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Landslide Susceptibility Modelling on Infinite Slopes and Relation to Laminar Erosion Processes, Using Geoprocessing Techniques, in the Direct Contribution Basin of Batalha Hydroelectric Power Plant

Modelagem da Suscetibilidade a Deslizamentos em Taludes Infinitos e sua Relação com Processos Erosivos Laminares, por Meio de Técnicas de Geoprocessamento, na Bacia de Contribuição Direta da UHE Batalha

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Abstract: In areas of irregular relief, slope stability analysis techniques can be applied to estimate safety conditions. The main variables in slope stability analysis include the morphological, pedological and soil physical parameters. In this context, this study applies geoprocessing techniques at a scale of 1:25,000 to analyse the relationship between the stability of infinite slopes and the occurrence of laminar erosion processes in the Direct Contribution Basin (DCB) of the Batalha HPP reservoir. The aim of this research is to estimate a predictive model for landslides on natural slopes, based on the Preliminary Safety Factor (PSF). The methodology was based on the limit equilibrium method for infinite slopes, using techniques available in Geographic Information Systems. Scenarios with zero cohesion and neutral pressure increased the susceptibility to mass movements, reducing the Preliminary Safety Factors. Due to the proximity of the reservoir to the slopes and considering the seasonality between the dry and wet seasons, there is constant variation in the parameters of cohesion and neutral pressure, resulting in maps with dynamic characteristics in the analysis of slope stability.

Keywords: Geotechnical Stability, Hydraulic Stability, Erosion Processes

Resumo: Técnicas de análise de estabilidade de taludes aplicadas ao estudo de encostas suscetíveis a movimentos gravitacionais de massa permitem estimar as condições de estabilidade em áreas de relevo irregular. O conhecimento dos parâmetros morfológicos, pedológicos e físicos dos solos é fundamental, pois representam variáveis importantes na análise de estabilidade. Neste contexto, este estudo aplica técnicas de geoprocessamento, na escala de 1:25.000, para analisar a relação entre a estabilidade de taludes infinitos e a ocorrência de processos erosivos laminares na Bacia de Contribuição Direta (BCD) do reservatório da UHE Batalha. Deste modo, esta pesquisa tem por objetivo estimar um modelo preditivo de escorregamentos em vertentes naturais, com base no Fator de Segurança preliminar (FSp). Na metodologia aplicada, o FSp foi calculado pelo método de equilíbrio limite de vertentes infinitas, utilizando técnicas disponíveis em Sistema de Informação Geográfica. Observou-se que cenários com coesão zero e presença de pressão neutra influenciam negativamente os resultados do Fator de Segurança preliminar (FSp), aumentando a suscetibilidade a movimentos de massa. Além disso, verificou-se que os mapas de estabilidade são dinâmicos, sendo influenciados pela variação dos parâmetros de coesão e da pressão neutra, representando a sazonalidade local ou transição da época seca para época chuvosa e também a proximidade do reservatório das encostas da BCD.

Palavras-chave: Estabilidade Geotécnica, Estabilidade Hidráulica, Processos Erosivos

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1. Introduction

The construction of a hydroelectric power plant generates a series of impacts on the reservoir's flooding area, as well as on its entire Direct Contribution Basin (DCB). Environmental elements that were located in the flooded area are disturbed, affecting local biodiversity, as well as the aquatic and terrestrial ecosystems.

Due the aggradations of reservoirs, the stability of the slopes in the DCB should be investigated, especially in areas of irregular relief. The gravitational mass movement susceptibility processes can be assessed by studying the slope stability, considering, in particular, local geological and geotechnical variables.

The limit equilibrium method is used as one of the main tools for analysing the stability of slopes in earth and/or rock masses. For the stability analysis, it was adopted the definition of infinite slope, represented by a massive of great extension, with a thickness of material subject to slippage is smaller than the height of the slope, obtaining a rupture surface parallel to the slope.

Considering the study area proposed for the reservoir, laminar erosion was identified in the DCB and laboratory tests were carried out on soil samples. The occurrence of laminar erosion features was determined by visual inspection of Google Earth images, keeping the visualisation cartographic scale under control.

The results of the soil erodibility classification, based on indirect tests according to the MCT criteria, were also considered, including infiltrability and mass loss by immersion tests.

Therefore, the study sought to apply Geographic Information System techniques to estimate a deterministic predictive model of landslides, considering as natural slopes, based on the Factor of Safety index, using the infinite slope limit equilibrium method, in the DCB of the Batalha reservoir.

2. Methodology

This research is part of the P&D Sediments project (SALES et al., 2020), where morphological data was compiled (slope inclination; slope characteristics); pedological and geotechnical data (layer thickness, specific weight, cohesion, soil friction angle); a survey of erosion processes; etc.

2.1. Pedological and morphological parameters

The database used to draw up the soil and texture maps was developed as part of the P&D Sediments project. In this process, the scale was adjusted to 1/25,000 with the advent of a Digital Elevation Model (DEM), processed from NASADEM (ROMÃO et al. 2024).

The geotechnical parameters were estimated according to the soil texture map produced by Romão et al. (2024). In addition, the current study refined the database by reviewing studies in the area, tactile visual sampling and laboratory results of Erodibility MCT (Miniature Compacted Tropical), correlating the data with the unified soil classification system.

Morphological parameters have a significant influence on the occurrence of landslides. For modelling the Safety Factor, the gradient and slope orientation data was developed by Medeiros (2025).

