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Research Paper

Multivariate Insights into SDIM: Understanding the Effects of Different Elements in Slope Analysis

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ABSTRACT

Slope stability analysis is a critical component of geotechnical engineering, with its implications reaching far and wide, from infrastructure development to environmental management. This study delves into the innovative Stress Deviator Increasing Method (SDIM) and its implications for slope analysis, focusing on the interaction of various components in this intricate process. This study acknowledges the evolution of slope stability analysis, transitioning from traditional methods such as the Limit Equilibrium Method (LEM) to modern approaches, and introduces SDIM as a promising alternative. Bouzid's SDIM combines the Finite Element Method (FEM) with Mohr's circles to offer a comprehensive understanding of slope behavior, particularly under complex stress conditions. The study meticulously examines SDIM's application through the S4DINA (soil stability study by Stress Deviator Increasing using Numerical Analysis) program, highlighting parameter sensitivity and the significance of considering specific conditions. The results underscore the sensitivity of SDIM to certain parameters, including the associated flow rule, finite element number, and embankment with or without foundations. Careful application of SDIM enhances the accuracy of slope stability assessments, allowing for more reliable results. This study represents a significant step in the field of geotechnical engineering, offering a dynamic and comprehensive approach that can address a wide range of scenarios and enhance the reliability of slope stability assessments.

Keywords: Condition Number; FEM; Parameter Sensitivity; SDIM; Slope Stability Analysis; S^4DINA

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1. Introduction

Slope stability analysis stands as a cornerstone within the field of geotechnical engineering, marked by its continuous evolution and the development of diverse analytical methodologies. Over time, methods such as Bishop's circular slip analysis, the limit equilibrium (LE) approach, and the comprehensive framework introduced by Morgenstern and Price have significantly advanced our understanding of slope behavior [1-4]. In this dynamic landscape of analytical techniques, the Stress Deviator Increasing Method (SDIM) emerges as an innovation, proposed by Djillali Amar Bouzid. SDIM represents a novel integration of the Finite Element Method (FEM) with the geometric elegance of Mohr's circles. In contrast to traditional methods, SDIM transcends mere numerical computation; it orchestrates a comprehensive analysis of stress evolution within a slope. Guided by Mohr's circle principles, SDIM iteratively increases the mobilized principal stress deviator, affording a nuanced understanding of the progression from equilibrium to failure.

SDIM is an innovative approach for slope stability analysis, particularly in calculating the Factor of Safety (FOS)[5]. Unlike traditional methods, which rely on simplifications and predefined failure surfaces, SDIM employs an incremental stress deviator increase to model slope behavior more realistically. This dynamic approach accounts for complex geometries and varying soil conditions, resulting in a more accurate assessment of slope stability. SDIM, as a dynamic and comprehensive method for slope stability analysis, considers factors like stress deviator increment and material properties continuously it is well-suited for complex slopes and offers a more realistic assessment of stability compared to traditional LEM, which relies on simplified assumptions and predefined failure surfaces. LEMs may provide conservative estimates of stability but may not capture complex conditions as effectively. The choice between SDIM and LEMs depends on specific analysis needs and available resources.

A novel approach SDIM for slope stability analysis, offers a mechanistic, comprehensive, and adaptable method that emphasizes a continuous evaluation of stress and deformation within the slope. This approach contrasts with traditional methods like SRM and is well-suited for complex, heterogeneous soil conditions[6]. However, other techniques like FEM, FELA, and FDEM have their strengths, with varying capabilities to handle complexity and parameter interactions[7,8]. SDIM behaves uniquely by incrementally increasing the stress deviator within the slope, continuously monitoring failure development without predefined surfaces, and dynamically identifying critical slip surfaces. FEM is applied to analyze slope stability problems and serves as the foundation for Bouzid's new method. FEM breaks down the problem domain into discrete elements, uses polynomial functions within each element, and leverages functional analysis to ensure optimal solutions within finite-dimensional sub-spaces[9-11]. This versatile technique is crucial for tackling complex differential equations in various fields, including slope stability analysis.

This study introduces the innovative SDIM, which combines FEM with Mohr's circles to provide a more detailed and precise understanding of slope behavior under complex stress conditions. The research meticulously examines the sensitivity of SDIM to critical parameters and highlights the importance of considering specific conditions in its application. Furthermore, the study emphasizes that the careful use of SDIM can significantly enhance the accuracy and reliability of slope stability assessments. By integrating SDIM with advanced software tools like S^4DINA, this research offers a versatile and dynamic approach to slope stability analysis, capable of addressing a wide range of scenarios and enhancing the precision of geotechnical engineering practices. Overall, this study's findings mark a substantial advancement in the field, promising to revolutionize our approach to understanding and predicting slope behavior while contributing to safer and more reliable construction practices.

2. Materials and methods

2.1. Materials

Table 1 functions as a detailed inventory of the carefully chosen materials essential to our study's execution. These materials constitute the bedrock of our research, serving as the basis for our investigations and analyses. This table offers clarity and a convenient reference for comprehending the core components central to our research endeavors. Each material has a specific purpose, whether as input parameters, analytical tools, or data sources and is pivotal to achieving our research objectives. Through Table 1, readers can gain insights into the diverse array of materials that underlie our study, enabling a deeper grasp of our methodology, processes, and the diverse elements contributing to our research findings.

