Slope Stability Analysis of Suichang Gold Mine Based on Numerical Simulation Method

Tao Peng[1,a], Yali Sun[1,2,3,b*], Jianping Fang[2,]

[1]College of Civil Engineering, Anhui Jianzhu University, Hefei, China
[2]College of Civil Engineering and Architecture, Quzhou University, Quzhou, China
[3]College of Transportation and Civil Engineering, Fujian Agriculture and Forestry University, Fuzhou, Fujian, People's Republic of China

[a]1443957552@qq.com, [b*]sunyl761@126.com

Abstract. The safety factor of typical slopes was determined by using Flac3D, which is based on the strength reduction method, and GeoStudio, which is based on the limit equilibrium method. Based on the analysis, the following conclusions were drawn. In the Flac3D software, it has been observed that slopes with varying extension lengths within a given section exhibit consistent safety factors. Furthermore, the slip surface's position and shape remain largely unchanged across these slopes. The safety factor determined through calculations in Flac3D exceeds that of GeoStudio. The calculated potential slip plane positions obtained from the Flac3D and GeoStudio software packages exhibit a high degree of similarity. The stability analysis of the slope at the entrance waiting area of Suichang Gold Mine National Mine Park was conducted by integrating the safety factor obtained from GeoStudio and the incremental cloud map of displacement, stress, and shear strain obtained from Flac3D. The analysis revealed that no slip surface was identified on the slope; however, the occurrence of rockfall was anticipated. Consequently, it is recommended to implement anti-rockfall measures in order to mitigate potential hazards.

Keywords: Strength reduction method; Limit equilibrium method; Suichang Gold Mine; Numerical simulation; Slope stability.

1 Introduction

In recent years, the economic development in our nation has led to the formation of various slope types, resulting from both natural and human factors. These slopes have had a dual impact, simplifying human life while also posing a significant threat to public safety[1]. The geological setting within our nation is intricate, with a notable issue of slope instability prevalent in mountainous regions, so slope stability has always been an important research issue in mountain scenic area construction. Many scholars have carried out a large number of valuable researches on slope stability based on numerical simulation, such as: Zhou Guimei[2] et al. conducted stability analysis of different landslide reinforcement schemes in GeoStudio, and determined the most feasible prevention

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and control measures combined with the economic cost of the project. E.C.Leong[3] et al. used two-dimensional and three-dimensional slope stability analysis to re-analyze the Singapore residual soil slope that failed twice in 1989 and 1991, and the stability analysis of the slope that failed in 1989 showed that the safety factor obtained by the two-dimensional slope stability analysis was not necessarily more conservative than that of the three-dimensional slope stability analysis, and the analysis of the slope in 1991 showed that the difference in the safety factor between the two-dimensional and three-dimensional slope stability analysis under low groundwater level was greater than that of the high groundwater level. Fang Jian[4] et al. examined various slope models with distinct Angle profiles as subjects of investigation. Through a comparative analysis, they observed that the safety factor calculation results obtained from Flac were lower than those obtained from Flac3D.Yin, XJ[5] et al. established numerical models of slopes of different scales, different grid shapes and sizes for stability analysis, and proposed a simplified method suitable for the evaluation of the fine safety factor of multi-scale slopes based on the comprehensive influence of multiple scales on the stability analysis. Yang Jiaqan[6] et al. employed a combination of Flac3D and GeoStudio software to conduct simulations and analyses on five slope profiles. The researchers successfully demonstrated that the integration of these two software tools enables a comprehensive and unbiased assessment of slope stability levels. Zhang Qianqi[7] employs the software tools GeoStudio and Flac3D to conduct a simulation of a slope. The researcher then integrates the outcomes obtained from both software platforms to elucidate the underlying mechanisms and trajectory of landslide formation.

The above research uses different software to study the stability of slope, and combines different analysis software to study the stability of slope, which is a feasible means to improve the research accuracy. However, there are still some problems, such as how much size of the three-dimensional model in Flac3D can better fit the calculation results of the two-dimensional model in GeoStudio; The source of the difference between the calculation results of Flac3D and GeoStudio, whether there are differences in the calculation results. Therefore, this paper first analyzes the sources of differences in calculation results by introducing the calculation principles of the two software, and then takes the typical section as the research object to compare and analyze the simulation results of different length models of the same section in Flac3D, and compare them with the calculation results of GeoStudio. Then the stability of the high and steep slope at the entrance of Suichang Gold Mine National Mining Park is analyzed comprehensively by combining the two software.

