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Roads stability in the Brazilian Amazon: a section of BR-010 in the Pará State

Estabilidade nas estradas da Amazônia brasileira: um recorte da BR-010 no Estado do Pará

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Abstract: In Brazil, road construction processes started in the 1930s but were intensified in the 1960s due to the projects of national integration. Building a road requires the application of various geotechnical solutions, among other studies, to ensure the correct execution of the project. Slopes are commonly deployed, particularly in regions of rugged terrain, presenting steep inclines and declines. In this research work, slopes six were analyzed along, approximately, 36 km of the BR-010 road, in the Paragominas and Ipixuna do Pará, municipalities of Pará State in Brazil. These presented values of safety factors within the recommended limits; however, erosion and mass movement problems occur in most of them. Hence, it is necessary to employ preventive treatment to avoid block falls and landslides that could obstruct the road causing traffic interruption, environmental and economic harm or, even worse, detriments to human lives.

Keywords: Mapping; Highway; Erosion.

Resumo: O modal rodoviário foi implantado no Brasil a partir dos anos de 1930, sendo intensificado após o ano de 1960 com os projetos de integração nacional. A construção de uma rodovia requer, dentre outras, a aplicação de diversas soluções de geotecnia para a correta execução do projeto. Os taludes de corte e aterro são frequentes, especialmente em regiões de relevo acidentado, com aclives e declives. Neste trabalho foram analisados seis taludes de corte em aproximadamente 36 Km da rodovia BR-010, entre os municípios de Paragominas e Ipixuna do Pará, no Estado do Pará. Os taludes analisados apresentam fator de segurança dentro dos limites recomendáveis, no entanto, problemas de erosão e movimentos gravitacionais de massa ocorrem na maioria deles. Os taludes necessitam de tratamento preventivo para evitar que as quedas de bloco e os escorregamentos provoquem a interrupção da pista, com potencial para trazer danos a vidas humanas, ambientais e econômicos.

Palavras-chave: Mapeamento; Rodovia; Erosão.

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1. Introduction

Highways are land-based traffic routes used for the transportation of people, vehicles, and freight. The construction of roads in Brazil began in the 1930s with the establishment of a special fund for the construction and maintenance of federal highways. This process was accelerated with the National Highway Plan (PEREIRA; LESSA, 2011), which allocated financial resources to expand the sector.

According to the National Department of Infrastructure and Transportation (DNIT), the roads can be classified as: urban roads, which are roads located within the urban area; rural roads, which are roads connecting urban and industrial areas that cross rural areas and feeder roads, which are responsible for giving access to private properties and small rural communities.

The implementation of significant highway projects in the Amazon was mainly based on the integration of territories, in other words, the need to establish a connection between sparsely populated areas and the country's economic and political centers. During the 20th century, implemented roads reduced the distance between urban and rural centers, overcoming the physical barriers of these territories and, hence, causing an increase in the flux of people, vehicles, and trade of goods (OLIVEIRA NETO *et al*., 2021).

Following various types of guidelines to achieve minimal safety and quality patterns is a requirement for building a highway. Performing geological, climatological and geotechnical studies are a part of these guidelines (DNIT, 2019).

Executing road construction, depending on the topographical conditions, requires the implementation of diverse slopes. These slopes are strictly associated with erosion, once they expose rocks to weathering processes, mainly because of the rain. Erosion processes represent a significant problem and affect, with greater intensity, tropical countries due to their high rainfall rates.

The advance of erosive processes can cause mass movement, which is the most common problem in slopes around the world (TRAN *et al*., 2020) and has the potential to be catastrophic (GERSCOVICH *et al*., 2011; TRAN *et al*., 2015).

In Brazil, the safety factors for slope are stablished by the Brazilian Association of Technical Standards - NBR (11682/2009). Cut are subjected to weathering processes, which make them susceptible to failure events, especially in the rainy season (LI *et al*., 2009). Most problems that occur in these slopes are caused by errors in the planning projects, such as inadequate cutting shapes, height and inclination (SUTEJO; GOFAR, 2015). According to the terrain morphology, it is necessary to perform cuts in different shapes to guarantee the alignment and the slope of the highway agree with the initial project (ANDRADE, 2019).

The construction of BR-010 took place between the years1959 and 1974, it is a 1,960 km road connecting Belém to Brasília. It is a federal road that constitutes an important logistical pathway, connecting four Brazilian states: Pará; Maranhão; Tocantins, and Goiás (ANTERO, 2017). This highway is significant to the Amazonian region because it was the first and still is the main land connection between Amazonia and the west-central portion of Brazil, which allows migration flows and occupation of the Para State territory (PFAFF *et al*., 2009).

This research article aims to present the results of mapping the instability potential of BR-010 Road caused by the safety factor limitations related to the instability of the cut slopes. Six cuts were analyzed along 36 km of this road, located between Paragominas and Ipixuna do Pará, municipalities of Pará State, Brazil (Figure 1).

