The Change Law of Strength of Silty Mudrock Mass under Hygrothermal Conditions Based on Hoek-Brown Criterion

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Abstract. In order to study on the impact of hygrothermal condition on strength of silty mudrock mass, a series of uniaxial mechanical tests were carried out. According to the result of these tests, strength parameters of silty mudrock mass were figured out based on Hoek-Brown criterion, and the change law of strength parameters were analyzed. The results indicates when under hygrothermal condition, cohesion, internal friction angle and elastic modulus of silty mudrock mass decrease with the increase of temperature difference, decrease with the increase of soaked time; the reduction of those strength parameters were dramatically as the rock soaked water no more than 2 days, and will tend to be gentle as the rock soaked water more than 2 days; while the reduction of cohesion or elastic modulus was either greater than it of internal friction angle.

Introduction

Silty mudrock is easily impacted by temperature or water and lends to strength deterioration. In slope excavation, large deformation and instability failure of silty mudrock mass are easy to occur when the excavation face is in hygrothermal environment condition. In order to reduce engineering risk, the study of strength of silty mudrock mass is necessary. Some related research has been carried out at present: The micro mechanism of the strength softening of soaked mudstone has been studied\(^1\)\(^-\)\(^2\); some studies revealed the relationships between rock strength parameters and temperature/soaked time\(^3\)\(^-\)\(^4\). These studies only consider the strength change of rock, but not the rock mass. Merifield discussed the estimation of equivalent parameter between Hoek-Brown criterion and Mohr-Coulomb criterion\(^5\), which makes it possible to calculate rock mass strength based on rock strength.

Thus, in this paper, a series of experiments under different hygrothermal conditions have been carried out, the change of strength parameters of silty mudrock mass have been systematically studied.

Calculation Theory

The Generalized Hoek-Brown Criterion

Based on a large number of data of rock triaxial tests, E. Hoke and E. T. Brown put forward an empirical criterion for rock nonlinear failure. The generalized Hoek-Brown criterion\(^6\), the equation is as follows:

\[
\sigma_1 = \sigma_3 + \sigma_c \left( \frac{m \sigma_3}{\sigma_c} + s \right)^a
\]

In the above equation, \(\sigma_1\) is the maximum effective principal stress; \(\sigma_3\) is the minimum effective principal stress; \(\sigma_c\) is the uniaxial compressive strength; \(m, s, a\) are the parameters related to rock material.
The value of parameters $m$, $s$ and $a$ is directly related to the accuracy of equations. Based on RMR method evaluation system, Hoek\cite{7} introducing parameter $D$ to consider the weakening of rock mass, and put forward the methods of these parameters calculation, see Eq. 2 and Eq. 3.

$$m_s = \exp\left(\frac{RMR - 100}{28 - 14D}\right) \left(1 + \frac{16\sigma - \sigma_c}{\sigma_c}\right)$$

$$s = \exp\left(\frac{RMR - 100}{9.3D}\right)$$

$$a = 0.5 + \frac{1}{6}\left(e^{-RMR/15} - e^{-20/3}\right)$$

$$D = 1 - \left(\frac{V_p}{V_{p0}}\right)^4$$

In the above equation, $V_{p0}$ is the initial ultrasonic wave velocity of rock; $V_{pe}$ is the ultrasonic wave velocity of disturbed rock.

**Calculation Method of Rock Mass Parameters**

Based on the method of Equivalent parameter between Hoek-Brown criterion and Morh-Coulumb criterion\cite{5}, the strength parameters of rock mass can be calculated by RMR value and uniaxial mechanical indexes of rock, see in Eq. 4.

$$c = \frac{\sigma_c \left(1 - \sin \varphi\right)}{2 \cos \varphi}$$

$$\varphi = 90^\circ - \arcsin\left(\frac{2\tau}{\sqrt{3}\sigma_n}\right)$$

$$E = \left(1 - \frac{D}{2}\right) \sqrt{\frac{\sigma_n}{100}} \times 10^{(RMR-30)/10}$$

In the above equation, $c$ is the cohesion of rock mass; $\varphi$ is the internal friction angle of rock mass, $E$ is the elastic modulus of rock mass; $\tau$ is shear stress; $\sigma_n$ is normal stress; The value of $\tau$ and $\sigma_n$ in Eq. 4 are derived from the following equations:

$$\tau = \sigma_n \sqrt{1 + \frac{m_b}{2s}}$$

$$\sigma_n = \frac{2s\sigma_c}{4\sqrt{s} + m_b}$$

**Uniaxial Mechanical Test of Silty Mudrock**

**Test Scheme**

Samples of silty mudrock were collected on the YueLu Mountains, then these samples were sent to the laboratory immediately and made into cylinder specimens of $\phi 50 \times 100$mm and $\phi 50 \times 25$mm. Screened out specimens with ultrasonic wave velocity between 2200m/s and 2300m/s by non-metal ultrasonic detector. These specimens can be used for uniaxial test with different hygrothermal conditions.

