

Analysis of Factors Affecting Slope Stability Based on the Finite Element Strength Reduction Method

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Abstract: This study employs the finite element strength reduction method and ABAQUS software to conduct numerical investigations on the stability of two-dimensional homogeneous soil slopes and their influencing factors. The reliability of the computational model is validated by comparing results with those from the traditional limit equilibrium method. Using the control variable method, the effects of internal friction angle, cohesion, unit weight, elastic modulus, and Poisson's ratio on the slope safety factor are systematically examined. Results indicate that cohesion and internal friction angle exert the most significant influence on slope stability, both exhibiting positive correlations with the safety factor. Soil unit weight moderately affects stability, with the safety factor decreasing as it increases. Elastic modulus and Poisson's ratio have negligible effects on the safety factor. These findings provide theoretical reference for slope engineering stability assessments.

Keywords: Slope Stability; Influencing Factors; Finite Element Analysis; Strength Reduction Method; Numerical Simulation.

1. Introduction

With the rapid development of infrastructure construction in China, slope engineering applications have increased significantly in transportation, civil engineering, and water conservancy sectors. Slope stability directly impacts engineering safety and public life and property security, making a comprehensive analysis of influencing factors crucial for both theoretical and engineering significance [1].

Slope stability is constrained by multiple factors, including topography, geotechnical properties, and groundwater conditions. For embankment slopes, mechanical and geometric parameters such as cohesion, internal friction angle, and unit weight are key internal factors affecting stability. In engineering practice, the safety factor is commonly used as a stability evaluation metric, defined as the ratio of resisting forces to sliding forces on the potential slip plane. A value greater than 1 indicates slope stability, a value of 1 indicates limit equilibrium, and a value less than 1 indicates slope instability.

Among slope stability analysis methods, the limit equilibrium method [2] is widely applied and theoretically mature. Proposed by Swedish scholar Peterson in 1916, this method is based on the strip analysis concept and offers the advantages of simplicity and ease of application. However, the limit equilibrium method assumes soil as a rigid-plastic material, requires predefined slip plane geometry, and cannot reflect internal stress-strain relationships or failure progression within the soil mass, thus exhibiting certain limitations [3,4].

With advances in computer technology and geotechnical theory, numerical analysis methods have emerged as crucial complementary tools. Among these, the strength reduction elastic-plastic finite element method integrates the concept of strength reduction [5] with elastic-plastic finite element theory. It enables simulation of the entire slope failure process without requiring predefined slip surfaces and allows for the acquisition of stress and strain field distributions, demonstrating significant advantages in slope stability analysis [6].

Given the high cost and operational challenges of field

testing, conducting parametric analyses using finite element software like ABAQUS has become a practical research approach. This paper systematically analyzes the influence of parameters such as cohesion, internal friction angle, unit weight, elastic modulus, and Poisson's ratio on slope stability based on the strength reduction method. By setting different strength reduction coefficients as field variables, the development process of the plastic zone can be dynamically displayed, thereby achieving simulation of slope failure mechanisms and comprehensive stability evaluation.

2. Finite Element Strength Reduction Method

2.1. Fundamental Principle of Strength Reduction

In the strength reduction method, the safety factor for slope stability is defined as the ratio of the actual shear strength of the rock-soil mass to the reduced shear strength at critical failure. Based on the Mohr-Coulomb criterion, the key strength parameters in this method are the internal friction angle and cohesion [7]. The core principle of finite element strength reduction involves numerically simulating slope behavior by progressively diminishing these strength parameters. Specifically, the reduction coefficient is incrementally increased through iterative calculations until the slope reaches critical failure. The reduction coefficient employed at this point represents the slope's safety factor [8,9]. The reduction formulas for the internal friction angle and cohesion are as follows [10]:

$$C' = C / K_s \quad (1)$$

$$\varphi' = \arctan(\tan \varphi / K_s) \quad (2)$$

Where: C is the cohesion before strength reduction; φ is the angle of internal friction before strength reduction; C' is the cohesion after strength reduction; φ' is the angle of internal friction after strength reduction; K_s is the reduction factor.

