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In-situ rock tests for fault gouge zone：A case in Fengman hydropower station, China

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Abstract. The existence of faults in the dam site area threatens the stability and safety of large-scale hydropower projects in China. The fault argillaceous zone is the worst kind of fault fracture zone, and the determination of its deformation and strength parameters is the key point of rock engineering investigation. In this study, the in-situ bearing plate test and direct shear test were carried out on the gouge zone of F67 fault in the dam site of Fengman Hydropower Station. The test results show that the deformation and shear law of each test point is good, which is basically consistent with the actual condition of the measured rock mass. However, due to the limited number of measurements, the results are limited in terms of macroscopic representation. The experimental results provide scientific basis for subsequent engineering design and further enhance the understanding of mechanical properties of fault gouges.

1 Introduction

With the rapid development of China's economy, the pace of various types of energy and infrastructure construction is accelerating. Regional stability in the fields of open-pit mining, energy, transportation and water conservancy and hydropower engineering often plays a controlling role in the safety, feasibility and economy of the whole project [1, 2]. As an important factor affecting the fault engineering characteristics, the study on the mechanical properties of fault gouges is helpful to explain and predict the disaster risk in the fault crossing area [3].

From the perspective of engineering geology, the fault argillaceous zone is a kind of weak zone compared with surrounding rock, and it is the boundary condition for many geological disasters. From the perspective of rock mechanics, the fault argillaceous zone is the key research object of rock engineering due to its poor mechanical properties, low strength and wide distribution [4]. In the long-term engineering practice, the physical and mechanical properties of rock mass in fault zone have been extensively studied, and abundant test data have been accumulated. Many scholars have studied the physical and mechanical properties of fault fracture zones in depth [5-9]. In terms of the physical and mechanical research of fault gouges, Geng et al. conducted systematic experimental studies on the mechanical properties of fault gouge in Honghe fault, Yimu fault, Haiyuan fault, Fuyun fault and Xianshuihe-Xiaojiang fault, which made scholars have a preliminary understanding of the mechanical properties of fault gouge in China [10]. Han made a detailed study and analysis of the physical and mechanical parameters of fault gouges at the Daliushu dam site of the Black Three Gorges, and connected it with its formative environment, which provided a reliable basis for demonstrating the quality of loose rock mass in the Black Three Gorges [11]. Klima conducted shear tests on clay-rich fault gouge samples and established a probabilistic prediction model for the shear strength performance [12].

The strength and integrity of dam foundation rock mass is one of the key factors affecting the dam safety [13]. The reasonable determination of mechanical parameters of dam foundation rock masses is the basis of stability analysis and safety evaluation of dam engineering. In-situ rock test is the main method to study the mechanism of rock mass deformation and failure, evaluate the mechanical properties of engineering rock mass and solve complex rock engineering problems [14].

The F67 fault is the largest developed fault zone with the worst engineering geological conditions in the dam site of the Fengman Hydropower Station. It has a great influence on the dam foundation deformation, anti-sliding and seepage stability. The purpose of this study is to determine the shear and deformation properties of the fault argillaceous zone of the F67 fault on the foundation plane of the dam foundation. It is proposed to use fine in-

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situ rock testing to provide scientific basis for subsequent engineering design and further enhance the understanding of mechanical properties of fault gouges.

2 Study area

2.1 Project overview

Fengman Hydropower Station is a large-scale hydroelectric power station built on the Songhua River in the Jilin City, Jilin Province. It mainly generates electricity, and also takes into account flood control, water supply, irrigation, ecological environment protection and tourism (Fig. 1). The project is 210 km away from the upstream Baishan Hydropower Station, and 16 km away from the downstream Jilin City. Chang-Ji Expressway is directly connected with the project area through National Road 202, with convenient transportation.

The Fengman Hydropower Station project is a renovation and upgrading project, and the project grade is first class. The dam, the spillway, diversion tunnel and the powerhouse are first-class buildings. The dam site is arranged 120 m downstream of the original dam site. The dam type is selected as a roller compacted concrete gravity dam. The dam crest is 269.9 m high and 1068.0 m long. The maximum dam height is 94.5 m.

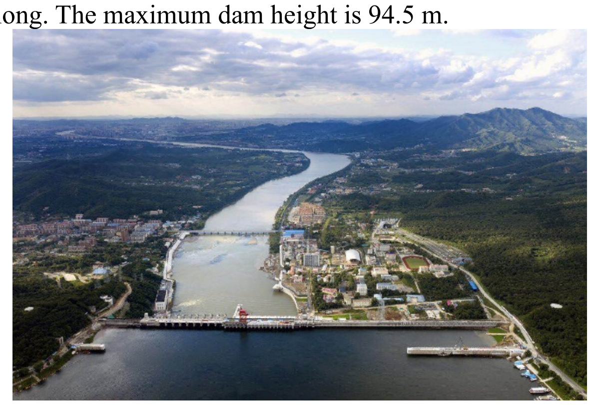

Fig. 1 anorama of the Fengman Hydropower Station.

