of maintenance of the construction — it assesses whether the building is in good enough condition to do its job. Resistance factors and their respective categories were determined based on their potential resistance capacity when facing a landslide hazard on a scale from 0 (least resistant) to 1 (most resistant). Table 1 shows the categories for each factor and their respective ratings.

Table 1 - Resistance factors of exposed elements in the study area

Elements		Factors	Description	Rating	Source
Buildings		Structural typology (β_{st})	Concrete	1.00	Adapted from Li et al. (2010)
			Metal	0.80	
			Brick	0.50	
			Timber	0.10	
		Number of floors (β_{nf})	≥5.6	1.00	
			3.4	0.75	
			2	0.50	
			1	0.25	
		Quality of construction (β_{qc})	High	1.00	Adapted from Singh et al. (2019)
			Medium	0.50	
			Low	0.25	
		State of maintenance (β_{sm})	Excellent	1.00	Adapted from Li et al. (2010)
			Good	0.75	
			Average	0.50	
			Poor	0.25	
Infra struc ture	Road ways	Construction material (β_{cm})	Concrete	1.00	The authors, 2023.
			Asphalt	0.90	
			Cobblestones	0.70	
			Surface coating	0.50	
			Rammed earth	0.30	
		Type of road (β_{tr})	Highway	1.00	
			Secondary road	0.80	
			Unpaved road	0.50	
		Pavement thickness (β_{pt})	Thick	1.00	
			Medium	0.80	
			Thin	0.50	
		State of maintenance (β_{sm})	Excellent	1.00	
			Good	0.80	
			Average	0.60	
			Poor	0.30	
	LSS	Construction material (β_{cm})	Steel	1.00	
			Concrete	0.90	
			Timber	0.70	
			Masonry	0.60	
			Advanced	1.00	
			Standard	0.80	

		Structural engineering design (β_{sed})	Basic	0.60	
			Out-of-date	0.20	
		State of maintenance (β_{sm})	Excellent	1.00	
			Good	0.80	
			Average	0.60	
			Poor	0.40	
			Precarious	0.20	
Population		Population density (β_{pd})	0 - 1000	0.90	Adapted from Peng et al. (2014)
			1000 - 5000	0.60	
			5000 - 10000	0.30	
			> 10000	0.10	
		Age (β_{a})	0 - 13 14 - 59 ≥ 60	$\frac{Persons_{age\,(14\sim59)}}{Total\ persons}$	
		Education (β_{e})	Excellent	0.90	
			Good	0.80	
			Average	0.50	
			Poor	0.10	

Compilation: The authors, 2023.

Resistance factors of infrastructure

In the study area, infrastructure consisted of a 30 km stretch of the Régis Bittencourt highway, 300 m of the Ribeirão do Veado-Perebá local road, 5 km of rural roads, and the Large-Scale Structures (LSS) (seven bridges and three overpasses). Data on the highway and the LSS were obtained from the highway concessionaire, Arteris S.A., and data on the local roads and rural roads were obtained from aerial images. The highway is the most important piece of infrastructure within the study area because it is essential for the national-level traffic of people and goods. However, the local and rural roads were also considered because the former is the main access route to the urban area. At the same time, the latter plays a key role in rural communities' social, economic, and cultural development, providing access to services, connections, economic opportunities, and improved quality of life.

Given the limited number of studies calculating the resistance of roadways and LSS, we had to determine the relevant factors and their categories to assess the resistance of this kind of structure. Infrastructure resistance relies on the adopted engineering design standards, construction materials, and expertise. However, some of these data were unavailable, so we had to estimate the ratings through certain generalizations.

We have split the resistance analysis between roadways (highways, local roads, and rural roads) and LSS (bridges and overpasses). For roadways, we selected four resistance factors: β_{cm} is the resistance factor related to the type of roadway material — considering its durability and capacity to withstand heavy loads and weather conditions; β_{tr} is the resistance factor related to the type of road — certain road features can affect its resistance, such as the width of lanes, traffic density, and the presence of a shoulder; β_{pt} refers to the resistance factor for the pavement thickness — the thicker the paving, the greater its resistance tends to be; β_{sm} refers to the resistance factor for the state of maintenance — roads in a good state of maintenance tend to have greater resistance and durability. Table 1 shows the categories and their ratings for each resistance factor.

