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Tailings Dam Stability Evaluation using 3D Numerical Modelling

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Abstract The disposal of tailings represents a significant engineering challenge in the mining industry, primarily due to the vast volume of material involved and the potential environmental risks. As such, the assessment of tailing dam stability is a critical component of the engineering process, alongside design considerations. Terrain topography plays a pivotal role in both design and stability assessment; flat terrains generally simplify these processes. In contrast, complex terrain conditions necessitate a design that accommodates spatial constraints, which in turn makes stability assessment more intricate and demanding.

Traditionally, 2D limit equilibrium and stress-strain analyses have been the standard, offering reliability for simpler design scenarios. However, for more complex designs, these traditional methods fall short due to complex boundary conditions that significantly impact the stability of tailing dams. These complex conditions can only be accurately assessed through 3D analysis. This paper delves into a comparative study of 2D versus 3D limit equilibrium and stress-strain analyses in tailings dam design and stability assessments.

Beyond the complex boundary conditions inadequately captured by 2D analysis, the distribution of pore pressure within the dam material also undergoes significant variations, which 3D methods can more accurately account for. The advantages of 3D analysis become particularly evident in the identification of risks associated with the intricate designs of tailing dams. Neglecting these complexities and resorting to oversimplified methods for stability assessments can escalate environmental risks, potentially leading to dire consequences. Thus, this paper underscores the importance of adopting advanced techniques in managing the stability risks of tailing dams in complex geological settings.

Keywords tailings dam, stability, numerical methods

Introduction

Tailings dams are engineered structures designed for storing by-products of mineral processing in the mining industry. These by-products, known as tailings, consist of a mixture of fine particles, water, and various chemicals used in the processing. The mixture is transported to a designated area for deposition, where excess water is removed using hydrocyclones. The coarser sand material is then utilized to construct the dam, which serves the purpose of containing the remaining material within the pond. However, these processes and the tailings dams themselves pose significant environmental risks. Historical records document catastrophic events (Morgenstern et al, 2016), with the Brumadinho dam disaster in Brazil being one of the most recent and notable examples.

Tailings dam design varies based on the terrain where it is planned to be located. In flat areas, construction is straightforward and easy to manage throughout the production process. However, more complex terrains, such as hilly areas and valleys, necessitate intricate designs and management strategies. As a result, stability evaluation becomes significantly more critical with complex designs (Vick, 1990). Until recently, stability evaluations were performed using available 2D tools that relied on the finite element method and the limit equilibrium method. Planar analysis, however, has substantial limitations in capturing the boundary conditions of the structure being analyzed. It requires the identification and analysis of numerous cross-sections for stability, especially in cases requiring complex designs. The adoption of 3D tools, which are increasingly becoming standard in engineering practice, allows for the analysis of complex structures as whole entities. This approach considers both the mechanical behavior and the influence of water levels, offering a more comprehensive analysis.

This paper is dedicated to showcasing the use of 3D numerical modeling in assessing the stability of tailings dams. It elaborates on the creation and validation of a 3D model designed specifically to mimic the intricate systems of tailings dams. Through an exploration of the strengths and weaknesses of 3D numerical modeling in the context of tailings dam stability evaluations, this paper aims to enrich the domain of tailings dam safety. Its goal is to lay the groundwork for the creation of more precise and dependable forecasting tools, thereby advancing safer tailings management methodologies.

Preliminary considerations

Figure 1 illustrates a tailings dam situated in a valley, highlighting the location of a typical cross-section used for evaluating planar stability. This representation significantly simplifies the actual construction, a critical point to bear in mind as evident from the figure itself. Figure 2 depicts the material structure, showing that the initial dam is constructed from rock material, followed by layers of sand, with the majority of the volume comprising tailings. Owing to the nature of the tailings discharged from the flotation plant and the segregation of material fractions during operation, a transitional zone between the sand and tailings (mud) has been identified (Duncan et al, 2014).

The stability evaluation involves assessing the slope stability across various cross-sections that are representatively defined. These cross-sections must be delineated in a way that captures the essential features of the structure. There is a potential risk if too few sections are selected, leading to the omission of critical parts of the tailings dam from the analysis. Apart from the slope itself, failure could also result from sliding over the ground rock mass or from the failure of the ground itself.