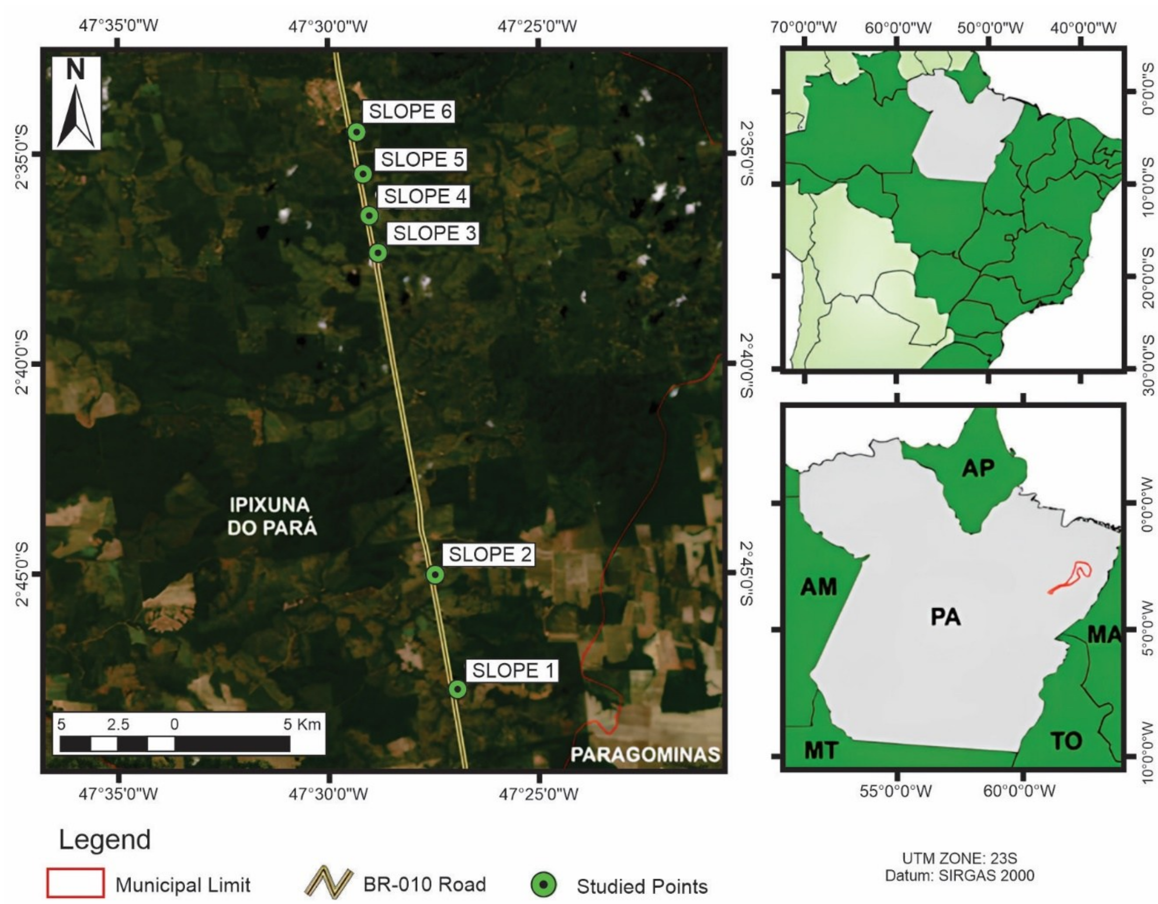

Figure 1 – BR-010 Road location between Paragominas and Ipixuna do Pará, municipalities of Pará State, Brazil. Source: Authors (2024).

2. Methodology

This research work used techniques that allowed identification, diagnosis, and understanding of the dynamics and nature of the geological and geotechnical phenomenon. To achieve the above-mentioned goals, a detailed bibliographic study was performed along with a field survey to build a database related to this field of study.

The creation of the cartographic base was carried out using ArcGIS software, version 10.5, following the methodology outlined by Silva et al. (2018). Geological mapping was conducted through fieldwork, employing the techniques described by Lisle et al. (2014), with a focus on observing lithological characteristics and their stratigraphic relationships.

The geotechnical survey was performed over two periods, the first one in the dry season (June) and the second one in the rainy season (April) among the years 2020 and 2021. The goal was to verify the stability, and the weathering process effects in the slopes.

Precipitation data from the Paragominas Station (A212) were obtained through the National Institute of Meteorology – INMET, available on its website (www.inmet.gov.br/portal/). These data were analyzed over a period of ten years, from May 2010 to April 2021. The Ipixuna do Pará municipality does not present a meteorological station, so data from Paragominas station were adopted to the whole extension of the study area. In these municipalities the dry period occurs from June to November and the rainy season starts in December and ends in May.

Stability studies were executed by adopting numerical analyses calculated using the GeoStudio 2012 software in the SLOPE/W platform, employing the Morgenstern-Price method (1965). Besides, a geotechnical report of erosion susceptibility was generated using the adaptation of the Zuquette and Gandolfi (2004) and Fernandes and Cerri (2011) methodologies.

To generate the geotechnical assessment report, field data and data available in official channels - such as the Brazilian Institute of Geography and Statistics (IBGE), the Geological Survey of Brazil (CPRM), and the MDE from the Earth Data Platform (NASA) - were used. During the elaboration of thematic maps, classes and their respective weights were defined according to a varying degree of erosion susceptibility (Table 1). The assigned weights vary from 1 to 3, with 1 indicating low erosion susceptibility, 2 indicating moderate erosion susceptibility, and 3 indicating high erosion susceptibility (CREPANI *et al*., 2001).

Table 1 – Variables and weights of the geotechnical factors used in the thematic maps.

THEMATIC MAPS	VARIABLE	WHEIGHT
SOIL	Dystrophic latosol with clayey texture	1
	Dystrophic latosol with medium texture	2
	Petric concretionary plinthosol presenting clayey and gravelly texture	3
GEOLOGY	Laterite Coverage	1
	Ipixuna Formação	3
USAGE AND SOIL OCCUPATION	Florestal Formation	1
	Savânica Formation Campestre Formation	2
	Farm (uncovered)	3
DECLIVITY (%)	0-7 7-12 12-18 18-23	1
	23-28 28-34 34-40	2
	40-48 48-69	3

Source: Adapted from Crepani et al. (2001); CPRM, (2021); EMBRAPA (2018); Oliveira (2011).