For LSS, we selected three resistance factors: β_{cm} is related to the construction material — it refers to its impact on the construction's resistance; β_{sed} is related to the structural engineering design — how the LSS was designed to withstand the loads and operational requirements expected; and β_{sm} is related to the state of maintenance — it refers to the impact of maintenance on the LSS resistance over time.

These definitions aim to ensure a broad scope for the methodology by considering different scenarios. Thus, even if one or the other is missing, these factors can still be applied to other parts of the world, considering regional variations.

Ratings assigned to the categories of each factor were also intended to cover different scenarios and conditions. Each category was defined according to the key aspects of the resistance and performance of roads and LSS. Ratings were determined based on technical studies and empirical experience, aiming to accurately represent the actual situation and promote the safety of roadways and LSS. These numbers can be reviewed and updated to keep up with new developments and ensure that the best practices and expertise are being applied. It is worth noting that different ratings may be required in different regions or contexts, considering the local conditions, available materials, and particular regulations. Therefore, flexible ratings are crucial to ensure that structures are adapted to the requirements of each location.

For the LSS, we defined the state of maintenance category (β_{sm}) based on monitoring reports for each LSS provided by the highway concessionaire, covering 2022. These reports have assessed the conditions of several components, such as slab, beam, mesostructure, infrastructure, pavement/entry point, and structural performance parameters. They assigned a technical score ranging from 0 to 1, which was used to define the state of maintenance category.

Resistance factors of the local population

Resistance of the local population is related to their capacity to withstand and evacuate in a landslide situation. According to Li et al. (2010) and Peng et al. (2014), resistance capacity is determined by a combination of some elements inherent to people, *i.e.*, physical and intellectual individual abilities to avoid or reduce a threat, and some external elements of the context, such as population density and the attention paid by the government, for example.

We calculated the population's resistance capacity by adapting the model proposed by Peng et al. (2014), considering three factors: population density for external elements, age for physical capacity, and education, taking into account the literacy level for intellectual capacity. The first one is β_{pd} (population density), which refers to the impact of population density on an individual's chances of escaping from a hazard of a given intensity (the higher the population density, the more difficult it is to escape due to possible overcrowding of escape routes, insufficient safe places, or challenges in coordinating mass evacuation events). The second one is the β_{a} (age) factor, which reflects the influence of age on the population's physical ability to resist a landslide; it considers that different age groups may have unequal physical abilities to deal with the consequences of a landslide (for example, younger people may be more agile to escape or resilient to withstand landslide conditions). Finally, the third factor is β_{e} (education), which refers to the proportion of illiterate people within the area of study; it considers the level of awareness about the risks of landslides and key preventive measures (people with greater awareness and better decision-making skills are more likely to react properly and efficiently in hazardous situations). Table 1 shows the categories of each resistance factor and their ratings.

We calculated the population density for the four census tracts comprising the study area using the number of people per km² available when the study was conducted, according to the 2010 census data (IBGE, 2010). The age factor has shown the lowest levels of resilience within some age groups, taking the 14 to 59 age group as a reference. It was calculated as the ratio between the adults (14 - 59) and the total number of persons in the area.