Table 1. Soil Parametric

Parametric	**Symbol**
Friction Angle	φ °
cohesion	C‘
Dilatancy Angle	Ψ‘
Young Modulus	E‘
Poisson ratio	ν'
Volumic weigh	γ'

Our research harnessed a suite of carefully chosen software tools, each serving a specific purpose in our comprehensive analysis of slope stability. Rocscience Slide 6.0 established a traditional benchmark for the factor of safety assessments using LEM [12,13]. Tecplot visually depicted plastic zones and stress contours, enriching our comprehension of slope behavior [14]. S^4DINA took center stage, conducting finite element analyses with the Stress Deviator Increasing Method (SDIM), introducing a modern and nuanced approach to slope stability assessment. Origin Pro facilitated data visualization and interpretation [15]. These software tools collectively formed the basis of our research, allowing for a thorough analysis of slope stability, encompassing traditional LEM assessments and innovative SDIM applications. Through their integration, we conducted a comprehensive exploration of slope stability, offering analytical flexibility and compatibility with established techniques. The model profile used for evaluation was precisely represented, ensuring fidelity to the configurations integrated into the S^4DINA framework, and eliminating potential discrepancies in model depiction.

Case 1: we conducted an in-depth examination of a profile characterized by the presence of sliding surfaces within its foundation. The profile's comprehensive description is visually presented in a pictorial representation, highlighting the key measurements and parameters that have been meticulously taken into account for this analytical investigation.

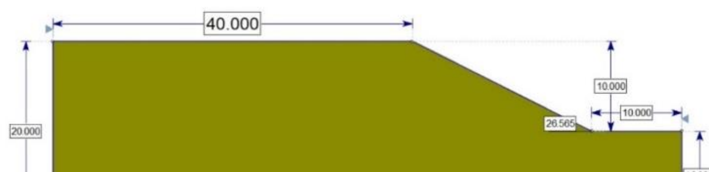

Figure 1. Embankment with foundation layer.

***Case 2**:* In Case 1, a pivotal phase involves the deliberate exclusion of the foundation, thereby facilitating a focused investigation into the inherent characteristics of the slope itself. The selected profile for this analytical segment has been thoughtfully chosen to serve as a guiding framework for our analyses. This strategic selection ensures a comprehensive exploration of the disassembled constituents within the project, thereby enhancing our grasp of the complex interplay among various elements.

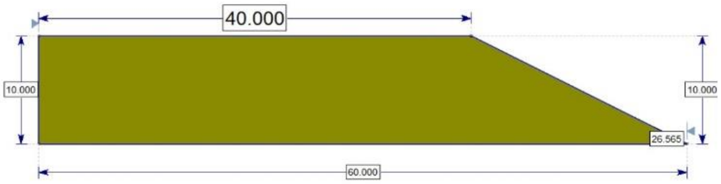

Figure 2. Embankment without foundation Profile.

We aim to gain a comprehensive understanding of the complex factors affecting slope stability by breaking it down into its fundamental components. This refined approach offers nuanced insights and robust assessments of stability conditions. In the context of S^{4}DINA, we'll employ two separate input files for the slope profiles—one with a foundation and one without. Analytical tasks within S^{4}DINA will be executed using the MSDV COMPILER, accommodating both associated and non-associated studies based on the parameter psi.

2.1.1. Analysis of input parameter influence

The comparative analysis between the LEM and the SDIM involves assessing calculation and deformation parameters to understand their impact on the actor of safety values. While Slide 6.0 yields consistent results, S^{4}DINA exhibits variability due to parameter sensitivity. The analysis aims to uncover the interaction among these parameters, shaping computed factor of safety values and enhancing our understanding of both methodologies. Two categories are examined: Calculation Parameters, including Interaction Number and Number of Finite Elements, and Deformation Parameters. The Interaction Number dictates convergence iterations, and the Number of Finite Elements defines spatial discretization. This analysis is crucial for robust stability assessments.

2.1.2. Iteration number slope with foundation and without foundation.

Table 2, Table 3, Table 4, and Table 5 provide insights into the influence of iteration count on the factor of safety within the context of the three primary methods highlighted in this research. These tables present valuable data illustrating how variations in iteration count affect the stability assessment outcomes, shedding light on the performance of each method. The analysis of these tables underscores the significance of iteration count as a critical parameter in slope stability assessments, offering a clearer understanding of the sensitivity and behavior of the methods examined in this study.

Table 2. Associated flow rule with foundation

N^0 Interaction	Bishops	Morgenstern and Price	Bouzid (SDIM)
100	0.999	0.997	0.957
200			0.979
300			0.989
400			0.990
500			0.991
600			0.991
700			0.991
800			0.991
900			0.991
1000			0.992
1100			0.992
1200			0.992
1300			0.992
1400			0.992

Table 2 conducts a comprehensive analysis of the impact of the number of iterations on a factor of safety values in three methods: LEM, Bishop's method, Morgenstern and Price's method, and SDIM. The study explores the intricate relationship between convergence behavior and the factor of safety through systematic experimentation. It highlights that more iterations enhance result precision but should be balanced with computational efficiency to avoid unnecessary analysis duration.

Table 3. Non -Associated flow rule without foundation

N^0 Interaction	Bishops	Morgenstern and Price	Bouzid(SDIM)
100	0.999	0.997	0.914
200			0.914
300			0.938
400			0.949
500			0.951
600			0.953
700			0.954
800			0.955
900			0.956
1000			0.957
1100			0.958
1200			0.959
1300			0.959
1400			0.959
1500			0.959

Table 3 subtle change in the factor of safety when considering plasticity assumptions, demonstrating the effectiveness of SDIM method under specific conditions. Both methods show promise, with Bouzid's method standing out. The study emphasizes the importance of iteration count in SDIM, suggesting a higher count for stability. In contrast, the Limit Equilibrium Method produces consistent results. The findings emphasize the need for careful parameter selection in geotechnical analysis and offer practical insights for real-world engineering applications, enhancing our understanding of these methods.