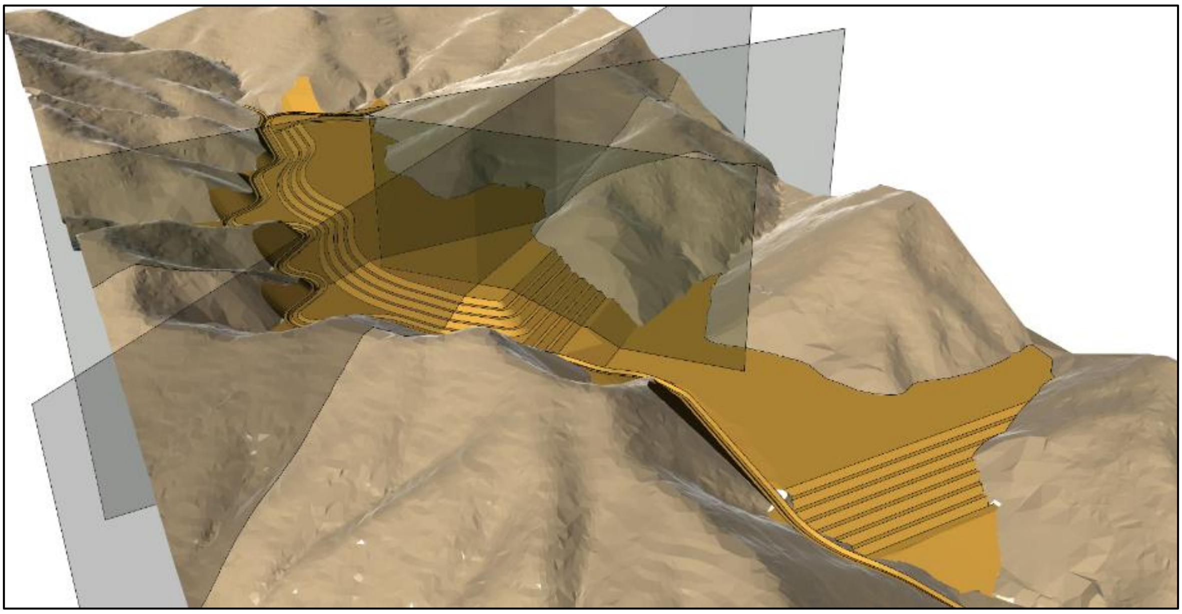
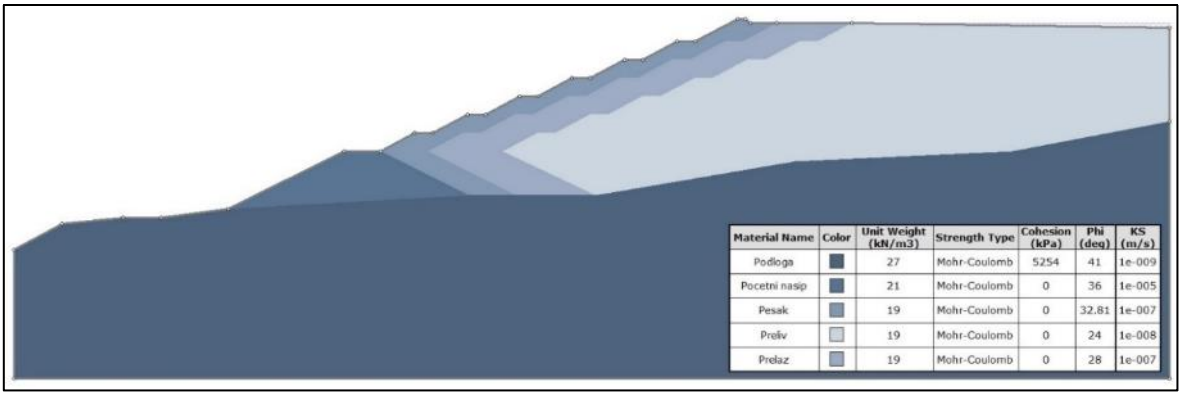


Figure 1 Tailing dam construction



Material Name	Color	Unit Weight (kN/m3)	Strength Type	Cohesion (kPa)	Phi (deg)	KS (m/s)
Podloga	■	27	Mohr-Coulomb	5254	41	1e-009
Pocetni nasip	■	21	Mohr-Coulomb	0	36	1e-005
Pesak	■	19	Mohr-Coulomb	0	32.81	1e-007
Preliv	□	19	Mohr-Coulomb	0	24	1e-008
Prelaz	■	19	Mohr-Coulomb	0	28	1e-007

Figure 2 Geomechanical cross section used for 2D models

Figure 2 illustrates the geomechanical cross-section utilized for creating the 2D models, with the results of the limit equilibrium model shown for simplicity. The same figure also details the material properties used in the analysis. To depict the worst-case scenario, the model simulates conditions where the pond is at its maximum water level.

