Study on the Deformation Characteristics of Fractured Basalt Under Coupling of Three-Dimensional Stress and Water Pressure Cycling

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Abstract. The seepage-stress coupling of fractured rock masses is a physical, chemical and mechanical process that depends strongly on the lithological conditions, structural state, initial stress level and stress path for the hydraulic coupling during water storage. A newly developed true triaxial hydraulic coupling test system named HMTS-1200 was used to carry out triaxial hydromechanical coupling deformation tests on fractured basalt under water pressure along a cyclic loading and unloading path. The following test results were obtained. During cyclic water pressure loading and unloading, the additional axial deformation exhibits the characteristic fluctuations of compression-expansion-compression, whereas the lateral deformation exhibits the characteristic fluctuations of expansion-compression-expansion. Under hydraulic-mechanical coupling, the coupling of the axial pressure and the water pressure is noticeable. The lower the axial pressure is, the more noticeable the additional specimen deformation is. The deformation modulus of the fractured basalt under triaxial stress-hydraulic pressure coupling depends strongly on the loading-unloading of the water pressure and the confining pressure. The deformation modulus is logarithmic in the number of cycles and linear in the water pressure. The abovementioned test results serve as an important reference for the study of hydraulic coupling characteristics of and time effects on bank rock mass deformation parameters during reservoir operation.

Keywords: Fractured rock mass; Hydraulic-mechanical coupling test; cyclic loading and unloading water pressure; deformation parameters
1. Introduction

Successive construction and operation of high dams and reservoirs in Western China has significantly changed the seepage field and in situ stress field of reservoir bank rock masses, which are affected by periodic changes in reservoir water levels. New geological and environmental problems have arisen. The water-rock interaction is a dominant factor for the deformation of bank slopes and the generation of major engineering disasters after reservoir impoundment. The variation law of the deformation parameters of fractured rock masses under stress-water pressure coupling action is an important topic for investigating the deformation and failure mechanism of reservoir bank rock masses.

Fractured rock masses soften upon contacting water, and scholars have made many important research achievements on this subject. For example, Baud P, Duda M and Teng T studied the water-softening effect of sandstone using triaxial tests\cite{1-3}; and Cherblanc F and Xie X elucidated the microscopic mechanism by which water softens rocks\cite{4-5}. Researchers have also investigated the influence of the water content on rock mechanical properties: Hawkins A B carried out an experimental study on the sensitivity of the water content to the deformation and strength of sandstone\cite{6}; Erguler Z A measured the uniaxial compressive strength, tensile strength and elastic modulus of specimens with different water contents and established a method for estimating the rock strength and deformation modulus based on physical properties\cite{7}; Yilmaz I established an empirical relationship between the water content and the uniaxial compressive strength\cite{8}; Vásárhelyi B and Wong L N Y statistically analysed the influence of the water content on the strength of sandstone and limestone\cite{9-11}; Li B and Pan Z carried out triaxial compression tests on raw coal with different moisture contents and obtained the variation law of coal rock deformation with the moisture content\cite{12-13}. Studies have been carried out to determine the influence of the soaking time and soaking pressure on rock: Bian K performed laboratory tests to determine the variation in the mechanical properties of shale samples with the soaking time\cite{14}; Wang R studied the softening effect and deformation characteristics of fractured rocks after pressure immersion and long-term immersion\cite{15}; Huang Z used uniaxial tests and scanning electron microscopy to study the variation laws of the compressive strength and deformation modulus of argillaceous slate with the water absorption time\cite{16}; Chen P studied the influence of different soaking heights and water distributions on the short- and long-term mechanical behaviour of rock\cite{17}; and Tang S established an empirical relationship between the mechanical properties and the water content and soaking time of black sandstone\cite{18}.

Liu X, Lin M L, Hale P A, Özbek A, Zhou Z, Deng H, et al. Deng Huafeng et al. investigated the mechanism and rules of the effect of periodic variations in the reservoir water level on sloped rock masses by carrying out rock mechanics tests after different dry-wet cycles for different lithologic samples: the degradation law for the shear strength after the water saturated-dry cycles and empirical equations of the influence of the dry-wet cycles on the rock mechanical properties were obtained\cite{19-24}; Li J, Tang H, Wasantha P L P carried out triaxial hydraulic-mechanical coupling tests on a rock mass in deep reservoir water to study the effect of high water pressure on the rock deformation parameters\cite{25-27}.

