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Stability Assessment of Landfill Slopes: A Two-Dimensional Analysis and Sensitivity Analysis of Safety Factor

Avaliação da estabilidade de taludes de aterro sanitário: uma análise bidimensional e de sensibilidade do fator de segurança

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Abstract: The growing demand for effective solid waste management in urban areas, coupled with the challenges associated with the development of new landfills, has led to the practice of elevating existing landfills as a viable strategy to enhance waste capacity. Conversely, the risks associated with this practice, such as landslides, pose significant environmental and social challenges. Accordingly, this study aims to evaluate the stability of slopes in a landfill situated in the Brazilian semiarid region. The methodology involved two-dimensional stability analysis and sensitivity analysis of the safety factor concerning variations in geotechnical parameters. Two scenarios were simulated: one representing the landfill in an unsaturated state and the other under saturated conditions. The analyses were conducted using the Slope/W and Slide/2 software. The results demonstrate that slope stability is strongly influenced by the geotechnical properties of the waste and the presence of a piezometric liquid level within the landfill. Numerical simulations may show minor discrepancies when conducted with different software programs, and the accuracy of identifying critical failure surfaces is contingent on the quality and representativeness of the input data.

Keywords: Safety factor; Geotechnical parameters; Deterministic analysis; Stability analysis.

Resumo: Devido à crescente demanda pela disposição de resíduos sólidos urbanos e às barreiras encontradas para a instalação de novos aterros sanitários, o alteamento dessas estruturas tem sido uma estratégia adotada para ampliar a capacidade de disposição de resíduos. Por outro lado, os riscos associados a essa prática, como os deslizamentos, podem causar grandes impactos ambientais e sociais. Diante disso, a proposta deste estudo consiste em analisar a estabilidade de taludes em um aterro sanitário localizado no semiárido brasileiro. A metodologia envolveu análises de estabilidade bidimensionais e análises de sensibilidade do fator de segurança a variações dos parâmetros geotécnicos. Foram simulados dois cenários: um com o aterro em estado não saturado e outro em condições de saturação. As análises foram realizadas nos *softwares slope/W* e no *slide/2*. Os resultados indicam que a estabilidade dos taludes está intimamente relacionada às propriedades geotécnicas dos RSU e à presença do nível piezométrico de líquidos no maciço. Suponha-se que as simulações numéricas podem apresentar pequenas discrepâncias quando realizadas em dois *softwares* diferentes e que a precisão das potenciais superfícies de ruptura crítica está condicionada à qualidade e representatividade dos dados de entrada.

Palavras-chave: Fator de segurança; Parâmetros geotécnicos; Análise determinística; Análise de estabilidade.

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1. Introduction

The increasing generation of Municipal Solid Waste (MSW) and stricter environmental regulations on new landfill development have driven the adoption of strategies to enhance the capacity of existing sites. These strategies, such as vertical expansion and lateral extension of landfill areas (Ghasemian et al., 2024), optimize available space, reduce costs associated with constructing new landfills, and minimize the need for additional land allocation. (Lü *et al.*, 2019).

However, raising landfill structures poses significant concerns, especially considering numerous incidents over recent decades where MSW landslides escalated into high-magnitude disasters, causing substantial harm to both populations and the environment (Li et al., 2023). In this context, slope stability remains a primary engineering concern throughout landfill operations (Gao et al., 2018) and represents a critical challenge across the entire lifespan of such projects. Consequently, assessing landfill slope stability is essential to address the environmental risks and potential disasters associated with these structures.

Studies by Strauss (1998), Zhan et al. (2008), Basha and Raviteja (2018), Remédio (2014), Silva (2011), Jahanfar et al. (2017), Lu et al. (2019), Cirolini et al. (2020), Medeiros et al. (2020), and Damasceno et al. (2020) have conducted stability analyses for various landfills, primarily employing two-dimensional approaches. This practice reflects a well-established tradition in the technical literature. In particular, Daciolo (2020) and Jahanfar et al. (2017) identified several factors that influence variations in the safety factor, including the elevation of the landfill cell, shear strength, and pore pressure parameters. Their findings emphasize the significance of understanding how these factors affect the safety factor of critical sections within landfills. Designers and operators must consider these variables during the design, operational, and closure phases of landfill projects. Furthermore, careful attention to the unique characteristics and compositions of the waste deposited throughout the operational lifespan of a landfill is crucial for ensuring stability and safety.

Parametric sensitivity analysis can be conducted to identify and evaluate the factors influencing slope stability systematically. These analyses independently vary parameters such as cohesion, internal friction angle, waste specific gravity, pore pressure levels, and applied loads to assess their impact on the safety factor. This approach enables the assessment of how the geotechnical properties of the materials constituting the landfill body affect the overall stability of the structure.

Given the significant risks associated with landfill failures, this study aims to analyze slope stability in a landfill situated in the Brazilian semiarid region, emphasizing the sensitivity of the safety factor to variations in shear strength parameters. Furthermore, the research compares the performance of two-dimensional analysis software tools by evaluating their effectiveness in assessing the stability of critical sections under different shear strength conditions.

