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Study on the Seepage Stability of Dam Slope based on Advanced Fluid Mechanics

Zhang Zhenyu, Cao Zhengzheng*, Lin Haixiao, Wang Wenzhen
School of Civil Engineering, Henan Polytechnic University, Jiaozuo 454003, Henan, China
**Corresponding Author*

Abstract: In dam engineering, slope stability analysis is crucial for determining the safety of the structure. This study conducts a numerical simulation of dam slope stability using the COMSOL Multiphysics platform, employing an elastoplastic finite element analysis. By incorporating the Strength Reduction Method (SRM) and the Mohr-Coulomb yield criterion, a two-dimensional plane strain model of the dam is established to account for the coupled effects of seepage and stress fields. The study systematically investigates the influence mechanisms of pore water pressure distribution, plastic strain evolution, and safety factor thresholds on slope failure. The results indicate that when the factor of safety (FOS) drops to 1.6, the elastoplastic analysis fails to converge due to the accumulation of plastic strain and the degradation of shear strength, suggesting that the dam is in a critical state of failure. Therefore, FOS = 1.6 can be regarded as the threshold for the dam slope stability analysis. The pressure head distribution (0–10 m) reveals the significant influence of the phreatic surface position on the mechanical behavior of saturated and unsaturated soil zones. The presence of pore water pressure in saturated soils accelerates the development of plastic strain, making it a key factor in triggering instability. The distribution of equivalent plastic strain shows a progressive expansion of the plastic zone prior to failure, indicating the formation of a potential slip surface. Displacement field analysis reveals shear sliding of the soil along the slip surface; however, due to the fixed constraint at the lower boundary, the displacement of the soil in the lower right corner is limited, confirming the rationality of the model’s boundary conditions.
Keywords: slope stability; numerical simulation; strength reduction method; safety factor

I. Introduction

Slope stability is one of the core topics in geotechnical engineering, geological engineering and environmental engineering. With the acceleration of global industrialization and the continuous expansion of infrastructure construction, human engineering activities have increasingly disturbed the natural geological environment. Highways, railways, water conservancy and hydropower projects, mining and urban construction frequently involve the excavation and filling of steep slopes. Complex geological conditions (such as faults, weak interlayers, and development of joints and fissures), hydrological effects (rainfall infiltration, groundwater changes), and natural factors such as earthquakes and freeze-thaw cycles can easily cause slope instability. In recent years, geological disasters such as landslides and collapses have occurred frequently around the world, such as the Vajont landslide in Italy and the landslide group in the Three Gorges Reservoir area of China [1]. These major disasters have not only caused huge economic losses, but also threatened people's lives and the ecological environment. Although traditional slope stability analysis methods (such as the limit equilibrium method [2] and rigid body sliding theory) are relatively mature, they still have limitations when dealing with heterogeneous materials, complex boundary conditions and multi-field coupling. With the development of computer technology, the rise of numerical simulation methods (finite element method, discrete element method, fluid-solid coupling analysis) and intelligent monitoring technology (InSAR, Beidou displacement monitoring, fiber optic sensing) has provided new technical means for slope stability research. Zhao Zhiyun et al. conducted a slope stability analysis of the Shenyan Xiwan open-pit coal mine based on numerical simulation [3]. With the increase of extreme rainfall events under the background of climate change, Liu Yuxiang conducted a study on the impact of vegetation planting on the stability of reservoir slopes under rainfall [4]. The extension of human engineering activities to deep and high-stress areas further highlights the urgency of slope stability research.

Foreign slope stability research began in the early 20th century, and the early limit equilibrium theory was dominant. In the 1950s, Fellenius proposed the circular arc sliding method[5], which was later improved by Bishop, Morgenstern-Price and others to form the classic limit equilibrium method system[6]. In the 1970s, the strength reduction method (SRM) [7] was proposed as a stability evaluation method based on numerical analysis. Zienkiewicz et al. first introduced the concept of strength reduction into finite element analysis. By gradually reducing the shear strength parameters (c, φ) of the rock mass until the slope reaches a critical instability state, the safety factor is determined. At the end of the 20th century, numerical simulation methods gradually matured. For example, Cundall proposed the discrete element method (DEM) and developed the PFC software. Itasca launched the FLAC and FLAC3D software. FLAC3D has a built-in strength reduction method module, which has become a standardized tool for slope stability analysis. In recent years, the strength reduction method has been combined with the multi-field coupling model to further expand its application scenarios.

