Landslide Risk Mapping in urban areas of the municipality of Moreno-PE

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Abstract

The most recurrent disasters in Brazil are related to geological and hydrological events, such as mass movement and floods that annually cause damage and victims in different regions of the country. These disasters can be related to several factors, as climatic variability and its extremes, aspects related to social problems, and the absence of public policies on urban planning and land use. Extreme events cause disasters on every continent, but in developed countries, the number of victims is usually lower when comparing to similar cases in developing countries. In this sense, Brazil has created laws that establish governmental attributions and guidelines at federal, state, and municipal levels. These laws, highlighting the Statute of the Cities (Law No. 10.257/2001), the National Policy for Civil Protection and Defense (Law No. 12.608/2012) and, the most recent, the Statute of the Metropolis (Law No. 13.089/2015), intend to manage and reduce risks and disasters through public policies for urban and territorial planning and preventive actions. Therefore, this work has as main objective to present the landslide risk mapping in occupied areas of Moreno municipality. The study area, Moreno, is in the Recife Metropolitan Region. Moreno has an area of 191.3 km² and a population of 62,784 people. The region is constituted geomorphologically by steep hills and flood plains. It was disorderly occupied that contributes to the occurrence and predisposition of processes related to landslides, erosion, falling blocks, and flooding. The predominant geology is the Crystalline Basement composed of migmatitic-gneiss rocks (orthogneisses of granitic and dioritic composition, migmatized). The risk situation of 8 sectors, distributed throughout the city, was evaluated. The study area has a total of 1.57 km². The semi-quantitative methodology proposed by GEGEP/UFPE was applied. It bases on previous experiences, associating the susceptibility from information about geological-geotechnical, geomorphological, land use, and occupation. To assess the consequences, associations between the elements at risk and their vulnerability through physical-environmental, socioeconomic, and cultural indicators, were made. It was found the degree of risk by employing a matrix that correlates hazards and consequences. The eight sectors of risk were divided into fifty subsectors, and then the risk degree was defined over these territorial units. The results found eight subsectors as a very high-risk degree, twenty-five as a high, sixteen as a medium, and one as a low. The adopted methodology well represented the field conditions.

1 INTRODUCTION

Risk mapping is an important management public policy tool for the cities, states, and countries' governance. It allows hierarchizing problems, assessing the investment costs, and supporting negotiations with the community.

The Statute of the Cities (Law nº 10.257/2001), the National Policy for Civil Protection and Defense (Law nº 12.608/2012) and, the most recent, the Statute of the Metropolises (Law nº 13.089/2015) meet the various guidelines of the Brazilian laws that aim to promote the development of public policies for disaster risk reduction and planning of land use, occupation and parceling in cities.

In 2012, the Brazilian Federal government created the Risk Management and Disaster Response Program. In this program, the efforts to prevent disasters stand out and it was structured to identify the main disasters that occur in the country.

Within this context, this work is one of the results of the project entitled “Vulnerability and risk assessment in susceptibles areas to landslide and floods in Pernambuco", which is a technical cooperation between a Ministery of the Brazilian Federal Government and the Federal University of Pernambuco (UFPE) through the Geotechnical Engineering Group for Hillsides, Plains and Disasters (GEGEP) coordinated by Professor Dr. Roberto Quental Coutinho.

For a better understanding of this work, it is essential to present the main definitions used in the risk analysis.

Risk is the measure of the probability and severity of an adverse effect on health, property, or the environment. Risk (R) is often estimated by the result of the Hazard (H) of a phenomenon with a specific magnitude to happen multiplied by the Consequences (C) that can result from this phenomenon, where C depends on the Vulnerability (V) and the Exposed elements (E). This definition is widely recognized by Fell et al. (2008), Corominas et al.(2014), and UNDRR (2019), being mathematically expressed by Equation 1.

$$R = HxC \qquad \text{Where: } C\ (ExV) \qquad (1)$$

This paper has as main objective to present the landslide risk mapping in occupied areas of Moreno municipality, in Pernambuco State, Northeast Brazil.

1.1 Socio-environmental disasters in Brazil

The Technological Research Institute of São Paulo State (Macedo e Martins, 2015) revealed that Brazil has registered 773 cataloged disaster events from 1988 to April 2015, constituting 3,396 fatalities.