2.1.3. Iteration count and slope analysis without foundation

The study explores the impact of the iteration count on the factor safety in slope stability analyses. Starting with 100 iterations, a consistent trend of underestimating factor of safety values is observed due to the complex geometry. Limited iterations can hinder convergence, leading to imprecise results, evident in non-convergence indicators. Additionally, when assuming an associated flow rule, SDIM and LEM yield similar factors of safety values, indicating convergence towards comparable outcomes under this rule.

Table 4. Associated flow rule without foundation

N⁰ Interaction	Bishops	Morgenstern and Price	Bouzid (SDIM)
100	0.989	0.984	0.949
200			0.969
300			0.978
400			0.982
500			0.983
600			0.985
700			0.985
800			0.986
900			0.986
1000			0.986
1100			0.987
1200			0.987
1300			0.987
1400			0.987
1500			0.987

Table 5. Non-Associated flow rule without foundation

N⁰ Interaction	Bishops	Morgenstern and Price	Bouzid (SDIM)
100	0.989	0.984	0.914
200			0.924
300			0.928
400			0.929
500			0.931
600			0.933
700			0.936
800			0.938
900			0.938
1000			0.938
1100			0.938
1200			0.938
1300			0.940
1400			0.940
1500			0.940

In contrast, using a non-associated flow rule results in a distinct pattern. SDIM's factor of safety significantly differs from that of LEM, indicating the substantial impact of the flow rule choice. The non-associated flow rule appears to reduce soil resistance, leading to a notable deviation in the factor of safety from LEM. This study emphasizes the critical role of iteration count and flow rule assumptions in shaping factors of safety outcomes. It underscores the need for a careful approach when determining iteration counts and considering flow rule assumptions, essential for accuracy and reliability in slope stability analysis. The findings highlight the intricate relationship between numerical parameters and geotechnical behavior.

2.2. Iterative method

Iterative methods are numerical techniques used for approximating solutions to mathematical problems, particularly in solving linear systems of equations or finding equation roots. They work by starting with an initial guess and iteratively refining it using specific algorithms until predefined termination conditions are satisfied. These methods are widely applied in mathematics, physics, engineering, and computer science, particularly for large-scale problems and systems of equations, offering advantages in memory efficiency and computational speed over direct methods. They are memory-efficient as they rely on matrix-vector and vector-vector products, reducing memory usage compared to direct methods. The choice of iterative method depends on the properties of the matrix[16]. Preconditioners, like Richardson's method, are often used to improve convergence by introducing a matrix B into the equation. Optimal preconditioners, known as multi-level preconditioners, ensure convergence independently of mesh resolution by creating a hierarchy of matrix A representations and accelerating convergence using coarser representations and interpolation and prolongation operations.

To enhance convergence, preconditioners are commonly used. In Richardson's method, a preconditioner matrix B is introduced, and the equation becomes[17]:

$$x_{k+1} = x_k + B^{-1}(b - Ax_k). \tag{1}$$

Ideally, B should be a good approximation to A, and computing B^{-1} should be more efficient than computing A^{-1}.

2.2.1. Stress deviator increasing method

SDIM, or the Stress Deviator Increasing Method, is a remarkable approach to slope stability analysis. It sets itself apart by gradually increasing the mobilized principal stress deviator within the soil mass, replicating the progressive loading and deformation of slopes under changing stress conditions. This method offers a more realistic and comprehensive insight into slope behavior, particularly in complex scenarios, enhancing the accuracy of slope stability assessments. SDIM introduces an innovative finite element procedure for assessing slope stability in geotechnical engineering. It focuses on calculating the critical factor of safety, utilizing Mohr's circles uniquely to broaden the consideration of stress conditions. SDIM capitalizes on the linearity of the Mohr-Coulomb criterion, incrementally increasing the stress deviator to simulate slope failure conditions based on a non-convergence criterion. This approach integrates stress analysis, numerical iteration, and linearity, offering the potential to provide deeper insights into slope behavior and failure mechanisms under varying stress scenarios. In essence, SDIM has the promise to advance our understanding and prediction of slope behavior in geotechnical engineering.

Bouzid's perspective introduces a foundational equation that is central to the analytical evaluation of the Factor of Safety (FOS) in geotechnical engineering. This equation serves as a fundamental framework for assessing slope stability and allows geotechnical engineers to calculate the FOS, a critical parameter for ensuring the safety and stability of earth structures

$$FOS_{SDIM}^{sp} = \frac{2c}{D_0 cos\phi} + tan^2\phi\,(\frac{S_0}{D_0 sin\phi} - 1) \quad (2)$$

For a purely cohesive soil, the analytical expression of FOS_{SDIM}^{sp} is

$$FOS_{SDIM}^{sp} = 2c/D_0 \quad (3)$$

where c and ϕ are the effective soil strength parameters, S_0 and D_0 stand respectively for the mobilized principal stress deviator and principal stress sum, FOS_{SDIM}^{sp} is the factor of safety at stress point[18].

2.2.2. Evolution of slope stability analysis

SDIM is a ground-breaking numerical technique revolutionizing slope stability assessment by gradually increasing the stress deviator until failure occurs, capturing dynamic slope failure. It marks a significant shift from traditional LEM to the more versatile FEM [19]. Bouzid's recent research marks a significant advancement in applying the Finite Element Method (FEM) to handle complex stress distributions with enhanced detail and accuracy. This pioneering work led to the development of the Stress Deviator Increasing Method (SDIM), a transformative approach in slope stability analysis. A notable aspect of SDIM is the Mohr's circle expansion factor, which serves as a global indicator of slope stability, particularly valuable when convergence is not achieved. Detailed equations for this factor are provided, and the S^4DINA program is introduced for the or SDIM application. The reliability and accuracy of SDIM are rigorously assessed through comprehensive comparisons with established methods such as the Simplified Bishop's Method (SRM) and LEM [20]. This work signifies a transformative advancement in slope stability analysis, offering a more dynamic and precise approach.