2.2. Thickness of the soil layer (H)

The slope shapes map represents the curvature of the relief, indicating different soil characteristics according to the type of slope. According to Augusto Filho (1988), linear slopes tend to have shallower soils, while concave slopes are associated with intermediate thickness soils. On convex slopes, it is common to find thicker and deeper soils.

Augusto Filho (1988) and Kozciak (2005) said that the variation in soil thickness in tropical climate regions is related to the shape of the slope, so the authors opted to increase the soil thickness by 50% for areas with convex slopes. For areas with rectilinear slopes, the authors attributed a 50 per cent decrease in soil thickness, and for areas whose slopes were classified as concave, they did not attribute corrections to soil thickness.

The thickness of the soil layer was determined based on the classification provided by Embrapa's Brazilian Soil Classification System (2018). After surveying the soil classes, the thickness “H” was generated according to the guidelines presented by Kozciak (2005).

Table 1: Soil Layer Thickness - Batalha HPP (m)

Soils	Thickness (m)
CAMBISSOLO HÁPLICO Tb Typical dystrophic	1
GLEISSOLO HÁPLICO Tb Typical dystrophic	1
GLEISSOLO MELÂNICO Tb Dystrophic	0,4
LATOSSOLO VERMELHO Typical dystrophic	1
LATOSSOLO VERMELHO-AMARELO Typical dystrophic	1
NEOSSOLO FLÚVICO Tb Eutrophic gleissolic	0,5
NEOSSOLO LITOLICO Typical dystrophic	0,5
PLINTOSSOLO PÉTRICO Typical concrecionary	2
PLINTOSSOLO PÉTRICO Lithoplintic endemic	2

Source: Embrapa (2018). Organized by the authors

2.3. Physical and mechanical soil parameters

The parameters of cohesion, friction angle and specific weight were estimated from literature reviews presented in Table 2. The quantification of these parameters was based on the soil texture provided in the 1/25,000 scale pedological database developed by Romão et al. (2024) in the P&D Sediments project.

The soils were classified according to their erodibility resistance as defined by Medeiros (2025) based on indirect erodibility tests using the 'MCT Erodibility Criterion'. Initially proposed by Nogami and Villibor (1979 and 1995), the indirect erodibility assessment was adapted by other researchers aiming to facilitate testing methods (BASTOS, 1999; MATAMOROS SEVILLA, 2016). The MCT Erodibility Criterion presented by Nogami and Vilibor (1979) is essentially empirical, based on two parameters: the modified immersion mass loss (pi), which represents specific erodibility, obtained from the specific erodibility test, and the sorption coefficient (s), which represents infiltrability, obtained from the infiltrability test.

Table 2: Cohesion, friction angle and specific weight based on literature

Texture	c' (kPa)	Φ' (°)	γ (kN/m3)	Source
Sand	0,085	29,7	16	Cobbold *et al.* (2001)
Sand	0,105	30		Bonini *et al.* (2000)
Sand	0,3	30,1	17,5	Krantz (1991)
Sand	0,02	30,9	16,9	Gutscher *et al.* (1998)
Sand	0,021	35,5	-	Panien *et al.* (2006)
Sand	0,0363	42,7	15,2	Gomes e Caldeira (2011)
Sand	17,3	44,1		Vieira, Pereira e Lopes (2014)
Sand	4,3	42	-	Silva *et al.* (2019
Sand	16,3	37,6	-	Vieira *et al.* (2020
Sand	18	40,3	-	Vieira e Pereira (2022)
Sand	17,1	31,2		Georgetti e Carminati (2022)
Sand	0	39,3	16,3	Oliveira (2014)
Clayey sand	14	33	19	Silva (2017)
Clayey sand	18	36	18	Trevizolli *et al.* (2017)
Clayey sand	38,76	26,84	15,6	Oliveira (2014)
Clayey sand	47,88	31,61	17,5	Oliveira (2014)
Silty sand	20	31	19,36	Reis (2022)
Silty sand	9,1	30,2	-	Schuch *et al.* (2024)
Silty sand	7,5	37,6	-	Oliveira e Rodriguez (2022)
Silty sand	4,2	38,9	-	Oliveira e Rodriguez (2020)
Silty sand	10,4	26,4		Veloso *et al.* (2021)
Silty sand	7,5	37,6	16,41	Oliveira e Rodrigues (2020)
Clay	107,48	35,16	-	Castro *et al.* (2019)
Clay	80	27,3	16,1	Zagatto Penha *et al.* (2015)
Clay	60,4	30,5	16,8	Júnior *et al.* (2018)

Texture	c' (kPa)	Φ' (°)	γ (kN/m3)	Source
Clay	37,6	30,7	17,1	Georgetti e Carminati (2022)
Clay	42	38		Morais (2017)
Clay	28,81	51,09	-	Maicá *et al.* (2022)
Clay	30,55	51,87	-	Maicá *et al.* (2022)
Clay	89,8	7,17	13,1	Oliveira (2014)
Sandy clay	7,1	30,1	16,92	Kozciak (2005)
Sandy clay	13,5	21,7	17,16	Kozciak (2005)
Sandy clay	15	33	19	Rodrigues (2020)
Sandy clay	19,8	17,9		Oliveira e Rodrigues (2020)
Sandy clay	5,84	30,51	18,4	Borchardt (2005)
Sandy clay	15	30,5	16,8	Trevizolli *et al.* (2017)
Sandy clay	69,97	13,58	14,3	Oliveira (2014)
Sandy-silty clay (flooded)	8,72	24,2	19,27	Magalhães (2013)
Sandy-silty clay (flooded)	6,97	29,5	19,9	Magalhães (2013)
Sandy-silty clay (flooded)	3,3	35	19,04	Magalhães (2013)
Sandy-silty clay (natural)	27,39	25,7	16,93	Magalhães (2013)
Sandy-silty clay (natural)	35,08	28,1	19,13	Magalhães (2013)
Sandy-silty clay (natural)	13,76	36,5	16,29	Magalhães (2013)
Silty clay	7,185	24,56	17,9	Borchardt (2005)
Silty clay	13	21	19	Barbosa, Araújo e Ferreira (2019)
Silty clay	29	16,5	17	Botelho *et al.* (2016)
Silty clay	15	24,3	15	Botelho *et al.* (2016)
Silty clay	14,2	39,6	21	Botelho *et al.* (2016)
Silty clay	21,43	29,5	17,73	Santos, Filho e Herrera (2019)
Silty clay	27,5	28	18	Pereira (2015)