According to the Database of Emergency Events (EM-DT), Brazil registered 61 deaths mainly caused by floods and landslides in the first 40 days of 2020. The Brazilian States of Minas Gerais and Espírito Santo were the ones that suffered most with damages from the heavy rains. In the city of Belo Horizonte, according to the National Meteorology Institute (Inmet), rain reached record levels in January. In this month, the precipitation volume was the highest in 112 years, around two times the average volume for January.

The study developed by IBGE (2018) has other data to be considered. It presents an analysis of the growth index of the population exposed to natural disaster risk and also the characterization of these vulnerable populations. According to this study, Brazil has 8,270,127 people living in disaster-prone areas. Pernambuco State has 829,058 people living in disaster risk areas.

In the study area of this work, Moreno, IBGE accounts that 9, 373 people live in risk areas, which corresponds to 16,7% of the city total population.

2 METHODOLOGY

The described methodology hereafter is an improvement on the methodology presented by Coutinho et al (2016).

Forms application is performed in the field as activities to gather information. It is recommended the study regions' division (nominated sectors) into subregions (subsectors); thus, it enables the analysis to be made on homogeneous conditions areas. This procedure allows to obtain more refined evaluations and better representation of the areas.

Hereafter, it will be presented the main work stages adopted in this methodology: I. Activity planning; II. Agreement with the municipality; III. Collection of pre-existing data; IV. Recognition visits; V. Choice of the pilot sector; VI. Subsectors delimitation; VII. Survey of consequences and susceptibility; VIII. Structuring the database; IX. Data analysis; X. Field validation of the analyzed data; XI. Replication of the processes conducted in the pilot area in the other sectors; XII. Analysis of the results of all subsectors; XIII. Proposals for structural interventions in areas of high and very high risk; XIV. Generation of products (maps and reports).

The work scale for the development of activities in the field must be 1:2000.

2.1 Methodology to analyze vulnerability in mass movement areas

Consequences are the possible results that arise from the occurrence of a landslide in terms of loss, disadvantage or gain, damage, injury, or loss of lives (Fell et al. 2008), Equation 1.

Due to the socio-economic conditions of Moreno, the authors determined that the elements at risk are directly associated with the vulnerability assessment. In this sense, the same vulnerability degree was associated with the consequences, since, if a landslide occurs, the damage is integral (total) for buildings, people, and the environment.

The following elements at risk were determined: the quantity of building, demographic density, and environment.

To define the vulnerability, it was determined two dimensions that grouped several indicators to obtain the necessary information for such analyses.

Physical-environmental dimension: 1. Building Characteristics; 2. Characteristics of access to the building; 3. Characteristics of access to the subsector; 4. Building location; 5. Basic infrastructure.

Socioeconomic and cultural dimension: 1. Household income; 2. Mobility capacity/autonomy; 3. Education level; 4. Access to the media; 5. Social problems; 6. Community organization and leadership; 7. Training of residents; 8. Distance from support points in the event of a disaster.

A systematic analysis of the vulnerability, similar to the one adopted here, is observed in the work of Graziano and Rizzi (2016). The authors propose the construction of a system of indicators using variables to analyze economic, social, and environmental vulnerability.

Based on data from government agencies, on-site visits, surveys carried out and the researchers' experience, sub-indicators were generated for each indicator. Forms were prepared to collect these factors in the field.

Interviews with residents of at least 25% of the houses must be conducted in the study sectors to collect information. These interviews with the population intended to know the local reality.

For example, Table 1 presents a sub-indicator of the indicator "Building characteristics", its intervals, degrees, weights and justifications.

2.1.1 - Determining the vulnerability degree

Each indicator is analyzed based on the identification of each sub-indicator degree that will be calculated by the weighted average of its intervals. The factors were rated 1 (low), 2 (medium), 3 (high), 4 (very high), and, as already mentioned, each sub-indicator is assigned weights.

The mathematical model for analyzing the each sub-indicator degree is given by Equation 2:

$$GVSub = GintSubxPSub \quad (2)$$

$GVSub$ = degree of vulnerability of the sub-indicator;

$GintSub$ = degree of vulnerability of the sub-indicator interval. This value is obtained with the arithmetic average of the buildings interviewed in each subsector;

$PSub$ = sub-indicador weight.

