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# Experimental investigation on shear creep properties of undisturbed rock discontinuity in Baihetan Hydropower Station

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## 1. Introduction

In nature, it is common that rock masses are discontinuous because they are always broken by joints, fractures, bedding planes, rock cleavage, foliation, shear zones, and faults.[1] Currently, a very large construction project, that of the Baihetan Hydropower Station, is underway in Southwest China. Field geological investigations have indicated that many discontinuities, such as inter-layer bedding planes, inner-layer bedding planes, faults, and base cracks have developed in the rock masses of the Baihetan Dam region. Such materials possess higher humidity as well as lower density and strength. In addition, the filling materials are weak. Therefore, discontinuities with the aforementioned poor physical character play a significant role in engineering the stability and safety of hydropower stations.

Baihetan Hydropower Station is an arch dam and underground hydroelectric power plant currently being constructed on the Jinsha River, a tributary of the Yangtze River in the Yunnan and Sichuan provinces of China. When finished, it will be the second-largest dam in China and the third largest in the world, in terms of installed capacity. It was designed to provide power generation, farmland irrigation, and sediment and flood control, as well as to improve navigation downstream. The length of Baihetan Dam, of concrete gravity type, is 280 m. The total capacity of the hydropower plant will be 14,000 MW.

The creep of discontinuities is one of the most important characteristics of rock mass.[2–4] Delay failure may occur several days or years after excavation.[5] Laboratory shear tests are the most common practice implemented to investigate creep in discontinuities.[6] However, most shear experiments have been carried out on artificial discontinuity samples because it is very difficult to collect undisturbed samples.[7,8] In order to evaluate the long-term safety and stability of Baihetan Hydropower Station, laboratory shear creep tests were carried out on fault F17 of the Baihetan Dam region. The results could provide a useful reference for the analysis of the long-term stability and safety of Baihetan Hydropower Station.

## 2. Methodology

### 2.1. Material characterization and sample preparation

Fault F17 is a discontinuity in the left-hand bank of the Jinsha River in the Baihetan Dam region (Fig. 1). This fault skew crosses the middle part of the dam region and extends more than 1400 m. The occurrence is at N30°∼60°E/NW∠70–85°. The discontinuity plane of fault F17 is filled with cataclasite mixed with fault mud, while the fault damage zone is breccia lava (Fig. 2). The fill materials are composed of andreattite (45%), chlorite (25%), illite (15%), feldspar (5%), quartz (5%), and hematite (5%). Physical property experiments were conducted on the fill materials and the results indicate that the natural density is 2.13 $g/cm^3$ and the water content is 5.45%, thereby the mean dry density of the discontinuity is 2.02 $g/cm^3$.

The undisturbed sample preparation is the most difficult part of the experimental setup. In order to minimize disturbance to the samples, they were prepared directly in the field. The sampling procedure can be divided into site selection, protection and cutting (Fig. 3). Particular attention was paid to preventing movement along the fracture surface. For this reason, wires were used to bind the two walls of the fault sample. The digged areas were filled with low-strength mortar. The surfaces of the sample were covered by mortar, and the sample was then polished to a cubic shape with a length of 150 mm. The shear plane was set in the middle of the sample. The samples were wrapped with plastic before testing in order to preserve the in situ moisture content.

### 2.2. Test equipment

Creep experiments were carried out on a CSS-3940YJ rock biaxial rheological testing machine produced by the Changchun Testing Machine Research Institute in China. This equipment comprised loading, measurement, and monitoring systems. Its maximum loading capacity is 400 kN. Shear deformation is measured by two linear, variable-displacement transducers (LVDTs) mounted on the shear box. The accuracy of the displacement transducers is 0.005 mm. All of the measured data are directly monitored by computer.

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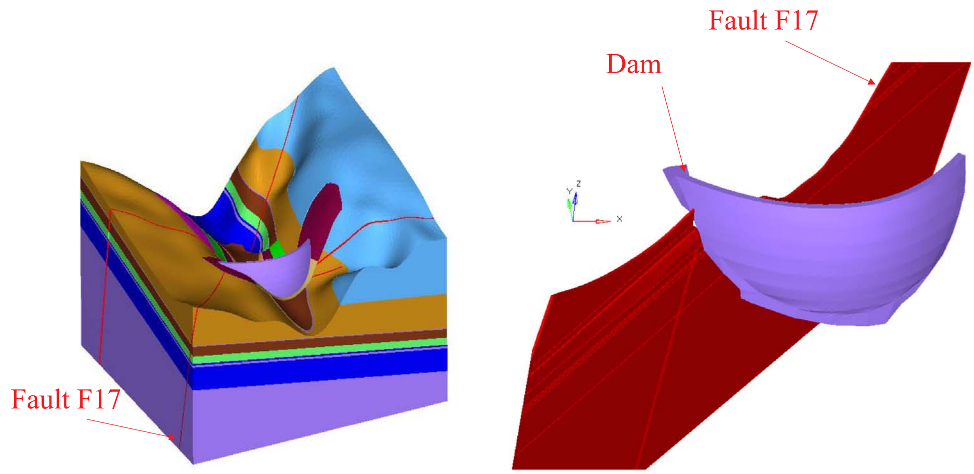


