Research Article

Study on Relationship between Joint Surface’s Shear Strength and Morphology Parameter Deterioration of Typical Bank Slope in Wudongde

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The change of typical bank slope’s water occurrence environment and the special climatic condition of dry hot valley in Wudongde reservoir area will make the shear characteristics of jointed rock mass on bank slope deteriorate continuously. Based on this, the shear test of joint surface under heat-wet cycles is carried out. The results show the following. (1) The shear strength and joint roughness deteriorate significantly with the increasing test cycles, and the deterioration ranges are 70.90%–84.48% and 29.33%–61.56% in the first 5 cycles. (2) The shear strength’s deterioration caused by repeated shear is mainly in the initial state, and the shear strength’s deterioration caused by heat-wet cycles increases firstly and decreases later with the test cycles. (3) By introducing the equivalent damage coefficient of morphology, the shear strength calculation formula is improved, and it can be seen that the estimated value coincides with the modified test value. The research results can provide a reference for long-term variation and calculation method of joint surface’s shear strength under different water-rock interactions.

1. Introduction

Reservoir water level fluctuation will change the water occurrence environment of bank slope, and different ways of water-rock interaction such as long-term immersion and dry-wet cycles will weaken the physical and mechanical parameters of rock to different degrees on bank slope. Actually, the stability of rock slope is mainly controlled by the joint surface inside rock mass. As the joint surface frequently reacts with water, its shear strength will deteriorate over time [1, 2] that will eventually lead to partial instability of the slope and even cause a wider range of collapse. Therefore, affected by the rise and fall of reservoir water level with the influence of changing water levers, the shear characteristics’ long-term variation of joint surfaces in hydro-fluctuation belt is crucial to the study of slope stability.

There are many studies on shear characteristics about joint surface or fracture under different water-rock interactions. For example, some scholars [3–7] studied the variation law of joint surface’s shear characteristics under different immersion times and found that the shear characteristics deteriorated significantly. Some scholars [8–14] also found the regular pattern of influence on dry-wet cycle on joint surface’s shear characteristics and deduced the deterioration formula of shear strength combined with the change of morphology parameters. The rock itself is a bad heat conductor, so in the process of water-rock interaction, it is necessary to consider the influence of temperature. Especially in the hot and dry valley areas of the Jinsha River.
where there are abundant light and heat resources, the shear characteristics of the jointed rock mass on the surface of the bank slope under the heat-wet cycles need attention. In particular, large reservoirs such as Baihetan and Wudongde make part of the jointed rock mass on the bank slope in this water environment.

At present, there are many studies on the deterioration of rock physical and mechanical parameters under heat-wet cycles [15–17], but there are few results about joint surface or fracture. Therefore, this paper carried out the test on influence of heat-wet cycles about the shear strength and morphology parameters of joint surface and obtained the variation law of shear characteristics and morphology parameters and then deduced the shear strength deterioration formula. The results can provide ideas for the analysis on the stability of bank slopes under long-term operation conditions of large reservoir in hot and dry valley.

1.1. Experimental Procedure. In this paper, in order to reduce the discrete effect caused by the difference of joint surface morphology, the single-joint repeated shear method was adopted [18]. The sandstone rock from the typical bank slope in upstream of Wudongde reservoir area was made into a cube block with a length of 100 mm. Then, the block was split along its axis to form a single-joint specimen, as shown in Figure 1. From the prepared single-joint specimens, the specimens with similar morphology parameters of joint surface were chosen as the test specimen.

