Journal of Environment and Sustainable Mining Vol.1 No.1 (2023) 69-78

University of Sistan and Baluchestan

Journal of Environment and Sustainable Mining

Available online at http://https://jesm.usb.ac.ir//

JESM

Determination of Shear Strength Parameters Using Back Analysis and Comparing with Physical and Numerical Modeling

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ABSTRACT

Analyzing slope stability is one of the most important issues in civil engineering. Sliding failure is a common mode of instability that may occur in geotechnical projects. In this study, sliding failure is investigated using physical modeling, limit equilibrium, and finite element approaches. Phase2, as software written based on the finite element method (FEM), was used in this research. The GLE method for slope stability analysis, which is the most comprehensive method, has been employed. Three experimental tests were carried out through a tilting table device. The geotechnical properties such as cohesion and internal friction angle were achieved via back analysis. These parameters were obtained at 550 Pa and 28.5 degrees, applying sensitivity analyses, respectively. In the subsequent phase, the compromised slope underwent modeling employing the finite element method (FEM) with Phase2 software, wherein the back-calculated values of shear strength parameters were integrated. The comparison between numerical modeling and physical tests revealed a maximum error of 14 percent, a tolerable margin attributable to the intricacies inherent in the failure mechanism. The results unequivocally indicated that the failure was primarily governed by the shear mechanism. These findings attest to the efficacy of the proposed approach in examining slope stability and recommending investigating stabilization measures.

Article history:
Received: 2022-12-11
Received in revised form: 2023-11-10
Accepted: 2023-11-11
Published online: 2023-11-11

Keywords:
Slope Stability; Back Analysis; Physical Modeling; Numerical Modeling; Finite Element Method.

1 .Introduction

Slope failure is one of the most common natural rock slope disasters that can occur in any geological situation and slope geometries [1-3]. Slope instabilities can contribute to a major hazard for open pit mining and may cause significant loss and casualties [4]. Slides usually occur because of stress field redistribution [5]. Slope stability analysis is usually performed to design a stable slope with a minimizing waste-to-ore ratio. Each rock or soil slope failure can be assumed as an in-situ shear test performed naturally on a field scale. A back analysis is a computational process to understand the failure mechanism and to gather the geotechnical properties and essential information for a mass failure [6]. The results of a back-analyzed rock mass failure are more reliable than the laboratory or in-situ tests influenced by the scale effect. Therefore,

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this method is the most robust approach to evaluating the geotechnical characteristics of failed materials. These parameters may not only be used to redesign a failed slope but also to determine new working/final pit slopes under similar geotechnical conditions [6]. A comprehensive understanding of an instability mechanism is vital for precise back analysis. Generally, stability analyses of rock slopes are divided into two major categories: the first approach can cope with jointed hard rock masses, and the second method is desirable for heavily jointed and weak rocks such as porphyry rock masses [7]. The failure in the first class is more local, and the main structural defects control its mechanism. The main features of these kinds of failures are planar, wedge, and toppling failure mechanisms. In these mechanisms, the failure is governed by discontinuity orientations and the shear strength along the defects [8, 9]. In this category, estimating the rock mass strength is not straight forward, and back analytical approaches can be used to calculate the rock mass in-situ shear strength parameters of discontinuities along the sliding direction [10]. Considering the complexity of this issue, the back analysis of a failed slope can be carried out using the limit equilibrium method (LEM). LEM is applicable for both of the rock mentioned above mass classes. In other words, to utilize LEM for a rock slope in the second class, the discontinuum is assumed as a continuum rock mass [11]. Complex distribution of stress, strain, and failure modes in depth can be investigated by numerical or physical modeling techniques [12-15]. Back analyses of a failed slope can be considered as an in-situ mechanical test providing an accurate estimation of geotechnical parameters of a porphyry rock mass [13]. On the other hand, some methods have been developed based on optimization and sensitivity analyses for probabilistic back analysis of slope failures [16]. The finite element method (FEM) is a numerical method that is most suitable for problems in the continuum and equivalent continuum rock mass. It has been successfully used in slope stability problems [17]. Back analysis has also been used to estimate geotechnical parameters in shield tunneling and deep excavation [18-19].