2 Principles of Flac3D and GeoStudio computing

2.1 Calculation principle of Flac3D

The strength reduction method is employed by Flac3D in order to determine the safety factor. The fundamental concept of the strength reduction method involves the computation of the safety factor of a slope by iteratively reducing its cohesion and internal friction angle until failure occurs and the corresponding reduction factor is obtained, indicating the slope's stability at a critical state[8]. The expression can be represented as follows:

$$c' = \frac{c}{F} \tag{1}$$

$$\varphi' = \arctan \frac{\tan \varphi}{F} \tag{2}$$

where, c is the initial cohesion, φ is the initial internal friction angle, c', φ' are the reduced cohesion and internal friction angle.

The strength reduction method primarily assesses the stability of a slope based on three key factors.: ①The question at hand pertains to the attainment of convergence in the calculation. If the material fails to meet the convergence criterion within a specified number of computed iterations, it is deemed to have incurred damage. The determination of slope stability using convergence analysis is influenced by various factors, including boundary conditions, mesh refinement, and the choice of yield criterion. Consequently, the general applicability of this method is affected by these factors. ②The inquiry pertains to the existence of displacement mutations. When the slope experiences damage, the soil the soil sliding along the sliding plane will undergo significant displacement, transitioning from its initial static state to a state of motion. Hence, it is possible to designate a feature point on the slope and utilize this point to ascertain whether the slope exhibits displacement mutation. The stability condition of the slope can also be assessed based on the abrupt variation in displacement increment. ③The question at hand pertains to the extent of the plastic zone. The instability of a slope is indicated when the plastic zone extends from the base to the crest of the slope. The utilization of shear strain cloud map or plastic zone in Flac3D can be employed as a means to ascertain the occurrence of slope failure[9-13].

Strength reduction can be implemented in Flac3D using a safety factor model. The program has a number of steps (N_r) representing the response time of the system, which is found by setting the material strength (for Mohr-Coulomb material, cohesion and tension) to a large value, making a large change in the internal stress, and finding the number of steps required for the system to return to equilibrium. The size of the N_r value can be set, with a default upper limit of 50000. In the event that the model fails to achieve equilibrium within a span of 50000 steps, the calculation is terminated, resulting in the inability to determine the safety factor.

2.2 Calculation principle of GeoStudio

The calculations performed by GeoStudio are founded upon the principles of the limit equilibrium method. The limit equilibrium method is a commonly employed and well-established approach for analyzing slope stability. The approach primarily relies on the Morh-Coulomb failure criterion, assuming a straightforward failure surface. The sliding body situated above the sliding surface is divided into vertical soil strips, followed by the establishment of the static equilibrium equation to determine the safety factor. Through the process of evaluating the safety factor across multiple hypothesized failure surfaces, it is determined that the sliding surface associated with the lowest safety factor is the most critical in terms of potential hazards[14].

The basic assumption of the limit equilibrium method has three aspects: ①the internal deformation is ignored in the process of analyzing the force and deformation of the soil strip; ②In the event of failure, the sliding soil strip can be said to be in a state of ultimate strength, ③In instances of failure, the sliding body is in a state of static equilibrium. The limit equilibrium analysis methods can be categorized based on the various interaction factors between soil blocks. These methods include the Sweden Arc method, simplified Bishop method, Janbu method, Morgenstern-Price method, and others. The Sweden Arc method can be considered a long-standing approach. The assumption is made that the sliding surface takes the form of a circular arc. The operation process does not take into account the mutual influence of forces between each strip, resulting in a relatively straightforward process that does not require iterative solving. The simplified Bishop method incorporates the interbar force by building upon the Swedish arc method. However, it solely accounts for the normal force between the bars and does not take into consideration the tangential force. The Janbu method demonstrates suitability not only for circular arc glide plane, but also for various other intricate geometries. In contrast to the simplified Bishop method, the calculation of the method under consideration not only ensures the equilibrium of vertical force and moment for each strip, but also ensures the equilibrium of horizontal force. The Morgenstern-Price method involves the derivation of a differential equation that describes the balance of forces and moments on a sliding plane. This equation considers the coordinates of the normal and tangential forces between adjacent bars in the horizontal direction as a function. By examining the overall force and moment balance, the method determines the safety factor. The examination of this approach is characterized by a heightened level of rigor, necessitating multiple iterations to ascertain the safety factor[15-19].

