Analysis of Slope Instability Processes Through Comparison of Limit Equilibrium and Finite Element Methods

Análisis de procesos de inestabilidad en taludes mediante comparativo entre métodos de equilibrio límite y elementos finitos

Análise dos processos de instabilidade de taludes através de comparação entre métodos de equilíbrio limite e elementos finitos

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Abstract

Introduction: The article presents research results on the analysis of slope instability processes, conducted at the Universidad Pedagógica y Tecnológica de Colombia in 2019.

Problem: Slope instability processes are permanently present in the state of Boyacá – Colombia. The stability analysis through the application of conventional limit equilibrium methods does not reflect the real conditions of mechanical resistance of the materials found.

Aim: Analyze slope instability processes utilizing the finite element method in two critical spots located on the road that connects the city of Tunja with the town of Miraflores.

Methods: Start with the search and compilation of information from critical spots with relevant geotechnical characterization on roads in the state, thereby permitting the identification of two unstable critical spots. With the use of geological, geotechnical and hydrological information, the mechanical behavior of the materials is modelled through the software Slide and Midas GTS NX.

Results: The estimation of material stability through the finite element method shows more reliable results compared to the actual behavior of the studied locations and compared to the methods based on limit equilibrium.

Conclusion: The use of this numerical simulation technique is recommended to replace conventional methods, being an affordable and effective tool for the analysis of instability processes.

Originality: Most analyses of instability processes conducted in the state of Boyacá – Colombia do not use the finite element method.

Limitations: The estimation of material stability is based on a constitutive model for soil and another for rock.

Keywords: material instability, slope stability, limit equilibrium, finite elements.

Resumen

Introducción: el artículo presenta resultados de investigación sobre el análisis de procesos de inestabilidad en taludes desarrollado en la Universidad Pedagógica y Tecnológica de Colombia en el año 2019.

Problema: los procesos de inestabilidad en taludes están presentes en el Departamento de Boyacá (Colombia) de manera permanente. El análisis de estabilidad mediante la aplicación de métodos convencionales de equilibrio límite no refleja las condiciones reales de resistencia mecánica de los materiales encontrados.

Objetivo: analizar los procesos de inestabilidad en taludes empleando el método de elementos finitos en dos puntos críticos localizados en la vía que comunica la ciudad de Tunja con el municipio de Miraflores.

Metodología: inicia con la búsqueda y recopilación de información relevante de puntos críticos con caracterización geotécnica en corredores viales del Departamento, lo que permite la identificación de dos puntos críticos inestables. Con el empleo de información geológica, geotécnica e hidrológica se modela el comportamiento mecánico de los materiales a través del software Slide y Midas GTS NX.

Resultados: la estimación de la estabilidad de los materiales por el método de elementos finitos presenta resultados más confiables frente al comportamiento real de los sitios estudiados, en comparación con los métodos basados en equilibrio límite.

Conclusión: es recomendable el empleo de esta técnica de simulación numérica en reemplazo de los métodos convencionales, siendo una herramienta asequible y efectiva para el análisis de procesos de inestabilidad.

Originalidad: la mayoría de los análisis de procesos de inestabilidad realizados en el Departamento de Boyacá no aplican el método de elementos finitos.

Limitaciones: la estimación de la estabilidad de los materiales está basada en un modelo constitutivo para suelo y otro para roca.

Palabras clave: inestabilidad material, estabilidad de taludes, equilibrio límite, elementos finitos.

Resumo

Introdução: O artigo apresenta resultados de pesquisas sobre a análise de processos de instabilidade de taludes desenvolvidos na Universidade Pedagógica e Tecnológica da Colômbia em 2019.

Problema: Os processos de instabilidade de taludes estão presentes no Departamento de Boyacá (Colômbia) permanentemente. A análise de estabilidade através da aplicação de métodos convencionais de equilíbrio limite não reflete as condições reais de resistência mecânica dos materiais encontrados.

Objetivo: Analisar os processos de instabilidade em taludes, utilizando o método dos elementos finitos, em dois pontos críticos localizados na estrada que liga a cidade de Tunja ao município de Miraflores.

Metodologia: Inicia-se com a busca e coleta de informações relevantes de pontos críticos com caracterização geotécnica nos corredores rodoviários do Departamento, o que permite a identificação de dois pontos críticos instáveis. Com o uso de informações geológicas, geotécnicas e hidrológicas, o comportamento mecânico dos materiais é modelado pelo software Slide e Midas GTS NX.

Resultados: A estimativa da estabilidade dos materiais pelo método dos elementos finitos apresenta resultados mais confiáveis em comparação com o comportamento real dos locais estudados, em comparação com os métodos baseados no equilíbrio limite.

Conclusão: É recomendável usar esta técnica de simulação numérica em vez de métodos convencionais, sendo uma ferramenta acessível e eficaz para a análise de processos de instabilidade.

Originalidade: A maioria das análises de processos de instabilidade realizadas no Departamento de Boyacá não aplica o método dos elementos finitos.

Limitações: A estimativa da estabilidade dos materiais é baseada em um modelo constitutivo para o solo e outro para rochas.

Palavras-chave: instabilidade do material, estabilidade da encosta, balanço limite, elementos finitos.

1. INTRODUCTION

The occurrence of mass movement processes in Colombia is permanent and increasingly worrisome during the rainy periods, where 18% of the national territory is located in areas of high and very high threat, mainly in the departments of the Andean region that have a large percentage of their area exposed to this phenomenon such as: Boyacá (74%), Cundinamarca (65%), Risaralda (61%) and Caldas 59% [1]. The numbers of natural disasters increase year after year in the country, where from just between 2006 and 2014 there were 3181 dead and 12.3 million affected people, that is, a quarter of the national population has been affected, with floods and landslides being the phenomena with greater occurrence [2]. Colombia was positioned 19th in the 2017 Global Climate Risk Index, indicating a level of exposure and vulnerability to extreme events whose frequency and impact is increasing, constituting clear evidence of climate change on the planet [3]. In the specific case of landslides, 3.7 million square kilometers of land and 300 million people are at risk worldwide [4]. The failure mechanisms of these phenomena are very complex and include very difficult factors to investigate with conventional analyses (such as limit equilibrium), limiting themselves to relatively simple problems that include very little information on the failure mechanism and do not take into account that it is a progressive process and that it does not begin at the same time, generating the need for other more reliable methods of analysis such as numerical simulation that determine, in detail, the closest behaviors to the reality of the different mass movement processes.

1.1 Literature Review

Different databases was taken into consideration during the development of this research project such as: Web of Science (WOS), Scopus and Springer, finding published articles in the years 2000, 2001, 2004, 2007, 2009, 2013, 2016, 2019, that allowed for the revision of the evolution of this topic, forming a third of all the utilized references in this article. Likewise, information was also taken from some internationally recognized books in the field of geotechnics and specifically in slope stability. The other references correspond to governmental information on slope instability processes at the national and departmental level published between 2014 and 2019, whose information is available in Spanish, unlike those obtained in the databases and books that are in English. Consequently, the main concepts that frame the investigation topic are presented, followed by the factors that have influenced slope stability and possible causes of these mass movement processes.

Every mass of soil that constitutes a natural slope, embankment or cut slope, has a tendency to move towards the bottom and the front due to its own weight [5]. When the resistance to the shear stress of the ground counteracts that tendency, the slope is stable; otherwise, a landslide occurs, determined as a movement of a mass of rock, soil or debris down a slope [6]. Varnes [7] defines a landslide as a downward and outward movement of material that forms the slope under the influence of gravity. The stability of a slope is influenced by several factors that are mostly constant, such as geometry, some soil properties and stratification [8]. Other authors prefer to use the term mass movement, which are caused by contributing and triggering factors [9]–[11]. In general, the degree of inclination, altitude, fault, lithology, drainage, soil use and type of soil are considered contributing factors, while precipitation, earthquakes and human interventions are triggering factors. In particular, the rapid increase in positive pore pressures was considered the most important cause in surface landslides

[12]–[14]. Some studies have focused on the hydrological characteristics that cause the increase in pore pressure of unsaturated soils and detonate surface landslides [15]–[17], where [8] determines that pore pressures could be quite predictable from the meteorological point of view using finite element analysis; the bi-seasonal response in the slope being the most important hydrological finding of his experiment, demonstrating a typical summer and winter nature.

2. METHODOLOGY

For the development of the present investigation, different methods are implemented starting with those of analysis and synthesis that define a stage of gathering information regarding the physical and mechanical parameters of the soil, information about the geology, geomorphology, topography and hydrology of different areas that are analyzed to obtain the behavioral model that produces instability problems. For its development, there is information on studies carried out in the Department of Boyacá by some institutions such as: National Roads Institute - INVIAS, Colombian Geological Service - SGC and its Mass Movement Information System - SIMMA and Institute of Hydrology, Meteorology and Environmental Studies IDEAM, allowing for the identification of unstable critical points that are subject to analysis through criteria such as: reported failure mechanism, topography, geological complexity, hydrogeology, slope height and slope inclination, type of material, hydrology, proximity to urban environments, economic costs and land use.

Having the necessary information of the critical points that identifies the instability mechanisms and triggering agents of the mass movement processes, they are modeled with limit equilibrium and finite element methods to simulate the field conditions with the Slide and Midas GTS NX software. The explanatory method is immersed in the research since it is applied during the processing, interpretation and analysis of the information gathered (Figure 1).