Domestic research started late but has developed rapidly. The team of Academician Chen Zuyu proposed a generalized solution of the strict limit equilibrium method, which significantly improved the calculation accuracy of non-circular sliding surfaces [8]. In the field of numerical simulation, the strength reduction method has been widely used and improved. The team led by Academician Zheng Yingren systematically demonstrated the applicability of the finite element strength reduction method and proposed to use the plastic zone penetration and displacement mutation as the instability criterion, solving the problem of the traditional limit equilibrium method's dependence on the sliding surface assumption [9]. In terms of numerical simulation, the team led by Zhu Hehua of Tongji University developed GeoFBA3D software, which supports the coupled analysis of the strength reduction method and three-dimensional geological model; China University of Mining and Technology used the RFPA (Real Fracture Process Analysis) model to reveal the instability mechanism of jointed rock mass [10]. In recent years, domestic scholars have combined the strength reduction method with machine learning, such as Liu Jianyu's research on slope stability analysis and prevention measures based on the strength reduction method and neural network [11]. In order to solve the problem of embankment slope stability, the author used the strength reduction method and conducted numerical simulation through COMSO to study the relationship between the safety factor (FOS) and the stability of the dam body when the elastic-plastic analysis adopts the Mohr-Coulomb criterion.

II. Theoretical basis

The Mohr–Coulomb yield function and associated plastic potential is[12]

$$F = Q = m\sqrt{J_2} + \alpha I_1 - k$$

Where

$$\alpha = \frac{\sin\phi}{3}, \quad k = C\cos\phi$$

The parameterized cohesion C and angle of internal friction Φ are given as

$$C = \frac{c}{FOS}, \Phi = \mathrm{atan}\frac{\tan\phi_u}{\mathrm{FOS}}(p < 0) + atan\frac{tan\phi_s}{FOS}(p \geq 0)$$

Where c is the material cohesion, ϕ_u and ϕ_s are angles of internal friction for unsaturated and saturated soils, and p is the pore pressure given by Darcy's law.

Darcy's law is the core equation describing the low-speed flow of fluids in porous media. It was first proposed by French engineer Henry Darcy through sand column seepage experiments in 1856. This law reveals the linear relationship between seepage velocity and hydraulic gradient, and lays a theoretical foundation for quantitative analysis in fields such as groundwater flow, reservoir engineering and soil seepage.

The integral form of Darcy's law can be expressed as:

$$Q = -K \cdot A \cdot \frac{\Delta h}{L}$$

where：

Q is the volume flow rate (unit:m^3/s）

K is the permeability coefficient of the medium (unit: m/s), which is related to the fluid properties (viscosity, density) and pore structure;

A is the cross-sectional area perpendicular to the flow direction (unit: m^2);

Δh is the head difference along the flow path (unit: m);

L is the flow path length (unit: m).

In differential form, Darcy's law can be generalized to vector form:

$$q = -K\nabla h$$

where：

q is the Darcy velocity (unit: m/s), defined as the volume flow rate of the fluid through a unit area;

∇h is the hydraulic gradient (dimensionless), which represents the change in hydraulic head per unit length.

The permeability coefficient K can be further decomposed by the following formula:

$$K = \frac{k\rho g}{\mu}$$

Where:

K is the intrinsic permeability of the medium (unit: m^2), which depends only on the pore structure;
ρ is the fluid density (unit: kg/m^3);
μ is the fluid dynamic viscosity (unit: Pa · s);
g is the acceleration due to gravity (unit: m/s^2).