3 Example calculation and analysis

3.1 Calculation model and parameters

The Flac3D model is established as shown in Fig.1. The size and mesh division of each slope profile are consistent, with a height of 10 meters and the slope angle is 45 degrees. The extension lengths from left to right slopes are 1m, 3m, 5m, 10m and 20m respectively. Normal constraints are applied to all sides of the slope, and the bottom is a fixed edge. The GeoStudio model is shown in Fig.2. The model parameters are shown in Table 1.

Table 1. Table of model parameters

Gravity/($kN \cdot m^{-3}$)	Elastic modular/MPa	Cohesion/KPa	Friction angle/°	Poisson's ratio
20	70	15	20	0.3

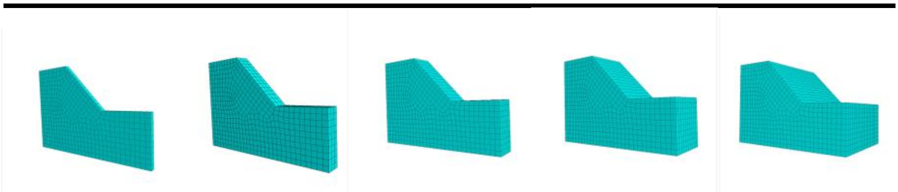


Fig. 1. Flac3D mesh model

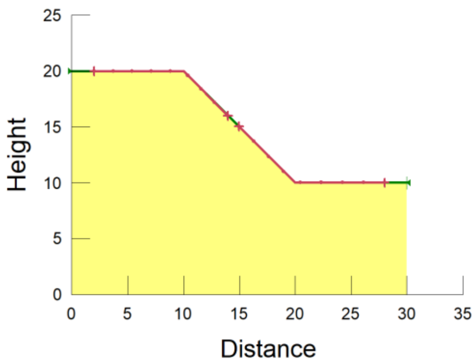


Fig. 2. GeoStudio slope model

3.2 Simulation results and analysis

The calculation results of safety factors of different models in Flac3D are shown in Table 2, and the cloud diagram of shear strain increment and displacement vector diagram are shown in Fig.3, Fig.4, Fig.5, Fig.6 and Fig.7 respectively. Fig.8 shows the most dangerous slip plane calculated by GeoStudio and the corresponding safety factor.

Table 2. Calculation results of different stretch lengths of Flac3D

Length of stretch/m	1	3	5	10	20
Factor of safety	1.1060	1.160	1.160	1.160	1.160

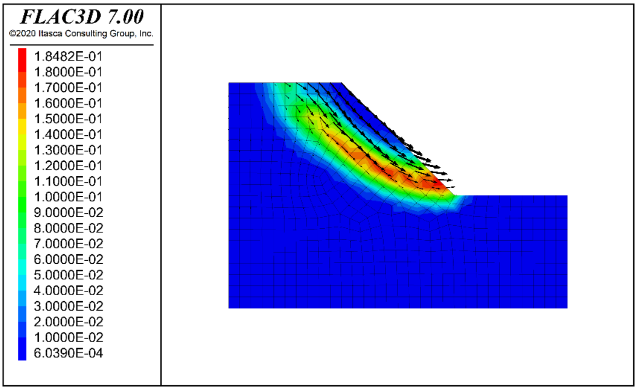


Fig. 3. Shear strain increment cloud map and displacement vector map of 1m length