2.4. The limit equilibrium method to determine the Preliminary Safety Factor (PSF)

The Safety Factor, according to Fiori and Carmignani (2009), is influenced by many factors. The study was based on the theory of limit equilibrium for the sliding condition of infinite slopes, which considers the hypothesis of equilibrium in a rigid-plastic soil mass in the imminence of a sliding process (MASSAD, 2010).

Massad (2010) defines infinite slopes as natural slopes of great length (hundreds of metres) and a small soil mantle thickness, usually only a few metres thick (Figure 1). Guerra (2015) explains that rupture generally occurs at the contact between different strength materials, resulting in translational slippage parallel to the surface.

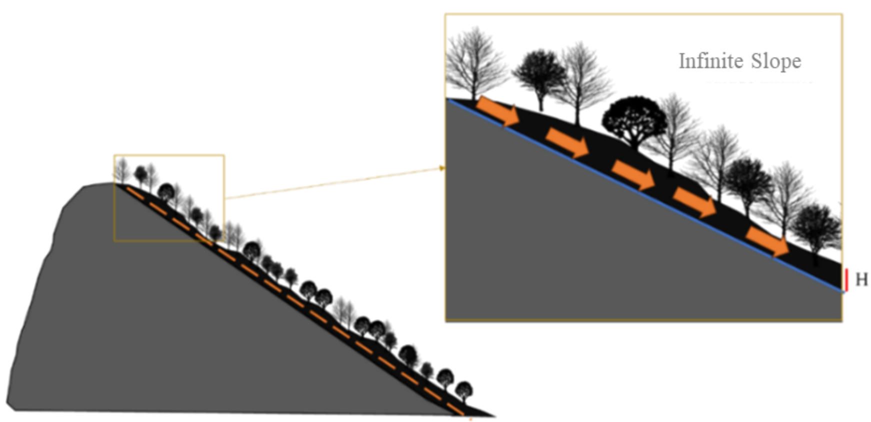


Figure 1: Planar rupture surface in large slopes
Source: Authors

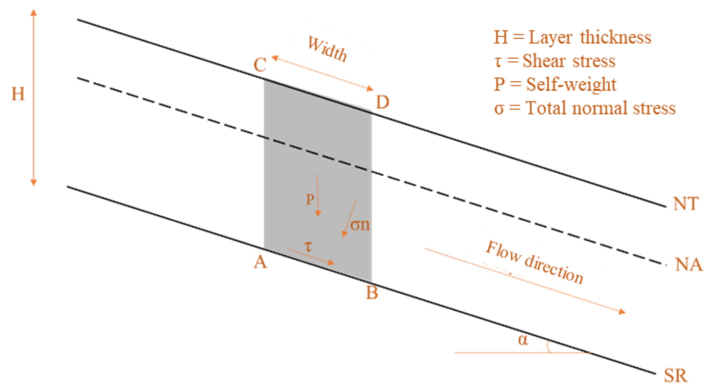


Figure 2: Schematic representation of an infinite slope
Source: Adapted from Massad (2010)

Gerscovich (2016) describes translational landslides as mass movements that occur along flat rupture surfaces, generally associated with discontinuities or planes of weakness in the soil or rock, and are common in thin mantles of colluvium.

In this study, a maximum initial thickness of 2 metres was adopted for soils as a safety criterion, even those that normally have greater thicknesses, such as mature soils with more developed profiles. This choice represents a more critical and conservative situation than if the average values for each soil class were used. Therefore, it was considered that the slip occurred translationally and parallel to the surface.

The Factor of Safety can be determined using the resistance criterion, where the stresses acting on the base of a generic vertical slice ABCD (Figure 2) of unity width are considered, assuming for general cases a Water Level (WL) parallel to the Rupture Surface (SR).

Stability conditions are defined by the Safety Factor, which represents the ratio between the slip resistance forces by the resultant of the acting forces. The analysis, based on the limit equilibrium theory, assumes that the rupture forces are precisely balanced by the resistance forces. For the infinite slope method and following Figure 2, the SF will be:

$$FS = \frac{c^{'} + (\gamma.H.\cos\alpha^2 - u).\tan\varphi'}{\gamma.H.\sin\alpha.\cos\alpha} \quad \text{Equation 1}$$

FS = Safety Factor;
c' = effective cohesion of the superficial material;
γ = specific weight of the surface material;
H = height of topsoil;
α = slope;
φ'= internal friction angle;
u = neutral pressure.

The soil resistance properties (cohesion and friction angle) were estimated from the pedological classification. The specific weight does not diverge significantly between different soils, so we adopted the average of the values published in the literature, as shown in Table 3.