Soil maps were defined using varying degrees of erosion susceptibility and were correlated with the IBGE Pedometric Map (2021) and the work of Nogami and Villibor (1979). Geographical data on soil types and vector structure (polygons) were obtained from the IBGE Geosciences Portal. Weight attribution was performed based on the soil vulnerability scale developed by Crepani et al. (2001).

Map generation was carried out by assigning weights based on the resistance and erosion of lithological layers, using the geological map database of the Pará State (Vasquez and Rosa-Costa, 2008). Geological data were obtained from GeoSBG, the Brazilian Geological Service database (CPRM, 2021). One of the attributes in the database is the resistance to physical weathering of each rock type or rock group. The classes in RGIPI range from low to high and moderate to high. In the study area, sedimentary rocks are predominant, and they were classified with different weights, ranging from 1 to 3, based on their resistance. A weight of 1 indicates the highest resistance to erosion, 2 indicates moderate susceptibility to erosion, and 3 is used for rocks with low resistance to erosion.

Data from the MapBiomas Project (2022) were used for the Map of Soil Usage and Occupation. The weights applied to the vegetation cover were defined according to Oliveira’s (2011) work, hence the NDVI image was reclassified so that each pixel presented a value of weight, such as the greater the vegetation cover, the smaller the susceptibility to environmental degradation.

In the Declivity Map, weights were defined according to the classes in the study area: areas of greater declivity are more susceptible to erosion processes. In this work, the authors adopted the scale developed by EMBRAPA (2018). This scale considers that the higher the slope, the greater the chance of erosion, especially when combined with other factors, like the absence of vegetation coverage, the soil type and the type of activity carried out in the area.

After elaborating the thematic maps and using the weights of each class, it was possible to initiate the reclassification procedure employing the reclassify tool of ArcGis 10.5. Using new grades and weights, four new raster files were generated. These data were used to determine new weights for each theme according to their greater or smaller influence on erosion processes.

Após a elaboração dos mapas temáticos e utilizando os pesos para cada classe, foi possível realizar o procedimento de reclassificação, utilizando a ferramenta reclassify no ArcGis 10.5, com novas notas e pesos atribuídos, gerando quatro novos arquivos raster reclassificados. Com estes dados, foram determinados novos pesos para cada tema de acordo com sua maior ou menor influência no processo erosivo.

An adaptation of the multicriteria analysis of Moura (2009) was applied to define the weights of each class and themes. His work is a methodological procedure of crossing variables that is widely accepted in spatial analyses. Using it, the spatial analysis is performed based on the combination of a variable set, in which each new analysis will require a new choice of variable set, and the weight that each of them will have in the result is related to the context of the analysis. This procedure implies the mapping of variables for each information layer and the definition of the relevance degree of each information layer together with their legend complement to the construction of the result. Therefore, weights were attributed to each information layer (theme) regarding the relative importance between them (Table 2).

Table 2 – Weights of geotechnical factors used in the reclassified thematic maps.

THEMATIC MAPS	WEIGHTS
SOILS	0.25
GEOLOGY	0.15
SOIL USAGE AND OCCUPATION	0.35
DECLIVITY (%)	0.30

Source: Authors (2024).

Thus, the algebraic expression used in the *raster calculator* tool of ARCGIS 10.5 software was: (“DECLIVITY” * 0,30) + (“GEOLOGY” * 0,15) + (“SOILS” * 0,25) + (“USAGEANDOCUPPATION” * 0,35). The result is a raster file with the geotechnical report of erosion susceptibility of the study area.

3. Results and discussion

The study area’s geology is mainly composed of sedimentary rocks inserted in the Meso-Cenozoic context. It is located between the northwest portion of Grajaú Basin and the southern portion of Bragantina Platform (KOTSCHOUBEY *et al*., 2005).

Estuarine-lagoon deposits from Itapecuru Group compose the bottom of this lithostratigraphic section (ANAISSE *et al*., 2001; CUNHA *et al*., 2019), in which the following lithotypes were described: conglomerate with clay and quartz pebbles and friable, medium to coarse-grained sandstones interbedded with claystones.

These rocks are overlain by the deposits from an estuarine-fluvial system of Ipixuna Formation (SANTOS JR.; ROSSETTI, 2002), which is characterized by the intercalation of kaolinitic sandstones and claystones. The sandstones are well stratified and sometimes exhibit different Liesegang rings patterns, generated by iron dispersion through water flow within sediments. A ferruginous/aluminous lateritic crust marks the limit of this deposit.

At the top, deposits of tidal-dominated coastal environment of Barreiras Formation are present (GÓES *et al*., 1990; SANTOS JR.; ROSSETTI, 2003). Friable, fine to medium-grained sandstones intercalated with stratified mudstones are observed in this section (Figure 2).

