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Utilization of UAV in the evaluation of susceptibility to mass movements in urban expansion areas in the municipality of Rio Piracicaba-MG, Brazil

Utilisation d'UAV dans l'évaluation de la sensibilité aux mouvements de masse dans les zones d'expansion urbaine de la municipalité de Rio Piracicaba-MG, Brésil

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ABSTRACT: This work evaluates the susceptibility to mass movements in the Brazilian city of Rio Piracicaba (Minas Gerais State), through geological-geotechnical data, obtained through laboratory tests, and digital cartographic products, generated from the electronic treatment of aerial images, obtained by aerophotogrammetry with UAV, and SRTM supports. The territory presents an urban expansion with irregular settlements, advancing over steep slopes areas, and a history of mass movements, in a region under high precipitation intensities. Computational subsidies were developed for GIS' terrain modeling, such as the Digital Elevation Model and the slope ingrimity map of the terrain. This information was associated with physical and resistance parameters of the local soil, obtained from geotechnical tests with undisturbed samples from the areas of interest, with characteristics of young and mature residual soils, according to the municipal reality. Therefore, slope rupture's simulations were performed to assess the safety's degree of occupied areas in high slope regions.

RÉSUMÉ : Ce travail évalue la sensibilité aux mouvements de masse dans la ville brésilienne de Rio Piracicaba (État du Minas Gerais), à travers des données géologique-géotechniques, obtenues par des tests en laboratoire, et des produits cartographiques numériques, générés à partir du traitement électronique d'images aériennes, obtenues par aérophotogrammétrie avec Prise en charge des UAV et SRTM. Le territoire présente une expansion urbaine avec des habitations irrégulières, progressant sur des zones de fortes pentes, et une histoire de mouvements de masse, dans une région à fortes intensités de précipitations. Des subventions informatiques ont été développées pour la modélisation du terrain du SIG, comme le modèle numérique d'élévation et la carte des pentes du terrain. Ces informations étaient associées à des paramètres physiques et de résistance du sol local, obtenus à partir d'essais géotechniques avec des échantillons non perturbés des zones d'intérêt, avec des caractéristiques de sols résiduels jeunes et matures, selon la réalité municipale. Par conséquent, des simulations de rupture de pente ont été effectuées pour évaluer le degré de sécurité des zones occupées dans les régions à forte pente.

KEYWORDS: Urban Planning. Remote Sensing. Areas of Susceptibility. Slopes. Informal Settlements.

1 INTRODUCTION

Contemporary cities face the challenge of disorderly growth and the emergence of informal settlements, the consequences of deficient or non-existent planning. In this way, the anthropic action gives the natural space new characteristics that generate or accentuate its instability in the face of environmental phenomena, such as rains, erosion, seismic events, etc., increasing the probability of occurrences such as morphodynamical deflagrations on slopes, often associated with periods of high rainfall and lack of urban infrastructure.

In view of the aforementioned reality, it becomes evident the need for the adoption of city space management procedures in order to improve the quality of life of the population, ensuring their physical integrity and the perception of security in these spaces. In this process, remote sensing using UAVs presents itself as an accessory resource of satisfactory efficiency, in the acquisition of auxiliary data for the assessment of relief features, management of land use and occupation and city planning.

Thus, this work aims to evaluate areas of urban expansion in the municipality of Rio Piracicaba (MG), in order to identify regions susceptible to mass movements, through the collection of data by suborbital remote sensing with UAV, geological-geotechnical investigations and computer simulations. The main motivators of the study on this territory are the process of rapid urban expansion, resulting from irregular settlements, advancing

over steep slopes and marked by a history of mass movements, especially the shallow translational landslides, with planar rupture surface, in a region of high precipitation (Assis 2017).

