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Analysis of Slope Stability in Construction

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ABSTRACT: This paper aims to systematically analyze multiple critical factors influencing slope stability, particularly the interrelationship among pore pressure, evolution of material properties, and the factor of safety (FOS). By establishing a finite element model, an in-depth investigation into slope sliding behavior was conducted, leading to the following conclusions: (1) When the factor of safety (FOS) reaches 1.9, the slope exhibits non-convergence, indicating the onset of instability, which highlights the necessity of particular attention to stability during the design process under critical conditions; (2) The non-uniform distribution of pore pressure and the presence of unsaturated soil layers significantly impact slope stability. This is particularly critical in the toe region, where sliding phenomena are notably severe and warrant close scrutiny; (3) The study reveals a nonlinear relationship between maximum slope displacement and FOS, especially as values approach the limit, characterized by a sharp decline in stability. The findings provide crucial data support and theoretical guidance for slope design, reinforcement measures, groundwater management strategies, and the development of monitoring systems in hazardous areas.

KEYWORDS: slope stability; factor of safety; unsaturated soils; nonlinearities; building slopes

I. INTRODUCTION

The stability of building slopes is a widely discussed issue in the field of civil engineering. Particularly, with the ongoing process of urbanization, an increasing number of civil engineering projects rely on the safety of slope structures to ensure the overall stability of buildings^[1]. In recent years, methods for analyzing slope stability have become more diversified, evolving from traditional limit equilibrium methods to modern numerical simulation techniques, such as finite element analysis, which have become practical tools^[2,3]. Despite the extensive body of research dedicated to the analysis of slope stability, systematic studies that focus on the coupled analysis of factors such as pore pressure within soil, evolution of material properties, and safety factors remain relatively scarce^[4].

This study aims to investigate the elastoplastic behavior of slopes under the influence of gravity and hydrostatic pressure through finite element modeling, with a particular focus on the impact of safety factors and the evolution of material properties on slope stability. In the context of building slope stability, pore water pressure is a critical factor affecting soil strength^[5]. Darcy's law is extensively used to describe the hydraulic dynamics within soil; however, its significant impact on slope stability analysis is often overlooked^[6]. Additionally, research on the evolution of material properties based on safety factors (FOS) has not received adequate attention, and its implications may lead to slope instability under specific loading conditions, thereby affecting the corresponding structural safety^[7]. Therefore, this study will establish a two-dimensional model using finite element analysis methods, incorporating elastoplastic theory and the Mohr-Coulomb criterion, and apply Darcy's law to describe the hydraulic dynamics within the soil. The impact of changes in FOS on slope stability will be studied through numerical simulations, thereby deepening our understanding of the mechanisms of slope failure.

II. FINITE ELEMENT MODELING OF BUILDING SLOPES AND PLASTICITY CRITERIA

The plastic potential of the building slope is described using the Mohr-Coulomb yield function^[3]

$$F = m\sqrt{J_2} + \alpha I_1 - k \quad (1)$$

Among them, $\alpha = \frac{\sin \Phi}{3}$, $k = C \cos \Phi$

Parametric characterization of cohesion C and friction angle Φ is conducted as follows:

$$C = \frac{c}{FOS}, \Phi = \left(\frac{\tan \varphi_u}{FOS} \right) (P < 0) + \arctan \left(\frac{\tan \varphi_s}{FOS} \right) (P \geq 0) \quad (2)$$

where c represents the cohesion of the material, φ_u and φ_s denote the friction angles for unsaturated soil and saturated soil, respectively, and p indicates the pore pressure as given by Darcy's law.

This study employed COMSOL Multiphysics finite element analysis to model the aforementioned problem. The dimensions of the model, boundary conditions, and meshing are illustrated in Figure 1, while the computational parameters are provided in Table 1.