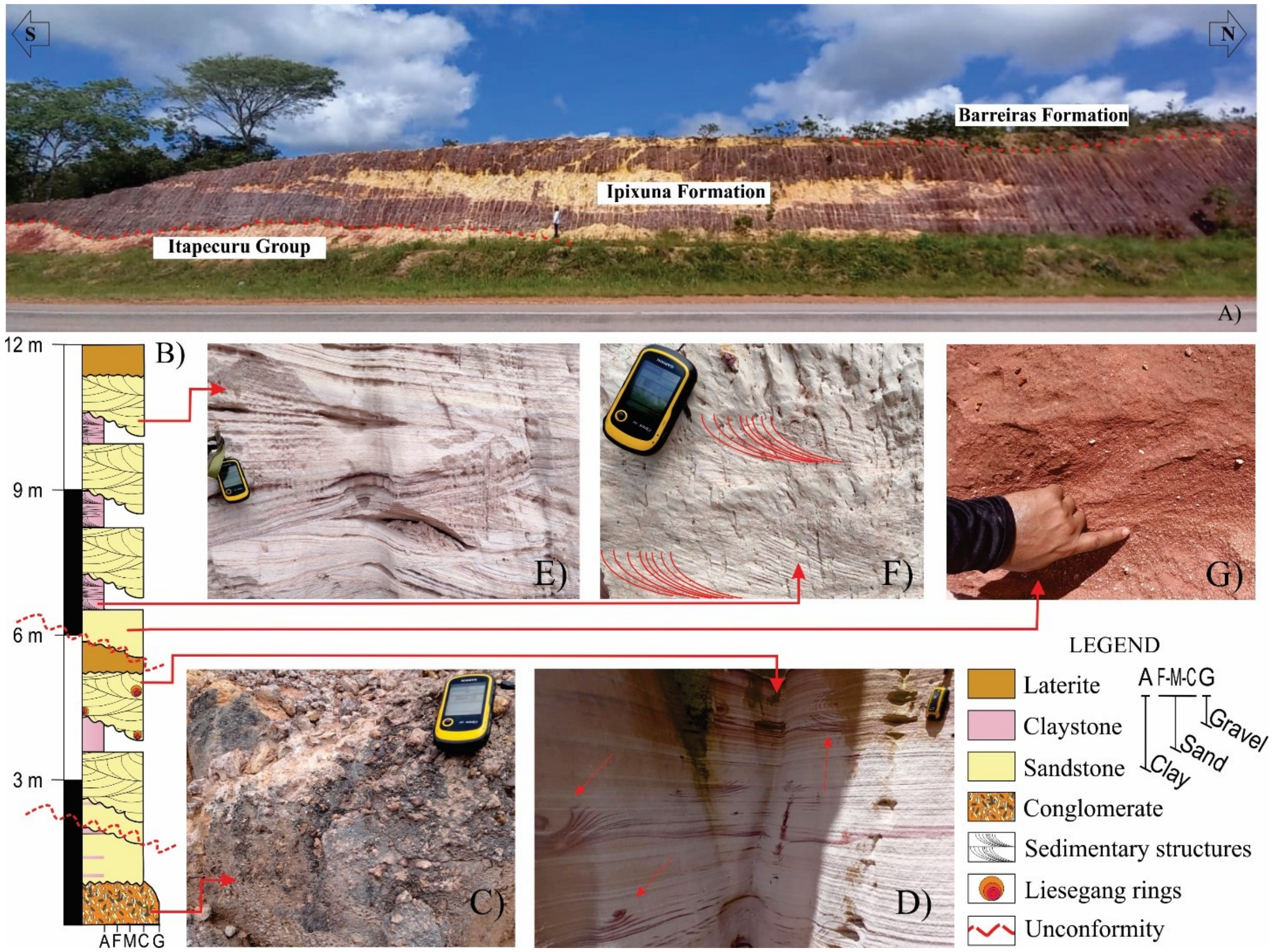

Figure 2 – Geological setting of the study area. A) Vertical succession and contact relation among unities, limited by the erosive surfaces (dotted lines); B) Lithostratigraphic profile of the study area; C) Conglomerate with sandy matrix and clasts of sandstones and mudstones; D: Sandstones presenting features of Liesegang rings; E: Stratified Sandstone; F: Stratified Mudstone; G: Medium to coarse-grained massive sandstone.
Source: Authors (2024).

To construct the Br-010 Road various plateaus were totally or partially removed, and this material was used as landfill on steep areas. This procedure significantly removed the vegetation coverage, which is important in protecting the soil against erosion, reducing the raindrops impact and increasing its resistance to superficial flow (SILVA *et al*., 2020). Additionally, length and inclination of the slopes were altered, making them more susceptible to erosion after the cut was performed (RIZZO *et al*., 2022).

Amazon has been undergoing recurrent extreme climate episodes, among which excessive rain rates are more harmful to the slopes stability. According to Lira *et al*. (2020), the Pará State is characterized by a tropical climate with high rainfall variation due to different atmospheric systems. It has a tropical climate with high rainfall rates and is predominantly warm and humid. The annual rainfall average is 3,000 mm, concentrated from December to May (SEMAS, 2022).

Meteorological data from the historical series for the last ten years (2011 a 2020) attest to high rainfall rates in the study area (Figure 3).