The modeling of the information aims at the development of guiding subsidies to the Public Sector, designed to meet the guidelines of the Brazilian National Policy for Civil Protection and Defense (PNPDEC), instituted by federal law No. 12608 of 2012, which, among its main objectives, aims to "Promoting the identification and assessment of threats, susceptibilities and vulnerabilities to disasters [...], [as well as] combating the occupation of environmentally vulnerable and at-risk areas and promoting the relocation of the population residing in these areas" (Brazil 2012).

2 THEORETICAL REFERENCE

2.1 Terrain Relief Modeling

The Digital Elevation Model (DEM) is the digital representation of a stretch of the Earth's surface with a view to its morphological description, identifying and continuously registering its elevation dimensions, disregarding any objects present on the ground, the example of vegetation cover, vehicles, infrastructure elements and / or buildings (Gripp Jr. 2009; Viana 2017; Zanetti 2017).

2.2 Stability Analysis

The Brazilian technical standard ABNT NBR 11682: 2009 conceptualizes the safety factor (FS) of a slope as the ratio between the resistant stresses of the massif (shear strength) and the active stresses that cause slipping, as shown in Eq. 1. Thus, in face of the applied stresses, the higher the values of resistance of the massif, the greater its safety factor, which indicates a greater degree of stability to morphodynamic effects (Assis 2017).

$$FS = \frac{\text{Resistant Stresses } (S)}{\text{Active Stresses } (\sigma)} \quad (1)$$

3 METHODOLOGY

3.1 Suborbital Sensing with UAV and Relief Modeling

The aerophotogrammetric flight was carried out with a UAV SenseFly Swinglet CAM, with an embedded Canon IXUS220HS RGB camera, with a resolution of 12 megapixels, calibrated to obtain images with GSD (spatial resolution) between 7 to 30 cm/pixel. Flight control was performed using the SenseFly E-motion software, with the subsequent processing of 49 aerial photographs in Pix4UAV and assembly of the orthomosaic in Pix4MAP. The orthomosaic and the SRTM 19s435 chart (INPE 2020) based the elaboration of cartographic products of interest, notably the Digital Elevation Model (DEM) and the Declivity Map.

3.2 Extraction of Soil Samples and Geotechnical Tests

Samples of mature and saprolitic (young residual) residual soil were collected and were subjected to physical characterization tests and also to the direct shear test, to obtain the resistance parameters (cohesion and friction angle), in accordance with ABNT and ASTM.

3.3 Slope Stability Analysis

After the elaboration of each topographic profile (from the relief modeling information), definition of the layers and their respective materials (with the data from the geological-geotechnical tests), positioning of the piezometric line and location of the surface entry and exit zone the slopes were subjected to rupture simulation by the Bishop, Janbu and Morgenstern-Price Methods, in the student version of GeoStudio SLOPE / W 2019, a process through which their safety factors (SF) were obtained.

4 RESULTS

4.1 Relief Modeling and Extraction of Topographic Profiles

The computational modeling of the terrain, in ArcMap 10.3.1, allowed the elaboration of the Digital Elevation Model (DEM), of the headquarters region of the municipality of Rio Piracicaba, as recorded in figure 1 below.

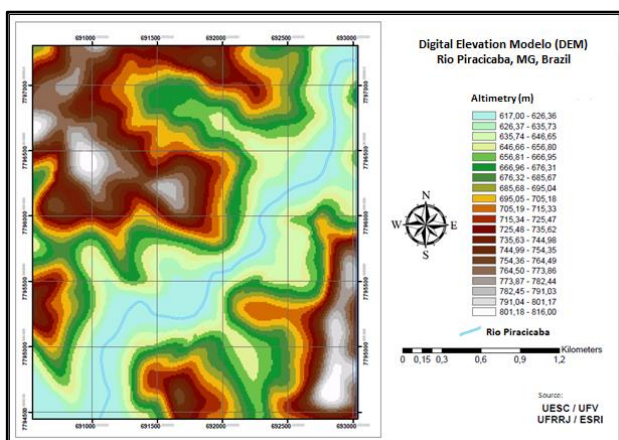


Figure 1. Digital Elevation Model (DEM) of Urban Zone.

