The Application of Cohesive Element Method in the Stability Analysis of Jointed Slope

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Abstract. A coupled numerical method (FEM/DEM) is generated to model the complete fracture processes of rock material. Cohesive elements are inserted along the boundaries of the discretized elements to model the fracture initiation and propagation in rock material. Then this method is applied to the jointed slope, and the stability of the slope under different joint cohesion is studied. By comparing theoretical values and numerical results, it is verified that this numerical method can effectively and reliably study the stability of jointed slopes.

1. Introduction
The rock mass is usually composed of rocks and joint fissures. The existence of joint fissures will form a weak structural surface inside the slope, which will significantly affect the strength of the slope body, reduce its stability, and even directly form a slip surface at the joint to cause massive destruction.

In fact, the failure of the slope includes the whole process of the slope body from deformation to failure, from continuous to discontinuous. The continuum assumptions of the finite element method and the finite difference method make it unsuitable for simulating the failure of the crack initiation, propagation and other issues of slope body [1-3]; the discrete element method regards the rigid body as the basic unit, although it can simulate the failure process of the slope, it can’t reflect the deformation process of the slope [4,5].

In order to fully simulate the entire process from deformation to failure of a slope, this paper builds a continuous-discontinuous numerical method based on cohesion elements based on the FEM platform and with the help of zero-thickness cohesion elements, which can be better reflects the instability failure process of the jointed slope.

2. Cohesive element method

2.1. Method introduction
In this method, the rock mass is idealized as a collection of elastomeric units, which are connected together by cohesive elements along their boundaries. Before failure, the continuous behavior of the rock material is controlled by the constitutive relationship of the elastic element and the stiffness of the cohesive element, while the discontinuous failure process is captured by the cohesive element. Once the stress state of the cohesive element reaches its failure criterion, the element will be completely
damaged and removed from the model.

2.2. Constitutive equation of cohesive element

In the cohesive model, the constitutive response of the cohesive layer can be directly defined by an arbitrary traction-separation law, which can be used to evaluate the cracking behavior at the interface. In this study, a bilinear traction-separation law [6-8] is adopted to reflect the response of the cohesive elements, as shown in figure 3.

Figure 1. Constitutive relations of the cohesive elements
(a) $t_n - \delta_n$ curve in the normal direction; (b) $t_i (\delta_i)$ curve in the tangential direction

As shown in Figure 1.(a), the normal traction $t_n$ force of the cohesive element increases linearly with the increase of the normal relative displacement $\delta_n$. Once the normal traction $t_n$ reaches its peak $t_n^0$, the linear damage evolution law begins to be used, the normal stiffness $k_n$ of the cohesive element begins to degenerate, the cohesive element completely fails (corresponding to the failure displacement $\delta_n^f$); the normal constitutive response process of the cohesive element is shown in the formula (1). The constitutive process of the other two tangential directions is similar to that of normal directions (formula 1 and 2), so this article will not elaborate.

\[
t_n = \begin{cases} k_n \delta_n, & \delta_n \leq \delta_n^0 \\ (1-D)k_n \delta_n, & \delta_n^0 < \delta_n \leq \delta_n^f \\ 0, & \delta_n^f < \delta_n \end{cases}
\]

(1)

\[
t_i = \begin{cases} k_i \delta_i, & \delta_i \leq \delta_i^0 \\ (1-D)k_i \delta_i, & \delta_i^0 < \delta_i \leq \delta_i^f \\ 0, & \delta_i^f < \delta_i \end{cases}
\]

(2)

\[
t_i = \begin{cases} k_i \delta_i, & \delta_i \leq \delta_i^0 \\ (1-D)k_i \delta_i, & \delta_i^0 < \delta_i \leq \delta_i^f \\ 0, & \delta_i^f < \delta_i \end{cases}
\]

(3)

where $\delta_n^0$ is the relative normal displacement at damage initiation, $D$ is the damage variable, $\delta_i^0(\delta_i^0)$ is the relative shear-displacement at damage initiation.
3. Numerical calculation of joint slope

3.1. Model generation and boundary conditions
The model is a slope model [9] with straight-line joints, the slope height is 20 m, the slope angle is 30°, and the remaining dimensions are shown in the figure 2. There is an irregular unshed body on the slope that is bonded to a whole (the joint position is shown by the red dashed line in the figure), the unshed body may slide down the slope as the joint fails at any time.

![Natural joint](image)

Figure 2. The geometric dimensions of joint slope model

The established numerical model is shown in Figure 3, and its macroscopic size is consistent with the actual size of the joint slope. Then FEM software is used to mesh the established model, and the mesh type is C3D6. The cohesive force element (C3D8) is inserted at the joint position of the meshed finite element slope model to simulate the internal joint of the slope. The nature of the cohesive force element is used to reflect the nature of the joint; Intuitively display the cohesion unit at the joint and enlarge it, as shown in the green unit in Figure 3.

At the left and right side of the slope body, the horizontal displacement cannot be generated because the horizontal displacement is constrained. All the horizontal and vertical degrees of freedom are constrained at the bottom boundary of the slope body, so that it can neither translate nor produce displacement in the vertical direction.

![Cohesive element](image)

Figure 3. The numerical model of joined slope

3.2. Calculation parameters
The main calculation parameters of the model are shown in the following table. The parameters of the solid element are consistent with the real parameters of the joint slope. The specific values are derived from the calculation parameters in the literature [9].

| Element type   | Parameter name / E | Value   | Unit   |
|----------------|-------------------|---------|--------|
| Solid element  | Elastic modulus   | $1 \times 10^{10}$ Pa |

3.3. Numerical results

In order to verify the applicability of the cohesive element method in jointed slopes, six sets of numerical experiments and theoretical solutions were designed for comparison. The six sets of numerical experiments adopt the controlled variable method, strictly maintaining the joint internal friction angle $\phi = 20^\circ$, and then set six different joint cohesion ($c = 15, 25, 35, 45, 55, 65$ kPa) perform numerical experiments.

The slope vector and safety factor [10,11,12] obtained by the numerical experiment are shown as the black line in figure 4, and the safety factor obtained from the theoretical solution is shown as the red line in the figure 4. It can be found that the magnitude, change trend and theory of the safety factor calculated by the numerical method are the same and the degree of agreement is relatively high, indicating that the cohesive element method can be widely used in the numerical simulation of the jointed slopes used in this section. In the process of joint failure, the stress change inside the slope body is shown in Figure 5, which conforms to the general law.

| Cohesive element | Poisson's ratio / $v$ | 0.25 |
|------------------|----------------------|------|
| Density /$\rho$  | 2700 kg/m$^3$        |      |
| Normal stiffness / $E_{33}$ | $1.5 \times 10^9$ N/m |
| Tangential stiffness / $G_{13}$ | $1.5 \times 10^8$ N/m |
| Tangential stiffness / $G_{23}$ | $1.5 \times 10^8$ N/m |
| Cohesion / $c$   | $5 \times 10^4$ Pa   |
| Internal friction angle / $\phi$ | 20 $^\circ$ |

Figure 4. The relationship between joint cohesion and slope safety factor
4. Conclusions

With the help of the cohesive element method, a continuous-discontinuous numerical method is realized, which can more truly reflect the whole process from deformation to fracture failure when the slope is broken. Furthermore, the above method is applied to the jointed slope. By comparing the results of six sets of numerical calculation models with different joint cohesion and theoretical results, it is verified that the application of this method to the study of jointed slopes is effective and feasible.

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