Numerical Simulation Test on Mechanical Properties of Jointed Rock Mass

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Keywords: Jointed rock mass, Mechanical properties, Numerical simulation test.

Abstract. In the paper, the loading test of jointed rock mass is simulated by the finite element software. The numerical simulation experiment was completed on the intact rock mass, and results are compared with the laboratory test. Results show that numerical simulation method to study mechanical characteristics of jointed rock mass is feasible. Based on numerical simulation results on jointed rock mass, four types of failure of jointed rock mass are put forward, which are rock mass loading failure, joint loading failure, shear failure and approximate shear failure. Relative the joint thickness, the joint angle has more influence for shear strength properties of jointed rock mass. The elastic modulus of jointed rock mass is greatly influenced by the joint thickness and joint angle. With the different joint thickness, the elastic modulus of jointed rock mass is basically reached the minimum value when the joint angle is 10°~25°.

Introduction

At present, domestic and foreign scholars have made use of a lot of research with laboratory test for the mechanical properties of jointed rock [1-5]. However, there are not enough natural joint rock samples in the laboratory tests. When prefabricated artificial joints, it is easy to cause rock damage, and some joint factors (such as joints inclination, joint thickness and connectivity rate) can not be systematically analyzed. Therefore, many scholars study the mechanical properties of jointed rock mass with the viewpoint of numerical simulation in turn. In this paper, finite element method (FEM) is used to study the effect of joint thickness and dip angle on the mechanical properties of jointed rock mass.

Complete Rock Mass Numerical Simulation Test Research

The finite element software ADINA and ANSYS were used to simulate the three-axis loading test of the column-like red sandstone specimen with diameter of 5cm and height of 10cm in reference [6]. ADINA software uses Mohr-Coulomb yield criteria (hereinafter referred to as: M-C criteria), ANSYS software uses Drucker-Prager yield criteria (hereinafter referred to as: D-P criteria). After the numerical simulation test, the relationship between the ultimate axial pressure and the confining pressure in the statistical laboratory test and the numerical simulation test are shown in Table 1.

<table>
<thead>
<tr>
<th>Confining pressure/MPa</th>
<th>Laboratory test results</th>
<th>ANSYS Simulation results (D-P criteria)</th>
<th>ADINA Simulation results (M-C criteria)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>66.60</td>
<td>81.62</td>
<td>93.41</td>
</tr>
<tr>
<td>5</td>
<td>126.20</td>
<td>111.20</td>
<td>124.56</td>
</tr>
<tr>
<td>10</td>
<td>146.80</td>
<td>140.76</td>
<td>156.02</td>
</tr>
<tr>
<td>20</td>
<td>214.35</td>
<td>200.56</td>
<td>224.82</td>
</tr>
<tr>
<td>30</td>
<td>260.57</td>
<td>259.41</td>
<td>287.54</td>
</tr>
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</table>
Table 1 shows that, under the same conditions, the ultimate axial compression obtained by the D-P criteria is larger than the M-C criteria obtained. The strength parameters were fitted by least square method, the cohesion calculated by the D-P criteria is 18.02MPa and the internal friction angle is 47.24°; the cohesion calculated by the M-C criteria is 16.75MPa and the internal friction angle is 45.33°. The results of numerical simulation are close to the results of laboratory tests (cohesion is 16.40MPa, internal friction angle is 46.33°), but the results simulated by M-C criteria are more reasonable. The above results prove that it is feasible to study the mechanical properties of jointed rock mass by numerical simulation method, and it is better to use M-C criteria for numerical simulation test.