It is always important to emphasise that if the safety factor is greater than 1, resistance forces are greater than the acting forces, maintaining the slope in equilibrium. FS values less than 1 indicate that the acting forces exceed the resistance forces, putting the slope in disequilibrium.

Table 3: Cohesion and friction angle average values according to literature

Texture	c' average (kPa)	σ	c' Maximum (kPa)	φ' average (°)	σ	φ' minimum (°)	φ' maximum (°)	γd average (kN/m3)
Sand	0,203	7,9	8,103	36,55	5,308	31,242	41,858	16,3
Clayey sand	28,38	14,106	42,486	32,305	3,305	29	35,61	17,75
Silty sand	8,3	4,947	13,247	34,3	4,659	29,641	38,959	17,885
Clay	51,2	27,855	79,055	32,93	13,307	19,623	46,237	16,45
Sandy clay	15	20,531	35,531	30,1	6,986	23,114	37,086	17,04
Silty clay	15	7,447	22,447	24,56	6,773	17,787	31,333	17,9
Clayey silt	20	12,615	32,615	30	6,128	23,872	36,128	16,5

Source: Organized by the authors.

The limit equilibrium method simplifies the problem by considering the soil as a rigid material and the static behaviour of the slide. For these reasons, the acceptable FS should be above 1.5 or values stipulated in the specific standard NBR 11682 (2009). Based on field conditions and geotechnical parameters, 6 (six) possible scenarios were adopted for analysing the safety factor (Table 1).

Chart 1: Modelling scenarios

Scenario	Parameters
I	Average cohesion (c'med); Average friction angle (θ' med); Water level (NA=0)
II	Average cohesion (c'med); Average friction angle (θ' med); Water level (NA=H)
III	Minimum cohesion (c'min = 0); Average friction angle (θ'med); Water level (NA=0)
IV	Minimum cohesion (c'min = 0); Average friction angle (θ'med); Water level (NA=H)
V	Maximum cohesion (c'max); Minimum friction angle (θ'min); Water level (WL=0)
VI	Maximum cohesion (c'max); Minimum friction angle (θ'min); Water level (WL=H)

Source: Authors

Notes that the worst condition is represented by scenarios II, IV and VI, which considered total immersion of the soil layer. So the height of the water table (hw) was considered equivalent to the thickness of the soil layer (H), which was crucial to the determination the neutral pressure. In contrast, scenarios I, III and V were modelled without the presence of neutral pressure i.e. the influence of water in the soil layer was disregarded. Therefore, the study covered both the conditions of maximum saturation and those without the influence of neutral pressure.

2.5. Preliminary Safety Factor (PSF) modelling in a GIS system

Due to the fact of considering the geotechnical parameters of soil resistance based on the literature (Table 3), it was decided to adopt the nomenclature of Preliminary Safety Factor (PSF).

Table 4: Safety Factor classification according to literature

Class	Range	Classification	Classification	Classification
		FS Value	Area Susceptibility	Preliminary Safety Factor
1	< 1,0	Very Unstable	Very High	Low
2	1,0 a 1,5	Unstable	High	Medium
3	1,5 a 2,0	Stable	Moderate	Intermediate
4	> 2,0	Very Stable	Low	High
Source: Modified from:		*Kozciak (2005)*	*Millán (2015)*	*Acevedo (2017)*

Source: Organized by the authors.

Table 5: Safety Factor classification for this study

Class	Range	Classification FS Value	Classification Area Susceptibility
1	< 1,5	Unstable	High
2	> 1,5	Stable	Low

Source: Authors

To generate the PSF model for the study area, it was necessary to integrate the results obtained from the soil characterisation, the products from the morphological analysis and the data available in the literature. FSp was determined using the mathematical model shown in Equation 1, and the modelling was developed in a GIS environment.

Millan (2015) classified into four classes the results of the Safety Factor in terms of translational landslides susceptibility.

Table 4 shows the classification of Safety Factors and the susceptibility classification of the area adopted by Kozciak (2005) and ACEVEDO (2017). As this is a preliminary analysis, this study proposed adopting only two classes, classifying the slope as Unstable or Stable (Table 5). As previously indicated, a minimum PSF of 1.5 was adopted since the infinite slope method is simplified and the parameters are estimated. The aim of choosing just two classes is to identify the critical areas, enabling future studies to be carried out in detail, with laboratory tests and topographical surveys of the slope features.

3. Results and discussion

3.1. Preliminary Safety Factor (PSF) modelling

Figure 3 shows mostly areas with (FS > 1.5) in all scenarios, indicating that the resistance forces outweigh the acting forces, keeping the slope in equilibrium in most of the areas under study. The occurrence of areas with (FS < 1.5) was identified in scenarios I, II, III and IV.

Scenarios II and IV show the highest proportions of slopes with (FS < 1.5). In scenario II, these areas account for 3.6 per cent of occurrences. In scenario IV, the percentages range around 7.5 per cent.

Scenarios I, III and V show the importance of neutral pressure in determining PSF. The absence of water results in a significant reduction in areas with (FS < 1.5), reaching 0% in the Batalha DCB. This reduction highlights the importance of soil cohesion in slope stability.

In scenarios V and VI, 100 per cent of the area presented (FS > 1.5). This result shows the importance of the friction angle of soils in slope stability, demonstrating that the parameters of cohesion and presence of water alone are not enough to estimate the slope's sliding stability.