2.2 Test section description

The F67 fault is the largest developed fault fracture zone with the worst engineering geological conditions in the dam site area. It passes through the dam site area along the river at the terrace on the right bank and is nearly orthogonal to the dam axis. The fault fracture zone is composed of multiple faults such as F67-1, F67-2, F67-3, F67-4 and F67-5. The overall trend of faults is N15°~50°W, with dip direction of SW and dip angle of 60°~85°. Due to the multi-period activities of the F67 fault, the fracture zone has a large number of faults and their distances are relatively close. In addition, under the influence of weathering, the faults have different widths and different characteristics. However, the width of the fracture zone gradually decreases from top to bottom, and the degree of fracture decreases with the increase of the depth. The argillaceous zone in the central zone of F67-1, F67-2 and F67-3 faults accounts for about 2.3% of the total width of the fault fracture zone. The F67-1 fault argillaceous zone has a width of about 0.5~0.7 m, and can be up to 2.5 m locally (revealed by drilling FZK138). As shown in Fig. 2, the fault gouge is composed of grey to grayish yellow mud and rock debris, which is plastic when wet. The widths of the argillaceous zone of F67-2 fault and F67-3 fault are 0.4~0.6 m and 0.05~0.1 m, respectively, and both of them are composed of mud and rock debris.

Fig. 2 The fault gouge of the F67 fault.

3 Methodology

3.1 Instrument and equipment

The main instrument and equipment used in this study include: the specimen processing equipment, reaction force device, normal load system, shear load system, measurement system and calibration system (Fig. 3a). Among them, the reaction force device uses anchor rods to provide the reaction load (Fig. 3b).

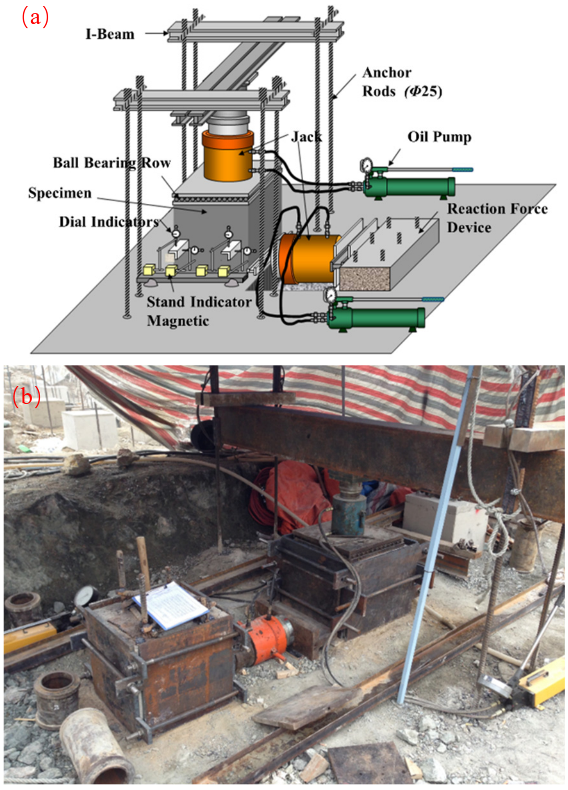

Fig. 3 Test equipments.

(a) Diagram of direct shear test. (b) The reaction force.

3.2 Processing of test points

In order to accurately select representative test sections and test points, it is necessary to clean up the gravel left by the excavation of the test site. As shown in Fig. 4, the cleaning method adopts waterwheel scouring and manual cleaning.

Fig. 4 Test site cleaning.

(a) Waterwheel scouring. (b) Manual cleaning.

3.2.1 Deformation test points processing

According to the requirements of "Rock Test Regulations for Hydropower and Hydraulic Engineering" (DL/T 5368-2007), the bearing plate method was used in the deformation test in this study. According to the requirements of test point processing, the steel drill and hand hammer were used to remove loose rock mass at first, and then flatten the Φ200 cm area centered on the test point, with the undulation difference controlled within 3~5 cm. A total of 6 test sites were set up. For specific operation, refer to the "Rock Test Regulations for Hydropower and Water Conservancy Engineering" (DL/T 5368-2007). The on-site work photos are shown in Fig. 5.