2. Methodology

2.1 Characterization of the study area

Figure 1 presents the landfill analyzed in this study. According to data from AESA (2022), the region is characterized by a semi-arid climate, with an average annual maximum temperature of 28.6°C and a minimum of 19.5°C, resulting in a mean temperature of 22.7°C. The mean annual evaporation is approximately 1417.4 mm, while the average annual precipitation is 802.7 mm.

Figure 1 –Landfill under study.
Source: Adapted from Google Earth Pro (2020).

Since the commencement of its operation up to the period covered in this study, the landfill has progressively integrated four cells, identified as C1, C2, C3, and C4, as depicted in Figure 2. Initially, the cells remained distinct and independent (Figure 2a). Over time, strategic placement of waste and soil between them facilitated their combination (Figure 2b), forming a single waste mass and enabling the gradual integration of the landfill cells.

Figure 2 – Landfill cells: (a) prior to the initiation of the joining process and (b) following the commencement of the joining process.
Source: Adapted from Guedes (2018).

The integration of Cells C1, C2, C3, and C4 formed a single cell measuring 225 x 225 meters, as shown in Figure 3. The unified cell comprises distinct layers of residues from the individual cells, each with varying backfill ages.

Figure 3 – Landfill cell after joining C1, C2, C3 and C4.
Source: Adapted from Souza (2021).

During this period, the landfill exhibited variations in the thickness of the cover layers, ranging from 0.6 to 1.0 m of compacted soil (Araújo Neto, 2016; Souza, 2021). Consequently, an average thickness of 0.8 m was adopted for the cover layer and 0.6 m for the soil liner (Silva, 2017). Subsoil investigations conducted using the Standard Penetration Test (SPT) revealed soil depths between 0.4 and 0.8 m, leading to the adoption of an average thickness of 0.6 m for stability analyses. The waste body comprised layers with different filling periods: recently filled (0 years), 1 year, and 2 years. The determination of these layer thicknesses was based on continuous monitoring of landfill operations, supplemented by topographic surveys, ensuring the representativeness of the generated models.

2.2 Input Data for Stability Analysis Using Computational Tools

The input data for stability analyses include the geotechnical parameters and the piezometric level within the landfill body. In this study, the geotechnical parameters—friction angle, cohesion, and specific gravity— of the MSW and soils, along with the piezometric level of liquids, were obtained from the studies conducted by Araújo Neto (2021). The stability analyses were performed under two scenarios based on the piezometric conditions within the landfill mass:

- Scenario 1 (Unsaturated Condition): Absence of a piezometric head within the landfill body, represents the most favorable condition for the overall stability of the landfill mass.
- Scenario 2 (Saturated Condition): Presence of a 17-meter piezometric level within the landfill body, corresponding to the highest level recorded during landfill monitoring and representing the most unfavorable condition for stability.

Table 1 – Geotechnical Parameters for the Analyzed Scenarios.

Material	Specific Gravity (KN/m³)	Cohesion (kPa)		Friction Angle (°)	
		Scenario 1	Scenario 2	Scenario 1	Scenario 2
Fresh MSW	10	1.4	5.2	28.3	21.6
One-year-old landfill waste	15	41	52.7	35.6	27
One-year-old landfill waste	15	41.6	28.4	31.9	29.7
Cover layer	14.5	7.8	7.8	31	31
Liner layer	18.8	1.7	1.7	26	26
Subsoil	14.5	7.8	7.8	31	31
Rock	26	-	-	-	-

Source: Adapted from Araújo Neto (2021).

Piezometric level data were obtained through continuous monitoring of piezometers installed within the landfill cell using an electronic level sensor. For this study, the most critical value recorded throughout the monitoring period, 17 meters, was considered. Figure 4 presents the layout and arrangement of the piezometers within the landfill.

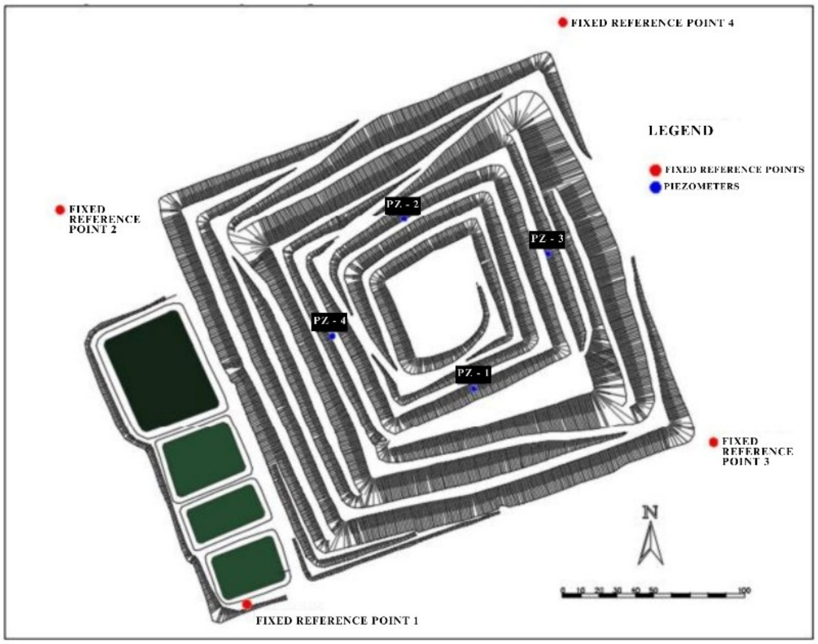

Figure 4 – Location of Piezometers Pz1, Pz2, Pz3, and Pz4 in the Landfill.
Source: Adapted from Araújo Neto (2023).