Table 1. Indicator composition example

Indicator: Building characteristics				
Sub-indicator	Interval	Degree	Weight	Justification
Building type	Detached House	V1	0,2	The proximity of the houses and the number of people transiting in these spaces
	Conjugated housing	V2		
	Comercial building	V3		
	Churches, public buildings, schools	V4		

The degree of vulnerability of the indicator is obtained by the sum of each sub-indicator that was obtained by Equation 1, as shown in Equation 3:

$$\mathrm{GVind} = \sum \mathrm{GVsub} \quad (3)$$

$GVind$ = degree of vulnerability of the indicator;

$GVSub$ = degree of vulnerability of the sub-indicator.

The degree of vulnerability of each indicator permits to obtain the vulnerability of each dimension. Through these, it is possible to reach the final degree of vulnerability. The degree of vulnerability of the dimension is calculated by summing the indicators multiplied by their respective weights, as shown in Equation 4:

$$\mathrm{GVD} = \sum \mathrm{GVindxPi} \quad (4)$$

GVD = degree of vulnerability of each dimension (physical-environmental, socio-economic and cultural);

$GVind$ = degree of vulnerability of the indicator;

Pi = attributed weight for each indicator.

The sum of the weights of all indicators of each dimension is always equal to 1.0.

Finally, the final degree of vulnerability is reached for each subsector; it is determined by the average of the results obtained for each dimension, according to Equation 5:

$$\mathrm{GVf} = \frac{(\mathrm{D1xPd1})+(\mathrm{D2xPd2})}{\mathrm{Pd1+Pd2}} \quad (5)$$

GVf = final degree of vulnerability;

$D1$, $D2$ = vulnerability of the corresponding dimension;

$Pd1$, $Pd2$= attributed weight to each dimension.

The sum of the weights of the two dimensions is equal to 1.0.

The degrees of risk were classified into four ranges to evaluate the degree of vulnerability, as shown in Table 2.

Table 2. Representation of the classes to classify the final degree of vulnerability

Degree	Class
1 (low)	≤ 1,75
2 (medium)	> 1,75 a ≤ 2,5
3 (high)	> 2,5 a ≤ 3,25
4 (very high)	> 3,25 a 4,0

2.2 Methodology for susceptibility analysis in mass movement areas

For the methodology, field data sheets were prepared that allowed standardizing the data to be collected. It was taken into account the main groups of attributes that affect the slopes stability and erosion processes. The following indicators were determined: Geological-Geotechnical, Geomorphology, and Land Use and Occupation. Sub-indicators associated with the susceptibility characteristics for mass movements were generated from these three characteristics, as shown below.

In this work, there was difficulty in obtaining in detail some parameters related to the hazard, such as intensity, volume, and history of landslides. Due to this fact, the susceptibility to landslides was adopted according to its factors conditioning.

Geological-Geotechnical: 1. Geological formation; 2. Structural features; 3. Geotechnical profile (structure, lithology and texture); 4. Pedological characteristics; 5. Evidence of movements.

Geomophology: 1. Relief; 2. Hillside overview: height (m), extension (m) and slope angle (°); 3. Hillside curvature class: vertical and horizontal; 4. Slope cut/landfill view of the hillside: height (m), extension (m), width (m) and slope angle (°).

Land Use and Occupation: 1. Occupation category (occupation stage, occupation mode, predominance of buildings, building pattern); 2. Surface coverage (type of surface coverage, percentage of deforestation); 3. Treatment condition (slope lining condition, slope percentage that has lining, condition of the containment structure and percentage, drainage system condition and percentage); 4. Anthropic factors (surface drainage system, direction of the rainwater collection system from the roofs, sewage destination, water supply and aggravating factors).

The sub-indicators had intervals associated with a scale of four terms, 1 (low), 2 (medium), 3 (high), 4 (very high). According to the importance in the process, each indicator had an associated weight. This scale is related to the probability of a dangerous process to happen. Thus, 1 (low) refers to the low potential for the processes development; 2 (medium), the susceptibility factors in the subsector are of medium potentiality for the processes development. In this class, the presence of some instability evidence(s); however incipient(s); 3 (high), the susceptibility factors in the subsector are of high potentiality for the process development. The significant presence of instability evidence(s) is observed; finally, 4 (very high), the susceptibility conditions are of very high potentiality for the process development.