Scholars have intensively investigated the variation law of the mechanical properties of reservoir rock bank masses resulting from reservoir impoundment. However, most current studies have consisted of indoor tests performed on standard size specimens, and the test results mostly reflect the softening effect, the deterioration law of mechanical properties under dry-wet cycles, and the
influence mechanism of water pressure on the mechanical properties of intact rocks. To overcome the limitation of the rock sample size and perform an in-depth analysis of the deformation and strength characteristics of fractured rock masses under complex stress-water pressure coupling, a newly developed HMTS-1200 hydraulic-mechanical coupling test system was used to carry out triaxial hydromechanical coupling deformation tests on fractured basalt under water pressure during cycling loading. The specimen dimensions were 310 mm×310 mm×620 mm. The deformation law of the fractured rock mass under stress-water pressure coupling was obtained. The experimental results reveal the evolution law of the deformation parameters of fractured rock masses under stress-water pressure coupling. This law reflects the coupling mechanism of the rock mass structure, three-dimensional stress field and water pressure.

2. Cyclic loading and unloading tests of a rock mass under stress-water pressure coupling

A series of triaxial deformation tests under stress-water pressure coupling are designed to investigate the deformation mechanism during hydromechanical coupling of a fractured rock mass in a reservoir with fluctuating water levels. Basalt specimens are obtained from the dam area of the XLD hydropower station. The specimen dimensions are 310 mm×310 mm×620 mm. Cracks on the surface of the specimen are developed and are mostly closed to slightly open, with no filling (Fig. 1). The experimental equipment adopted is the newly developed HMTS-1200 hydromechanical coupling true triaxial test system (Fig. 2).

The loading steps are given below.

① Apply equal confining pressures $\sigma_1=\sigma_2=\sigma_3$ until constant values are reached;
② Maintain $\sigma_2$ and $\sigma_3$ unchanged and apply $\sigma_1$ until a predetermined value is reached;
③ Maintain the values of $\sigma_1$, $\sigma_2$, and $\sigma_3$ unchanged; load the water pressure to 3 MPa and then unload the water pressure to 0 MPa in steps for four consecutive cycles;
④ Change the initial predetermined values of $\sigma_1$, $\sigma_2$, and $\sigma_3$; repeat steps ①-③ up to the end of the test.

Fig. 1 Photo of the basalt sample   Fig. 2 HMTS-1200 hydraulic-mechanical coupling test system

Typical whole process curves of the deformation test of the basalt specimen under triaxial stress-water pressure cyclic loading-unloading coupling are shown in Fig. 3 – Fig. 5 (the compression deformation is positive and the expansion deformation is negative in the figures). The additional deformation of the specimen exhibits the following characteristics with changing water pressure.
(1) During the loading and unloading of the water pressure, the axial additional deformation exhibits characteristic fluctuations of compression-expansion-compression, whereas the lateral deformation exhibits characteristic fluctuations of expansion-compression-expansion.

(2) During water pressure loading and unloading, the two additional lateral horizontal deformations of the specimen are not completely consistent, and the additional deformation of the specimen caused by water pressure loading and unloading exhibits clear anisotropic characteristics.

(3) At low axial and confining pressures, the compression deformation or expansion deformation caused by water pressure loading and unloading are noticeable, indicating that an increase in the initial stress level of the sample has a significant inhibitory effect on the additional sample deformation from the change in the water pressure.

(4) At the end of each water pressure loading and unloading cycle, the residual deformation of the specimen results in overall compression or expansion in the respective direction.

Fig. 3 Strain-water pressure-time test curves of specimen T1-2

Fig. 4 Strain-water pressure-time test curves of specimen T1-3
The incremental Hooke's law can be used to derive equation (1) for the deformation modulus of basalt under triaxial stress-water pressure coupling:

\[
E = \frac{\Delta \sigma_i}{\Delta \epsilon_i}, \quad (\Delta \sigma_2 = \Delta \sigma_3 = 0)
\]

\[
v_{12} = -\frac{\Delta \epsilon_2}{\Delta \epsilon_1},
\]

\[
v_{13} = -\frac{\Delta \epsilon_3}{\Delta \epsilon_1},
\]

where \( \epsilon_1, \epsilon_2, \) and \( \epsilon_3 \) are the normal strains in the three directions of the sample; \( E \) is the axial deformation modulus of the specimen; \( v_{12} \) and \( v_{13} \) are Poisson's ratios; and \( \sigma_1, \sigma_2, \) and \( \sigma_3 \) are the normal stresses in the three directions of the sample (MPa).

The deformation modulus of the specimens under different lateral pressure-axial compression-water pressure couplings can be calculated by equation (1), and the results are shown in Table 1. The following conclusions are drawn from a statistical analysis.

(1) Under a constant initial stress, the deformation modulus of basalt is approximately negatively linearly correlated with the water pressure (Fig. 6).

(2) For a fixed water pressure, the higher the lateral pressure and the axial compression are, the higher the deformation modulus is, and the relationship between the deformation modulus and the axial compression can be fitted by an exponential function (Fig. 7).
(3) Under the action of the water pressure circulation, increasing the repeated loading times of the water pressure causes the deformation modulus of basalt corresponding to the same water pressure environment to gradually decrease and finally stabilise. For the same stress-water pressure coupling state, there is a logarithmic relationship between the deformation modulus and cyclic loading and unloading times (Fig. 8).