2.3 Two-dimensional critical section

Araújo Neto (2021) emphasized that the determination of critical sections for the two-dimensional analyses involved modeling the sections with the highest topographic elevations. This approach ensured that the selected sections represented the most unfavorable stability conditions. Figure 5 illustrates the geometry, while Figure 6 presents the sections used in the stability analyses.

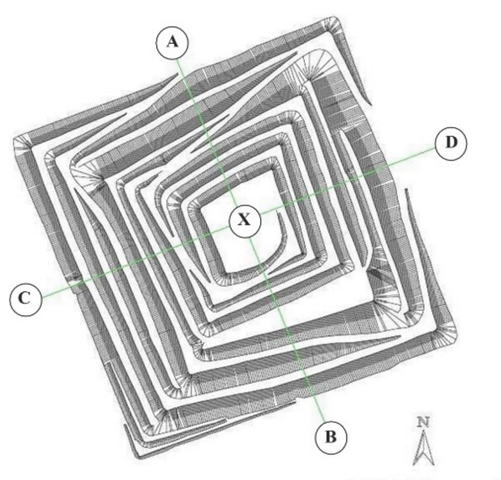

Figure 5 – Geometry considered in the stability analyses.
Source: Adapted from Araújo Neto (2021).

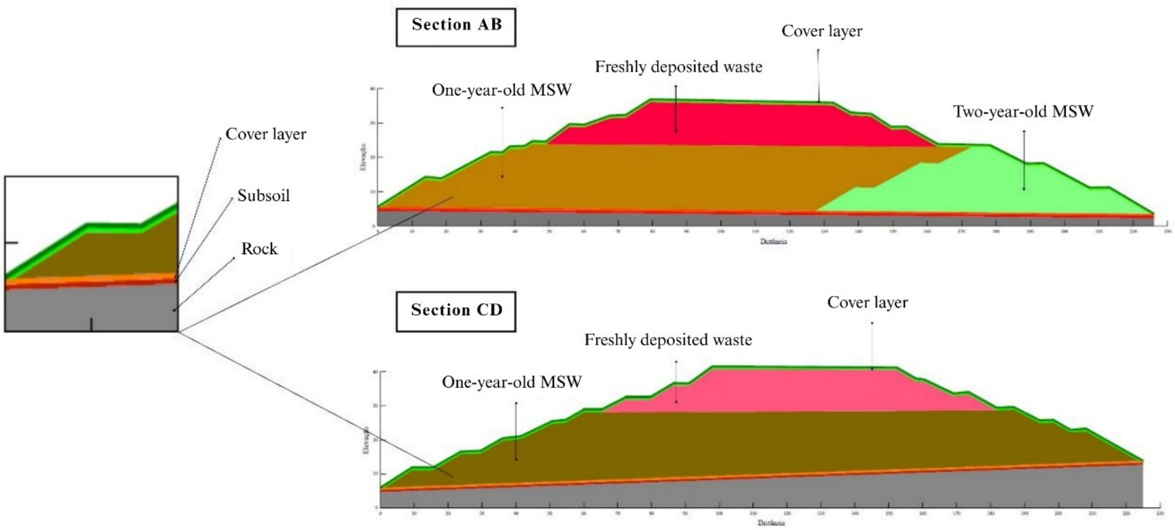

Figure 6 – Critical sections AB and CD.
Source: Adapted from Aráujo Neto (2021).

2.4 Slope stability and sensitivity analyses

The stability analysis of landfill slopes in this study was conducted using the limit equilibrium method, a widely recognized and conventional approach for evaluating the stability of soil slopes (Qi et al., 2021). Several studies have applied this method in landfill stability assessments, including those by Seed et al. (1990), Strauss (1998), Zhan et al. (2008), Remédio (2014), Silva (2011), Jahanfar et al. (2017), Basha and Raviteja (2018), Andrades (2018), Lu et al. (2019), Daciolo (2020), Damasceno et al. (2020), and Medeiros et al. (2020). Among the various limit equilibrium techniques, the Morgenstern-Price method was selected for this study, as it satisfies all static equilibrium conditions and is widely adopted in engineering practice. Additionally, this method is known for its robustness and conservative nature, yielding reliable safety estimates for slope stability (Bretas, 2020).

This study utilized Slope/W (GeoStudio) and Slide/2 (Rocscience) software tools, selected based on a comprehensive bibliographic review. The review examined numerous studies on landfill slope stability, revealing that researchers frequently use these software programs for geotechnical analyses in various regions. Daciolo (2020) applied Slide/2, while Andrades (2018) used both Slide/2 and Slope/W. Additionally, Remédio (2014), Silva (2014), Medeiros et al. (2020), Damasceno et al. (2020), Cirolini et al. (2020), Jahanfar et al. (2017), and Lu et al. (2019) conducted stability analyses with Slope/W. These studies highlight not only the effectiveness of these tools but also their relevance in geotechnical assessments of landfill stability.