2.2.3. Condition number

The condition number in numerical analysis measures a mathematical function's sensitivity to changes in its input data, indicating how much the output varies with small input perturbations [21,22]. A low condition number signifies a well-conditioned problem, where input errors have minimal impact on output accuracy. Conversely, a high condition number indicates an ill-conditioned problem, making it challenging to find accurate solutions due to heightened sensitivity to input variations. This concept applies not only to linear algebra but also to nonlinear functions, as seen in areas like linear regression. In computational fields like FEM[23], where matrices governing discretized systems can exhibit poor conditioning, understanding the condition number is crucial for selecting appropriate solvers and preconditioners to ensure numerical stability and precision in simulations.

A general theory of condition numbers was developed by Rice (1966). The most well-known example of a condition number is the condition number of a non-singular square matrix A, which is

$$cond(A) = \| A \| \cdot \| A - 1 \| \quad (4)$$

2.2.4. Use of finite element method

Bouzid's Stress Deviator Increasing Method (SDIM) employs the Finite Element Method (FEM). Unlike Bishop and Morgenstern-Price methods, SDIM leverages FEM's capability to handle complex stress distributions and interactions in a more comprehensive manner [24,25].

2.2.5. Factor of safety determination

The Bishop method calculates a global factor of safety for the entire slope failure surface. Morgenstern and Price Method Similar to Bishop's method, Morgenstern and Price's approach also calculates a global factor of safety, but with variations in inter-slice forces accounted for [26,27]

2.2.6. Mohr's circle expansion factor

SDIM introduces the cons of Mohr's circle expansion factor, which controls the expansion of Mohr's circles and represents the slope stability factor [5,18]. This factor is utilized when SDIM's iterative process fails to converge.

2.2.7. Precision and accuracy

The Stress Deviator Increasing Method (SDIM), employs the Finite Element Method (FEM) for more precise and detailed stress distribution analysis in slope stability assessments. This approach offers a more comprehensive understanding of slope behavior under varying stress conditions compared to the simplified assumptions of traditional methods like Bishop and Morgenstern-Price. The key distinction lies in the methodological approach, with SDIM using FEM to provide a more accurate analysis of slope stability, especially regarding stress distribution and failure mechanisms [28]. This method aims to maintain consistent stress levels and local factors of safety throughout the analysis by keeping mobilized normal stress and slip orientation identical in equilibrium and failure states. This is achieved by incrementally bringing the mobilized Mohr's circle to the point of failure through alignment with the failure envelope.

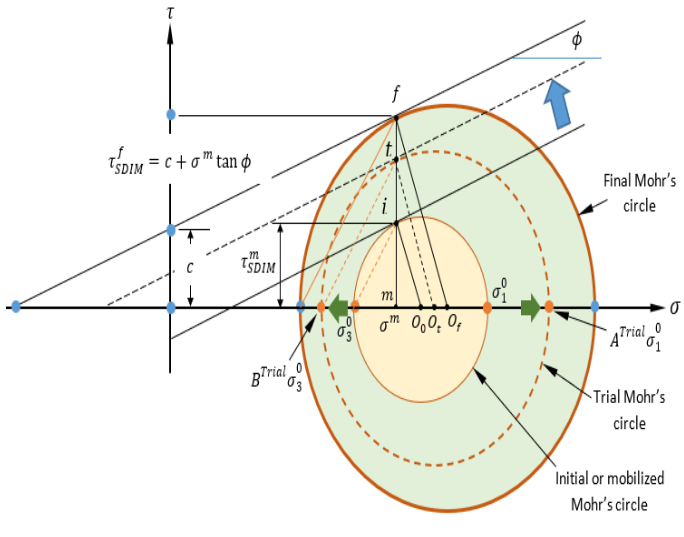

Figure 3. Evolution of principal stresses in the Stress Deviator Increasing Method (SDIM)[18].

Bouzid's method is significant as it provides a clear representation of stress distribution and safety considerations throughout the analysis, aiming for an accurate portrayal of slope behavior under varying stress conditions. It focuses on the mobilized principal stress deviator, enhancing our understanding of slope failure mechanisms. The efficacy of SDIM was confirmed through a comprehensive comparison with established slice methods, evaluating slope stability and safety. The results indicated that Finite Element Analysis closely matched results from the traditional LEM for slope stability assessment, including both associated and non-associated cases. Bouzid's work has the potential to advance geotechnical engineering practices and contribute to the field's development. Therefore, the accuracy of FOS_{SDIM} depends obviously on the accuracy of FOS^{SP}_{SDIM} as can be seen in Eq. (5).

$$F^{Trial} = \min(FOS^{SP}_{SDIM}) \qquad (5)$$

3. Results and Discussion

3.1. Analysis of plastic zones and stress contours

This section shifts its focus towards an examination of plastic zones and stress contours in the context of slope stability, utilizing the innovative SDIM. The visualization and analysis are facilitated by Tecplot, a versatile data visualization tool[29]. The primary goal is to scrutinize the plastic zones and stress contours resulting from SDIM while considering various input parameters. These parameters are used in conjunction with data extracted from the S^{4}DINA report file, which is then transformed into a compatible format for Tecplot. The visualization involves two scenarios: slopes with and without foundations, providing insights into how foundations impact plastic deformation and stress distribution. By comparing these scenarios, the study seeks to uncover the nuanced dynamics of plastic deformation zones and stress distribution in slope stability assessment. This analysis not only enhances comprehension of the SDIM method but also contributes to a broader understanding of geotechnical factors governing slope behavior and stability.