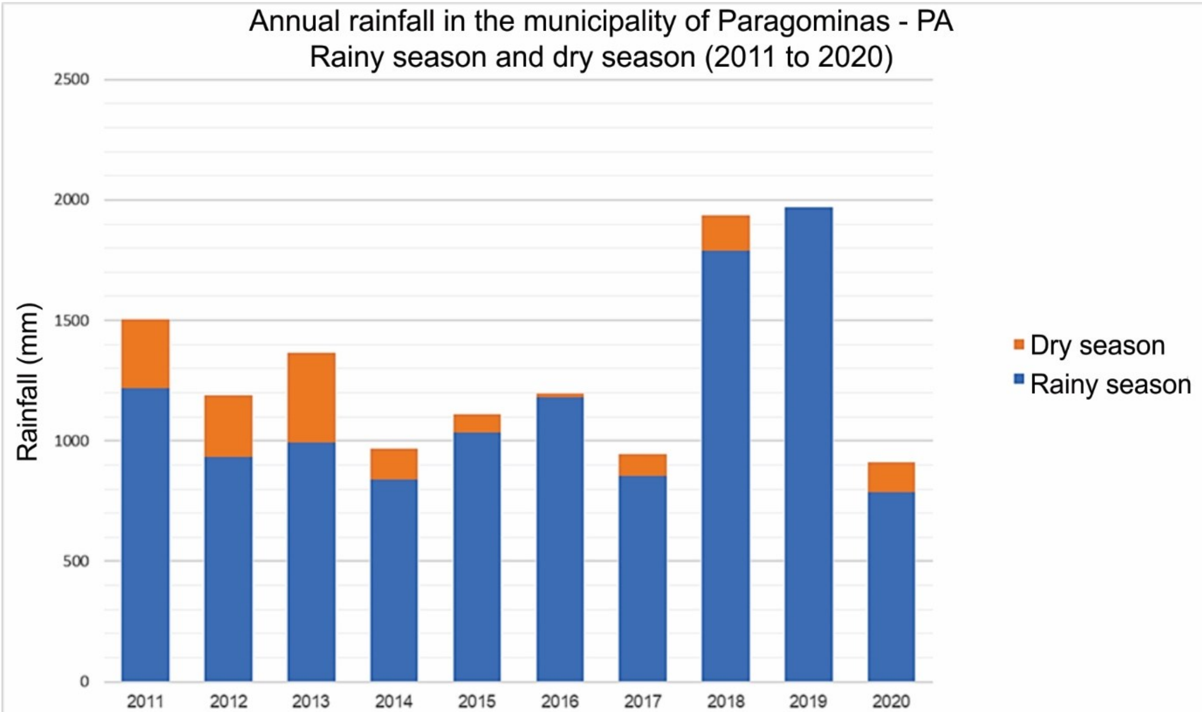

Figure 3 – Rainfall historical series of Paragominas and Ipixuna do Pará for the years between 2011 and 2020. Note the lack of information on the dry period of 2019 as a result of data absence at the meteorological station.
Source: INMET (2011-2020).

Rain volume accumulated over a specific period compromises the water flow. Fredlund and Xing (1994) stated the volumetric humidity content in a saturated condition and the input of air value generally increases with the soil plasticity.

Terrain infiltration depends on the material type, for example, sandy soils easily allow water infiltration while water promotes clay expansion in clayey soils, turning them into an impermeable layer (SHENG, 1990; SHI *et al*., 2002; YILMAZ, 2008). Subject to the soil type, infiltration rate and superficial velocity flow, water can cause various erosion processes in raining periods and during gravitational mass movements (OLIVEIRA *et al*., 2010).

The analyzed slopes did not present vegetation protection against the impact of raindrops, favoring the implantation of erosive processes in rainy periods - hydric erosion (GUERRA e JORGE, 2012). The raindrops impact consists of separating soil particles that, in torrential rain events, can mean the loss of a significant amount of soil (JEMAI *et al*., 2021).

Strong and long rainy periods in the Amazon cause saturation of the soils in the study area. The lithotypes analyzed in field are essentially sedimentary which favors water infiltration. The presence of some clayey horizons can provide some degree of impermeability; however, this barrier is overcome due to increases in the rainfall rate, improving the internal pressure of layers.

Soil gravitational mass movements are, in general, a result of water infiltration. These movements occur as a function of soil saturation, increased neutral pressure and, consequently, reduction in suction values. Sometimes, the rise of the water table can also occur (CALVELLO *et al*., 2008). Depending on the soil's capacity to retain water, its hydraulic conductivity, the slopes geotechnical profile and the pluviometric condition, like duration and rainfall intensity, these movements can occur immediately or shortly after the rainfall event (SANTOS *et al*., 2019; SILVA *et al*., 2019).

Slopes stability represents a relevant fact in safety, instability risks in soil and rocks masses must be minimized, as landslides can cause accidents of significant consequences (GERSCOVICH *et al*., 2011). In specific situations, especially in road construction, it is unavoidable for some slopes to present values of safety factors below the acceptable limit. In such cases, it's important to adopt as many engineering solutions as possible to minimize the risks.

In Brazil, the safety factor (FS) of slopes' stability is based on methods of equilibrium limit (NBR-11.682/2009), which classifies the degree of safety as low (FS= 1,15), medium (FS= 1,30), and high (FS= 1,50).

Out of the six mapped (Figure 1), two were selected to calculate the critical point of stability (Table 3). They were chosen for exhibiting advanced signs of instability.

Table 3 – Slopes mapped in the study area selected to calculate their stability.

Nº	REMARKS
5	Slope presenting erosion and gravitational mass movement of the wedge-slide type
2	Slope presenting erosion and gravitational mass movement of the planar type

Source: Authors (2024).

Analyses of slopes stability were based on the equilibrium limit method, which results in finding a safety factor according to the parameters displayed in Table 4.

Table 4 –Analytic parameters applied to calculate the safety factors.

LITHOLOGY	SPECIFIC WEIGHT (kN/m^3)	EFFECTIVE COESION (kPa)	FRICTION ANGLE (º)
Kaolinitic Sandstone	21	15	30
Clayey Sandstone	23	18	30
Mudstone	20	18	30
Laterite	30	20	30

Source: Adapted of Vaz et al. (2018); Araújo (1992); Futai et al. (2012); Braida et al. (2007); Morais et al. (2020).

