Cinite Element Analysis of Hydraulic Slope Stability Based on Strength Reduction Method

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Abstract. Slope stability analysis is a hot research topic in geotechnical engineering. According to the actual engineering hydraulic slope stress, based on the strength reduction method theory, the finite element software ANSYS is used to analyze the stability of a hydraulic slope engineering, and the effective safety factor of the slope is obtained, which is safe for other slopes. Support design provides a reference.

1. Introduction
There are many factors in the instability of the slope, including: the reduction of shear strength (C, φ) in the rock and soil, the increase of the bulk density g, the disturbance of the slope excavation, and the excessive load on the top of the slope. For natural slopes, the damage of the slope is caused by the decrease of the shear strength of the slope soil and the increase of the bulk density of the soil. The stability of the slope is analyzed by the reduction of the shear strength (C, φ) of the slope soil and the increase of the bulk density g of the soil, which is called the finite element strength reduction method. By continuously reducing the shear strength of the slope soil, the slope gradually changes from stable to sliding failure, and finds the weakest part of the slope rock and soil, which provides a basis for slope reinforcement.

2. Instability criteria for finite element strength reduction
When the finite element strength reduction method is used to judge the instability condition of the slope, the shear strength of the soil is gradually reduced. Then analyze the change of any point inside the soil at different strength reduction factors to judge whether the slope is unstable. The slope instability criterion is as follows:
   (1) Convergence criterion: Iterative convergence of force or displacement is used as a sign of slope instability judgment.
   (2) Mutation criterion: a sudden change in the sliding surface or a certain point of the slope and the infinite development as a sign of the instability of the slope.
   (3) Plastic zone penetration criterion: the penetration of the equivalent plastic strain or generalized plastic strain from the bottom of the slope to the top of the slope is used as a sign of instability of the slope.
3. Overview of actual hydraulic slope engineering

A reservoir project is mainly used for agricultural irrigation, taking into account power generation and human and animal water use. The reservoir hub building consists of concrete face rockfill dam, left bank spillway and water transfer tunnel, right bank power house and flood discharge tunnel. The design of the dam crest is 280m long, with a total storage capacity of 42 million m³ and a total installed capacity of 8000 kW. It is necessary to excavate the spillway on the left bank. In order to ensure the safety of construction and the safety of permanent buildings, it is necessary to calculate the stability of the left bank slope and take effective and effective reinforcement measures as needed. The hydraulic slope is a longitudinal long slope, and the surrounding rock materials of the lower part and the upper part are inconsistent. Its horizontal key dimensions are shown in Figure 1.

![Figure 1. Schematic diagram of hydraulic slope (unit: m)](image)

The material properties of the surrounding rock 1 and surrounding rock 2 of the slope are shown in Table 1.

| Category                  | Modulus of elasticity /GPa | Poisson's ratio | Density / (kg / m³) | Cohesion / Pa | Internal friction angle / ° |
|---------------------------|----------------------------|-----------------|---------------------|---------------|----------------------------|
| Surrounding rock 1        | 20                         | 0.30            | 2500                | 69600         | 46                         |
| (elastoplasticity)        |                            |                 |                     |               |                            |
| Surrounding rock 2        | 29                         | 0.28            | 2700                | —             | —                          |
| (elasticity)              |                            |                 |                     |               |                            |

4. PLANE82 unit modeling

The Plane82 unit is defined by 8 nodes, each node having 2 degrees of freedom, ie x, y direction. It can be used for planar elements as well as for axisymmetric elements. This unit has the ability to plasticity, creep, radiation expansion, stress stiffness, large deformation and large strain.

![Figure 2. PLANE82 unit geometry.](image)

5. Slope stability analysis based on strength reduction method

5.1. Analysis of the first principal stress of the slope

The first principal stress of the slope can be analyzed by the theory of maximum tensile stress strength, and the cloud diagram of the first principal stress under different reduction factors is obtained, as shown in Fig. 3.
Figure 3. Principal stress cloud diagram with different reduction factors at F=1.0, 2.0, 2.1

As shown in Fig. 3, the first principal stress is 19041Pa when F=1.0, and the first principal stress is sharply increased to 54964Pa as the strength reduction factor increases continuously to F=2.0. However, when F=2.1, the first principal stress drops to 51383Pa, and the slope has been destroyed. That is, when F=2.0, the slope stability has reached the limit, and the slope safety factor is 2.0.