![Fig. 7 Variation in the deformation modulus with the axial compression](image)

**Fig. 7** Variation in the deformation modulus with the axial compression

### Tab. 1 Deformation modulus of basalt under hydromechanical coupling

| No. | Lateral Pressure /MPa | Axial compression /MPa | Cycle index | Water pressure/MPa |
|-----|-----------------------|-----------------------|-------------|-------------------|
|     |                       |                       | 0 | 1 | 2 | 3 |
| T1-2 | 0                      | 9                     | 1 | 24.1 | 22.2 | 20.5 | 18.9 |
|      |                        |                       | 2 | 20.6 | 19.8 | 18.9 | 18.2 |
|      |                        |                       | 3 | 19.9 | 19.1 | 18.3 | 17.6 |
|      |                        |                       | 4 | 19.2 | 18.9 | 18.2 | 17.4 |
|      |                        |                       | 1 | 49.7 | 45.7 | 42.2 | 41 |
|      |                        |                       | 2 | 44.9 | 41.5 | 40.1 | 38.6 |
|      |                        |                       | 3 | 41.6 | 40.9 | 39.1 | 37.4 |
| T1-3 | 4                      |                       | 4 | 39.5 | 38.2 | 37  | 35.5 |
|      |                        |                       | 1 | 49.2 | 48.2 | 47.1 | 44.7 |
|      |                        |                       | 2 | 46.8 | 45.8 | 45.4 | 44.6 |
|      |                        |                       | 3 | 49.5 | 49   | 47.8 | 47.2 |
|      |                        |                       | 4 | 48.2 | 48.4 | 46.8 | 45.4 |
4. Hydraulic-mechanical coupling model for deformation parameters of basalt

The analysis presented above shows that the deformation modulus of basalt depends strongly on the water pressure and cyclic loading and unloading times. The effect of the water pressure and cyclic loading and unloading times on the deformation modulus of basalt can be expressed by the following composite function:

\[ E = a\sigma_w + b \ln(N) + c \]

where \( N \) is the loading and unloading cycle times of the water pressure and \( a, b, \) and \( c \) are fitting constants. This equation is analysed below.

1. When the water pressure is constant, the equation degenerates to

\[ E = b \ln(N) + C \]

where \( b \) and \( C \) are fitting constants.

That is, the deformation modulus of the fractured rock mass is logarithmic in the loading and unloading times of the water pressure.

2. When \( N \) is a constant, equation (2) degenerates to

\[ E = a\sigma_w + C \]

where \( a \) and \( C \) are fitting constants.

This result shows that during a given water pressure loading and unloading cycle, the deformation modulus of the fractured rock mass is linear in the water pressure.

The regression coefficients of basalt samples obtained from regression fitting under different stress-water pressure coupling states and the fitting values calculated by equation (2) are shown in Table 2 and Fig. 9 to Fig. 11.

A comparative analysis of the fitted and experimental values shows that the error in the model results is within ±9%.

Equation (2) for the composite function model accurately describes the variation law of the deformation modulus of the fractured rock mass under a given stress field with the cyclic loading and unloading process of the water pressure.
### Tab. 2 Regression models and fitted values of the deformation modulus of basalt under different stress-water pressure coupling states