The interpretation of the DEM allows to verify that the urban headquarters of the municipality is located around the valley of the Rio Piracicaba, with elevations alternating between 617 and 816 m, in a mountainous region and full of medium altitude hills, in a maximum prominence of about 200 m.

Then, the Declivity Map was drawn up, indicating the percentage of slope of the terrain, in relation to the horizontal, as shown in Figure 2.

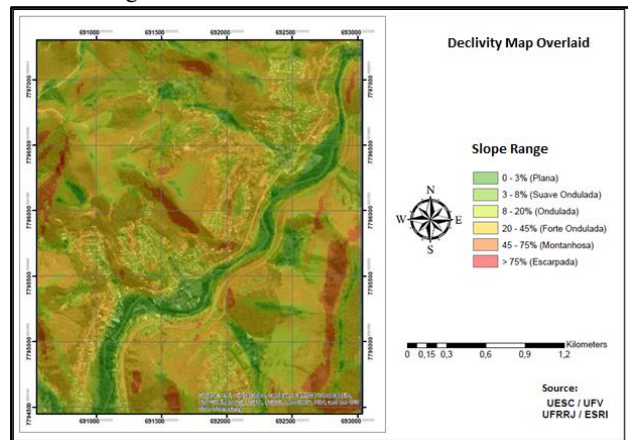


Figure 2. Declivity Map overlaid on the Aerial Image.

The urban area has considerable zones of steep slopes, with more than 60% of the region between the lower (20%) and upper (> 75%) limits, respectively, of the Strongly Wavy and Craggy bands. However, Brazilian Federal Law 6766 does not authorize constructive practice on areas with a slope declivity equal to or greater than 30%, which are included in the classification of *non aedificandi* areas.

Therefore, with the support of the contour graph, the urban map and the slopes' declivity seen in Figure 2, analysis points were demarcated in areas of steep slopes with presence of human settlements, as shown in Figure 3, evidencing the confidence interval adopted, for greater accuracy, in which zones were considerate unsuitable for occupation from the Strongly Wavy band (with a declivity greater than or equal to 20%). In Figure 3, the polygonal ones in red indicate the approximate limits of the chosen slopes, while the polygonal ones in blue delimit the occupation areas possibly affected by eventual mass movements of these slopes.

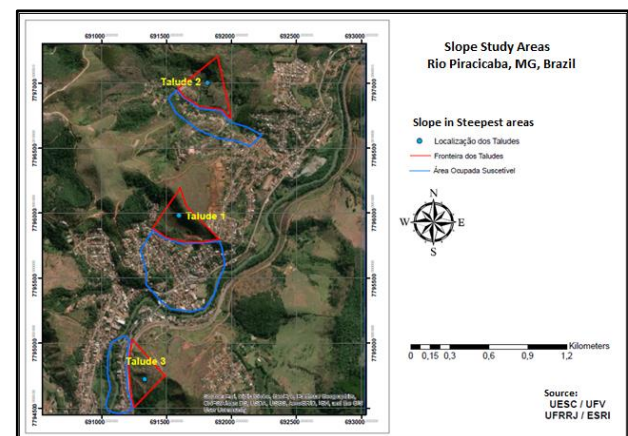


Figure 3. Analysis Points of Chosen Slopes.

Slopes 1, 2 and 3 were chosen for simulation in GEO-SLOPE GeoStudio® 2019, as they present the most unfavorable configurations of human settlements in areas of steep slope, above the 20% range, where buildings would not be recommended, as deal with regions that are more prone to mass movements.

The Map of Extracted Profiles for Susceptibility Analysis, shown in Figure 4, obtained by crossing the information from the

Slope Map and from the Slope Analyzed Points, together with the overlapping of the contour lines (with 10 m interval isolines), allows better identification of the extension of the slope profiles chosen for testing, represented by their topographic profile interpolated lines.