2.2.1 Analysis of the susceptibility degree

The degree of susceptibility of each indicator will be calculated based on the identification of the degree of susceptibility for each sub-indicator. Each sub-indicator will be calculated by the weighted average of its intervals. The factors were given ratings 1 (low), 2 (medium), 3 (high), 4 (very high). For each sub-indicator was attributed weight. The mathematical model for analyzing the degree of susceptibility of the indicator is given bellow:

$$\mathrm{GSSubInd} = \frac{\sum \mathrm{PixInt}}{\sum \mathrm{Pi}} \quad (6)$$

GSSubInd = degree of susceptibility of the sub-indicator;

Pi = attributed weight;

Int = interval sub-indicator.

The degree of susceptibility of the indicator is obtained by summing each sub-indicator determined with Equation 5, as shown in Equation 7:

$$\mathrm{GSind} = \sum \mathrm{GSub} \quad (7)$$

$GSind$ = degree of susceptibility of the indicator;

$GSSub$ = degree of susceptibility of the sub-indicator;

Finally, the final degree of susceptibility for each subsector is determined by the average of the result obtained for each indicator, according to Equation 8:

$$\mathrm{GSf} = \sum \mathrm{GSindxPi} \quad (8)$$

GSf = final degree of susceptibility; $GSind$ = degree of susceptibility of the indicator;

Pi = attributed weight to each indicator.

The sum of the weights of all indicators is equal to 1.0.

The degrees of risk were classified into four ranges to assess the susceptibility degree, presented according to table 2 mentioned above.

2.3 Risk Degree Assessment

The correlation matrix used to determine the degree of risk for mass movement processes (susceptibility vs consequences) is shown in Table 3.

Table 3. Matrix used to assessment and determination of the risk degree (AGS, 2007)

EVENT / PROBABILITY	CONSEQUENCES FOR PROPERTIES/POPULATION			
	Very High	**High**	**Medium**	**Low**
Very High	Very High	Very High	High	High
High	Very High	High	High	Medium
Medium	High	High	Medium	Medium
Low	Medium	Medium	Medium	Low

3 STUDY AREA CHARACTERIZATION

The municipality of Moreno is located in the Metropolitan mesoregion and in the Recife Microregion of Pernambuco State (Figure 1). It is estimated that in 2019 the population of the municipality corresponds to 62,784 people.

- Climate

Moreno has an average annual rainfall of 1309.9 mm and an average temperature of 26 ° C. Regarding the temporal precipitation distribution, the rainy season is concentrated from March to August.

This period is considered an alert for civil defenses in Recife Metropolitan Region. The maximum monthly rainfall is recorded in May, June, and July. The period from September to February presents, on average, low monthly rainfall. Regarding the temperature, it is possible to observe a minimum and maximum variation around 18 ° C and 32 ° C, respectively.

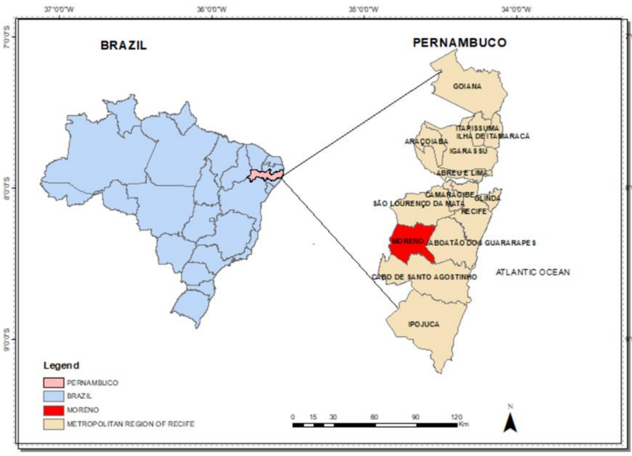

Figure 1. Location of Moreno municipality

- Geology and Geomorphology

The geological and geomorphological dynamics of the study area, the urban core relief is practically formed by hills, gneisses hills and weathered mantle. The crystalline basement appears in all areas that have been visited in the field. The visits were made in different places, even so, always in contact with gneiss outcrops. The crystalline basement is composed of migmatitic-gneiss rocks (orthogneisses of granitic and dioritic composition, migmatized). With granitic and dioritic plutonic rocks as protoliths that have undergone metamorphism, there are traces of possible compressional stresses in two directions, 30º with each of the preferred fracture directions found in the rocks.