The critical Factor of Safety (FOS) identified using Limit Equilibrium Method (LEM) modeling occurs in cross section 1, with a critical water level resulting in a FOS value of 1.197 (Figure 3). This example serves as a reference to highlight the differences between 2D and 3D modeling approaches. Rocscience Slide (Rocscience, 2023) was used in this case.

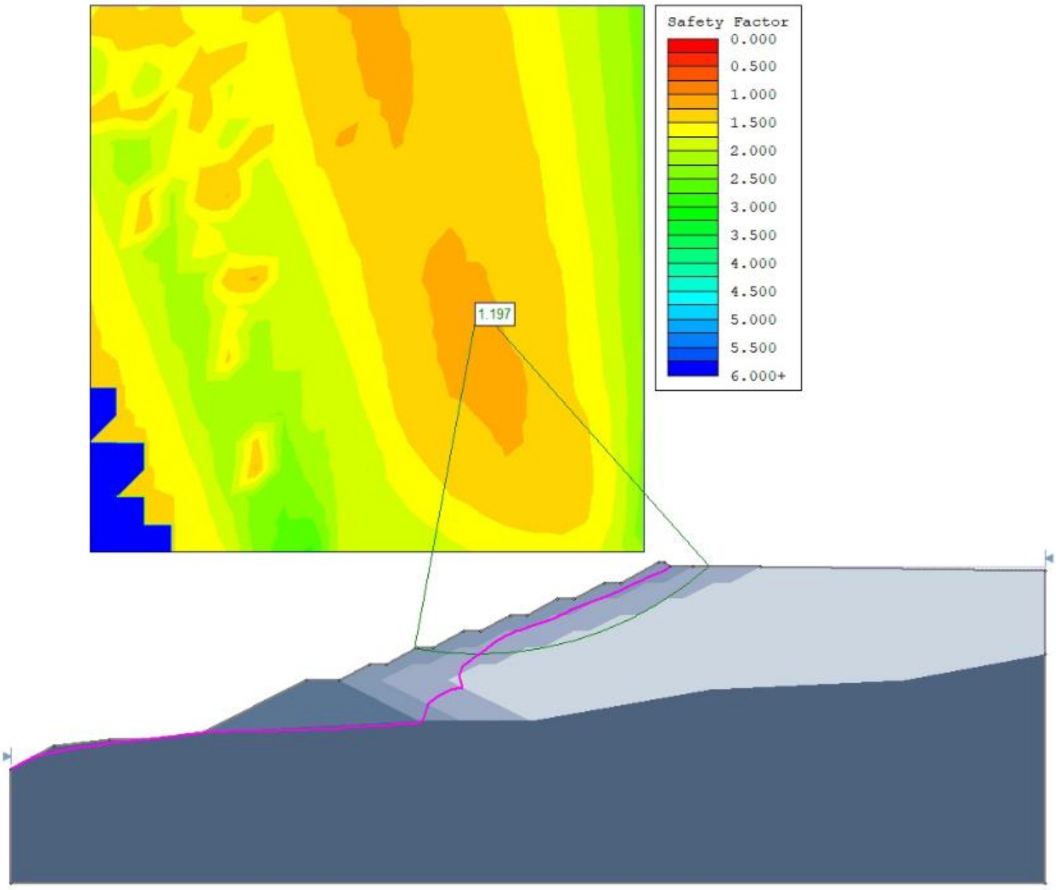


Figure 3 FOS for 2D LEM model

3D approach of modelling tailing dam stability

Planar models greatly simplify the representation of tailing dams, especially in scenarios where the terrain's configuration is a key factor. Complex structures, like the one shown in Figure 1, are inherently three-dimensional problems when evaluating stability due to their complex boundary conditions. The planar representation of such structures overlooks the boundary conditions that are crucial to stability assessments. Consequently, the Factor of Safety (FOS) values calculated using two-dimensional (2D) and three-dimensional (3D) models show significant differences.