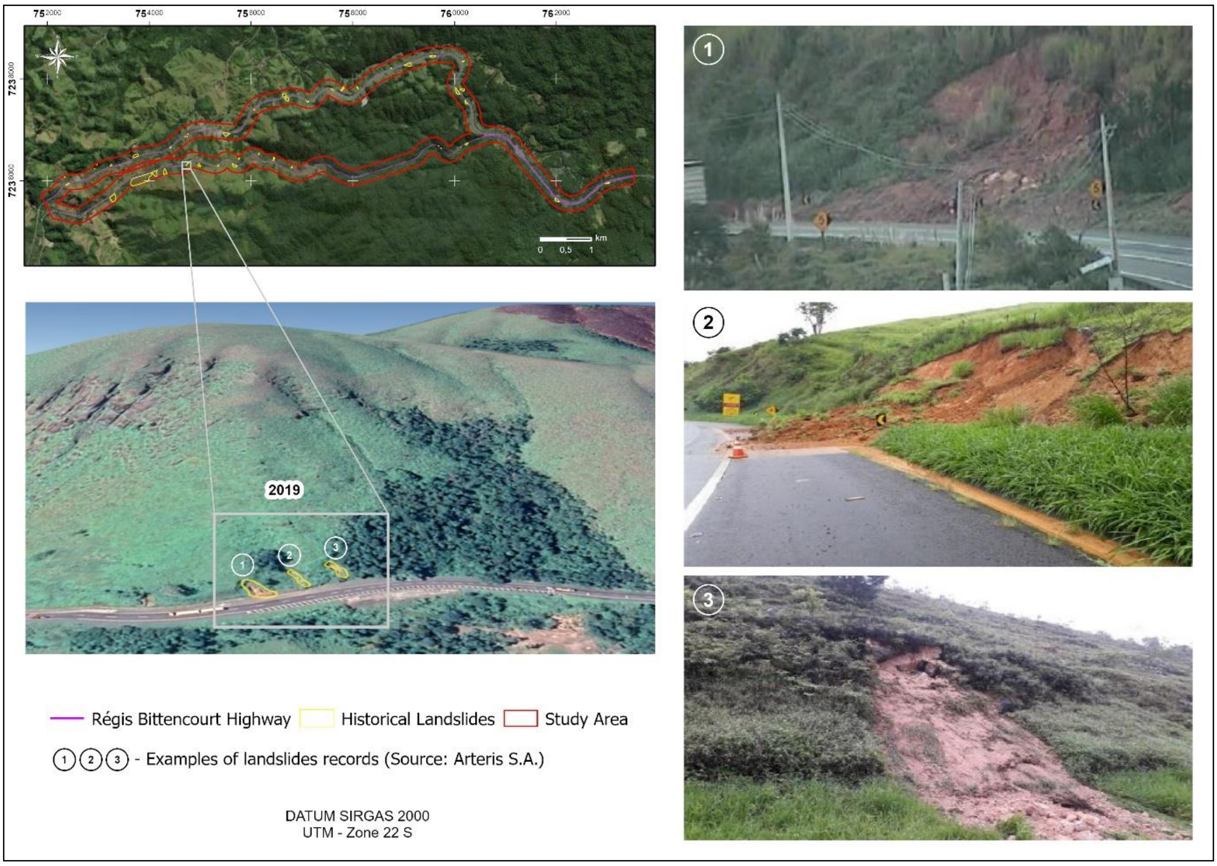
In this study, it should be noted that the analysis of resistance capacity considered the population at home since it is difficult to map exactly where people might be when a landslide occurs. In rural areas, or in those areas that border highways, it is usual for the population to be constantly on the move, either working on or traveling along the highway. This mobile nature makes it difficult to get data on the exact location and number of people each time. We therefore decided to focus on the resident population, which represents a stationary group that can easily be located. While this approach may fail to cover the population affected by a potential landslide fully, it still provides a baseline of the local community's resistance capacity.

RESULTS AND DISCUSSION

Landslide intensity within the study area

Google Earth images between 2012 and 2022, which formed the inventory of the study area, revealed 20 shallow translational slides (Figure 3).

Figure 3 - Survey of previous landslides within the study area



Compilation: The authors, 2023.

Based on the area of the polygons obtained from mapping previous landslides, we calculated two average volumes: 182.5 m³ using Equation 3 (GUZZETTI et al., 2009) and 205.8 m³ using Equation 4 (DIAS et al., 2022). We considered 205.8 m³ to prioritize safety as the average volume of landslides in the study area, which was classified in the "low" category, according to the Sarkar et al. (2015) model.

We then applied the geometric parameters of the polygons to a Matlab code based on the Energy Line method (MARINELLI et al., 2022), and we found a 5.26 m/s² estimated average velocity. According to the velocity scale proposed by Cruden and Varnes (1996), this one corresponds to an extremely rapid sliding.

Based on the landslide intensity matrix by Singh et al. (2019), the landslide intensity level (*I*) was classified as moderate, scoring 0.4 on a scale that ranges from 0 to 1.

