Three-dimensional Stability Analysis of Considering Seepage Effect on Complex Loose Slope

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Abstract: in order to analyze the influence of seepage on the stability of loose accumulation slope, this paper establishes a three-dimensional slope stress calculation model based on practical engineering cases, carries out the seepage stress coupling analysis, designs three analysis conditions, and studies the influence of seepage and tailings pressure on the stability of slope. The results show that the tailings pressure will strengthen the safety factor of slope stability, but the seepage will reduce the safety factor of slope stability. The influence degree of seepage on slope stability is revealed, which provides a reference for the design of loose slope.

1. Introduction
The waste dump of nonferrous metal mine is the place where the waste earth and rock are piled up. It is a kind of large loose accumulation because it only relies on its own consolidation action such as self weight and vehicle load without any rolling measures. Under the seepage effect of rainwater and groundwater, the shear strength of the accumulated material will be reduced compared with the dry state. At the same time, the material bears the buoyance force, which makes the vertical force decrease. Therefore, the seepage effect is the unstable factor of seepage.

The traditional method for slope stability analysis under seepage effect is based on the limit equilibrium method [1], which divides the slope in the assumed sliding range into several vertical strips, and considers that each strip is a rigid body, without internal deformation, only displacement occurs at the sliding surface. For the strip below the saturation line, it is assumed that the reaction center of water is at the center of the bottom end of the strip, and the size is the osmotic pressure at that point [2]. Although this hypothetical treatment method is reasonable to some extent, it is simple and has large error, so the interaction between water and loose reactor cannot be considered [3] [4]. Based on this, this paper studies the numerical simulation method of three-dimensional slope based on strength reduction method, considering the stress coupling effect of water and loose material, and explores the influence degree of seepage on the stability of three-dimensional slope.

2. Strength Reduction Method
The stability analysis of dam slope by the finite element method is a kind of approximate real situation method, which can meet the requirements of balance force condition, coordination condition, constitutive equation and boundary condition. This method can simulate the failure mode of dam slope and better reflect the site conditions, and then get the minimum safety factor of dam slope and the detailed information of failure behavior of dam slope. In addition, the failure process of dam slope is automatically completed, and the failure surface does not need to be assumed. The strength reduction method is to reduce the shear strength of soil gradually until the calculation of a point is not
It is considered that the point is in a state of failure, and the maximum strength reduction rate is the minimum safety factor. This method can get more accurate results and analyze the deformation process from the initial state to the failure state of dam slope without assuming the failure surface.

In order to simulate the failure state of the dam slope, it is necessary to calculate the safety factor of any point. When the Mohr’s circle of the point contacts with the failure envelope, the point is considered to be in the failure state. When the failure state expands, the dam slope will be damaged as a whole, and the finite element analysis will diverge, and the safety factor is the minimum safety factor.

The soil material model used in strength reduction method includes Mohr Coulomb, Drucker Prager and modified Mohr Coulomb. In the analysis process, the constitutive parameters are variable except cohesion $c$, internal friction angle $\phi$ and expansion angle, and the other parameters are unchanged. The calculation formula is as follows:

$$f_c = \frac{c}{SRF}$$

$$\phi_f = \tan^{-1}\left(\frac{\tan \phi}{SRF}\right)$$

In the formula, $c_f$ is the reduced cohesion, $\phi_f$ is the reduced friction angle, SRF is the reduction coefficient, and the reduction coefficient in case of critical failure is the safety coefficient of dam slope instability.

3. Three-dimensional Slope Stability Analysis

The stacking elevation of the downstream expansion of a waste dump is between +450m and +670m, the stacking height is 220m, the stacking height of the final stage (step) is 30m, the total slope is 23°, the slope angle of single stage is 34°, and the effective volume of the waste dump is 80 million m$^3$.

| Material name                  | Unit weight (kN/m$^3$) | Cohesion c (kPa) | Friction angle (°) | Permeability coefficient k (cm/s) |
|--------------------------------|------------------------|------------------|-------------------|----------------------------------|
| Gold mine waste dump           | 20.2                   | 20.0             | 24.0              | 3.6×10$^{-2}$                    |
| Soil waste dump                | 19.7                   | 25.0             | 28.0              | 2.0×10$^{-5}$                    |
| Gravelly silty clay            | 19.0                   | 23.0             | 22.0              | 4.6×10$^{-5}$                    |
| Sand-like strongly weathered phylite | 21.0                   | 30.0             | 35.0              | 4.2×10$^{-4}$                    |
| Moderately weathered phylite  | 26.0                   | 830.0            | 41.0              | 5.0×10$^{-6}$                    |

During the operation period, the water in the tailings pond penetrates into the pile body, which will not only soften the loose materials in the slag yard and the Quaternary topsoil and strongly weathered bedrock in the foundation [5], reduce the physical strength of the loose materials and the foundation, moreover, produced uplift pressure reduces the effective load of the soil body and weakens the stability of the slag yard and the foundation.

According to the above factors, the selected conditions for the design static stability calculation are as follows: working condition 1: (only self weight) the current slope stability of the three storage yards; working condition 2: (self weight + tailings pressure) the stability of the three storage yards under the different tailings stacking elevation (330m, 390m, 450m) in the operation period; working condition 3: (self weight + tailings pressure + buoyance) the stability of the three storage yards under the seepage action under the different water level elevation (330m, 390m, 450m) in the reservoir.

See Fig. 1 for the three-dimensional stability calculation model of waste dump. The model includes 126,503 units and 57,111 nodes. It is specified that X direction is vertical to the waste dump, Y
direction is parallel to the waste dump, and Z direction is vertical. The simulation range is 1950m in X direction, 1050m in Y direction and 470m in Z direction.

![Figure 1. Three-dimensional stability calculation model of waste dump](image1)

See Table 2 and Fig. 2 to Fig. 4 for the calculation results of slope stability of waste dump under various working conditions.

| Work condition | Work condition 1 | Work condition 2 | Work condition 3 |
|----------------|------------------|------------------|------------------|
| Safety factor  | 1.691            | 1.708            | 1.490            |

![Figure 2. Cloud chart of maximum shear strain of waste dump under working condition 1](image2)

![Figure 3. Cloud chart of maximum shear strain of waste dump under working condition 2](image3)

![Figure 4. Cloud chart of maximum shear strain of waste dump under working condition 3](image4)

4. Conclusion

Based on an engineering example, a three-dimensional finite element model of slope is established, and the slope stability analysis under the seepage-stress coupling effect is carried out. The following conclusions are drawn:

(1) When only considering the self weight, the bottom of the most dangerous slip arc is located at the bottom of the slope, which is related to the stress concentration caused by the sharp angle at the bottom of the slope. The loose accumulation will produce local damage and release the concentrated stress when suffering from the stress concentration, but the most dangerous slip arc will still occur here due to the presence of the free surface.

(2) When the numerical calculation method is used, under the seepage-stress coupling effect, the safety factor of slope stability is 11.9% lower than that when only considering the self weight effect, and 12.7% lower than that when considering the tail sand and self weight effect. The calculation results are in line with the general engineering conclusions.

(3) Considering the seepage-stress coupling effect, the maximum shear strain area of the slope is concentrated at the toe of the slope, which indicates that the toe of the slope is a dangerous area under the action of seepage. Drainage measures or engineering reinforcement measures should be set at this place to strengthen the drainage of seepage and further ensure the safety of the slope.
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