Mathematical modeling applied to slopes nº2 and nº5 indicated a FS of 1.489 and 1.441, respectively, in other words, they presented a medium safety factor according to the NBR-11.682/2009 (Figure 4). However, adopting the rule causes uncertainties and divergences, mainly concerning substrate conditions and geological properties.

Figure 4 – Landslide in BR-010 Road. A-B) General and detailed view of slope n°5, note the risk of landslide of the wedge-slide type; C) Mathematical model of the safety factor FS = 1.441; D-E) General and detailed view of slope n°2, note the planar landslide reached the shoulder lane. F) Mathematical modeling of safety factor FS= 1.489.
Source: Authors (2024).

Factors such as mineralogy, presence of saprolites, lixiviation, chemical and physical weathering can contribute to causing soil heterogeneity, especially in regions of tropical climate like the Amazon, generating uncertainties in the estimation of shear resistance and in the identification of probable slide surfaces (EL-RAMLY *et al*., 2005).

According to NBR-11.682/2009, the safety factor is defined by the value of the ratio between the maximum shear tension and the shear tension acting on the rupture surface (Eq. 1). However, this value can vary with the slopes' condition and the environmental and economic risks, in cases offering danger to human life, *i.e.*, this is a subjective method once it allows multiple interpretations.

$$F.S = \frac{\text{Resistance to available shear}}{\text{Acting shear tensions}} \quad \text{(Eq.1)}$$

Another option is to attribute an admissible safety factor ($F.S_{adm}$), which is obtained as concerning the type of civil construction work and its useful life (Eq. 2), it also takes into account economic and/or human losses in case of eventual rupture (GERSCOVICH, 2016).

$$F.S = \frac{\tau f}{\tau mob}\begin{cases} > 1 \rightarrow \textit{stable civil construction work} \\ = 1 \rightarrow \textit{rupture ocurrence} \\ < 1 \rightarrow \textit{no physical meaning} \end{cases} \quad \text{(Eq. 2)}$$

Even presenting stability values within the limits established by NBR-11.682/2009, these slopes exhibit significant problems of mass movements and erosion. In clayey soils, like the one in the surveyed area, it is essential to take preventive action to overcome the effect of clay contraction and expansion, which together with pluviometric and gravity effects originate landslides (JIANG *et al*., 2013). The noticeable presence of clay-sized kaolinite in the Ipixuna Formation sandstones (KOTSCHOUBEY *et al*., 2005; SANTOS JR.; ROSSETTI, 2002) possibly influences the cohesion pattern of the analyzed slopes.

Sandstones intercalated with clay layers presenting high iron oxide contents have a predominance of massive texture, which favors erosion processes and landslides of the wedge-slide type, like observed in slope n° 5. This landslide shape is closely linked with rainfall conditions (HUANG *et al*., 2021). In the study area, this pattern is commonly observed in rocks from Barreiras Formation, except in regions with laterite, either ferruginous or aluminous, once they present strong cohesion and high resistance to weathering processes contributing to the slopes' stability (COSTA, 1991; MELFI, 1997).

Adjustment of kaolinite planes contributes to the development of block structures increasing rock cohesion (FERREIRA *et al*., 1999) and, consequently, causing planar mass movements and erosion processes more frequent, as observed in slope n°2.

Integrated analyses of the thematic maps of soil, geology, soil usage and occupation, and declivity (Figure 5) indicate the vulnerability of the study area to erosive processes.