In Slope/W, the search for potential failure surfaces is defined manually. For this study, the criterion adopted in Slope/W was to identify the most critical inputs and outputs. In contrast, Slide/2 employed an automated search to define the critical failure surface, focusing on the region with the highest risk of rupture based on the input design data. The safety factor in Slide/2 was calculated using limit equilibrium analysis methodologies.

This study performed sensitivity analyses using Slope/W and Slide/2 to evaluate how variations in shear strength parameters affect the safety factor in two-dimensional analyses. These analyses incorporated the geotechnical parameters, geometry, and scenarios outlined in Sections 2.2 and 2.3. Variation ranges were established for the geotechnical parameters of the materials representing the landfill structure in sections AB and CD, as well as for both considered scenarios. Each section was analyzed based on the geotechnical parameters of its respective scenario, specifically cohesion and friction angle. The variation ranges were defined relative to the fixed values used in the stability analyses.

3. Results and discussion

3.1 Two-dimensional analyses for Scenario 1

For Scenario 1, stability analyses were conducted for sections A-X, B-X, C-X, and D-X using Slope/W and Slide/2. Figure 7 presents the most critical safety factors obtained for each section and software.

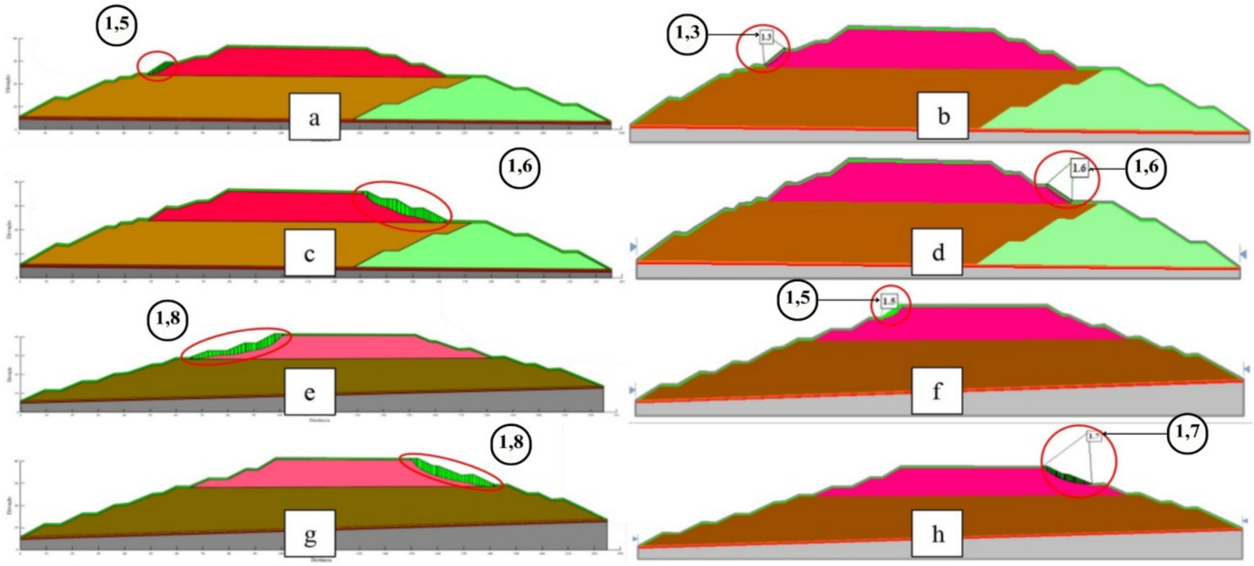

Figure 7 – Stability analysis for Scenario 1: (a) Section A-X (Cut AB) using Slope/W, (b) Section A-X (Cut AB) using Slide/2, (c) Section B-X (Cut AB) using Slope/W, (d) Section B-X (Cut AB) using Slide/2, (e) Section C-X (Cut CD) using Slope/W, (f) Section C-X (Cut CD) using Slide/2, (g) Section D-X (Cut CD) using Slope/W, and (h) Section D-X (Cut CD) using Slide/2.
Source: Authors (2024).

Figure 7 presents the stability analysis results for Scenario 1. In Section A–X, a comparison of the safety factors (SF) obtained from the two software programs reveals a strong convergence in identifying critical rupture regions, along with closely aligned SF values. In Section B–X, the SF values were identical; however, Slope/W identified a larger critical rupture surface area than Slide/2. In Section C–X, discrepancies were observed in both SF values and the extent of the critical rupture surfaces between the two programs. Conversely, in Section D–X, both SF values and rupture surface areas exhibited close agreement. Overall, for Scenario 1, the primary variations in SF can be attributed to differences in the algorithms employed by the two software programs to identify rupture surfaces.

In Slide/2, the slope search occurs automatically, with the software determining the region of highest rupture risk based on the input design parameters. In contrast, Slope/W requires a manual search for failure surface, which may introduce user-dependent variability and influence result accuracy. The observed discrepancies between the two geotechnical analysis software programs likely stem from differences in their underlying methodologies, including the algorithms used to model soil behavior and site conditions. Additionally, numerical modeling simplifications—such as model discretization and rupture surface identification algorithms—are necessary for computational efficiency but may introduce limitations. These limitations can lead to variations in predicted critical surfaces, even when similar analytical methods are applied.