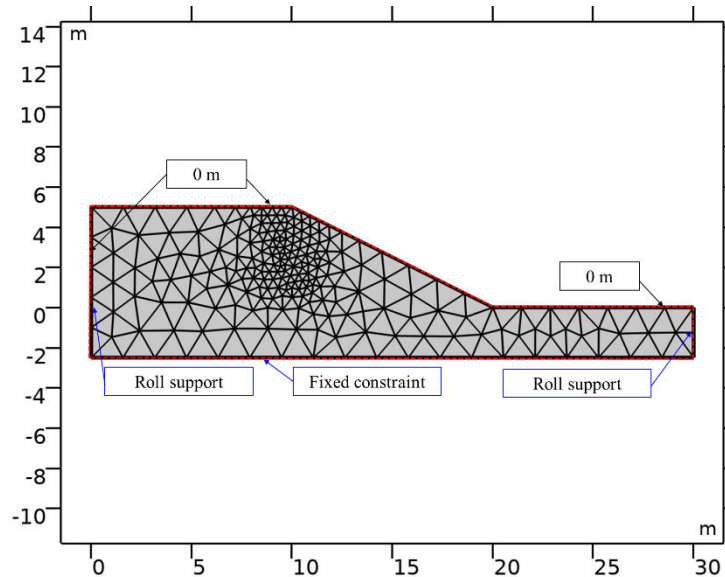


Figure 1 Illustrates the geometric dimensions of the model, boundary conditions, and meshing.

Table 1 Presents the detailed computational parameters.

Name	Symbolic	Value
underground water level /m	H_w	4
Young's modulus /MPa	E	100
Poisson's ratio	μ	0.3
soil density /(kg/m ³)	ρ_{soil}	2000
water density /(kg/m ³)	ρ_w	1000
porosity	φ	0.3
cohesion /kPa	c	10
Friction angle of saturated soil /(°)	φ_{sat}	30
Friction angle of unsaturated soil /(°)	φ_{un}	20

III. RESULTS AND DISCUSSION

The results obtained from the calculations for various safety factors (FOS) are presented, with the computation beginning to show non-convergence when $FOS = 1.9$, indicating the onset of slope instability. Figures 2 through 6 illustrate the outcomes for $FOS = 1.9$. The pore pressure distribution is shown in Figure 2, which indicates that the pore pressures range from -7.7 to 60 kPa along the height dimension, forming a non-uniform pressure gradient. This distribution suggests groundwater seepage from high-head areas to low-head areas, reflecting the dynamic migration of

moisture within the slope and the wetting state of the soil. The negative values of pore pressure are particularly significant as they indicate the presence of an unsaturated soil layer at the top of the slope, which may significantly affect the overall stability of the slope. The existence of this unsaturated soil layer can lead to different shear strengths and their variations. This can be observed in Figure 3, where the hydraulic conductivity of the unsaturated soil layer is relatively small.

Figure 4 illustrates the slip surface of the slope when FOS = 1.9, with arrows indicating the direction of displacement of soil particles. Due to the fixed constraint at the bottom boundary of the slope, the soil mass in the lower right corner does not exhibit sliding; instead, the sliding primarily occurs near the slope face, especially at the toe of the slope, where it is most severe. Detailed information can be further examined in Figure 5, which shows distinct plastic zones in the soil, with the highest value reaching 0.0144 at the toe of the slope. The maximum displacement observed at this time was 27.2 mm, as depicted in Figure 6. This result underscores the necessity of considering these risk-prone areas more carefully in slope design.

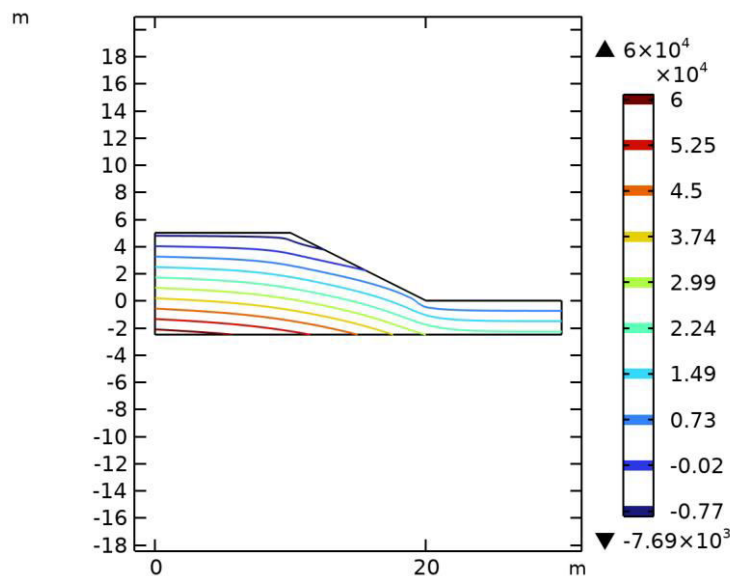


Figure 2 Pressure distribution (Pa)