In this study, parallel studies using the LEM and FEM methods were carried out to investigate the sliding failure. Shear strength parameters such as cohesion and internal friction angle were evaluated. The slope failure mechanism was also studied using Phase2 software as the finite element method.

2. Physical Modeling

Physical modeling is one of the common procedures for investigating the mechanism of instability in geomaterials. The tilting table machine used in this research is shown in Figure 1. In this study, three physical models were made with base friction powder. This powder is a commonly used material to construct physical models and is highly regarded for this research. Amini et al. [20] obtained the density, elasticity modulus, and Poisson ratio equal to 15.5 kg/m3, 3 GPa, and 0.25, respectively.

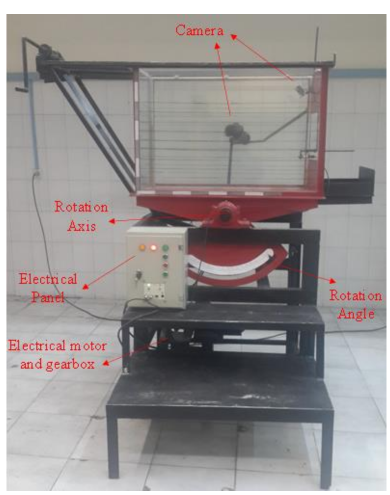

Figure 1- The tilting table apparatus used for physical modeling.

One of the most important and sensitive parameters in slopes is shear parameters such as cohesion and friction angle. These parameters have the greatest impact on slope stability. The back analysis is a useful solution that can be used to estimate the shear parameters of materials. Because the safety factor is equal to one in every slip, it is possible to obtain the initial shear parameters to reach the safety factor of one. For this purpose, physical modelings of sliding failure were performed for each gable height of 20, 24, and 30 cm. Tension cracks appeared in the slope by tilting the model, and a circular sliding occurred in the soil mass. The angle of the tilting table device in three models with a height of 20, 24, and 30 cm was equal to 33, 29, and 26 degrees, respectively. The schematic of the model with a height of 30 cm and pictures of the failure moment of slope at heights of 20, 24, and 30 cm are shown in Figure 2.

Figure 2- a) Schematic model with H=30cm, b) failed model in different heights.

3. LEM Back Analysis

In this study, the LEM and FEM methods were used to back-analyze the mass properties and investigate the slope failure mechanism. Slope failure could be analyzed using the continuum technique. In the first step, the shear strength parameters of the mass were back-calculated using the limit equilibrium method of slices, and sensitivity analyses were conducted. Then, incorporating the back-analyzed mass parameters, the slope failure mechanism was numerically studied through FEM modeling.

To evaluate the shear strength parameters, i.e., cohesion and friction angle, the slope failure was back-analyzed using slide software as the limit equilibrium program. The model was run with the Morgenstern-Price method. The potential failure surface with a safety factor equal to one for the model with a height of 30 cm is shown in Figure 3.

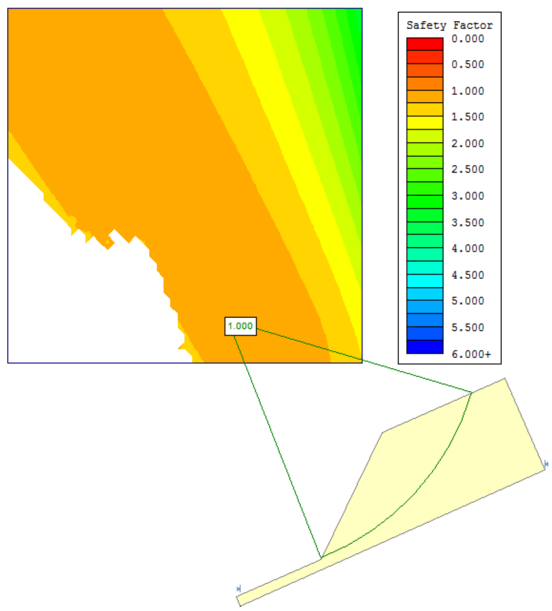

Figure 3- Model with a height of 30 cm in the slide software.