This paper designed 2 test schemes to research the influence of temperature difference and soaking time on silty mudrock which under hygrothermal conditions:

Test 1: This test soak natural specimens into a water bath 10 days, and periodically change the water temperature with different modes (see Figure 1) at the same time. At the end of test, uniaxial mechanical indexes and ultrasonic wave velocity of these specimens were measured.

Test 2: In this test, natural specimens were soaked in a water bath for 0.5, 1, 2, 10, 20, 60 and 120 days respectively, and periodically change the water temperature by temperature shift mode 3. Uniaxial mechanical indexes and ultrasonic wave velocity of these specimens were measured after the end of soaking.
Test Data

After the completion of the test 1, it can be observed that ultrasonic wave velocity ($V_p$), uniaxial compressive strength ($\sigma_c$) and splitting strength ($\sigma_t$) of silty mudrock are lower than they are in natural state, and decrease with the increase of temperature difference ($\Delta T$), see Table 1 and Fig. 2.

Table 1. Ultrasonic wave velocity of silty mudrock under different temperature difference (soaked 10 days).

<table>
<thead>
<tr>
<th>Temperature shift mode</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta T / ^\circ C$</td>
<td>-20</td>
<td>-10</td>
<td>0</td>
<td>10</td>
<td>20</td>
</tr>
<tr>
<td>$V_p / (m/s)$</td>
<td>1420</td>
<td>1335</td>
<td>1281</td>
<td>1212</td>
<td>1151</td>
</tr>
</tbody>
</table>

The result of test 2 show that $V_p$, $\sigma_c$, and $\sigma_t$ of silty mudrock decrease with the increase of soaked time ($t$), and their descending curves can be divided into 2 stages: $t \leq 2$ days, $V_p$, $\sigma_c$ and $\sigma_t$ were in steep decline; $t > 2$ days, the changes of $V_p$, $\sigma_c$ and $\sigma_t$ tends to slow, see in Table 2 and Fig. 3.

Table 2. Ultrasonic wave velocity of silty mudrock after different soaked time ($\Delta T=0^\circ C$).

<table>
<thead>
<tr>
<th>Soaked time /days</th>
<th>0</th>
<th>0.5</th>
<th>1</th>
<th>2</th>
<th>10</th>
<th>20</th>
<th>60</th>
<th>120</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_p / (m/s)$</td>
<td>2250</td>
<td>1853</td>
<td>1615</td>
<td>1472</td>
<td>1281</td>
<td>1172</td>
<td>1090</td>
<td>1009</td>
</tr>
</tbody>
</table>
According to the rock status before/after test 1 and 2, the grading value were graded based on RMR method evaluation system, see in Table 3.

Table 3. RMR grade of silty mudrock.

<table>
<thead>
<tr>
<th>Rock state</th>
<th>RMR grade</th>
<th>Compressive strength</th>
<th>RQD</th>
<th>Joint spacing</th>
<th>Joint state water</th>
<th>Total value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural</td>
<td>2</td>
<td>14</td>
<td>5</td>
<td>18</td>
<td>8</td>
<td>47</td>
</tr>
<tr>
<td>Soaked 0-2 days</td>
<td>2</td>
<td>14</td>
<td>5</td>
<td>18</td>
<td>6</td>
<td>45</td>
</tr>
<tr>
<td>Soaked more than 2 days</td>
<td>2</td>
<td>13</td>
<td>5</td>
<td>17</td>
<td>5</td>
<td>42</td>
</tr>
</tbody>
</table>

Analysis and Results

According to the above test data and eq. 2 - 5, cohesion(c), internal friction(\(\phi\)) angle and elastic modulus(\(E\)) of silty mudrock mass were calculated, then draw these date into several charts for analysis.

Influence of Temperature Difference

It is know from Fig. 4, c, \(\phi\) and \(E\) of rock mass are all less than they are in natural state when silty mudrock soaked in water bath 10 days with different water temperature shift mode, and these strength parameters decrease with the increase of temperature difference (\(\Delta T\)); the reduction rate of these strength parameters are larger when temperature difference is greater than 0\(^\circ\)C, and smaller when temperature difference is less than 0\(^\circ\)C. The results indicated that silty mudrock mass is earier to deteriorate under higher temperature difference.
Influence of Soaked Time

It is known from Fig. 5, $c$, $\varphi$ and $E$ of silty mudrock mass decrease with the increase of soaked time when silty mudrock soaked in water bath different days with water temperature shift mode 3, and the reduction of $c$ or $E$ modulus was either greater than it of $\varphi$. According to the lowering rate of these data curves, the process of strength degradation of silty mudrock can be divided into 2 periods: Rapidly degradation period, when the soaked time is less than 2 days, strength parameters of silty mudrock decelerate rapidly this period; Deceleration degradation period, when the soaked time is more than 2 days, the decelerate rate of strength parameters this period decrease with soaked time, and finally reach a steady-state.

Conclusions

Our research shows that strength parameters of silty mudrock mass all decrease with the increase of temperature difference, and decrease rapidly when soaking less than 2 days. It is indicated that silty mudrock mass is easier to deteriorate under higher temperature difference or short-term soaking.

References