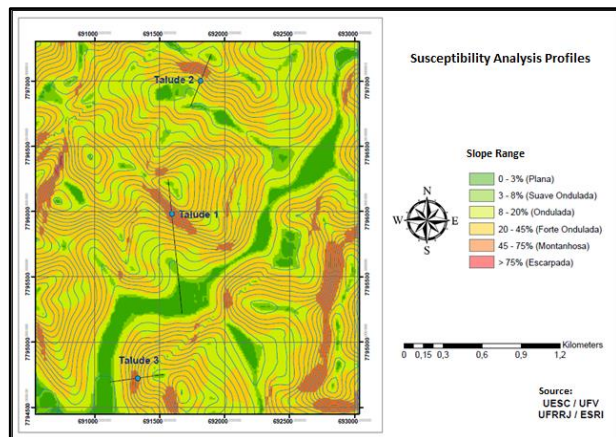


Figure 4. Chosen Profile Lines for Susceptibility Analysis to Mass Movements.

Slopes 1, 2 and 3 have prominences (relative heights) of 170, 100 and 107 m, respectively, with horizontal extensions of 800, 410 and 420 m.

4.2 Geological-Geotechnical Parameters

The geological-geotechnical investigation indicated the presence of mature residual soil and young residual soil in the relief composition of the sample collection regions. The laboratory analyzes, carried out for both types of soil, using Characterization Tests and Direct Shear Tests, allowed the obtainment of the physical parameters (Table 1 - Source: Authors) and resistance (Table 2 - Source: Authors), specified below.

Table 1. Physical Parameters of Soils Tested in the Laboratory.

Soil	Clay %	Silt %	Sand %	Gravel %	Liquid Limit (%)	Plasticity Index (%)	Natural Specific Weight (kN/m ³)	Specific Weight of Solids (kN/m ³)
Mature Residual	21	49	30	0	55	31	15,57	28,70
Young Residual	16	34	50	0	-	-	NP	15,67

Table 1, from the characterization tests, allows the classification of the mature residual soil in the region as sandy silte without boulders; while the young residual soil (saprolitic) is predominantly silty sand with non-plastic fines.

Table 2. Strength Parameters of Laboratory Tested Soils.

Soil	Maximum Friction Angle ϕ^* (°)		Cohesion c^* (kPa)	
	Dry (Natural Humidity)	Saturated	Dry (Natural Humidity)	Saturated
Mature Residual	30.7	30.7	78.3	20.2
Young Residual	34.0	34.0	51.1	7.1

Table 2 shows how the drainage conditions of the material (soil) can influence the cohesion values, in such a way that, with the saturated soil, there was an approximate drop of 74% and 86%, respectively, in the values of cohesion of mature residual and saprolitic soils (young residual ones).

4.3 Stability Analysis of Selected Slopes

The computational analysis of Slope Stability performed in the GeoStudio® SLOPE/W 2019 software, based on the physical and strength parameters of the local soil, in addition to the relief features extracted from the GIS environment, allowed the simulation of the rupture configuration and obtaining of the safety factors (SF) of the slope profiles tested, using the analysis methods described, with the results obtained detailed in Table 3 (Source: Authors), below.

Tabela 3. Safety Factors Obtained for the Three Demarcated Slopes.

Stability Analysis Method	Safety Factor (SF)		
	Slope 1	Slope 2	Slope 3
Morgenstern-Price	1,278	0,997	0,931
Bishop	1,279	0,979	0,903
Janbu	1,241	0,931	0,894

Figure 5 (Source: Authors) shows the graphic result of the stability analysis of Slopes 1, 2 and 3, in the Janbu Method (where the smallest SF's were verified), indicating its probable rupture surface, in the condition of saturated soil. In all cases, the most superficial layer corresponds to mature residual soil, while the intermediate layer is composed of saprolitic soil, both with a thin aspect, with average depths in the range of 5 meters, and supported on the rocky bed (simulated in the condition of impenetrable rock).