To assess the stability of tailing dams, available 3D tools rely on stress-strain analysis using finite element method (FEM) and 3D limit equilibrium. This discussion covers the application of both methods.

3D FEM stability analysis

Rocscience RS3 (Rocscience, 2023) offers an outstanding tool for three-dimensional stress-strain analysis using the finite element method, and it is showcased to demonstrate its capabilities in evaluating the stability of tailing dams, as depicted in Figure 1. The model is constructed and illustrated in Figure 4, with the hatched area indicating the critical position of the water level within the pond, or scenarios where the water level reaches the dam itself. This step also establishes the boundary conditions necessary for calculating the pore pressure distribution within the model. Figure 5 displays the model's discretization along with its mechanical boundary conditions.

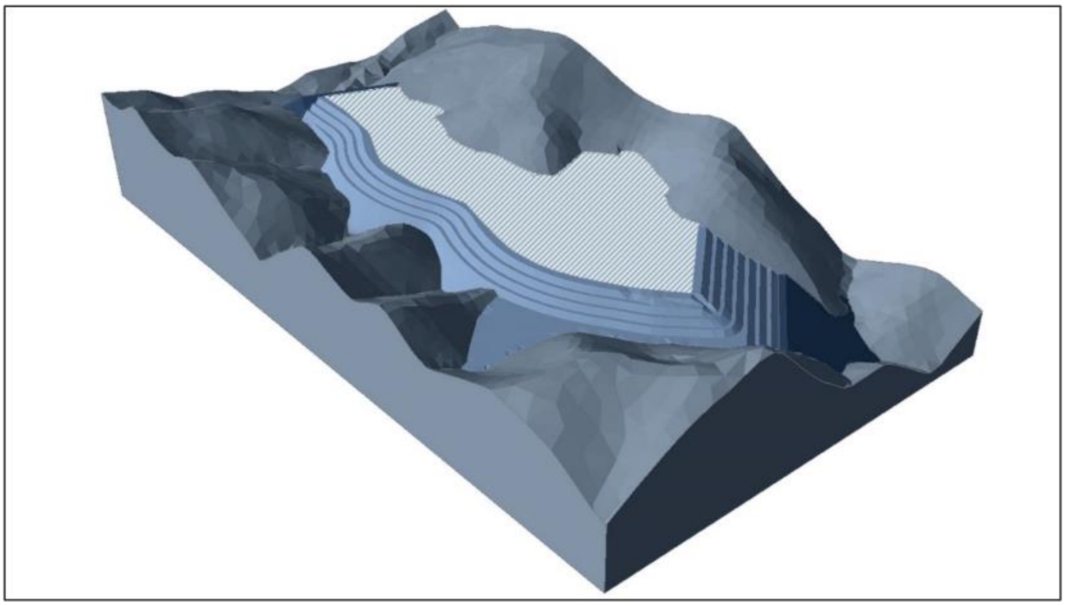


Figure 4 3D finite element model

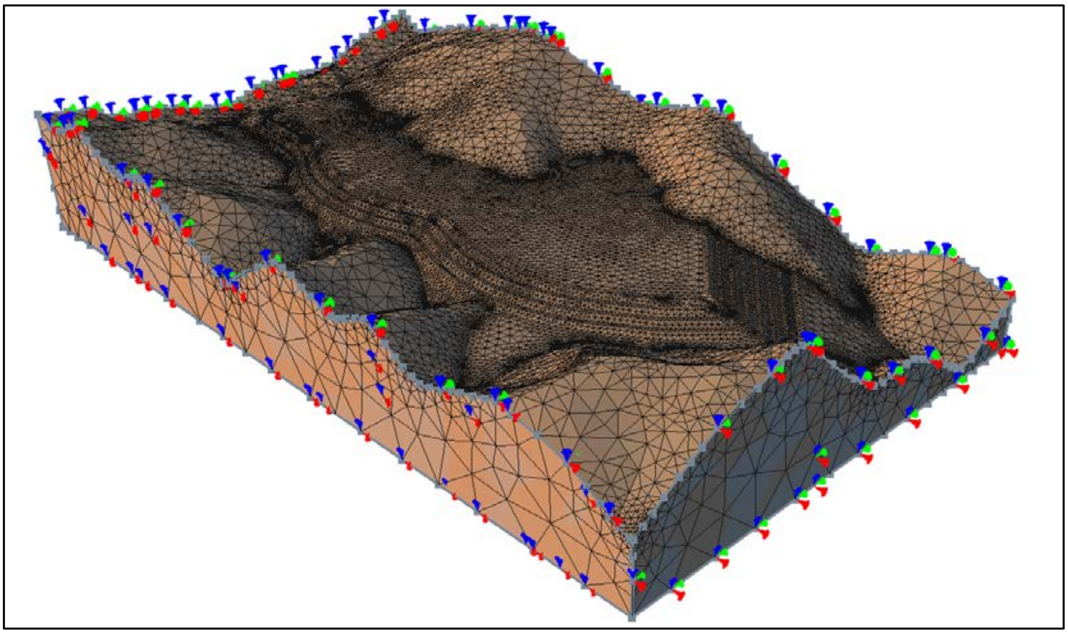


Figure 5 3D finite element mesh and boundary conditions

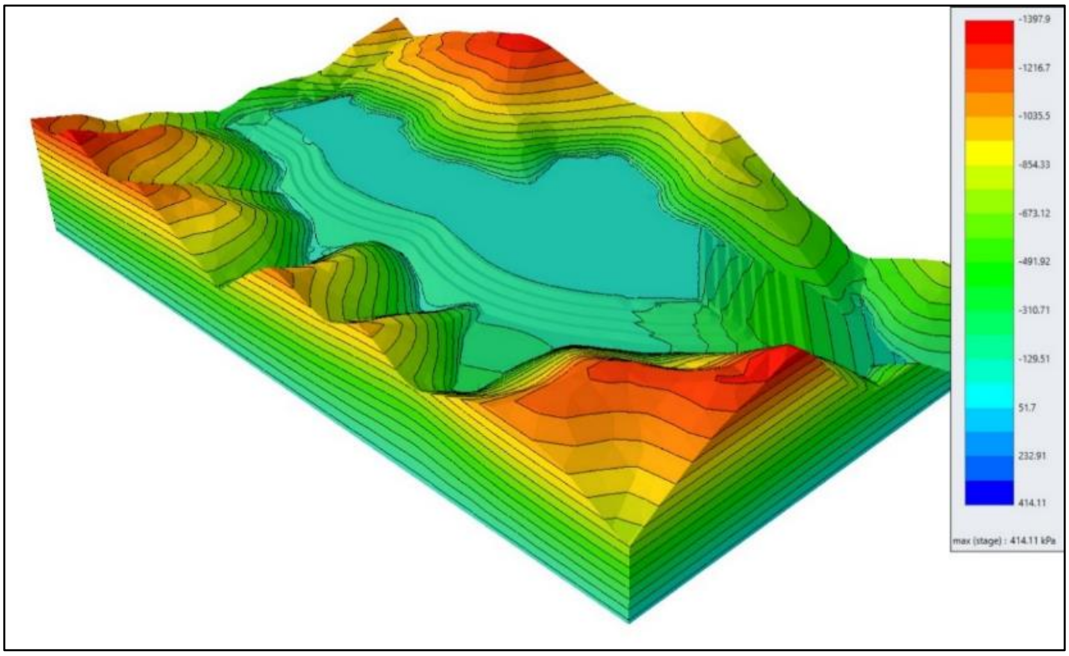


Figure 6 Pore pressure distribution within the model

Following the establishment of the model's geometry and the definition of boundary conditions for mechanical analysis, the strength reduction procedure also includes defining water level conditions. This is essential for determining the spatial distribution of pore pressure within the tailing dam and the pond. The first step involves presenting the pore pressure distributions, as shown in Figure 6.

The distribution of pore pressure is affected by both the construction of the tailing dam and the configuration of the surrounding terrain. Knowing the groundwater level within the surrounding rock mass enables the assessment of how water from the rock mass and the pond will interact, from an environmental perspective.

The main method used to determine the Factor of Safety (FOS) is strength reduction, and the results shown in Figure 7 highlight a clear distinction in areas where zones of increased displacements may occur, illustrating the shape of the failure body. In this case, the critical FOS is 2.25, which is significantly higher than the FOS value determined by 2D analysis. The primary reason for this difference is the boundary conditions; in 3D models, there is significantly higher resistance. This effect is particularly pronounced in constructions with irregular dam shapes, as demonstrated by the example provided.