Sensitivity analysis helps researchers to evaluate the impact of an individual unknown variable, assuming that all other slope parameters are known. In this analysis, one parameter changes, and other input parameters are kept constant in their mean values. A sensitivity analysis indicates which input parameter may be critical to the slope stability assessment and which parameter has a smaller effect on the instability. Performing a sensitivity analysis, the cohesion and friction angle of the failure surface were back-analyzed. The results are presented in the form of sensitivity graphs of three physical models in Figure 4 to Figure 6, in which the vertical axis represents the safety factor, and the horizontal axis represents the friction angle.

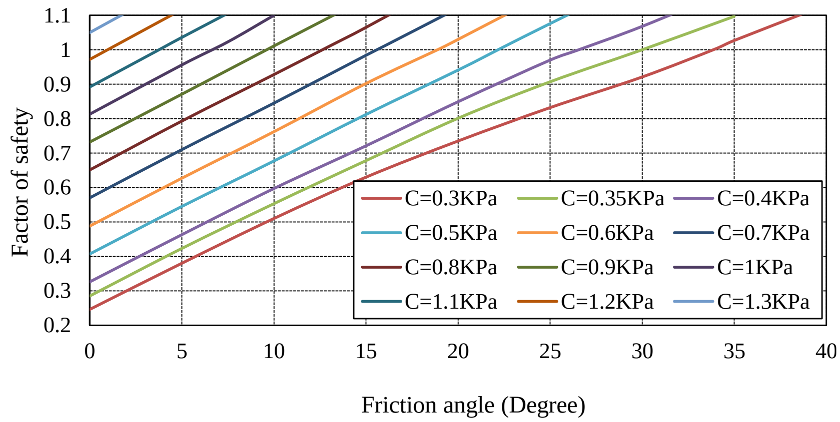

Figure 4- The results of the sensitivity analysis of the model with a height of 20 cm.

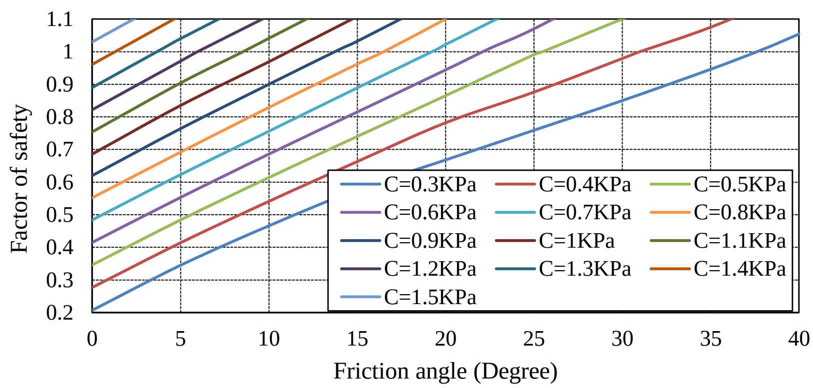

Figure 5- The results of the sensitivity analysis of the model with a height of 24 cm.