At this point, it becomes clear that the subtle slip lines are beginning to appear near the base of the slope, and there's an initial deformation pattern emerging. However, it's important to emphasize that this early deformation might lead engineers to a premature conclusion that the failure process has been initiated. In actuality, this perception can be misleading, mainly because there is no convergence at this particular stage of the analysis. The ongoing deformation process has not yet reached a critical and significant state.

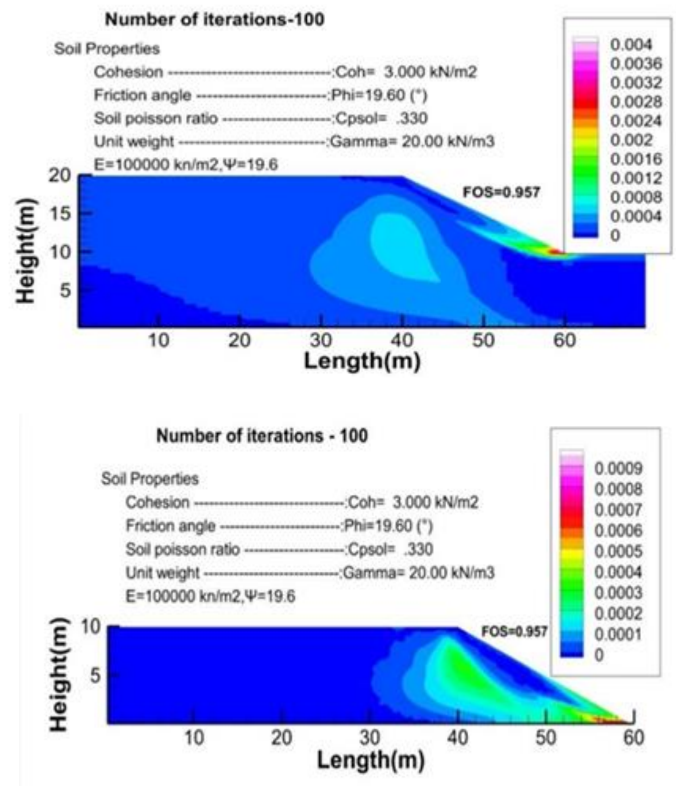

Figure 4. Strain contours corresponding to the step of failure for 100 iterations. With associated flow rule.

Upon reaching the 1000th iteration, a notable achievement was made: convergence was attained. At this stage, the calculated factor of safety reached an acceptable level, signifying a stable and reliable outcome. It's important to emphasize that even with a subsequent increase in the iteration count, negligible alterations were expected in the results. The reason for this lay in the fact that the failure process had already been initiated and was well underway. Therefore, beyond this point, there was no compelling need to continue escalating the number of iterations. The convergence achieved at the 1000th iteration ensured that the analysis had appropriately captured the critical dynamics of the slope stability scenario. Further increasing the iteration count would have yielded diminishing returns in terms of result accuracy, as the significant phase of failure progression had already commenced. This underscored the importance of selecting an appropriate number of iterations to strike a balance between computational efficiency and capturing accurate deformation behavior.

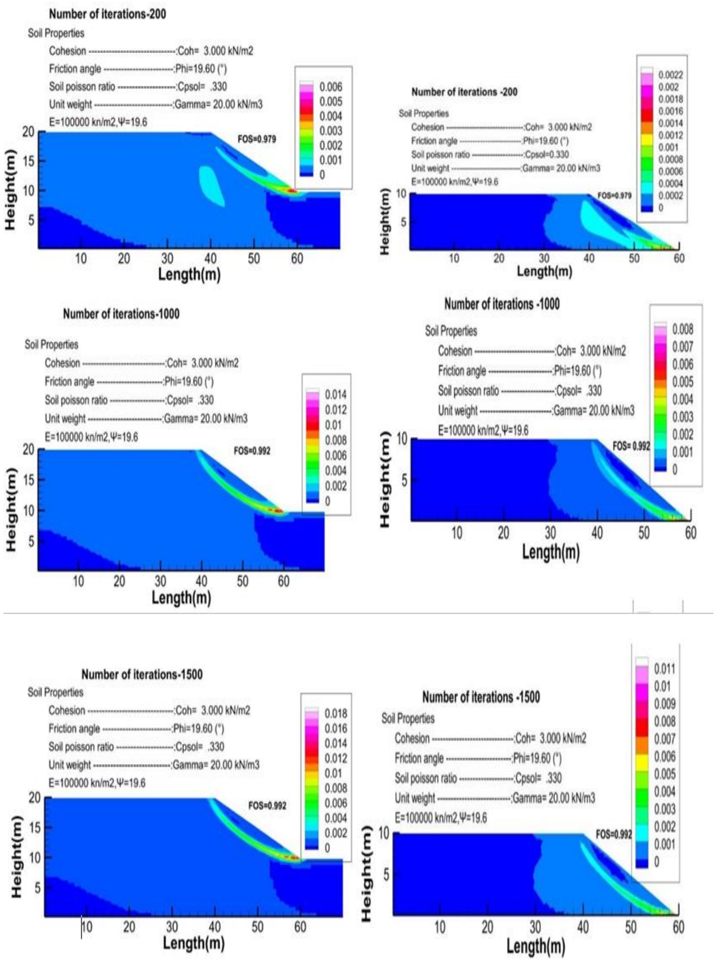

Figure 5. Strain contours corresponding to the step of failure for 200 to 1500 iterations.

In the realm of the non-associated flow rule, early iterations reveal a lack of resistance in the slope, emphasizing the importance of considering the dilatancy angle in these analyses. However, as iterations progress, stress concentration around the slope's toe increases, and slip lines become more defined. This highlights the effectiveness of SDIM, with clear and smooth contours showcasing its capabilities. When combined with other approaches, it provides geotechnical engineers with enhanced judgment and insight into slope analysis, facilitating a deeper understanding of slope behavior and informed decision-making in geotechnical engineering.