The numerical simulation test can inverse the elastic modulus of jointed rock mass with the following formula

$$E = \frac{(\Delta \sigma_1 + \Delta \sigma_2 + \Delta \sigma_3)(\Delta \sigma_1 - \Delta \sigma_2)\Delta \varepsilon_1 + (\Delta \sigma_1 - \Delta \sigma_3)\Delta \varepsilon_2}{(\Delta \sigma_1 + \Delta \sigma_2)\Delta \varepsilon_1 - (\Delta \sigma_2 + \Delta \sigma_3)\Delta \varepsilon_2}$$

The results of numerical simulation of the elastic modulus inversion are shown in Table 2, which shows that: (1) The numerical simulation results show that the elastic modulus is larger than that of the laboratory test, because of the finite element software just considered the deformation of the maximum principal stress direction, neglecting the influence of the axial stress on the lateral strain. (2) With the increase of confining pressure, the inversion of the elastic modulus is also increasing, indicating that confining pressure has a greater impact on the elastic modulus. (3) Overall, the numerical simulation test results and the laboratory test results are more consistent, indicating that the numerical simulation test results are reasonable.

<table>
<thead>
<tr>
<th>Confining pressure/MPa</th>
<th>Elastic Modulus/GPa</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Laboratory test results</td>
</tr>
<tr>
<td>0</td>
<td>9.39</td>
</tr>
<tr>
<td>5</td>
<td>16.57</td>
</tr>
<tr>
<td>10</td>
<td>18.14</td>
</tr>
<tr>
<td>20</td>
<td>21.09</td>
</tr>
<tr>
<td>30</td>
<td>24.34</td>
</tr>
</tbody>
</table>

**Jointed Rock Mass Numerical Simulation Experiment Research**

We developed a program for modeling jointed rock masses by ANSYS secondary exploration in this paper. The program will considered the joint thickness, joint angle, jointing rate, rock sample size, through the way and other factors, with the interface software to the rock model into ADINA software. The joints and rock units are connected by the unique Face Link function of ADINA software. The yield criteria is based on the M-C criteria.

**Numerical Simulation Test Program**

The rock mechanics parameters of jointed rock mass are the mechanical parameters of the indoor test in reference [7], as shown in Table 3. Since the internal friction angle of the intact rock mass is 44.3° and the internal friction angle of the joint is 23°, the joint inclination angle $\theta$ in the numerical simulation test is 0°, 10°, 15°, 20°, 25°, 30°.The joint thickness $h$ is considered as 1mm, 2mm, 3mm, 4mm, 5mm, 6mm, 8mm, and some of the jointed rock mass specimens are shown in Figure 1.

<table>
<thead>
<tr>
<th>Material</th>
<th>Density/kN/m³</th>
<th>Elastic Modulus/GPa</th>
<th>Poisson's ratio</th>
<th>Cohesion/MPa</th>
<th>Internal friction angle/°</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rock mass</td>
<td>26</td>
<td>7.58</td>
<td>0.404</td>
<td>16.2</td>
<td>44.3</td>
</tr>
<tr>
<td>Joint</td>
<td>21</td>
<td>0.20</td>
<td>0.300</td>
<td>0.1</td>
<td>23.0</td>
</tr>
</tbody>
</table>

Table 3. Mechanical parameters of rock mass and joint in jointed rock mass.
Numerical Simulation Test Results Analysis

**Analysis of Failure Modes of Jointed Rock Mass.** The results of numerical simulation of uniaxial test shows that there are four main failure modes of jointed rock mass: rock mass loading failure, joint loading failure, shear failure, approximate shear failure, as shown in Figure 2.

![Figure 2. Distribution of plastic zone in failure of jointed rock specimen.](image)

In Figure 2(a), when the joint inclination and the joint thickness are small, the plastic zone of rock specimen is mainly produced at joint and bottom, mainly at the bottom. The rock body was damaged, it belongs to the rock body loading damage. In Figure 2(b), when the joint inclination is small and the joint thickness is larger, the plastic zone of the rock is mainly produced in the joint, the rock itself is not damaged, and the horizontal displacement of the rock specimen is not very large. In Figure 2(c) and (d), when the joint inclination is increasing and the rock specimen is damaged, the plastic deformation mainly occurs at the joint, the displacement of the top rock specimen along the joint direction rapidly increases, and the rock specimen shear failure will occur. In Figure 2(e) and (f), there is a transition zone in the process of rock mass loading failure and joint loading failure, and shear failure occurs along the joint. Joint inclination and joint thickness is not big enough, so the joint near the rock also produced plastic deformation, damage, which is similar to the shear failure.