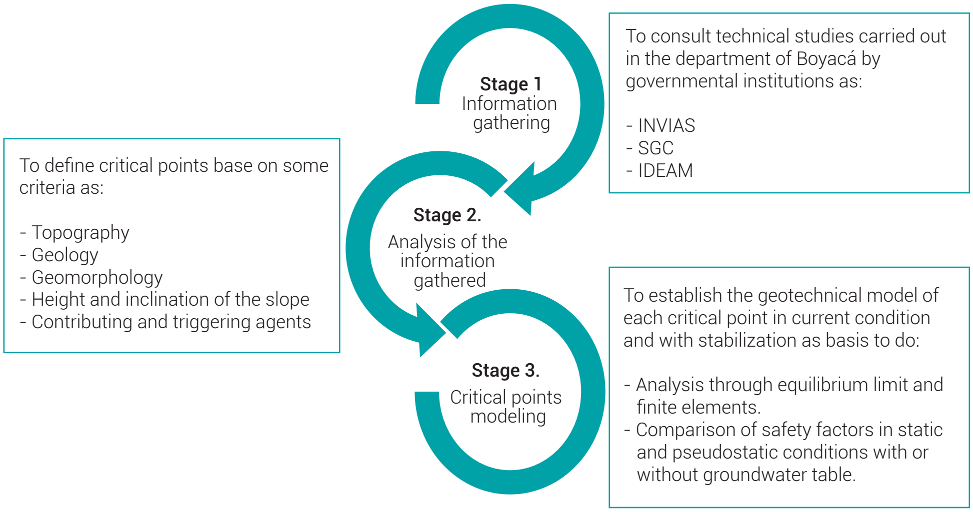


Figure 1. Investigation Methodology
Source: own work

2.1 Limit equilibrium analysis

Most limit equilibrium methods have in common the comparison of the strength or moments that are resistant and applied on a given failure surface. Fellenius [18] takes the safety factor as the relationship between the actual shear strength, calculated from the material in the slope and the critical shear stresses that attempt to produce the fault, along an assumed surface of possible failure; most analysis systems assume the Coulomb failure criterion along a given surface.

2.2 Finite element analysis

Clough y Woodward [19] introduced the finite element method that analyzes stresses and deformations in the nodes of the elements that form the slope, providing more information about their behavior in the light of the action of triggering agents (water, earthquake, anthropic activities, etc.) that generate different failure mechanisms. The Strength Reduction Method (SRM) utilizes a finite element model to perform slope stability analysis, by gradually decreasing the shear strength until the calculation does not converge and the slope failure is considered, providing the stresses of the elements that form the ground, displacements and deformations.

3. LOCATION OF THE STUDY

The analysis of slope instability processes located in road segments of the Department of Boyacá requires having sufficient and truthful information, so consultations were conducted in different state institutions, mainly obtaining information from INVIAS about the previous studies carried out in different road corridors in the Department. INVIAS is a public institution assigned to the Ministry of Transportation whose purpose is the execution of the policies, strategies, plans, programs and projects of the non-concessioned infrastructure of the National Road Network of primary and tertiary roads, rail, river and maritime infrastructure roads, in accordance with the guidelines given by the Ministry of Transportation [20].

Once all the collected information was analyzed, it was selected as an information source of the contract 2127 of 2011 called "Update of the studies and designs for the improvement of the Tunja - Ramiriquí - Miraflores - Páez road between PR 0 and PR 118, route 60 in the Department of Boyacá", executed between April 12th, 2012 and November 30th 2014 [21]; a road which currently shows active mass movement processes, many of them considered complex.

The Department of Boyacá is located on the Eastern Cordillera of Colombia, conformed by one hundred and twenty-three towns that develop different economic activities such as: agriculture, livestock, mining and industry; furthermore, important cultural activities related to: art, religion, literature and gastronomy, being an attractive tourist destination at the national and international level (Figure 2).

The Department has a road network about 17750 km distributed among first, second and third order roads, connecting different rural and urban areas, overcoming a complex geomorphology added to geotechnical, hydrological and anthropic conditions that contribute to the generation of mass movement processes at different points of the road segments throughout the region and suffering, in many cases, human and economic losses.

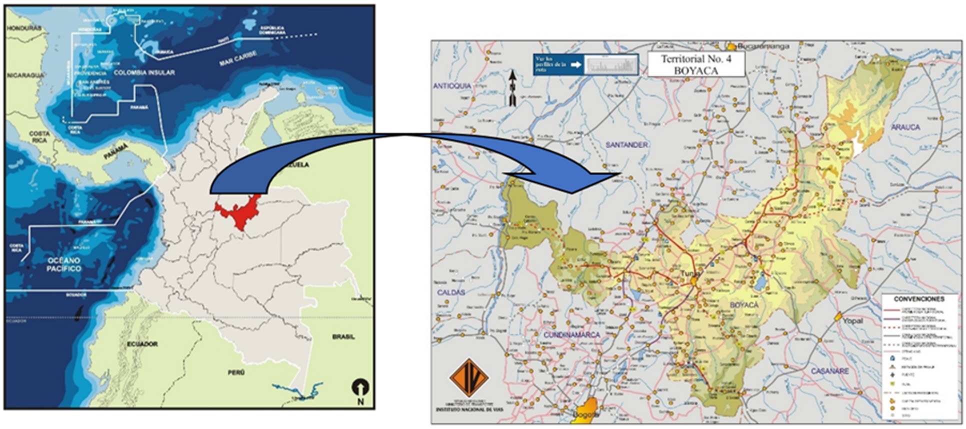


Figure 2. Department of Boyacá (Colombia) localization
Source: based on [22], [23]

Figure 3 shows the distribution of responsibility for the road network of the Department of Boyacá (be it the Nation, the Department or its towns) where 76% are gravel roads (13433 km) and only 24% are paved roads (4319 km).

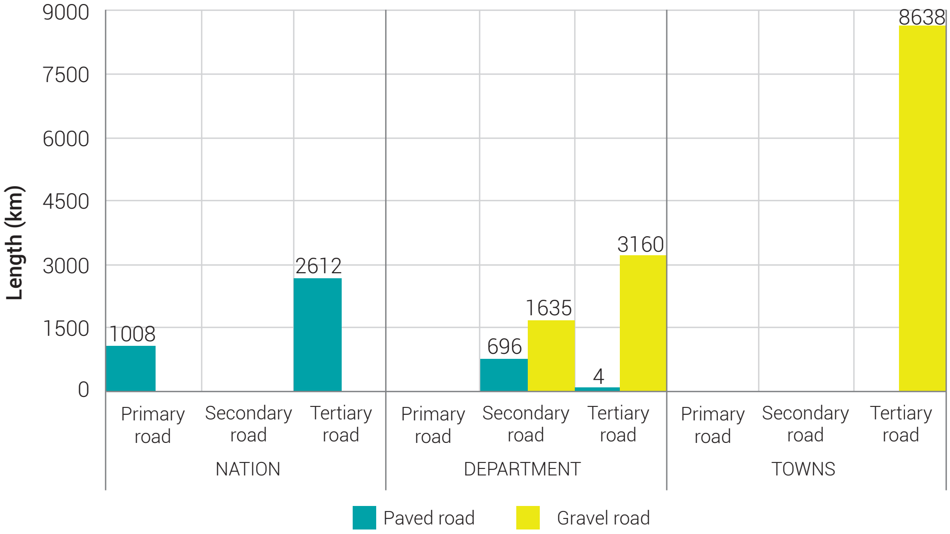


Figure 3. National Road Network of the Department of Boyacá
Source: based on [24]

Boyacá has an area of 23189 km^2 of which 3% of the territory has a very high susceptibility to landslides and approximately 53% of the area has a high susceptibility to this type of event, especially when there is an inappropriate use of the soil, in times of heavy rains or due to seismic movements. The presence of landslides is latent in eighty-one (81) municipal centers and one hundred twenty-two (122) out of one hundred twenty-three (123) that conform Boyacá (Figure 4). The towns with the highest percentage of area with very high susceptibility to landslides are Rondón, San José de Pare and Santana, exceeding 35% of the total area in each of them [25].

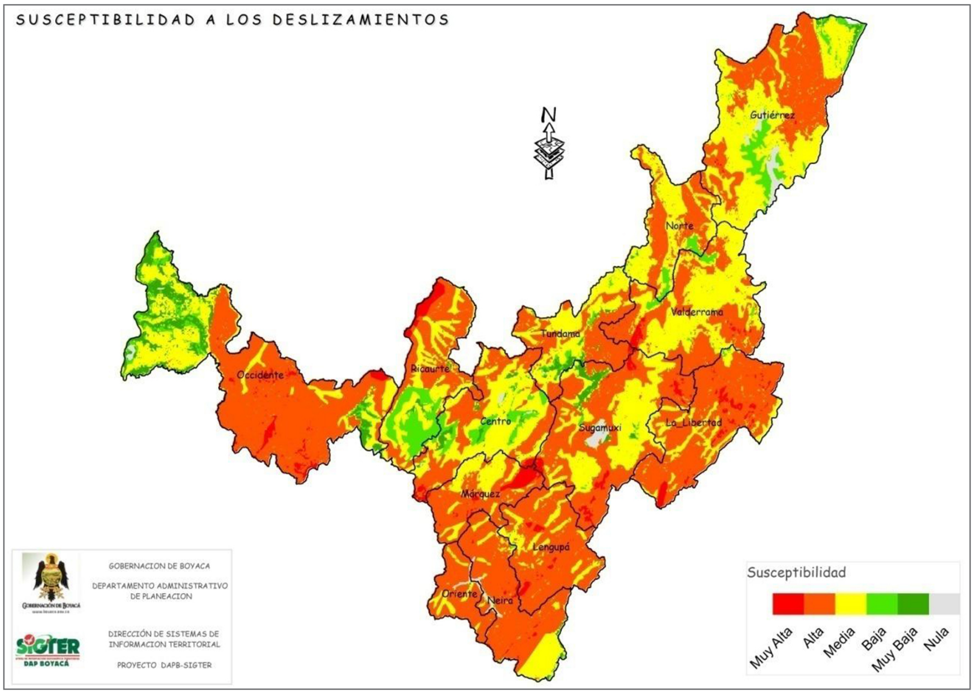


Figure 4. Landslide susceptibility map in the Department of Boyacá
Source: based on [25]

The road corridor under analysis is located in the central eastern part of the country in the Andean region over the Eastern Cordillera, in the southeast of the Department of Boyacá (Figure 5). It is a primary road developed on mountainous terrain, with a total length of 118 km, track width that does not exceed 6.50 m on average and with two lanes. The influence area is approximately 1700 km^2, where 53000 habitants of the provinces are located: Centro, Márquez and Lengupá.