Figure 7 demonstrates that the lowest SF derived from both software programs correspond to areas containing recently filled waste layers. The upper layers of the waste cells, composed of the fresh MSW, display reduced shear strength due to their geotechnical parameters being lower than those of MSW that has undergone one or two years of consolidation. In the landfill configuration analyzed in this study, the newly placed MSW layers had not yet experienced the full effects of overburden pressures from the upper layers.

3.2 Two-dimensional analyses for Scenario 2

Figure 8 presents the safety factor results for each section and the respective software used in Scenario 2.

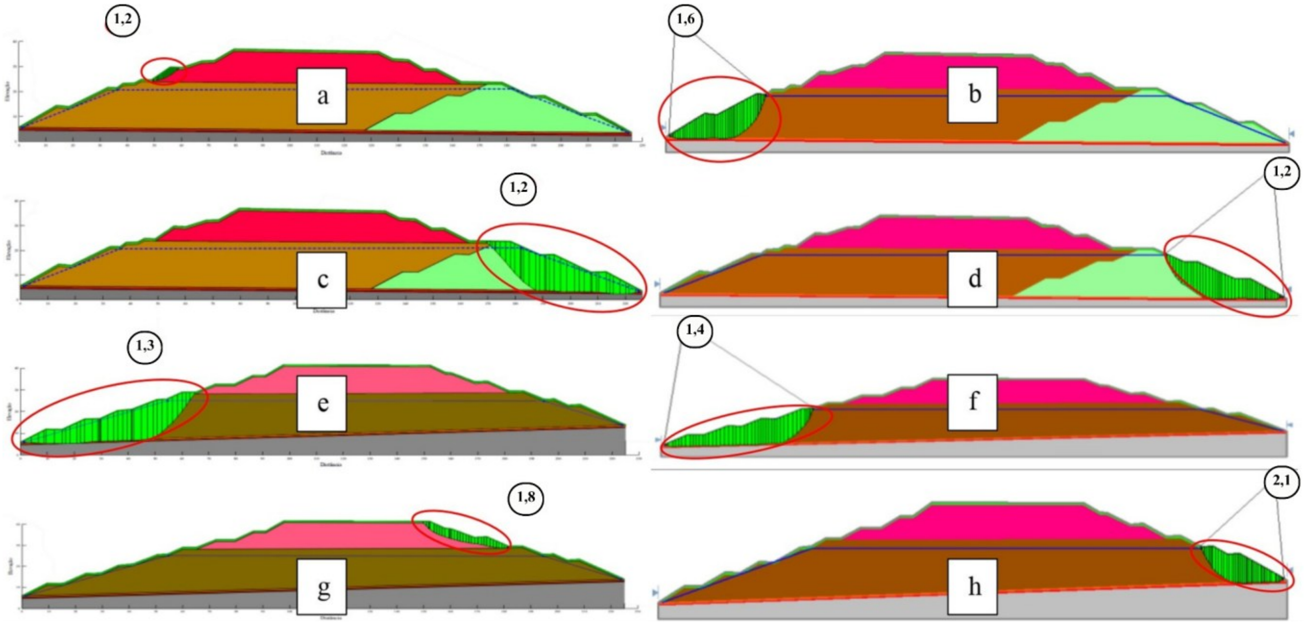

Figure 8 – Stability analysis for Scenario 2: (a) Section A-X (Cut AB) using Slope/W, (b) Section A-X (Cut AB) using Slide/2, (c) Section B-X (Cut AB) using Slope/W, (d) Section B-X (Cut AB) using Slide/2, (e) Section C-X (Cut CD) using Slope/W, (f) Section C-X (Cut CD) using Slide/2, (g) Section D-X (Cut CD) using Slope/W, and (h) Section D-X (Cut CD) using Slide/2.
Source: Authors (2024).

In Section A–X, the SF obtained from Slope/W and Slide/2 were similar; however, the most critical potential rupture surfaces were identified in different regions by each software. In Section B–X, as shown in Figure 8, both software produced identical SF values, with the most critical rupture surfaces occupying nearly the same region. Similarly, in Section C–X, the SF values were closely aligned, and the most critical rupture surface encompassed the same area in both analyses. Conversely, in Section D–X, while the SF values remained consistent between the two software programs, the location of the most critical rupture surface varied, mirroring the pattern observed in Section A–X.

In Sections B-X and C-X, across both scenarios, the safety factors in Scenario 2 were consistently lower than those in Scenario 1 in both Slope/W and Slide/2. This reduction in SF is primarily due to the positioning of the most critical failure surface, which was located below the piezometric line in both software analyses. In contrast, for Sections A-X and D-X, the SF values in Scenario 2, as computed in Slide/2, were higher than those in Scenario 1. This outcome stems from the consideration of excess pore pressure in the design configuration. Notably, Slide/2 constrains the search for the most critical failure surfaces to the region below the piezometric line, leading to an increase in the SF values compared to those obtained using Slope/W for Scenario 2.