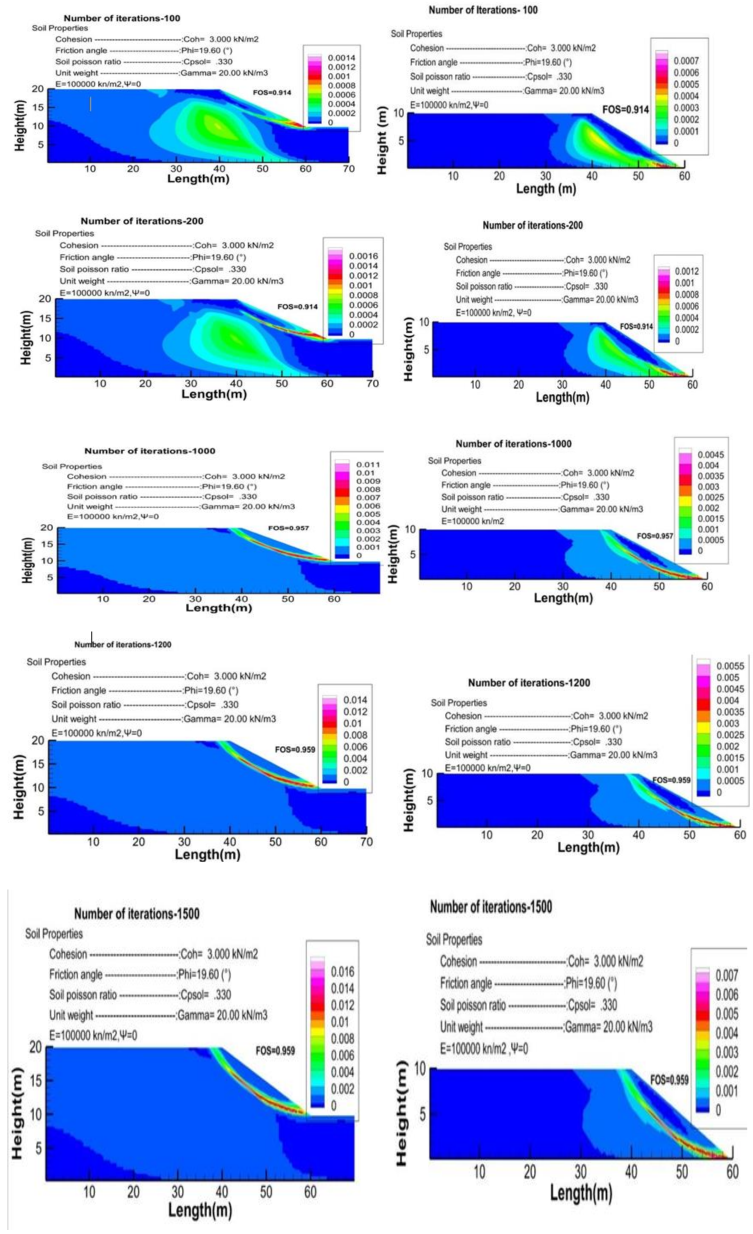

Figure 6. Strain contours corresponding to the step of failure for 100 to 1500 iterations, with Non-associated flow rule.

3.2. Evaluation of the influence of finite element count

In this study, we've investigated the impact of varying the number of finite elements on a factor of safety calculations. Finite elements are crucial in numerical simulations, breaking down complex domains into manageable segments. Adjusting the number of finite elements refines the analysis granularity. More elements create a finer mesh, improving accuracy in stress and deformation predictions, and directly influencing the factor of safety. However, a balance is needed to avoid excessive computational demands or oversimplification. Systematically varying element counts helped identify a convergence point, indicating stable and consistent results. This analysis provides valuable insights into the reliability and robustness of our numerical approach.

It becomes evident that with a lower number of finite elements, the factor of safety is prone to overestimation. Ensuring an appropriate and adequate number of finite elements becomes pivotal in achieving a factor of safety values that faithfully represent the true state of the studied case. Striking the right balance in selecting the number of finite elements is crucial for a reliable and precise analysis outcome. This equilibrium ensures that the numerical solution captures the intricate interactions and behavior within the slope system while avoiding unnecessary computational complexities or oversimplifications that might skew the results."

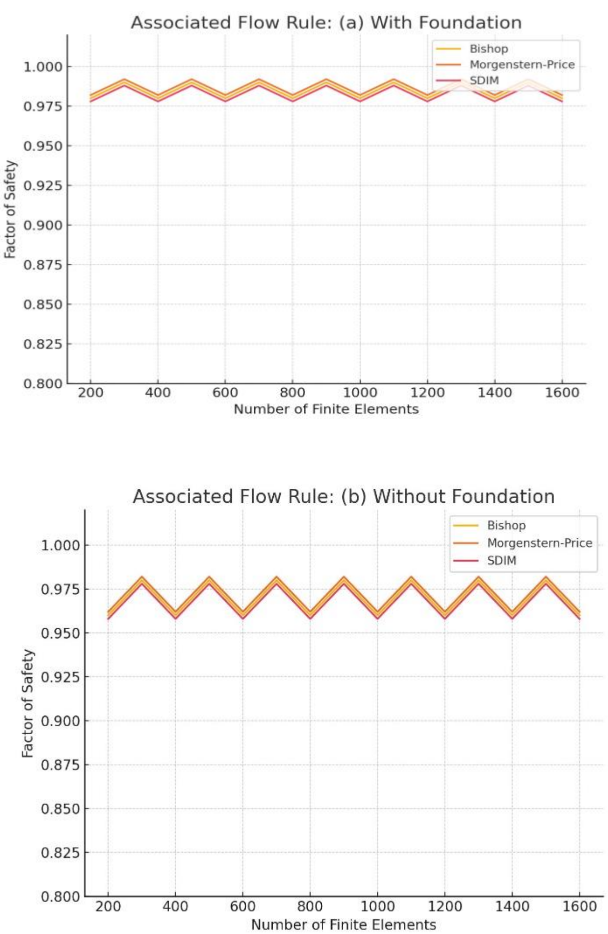

Figure 7. Comparison of factor of safety versus the number of finite elements for the associated flow rule. (a) With foundation and (b) without foundation. (Parameters: **γ** = 20 KN/m², **φ** = 19.6°, **c** = 3 KPa, Poisson ratio = 0.33, **E** = 100000 KN/m², **ψ** = 19.6°)