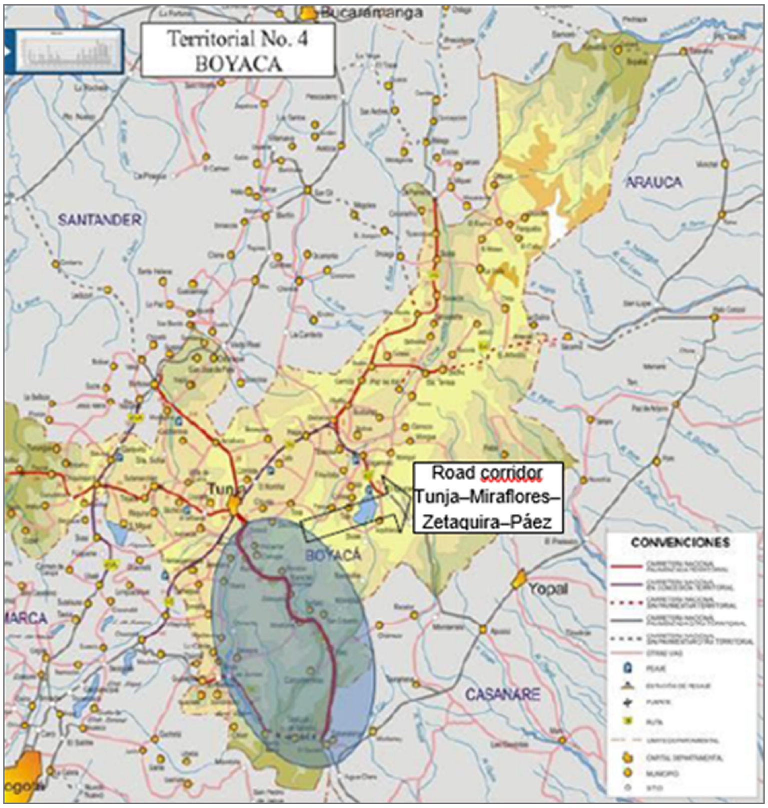
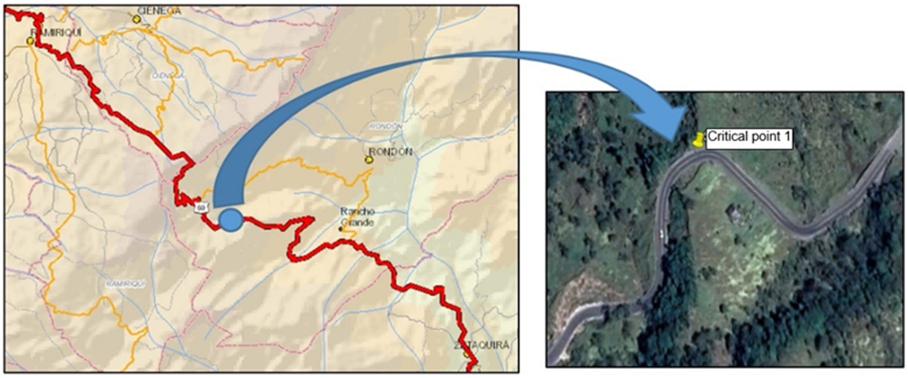


Figure 5. Road corridor localization, Department of Boyacá (Colombia)
Source: based on [23]

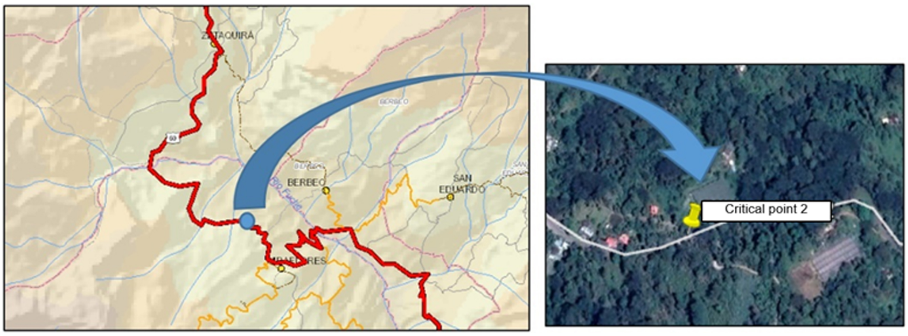
From the different critical points identified in the INVIAS study related to Tunja – Ramiriquí – Miraflores - Páez road, two of them have been prioritized bearing in mind criteria such as: volume of mass movement, mechanism of reported failure, topography, geological complexity, hydrogeology, slope height and slope inclination, type of material, land use, among others.

3.1 Critical points localization

The first critical point is located between the towns of Ramiriquí and Rondón in the abscissas K43+840 to K43+870 (coordinates 1081571.82N, 1090346.96E and 1081546.48N, 1090299.69E respectively). The second critical point is located between the towns of Zetaquira and Miraflores in the abscissas K79+240 to K79+320 (coordinates 1068432.02N, 1101556.95E and 1068462.92N, 1101509.13E respectively) as shown in Figure 6.



a) Critical point Ramiriquí – Rondón



b) Critical point Zetaquira – Miraflores

Figure 6. Critical points localization, Department of Boyacá (Colombia)
Source: based on [26]

3.2 Geology and geomorphology

In the area of influence of the whole road corridor, rocks corresponding to sedimentary sequences of marine and continental origin emerge with ages ranging from the Jurassic to the Tertiary, partially covered by Quaternary deposits of colluvial origin, alluvial and residual soil. The Ramiriquí - Rondón critical point is located in colluvial deposits and breccias (Qc-Br) in the Concentration Formation (Tc) composed of conglomerate quartz sandstones, gray-green clays. It has an abrupt low relief, composed of gently inclined flat surfaces and convex and concave surfaces of an asymmetric nature, whose axes are parallel to each other and orthogonal to the road line and are tectonic in nature. This guideline is integrated by succession of curves that mark the horizontal perimeter silhouette of the relief.

The stretch in which the Zetaquira - Miraflores critical point is located, presents rocks of shale type, laminar, soft resistance (Rb1), with thin layers of sandstone and limestone, belonging to the Fómeque Formation (Kif), of shale composition, in laminar stratification, of soft resistance, on highly weathered surfaces; there are thin sandstone and limestone intercalations. There are mainly landforms or slopes with inversed pitch, that is, those in which the rock components dip in the opposite direction to the slopes and landforms of denudative-cumulative origin corresponding to colluvial deposits.

3.3 Precipitation

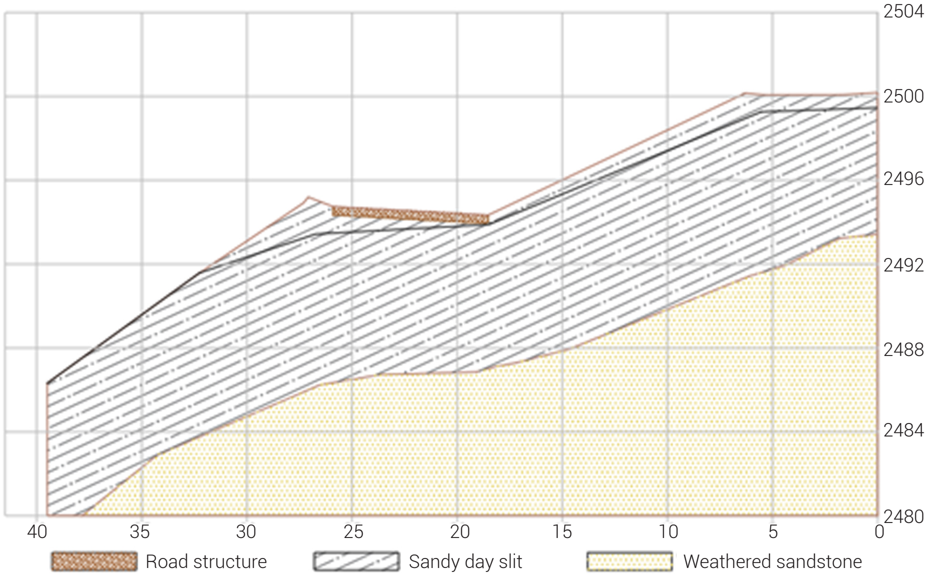
The two critical points present rains with a bimodal tendency, unique to a transition zone between the Andean region and the Piedemonte Llanero, with a long wet period from April to August and a short rest period in the month of September; following with the winter of October to November and low rains from December to March, with maximum in June and minimum in January. The information was based on the Tibaná, Rondón and Zetaquira stations managed by IDEAM, whose average multi-year rainfall is 1700 mm with an average maximum in 24 hours of 109 mm. Historical rainfall data in these towns showed the importance of maintaining the surface and subsurface drainage working to technically evacuate the waters and not affect the structure of the road, the existing slopes and embankments.