Sheng et al. (2021) similarly identified the adverse effects of liquids on landfill stability. Their investigation into the vertical expansion of these structures, particularly in the presence of leachate, revealed a reduction in the safety factor. Specifically, they observed that an increase in leachate level from 2 m to 20 m led to a 13.2–15.4% decrease in the landfill safety factor. These findings align with the results of this study, where sections B–X and C–X also showed a reduction in the safety factor under Scenario 2. Andrades (2018) analyzed landfill stability using 12 months of piezometric level monitoring data and geotechnical parameters for municipal solid waste obtained from established technical literature. In line with this approach, the present study highlights the importance of utilizing multiple software tools to assess variations in safety factors, enhancing the reliability of stability evaluations.

According to NBR 11682 (ABNT, 2009), landfill stability should be evaluated based on the safety factors obtained for the analyzed scenarios. This standard establishes that safety factors below 1.5 do not meet the minimum requirement. A factor of 1.5 or higher indicates a high level of safety concerning material and environmental risks and a medium level regarding potential loss of human life. Table 2 presents the classification of the safety factors for each section, indicating compliance or non-compliance with the minimum threshold set by NBR 11682 (ABNT, 2009).

Table 2 – Classification of safety factors by section according to NBR 11682 (ABNT, 2009).

Scenario	Section	*slope/w*	Situation	*slide/2*	Situation
1	A-X	1.5	Compliance	1.3	Non-compliance
	B-X	1.6	Compliance	1.6	Compliance
	C-X	1.8	Compliance	1.5	Compliance
	D-X	1.8	Compliance	1.7	Compliance
2	A-X	1.5	Compliance	1.6	Compliance
	B-X	1.2	Non-compliance	1.2	Non-compliance
	C-X	1.3	Non-compliance	1.4	Non-compliance
	D-X	1.8	Compliance	2.1	Compliance

Source: Authors (2024).

Araújo Neto (2021) also analyzed the stability of the slopes in the landfill under study and reported higher safety factor values than those obtained in the present research. These discrepancies likely result from differences in the search methods used to identify the most critical failure surfaces. In the study by Araújo Neto, the search was performed by varying the radius and center of the circle intersecting the landfill in the GEO5 2021 software. Consequently, this method may not have captured potential localized failures along the slopes. While this approach provides a broad assessment of slope behavior, it may underestimate the likelihood of point failures, which could significantly influence overall stability.

The safety factors derived in this study align closely with findings from prior research by Strauss (1998), Remédio (2014), Andrades (2018), Daciolo (2020), Sheng et al. (2021), and Awad-Allah (2022). This consistency arises because the geotechnical parameters for MSW were derived from analogous data collection methods, analytical approaches, and field conditions. The use of site-specific data, which directly reflects the actual geotechnical and operational context of the landfill, enhances the practical significance of these results.

3.3 Sensitivity analysis

Sensitivity analysis represents a critical tool in geotechnical engineering, enabling the identification of input parameters that exert the most significant influence on slope stability. This approach allows engineers to prioritize key factors and optimize design considerations. Figures 9 and 10 present the results of the sensitivity analysis for the shear strength parameters of MSW and soils, evaluating their impact on the safety factor in Section A-X. The analyses were performed for both scenarios using Slope/W and Slide/2, offering valuable insights into the effects of variations in cohesion and friction angle on overall stability.

In the conducted analyses, the variation in geotechnical parameters differs between Slope/W and Slide/2. Slope/W represents changes in friction angle and cohesion using a standardized sensitivity range from -1 to +1, where -1 corresponds to the lowest parameter value and +1 to the highest. In contrast, Slide/2 employs a sensitivity range from 0% to 100%, with 0% representing the lowest values of friction angle and cohesion and 100% representing the highest. The vertical axis in both cases corresponds to the safety factor.

Sensitivity is assessed by analyzing the slope of the lines, which indicate changes in the safety factor in response to variations in each parameter. The point of convergence of all lines represents the SF for analyses based on the parameter values presented in Table 1.