Darcy's law essentially reflects the energy conservation principle of fluid flow in porous media. The head difference Δh drives the fluid movement, while the permeability coefficient K represents the medium's resistance to flow. This law can be regarded as a simplified form of the linear momentum equation under low Reynolds number conditions, and its microscopic mechanism can be derived by averaging the Navier-Stokes equation at the pore scale.

III. Numerical simulation of dam slope stability

Figure 1 is a schematic diagram of the embankment. The embankment length (left) L1, embankment length (top) L2 and embankment length (right) L3 are 15 m, 5 m and 25 m respectively, and the embankment height L4 is 15 m . The water level Hw is 10 m and the possible seepage height Hs is 5 m.

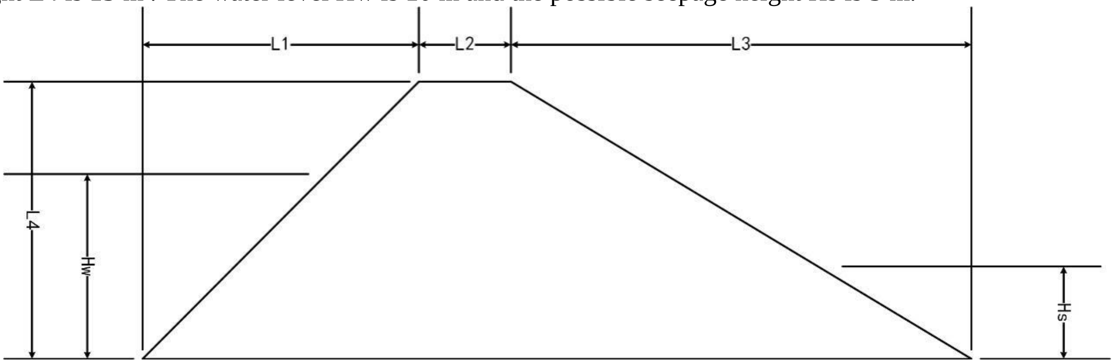

Figure 1: Illustration of the embankment dam

The embankment parameters are shown in Table 1. The total width of the embankment is L1+L2+L3. In order to avoid boundary effects, a soil domain is added below the embankment (not shown in Figure 1).

Table 1: Dam Model Parameters

Name	Expression	Value	Description
L1	15[m]	15 m	Length of dam (left)
L2	5[m]	5 m	Length of dam (top)
L3	25[m]	25 m	Length of dam (right)
L4	15[m]	15 m	Dam height
Hw	10[m]	10 m	Water Level
Hs	5[m]	5 m	Possible seepage sites

Physics adds solid mechanics and Darcy's law for fluid-structure interaction. The dam is modeled in 2D using the plane strain approximation. The effects of gravity and hydrostatic pressure are also included.

The Young's modulus of the dam is 100 MPa, the Poisson's ratio is 0.4, the soil density is 2000 m^3kg/ , the water density is 1000 kg/m^3, the porosity is set to 0.3, the cohesion is 25 kPa, the saturated soil friction angle is 0.5236 rad, and the unsaturated soil friction angle is 0.34907 rad. The material parameters are shown in Table 2

Table 2: Definition of Material Parameters

Name	Expression	Value	Description
E_soil	100[MPa]	1E8 Pa	Young's modulus
nu_soil	0.4	0.4	Poisson's ratio
rho_soil	2000[kg/m^3]	2000 kg/m³	Soil density
rho_wat	1000[kg/m^3]	1000 kg/m³	Water density
psi	0.3[1]	0.3	Porosity
c	25[kPa]	25000 Pa	Cohesion
phi_sat	30[deg]	0.5236 rad	Friction angle of saturated soil
phi_un	20[deg]	0.34907 rad	Friction angle of unsaturated soil

Add pressure heads to the underwater parts on the downstream and upstream sides of the dam. Set the edge of the dam body that touches the water level on the left side to Pressure Head 1, and the right boundary to Pressure Head 2 and 3. Add the water pressure as a boundary load on the downstream side of the dam. Set the bottom to Fixed Constraint and the two sides to Roller Support.