As the height of Wudongde reservoir hydro-fluctuation belt is 30 m (945 m–975 m) and the jointed rock mass at the bottom of hydro-fluctuation belt still bears a certain water pressure, its deterioration effect is more obvious [19]. For experimental convenience, 0.3 MPa water pressure was set. Referring to the actual situation, the heating temperature is set to 70°C and the heating time is 8 h. According to the water quality test report of Wudongde reservoir, the pH of the immersion solution was set to 8.35. A total of 12 test cycles were set. After the end of initial saturated state, 1st, 3rd, 5th, 8th, and 12th immersion, the joint surface morphology scanning and shear test of the joint specimen were carried out. The normal stress of the direct shear test was set to 0.5 MPa, 1.0 MPa, 1.5 MPa, and 2.0 MPa. The test process is shown in Figure 2. The main test instruments include YRK-2 rock immersion-air drying test instrument (Figure 3),
2. Analysis of Joint Surfaces’ Shear Strength Deterioration Law

2.1. Joint Surface’s Shear Strength Curve. Under different normal stresses, the variation curves of shear strength of joint surface with test cycles and shear times are shown in Figure 6. As shown in Figure 6, the difference of 6 times shear strength in the initial state is significant. With the increase of test cycle, different strengths of repeated shear in each cycle gradually decrease. Taking the average value of the repeated shear strengths at each cycle, it can be seen that with the increase of the test cycle, the joint surface’s shear strength under different normal stresses decreases evidently in the first five cycles, and then slowly later. In general, under the combined action of repeated shear and heat-wet cycles, the joint surface’s shear strength deteriorates significantly.

2.2. Analysis of Joint Surfaces’ Shear Strength Deterioration Value. According to the method proposed in reference [18], the effects of repeated shear and heat-wet cycles on shear strength are distinguished, as shown in Figure 7. The deterioration value of joint surface’s shear strength caused by repeated shear is the most obvious one in the initial state, then decreases sharply, and tends to be stable with the increase of test cycles. The deterioration value of shear strength caused by heat-wet cycles is larger at the 1st and 3rd test cycle and then decreases sharply and gradually after the 5th cycle.

By eliminating the influence of repeated shear, the deterioration law curve of joint surface’s shear strength only under heat-wet cycles is obtained, as shown in Figure 8. From Figure 8, it can be seen that under heat-wet cycles only, with the increase of the test cycle, the joint surface’s shear strength shows a decreasing trend of “fast at first and slow later” and gradually tends to be stable after the 5th cycle. At the same test cycle, the normal stress has a great influence on the deterioration of joint surface’s shear strength. The greater the normal stress is, the greater the deterioration will be because in the shear process, the greater the normal stress is, the greater the damage of the joint surface will be and the more serious the structural damage in mineral particles of the joint surface will be. Finally, the deterioration effect of the heat-wet cycle on the joint surface is also magnified.

3. Analysis of Joint Surface Roughness and Shear Strength

The research shows that the roughness of joint surface has a strong association with the root mean square of slope of joint surface [20]. After each test, the morphology of joint surface was scanned. The morphology scanning result of typical joint surface is shown in Figure 9. The root mean square of slope is extracted. The roughness coefficient JRC of joint surface is calculated by the following formula:

$$JRC = 32.69 + 32.98 \cdot \lg(S_{dq})$$

where $S_{dq}$ is the joint surface’s root mean square of slope.

The normalized roughness coefficient curves of joint surfaces in different test cycles are shown in Figure 10. From Figure 10, it can be seen that under different normal stresses, the deterioration law of JRC is consistent, and the overall deterioration trend is “fast at first and slow
Figure 6: Variation of joint surface’s shear strength under different normal stresses. (a) 0.5 MPa. (b) 1.0 MPa. (c) 1.5 MPa. (d) 2.0 MPa.

Figure 7: Deterioration value of shear strength caused by repeated shear and heat-wet cycles. (a) Deterioration value of shear strength caused by repeated shear. (b) Deterioration value of shear strength caused by heat-wet cycles.
later.” After the fifth cycle, the change of JRC gradually tends to be stable, which is consistent with the deterioration law of the shear strength.