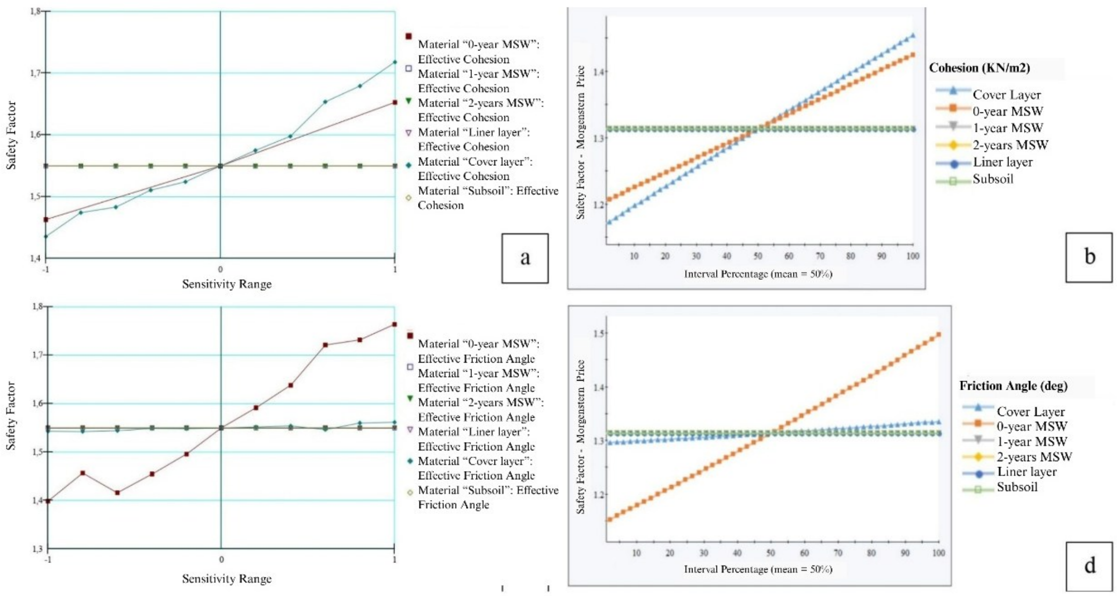

Figure 9 – Sensitivity analysis of Section A–X (Cut AB) for Scenario 1: (a) Variation in cohesion using Slope/W, (b) Variation in cohesion using Slide/2, (c) Variation in friction angle using Slope/W, and (d) Variation in friction angle using Slide/2.
Source: Authors (2024).

For Scenario 1, Figure 9 shows that in Section A–X analyzed with Slope/W, the cover layer exhibits the most significant fluctuations in the SF when cohesion varies, ranging from approximately 1.4 to 1.7. Similarly, the analysis using Slide/2 indicates that the cover layer again produces the most pronounced variations in the SF in response to cohesion changes. Furthermore, in Section A–X analyzed with Slope/W, the freshly deposited waste layer exhibits the most significant fluctuations in the SF when the friction angle varies, ranging from a minimum of 1.4 to nearly 1.8. Similarly, the analysis using Slide/2 indicates that this layer also produces the most pronounced variations in the SF in response to changes in the friction angle.

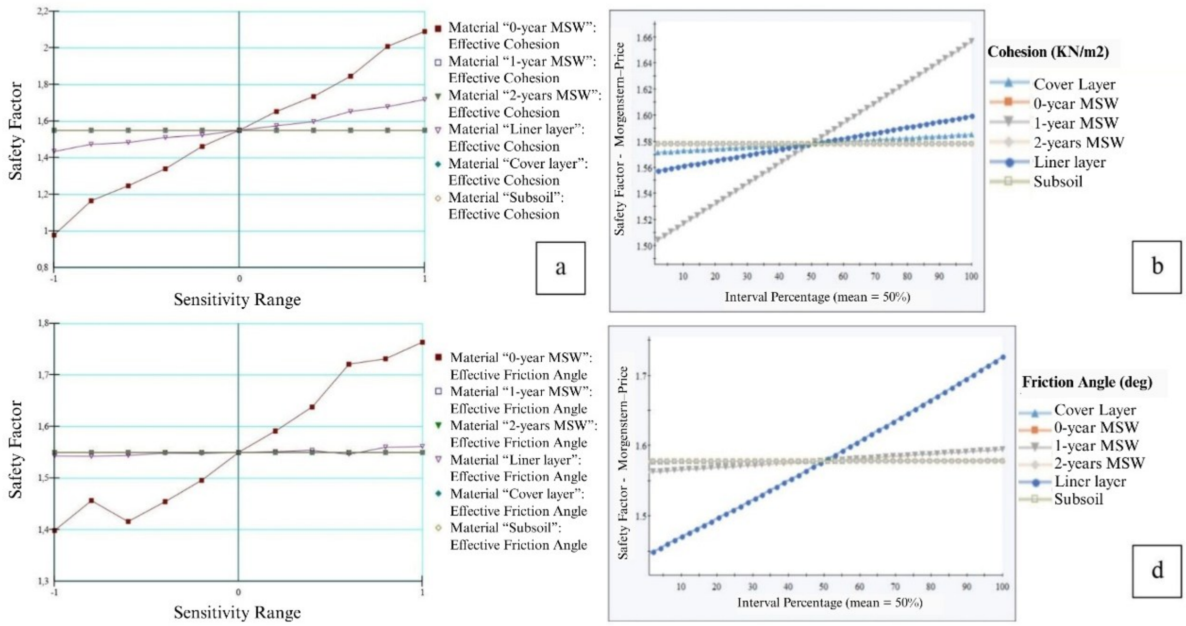

Figure 10 – Sensitivity analysis of Section A–X (Cut AB) for Scenario 2: (a) Variation in cohesion using Slope/W, (b) Variation in cohesion using Slide/2, (c) Variation in friction angle using Slope/W, and (d) Variation in friction angle using Slide/2.
Source: Authors (2024).

For Scenario 2, in the same section analyzed using Slope/W, the layer of recently filled waste exhibits the most significant oscillations in SF when cohesion is varied. In this layer, the SF ranges from a minimum of approximately 1.0 to a maximum of nearly 2.0. As shown in Figure 10, the layer of waste filled for one year demonstrates minor oscillations in the SF when cohesion is varied. Additionally, in the same section analyzed using Slope/W, the recently deposited waste layer also produces the most pronounced variations in the SF when the friction angle is varied, with the SF ranging from approximately 1.4 to nearly 1.8.