The sectors geomorphology varies widely from flood plains to hills with steep slopes. The shape of the predominant landform is of a dissected hill with a straight tabular top, the degree of carving in the valley is weak (20 to 160 m) and the slope forms considered as concave / convergent and convex / divergent.

- Geotechnical Characterization

The geotechnical characteristics were obtained through undisturbed (cubic blocks 0.3x0.3x0.3 m) and disturbed samples. The material presented as a silty clay with a liquid limit and a plasticity index of 44% e 24%, respectively. Through the oedometer test results, it was possible to notice that the soil is considered conditionally collapsible with collapse occurring when additional stress greater than the initial effective stress is applied. The block collected in the young residual soil presented higher cohesion (44 kPa; 8,3 kPa) and friction angle (39º) values than the block collected in the mature residual soil (17,3 kPa; 6,7 kPa e 30º). This direct shear test was performed with samples at their natural condition and under saturated condition.

- Characterization of Mass Movement Processes

Through recorded occurrences and by the observation itself, it was verified the predisposition to occur processes related to mass movement (landslides, erosion, block fall) and flood. The landslides observed were occasional, usually cut slopes that slid behind houses. A large proportion event was not registered in the municipality. The erosion processes identified were limited, more frequently, to laminar erosion, and some grooves. In some sectors, there was a tendency for the block to fall, even though there was no record of a process like this in the area. Flood is one of the phenomena with the greatest concern. The city has already experienced events of great magnitude, where the force and speed of the water destroyed houses, bridges and left hundreds homeless.

4 RESULTS AND ANALYSES

In the overall study of the project, analyses were carried out for two processes: floods, and mass movements. However, for this work, only the results for the mass movement process will be presented.

Eight sectors of mass movement risk were identified. Thus, 50 subsectors were obtained.

In Coutinho et al. (2016), the authors conducted interviews in all existing buildings in their risk sectors. Given the logistical and operational difficulties found by the authors, this study defined the adoption of a sample of interviews with 25% of buildings in the high-risk sector, a total of 683 buildings. It is worth emphasizing that the responses of the interviews are not related only to the respondent, but to all the members who inhabit the building. Thus, it was built a panorama where 2,222 people participated directly and indirectly in the survey.

- *Degree of consequences for mass movements:*

In the municipality, nineteen subsectors were diagnosed with a high consequence degree, twenty-nine subsectors with a medium, and two with a low. As the municipality of Moreno has areas of slopes that go from the most central and developed to the most peripheral regions associated with the fact that the river cuts through the entire city, the risk sectors are distributed throughout the urban perimeter. Thus, it is possible to notice a high density of buildings and population on the slopes. The social contrasts, which influenced the degrees of socioeconomic and cultural vulnerability, have a significant relationship in the effects of the consequences of a mass movement.

Even though vulnerability is, generally, specific to hazard, certain factors, such as poverty, lack of public policies and social support mechanisms, will aggravate or affect the levels of vulnerability, regardless of the type of hazard, as stated by Cardona et al. (2012). This statement indicates how important it is for municipal public managers to take steps to reduce vulnerability in the sectors identified in this study.

- *Final Degree of Susceptibility to mass movement*

The analyses resulted in sixteen subsectors classified as medium susceptibility, twenty-three classified as high, ten as very high, and one as low susceptibility. The particularities of the studied area geology added to the geomorphological formation, and, mainly, to the human action interfering in the environment, among many other factors, were decisive for the increase in the final degree of susceptibility. Humans interfere in the environment through actions such as removal of surface cover leaving the soil exposed, vertical cuts altering the slope geometry making it more unstable, inappropriate disposal of garbage and rubble on the slopes, water release served on the surface of the slopes.