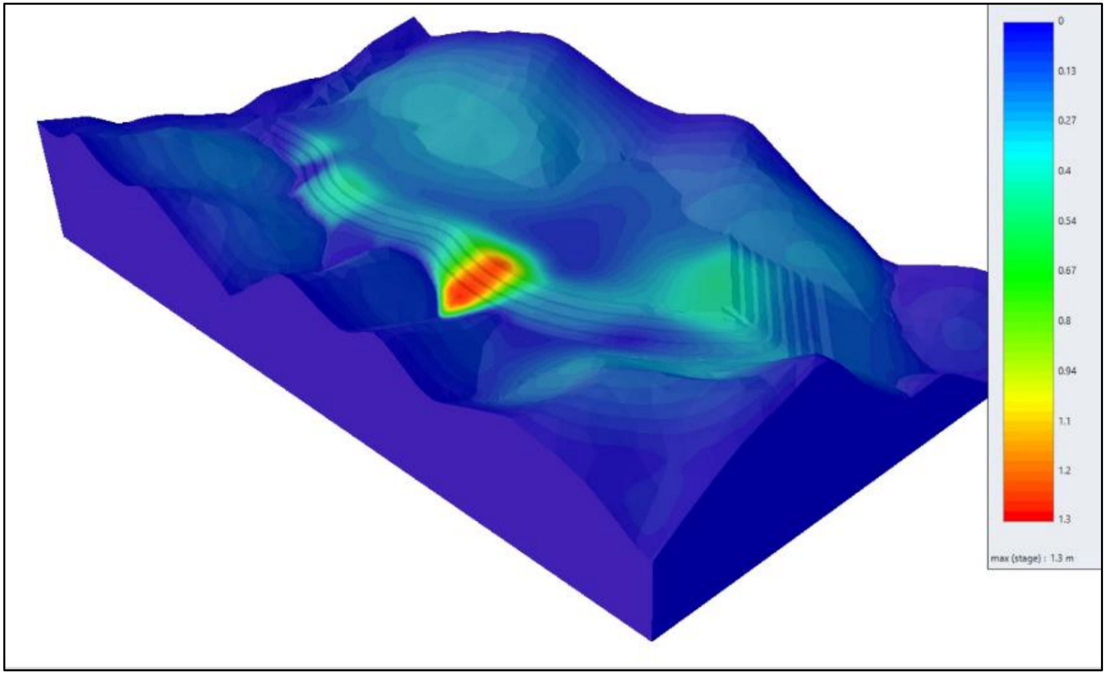


Figure 7 Resulting displacements after strength reduction procedure

In addition to identifying the critical failure body, it is observed that other locations within the model also exhibit increased displacements. Although these areas do not undergo progressive failure, it is beneficial to recognize them as potential risks. Evaluating these areas separately during the design and production phases is crucial for a comprehensive risk assessment.

3D limit equilibrium analysis

The analysis was conducted on the same geometry used for Finite Element Method (FEM) analysis, utilizing the Slide3 package (Rocscience, 2023). These software packages are compatible, allowing for the exchange of model files between them. However, a limitation of Slide 3 is that pore pressure calculations must be imported from RS3.

Unlike RS3, where the strength reduction procedure identifies the failure body, Slide3 performs a search across the model. It assumes a set of potential failure bodies and evaluates their stability one by one. This search is conducted within the model's boundaries, generating a series of spherical or elliptical surfaces for evaluation. The analysis results, presented in Figure 8, show that the failure body identified as critical corresponds to the one identified using FEM analysis in terms of position, shape, and dimension. In this case, the Factor of Safety (FOS) is 2.31 (Bishop). The volume of the failure is 90,000 cubic meters, with a smaller body contained within it having a volume of 16,000 cubic meters and a FOS of 1.58.

An important aspect of the limit equilibrium approach is accurately identifying the critical location where failure may occur and conducting an appropriate search. Inadequate searching could result in overlooking potentially unstable locations, thereby increasing the risk of misinterpreting the stability of the entire structure.

3D limit equilibrium analysis often results in higher Factor of Safety (FOS) values compared to the 2D approach. Given that the 3D approach is relatively new, it is prudent to exercise caution in its application until comprehensive validation has been conducted.