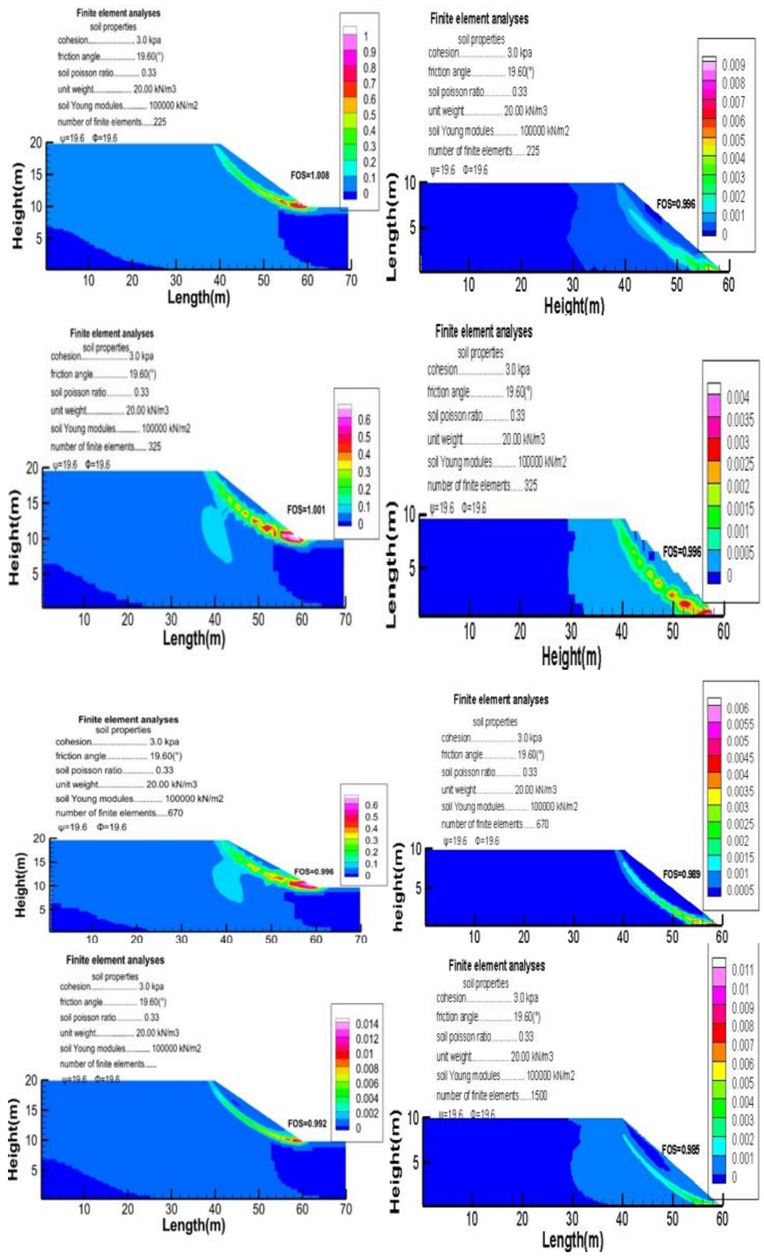

Figure 8. Strain contours corresponding to the step of failure for 225 to 1000, with the foundation

At the 1000th iteration, a significant milestone is reached: convergence is achieved, and the calculated factor of safety becomes stable and reliable. Importantly, further increasing the iteration count is not expected to substantially alter the results because the failure process is already in progress. Therefore, there's no need to continue increasing the number of iterations beyond this point. Convergence at the 1000th iteration ensures that the analysis accurately captures the critical dynamics of slope stability. Selecting the right number of iterations is crucial to balance computational efficiency with accurate deformation behavior, as additional iterations would provide diminishing returns in terms of result accuracy once the significant phase of failure progression has begun.