3.4 Geotechnical modeling

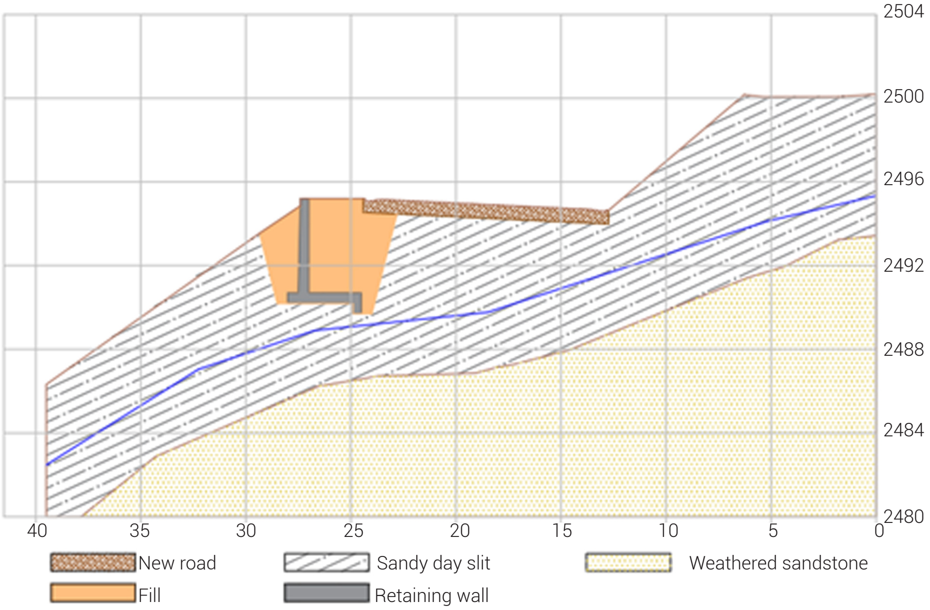
For each of the critical points, the geotechnical model was based on the information provided in the INVIAS study for the current conditions and establishing the resistance parameters of the materials used. The works recommended in the study were also incorporated into the model to guarantee the stability of each location.

3.4.1 Geotechnical model critical point Ramiriquí – Rondón

Figure 7 defines the geotechnical model of the critical point Ramiriquí - Rondón for the current conditions and with works, showing a sandy clay silt on a weathered sandstone and whose parameters are shown in Table 1. According to the INVIAS study, the construction of a concrete retaining wall 5.5 m high, 3.5 m base and 30 m long has been envisaged as has the construction of horizontal drains for the reduction of the existing groundwater table, as well as a coronation ditch.



a) Current condition



b) Condition with works

Figure 7. Geotechnical model critical point Ramiriquí - Rondón
Source: based on INVIAS study [21]

Table 1. Parameters of material resistance critical point Ramiriquí – Rondón

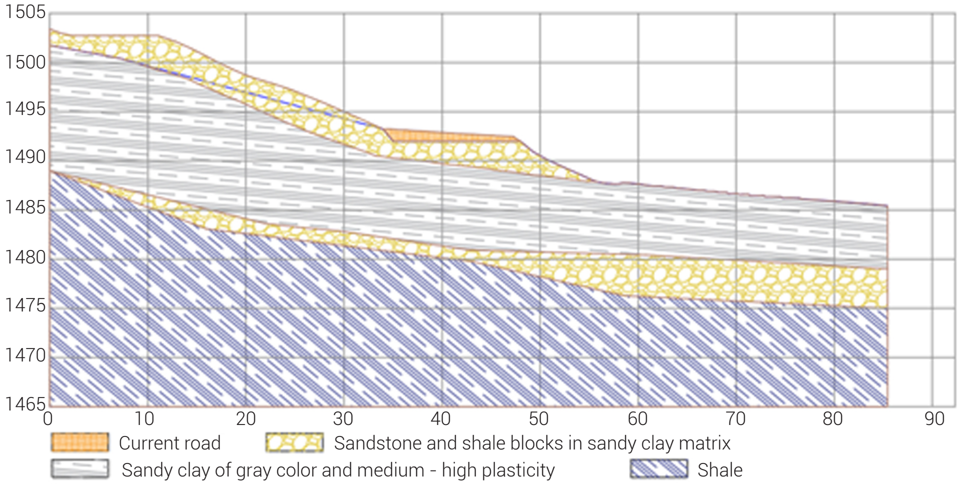
Material	**γ [t/m³]**	**C_u [t/m²]**	**ϕ [°]**
Current road	1.82	1.0	26.0
New road	2.00	1.0	35.0
Fill	1.90	1.5	35.0
Retaining wall (E: 2150000 t/m^2)	2.40	3000	0.0
Sandy clay silt	2.03	1.0	29.3
Weathered sandstone	2.11	UCS: 5000 t/m^2 m: 0.477966 s: 0.000240369 a: 0.505734	

Source: based on INVIAS study [21]

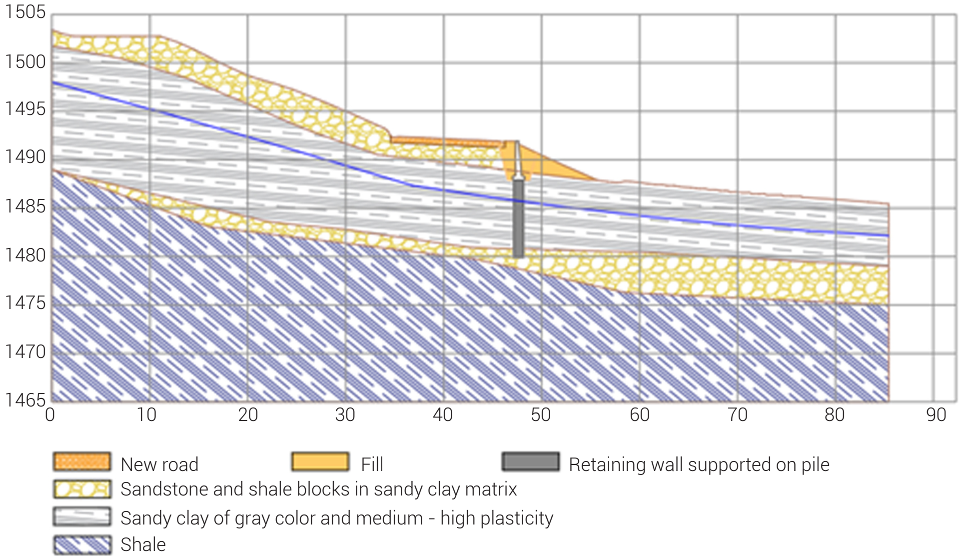
3.4.2 Geotechnical model critical point Zetaquira – Miraflores

Figure 8 shows the geotechnical model of the Zetaquira - Miraflores critical point for both conditions (current and with works). It is underlied by a colluvial deposit conformed by sandstone and shale blocks in a sandy clay matrix. Sandy clays are also present and as a base of all these lies a layer of shale, whose parameters are described in Table 2.

Within the stabilization works proposed in the INVIAS study, there is a retaining wall along the entire length of the critical point, 4.0 m high, supported on piles of 1.0 m diameter (spaced every 2.0 m between axes) and its foundation reaches down to a depth of 8.0 m from the base of the wall. To lower the groundwater table, a parallel subdrain on the road on the inner edge is proposed, as well as the construction of a drainage trench in the longitudinal direction and following the movement of the slope.



a) Current condition



b) Condition with works

Figure 8. Geotechnical model critical point Zetaquira - Miraflores

Source: based on INVIAS study [21]

Table 2. Parameters of material resistance critical point Zetaquira - Miraflores

Material	γ [t/m³]	C_u [t/m²]	ϕ [°]
Current road	1.82	1.0	26.0
New road	2.00	1.0	35.0
Fill	1.90	1.5	35.0
Retaining wall (E: 2150000 t/m²)	2.40	3000	0.0
Sandstone and shale blocks in sandy clay matrix (above)	1.90	0.0	26.8
Sandy clay of medium – high plasticity	1.93	1.0	17.0
Sandstone and shale blocks in sandy clay matrix (below)	1.90	0.0	35
Shale	2.41	21	10

Source: based on INVIAS study [21]

4. RESULTS AND ANALYSIS

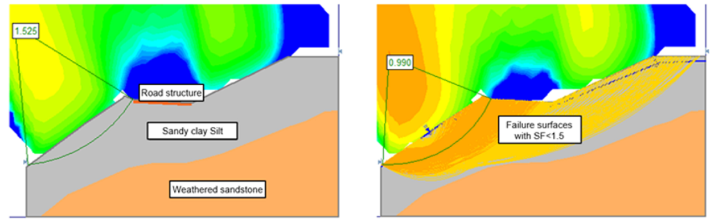
With the 2D geotechnical models of each critical point, the modeling is carried out in Slide and Midas GTS NX to generate the safety factor in the current conditions and with works, defining four cases of analysis that involve static and pseudostatic analysis with the presence and absence of a groundwater table. Taking advantage of the functionality of Midas GTS NX for three-dimensional analysis, the 3D model of the two critical points for the condition with works is generated and compared with the 2D results. It is relevant to note that the safety factors are obtained by two different methods (limit equilibrium and finite elements) and then compared, taking as a basis that the Colombian Regulation of Construction Earthquake Resistant NSR-10 in its title H about geotechnical studies, requires a minimum value of 1.5 in the static condition and 1.05 in the pseudostatic condition to guarantee stability (with the presence of a groundwater table if it exists) but it does not specify any calculation method.

