Research and analysis on residual shear strength of surrounding rock base on elastic-plastic softening model

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Abstract. The excavation of caverns caused the unloading of the surrounding rock, which decrease the strength of the rock mass. In this paper, an ideal elastic-plastic stress-strain softening model is used to analyse the shear strength sensitivity of the surrounding rock during cavern excavation, in order to research the relationship between deformation, stress, plastic zone and the strength parameters. The results show that the values of each shear strength parameter have a significant effect on the distance of the plastic zone, and the sensitivity of the plastic zone distance shows that the influence of peak internal friction angle, residual internal friction angle, residual cohesion and peak cohesion decreased successively.

1. Introduction
Massive excavation of underground rock will cause the adjustment of surrounding rock stress field inevitably, which will lead to the unloading of surrounding rock within a certain range[1]. The stress state of surrounding rock changes from a three-way stress state to a two-way or one-way stress state, and the strength of the rock mass decreased, then the surrounding rock yield or break down. According to the unloading test results, deformation and strength parameters of rock mass are obviously weakened during unloading failure[2,3]. In general elastic-plastic numerical analysis, the rock mass parameter is always a constant in the calculation process. In order to analyse the stability of excavation engineering more accurately, it is necessary to consider the weakening of rock mass strength parameter in the process of unloading failure[4].

The constitutive model is one of the important contents of rock mechanics research, and the commonly used constitutive models include elastic, nonlinear elastic, elastoplastic and rheological constitutive models. The stress-strain relation curve of rock can be approximated as linear at the beginning, which is the elastic property. And when the strain increases beyond the linear deformation stage, the stress-strain relationship may present several different nonlinear conditions: ideal elastic-plastic, elastic-plastic hardening and elastic-plastic softening[5]. The ideal elastic-plastic model shows that the strain continues to increase while the stress remains unchanged, the elastic-plastic hardening model shows that the strain can bear more stress after the strain increases, and the elastic-plastic softening model shows that the strength decreases gradually after the strain increases.
2. Constitutive model

The curve of ideal elastic-plastic stress-strain softening model is shown in Figure 1, stress and strain after the elastic stage, after the peak, ideal state along the peak strength into the yield platform, namely the ideal state that the residual strength into the yield platform, the yield stress and strain development platform, in reason can fully consider various combinations of stress path.

The stress-strain curve first passes through the elastic stage. After reaching the peak, the ideal state enters the yielding platform along the peak strength, and the softening model enters the yielding platform along the residual strength, so it can fully consider the effect of the stress path of multiple combinations.

In previous calculations, ideal elastic-plastic models are often used, which is the strain continues to increase while the stress remains unchanged. As a result, the strength of the surrounding rocks in the plastic area is overestimated, which affects the safety of the project. Therefore, by choosing a softening model, the strength of the surrounding rock in the plastic zone is taken as the participating strength, which reflects the actual situation.

3. Calculation analysis and sensitivity analysis

In order to study the elastic-plastic softening of rock mass after peak strength in the tunnel excavation, an underground cavern of a hydropower project was taken as an example. The cavern concludes main power house, main-transformed cavern and tailrace surge chamber, and excavated in layer and blocks. The excavation steps are called stage number, and the calculation model is shown in Figure 2. Mohr-Coulomb criterion was adopted in this paper to calculate the elastic-plastic softening model (high, medium and low parameters) and the ideal elastic-plastic model parameters respectively. The high, medium and low parameters of the elastic-plastic softening model are ①, ③ and ④, the ideal elastic-plastic model is ②, and the mechanical parameters for sensitivity analysis are shown in Figure 3.
The sensitivity analysis results show that the range of the yield zone (Figure 4) is positively related to the shear strength parameters of the surrounding rocks. The higher the parameters are, the smaller the yield area is. The range size of the plastic zone is sorted as: ① < ② < ③ < ④.

From the calculation results (Figure 5 and Figure 6), the excavation of step 8 occurred, the free face appeared. Shear strength, including peak strength and residual strength, have a significant effect on the total displacement, and the law of attenuation and acceleration appears as the parameter decreases. Due to the large values of tensile strength and shear strength in ①, there are still some residual stresses with the implementation of subsequent excavations.
Figure 6. Major principal stress with calculation step variation curve

The comparison of calculation parameters and displacement (Figure 7) shows that on the left wall, right wall and top arch, the displacement decrease gradually. It shows that the selection of parameters has a greater impact on the deformation of various parts. And the deformation of the right wall is the largest at the low residual strength parameter, which reaches 4.9mm. The higher calculation parameter has a significant increase of 8.8 times.

Figure 7. Comparison of calculation parameters and displacement

In order to research the influence of shear strength of surrounding rock on the distribution of plastic zone, the sensitivity of shear strength parameters of surrounding rock was analysed. In the calculation planes, the single parameters of shear strength increased by +6.0% and -10.0%, the sensitivity analysis calculation planes are shown in Table 1.
Table 1. Sensitivity analysis calculation planes

| Numerical procedure | Peak internal friction angle(°) (%) | Peak cohesion (MPa) | Residual internal friction angle(°) (%) | Residual cohesion (MPa) |
|---------------------|-----------------------------------|--------------------|---------------------------------------|------------------------|
| Plan 1-1            | 53 (+6%)                          | 1.50               | 40                                    | 1.20                   |
| Plan 1-2            | 50 (+0%)                          | 1.50               | 40                                    | 1.20                   |
| Plan 1-3            | 45 (-10%)                         | 1.50               | 40                                    | 1.20                   |
| Plan 2-1            | 50                                | 1.60 (+6%)         | 40                                    | 1.20                   |
| Plan 2-2            | 50                                | 1.50 (+0%)         | 40                                    | 1.20                   |
| Plan 2-3            | 50                                | 1.35 (-10%)        | 40                                    | 1.20                   |
| Plan 3-1            | 50                                | 1.50               | 42 (+6%)                              | 1.20                   |
| Plan 3-2            | 50                                | 1.50 (+0%)         | 40                                    | 1.20                   |
| Plan 3-3            | 50                                | 1.50               | 36 (-10%)                            | 1.20                   |
| Plan 4-1            | 50                                | 1.50               | 40                                    | 1.27 (+6%)             |
| Plan 4-2            | 50                                | 1.50               | 40                                    | 1.20 (+0%)             |
| Plan 4-3            | 50                                | 1.50               | 40                                    | 1.08 (-10%)            |

The sensitivity calculation results (Figure 8) show that the plastic zone distance of the right wall is the most sensitive to the peak internal friction angle, residual internal friction angle and residual cohesive force parameters, and its curve is steeper.

4. Conclusion
(1) Four types of surrounding rock shear strength parameters are used to compare the displacement, stress and yield zone during cavern excavation. And the calculation results show that the values of each shear strength parameter have a significant effect on the distance of the plastic zone, and the influence of the top arch is the largest.

(2) The sensitivity of the plastic zone distance to the four shear strength parameters is as follows: peak internal friction angle, residual internal friction angle, residual cohesion and peak cohesion. Therefore, the accurate evaluation of surrounding rock stability depends on the accurate shear strength parameters.

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