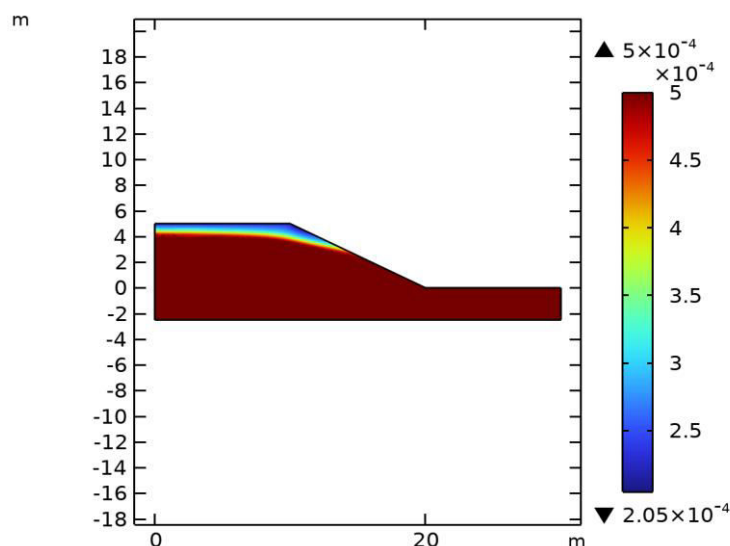


Figure 3 Hydraulic conductivity (m/s)