Resistance of exposed elements within the study area

Resistance of buildings

We used data from mapping the 144 buildings in the study area to survey their characteristics, establish the resistance factors, and calculate the resistance of each building according to Equation 5.

When analyzing the resistance factors, we found that masonry comprised most buildings, accounting for 77% of the total. Timber was found in 30% of buildings, while concrete buildings accounted for only 2% of the total, limited to toll plaza buildings. Regarding the number of floors, the vast majority, *i.e.*, 96%, had only one floor, while 2% had two floors. The toll plaza buildings were classified as having three floors because of an underground floor, accounting for 2% of the total.

As for the quality of the buildings, we found that 64% were of poor quality, with significant flaws in design and construction. This outcome is linked to several factors: insufficient regulation, inadequate materials, inappropriate construction methods, and no inspection or supervision during the building phase. The state of maintenance had a similar result, with 64% of the buildings classified as poor. This reflects not only wear and deterioration but also carelessness or failure to maintain properly.

Looking at the type of buildings, we found that 88% were residential buildings, 4% were commercial buildings (including snack bars, fishing grounds, and a repair shop), and 8% were classified as other types of buildings (including churches, a toll plaza, and the buildings of the Rio Turvo State Park).

Resistance of buildings ranged from 0.20 to 0.93, where 2% of buildings had a high level of resistance ($R \geq 0.9$), 5% had a moderate level ($0.5 < R < 0.9$), and 93% had a low level ($R \leq 0.5$).

These buildings have a limited resistance capacity because most of them belong to a population of low socioeconomic status. Most of these buildings were built on unstable ground and have not been designed by engineering experts, so they have not adopted landslide-resistant construction techniques. As a result, most of the buildings analyzed proved to have limited resilience to such events.

Resistance of infrastructure

We assigned the resistance factor ratings and calculated the resistance of roads and LSS based on the characteristics and infrastructure data for the study area.

Resistance ratings for roadways ranged from 0.39 to 0.92, and those for LSS ranged from 0.81 to 0.90. The highway, local road, and rural roads were each assigned to a different resistance category, corresponding to high ($R \geq 0.9$), moderate ($0.5 < R < 0.9$), and low ($R \leq 0.5$) levels of resistance, respectively. None of the LSS had a low level of resistance ($R \leq 0.5$), 22% had a moderate level ($0.5 < R < 0.9$), and 78% had a high level ($R \geq 0.9$).

The highway's high resistance level reveals it was in good condition and had a solid structure capable of withstanding the expected loads and operational requirements. The local road's moderate resistance level suggests some limitations but still had decent safety and operational conditions. Conversely, rural roads were classified as having low resistance levels, indicating they may need careful consideration because of potential structural flaws.

As for the LSS, it is worth noting that none of them were classified as having low levels of resistance, which is a welcome sign of structural safety, particularly regarding the possibility of landslides. This rating suggests that the LSS has a reliable structure, capable of withstanding the expected loads and operational requirements. However, it is also worth noting that two of them showed only a moderate resistance level. Therefore, they may require more frequent supervision and some measures to ensure their durability and safety over time.

Resistance of the local population

Population density, the total density, and the density of each census tract showed numbers below 1,000 inhabitants/m², typical of rural areas, where population distribution is sparser than in urban areas. Thus, the value of 0.90 was assigned. We estimated the age factor by looking at the percentage of the population aged between 14 and 59 in each census tract based on data from the 2010 census. The proportion of residents aged between 14 and 59 was 0.59, 0.49, 0.59, and 0.55 for each census tract.

For estimating the education factor, we looked at the percentage of illiterate persons in each census tract. According to the Brazilian census, a person is considered literate when "able to read and write a simple note" (IBGE, 2010). We selected the age group of 15 and over to assess the literacy and educational level of adults, given that most people in this age group have already had the chance to go to school and develop basic reading and writing skills.