However, the change of morphology parameters in test is the result of both repeated shear and heat-wet cycles. As the sandstone structure used in the test is relatively dense, the influence of heat-wet cycle on joint surface’s morphology parameters cannot be reflected directly, which can only be reflected from the modified influence on joint surface’s shear strength under heat-wet cycle. Therefore, in this paper, the ratio of shear strength’s deterioration value caused by heat-

### Table 1: Damage coefficient of JRC by heat-wet cycle.

<table>
<thead>
<tr>
<th>Test cycle/N</th>
<th>Normal stress/MPa</th>
<th>0.5</th>
<th>1.0</th>
<th>1.5</th>
<th>2.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.517</td>
<td>0.563</td>
<td>0.491</td>
<td>0.530</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>0.784</td>
<td>0.781</td>
<td>0.769</td>
<td>0.788</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>0.612</td>
<td>0.612</td>
<td>0.606</td>
<td>0.611</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>0.458</td>
<td>0.446</td>
<td>0.447</td>
<td>0.432</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>0.419</td>
<td>0.468</td>
<td>0.481</td>
<td>0.477</td>
<td></td>
</tr>
</tbody>
</table>

### Table 2: JRC under heat-wet cycles.

<table>
<thead>
<tr>
<th>Test cycle/N</th>
<th>Normal stress/MPa</th>
<th>0.5</th>
<th>1.0</th>
<th>1.5</th>
<th>2.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>15.569</td>
<td>12.739</td>
<td>12.545</td>
<td>12.546</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>14.894</td>
<td>11.892</td>
<td>11.534</td>
<td>11.483</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>13.632</td>
<td>10.323</td>
<td>9.836</td>
<td>9.760</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>12.991</td>
<td>9.460</td>
<td>9.114</td>
<td>8.620</td>
<td></td>
</tr>
</tbody>
</table>

### Figure 8: Deterioration law curve of shear strength of joint surface under heat-wet cycles.

### Figure 9: Scanning image of typical joint surface morphology.

### Figure 10: Normalized JRC change curves under heat-wet cycles and repeated shear.

### Figure 11: Deterioration curve of JRC under heat-wet cycles.
Table 3: Fitting formula and parameter statistics of JRC with heat-wet cycles.

<table>
<thead>
<tr>
<th>Normal stress/MPa</th>
<th>Fitting formula</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>( JRC_{0}^{H-W} = JRC_{0}^{H-W} (D + E \times F^{N}) )</td>
<td>0.823</td>
<td>0.181</td>
<td>0.681</td>
<td>0.993</td>
</tr>
<tr>
<td>1.0</td>
<td></td>
<td>0.726</td>
<td>0.282</td>
<td>0.679</td>
<td>0.992</td>
</tr>
<tr>
<td>1.5</td>
<td></td>
<td>0.711</td>
<td>0.296</td>
<td>0.653</td>
<td>0.993</td>
</tr>
<tr>
<td>2.0</td>
<td></td>
<td>0.669</td>
<td>0.337</td>
<td>0.699</td>
<td>0.998</td>
</tr>
</tbody>
</table>

Figure 12: Strength deterioration curve of rock wall on joint surface under heat-wet cycles.

Figure 13: Deterioration curve of basic internal friction angles under heat-wet cycles.

where \( \Delta \tau_{(N)}^{H-W} \) is the shear strength’s deterioration value caused by heat-wet cycles in the \( N_{th} \) test cycle.

According to formula (2), \( \delta_{(N)} \) is counted and the results are shown in Table 1.

The calculation formula of joint surface roughness coefficient in different test cycles is shown in the following formula:

\[
JRC_{(N+1)}^{H-W} = JRC_{(N+1)} + \sum^{N}_{N=0} [(1 - \delta_{(N+1)}) \Delta JRC_{(N+1)}],
\]

(3)

where \( JRC_{(N+1)}^{H-W} \) is the roughness coefficient caused by heat-wet cycles in \((N+1)_{th}\) test cycle, \( \Delta JRC_{(N+1)} \) is the deterioration value of joint surface roughness coefficient in \((N+1)_{th}\) test cycle, and \( \delta_{(N+1)} \) is the damage coefficient of joint surface roughness coefficient in \((N+1)_{th}\) test cycle.