2.2. Selection of Constitutive Models

Constitutive models describe the stress-strain relationship of materials and can be categorized into fundamental types such as elastic, plastic, and viscous, along with their combined forms. These can be further subdivided into various models including linear elastic and hyperelastic.

The Mohr-Coulomb criterion (M-C criterion) is a widely applied strength theory in geotechnical engineering. It reflects

$$f = 1/2I_1 \sin \varphi + (\cos \theta_\sigma - 1/\sqrt{3} \sin \theta_\sigma \sin \theta) \sqrt{J_2} - c \cos \theta \quad (3)$$

Where: I_1 is the first invariant of the stress tensor; J_2 is the second invariant of the stress tensor; θ_σ is the stress Rodotangent; c is the cohesion of the soil; φ is the internal friction angle of the soil.

In this study, ABAQUS was employed for numerical simulation using the extended Mohr-Coulomb criterion and a non-associated flow rule.

2.3. Basis for Slope Instability

Accurately determining whether a slope has reached an unstable state is critical when analyzing slope stability using the finite element strength reduction method. Currently, the commonly used instability criteria primarily include the following three aspects: convergence of numerical calculations; abrupt changes in displacement at characteristic points; and complete penetration of the plastic zone.

This paper primarily adopts numerical calculation non-convergence as the primary criterion for slope instability [11], supplemented by the presence of a fully penetrated plastic zone. In ABAQUS, if calculations fail to converge within the specified iteration limit, it indicates the soil fails to satisfy the

the shear failure behavior of materials under normal stress influence, where yield occurs when the ratio of shear stress to normal stress on a material surface reaches its limit. The parameters of this criterion possess clear physical significance, effectively simulating the shear response of granular materials under monotonic loading and accurately reflecting the actual yield characteristics of geomaterials. Its expression is:

constitutive relationship and overall equilibrium, thus confirming failure. Simultaneously, observing the plastic strain contour map, if a continuous plastic zone extends from the toe to the crest of the slope, it also confirms slope instability.

3. Stability Analysis of a Two-Dimensional Homogeneous Soil Slope

3.1. Problem Description: and Model Development

This study employs a homogeneous soil slope case analyzed by Dawson et al. and validated by multiple scholars (e.g., using FLAC) [12] to examine the reliability of ABAQUS's strength reduction method. This homogeneous slope has a height $H = 10$ m and a slope angle $\beta = 45^\circ$, with a safety factor of 1.0 obtained via the limit equilibrium method. The specific soil parameters are shown in Table 1, and the schematic diagram of the slope model is shown in Fig. 1.

Table 1. Soil Basic Parameters

Soil Unit Weight $\gamma / KN \cdot m^{-3}$	Internal friction angle $\varphi / (^\circ)$	Cohesion c / Kpa	Modulus of elasticity E / Mpa	Poisson's Ratio μ	Shear expansion angle $\psi / (^\circ)$
20	20	12.38	100	0.35	0

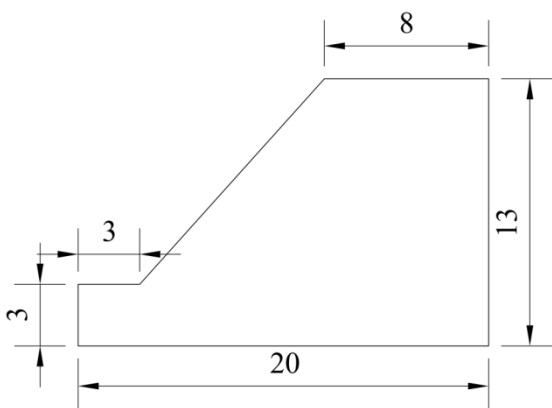


Fig 1. Schematic Diagram of Slope Calculation Model

3.2. Reduction Calculation of Parameters

To apply strength reduction in ABAQUS, the variation of internal friction angle and cohesion values with field variables must be specified. Both the plastic and viscous zones set the field variable to 1. Here, the field variable is defined as the strength reduction coefficient (or safety factor), varying

between 0.5 and 2. The reduced internal friction angle and cohesion values are shown in Table 2.