It can be concluded that, as soil cohesion increases, the FSp becomes more optimistic, resulting in a greater concentration of areas with (FS > 1.5), consequently with lower susceptibility to translational landslides. This behaviour is consistent with the results presented by Acevedo (2017).

Kozciak (2005) related the study of FS to soil erosion resistance, identifying a gradual reduction in soil erosion resistance after heavy rainfall events. Considering dry soil, the author observed less than 3% of the area characterised as unstable. However, considering the saturated soil, it was noted that more than 12% of the basin area was unstable, with FS values of less than 1.5.

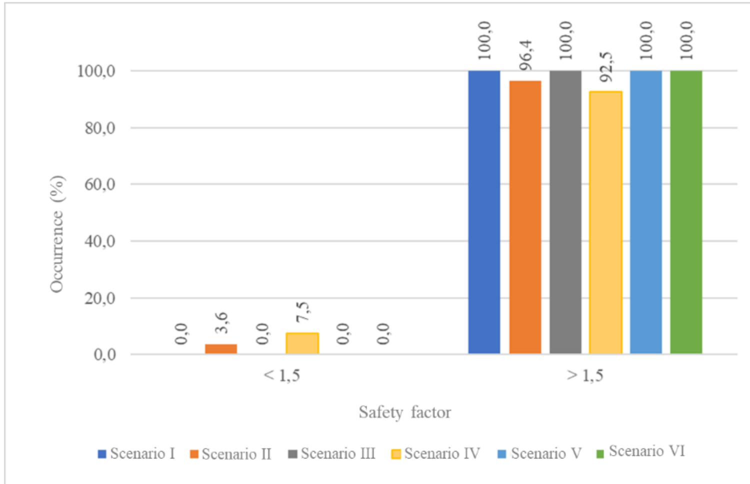
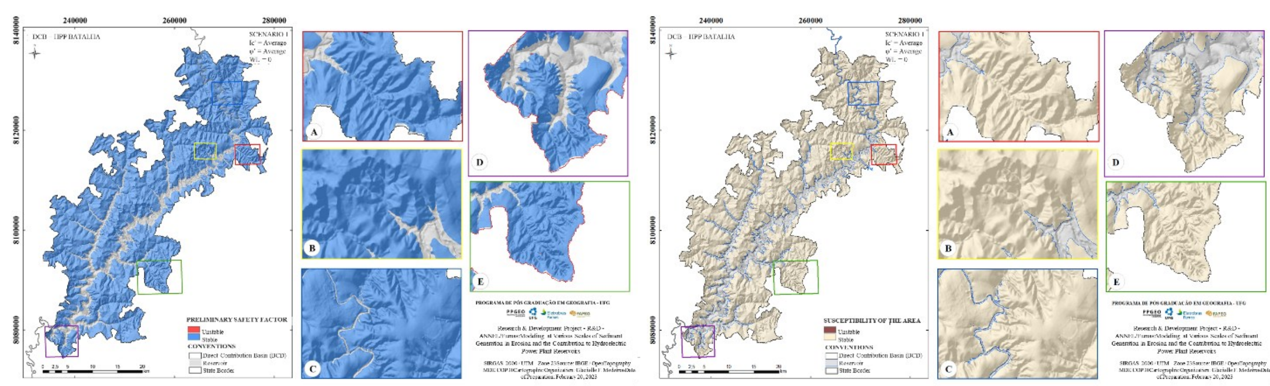


Figure 3: Preliminary Safety Factor (PSF) distribution in the Batalha DCB for the 6 scenarios analysed, determined based on the number of pixels in each scenario in relation to the total number of pixels in the basin.

In accordance with the results of this study, Acevedo (2017) observed that, as soil moisture increased, areas with low PSF increased and, consequently, areas with high PSF decreased.

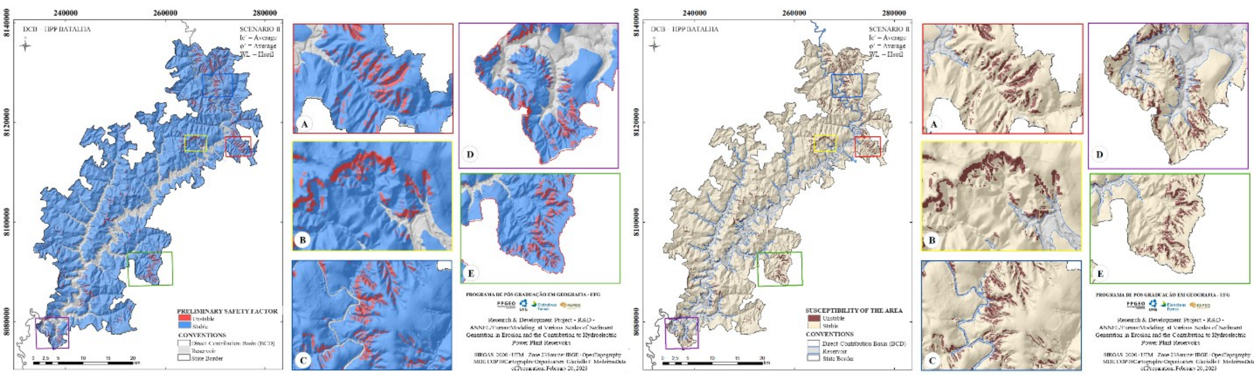
In this study, based on the scenarios analysed, it was concluded that, as the soil saturates, there is a reduction in stable areas with PSF above 1.5. This reduction in stability is directly related to the reduction in the soil's resistance to erosion and stability to the occurrence of translational slides, due to the increase in neutral pressure. In addition, it was observed that, for the cases studied, the effect of soil saturation causes greater slope instability compared to the loss of internal cohesion. In other words, the rainy season is more significant in reducing PSF.