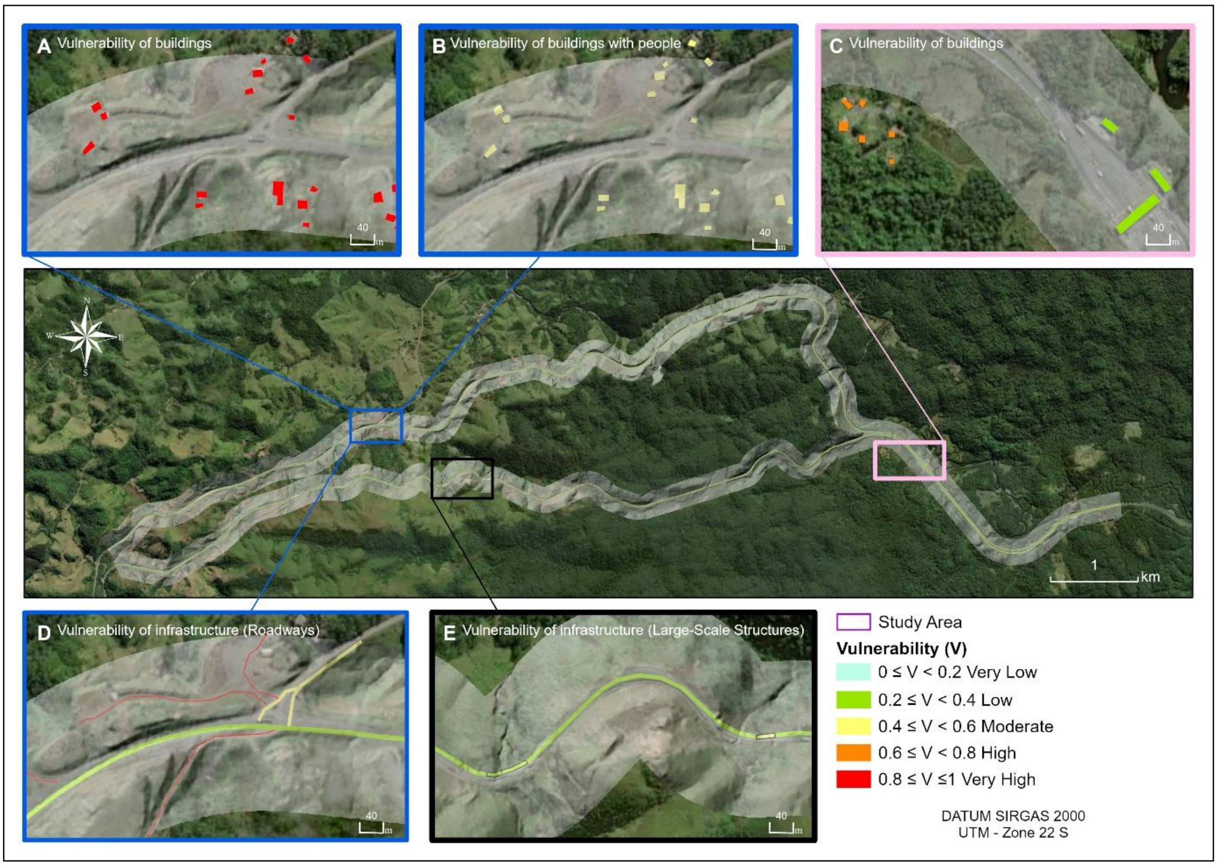
Illiteracy rates ranged from 13% to 27%. Thus, the education levels of all tracts were classified as "good", with a 0.80 rating. This means that most of the population in the study area had a decent level of awareness about the risks of landslides and the key preventive measures. This conclusion is supported by the fact that a significant share of the population can read and write, as shown by the low illiteracy rate.

Resistance ratings differed very little between census tracts, ranging from a minimum of 0.71 to a maximum of 0.75. Thus, the entire local population had a moderate resistance level ($0.5 < R < 0.9$), indicating average readiness, awareness, skills, and resources to deal with hazardous situations.

Vulnerability assessment

We have calculated the distribution of vulnerability based on the levels of landslide intensity (I = 0.4) on a scale ranging from 0 to 1 and the resistance levels of exposed elements, with a spatial distribution as shown in Figure 4 — which features the vulnerability of buildings (Figures 4A and 4C); the vulnerability of buildings with people (Figure 4B); and the vulnerability of infrastructure, roadways (Figure 4D), and LSS (Figure 4E).