5.2. Slope equivalent stress analysis

The equivalent stress follows the fourth strength theory of material mechanics, that is, the shape change specific energy theory. Equivalent stress can quickly determine the most dangerous area in the model, and the results are more realistic. The equivalent stress cloud diagram of different reduction factors is calculated by changing the slope strength reduction coefficient by ANSYS software.

Figure 4. Equivalent stress cloud diagram of different reduction factors at F=1.0, 2.0, 2.1

As can be seen from the analysis of Fig. 4, when F = 1.0, the equivalent stress value is 1.50 MPa. As the reduction factor continues to increase to F=2.0, the equivalent stress remains unchanged, but when the reduction factor increases to F=2.1, the equivalent stress value is 1.38 MPa, at which time the equivalent stress is abrupt. The corresponding safety factor is 2.0.

5.3. Analysis of safety factor of slope

According to the three instability criteria of the finite element strength reduction coefficient method, namely the convergence criterion, the mutation criterion, and the plastic zone penetration, the stability of the slope is analyzed in turn. The displacement cloud map and the strain map are obtained.

(1) Displacement cloud map of the slope in the X direction with different reduction factors.

Figure 5. Displacement cloud diagram of slope X direction with different reduction factors at F=1.0, 2.0, 2.1

As shown in Fig. 5, the comparison cloud map shows that the displacement in the X direction is 7.89×10^{-4}m when F=1.0, and the decreasing coefficient is gradually increased until F=1.9, and the displacement is increased to 1.085×10^{-3}m, but from F=2.0. The displacement is 1.372×10^{-3}m to F=2.1 and the displacement is 2.405×10^{-3}m. At this time, the displacement in the X direction is abrupt.
(2) Vertical displacement cloud map of slope with different reduction factors.

Figure 6. Vertical displacement cloud of slope when F=1.0, 2.0, 2.1 is used with different reduction factors

As shown in Fig. 6, the comparison cloud map shows that when F=1.0, the vertical displacement is $-4.096\times10^{-3}$ m, F=2.0 vertical displacement $-4.092\times10^{-3}$ m, F=2.1 vertical displacement $-3.844\times10^{-3}$ m, at which point the vertical displacement has changed.

(3) Slope total displacement cloud map with different reduction factors

Figure 7. The total displacement cloud map of the slope with different reduction factors at F=1.0, 2.0, 2.1

As shown in Fig. 7, the comparison cloud map shows that when F=1.0, the total displacement is $4.096\times10^{-3}$m, the total displacement from F=2.0 is $4.092\times10^{-3}$m to F=2.1 total displacement is $3.936\times10^{-3}$m, total displacement. A mutation has occurred. Through the above analysis, the slope nodes are all abrupt when F=2.0. The maximum displacement abrupt slope safety factor is 2.0.

(4) Slope plastic zone cloud map with different reduction factors

Figure 8. Strain diagram of the plastic zone of the slope with different reduction factors at F=1.0, 2.0, 2.1

As shown in Fig. 8, it can be seen from the analysis that when F = 1.0, no plastic strain occurs in the slope. Continue to increase the reduction factor until F=2.0. At this time, the plastic zone of the slope will be further developed, and a possible shear failure zone is formed. The slope deformation is gradually concentrated in the shear failure zone, that is, the slope reaches The critical failure state, but once the reduction factor continues to increase by 0.1 (ie, F = 2.1), the plastic zone of the slope foot and the upper weak structural plane are all penetrated, and the slope will have plastic rheology, resulting in the slope. The overall instability, and the calculations no longer converge. The analysis shows that the safety factor of the slope is 2.0.

6. Conclusion

Using ANSYS finite element software, based on the finite element strength reduction method, the stability of the actual engineering hydraulic slope is calculated and analyzed.
(1) Using the finite element strength reduction method, the distribution characteristics and variation laws of stress, strain and plastic zone of the slope under natural working conditions were simulated by ANSYS software, and the strain cloud diagram was drawn. According to the finite element strength reduction method to calculate the non-convergence and other criteria to analyze the stability of the slope, the safety factor of the slope under natural conditions is 2.0.

(2) Through the test of three different instability criteria, the safety factors of convergence criterion, mutation criterion and plastic zone penetration determination are basically the same. The finite element strength reduction method can be applied to guide engineering in simple rock quality. The stability analysis of the slope is feasible.

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