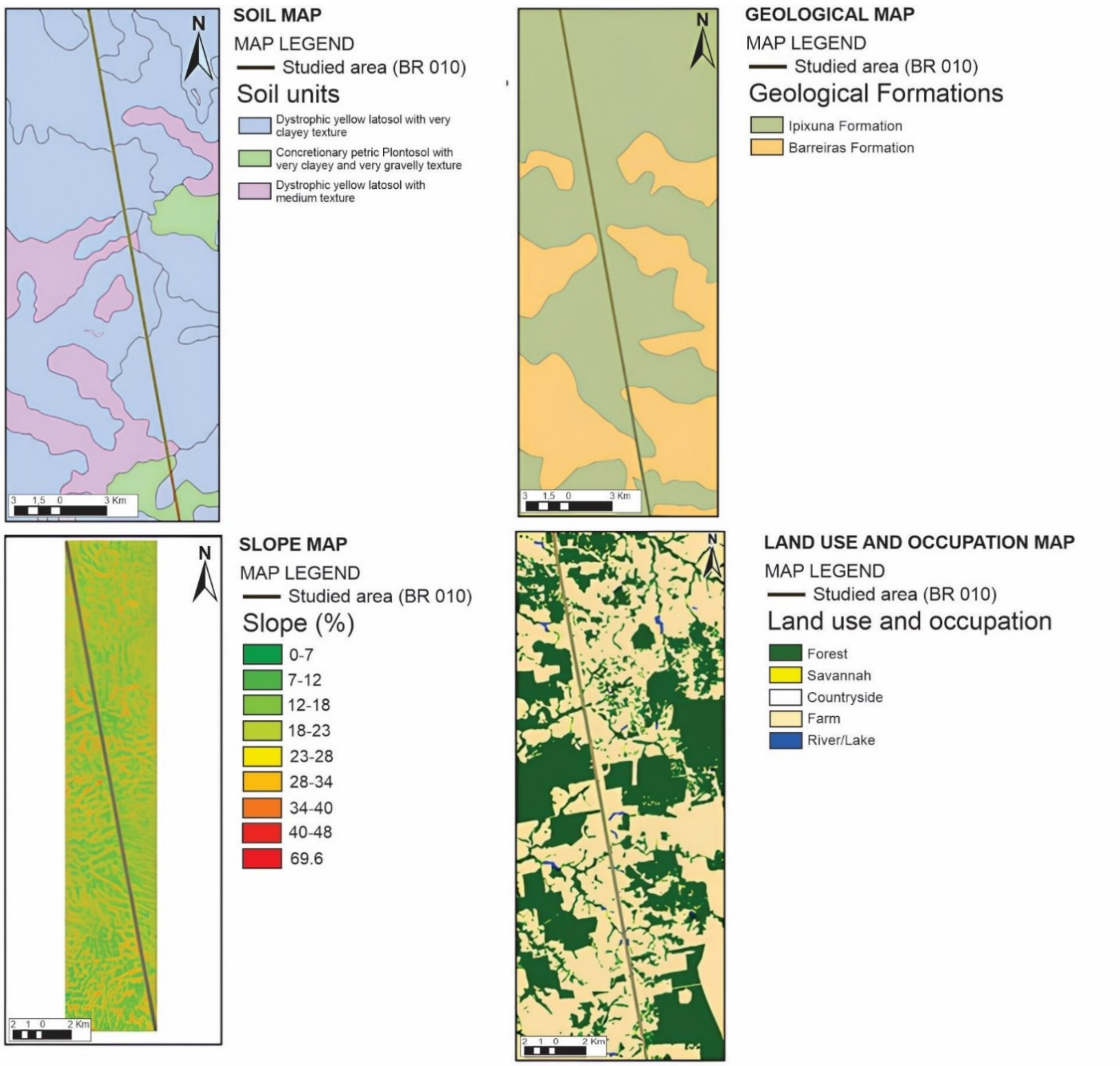

Figure 5 – Thematic maps of the surveyed area.
Source: Authors (2024).

The resulting geotechnical report of erosion susceptibility presents low-risk zones in blue, moderate-risk zones in yellow and high-risk values in red (Figure 6). The analyzed section of BR-010 Road presents high- to moderate-risk points. The susceptibility report predominantly shows moderate-risk zones, however, high-risk zones can be observed.