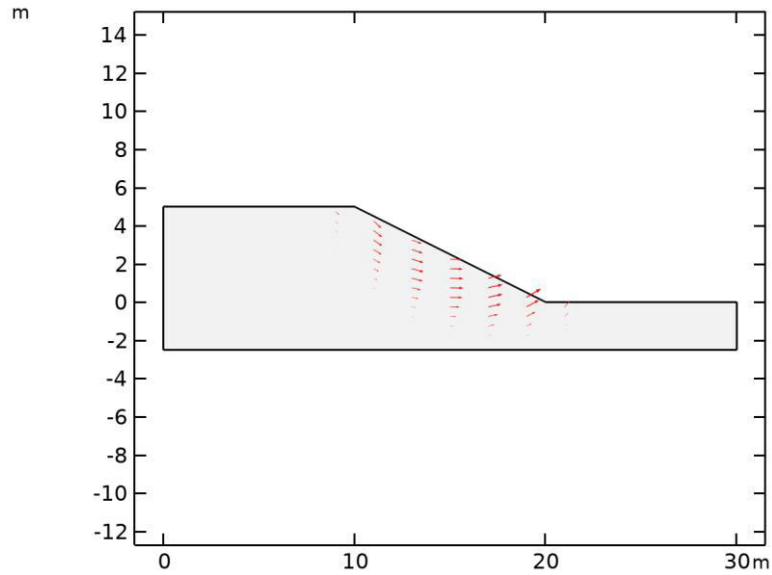


Figure 4 Slip surface

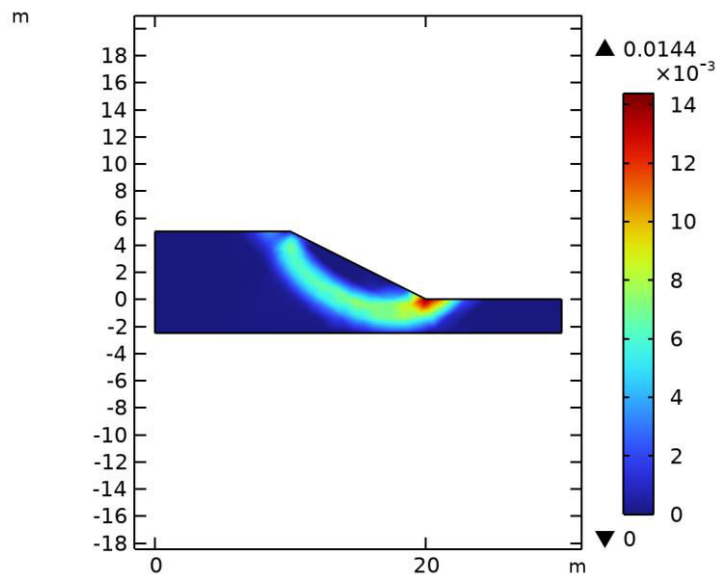


Figure 5 Equivalent plastic strain

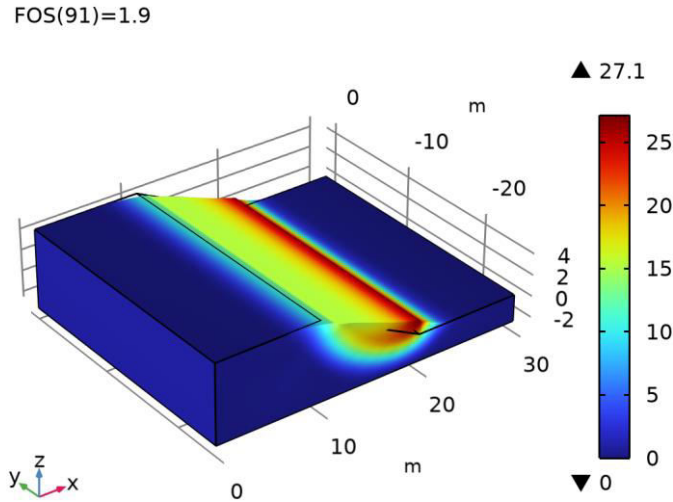


Figure 6 Displacement (mm)

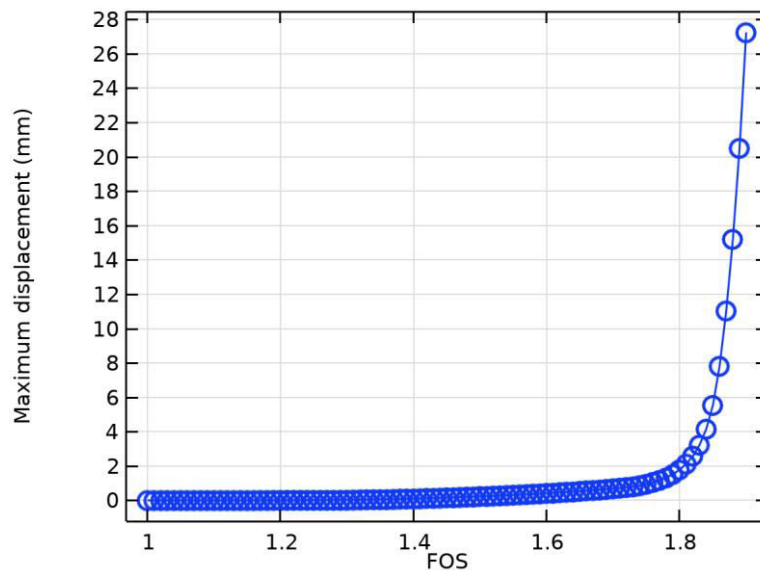


Figure 7 Relationship between maximum displacement and safety factor FOS

Figure 7 illustrates the variation in the maximum displacement of the slope for different values of FOS (Factor of Safety). It can be observed that the maximum displacement of the slope increases nonlinearly with an increase in FOS. When FOS = 1.0, the maximum displacement is almost zero. At FOS = 1.4, the maximum displacement is only 0.1 mm. When FOS = 1.76, the maximum displacement reaches 1.1 mm. As FOS increases to 1.87, the maximum displacement significantly increases to 11 mm, indicating a rapid decline in slope stability, followed by even greater displacements. When FOS = 1.9, the maximum displacement reaches its limit value of 27.1 mm. This nonlinear relationship suggests that as the safety factor FOS increases, the change in displacement of the slope is not a simple linear growth but rather exhibits a sharp increase after a critical point, leading to a rapid decline in slope stability.

IV. CONCLUSION

This study employs a finite element model to systematically analyze the interrelationships among pore pressure, material property evolution, and the factor of safety (FOS), particularly focusing on their specific manifestations in slope sliding behavior. The following conclusions have been drawn:

- (1) When the safety factor FOS reaches 1.9, the slope exhibits non-convergence phenomena, marking the onset of instability. This highlights the need to focus on stability under critical FOS conditions.
 - (2) The non-uniform distribution of pore pressure and the presence of unsaturated soil layers significantly impact slope stability, especially in the toe region where major sliding occurs.
 - (3) There is a nonlinear relationship between the maximum displacement of the slope and FOS, particularly near the limit value, where stability rapidly declines. This provides crucial data support for design and monitoring purposes.
- The research findings can guide civil engineering design schemes, including slope reinforcement measures, groundwater management strategies, and the development of hazard zone monitoring systems.

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