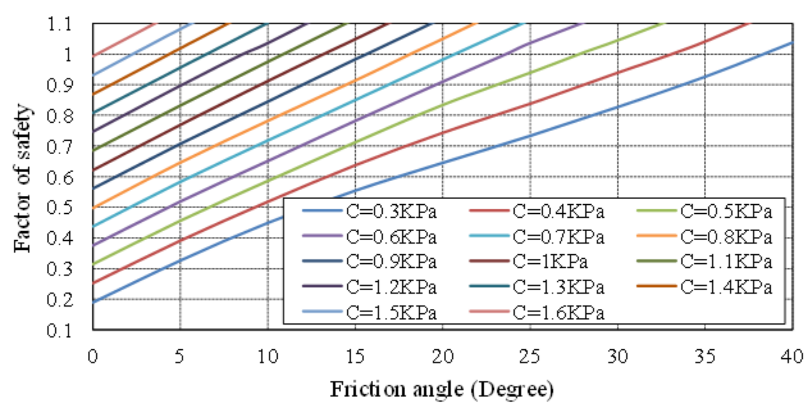

Figure 6- The results of the sensitivity analysis of the model with a height of 30 cm.

As can be seen from Figures 4 to 6, for each model, values of shear parameters leading to sliding failure, i.e., the safety factor of 1, can be found in these diagrams. These values are determined and plotted in Figure 7. As observed, the shear parameters to reach safety factor 1 include a wide range. According to the failure shape and the position of the tensile crack in the physical models, the friction angle is between 22 and 34 degrees, and the cohesion is between 450 and 700 Pa. The mentioned range represents the commonality between the ranges of shear parameter changes in physical models. In Figure 8, these values are plotted against each other. This graph shows that the mean values of the friction angle and cohesion are 28.50, and 550 Pa, respectively.

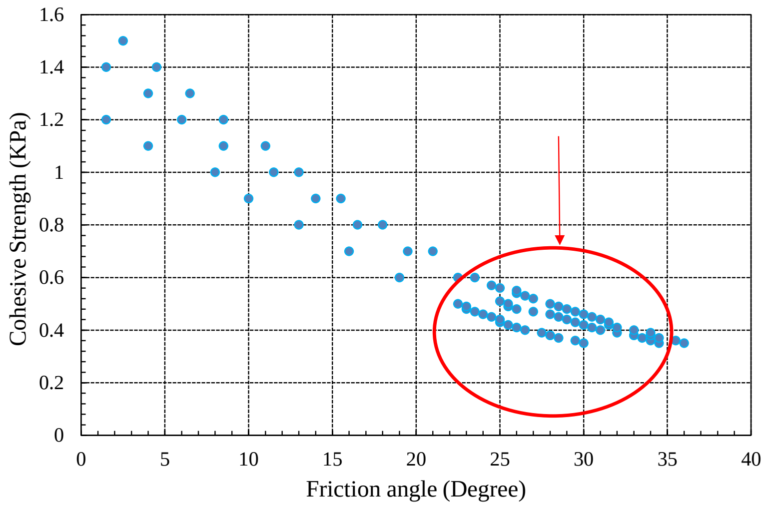

Figure 7- Values of shear parameters for the occurrence of sliding.

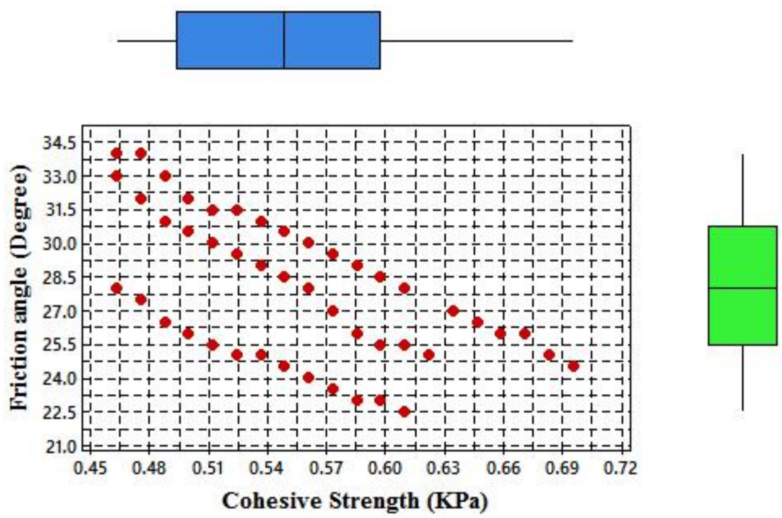

Figure 8- Box plot of shear parameters.