In addition to determining the PSF, it was possible to estimate the area's susceptibility to translational landslides based on the PSF. Scenarios I and II, presented in Figure 4 and Figure 5, show that the presence of neutral pressure in scenario II reduced FS values, resulting in an increase in the concentration of areas with (FS < 1.5). This reduction results in a higher percentage of susceptible areas to the occurrence of translational landslides (Figure 4 b), when compared to the percentage of susceptible areas identified in scenario I (Figure 5 b).



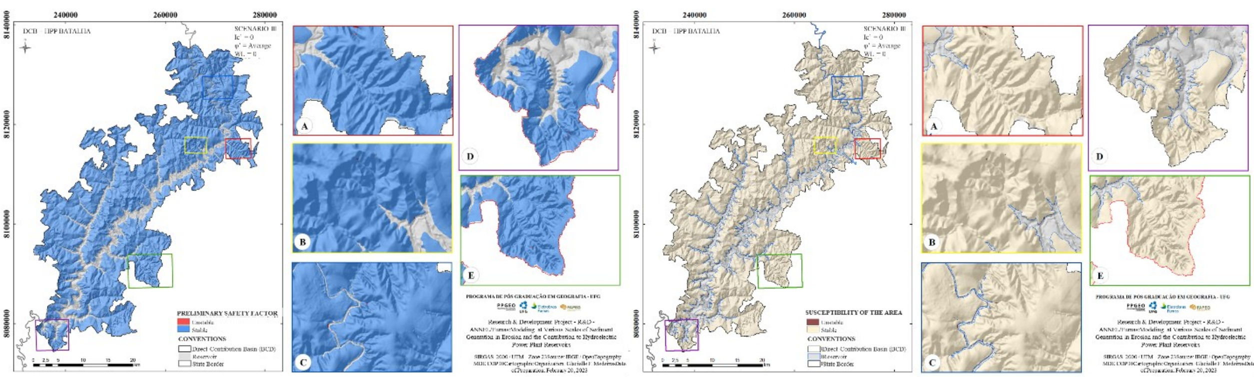
(a) (b)

Figure 4: (a) Preliminary Safety Factor (b) Susceptibility of the area based on the Preliminary Safety Factor - scenario I - Batalha HPP



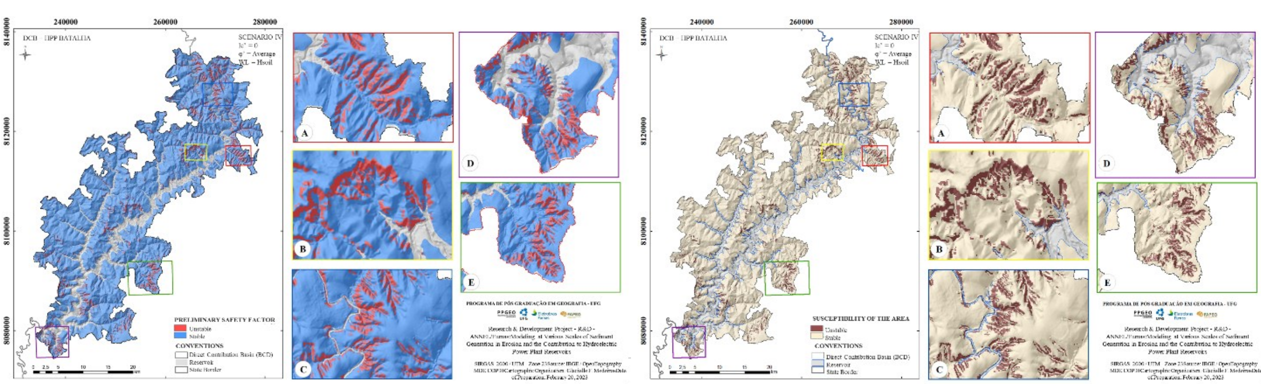
(a) *(b)*

Figure 5: (a) Preliminary Safety Factor (b) Susceptibility of the area based on the Preliminary Safety Factor - scenario II - Batalha HPP



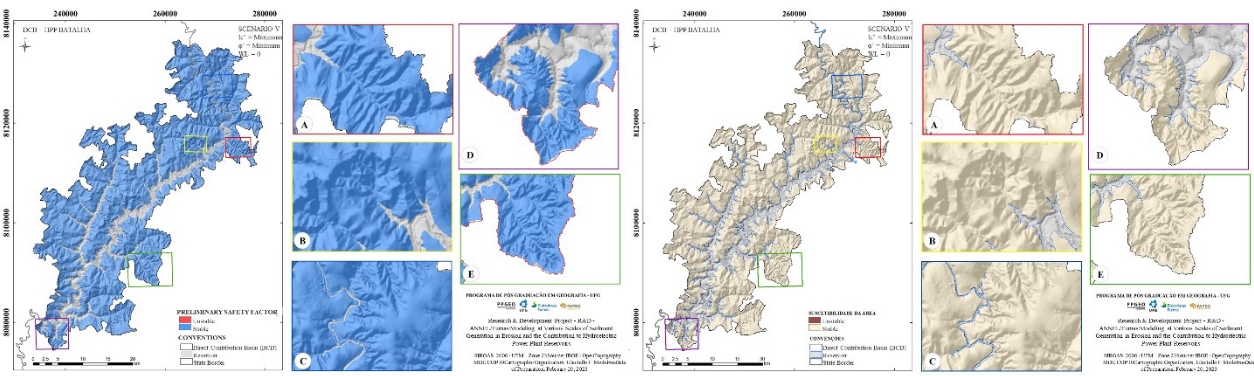
(a) *(b)*

Figure 6: (a) Preliminary Safety Factor (b) Susceptibility of the area based on the Preliminary Safety Factor - scenario III - Batalha HPP