3.3. Result Analysis

3.3.1. Safety Factor

Fig. 2 shows the contour plot of the slope safety factor (FV1) on the undeformed model. As shown in the figure, the slope safety factor at the end of the calculation is 1.058.

Using the combine function provided by ABAQUS, the curve of FV1 versus U1 is plotted as shown in Fig. 3. Analysis indicates: First, if numerical convergence is used as the criterion for slope stability, the corresponding safety factor is approximately 1.06. Additionally, a distinct inflection point is observed in the curve. If displacement inflection is used as the criterion, the safety factor at this point is 0.99. Both values are very close to the safety factor of 1.0 obtained from the limit equilibrium method, demonstrating the feasibility of this example.

Table 2. Calculated Values for Reduced Internal Friction Angle and Cohesion

Initial Internal Friction Angle $\phi / (^\circ)$	Reduced Internal Friction Angle $\phi / (^\circ)$	Shear expansion angle $\psi / (^\circ)$	Initial Cohesion c / Kpa	Reduced Cohesion c / Kpa	Plastic strain	Reduction factor
20	36.0524	0	12.38	24.76	0	0.5
20	25.887	0	12.38	16.50667	0	0.75
20	20	0	12.38	12.38	0	1
20	16.2343	0	12.38	9.904	0	1.25
20	13.639	0	12.38	8.253333	0	1.5
20	11.749	0	12.38	7.074286	0	1.75
20	10.3141	0	12.38	6.19	0	2