4. Numerical Modeling

In recent years, numerical simulation in rock mechanic problems has been widely accepted and used as a useful tool for the design and stability control of projects. In this paper, the physical model results are simulated using the numerical software of Phase2. Based on the finite element method, this software is a useful tool for analyzing soil and rock slopes and has been used successfully to examine circular failure. The Phase2 software can calculate stress and displacement during the investigation of slope stability and other issues. The safety factor can be used to check the stability of the slope. With regards to the shear failure, the safety factor is defined as shown in Equation (1):

$$FOS = \frac{\tau}{\tau_s} \quad (1)$$

Where τ and τ_s are the shear strength and shear stress on the slip surface, respectively, the shear strength is defined according to the Mohr-Coulomb criterion according to the following equation.

$$\tau = s_0 + \sigma_n \tan \phi \qquad (2)$$

Where s_0 and σ_n are the cohesion and normal stress on the slip surface, and φ is the friction angle. In this method, cohesion and friction angle parameters are continuously reduced to the failure threshold. The stress reduction factor is indicated by SRF. The reduced resistance parameters s_c and φ_c are obtained from equations (3) and (4), respectively.

$$S_c = \frac{S}{SRF} \qquad (3)$$

$$\varphi_c = \tan^{-1}\left(\frac{\tan \varphi}{SRF}\right) \qquad (4)$$

For the numerical modeling, the physical and mechanical properties of the materials should be available, in which; these properties are listed in Table 1. Values of cohesion and friction angle, which were obtained from the limit equilibrium method, were assigned to the model.

Table 1- Physical and mechanical properties of the materials used in the numerical modeling

Unit weight (kN/m^3)	Elasticity modulus (GPa)	Poison ratio	Tensile strength (kPa)	Friction angle (Degree)	Cohesion (Pa)
15.5	3	0.25	0	28.5	550

The Mohr-Coulomb friction law was used in the numerical modeling. The initial geometry of the three models was prepared at the instant of failure in the software. Then the model was analyzed by the shear strength reduction method. Sliding failure in the model with a height of 30 cm is shown in Figure 9. According to this Figure, the stress reduction factor is calculated at 1.