| No. | Lateral pressure /MPa | Axial compression /MPa | Cycle index | Water pressure/MPa | Fitting model |
|-----|-----------------------|------------------------|-------------|-------------------|--------------|
|     |                       |                        |             |                   | Test value   | Fitted value | Error  | Test value   | Fitted value | Error  | Test value   | Fitted value | Error  |
| T1-2 |                       |                        |             |                   | 0            | 24.1         | 24.1   | 0.0%         | 22.2         | 22.9   | 3.3%         | 20.5         | 21.8   | 6.1%         | 18.9         | 20.6   | 8.9%         |
| 1   |                       |                        |             |                   | 1            | 19.8         | 19.8   | 0.0%         | 19.8         | 19.8   | 0.0%         | 19.8         | 19.8   | 0.0%         | 19.8         | 19.8   | 0.0%         |
| 2   |                       |                        |             |                   | 2            | 19.2         | 19.4   | 1.0%         | 18.9         | 18.7   | 1.1%         | 18.4         | 18.9   | 2.7%         | 18.2         | 18.2   | 0.2%         |
| 3   |                       |                        |             |                   | 3            | 19.7         | 20.4   | 3.2%         | 19.2         | 19.7   | 2.8%         | 19.1         | 19.5   | 2.1%         | 18.7         | 19.1   | 2.4%         |
| 4   |                       |                        |             |                   | 4            | 20.4         | 20.6   | 1.0%         | 19.8         | 19.8   | 0.0%         | 19.7         | 19.8   | 0.5%         | 19.4         | 19.6   | 1.1%         |
| T1-3 |                       |                        |             |                   | 0            | 24.1         | 24.1   | 0.0%         | 22.2         | 22.9   | 3.3%         | 20.5         | 21.8   | 6.1%         | 18.9         | 20.6   | 8.9%         |
| 1   |                       |                        |             |                   | 1            | 19.8         | 19.8   | 0.0%         | 19.8         | 19.8   | 0.0%         | 19.8         | 19.8   | 0.0%         | 19.8         | 19.8   | 0.0%         |
| 2   |                       |                        |             |                   | 2            | 19.2         | 19.4   | 1.0%         | 18.9         | 18.7   | 1.1%         | 18.4         | 18.9   | 2.7%         | 18.2         | 18.2   | 0.2%         |
| 3   |                       |                        |             |                   | 3            | 19.7         | 20.4   | 3.2%         | 19.2         | 19.7   | 2.8%         | 19.1         | 19.5   | 2.1%         | 18.7         | 19.1   | 2.4%         |
| 4   |                       |                        |             |                   | 4            | 20.4         | 20.6   | 1.0%         | 19.8         | 19.8   | 0.0%         | 19.7         | 19.8   | 0.5%         | 19.4         | 19.6   | 1.1%         |
| T1-4 |                       |                        |             |                   | 0            | 24.1         | 24.1   | 0.0%         | 22.2         | 22.9   | 3.3%         | 20.5         | 21.8   | 6.1%         | 18.9         | 20.6   | 8.9%         |
| 1   |                       |                        |             |                   | 1            | 19.8         | 19.8   | 0.0%         | 19.8         | 19.8   | 0.0%         | 19.8         | 19.8   | 0.0%         | 19.8         | 19.8   | 0.0%         |
| 2   |                       |                        |             |                   | 2            | 19.2         | 19.4   | 1.0%         | 18.9         | 18.7   | 1.1%         | 18.4         | 18.9   | 2.7%         | 18.2         | 18.2   | 0.2%         |
| 3   |                       |                        |             |                   | 3            | 19.7         | 20.4   | 3.2%         | 19.2         | 19.7   | 2.8%         | 19.1         | 19.5   | 2.1%         | 18.7         | 19.1   | 2.4%         |
| 4   |                       |                        |             |                   | 4            | 20.4         | 20.6   | 1.0%         | 19.8         | 19.8   | 0.0%         | 19.7         | 19.8   | 0.5%         | 19.4         | 19.6   | 1.1%         |

Fitting models:
- \( E = -1.17 \sigma_y - 3.4N(\sigma_y) + 24.1 \)
- \( E = -1.90 \sigma_y - 7.4N(\sigma_y) + 49.7 \)
- \( E = -1.46 \sigma_y - 0.24N(\sigma_y) + 49.5 \)
- \( E = -1.31 \sigma_y - 2.9N(\sigma_y) + 58.3 \)
- \( E = -3.45 \sigma_y - 5.8N(\sigma_y) + 64.7 \)
- \( E = -2.10 \sigma_y - 9.9N(\sigma_y) + 65.5 \)
5. Conclusion

(1) A newly developed HMTS-1200 hydraulic-mechanical coupling test system for fractured rock masses was used to carry out triaxial hydromechanical coupling deformation tests on fractured basalt specimens with dimensions of 310 mm×310 mm×620 mm under cyclic water pressure loading-unloading.

(2) Under a constant initial stress and cyclic water pressure loading-unloading, the axial additional deformation exhibits the characteristic fluctuations of compression-expansion-compression, whereas the lateral deformation exhibits the characteristic fluctuations of expansion-compression-expansion, and the additional deformation from water pressure loading and unloading exhibits anisotropic characteristics. At low axial and confining pressures, the compression deformation or expansion deformation caused by water pressure loading and unloading are noticeable, indicating that the increase in the initial stress level of the sample has a significant inhibitory effect on the additional deformation of the sample caused by the change in the water pressure.

(3) The deformation modulus of the fractured basalt specimen under triaxial stress-hydraulic pressure coupling depends strongly on the loading-unloading of the water pressure and confining pressure. The higher the lateral pressure and the axial compression are, the higher the deformation modulus is. The deformation modulus of basalt decreases with increasing water pressure. Upon increasing the repeated loading times of the water pressure, the deformation modulus of basalt decreases gradually and finally stabilises.

(4) The deformation modulus is logarithmic in the number of cycles and linear in the water pressure. A composite function model can accurately describe the variation law of the deformation modulus of the fractured rock mass under a given stress field with the cyclic water pressure loading and unloading.

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