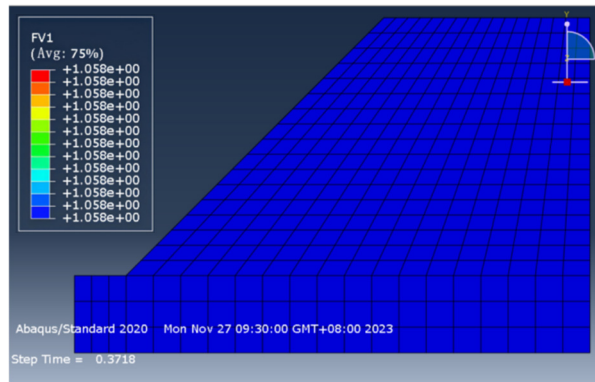


Fig 2. Contour Map of Slope Safety Factor

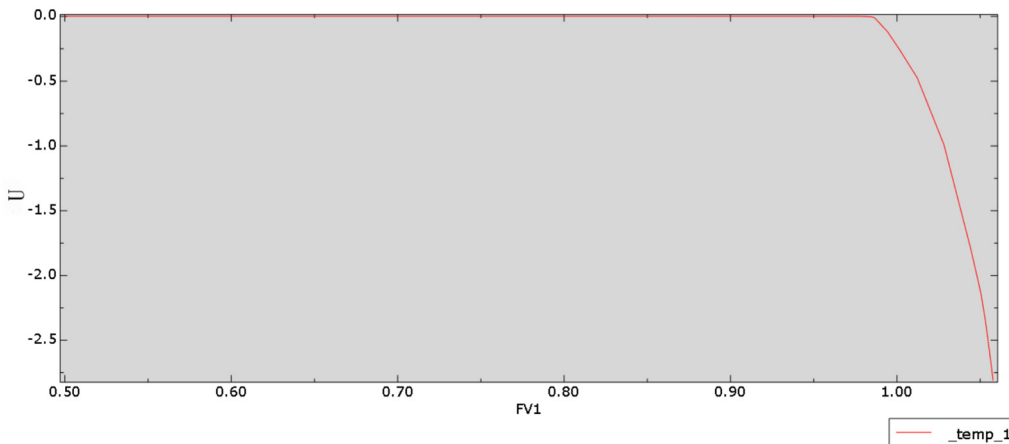


Fig 3. FV1 versus U1

3.3.2. Plastic Strain and Slip Surface Analysis

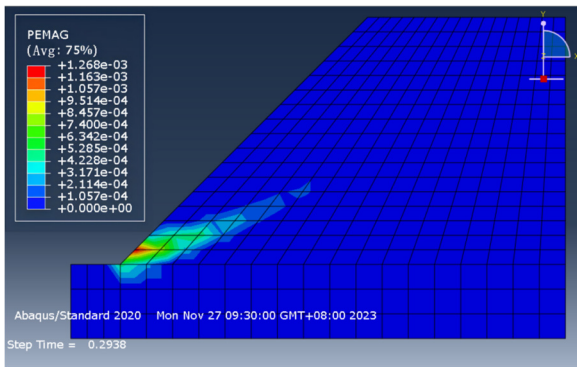
Plots of the PEMAG (plastic strain) contour maps at $t=0.2938$ and $t=0.3213$ during the reduction analysis step are presented. Fig. 4 visually traces the evolution of the slope's plastic zone: originating at the toe, it subsequently expands upward, ultimately forming a continuous zone at $t=0.3213$ with a safety factor of 0.98. This result closely aligns with the safety factor obtained via the displacement inflection point method. The location of the slope's slip surface is shown in Fig. 5. Its morphology matches the limit equilibrium method results, both exhibiting an approximate circular arc passing through the toe point.

4. Analysis of Factors Affecting Slope Stability

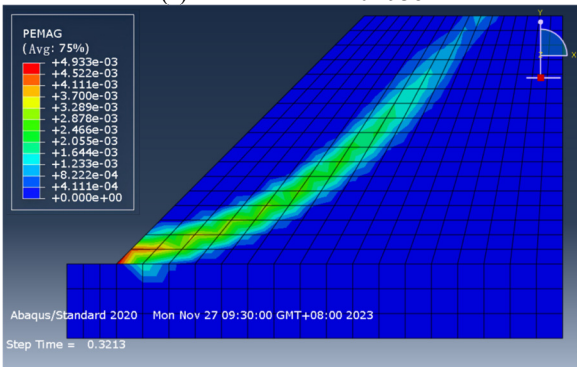
To investigate the impact of different soil parameters on slope stability, this study employs the control variable method. By fixing all other influencing factors and varying a single parameter by a fixed multiple, the effect of this single factor on slope stability is simulated.

This study systematically adjusted the values of internal friction angle, cohesion, unit weight, elastic modulus, and Poisson's ratio. Each parameter was multiplied by 0.4, 0.6, 0.8, 1.0, 1.2, and 1.4 times the initial values listed in Table 2, and

calculations were performed in ABAQUS. Ultimately, based on the computational results, relationship curves depicting the variation of the safety factor with different multiples of soil parameters were plotted, as shown in Fig. 6.