In the case of the earthquake effect, 2/3 of the value of the horizontal acceleration coefficient Aa obtained from Regulation NSR-10 was employed. The safety factors in Slide correspond to Spencer's limit equilibrium method that satisfies the equations of moment and force equilibrium and the forces in the slices. This method is utilized in the studies compiled by INVIAS. The constitutive model for soil material is Mohr Coulomb and for the rock material the generalized Hoek-Brown model is used as they are the most applied in INVIAS studies.

In the finite element modeling, the results depend on the quality of the meshes, ensuring mesh element sizes that offer reliable results and activating the "Higher Order Elements" option, for greater accuracy. 2D and 3D finite element modeling are based on the Strength Reduction Method (SRM), providing the stresses, as well as displacements and deformations. Moreover, the arc length method was activated, calculating the increase in the safety factor according to the convergence speed and obtaining a more reliable value; in case this option is not used, the calculation of the safety factor uses the increments established by the user.

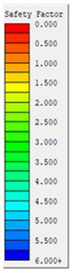
4.1 2D modeling in Slide software

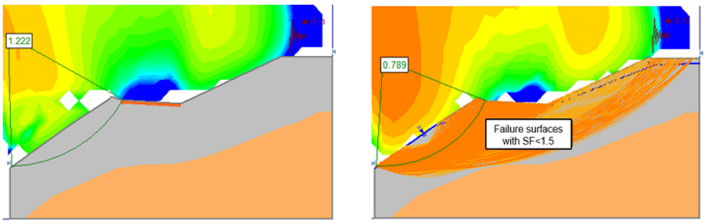
The results of 2D modeling under current conditions show the potential failure surfaces for safety factors less than 1.5 in static analyses and less than 1.05 in pseudostatic analyses, achieving for the critical point Ramiriquí - Rondón only in the analyses: static without groundwater table and pseudostatic without groundwater table. For the critical point Zetaquira - Miraflores the safety factors for each of the four cases of analysis do not meet the required minimum. The presence of a groundwater table becomes the main triggering agent of instability processes that can reach the critical point of Ramiriquí - Rondón for the entire depth of the sandy clay silt and at the critical point of Zetaquira - Miraflores it can have a presence along colluvial deposits conformed by sandstone and shale blocks in a sandy clay matrix, including sandy clays (Figures 9 and 10). The effect of the earthquake also reduces the safety factor against static conditions, but inferior to the effects of the groundwater table. The safety factors conclude the current presence of instability processes at both critical points.



a) Static analysis without groundwater table (SF=1.53)

b) Static analysis with groundwater table (SF=0.99)



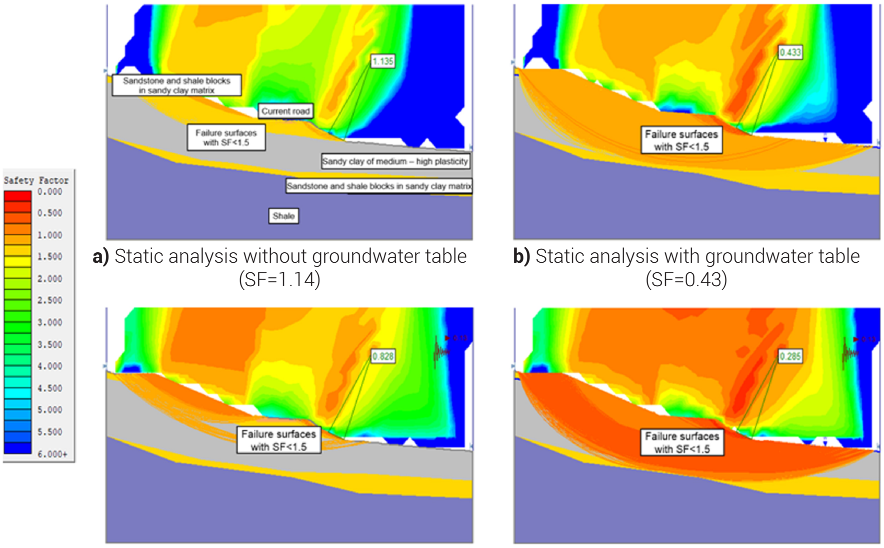


c) Pseudostatic analysis without groundwater table (SF=1.22)

d) Pseudostatic analysis with groundwater table (SF=0.79)

Figure 9. 2D modeling in Slide for the critical point Ramiriquí – Rondón (Current condition)

Source: own work



a) Static analysis without groundwater table (SF=1.14)

b) Static analysis with groundwater table (SF=0.43)

c) Pseudostatic analysis without groundwater table (SF=0.83)

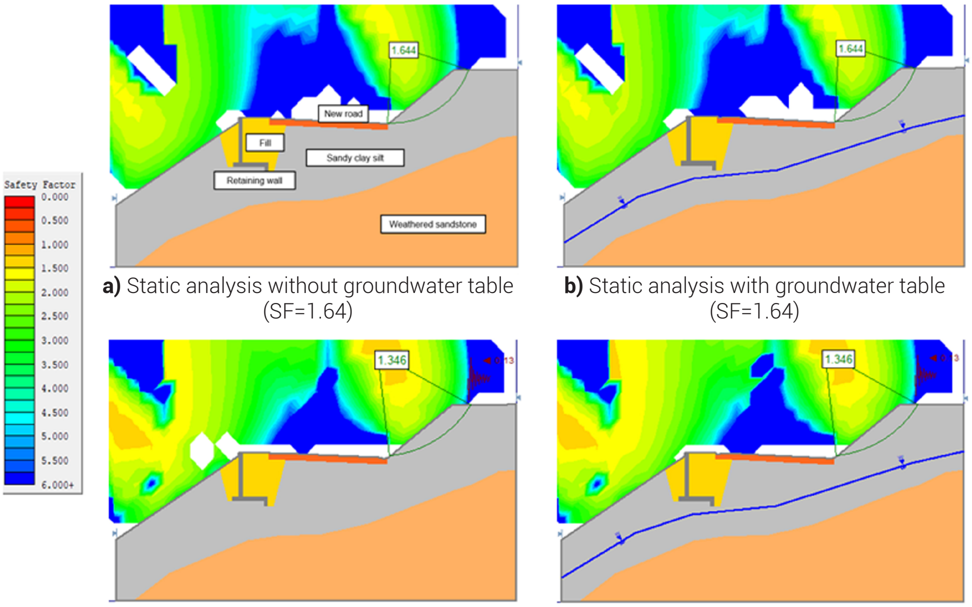
d) Pseudostatic analysis with groundwater table (SF=0.29)

Figure 10. 2D modeling in Slide for the critical point Zetaquira – Miraflores (Current condition)

Source: own work

In view of the need to implement stabilization works to guarantee the stability of the road corridor, the Ramiriquí - Rondón critical point includes: a retaining wall with its respective fill material and a new road structure; for the critical point Zetaquira – Miraflores, a retaining wall with fill material supported on a pile and a new road structure (Figures 11 and 12). The geometric characteristics of these works were described above, as well as the hydraulic works to reduce groundwater tables.

The resulting safety factors in the condition with works permit us to conclude that the lowering of the groundwater table no longer has an influence on stability in both static and pseudostatic analyses, unlike the effect of the earthquake that does reduce the safety factor in these types of analyses. Failure surfaces with the lowest safety factors are present in the upper slope of the road for the two critical points.



a) Static analysis without groundwater table (SF=1.64)

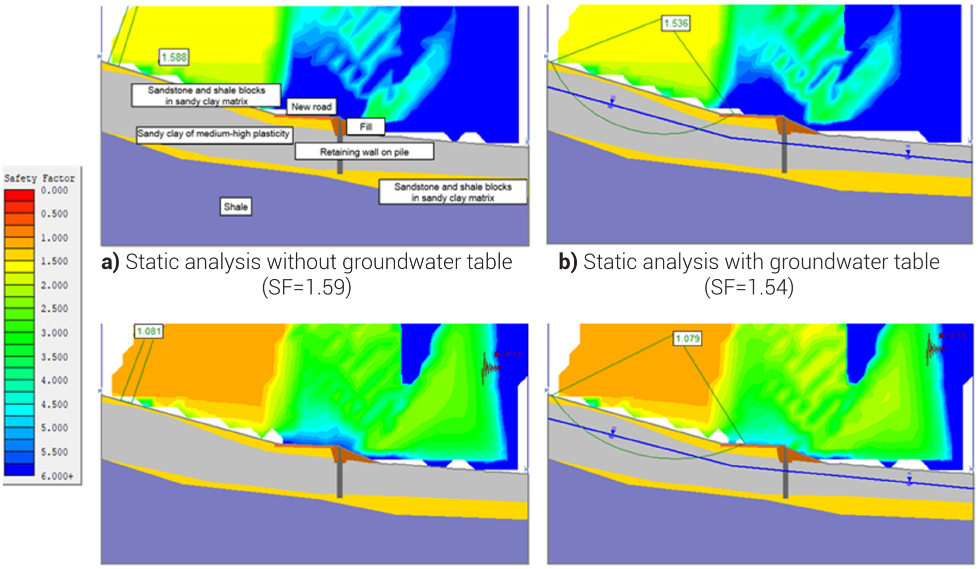
b) Static analysis with groundwater table (SF=1.64)

c) Pseudostatic analysis without groundwater table (SF=1.35)

d) Pseudostatic analysis with groundwater table (SF=1.35)