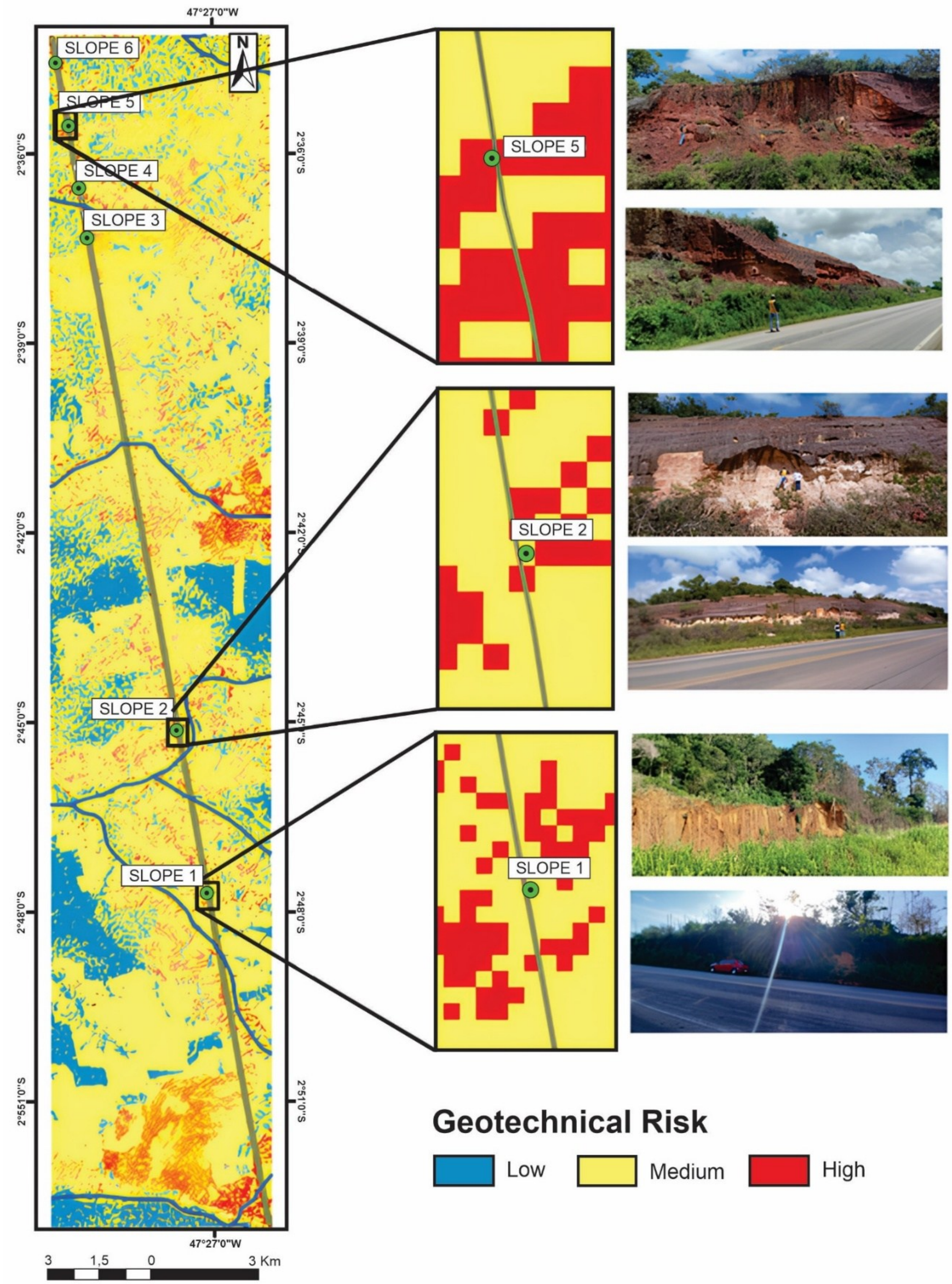

Figure 6 – BR-010 Road geotechnical report of erosion susceptibility between Paragominas and Ipixuna do Pará, municipalities of Pará, Brazil.
Source: Authors (2024).

4. Final considerations

The methodologies applied in the present study efficiently identified safety factors and zones susceptible to erosive processes and mass movements in the slopes identified along a 36 km section of BR-010 Road.

In summary, this section is located between Paragominas and Ipixuna do Pará and presents structural problems concerning the slopes' stability. Hence, integrated planning is necessary to adopt preventive actions guaranteeing traffic safety on the road, regardless of climate conditions.

The data integration discussed in this research work allowed the following considerations:

a) Safety factors calculated for slopes n° 5 (FS= 1.441) and n° 2 (FS= 1.489) indicate moderate stability conditions according to the NBR 11.682/2009;

b) The geotechnical report of erosion susceptibility pointed to the presence of critical zones regarding erosion and slopes in great stages of erosive processes and gravitational mass movements.

c) To increase the safety factor of slopes, a few solutions are suggested: slope scaling, soil anchoring, implementation of different surface drainage types, as well as bioengineering solutions (Figure 7).

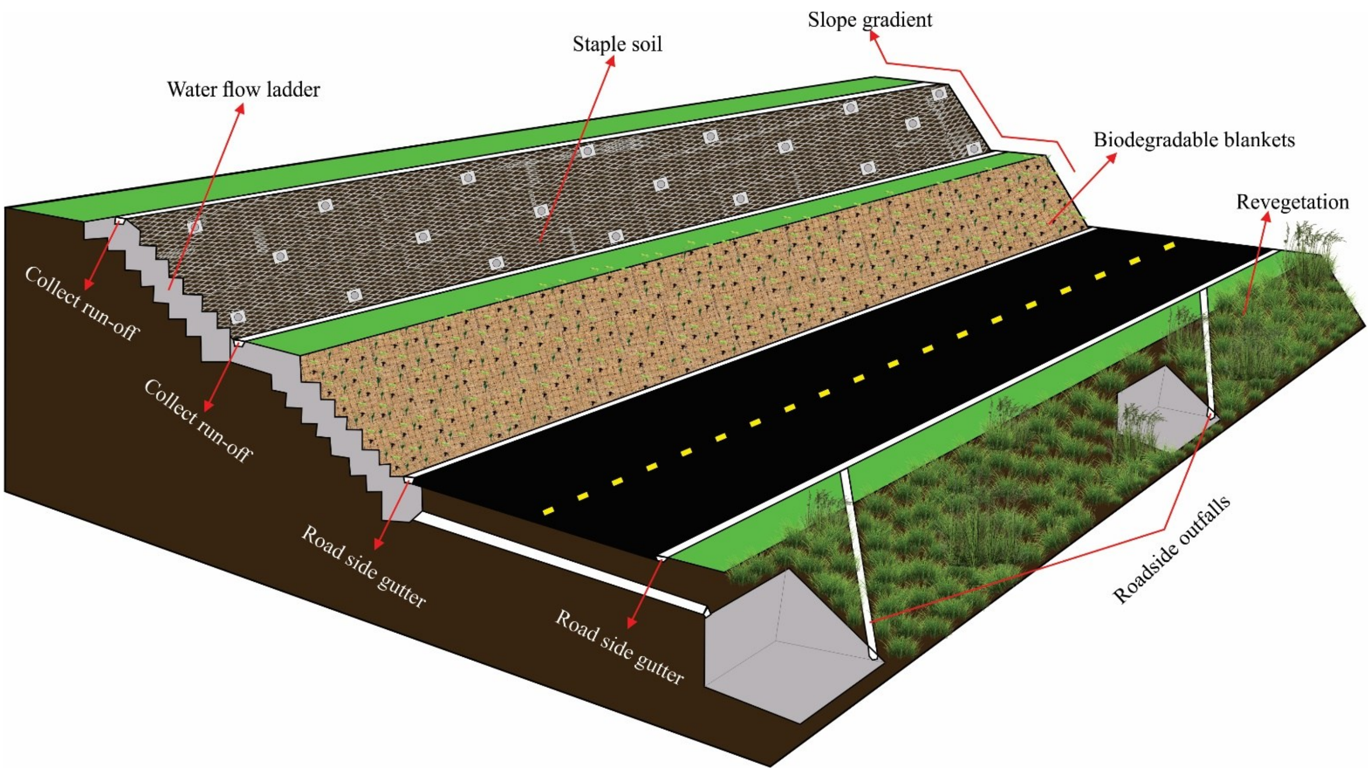

Figure 7 – Schematic section of some possible solutions that could be adopted to increase the safety factor and decrease the erosion susceptibility of slopes along the BR-010 Road, located between Paragominas and Ipixuna do Pará, municipalities of Pará Sate, Brazil.
Source: Authors (2024).

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