(a) Plastic zone at t=0.2938



(b) Plastic zone at t=0.3213

Fig 4. Plastic strain distribution of the slope

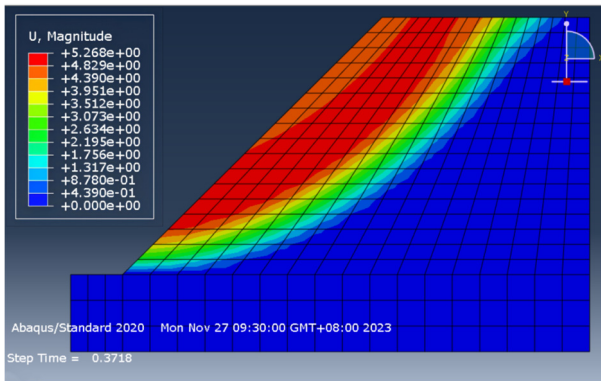
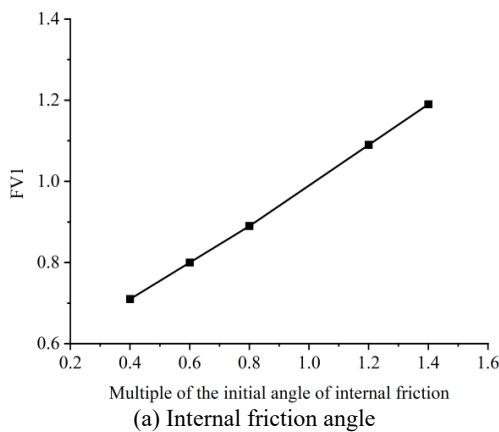
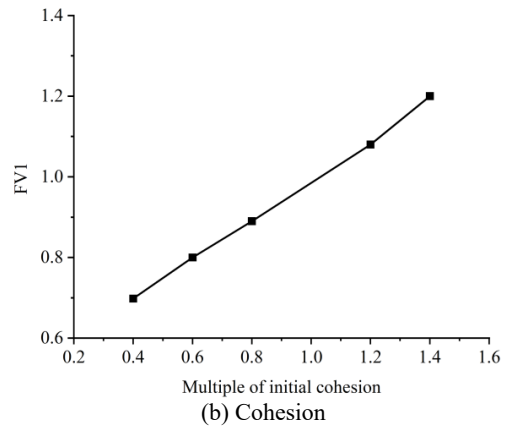


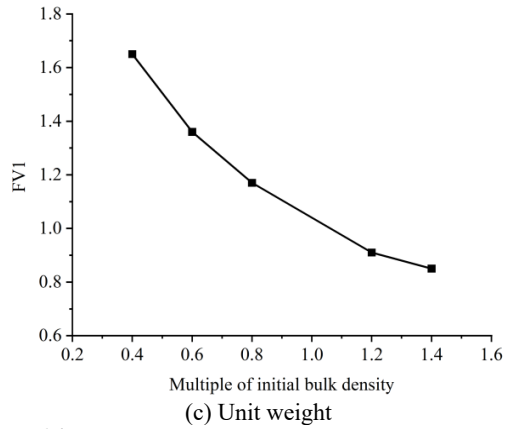
Fig 5. Displacement contour map of the slope