Figure 11. 2D modeling in Slide for the critical point Ramiriquí – Rondón (Condition with works)

Source: own work



a) Static analysis without groundwater table (SF=1.59)

b) Static analysis with groundwater table (SF=1.54)

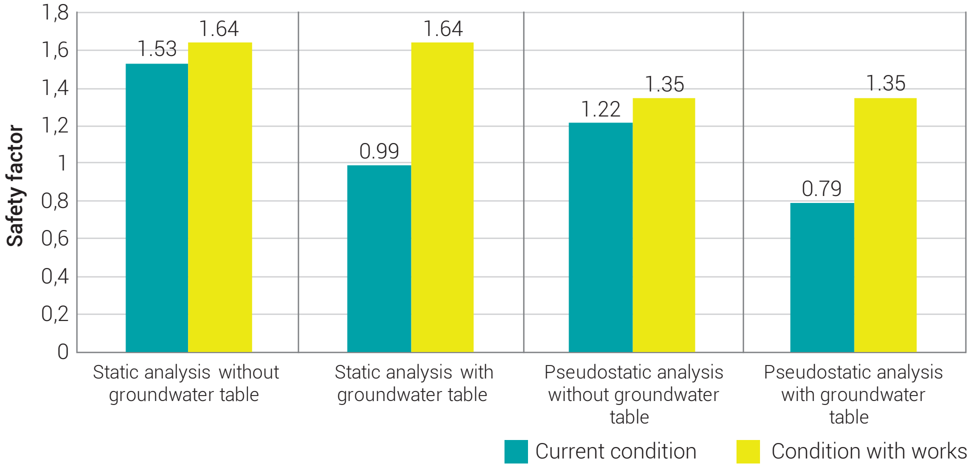
c) Pseudostatic analysis without groundwater table (SF=1.08)

d) Pseudostatic analysis with groundwater table (SF=1.08)

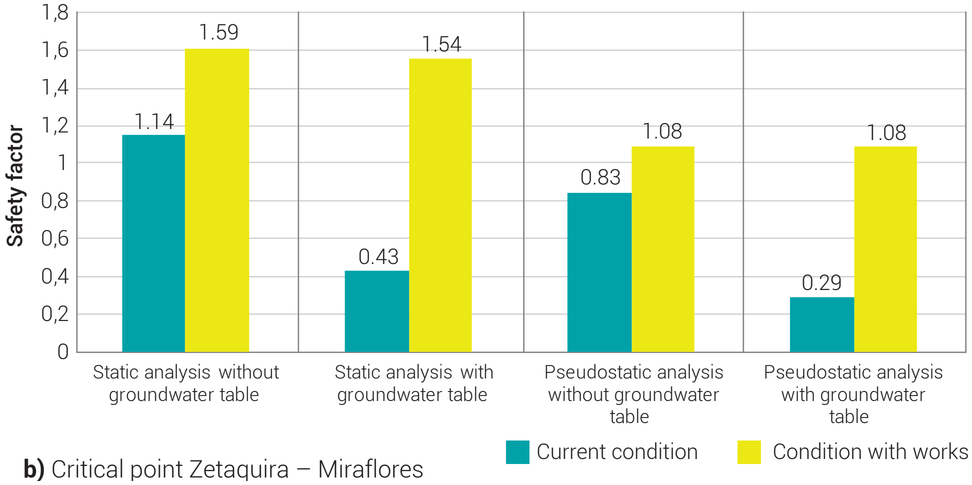
Figure 12. 2D modeling in Slide for the critical point Zetaquira – Miraflores (Condition with works)

Source: own work

Figure 13 presents the safety factors in both conditions (current and with works) for the two critical points, demonstrating an increase in the safety factor with the implementation of the works and reaching factors that meet the minimum requirements in the Regulation NSR-10. Comparing the safety factors of the current conditions and with works, for the critical point Ramiriquí - Rondón the increase varies from 7% in the static analysis without groundwater table (from 1.53 to 1.64) to 71% in the pseudostatic analysis with groundwater table (from 0.79 to 1.35). For the critical point Zetaquira - Miraflores, the percentages of the growth in the safety factor range from 30% in the pseudostatic analysis without groundwater table (from 0.83 to 1.08) to 272% in the pseudostatic analysis with groundwater table (from 0.29 to 1.08).



a) Critical point Ramiriquí – Rondón



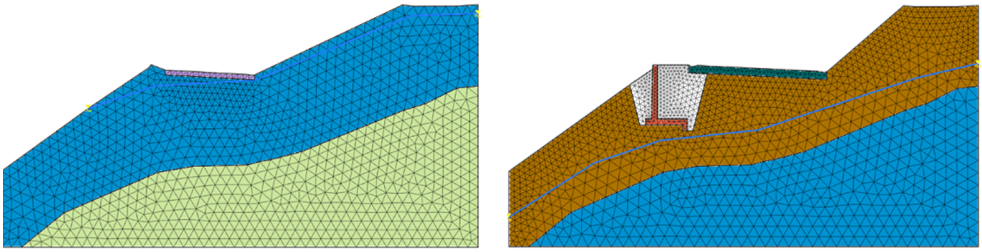
b) Critical point Zetaquira – Miraflores

Figure 13. Summary safety factors in 2D modeling with Slide

Source: own work

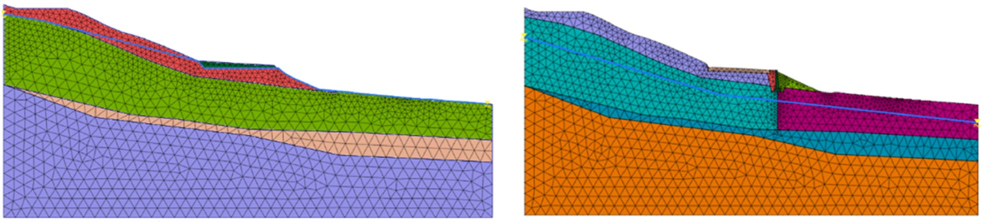
4.2 2D modeling in Midas GTS NX software

The same geometries modeled in Slide were incorporated into the Midas GTS NX software to obtain the safety factors by the finite element method. Figures 14 and 15 show the 2D meshes generated for the current conditions and with works.



a) Current condition **b)** Condition with works

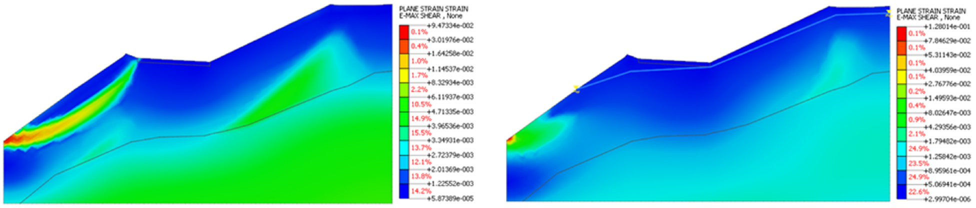
Figure 14. 2D meshes generated in Midas GTS NX for the critical point Ramiriquí – Rondón
Source: own work



a) Current condition **b)** Condition with works

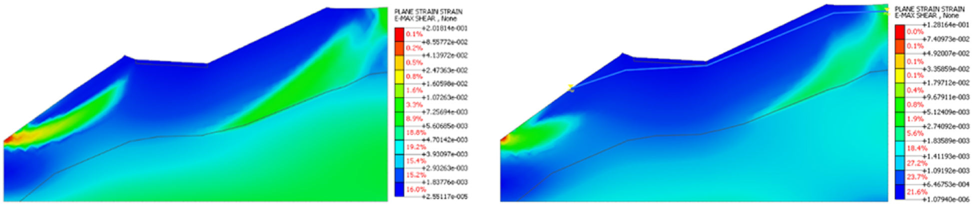
Figure 15. 2D meshes generated in Midas GTS NX for the critical point Zetaquira–Miraflores
Source: own work

Safety factors greater than 1.0 obtained for the current condition by finite elements have values very close to those obtained by limit equilibrium (Figures 16 and 17). Analyses that present safety factors less than 1.0 confirm instability processes currently on the road. The geometry of the failure surfaces generated in Midas GTS NX reaches the lower and upper slopes of the road, and the contact between the sandy clay silt and the weathered sandstone can be reached at the critical point Ramiriquí - Rondón. At the critical point Zetaquira - Miraflores the failure zone involves two layers of colluvial deposits and a layer of sandy clays. The presence of an almost superficial groundwater table is the greatest influence on the reduction of the safety factor, obtaining values well below those presented with the limit equilibrium method. The effect of the earthquake also reduces the safety factor but not in the same proportion as the groundwater table.