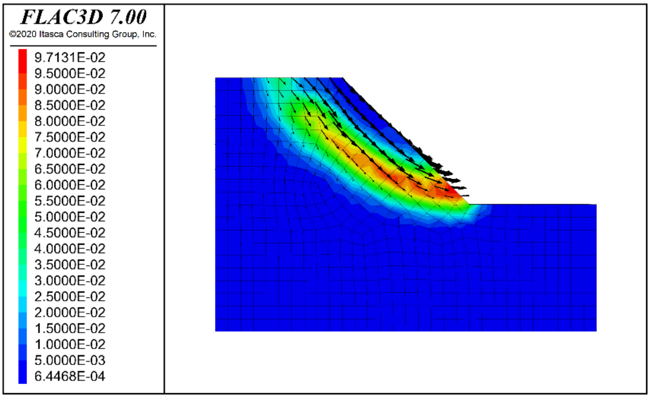


Fig. 4. Shear strain increment cloud map and displacement vector map of 3m length

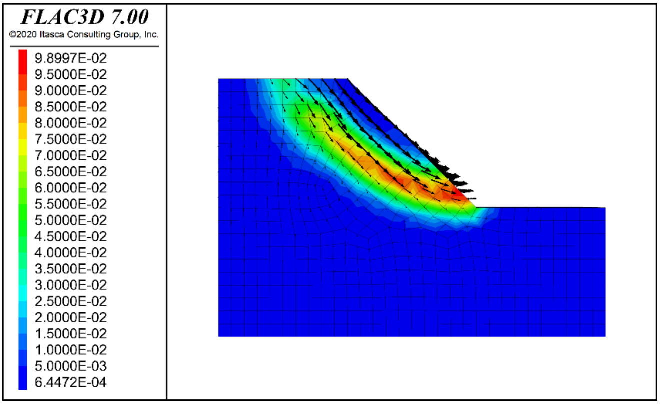


Fig. 5. Shear strain increment cloud map and displacement vector map of 5m length

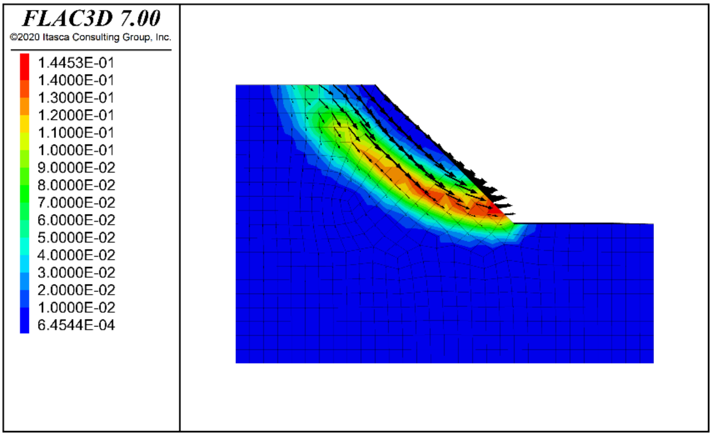


Fig. 6. Shear strain increment cloud map and displacement vector map of 10m length

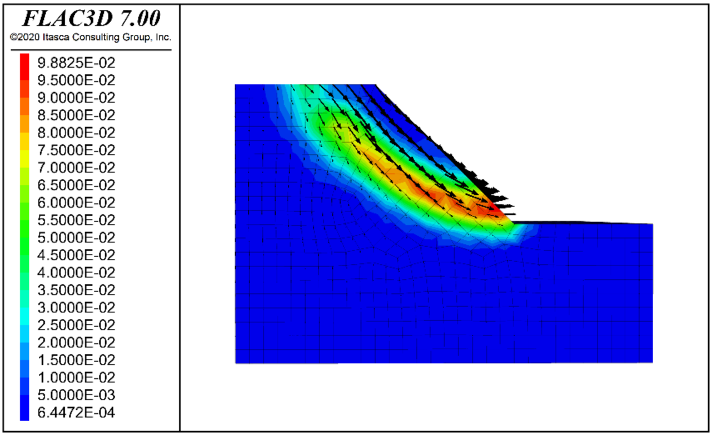


Fig. 7. Shear strain increment cloud map and displacement vector map of 20m length