Figure 4 - Map of the vulnerability of exposed elements



Compilation: The authors, 2023.

For the 144 buildings, vulnerability ranged from 0.37 to 1.00. Only 2% of the buildings had low levels of vulnerability ($V \leq 0.4$), 5% had moderate levels ($0.6 < V \leq 0.8$), and 93% of them were classified as having high levels of vulnerability ($0.8 < V \leq 1.0$). The lowest levels belong to the toll plaza buildings, designed according to safety and structural resistance criteria. As such, they were built in compliance with specific standards and regulations, including engineering and construction requirements, to ensure stability and resistance.

A prevalence of high levels of vulnerability reveals the fragility of the buildings in the study area. One of the main reasons for that is the low socioeconomic status of the local population, which leads to insufficient financial resources to spend on solid and safe buildings. Another reason is insufficient expertise and inadequate use of construction techniques. When expert professionals are not involved, inadequate materials or poor construction techniques may be used, compromising the buildings' stability and resistance.

Also, the location of these buildings needs to be considered, for they are often built in illegally populated areas. Thus, insufficient regulation and supervision of land use can result in the construction of buildings in hazardous places, which increases considerably the chances of serious damage to structures during landslide events.

For infrastructure, the highway had a 0.38 vulnerability level, the local road had a 0.47 level, and rural roads had a 1.00 level. These numbers reflect the vulnerability of roadways to damage caused by landslides. The highway had the lowest level of vulnerability, indicating that it was equipped with properties and safety measures that reduced its vulnerability to the consequences of a landslide. The local road, on the other hand, was slightly more vulnerable, showing less resilience. However, rural roads had the highest levels of vulnerability, meaning they were more likely to suffer substantial damage.

As for LSS (seven bridges and three overpasses), most structures had a 0.40 I vulnerability rating, suggesting a moderate resistance level. It means they can withstand the consequences of landslides and although they may suffer some damage, they are less prone to serious problems. However, two of the LSS showed a vulnerability level of 0.48, suggesting they are more vulnerable to the consequences of landslides and have a slightly lower resistance capacity than the others. Assessing the vulnerability of roadways and LSS is crucial to detecting the areas most at risk and designing preventive and mitigating measures to ensure that infrastructure remains safe and operational during a landslide.

The ratings for the local population's vulnerability ranged from 0.52 to 0.62. About 90% of the population had a moderate level of vulnerability ($0.4 < V \leq 0.6$), indicating that they were subject to a medium degree of risk in the event of a landslide. However, around 10% of the population was classified as having a high level of vulnerability ($0.6 < V \leq 0.8$), revealing that their living conditions expose them to greater danger and serious impact caused by landslides. These findings highlight the need to consider the distribution of the population's vulnerabilities when designing risk mitigation strategies. It is, therefore, essential to focus on protecting and assisting those most vulnerable if we want to reduce the impact of such events and guarantee the safety and well-being of the local community.

CONCLUSION

This study presents an assessment of the vulnerability of elements exposed to landslides in the rural area of Barra do Turvo, in the Serra Pelada, Brazil. We used an indicator-based methodology to define vulnerability as a function of landslide intensity and resistance of buildings, infrastructure, and local population. Intensity — which was determined according to the velocity and volume of landslides — was classified as moderate (I = 0.4), indicating that the region is likely to experience landslides. Resistance of exposed elements —estimated based on a range of selected factors — indicated that a large part of the elements has a moderate resistance level. We found that the vulnerability of buildings was predominantly high, and most structures were prone to substantial damage in the event of a landslide. Infrastructure showed some variation in its resistance levels, with the highway as the least vulnerable and rural roads as the most vulnerable. The local population also showed a moderate level of vulnerability. Still, around 10% of the population had a high level of vulnerability, which highlights the need for designing specific risk mitigation strategies for these vulnerable groups. Assessing vulnerability is crucial to identifying the most at-risk areas and targeting appropriate preventive and mitigating measures. Therefore, the methodology proposed in this study may be useful in other regions, helping to develop effective strategies to reduce the risk of landslides and improve the resilience of communities.

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