a) Static analysis without groundwater table (SF=1.55)

b) Static analysis with groundwater table (SF<0.10)

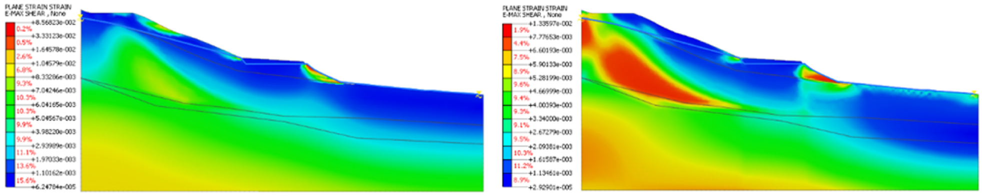


c) Pseudostatic analysis without groundwater table (SF=1.23)

d) Pseudostatic analysis with groundwater table (SF<0.10)

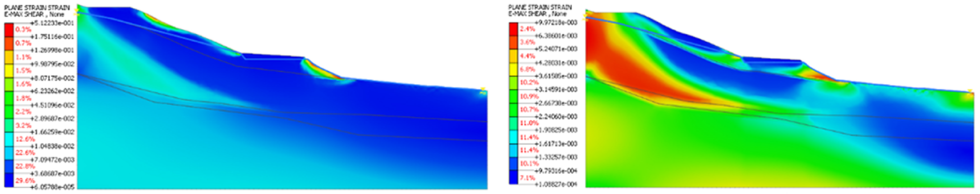
Figure 16. 2D modeling in Midas GTS NX for the critical point Ramiriquí – Rondón (Current condition)

Source: own work



a) Static analysis without groundwater table (SF=1.13)

b) Static analysis with groundwater table (SF<0.10)



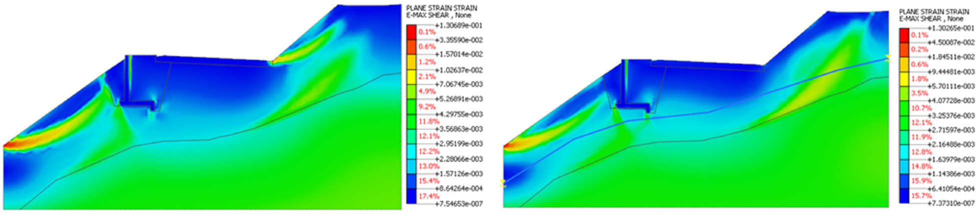
c) Pseudostatic analysis without groundwater table (SF=0.7)

d) Pseudostatic analysis with groundwater table (SF<0.10)

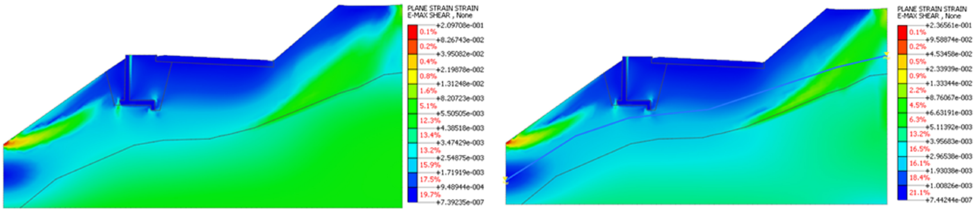
Figure 17. 2D modeling in Midas GTS NX for the critical point Zetaquira – Miraflores (Current condition)

Source: own work

The 2D modeling incorporated the same stabilization works utilized in the analyses with Slide (Figures 18 and 19), coinciding with the findings that the influence of the earthquake is greater when compared to the lowering of groundwater table.



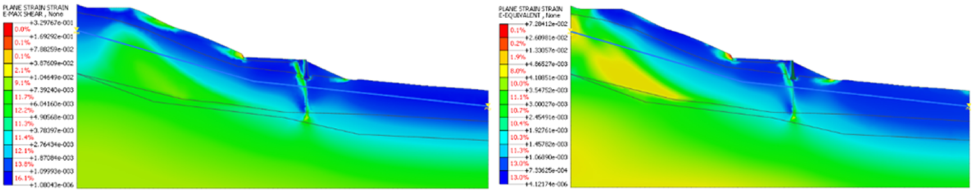
a) Static analysis without groundwater table (SF=1.59) **b)** Static analysis with groundwater table (SF=1.47)



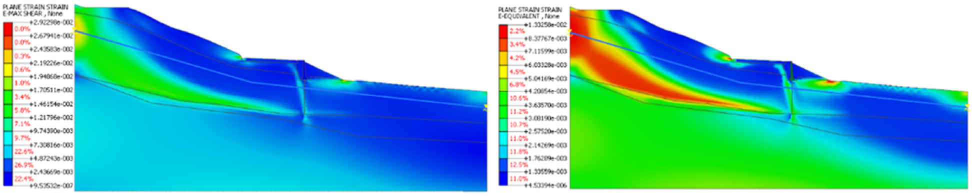
c) Pseudostatic analysis without groundwater table (SF=1.14) **d)** Pseudostatic analysis with groundwater table (SF=1.09)

Figure 18. 2D modeling in Midas GTS NX at the critical point Ramiriquí – Rondón (Condition with Works)

Source: own work



a) Static analysis without groundwater table (SF=1.06) **b)** Static analysis with groundwater table (SF=0.99)



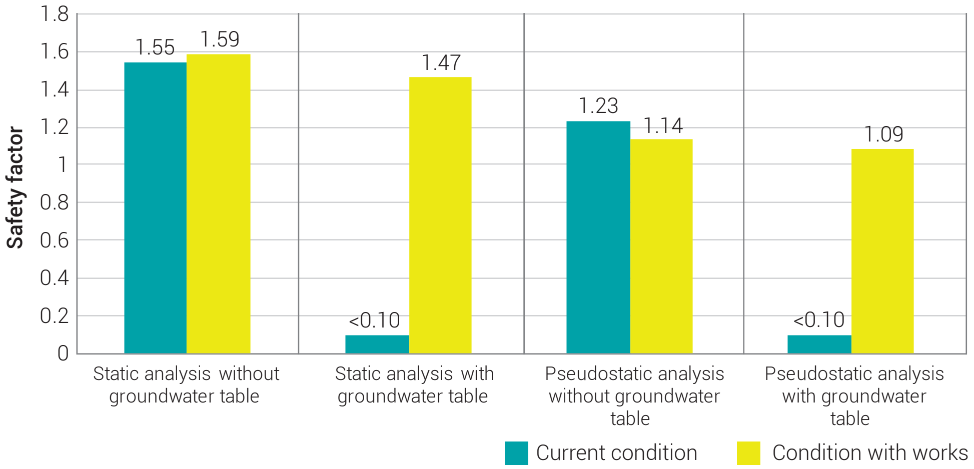
c) Pseudostatic analysis without groundwater table (SF=0.61) **d)** Pseudostatic analysis with groundwater table (SF=0.51)

Figure 19. 2D modeling in Midas GTS NX at the critical point Zetaquira – Miraflores (Condition with Works)

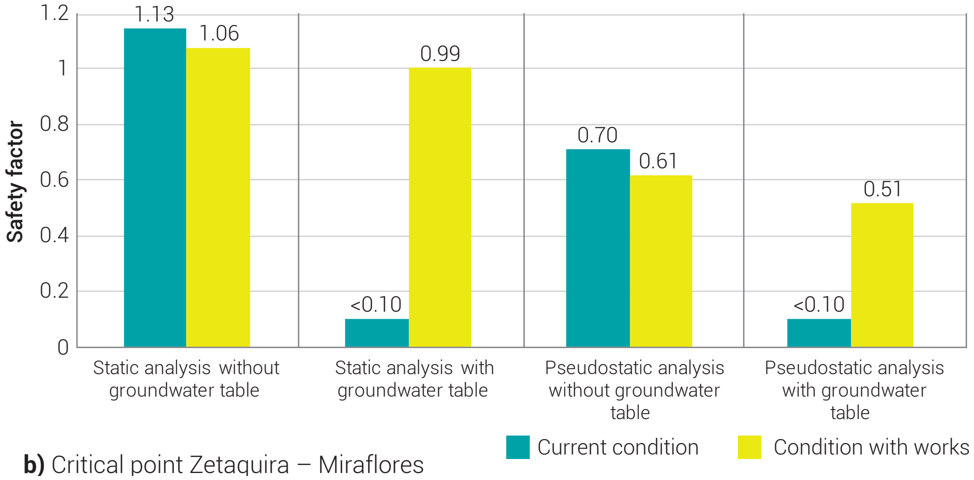
Source: own work

The geometry of the failure surfaces in the finite element model is visible in the lower and upper slopes of each section of the road, with the critical point Ramiriquí - Rondón being more remarkable on the lower slope and for the critical point Zetaquira - Miraflores in the upper slope of each road.