Based on the variation curve of joint surface roughness coefficient and \( \delta_{(N)} \) in Table 1, according to formula (3), the modified joint surface roughness coefficient under heat-wet cycle (Table 2) can be obtained. The normalized curve of joint surface roughness coefficient \( JRC_{(N)}^{H-W} \) only varying with heat-wet cycle is drawn, as shown in Figure 11.

From Figure 11, it can be seen that the JRC presents a deterioration trend of “fast at first and slow later” under heat-wet cycles only. The greater the normal stress is, the greater the deterioration range will be. The fitting results of joint surface roughness coefficient with heat-wet cycles under different normal stresses are shown in Table 3.

4. The Shear Strength Deterioration Formula of Joint Surface under Heat-Wet Cycles

According to the JRC-JCS model proposed by Barton and Choubey [21, 22], the shear strength of rock joint surface can be calculated by the following formula:

\[
\tau = \sigma_{n} \tan \left [ JRC \cdot \lg \frac{JCS}{\sigma_{n}} + \phi_{b} \right ],
\]

(4)

where \( \tau \) is the shear strength of joint surface, \( \sigma_{n} \) is the normal stress, JRC is the roughness coefficient of joint surface, JCS is the rock wall strength of joint surface, and \( \phi_{b} \) is the basic internal friction angle.

The uniaxial compressive strength of specimens with different heat-wet cycles is taken as the rock wall strength of joint surface. The variation curve is shown in Figure 12.

At the same time, the basic internal friction angles of joint surface with different heat-wet cycles were tested and counted. The variation curve is shown in Figure 13.
According to the test results and analysis above, bring the modified roughness coefficient $JRCH(N)$ of joint surface, the rock wall strength $JCS(N)$, and the basic internal friction angle $\varphi_b(N)$ at each heat-wet test cycle into formula (4). The deterioration formula of joint surface shear strength under heat-wet cycles can be obtained as follows:

$$
\tau_{(N)} = \sigma_n \tan \left[ JRCH_{(N)} \cdot \lg \left( \frac{JCS_{(N)}}{\sigma_n} \right) + \varphi_b_{(N)} \right],
$$

where $JRCH_{(N)}$, $JCS_{(N)}$, and $\varphi_b_{(N)}$ are the relationship functions among roughness coefficient of joint surface, rock wall strength of joint surface, and basic internal friction angle of joint surface and heat-wet cycle $N$ under different normal stress.

The shear strength of joint surface at each heat-wet test cycle under different normal stresses can be calculated by formula (5). The calculated values are compared with the modified test values, as shown in Figure 14.

From Figure 14, the shear strength of joint surface calculated by formula (5) coincides with the modified test values. The error range is $-5.94\%$–$-0.61\%$, $6.82\%$–$9.50\%$, $0.16\%$–$4.88\%$, and $2.32\%$–$9.19\%$ under different normal stress. The error is within the allowable range of estimation. It indicates that the above $JRCH$ equivalent deterioration method is reasonable and can estimate the shear strength of joint surface under heat-wet cycles well.

5. Conclusions

In this paper, the shear test of joint surface under heat-wet cycles is carried out and the following conclusions are obtained:

1. The shear strength and roughness coefficient of joint surface show a deterioration trend of “fast at first and slow later” with the increase of test cycles, and the deterioration rate is larger in the first 5 test cycles.

2. The deterioration of shear strength caused by repeated shear is the most obvious one in the initial state, then decreases sharply, and tends to be stable with the increase of test cycles. The deterioration value of shear strength caused by heat-wet cycle is obvious in the first 3 test cycles, then decreases significantly, and tends to be stable.

3. Considering the ratio coefficient of shear strength deterioration value caused by heat-wet cycles to the total deterioration value at current cycle as the equivalent damage coefficient of joint surface morphology parameters under heat-wet cycles, an improved method for calculating the shear strength of joint surface under heat-wet cycles is proposed. The estimated results coincide with the modified test values.

Data Availability

All data included in this study are available upon request by contact with the corresponding author.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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