IV. Simulation Results

The pressure head of the dam is shown in Figure 2; it varies from 0 to 10 m on the submerged wall and is 0 m on the seepage surface. A positive pressure head indicates positive pore pressure and represents saturated soil, while unsaturated soil is represented by a zero pressure head. The zero pressure head line in the figure is the location of the water table that separates saturated soil from unsaturated soil. The equivalent plastic strain before the dam fails is shown in Figure 3. The slip surface is shown in Figure 4, with arrows indicating the displacement direction of the soil particles. This figure illustrates the phenomenon of slip in the dam soil. Since the lower boundary of the dam is a fixed constraint, there is no slip in the soil at the lower right corner of the dam. Figure 5 shows the relationship between the maximum displacement and FOS. The maximum displacement increases significantly around FOS=1.6, which indicates that the dam begins to fail.

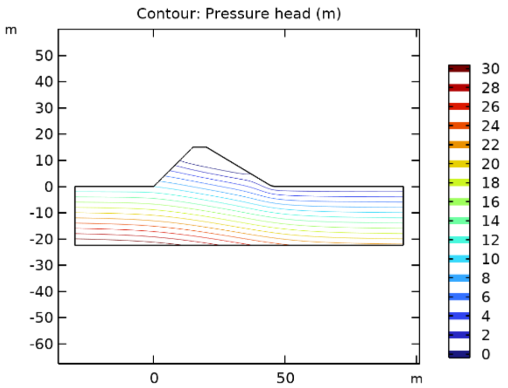

Figure 2: Pressure head in the embankment dam

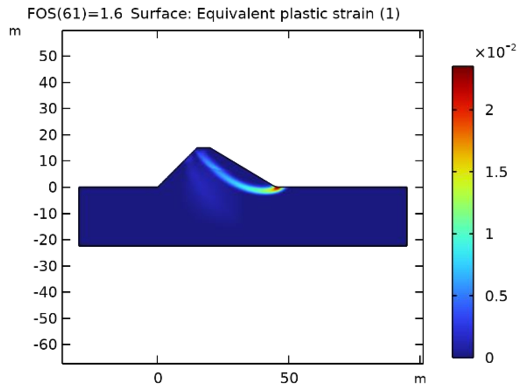

Figure 3: Equivalent plastic strain just before the collapse of the slope

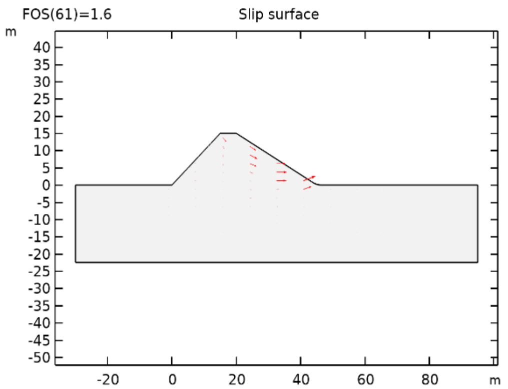

Figure 4: Slip circle just before the collapse of the slope

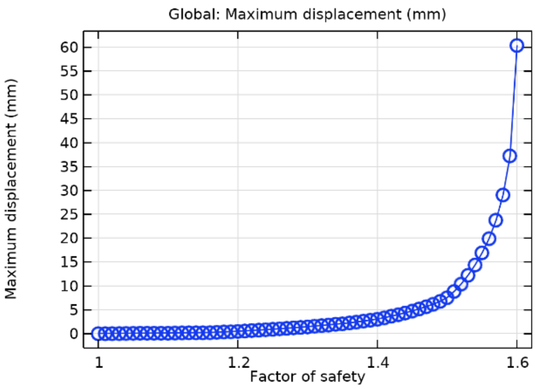

Figure 5: Maximum displacement versus the FOS

V. Conclusion

Based on the COMSOL Multiphysics platform, the study conducted a numerical simulation of the dam slope stability through elastic-plastic finite element analysis, revealing the critical state and failure mechanism of dam instability. The main conclusions are as follows:

1. **Critical safety factor and instability criterion:** When the safety factor (FOS) drops to 1.6 , the elastoplastic analysis cannot converge due to the accumulation of plastic strain and the degradation of shear strength, indicating that the dam enters a critical state of instability. FOS=1.6 can be used as the threshold for the slope stability analysis of the dam.
2. **Influence of seepage and pore water pressure:** The pressure head distribution (0-10m) reveals the significant influence of the water table position on the mechanical behavior of soil in saturated and unsaturated zones . The presence of pore water pressure in saturated soil exacerbates the development of plastic strain and is an important factor inducing instability.