The accuracy of the limit equilibrium approach is known to be sensitive to the density of the search network, necessitating extra caution in this area. Gradually increasing the density of the search network is a wise strategy for optimizing computational costs. This principle also applies to Finite Element Method (FEM) analysis, where the size of the elements and the density of the mesh directly affect the accuracy of the results.

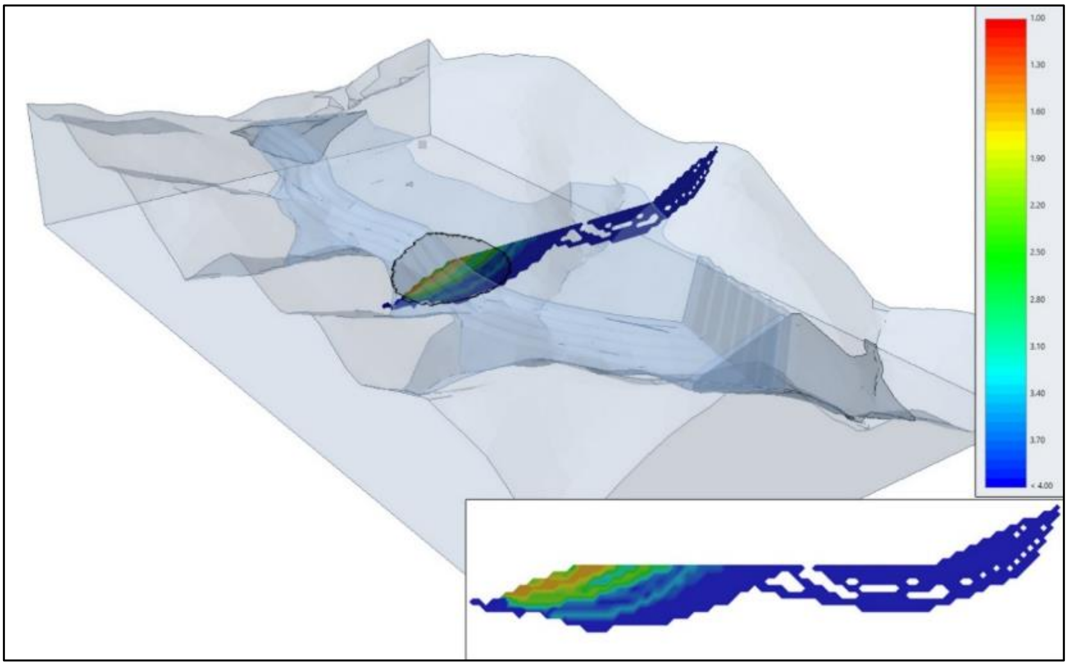


Figure 8 Results of 3D limit equilibrium analysis

Conclusion

Designing and evaluating the stability of tailings dams are critical engineering tasks that require meticulous attention to detail to prevent catastrophic events. The complexity of the design can significantly affect the complexity of the stability evaluation process. In scenarios where the terrain configuration leads to a complex design, only a 3D modeling approach can offer a comprehensive understanding of the structure's mechanical behavior. The 2D approach, on the other hand, necessitates the evaluation of numerous cross-sections. The selection of their locations must be informed by an understanding of the critical points in the design. As a result, there is a risk of overlooking these critical points when choosing a representative cross-section for analysis.

On the other hand, 3D analysis is considerably more complex and requires a significantly longer time for modeling and evaluating results. For instance, preparing the model mesh in the Finite Element Method (FEM) approach can be time-consuming for complex designs. However, once the model is set up, evaluating the critical aspects of the structure's stability becomes straightforward.

This paper demonstrates the application of 3D numerical tools (RS3 and Slide3) and how they can be utilized in the process of identifying critical aspects within the tailings dam. It is evident that the Factor of Safety (FOS) values obtained are significantly higher than those derived from 2D tools, thus highlighting the need for careful consideration before finalizing design decisions.

The typical approach discussed here involves evaluating several cross-sections using 2D models, which requires assuming the location of critical areas. However, if these areas are identified using a 3D approach, they can be further analyzed with 3D tools.

The comparison between the Finite Element Method (FEM) and the Limit Equilibrium Method (LEM) approaches showed that both methods identified the same areas of the structure as critical, with negligible differences.

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