**Analysis of Shear Strength Parameters of Jointed Rock Mass.** Four kinds of confining pressure are considered in the numerical simulation: 0MPa, 5MPa, 10MPa and 15MPa. First, the limit axial pressure of jointed rock mass is calculated under different confining pressure, and the strength parameters of jointed rock mass are calculated by using the least square method. The relationship
between strength parameters of jointed rock mass and joint dip angle and joint thickness is shown in Figure 3.

![Graphs showing relationships between strength parameters](image)

Figure 3. Relationship of strength parameters of jointed rock mass of joint inclination and joint thickness.

It can be seen from Figure 3 that, when the joint angle is larger than the internal friction angle, and less than the internal friction angle of the rock mass, the internal friction angle and the cohesive force of jointed rock sample become smaller with the increase of joint angle. When the joint angle is greater than the internal friction angle of the rock mass, the internal friction angle and cohesive force of the jointed rock sample are almost no longer affected by the joint dip angle. When the joint angle is larger than the internal friction angle of the rock mass is smaller, the internal friction angle and the cohesion of the joint sample become smaller with the increase of the joint thickness. When the joint angle is larger than the rock mass, the internal friction angle and cohesion of the jointed rock sample are almost no longer affected by the joint thickness. When the joint angle is less than the internal friction angle, the internal friction angle and cohesion of the jointed rock sample are affected by the joint dip and the joint thickness, and the effect of the two parameters on the strength parameters of the jointed rock mass is relatively different. The effect of joint dip angle on the internal friction angle and cohesion of jointed rock sample is larger.

**Analysis of Elastic Modulus of Jointed Rock Mass.** The elastic modulus of the uniaxial test of jointed rock mass changes with the joint inclination and joint thickness as shown in Figure 4, and the elastic modulus is consistent with the overall trend of the joint dip. When the joint thickness is 1mm~4mm and the joint inclination angle is 0°~20°, the elastic modulus becomes smaller with the increased of joint inclination. When the joint inclination is 20°~45°, the elastic modulus increases with the joint inclination. When the joint angle is more than 45°, the elastic modulus becomes smaller. When the joint inclination is 20°, the elastic modulus is the smallest. When the joint thickness is 5mm~8mm and the joint inclination angle is 0°~15°, the elastic modulus increases with the joint inclination. When the joint angle is 15°~45°, the elastic modulus increases with the joint inclination. When the joint angle is more than 40°, the modulus of elasticity tends to become smaller. When the joint angle is 15°, the elastic modulus is the smallest. It can be seen from Figure 4 that the elastic modulus of the jointed rock mass is greatly affected by the joint thickness and the joint angle. When the joint thickness is small, the elastic modulus reaches the minimum at the joint inclination angle of about 20°. The elastic modulus reaches a minimum at about 15°. Generally speaking, with the thickness of joint, the elastic modulus of jointed rock mass reaches the minimum value when the joint angle is 10°~25°.

**Conclusion**

In the paper, the numerical simulation experiment was completed on the intact rock mass, and results are compared with the laboratory test. Results show that numerical simulation method to study
mechanical characteristics of jointed rock mass is feasible. The failure mode of jointed rock mass is analyzed by numerical simulation test, and four types of failure of jointed rock mass are put forward, which are rock mass loading failure, joint loading failure, shear failure and approximate shear failure. It is found that, relative to the joint thickness, the joint angle has more influence for shear strength properties of jointed rock mass. The elastic modulus of jointed rock mass is greatly influenced by the joint thickness and joint angle. With the different joint thickness, the elastic modulus of jointed rock mass is basically reached the minimum value when the joint angle is $10^\circ$~$25^\circ$.

Figure 4. Curve of elastic modulus and joint inclination of rock specimen with different joint thickness.

Acknowledgement

This research was financially supported by the Natural Science Foundation of Hubei Province of China (No.2015CFB545).

References