- *Risk Degree to Mass Movement:*

Adopting the correlation matrix proposed by AGS (2007), 8 (16%) subsectors were identified with a very high degree of risk, 25 high (50%), 16 (32%) medium and 1(2%) low. Figure 2 presents the final risk map. Table 4 presents an integrated analysis of the results obtained.

High-risk areas correspond to 50% of the subsectors identified. It stands out that some sub-sectors are on the boundary of evolving to a very high degree of risk. It was observed that susceptibility, especially the indicator of land use and occupation, added to physical-environmental, and socio-economic and cultural indicators vulnerability contributed significantly to this result. Coutinho et al. (2019) add that the changes in urban spaces, made by the population in the pursuit of adequacy to pressing needs, have caused human and environmental damages.

Table 4. Risk degree to mass movement.

Sec	Subsec	D. V.	D. S.	D. R.
4	401 and 402	M	M	M
	403	M	H	H
5	501 and 503	H	V. H.	V. H.
	502	M	M	M
6	601, 602 and 604	H	H	H
	603, 605 and 606	M	M	M
7	701 and 702	H	H	H
	704	H	V. H.	V. H.
	705 and 706	M	H	H
	707	M	M	M
8	801	L	M	M
	802, 803, 805, 809 and 810	M	H	H
	806, 807, 808 and 817	M	M	M
	809 and 810	M	H	H
	813, 815 and 816	H	V. H.	V. H.
9	901 and 902	M	M	M
	903, 905 and 906	M	H	H
	904 and 907	H	H	H
10	1001 and 1004	H	V. H.	V. H.
	1002 and 1005	M	V. H.	H
	1003 and 1009	M	M	M
	1006	M	H	H
	1007 and 1008	H	H	H
	1010	L	L	L
11	1101 and 1102	H	H	H

Sec = sector; Subsec = subsector; D. V. = degree of vulnerability; D. S. = degree of sustainability; D. R. = degree of risk; L = low; M = Medium; H = High; V. H. = very high

Therefore, it is extremely important that the city authorities responsible for risk and disaster management use this risk mapping and all the information presented in this work to define an efficient risk policy through structural and non-structural actions;

itt will reduce risks and disasters as recommended in the Sendai Framework (UNDRR, 2015) and, more recently, in the Words in Action guidelines: Development of national disaster risk reduction strategies (UNDRR, 2019).

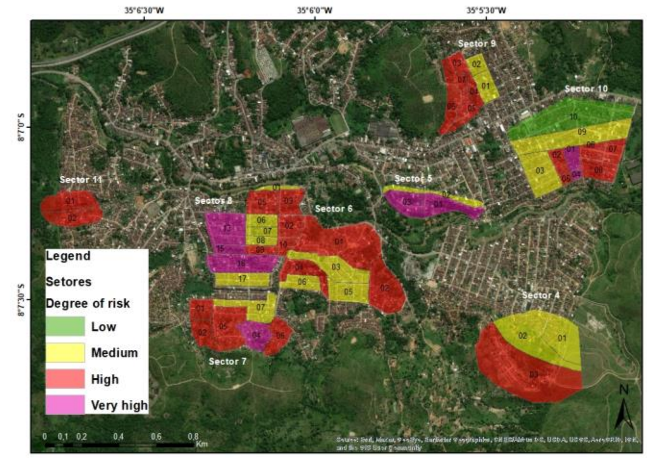

Figure 2. Risk map for mass movement of Moreno municipality

5 CONCLUSIONS

The adopted methodology was used for the assessment and determination of the landslide risk degree in Moreno. Shallow and punctual landslides were observed, usually found on slopes of cuts that rupture behind houses.

The methodology was improved from previous studies, allowing optimization of the fieldwork, besides providing better details of the factors and information, which implies a careful analysis of the probability of occurrence of mass movements and its consequences.

Eight sectors of risk to mass movements were studied and divided into 50 subsectors. The authors identified 8 (16%) subsectors where they classified the risk degree as very high, 25 (50%) as high, 16 (32%) as medium, and 1 (2%) as low. It was observed that the study area has a high population density and buildings; approximately 2,222 people live in risk areas.

The municipal management can use the maps and information generated as an urban planning instrument, indicating priority areas for carrying out interventions, whether structural or non-structural.

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