**Fig. 1.** Geological profile of Baihetan Dam region and fault F17 location.

### 2.3. Shear creep test procedures

Tests were conducted in the laboratory at constant temperature (24 ± 0.5 °C) and humidity. Because the discontinuity was under unconfined compression conditions, the normal stress should not be large. In this work, according to the field stress conditions, the normal stresses, 0.2, 0.6, and 1.0 MPa, were applied. The number of prepared samples were limited, and thus the multi-loading method was adopted.[9] First, the packaging was removed and the sample was placed into the shear box. It should be noted that the shear horizon is along the marked direction and parallel to the shear plane. Next, the shear box with the test sample was attached to the test machine, followed by pouring of fill sand into the fracture surface and filling with wax. Before doing this, the steel wires were cut off. Subsequently, the two LVDTs were installed in the shear box. Normal stress was achieved by loading to the desired value and was kept constant during the complete test. Finally, when the normal strain remained stable, multi-loading shear stress was applied under displacement-controlled conditions with a rate of 0.2 mm/min. Each shear stress level was maintained for approximately 72 h, which has been determined to be sufficiently long to reach the steady-state creep stage. When the shear displacement increased with a rate larger than threshold or the samples failed, data recording was stopped and the test ended. Before the shear creep tests, the direct shear tests were performed at the same normal stresses to determine the shear properties of the fault F17. The only difference of direct shear test from creep test was that the sample was subjected to continuous shear stress until failure. During the complete process, the normal stress was kept constant.

## 3. Experimental results

### 3.1. Direct shear test results

The stress-strain curves for fault F17 under a variety of normal stresses are presented in Fig. 4. A typical failed sample is shown in Fig. 5. In Fig. 4, the shear stress and shear strain are determined by measuring the area of the shear surface of the discontinuity samples. It is obvious that the shear strain at peak shear stress can reach $8 \times 10^{-2}$, which is much higher than that of intact rock. During the initial loading stage, the slopes of the curves are relatively small, which means that the shear stress increases slowly. This can be attributed to the closure of the pores and cracks between the rock debris and soil. With increasing shear stress, the pores and cracks have already closed. The slopes of the stress-strain curves increase rapidly, and when the stresses are near peak values, rock debris extrudes into soil, and slides and rolls along the fault planes. Therefore, the slopes of the curves decrease. After the peak


**Fig. 2.** Fault F17 in the dam region of Baihetan Hydropower Station.

stress is reached, the up and down parts of the discontinuity samples are thoroughly separated and the up-side slides and rolls along the failure plane. It is clear that the normal stress has a significant effect on the deformation behavior of the fault rock. The higher the normal stress, the higher the corresponding peak shear stress. The Mohr-Coulomb criteria were used to investigate the effect of normal stress on the strength of discontinuity. The results are given on the left-hand side of Fig. 4. It can be seen that both the peak strength and residual strength of fault F17 increase linearly with normal stress. The cohesions are 0.494 and 0.319 MPa and the corresponding internal friction angles 38.20° and 32.62°, respectively.

### 3.2. Shear creep test results

Considering that the creep property of rock discontinuities is significantly important for the long-term safety and stability of Baihetan Dam, multi-loading shear creep tests were carried out on fault F17 under different normal stresses. The stress conditions are given in Table 1. Based on the experimental results, the time-dependent deformation of fault F17 samples was identified.

#### 3.2.1. Creep strain behavior

As shown in Table 1, the shear creep tests were carried out on undisturbed samples under normal stresses of 0.2, 0.6, and 1.0 MPa. The loading procedures and deformation of the samples are presented in Fig. 6. It can be seen that for all three samples, apparent shear creep deformation was observed. Results in the literature show that the creep deformation of rock experiences three creep stages: transient creep, steady-state creep, and accelerated creep.[5,10] To identify the accuracy of creep deformation during the shear creep tests, a typical creep curve