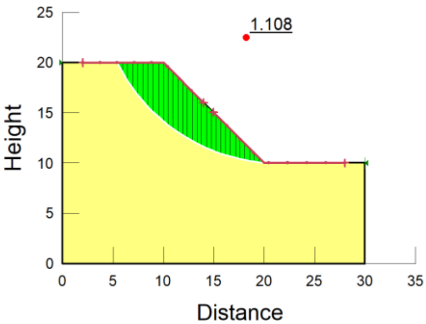


Fig. 8. Slip surface and safety factor of GeoStudio

3.2.1 Factor of safety analysis

The safety factor calculation results for 3D models with varying lengths, as presented in Table 2, demonstrate consistency when extended based on the identical section in Flac3D. Hence, it is advisable to limit the extension length in Flac3D when utilizing the 3D model for simulating strain issues in a two-dimensional plane or determining the slope safety factor. This precautionary measure aims to minimize the computational time of the software while maintaining the accuracy of the calculations. Therefore, the extension length of the model in Flac3D below is set to a smaller value, 3 m.

The safety factor determined by Flac3D, which is 1.160, exceeds the safety factor obtained from GeoStudio, which is 1.108. The limit equilibrium method relies on the application of the static equilibrium equation to analyze the slip-body divided into soil blocks and determine the safety factor. Consequently, the safety factor is influenced by the strength of the soil blocks comprising the slip-body above the failure plane. While the strength reduction method is utilized to determine the potential range of slip planes, the assessment of the safety factor takes into account not only the strength of the rock and soil mass above the failure plane. Hence, the safety factor determined through the strength reduction method exhibits greater magnitude compared to the safety factor obtained through the limit equilibrium method.

3.2.2 Potential slip plane and displacement analysis

The analysis of shear strain increment depicted in Fig.3 to 7 reveals that while the magnitudes of shear strain increment vary across slopes with different extension lengths, the overall shape and location of the potential slip plane remain consistent. Furthermore, these observations align closely with the position of the potential slip plane calculated by GeoStudio in Fig.8.According to the displacement vector diagram , the displacement direction at the top and middle of the slope is parallel to the slope surface, while the displacement direction at the lower part of the slope slides out along the slope foot. The landslide mode of this slope is circular. So Flac3D can therefore complement GeoStudio's lack of a comprehensive display of slope deformation and failure processes.

4 Calculation and analysis of engineering examples

4.1 Project overview

The route from the entrance ticket office of Suichang Gold Mine National Mine Park to the main scenic spots is characterized by numerous steep rock slopes, with the fourth series coverage on the top of these slopes being relatively sparse. The incline at the entrance checkpoint is characterized by a significant elevation ranging from 20m to 23.5m and a steep gradient ranging from 65° to 70°. The lithological composition of the slope is identified as biotite plagioclase gneiss, as shown in Fig.9. Following the manual cutting of the slope, notable unloading cracks and weathering cracks emerged on the surface of the slope. Consequently, certain rock blocks dislodged and descended, leaving behind depressions on the adjacent side slope. The slope is characterized by the presence of a mud interlayer, which spans approximately 13.8 meters in length and exhibits an average width of approximately 20 centimeters. The stability analysis conducted on the slope using Flac3D reveals that significant displacements are observed primarily at the mud interlayer, indicating a propensity for slippage[20].

Fig. 9. Slope at the entrance of the park

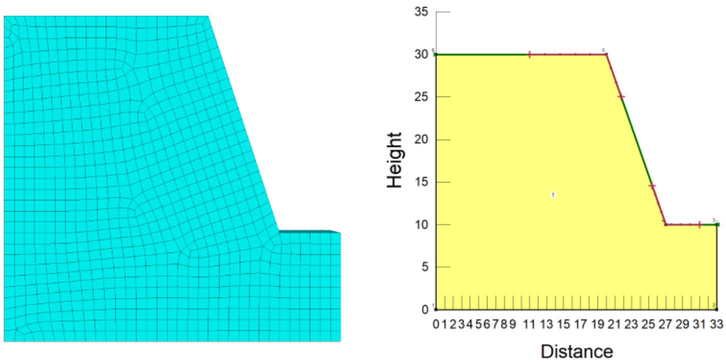
4.2 Numerical simulation analysis

4.2.1 Slope model and rock mechanics parameters

This paper focuses on the selection of the slope at the entrance of the scenic spot, and the lithology is biotite plagioclase gneiss, whose physical and mechanical parameters[21] are shown in Table 3. The elevation of the slope measures 20 meters, while the slope angle is 70 degrees. The overall length of the model is 33 meters, with a height of 30 meters. The length of the top of the side slope is 20 meters, and the length in the y direction is 3 meters. The boundary conditions around the slope adopt normal constraints, and the bottom is fixed constraints, as shown in Fig.10.