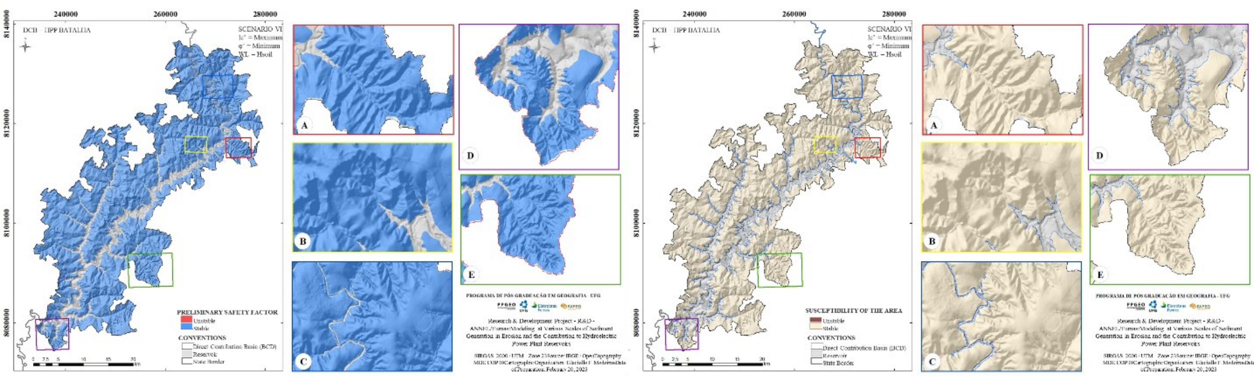
(a) *(b)*

Figure 7: (a) Preliminary Safety Factor (b) Susceptibility of the area based on the Preliminary Safety Factor - scenario IV - Batalha HPP



(a) (b)

Figure 8: (a) Preliminary Safety Factor (b) Susceptibility of the area based on the Preliminary Safety Factor - scenario V - Batalha HPP



(a) (b)

Figure 9: (a) Preliminary Safety Factor (b) Susceptibility of the area based on the Preliminary Safety Factor - scenario VI - Batalha HPP

In scenario IV (Figure 7) it is possible to observe a significant increase in the areas with a higher risk of translational landslides, especially when compared to scenario III (Figure 6). This increase is mainly due to the absence of cohesion in the soil and the presence of neutral pressure. This shows that cohesion alone cannot determine if an area is more or less susceptible to landslides. This result also highlights how the rainy season has a key influence on reducing the Factor of Safety (PSF).

Comparing scenarios V and VI (Figure 8 and Figure 9) with the previous ones, the increase in areas with (FS > 1.5) can be attributed to the adoption of maximum cohesion.

The reduction in friction angle values, from medium to minimum, associated with maximum cohesion parameters, shows an increase in slope stability. In both scenarios, with the presence of neutral pressure (Figure 9) and without presence of water (Figure 8), it is observed that practically 100 per cent of the area can be considered stable, with (FS >1.5).

The shape of the slope is a factor that directly influences the stability of the area, as it is associated with the thickness of the soil layer. Medeiros (2025) presents maps of vertical curvature, soil thickness related to curvature and declivity of the area under study. After processing the cartographic products generated by Medeiros (2025) with the results of this study, it can be seen that convex slopes predominate in areas of medium to low degrees of slope, and are characterised by lower safety factors (FS < 1.5) in scenarios II and IV, which indicates greater instability. In contrast, concave and rectilinear hillsides are associated with softer slopes and higher safety factors (FS > 1.5), characterising more stable regions, and the occurrence of translational landslides is practically non-existent in scenarios II and IV.

These results showed that there is a relationship between the shape of the hillsides and geotechnical stability, considering the thickness of the soil and the behaviour of the Preliminary Safety Factor (PSF), in agreement with the studies presented by Kozciak (2005).

In areas with thicker soil (convex relief), there is an increase in internal shear stresses, especially in areas with steeper slopes. The combination of high slopes and thick soil layers reduces the Safety Factor (PSF), indicating a high possibility of landslides, as observed in the scenarios analysed.

Furthermore, it was possible to observe that concave reliefs with less soil thickness, when associated with lower inclinations, reduce the magnitude of the acting forces, increasing the PSF and minimising the occurrence of mass movements, such as translational landslides.

3.2. Preliminary Factor of Safety (FSp) comparison with the occurrence of laminar erosion processes

As scenario IV was considered the most critical, it was decided to select it to analyse the occurrence of laminar erosion processes. The results of the MCT Erodibility Criterion tests and the identification of laminar erosion in the study area were compared, allowing a relationship between the areas susceptible to translational slippage and the occurrence of erosion processes.

According to the studies conducted by Paixão de Souza (2022) and Matamoros Sevilla (2016), thirteen of the 20 samples analysed showed erodible characteristics, three were considered to be tendentially erodible and four showed no propensity to erosion. Complementing these studies, Medeiros (2025) performed six new samples, all of them classified as erodible.