In the analysis of Scenario 2 using Slide/2, the liner layer exhibits the most significant oscillations in the SF when the friction angle is varied, with the SF ranging from approximately 1.5 to nearly 1.7. Furthermore, the sensitivity analyses across all sections reveal that variations in shear strength parameters, particularly in MSW with zero years of grounding (recently grounded), exert the greatest influence on the safety factor.

Table 3 summarizes the results of the sensitivity analyses, identifying the layers that most significantly influence fluctuations in the safety factor based on parameter variations for each section and software (Slope/W and Slide/2) across both analyzed scenarios.

Table 3 – Layers with the greatest influence on the safety factor based on parameter variations for each section and software.

Scenario	Section	Parameter Analyzed	Layer with the Highest Impact on SF	
			Slope/w	***Slide/2***
1	A-X	Cohesion	0-year-MSW Cover Layer	1-year-MSW Cover Layer
		Friction angle	0-year-MSW	0-year-MSW
	B-X	Cohesion	1-year-MSW	0-year-MSW Cover Layer
		Friction angle	0-year-MSW	0-year-MSW
	C-X	Cohesion	0-year-MSW Cover Layer	0-year-MSW Cover Layer
		Friction angle	0-year-MSW	0-year-MSW
	D-X	Cohesion	0-year-MSW Cover Layer	0-year-MSW
		Friction angle	0-year-MSW	0-year-MSW
2	A-X	Cohesion	0-year-MSW Cover Layer	1-year-MSW

	Friction angle	0-year-MSW	Liner Layer
B-X	Cohesion	2-years-MSW	2-years-MSW
	Friction angle	Liner Layer	Liner Layer
C-X	Cohesion	1-year-MSW	1-year-MSW
	Friction angle	Liner Layer	1-year-MSW
D-X	Cohesion	0-year-MSW Cover Layer	1-year-MSW
	Friction angle	0-year-MSW	Liner Layer

Source: Authors (2024).

Overall, in Scenario 1, the layers that exert the greatest influence on the SF vary depending on the parameter and section analyzed. Notably, the cover layer and the recently buried waste frequently play a significant role, particularly in response to variations in cohesion. This finding suggests that the stability of these sections is closely linked to the mechanical properties of these layers, especially when MSW has been recently deposited. The freshly deposited waste tends to exhibit greater heterogeneity in composition, and as it undergoes biodegradation, its characteristics and properties evolve until reaching a more stable state.

In Scenario 2, the layers exerting the greatest influence on the SF also vary depending on the parameter and section analyzed, with a more pronounced impact observed in the liner layer when the friction angle is varied. These findings underscore the necessity of accounting for the specific geotechnical characteristics of each material layer when assessing landfill stability, as variations in mechanical properties can significantly affect overall slope behavior.

Regarding the software, Scenario 1 reveals distinct sensitivities between Slope/W and Slide/2 concerning shear strength parameters. In Section A-X, the 0-year-old MSW cover layer exerts a greater influence on the SF in Slope/W, whereas in Slide/2, the 1-year-old MSW layer is more influential. In Scenario 2, differences between the software persist, with Slide/2 showing a greater sensitivity to variations in the friction angle, particularly in the liner layer, compared to Slope/W.

Previous studies, such as those by Daciolo (2020) and Jahanfar et al. (2017), emphasize the importance of accounting for factors that contribute to variations in the safety factor, particularly shear strength parameters. These studies demonstrate how such factors can substantially impact slope stability over time and under varying operational conditions. The geotechnical parameters that define the landfill body play a critical role in its overall stability and, consequently, in the safety factor of slopes. Khoshand et al. (2018) highlight the importance of considering these variations during embankment design to ensure long-term stability.

The sensitivity of the safety factor to variations in shear strength parameters underscores the critical need for ongoing monitoring of landfill conditions. Over time, changes in material characteristics—resulting from processes such as compaction, biodegradation, or water infiltration—can substantially influence slope stability, necessitating regular assessment. These findings emphasize the importance of precisely characterizing the materials disposed of in the landfill, particularly freshly deposited waste. A thorough understanding of the geotechnical properties of these materials is essential for accurately predicting slope behavior and ensuring long-term stability.

4. Final considerations

The safety factors derived from the two-dimensional stability analyses generally indicate that the landfill slopes under investigation comply with current standards. However, some concerns arise due to discrepancies observed in the numerical simulations, the high saturation levels of the waste, and the simplifications inherent in the analyses, which do not account for the effects of gas pressure and the biodegradation processes of the waste.

The accuracy of potential critical rupture surfaces identified in the numerical simulations of two-dimensional stability analyses depends largely on the quality and representativeness of the input data. This highlights the need for thorough field and laboratory testing to obtain reliable geotechnical parameters for MSW and soils, along with piezometric level data from pore pressure monitoring for greater accuracy.

Sensitivity analyses revealed that the greater variability in the safety factor in response to variations in resistance parameters is primarily associated with the properties of the freshly deposited municipal solid waste, which exhibits lower shear resistance.

Among the software evaluated in the two-dimensional stability analyses, Slope/W demonstrated superior performance in Scenario 2, as it more accurately identified critical rupture surfaces across the entire analyzed section. In contrast, Slide/2 showed the best performance for Scenario 1.

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