Table 3. Physical and mechanical parameters of rock[21]

Rock name	Elastic modular/ GPa	Ten-sile streng th/MP a	Friction angle/°	Cohesio/ MPa	Gravity /($kN \cdot m^{-3}$)	Poisson′s ratio
Biotite plagioclase gneiss	72.814	7.742	53	14.994	26.264	0.25



(a) Flac3D 2D model (b) GeoStudio 2D model

Fig. 10. Slope model

4.2.2 Analysis of simulation results

As depicted in Fig.11, the vertical downward displacement is observed in the upper and middle regions of the slope. Conversely, in a localized area near the base of the slope, the displacement aligns with the slope surface, without surpassing it. This observed behavior deviates significantly from the displacement direction exhibited by the landslide slope in the provided calculation example. The absence of a potential slip surface, as indicated by the GeoStudio calculation results, suggests that the slope is stable and unlikely to experience any slippage.

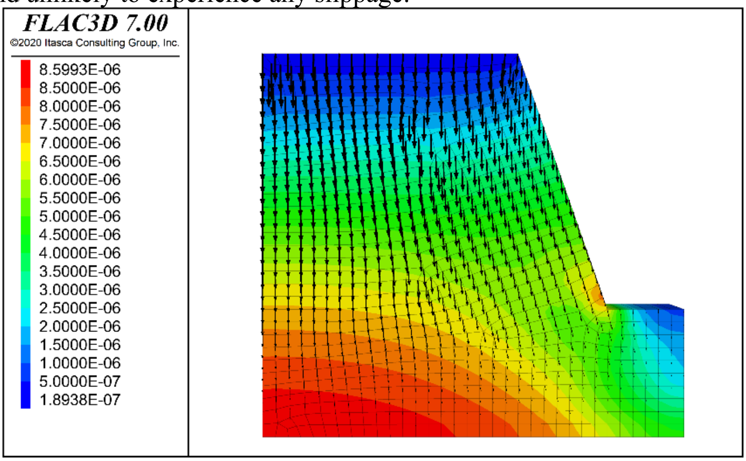


Fig. 11. Shear strain increment cloud map and displacement vector map

As depicted in Fig.12, the slope exhibits a maximum displacement magnitude of 0.016mm. This displacement predominantly occurs in an outward direction along the slope, potentially leading to the formation of cracks on the side slope and the dislodgement of loose rocks. Nevertheless, within a limited range, the displacement at the summit of the slope exhibits a negative trend, indicating that the extrusion transpires towards the interior of the slope. Consequently, this inward movement contributes to the fracturing of the uppermost rock layer. Hence, it is imperative to implement measures aimed at mitigating rock fall occurrences on the slope.

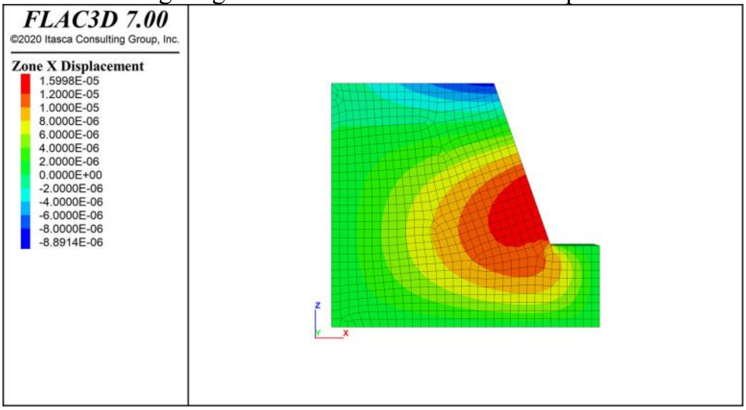


Fig. 12. Displacement cloud map of slope in X-direction

As shown in Fig.13, the maximum displacement of the slope is 0.14mm, which decreases from top to bottom, and the overall displacement value is relatively small, indicating that the compressive strength of the biotite plagioclase gneiss is relatively large, and the overall displacement is not abrupt, and the stability is well.