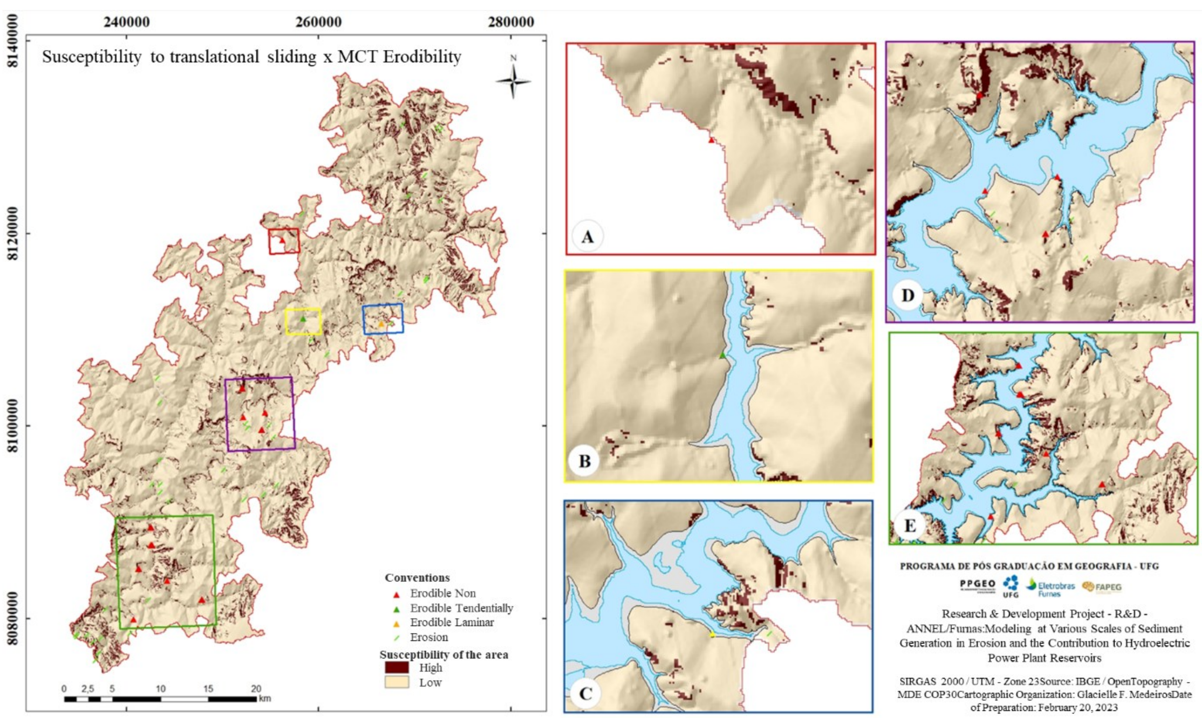


Figure 10: Susceptibility to translational sliding, location and classification of the samples tested by MCT erodibility and location of the laminar erosions identified in the DCB of the Batalha reservoir

The map shown in Figure 10 illustrates the distribution of the results of susceptibility to translational slippage, the sample points of the erodibility MCT test (and their classifications) and the location of laminar erosion. The majority of the samples classified as 'erodible' are located in areas of higher susceptibility to translational slippage, identified from the PSF.

The results of the indirect erodibility tests, combined with the presence of laminar erosion, provide parameters for a preliminary validation of the PSF model. Laminar erosion occurs significantly near or inside areas classified as being of medium to high susceptibility.

To correlate the occurrence of erosion with areas of higher susceptibility to mass movement, Santos Jr. et al. (2018) emphasises that during high-intensity rainfall, the water saturates the deposit, causing an increase in pore pressures with a consequent reduction in resistance. The deposit flow process is particularly associated with the capacity for surface erosion on high slopes, where during the runoff there is a transport of soil particles that become deposited downstream when the velocity of the runoff is reduced.

Lower soil cohesion means higher occurrence of areas with low PSF and, consequently, higher occurrence of areas with more susceptible soils. Similarly, translational movement and laminar erosion are susceptible due to the loss of surface cohesion. As the processes of laminar erosion remove the topsoil, surface cohesion is also lost and the exposed soil tends to crumble.

4. Considerações finais

Once the morphological parameters and PSF were spatially distributed, it was observed that areas of higher susceptibility are associated with areas of a higher inclination.

The deterministic method used to assess the stability of slopes made it possible to obtain the Safety Factor index, allowing to obtain the degrees of risk estimated by means of an absolute value. The PSF related to the classification of erodibility tests made it possible to identify the relationship between critical areas and slope stability.

The modeling considering the presence of neutral pressure shows its effects on reducing the resistance of soils against sliding. In scenario IV, considering neutral pressure, there is a increase of 27.10% in the areas susceptible to slipping when compared to scenario III, which was modelled with the same cohesion and friction angle parameters.

The PSF results emphasise the influence of the landform on geotechnical stability, showing that convex slopes, with larger soil thicknesses and high slopes, are more prone to instability due to the reduction in the Factor of Safety (PSF), while concave and rectilinear slopes, characterised by areas of lower slope, show higher stability and lower susceptibility to landslides.

In comparing the results of translational landslide stability and the occurrence of laminar erosion processes, there is a significant incidence of erosion near or within areas classified as medium to high susceptibility.

This study concluded that the limit equilibrium method for infinite slopes proved to be an effective method for analysing the stability of natural slopes, highlighting it as a deterministic approach with great predictive potential and applicability in regional and local studies.

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