Figure 20 summarizes the safety factors in both conditions (current and with works), showing that for the condition with works for the critical point Ramiriquí - Rondón that the factors reach the minimum required by the regulations; opposite to the case of the critical point Zetaquira - Miraflores whose safety factors do not fulfill the requirements of Regulation NSR-10, leading to a reevaluation of the defined stabilization works.



a) Critical point Ramiriquí – Rondón



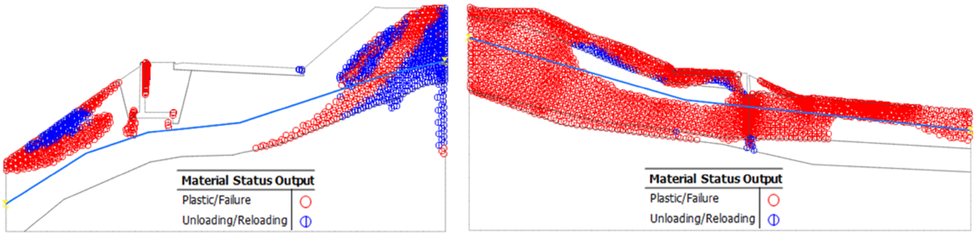
b) Critical point Zetaquira – Miraflores

Figure 20. Summary of safety factors in 2D modeling with Midas GTS NX

Source: own work

There are three cases where the safety factors for the condition with works decreases regarding the current condition; for example, in the pseudostatic analysis without groundwater table there are two critical points with an average reduction of 10%, perhaps due to the additional weight involved in the stabilization works. In general, the safety factors obtained for the condition with works in the finite element model are lower than those calculated by limit equilibrium.

One of the potential benefits of finite elements is to visualize the states of the material after modeling. Figure 21 shows the discharge-recharge and plastic states of the material that form each critical point.



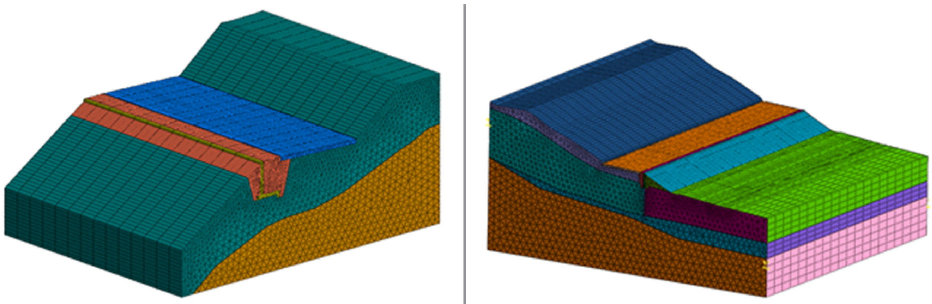
a) Critical point Ramiriquí – Rondón **b)** Critical point Zetaquira – Miraflores

Figure 21. States of the material according to 2D modeling in Midas GTS NX for condition with works (pseudostatic analysis with groundwater table)

Source: own work

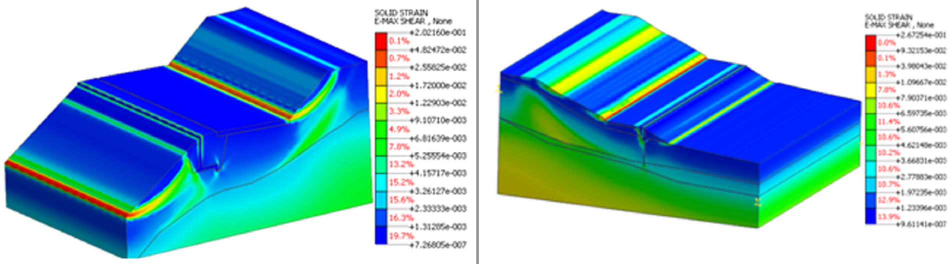
4.3 3D modeling in Midas GTS NX software

The 2D geometries modeled in Midas GTS NX were extruded to obtain 3D models. The extrusion distances are 30 m for the Ramiriquí - Rondón critical point and 80 m for the Zetaquira - Miraflores critical point, equivalent to the lengths where instability processes occur. It is clear that these models have limitations because they do not represent the variability in topography or in the layers of materials in depth, since this information is not available. The calculated safety factors only apply to static analyses (with and without groundwater table) in the condition with works, where the results show slightly higher values than those obtained in 2D analyses (Figure 22).



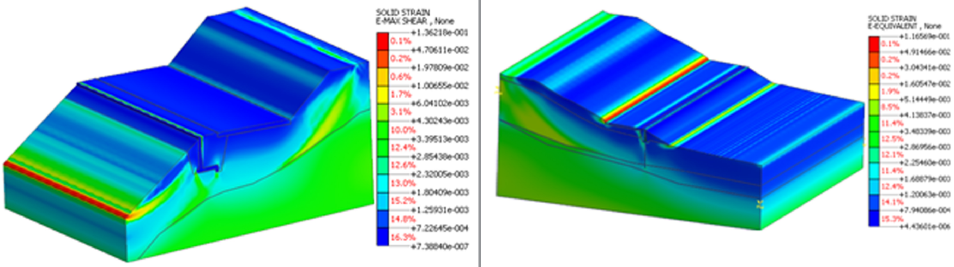
a) 3D Model
(Critical point Ramiriquí - Rondón)

b) 3D Model
(Critical point Zetaquira- Miraflores)



a.1) Static analysis without groundwater table
(SF=1.68)

b.1) Static analysis without groundwater table
(SF=1.14)



a.2) Static analysis with groundwater table
(SF=1.49)

b.2) Static analysis with groundwater table
(SF=1.03)

Figure 22. Summary of safety factors in 3D modeling with Midas GTS NX
(Condition with works)
Source: own work

Figure 23 compares the safety factors of 2D and 3D modeling by the finite element method for the condition with works. In the critical point Ramiriquí – Rondón, the 2D and 3D safety factors in the static analysis without groundwater table are 1.59 and 1.68 respectively with an increase close to 6%. In the static analysis with groundwater table, the safety factors are 1.47 in 2D and 1.49 in 3D, equivalent to an increase close to 2%. At the critical point Zetaquira - Miraflores the 2D and 3D safety factors in the static analysis without groundwater table are 1.06 and 1.14 respectively with an increase close to 8%. In the static analysis with groundwater table, the safety factors are 0.99 in 2D and 1.03 in 3D, equivalent to an increase of 4%. The increase in average for the analyzes performed is 5% and the lowering of the groundwater table still influences the reduction of the safety factors at the two critical points.

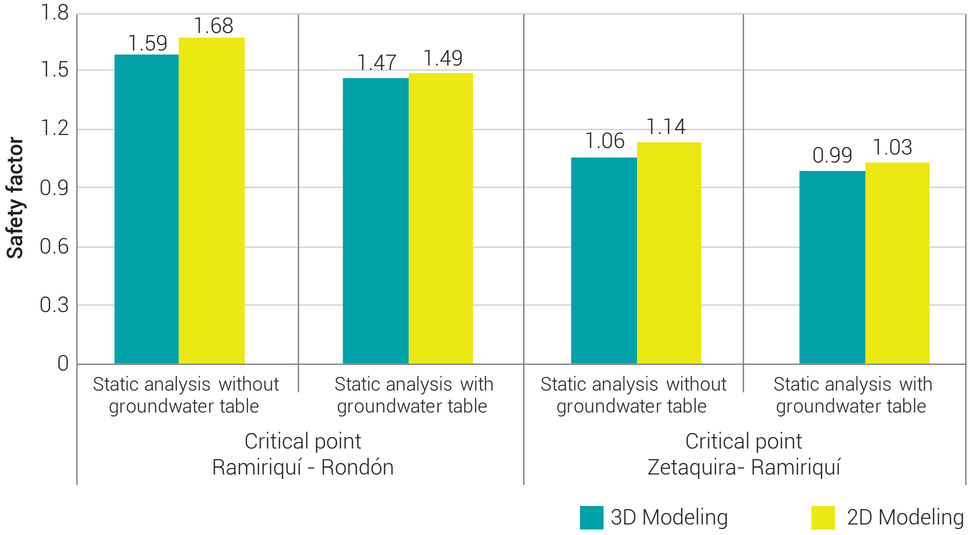


Figure 23. Safety factors obtained in 2D and 3D modeling by finite elements (Condition with works)
Source: own work

5. DISCUSSION AND CONCLUSIONS

The results of the analyzes carried out at the two critical points are consistent with the current state of mass movement processes, with a groundwater table almost at the surface level being its main triggering agent, whose influence on the reduction of the safety factor is greater in the modeling by finite elements than by the limit equilibrium method.

At the critical point Zetaquira - Miraflores (condition with works) the safety factors for limit equilibrium fulfill the regulatory requirements, but the opposite occurs with the finite element modeling, making it necessary to reconsider the proposed stabilization works that would not solve the current problem, and even more, to analyze that it is not only enough to determine a safety factor without knowing the advantages and limitations offered by the calculation method to be utilized.

The stabilization works are designed to offer adequate levels of security and therefore increase safety factors, but in 2D modeling by finite elements, three cases were found (with absence of groundwater table) where the behavior is the inverse, demonstrating that the implementation of works does not always favor stability conditions through the use of different methods of analysis.

A rigorous analysis is vital to determine preventive, corrective and / or mitigation actions that minimize the negative and catastrophic impacts resulting from the presence of mass movement processes, defining among others, failure mechanisms, contributing and / or triggering agents, through the application of updating numerical simulation techniques replacing traditional methods based on limit equilibrium.

The finite element modeling determines the stresses and deformations of the ground and identifies the presence of several failure mechanisms regardless of their geometry, being an affordable and effective tool for the analysis of instability processes. The above is supported by a rigorous field and laboratory study that obtains the parameters required for the analysis.

It is relevant to continue this research, including other constitutive models that generate results that are increasingly close to reality and taking into account the possible scenarios of climate change (temperature and precipitation variables), promoting the creation of 3D models to determine the variability in topography and depth of the layers.

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