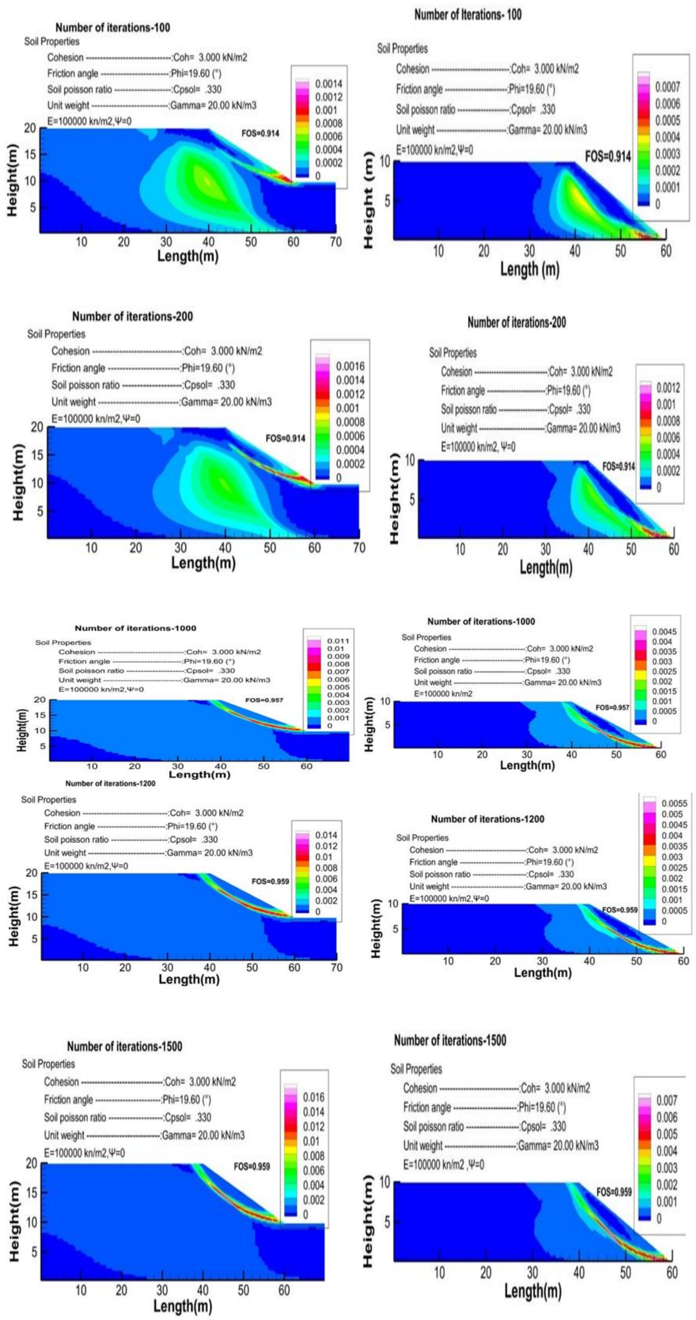

Figure 9. Strain contours corresponding to the step of failure for 100 to 1500 iterations, with non-associated flow rule.

In the non-associated flow rule context, early iterations reveal a lack of slope resistance, emphasizing the role of the dilatancy angle in these analyses. As iterations progress, stress concentration at the slope toe increases, and the slip line becomes more defined, showcasing the effectiveness of Bouzid's method. Clear and smooth contours highlight the approach's capabilities. Integrated with other methods, it enhances geotechnical engineers' judgment and insight for more informed slope analysis. This approach fosters a deeper understanding of slope behavior, aiding decision-making in geotechnical engineering.

This study was conducted under similar conditions, setting ψ (psi) to zero results in a significant decrease in system resistance, leading to distinct deformation that suggests unstable conditions. This highlights the sensitivity of this parameter and its substantial influence on slope behavior. Additionally, varying the number of finite elements during the examination reveals its significant impact on the analysis. A lower count tends to overestimate the factor of safety due to limited detail capture. Incrementally increasing finite elements leads to a convergence of the point, enhancing the factor of safety accuracy and overall precision in slope stability analysis.

4. Conclusion

Slope stability analysis has undergone a significant transformation, transitioning from traditional methods like LEM to modern approaches like SDIM. SDIM, developed by Bouzid, integrates FEM with Mohr's circles to provide a more detailed and precise understanding of slope behavior, particularly under complex stress conditions. This study, which evaluated SDIM's application using the S^{4}DINA program, emphasizes enhancing the potential reliability of slope stability assessments. By addressing the critical need for earth slope stabilization, this research introduces an innovative approach that has the power to revolutionize slope stability analysis and contribute to safer geotechnical engineering practices.

1. The field of slope stability analysis has witnessed a notable evolution, with traditional methods like the Limit Equilibrium Method (LEM) and modern approaches such as the Stress Deviator Increasing Method (SDIM) playing significant roles.
2. DIM, integrating the Finite Element Method (FEM) and Mohr's circles, offers a dynamic and comprehensive approach to slope stability analysis. It has the potential to enhance the precision and adaptability of assessments under varying conditions.
3. Our study underscores the sensitivity of SDIM to specific parameters, such as the associated flow rule, the number of finite elements, and the presence of foundations. These factors significantly influence the outcomes of slope stability analyses.
4. Careful application of SDIM enhances the accuracy of slope stability assessments, allowing for more reliable results. The consideration of various factors and conditions is pivotal in this process.
5. The integration of SDIM with S^{4}DINA represents a substantial advancement, providing geotechnical engineers with a valuable and adaptable tool. It enables more precise and reliable slope stability assessments under diverse conditions, ultimately contributing to the safety and reliability of geotechnical engineering projects.
6. The study's evaluation of SDIM and its integration with the S^{4}DINA software underscores its potential as a game-changing technique for slope stability analysis. This paper contributes to the evolving landscape of geotechnical engineering by offering a fresh perspective and a new tool that can address slope stability concerns with increased precision and reliability.

This study, while valuable, has limitations, focusing on the theoretical aspects of SDIM and S^{4}DINA without field testing or comprehensive sensitivity analysis. Future research should include real-world testing, broader parameter sensitivity analyses, and integration with advanced geotechnical tools to refine and enhance SDIM's applicability, fostering collaboration between geotechnical engineers and software developers.

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Conflict of Interest Statement

The authors must declare that there is no conflict of interest in the study.

CRediT Author Statement

Edson da Graça M. Cumbe: Conceptualization, Methodology, Visualization, Writing - original draft, Writing - Review & Editing. **Crimildo Maria A. Sitoe:** Conceptualization, Methodology, Visualization, Writing - original draft, Writing - Review & Editing. **Marc Nshimiyimana:** Writing - review & Methodology. **Philemon Niyogakiza:** Review & Editing. **Joel Kironde:** Review & Editing. **Angelo A. Pascoal:** Review & Editing.

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