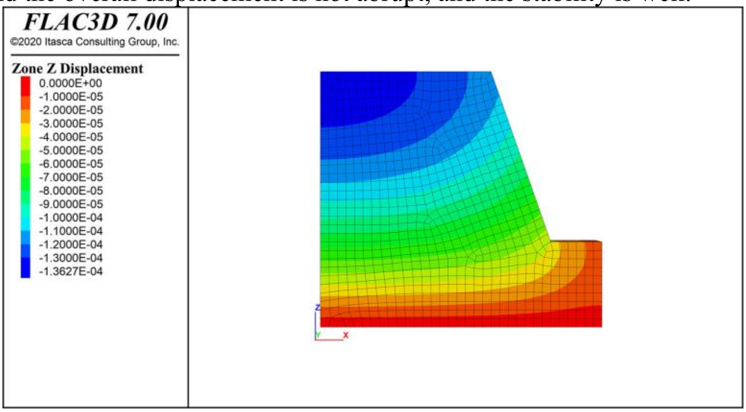


Fig. 13. Displacement cloud map of slope in Z-direction

5 Suggestions for slope protection

Based on the computational findings of Flac3D, it is determined that the slope at the entrance of Suichang Gold Mine exhibits stability and is unlikely to experience slippage. However, it is observed that the side slope is susceptible to an elevated risk of rock fall due to the significant occurrence of rock extrusion. In conjunction with the field investigation, it has been determined that significant unloading cracks, weathered cracks, and pits persist on the surface of the slope subsequent to rock fall disasters. Hence, it is imperative to take into account the potential hazard of rockfall calamity in slopes lacking mud intercalation, as well as the drainage and reinforcement measures required for the intercalation zone in slopes with mud intercalation.

The prevention and control of rockfall in mountain tourist attractions should take into account both safety and tourism needs. Engineering measures are generally likely to change the original form of rock mass and reduce the ornamental value, so the avoidance measures should be given priority[22]. Due to the slope's proximity to the entrance of the scenic spot, it is not feasible to implement avoidance measures. The presence of vegetation on the slope allows for the implementation of TBS vegetation technology, which involves the insertion of anchor rods into the slope, attachment of galvanized wire mesh to the anchors, and application of a flux-plastic substrate mixture onto the slope. This process facilitates the establishment of a material foundation that supports vegetation growth, thereby enhancing slope stability and promoting ecological restoration[23].

6 Conclusions

(1) The GeoStudio software exhibits a high computational efficiency, providing intuitive outputs for safety factor analysis and potential slip surface identification. On the other hand, the Flac3D software enables the visualization of slope failure mechanisms. The GeoStudio software encounters limitations in obtaining stress, displacement, and other relevant information when stabilizing slopes with high rock strength. Consequently, the resulting stability evaluation of the slope may be biased or incomplete. Hence, in the case of soil slopes or slopes characterized by low rock strength, the utilization of GeoStudio software facilitates the direct computation of the safety factor and identification of potential slip surfaces. To assess the stability of a rock slope characterized by high rock strength, it is recommended to employ the Flac3D software for conducting an analysis based on stress and displacement parameters.

(2) When GeoStudio and Flac3D software are combined to analyze the stability of landslide slope, the extension length of Flac3D model should not be set too long, which can not only reduce the calculation time of software without losing the accuracy of calculation results. Flac3D also complements GeoStudio's lack of a comprehensive view of the slope deformation process. The combined analysis of the two can not only directly and quickly obtain the safety factor and slip plane, but also monitor the force and displacement in the deformation process, predict its development trend, and obtain an objective and comprehensive evaluation of the stability of the slope.

(3) It is important to take into account the presence of muddy interlayer when considering the slope at the entrance of Suichang Gold Mine National Mining Park. In such cases, it is necessary to implement anti-slip reinforcement measures. Conversely, slopes without muddy interlayer should be addressed with anti-rockfall reinforcement measures. The application of TBS vegetation technology serves to enhance the mitigation of rock fall occurrences on slopes, enhance slope stability, and contribute to the restoration of ecological conditions.

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