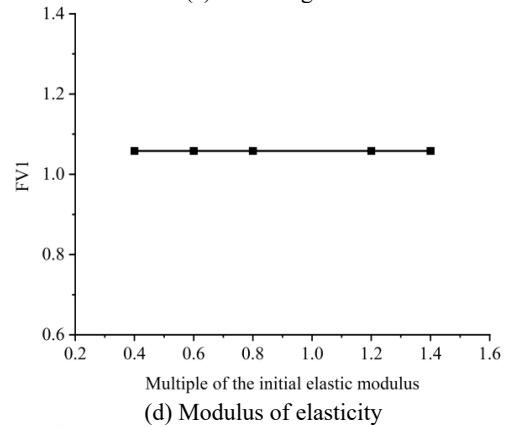
(a) Internal friction angle



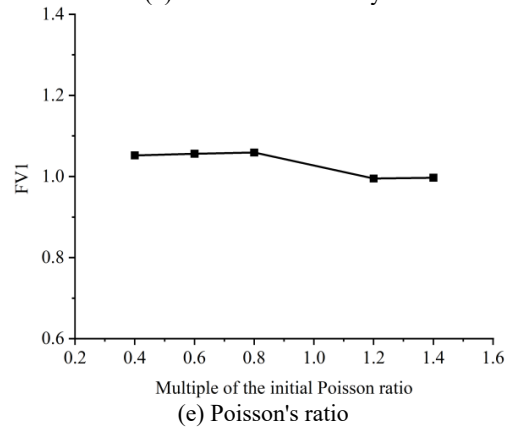
(b) Cohesion



(c) Unit weight



(d) Modulus of elasticity



(e) Poisson's ratio

Fig 6. Variation curves of safety factor with different soil parameters

The internal friction angle is a key indicator of shear strength in geotechnical engineering. As shown in Fig. 6(a), the slope safety factor increases nearly linearly with the internal friction angle. For every 1° increase in the internal friction angle, the safety factor rises by approximately 0.024

on average. This significant positive correlation stems from the direct influence of the internal friction angle on soil shear strength—a higher internal friction angle corresponds to greater shear strength and improved slope stability.

Cohesion, a crucial parameter reflecting the adhesive and binding forces between soil particles, exhibits a similar trend to the angle of internal friction. As shown in Fig. 6(b), cohesion also demonstrates a positive correlation with the safety factor. When cohesion increases from 0.4 times its initial value (4.952 kPa) to 1.4 times (17.332 kPa), the safety factor improves by 0.5326, transforming the slope from an unstable to a stable state. This demonstrates cohesion's significant influence on stability.

Unlike the aforementioned strength parameters, soil bulk density exerts a negative influence on stability. Fig. 6(c) shows that the safety factor gradually decreases with increasing bulk density. This occurs because higher bulk density increases the slope's self-weight, thereby amplifying the downward force and compromising overall stability.

As a characteristic of soil elastic deformation, changes in elastic modulus show no significant effect on the safety factor. Fig. 6(d) indicates that the safety factor remains largely unaffected by variations in elastic modulus. This occurs because elastic modulus primarily influences the deformation field, whereas the safety factor is defined as the ratio of resisting force to sliding force, relating solely to the stress field. Consequently, no direct dependency exists between the two.

The Poisson's ratio also exhibits negligible influence on the safety factor. Fig. 6(e) demonstrates that its variation does not induce significant changes in the safety factor, which remains stable near 1.0. However, computational contour plots further reveal that the Poisson's ratio regulates the extent of the plastic zone: a higher Poisson's ratio results in a smaller plastic zone, reflecting its potential impact on soil stress distribution and yield development.

5. Conclusion and Outlook

Based on a given case study and utilizing ABAQUS software, this paper analyzes the stability of a two-dimensional homogeneous soil slope through the finite element strength reduction method. The analysis focuses on the safety factor, distribution of the plastic zone, and morphology of the slip surface, investigating the influence patterns of various factors. The following conclusions are drawn:

(1) Cohesion and internal friction angle exert the most significant influence on slope stability, both exhibiting positive correlations with the safety factor, with cohesion having a slightly greater impact than internal friction angle. Therefore, enhancing soil strength can improve slope stability in engineering applications.

(2) The influence of soil unit weight on slope stability is moderate, with the safety factor decreasing as unit weight increases. Consequently, in practical engineering, embankment fill material should be selected based on reasonable unit weight determination through testing.

(3) The elastic modulus and Poisson's ratio exert negligible influence on the safety factor. However, Poisson's ratio significantly regulates the distribution of the plastic zone: a higher Poisson's ratio results in a smaller plastic zone.

(4) The application of the strength reduction method in ABAQUS overcomes the limitation of traditional limit equilibrium methods requiring predefined slip planes. It accurately reflects the internal stress-strain field and the entire failure process of the soil, enabling precise calculation of slope safety factors under various conditions.

This study is confined to two-dimensional homogeneous slopes under plane strain conditions. The applicability of the conclusions to three-dimensional slopes requires further verification. Additionally, the analysis considers only the influence of soil parameters, excluding practical environmental factors such as temperature, groundwater, adjacent loads, and seismic effects. It also does not account for the impact of time effects in short-term and long-term strength reduction processes. Future research may explore these aspects further.

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