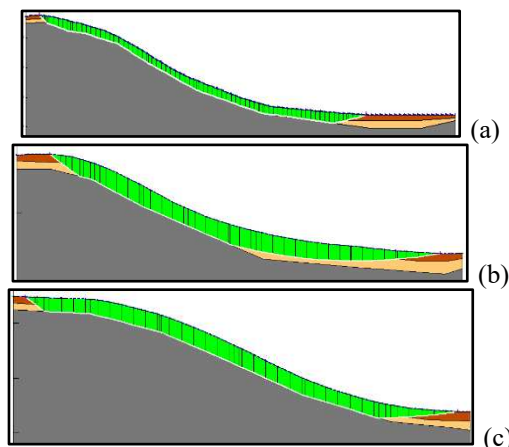


Figure 5. Slope Rupture Surface by the Janbu Method - (a) Slope 1, (b) Slope 2, (c) Slope 3.

In the analyzed condition, of saturated soil, the lowest values of safety factors were obtained in the simulations by the Janbu Method, resulting, for Slopes 1, 2 and 3, respectively, in the values of 1.241; 0.931 and 0.894. Considering that the slopes are located in areas that demand a high degree of safety (due to the presence of human settlements), all values are lower than the minimum SF of 1.5 recommended by the Brazilian slopes stability technical standard, NBR 11682: 2009. Slope 1 has, at least, SF higher than the unitary value, not being on the slipping limit, in the tested drainage conditions. Slopes 2 and 3, on the other hand, are below the minimum value of 1.15 (for situations of low security demand) and, even, with factors lower than the unit value, being in a situation of vulnerability, regarding the imminence of rupture, in the occurrence of intense rain, a fact that, possibly, would cause its collapse, especially in the case of Slope 3, which registered the lowest FS obtained.

For all slopes, there is a predominance of translational landslide with shallow planar rupture surface, in the region of the soil-rock interface, possibly due to the low depth of residual soil, supported on the rocky base, and due to the marked reduction of cohesion values observed in saturated superficial residual soils. This configuration is in accordance with the observations made

by Assis 2017, which points to the frequent occurrence of shallow planar landslides in the municipality of Rio Piracicaba.

5 CONCLUSIONS

It was found that the relief of the urban headquarters of Rio Piracicaba develops in mountainous and hill regions, around the valley of the eponymous river, at altitudes between 617 and 816 m above sea level, with more than 60% of the landscape dominated by regions of high slope, from the strongly undulating stretches to the steep areas, with numerous areas not suitable for occupation, with slopes higher than the adopted 20% criterion (beginning of the Strongly Wavy domain), including the non aedificandi typology (slope declivity equal to or greater than 30%).

The three urban regions evaluated for susceptibility to mass movements, by the intersection of the criteria of high declivity (above 20%) and the presence of human settlements, presented safety factors (SF) of 1.241; 0.931 and 0.894, respectively for Slopes 1, 2 and 3. All minimum values, by slope, were verified in the analyzes by the Janbu Method and for the condition of saturated soil (most unfavorable), all of which are below the SF parametric 1.5 established by the NBR 11682: 2009 standard, for regions that demand a high degree of security (due to the presence of human settlements), demanding special attention from the public authorities. The simulations showed the tendency to translational landslides, with a planar rupture surface, at the soil-rock interface.

The integrated information modeling allowed the compilation of important accessory data, for the evaluation and control of morphodynamic susceptibilities in the analyzed region. Inconsistencies related to the occupation of areas considered not suitable for settlements were identified, due to the combination of factors predisposing to the morphodynamic effects of the land, subjecting its occupants to the possible associated risks. Therefore, it is recommended to carry out studies to assess the degrees of risk of each location, the implementation of immediate mitigation actions, by the competent authorities, to guarantee safety to the local inhabitants of these areas and, even, corrective processes for elimination of factors generating instability.

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