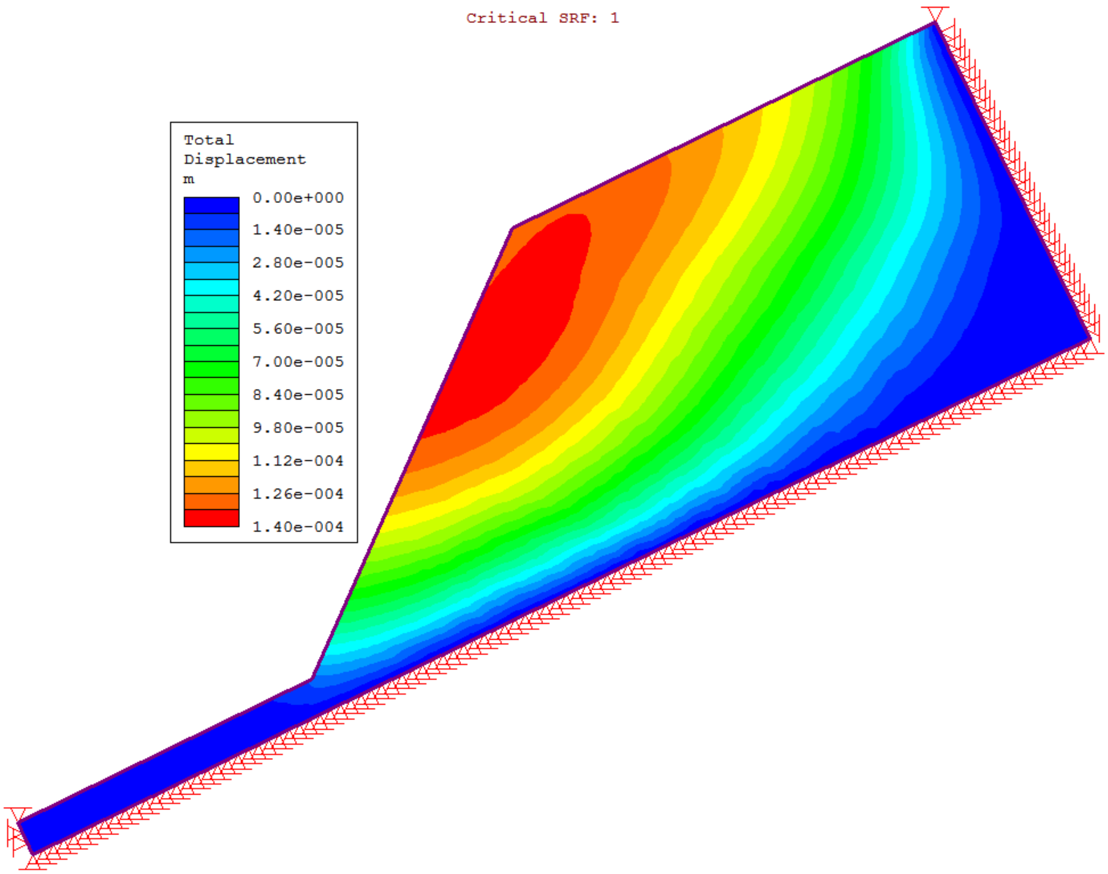

Figure 9- Contours of total displacement in the model with a height of 30 cm.

5. Results and Discussions

In this section, the numerical modeling results are compared with the corresponding physical modeling to validate the accuracy of the numerical simulation and the Phase2 software. Various diagrams and quantities are extracted from the numerical analysis, and the results of physical and numerical modeling are compared. On the other hand, the critical stress reduction factor is the most suitable quantity for comparing these models. It is possible that in numerical methods, this quantity can be assumed to be equivalent to a safety factor [21-23]. Since, at the moment of failure, the safety factor of physical models was equal to one, the critical stress reduction factor of all numerical models should also be equal to one. The safety factor (FS) of the physical model is compared with the stress reduction factor (SRF) of the numerical models in Table 2. The errors between physical and numerical results are less than 14%, which seems reasonable due to the complicacy of the failure mechanism. In which, it can be caused by factors such as the estimation of shear parameters obtained from the back analysis, and plane strain assumption in the numerical analysis, while the side-friction in the physical models violated this assumption. Additionally, the side-friction effect is different in the physical models due to the height.

Table 2- Comparison of numerical modeling results with corresponding physical models.

Models	H=20 cm	H=24 cm	H=30 cm
FS in physical modeling	1	1	1
SRF in numerical modeling	1.14	1.1	1
Error (%)	14	10	0

6. Conclusion

A common mode of slope instability is a sliding failure which may occur in geotechnical projects. In this paper, firstly, this failure is examined using physical modeling. Three experimental tests were conducted through a tilting table device. Subsequently, an innovative approach is introduced, combining the Limit Equilibrium Method (LEM) and Finite Element Method (FEM) for the back-analysis of a failed slope, treating the medium as a continuum. The LEM method is initially employed for sensitivity back analyses of the mass failure, revealing cohesion and friction angle values of 550 Pa and 28.5°, respectively, under failure conditions. The failed slope is further modeled using the FEM method with Phase2 software, incorporating the back-calculated shear strength parameters, and stress reduction factor for three models was obtained. A comparative analysis between numerical modeling and physical tests demonstrates a maximum error of 14%, deemed acceptable considering the inherent complexity of the failure mechanism. The results conclusively attribute the governing role in the failure to the shear mechanism. In light of these findings, the study underscores the robustness of the proposed approach in investigating slope stability and advocating appropriate stabilization measures. Overall, the findings contribute valuable insights into the understanding and analysis of sliding failures in geotechnical contexts.

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