3. **Failure mode and slip characteristics:** The equivalent plastic strain distribution shows that the plastic zone before instability shows a gradual expansion trend, indicating the formation of a potential slip surface. The displacement field analysis shows that the soil shears along the slip surface, but due to the fixed constraint of the lower boundary, the displacement of the soil in the lower right corner is limited, which verifies the rationality of the model boundary conditions.

This study provides a numerical analysis framework for the assessment of dam slope stability, emphasizing the effect of seepage field - stress field coupling on instability. In actual engineering, it is necessary to focus on the dynamic changes of the water table and the area of plastic strain accumulation, and it is recommended to verify the critical FOS value in combination with field monitoring data. For complex three-dimensional boundary conditions or local weak structures, full three-dimensional modeling can be further carried out to improve the prediction accuracy.

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Reference

[1]. Li Xinran, Zhang Guirong, Lin Cheng, et al. Research Progress on Landslide Reinforcement and Ecological Slope Protection Measures in the Three Gorges Reservoir Area [J]. Yangtze River, 2024, 55(01): 127–134.

[2]. F.W.C., W.M.G. Limit Analysis of Stability of Slopes [J]. Journal of the Soil Mechanics and Foundations Division, 1971, 97(1): 19–26.

[3]. Zhao Zhirong, Zhang Feiyun. Slope Stability Analysis of Shenyan Xiwan Open-pit Coal Mine Based on Numerical Simulation [J]. Shaanxi Coal, 2025, 44(01): 92–98.

[4]. Liu Yuxiang. Effect of Vegetation Planting on the Stability of Reservoir Slopes under Rainfall [J]. Shaanxi Water Conservancy, 2025, (02): 89–92.

[5]. Wang Ping, Liu Dongsheng. Radial Strip Model for Calculating the Safety Factor of Soil Slopes [J]. Engineering Mechanics, 2002, (03): 148–152.

[6]. Liu Shiyi. Research on Stability Analysis of Geotechnical Structures Based on the Finite Element Limit Equilibrium Method [D]. Dalian University of Technology, 2015.

[7]. Simatupang, P.T., & Ohtsuka, S. (2000). Static and Seismic Slope Stability Analyses Based on Strength Reduction Method. Journal of Applied Mechanics, 3, 235–246.

[8]. Chen Zuyu. Discussion on "Finite Element Calculation of Circular Sliding of Soil Slopes under Seepage" (I) [J]. Chinese Journal of Geotechnical Engineering, 2002, (03): 394–396.

[9]. Zheng Yingren, Zhao Shangyi. Application of the Finite Element Strength Reduction Method in Slope (Landslide) Stability [C]// Chinese Society of Mechanics, Beijing University of Technology. Abstracts of the 2005 Annual Meeting of the Chinese Society of Mechanics (Volume 1), 2005: 1.

[10]. Yu Qinglei, Yang Tianhong, Tang Chunan, et al. Three-dimensional Modeling and Preliminary Application of Quasi-brittle Materials Based on Real Mesostructure [J]. Chinese Journal of Computational Mechanics, 2010, 27(05): 887–894.

[11]. Liu Jianyu. Research on Slope Stability Analysis and Prevention Measures Based on the Strength Reduction Method and Neural Network [D]. Chang'an University, 2020.

[12]. Fan Yuhui, Wang Ning. Experimental Study on the Mechanical Properties of MMA-Reinforced Recycled Coarse Aggregate Concrete [J]. Journal of Henan Polytechnic University (Natural Science Edition), 2024, 43(1): 189-195.