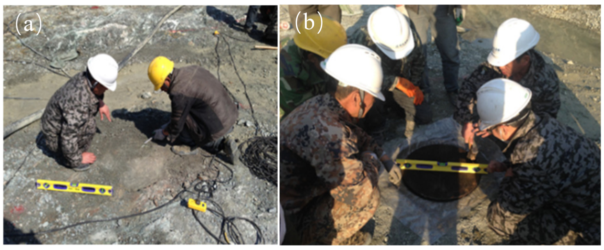

Fig. 5 Processing of on-site deformation test points.

3.2.2 Direct shear test pilot processing

The horizontal push method was used in the direct shear test of rock mass. During the test, the normal load direction applied to the sample was perpendicular to the shear plane, and the thrust direction of the sample was consistent with the predetermined shear direction. The rock surface around the sample was trimmed flat and in the same plane as the predetermined shear plane. According to the processing requirements of the specimen and to reduce the disturbance of the rock specimen, the method of step-by-step processing was used in this study. A total of 6 test sites were set up. The specific processing method refers to the "Rock Test Regulations for Hydropower and Water Conservancy Engineering" (DL/T 5368-2007). The photos of on-site work are shown in Fig. 6.

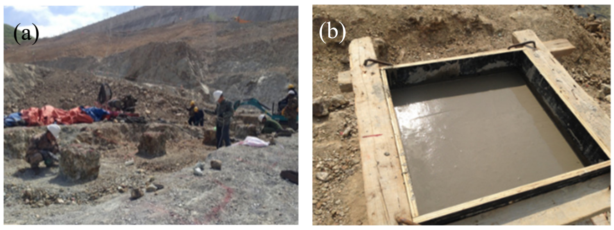

Fig. 6 Processing of on-site direct shear test points.

(a) Construction of test sites. (b) Encapsulation of test sites.

3.3 Rock mass deformation test

The principle of rock mass deformation test is based on the elastic theory. It is considered that rock mass is ideal uniform isotropic elastomer. The elastic modulus and deformation modulus of rock mass are calculated according to the Boussinesque formula of the elastic theory of half-space infinite body. The test deformation parameters of the rigid bearing plate method are calculated as follows:

$$E = \frac{\pi}{4} \cdot \frac{(1-\mu^2)pD}{W} \tag{1}$$

where E is the deformation modulus or elastic modulus; μ is Poisson's ratio of rock mass; p is the pressure calculated according to the unit area of the bearing surface; D is the diameter of the pressure plate; and W is the deformation of rock mass surface.

The deformation test of rock mass was carried out by rigid bearing plate method under the condition of artificial water immersion. The loading method adopts the step-by-step cyclic method, and the test pressure load is divided into five stages. The maximum engineering design load is 2.0 MPa, which is divided into five levels, i.e., the difference is 0.4 MPa. Therefore, it is preliminary determined that the stresses at all levels are 0.4 MPa, 0.8 MPa, 1.2 MPa, 1.6 MPa and 2.0 Ma, respectively. The field test photos are shown in Fig. 7.

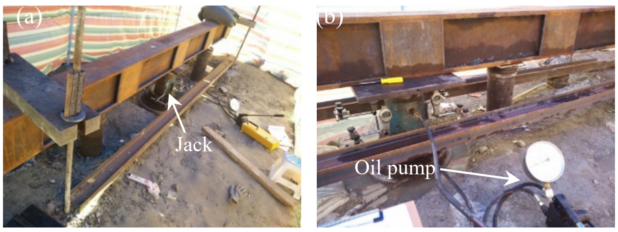

Fig. 7 Field photos of in-situ deformation tests.

According to the "Rock Test Regulations for Hydropower and Water Conservancy Engineering" (DL/T 5368-2007), the test results were comprehensively sorted, and the corresponding curves and charts were drawn and listed.

3.4 Rock mass direct shear test

In the direct shear test of rock mass, the shear failure of rock mass follows the Coulomb criterion, and its expression is as follows:

$$\tau = \sigma tg\varphi + C \tag{2}$$

where τ is the shear stress applied on the shear surface; σ is the normal stress applied on the shear surface; φ is the internal friction angle of the material; C is the cohesive force of the material.

The direct shear test of rock mass was carried out by horizontal pushing method under the condition of artificial water immersion. Significantly, the direction of shear load was consistent with the direction of engineering water thrust. According to the collected data, the foundation stress of Fengman Hydropower Station project is 2.0 MPa. Therefore, five levels with a difference of 0.4 MPa were adopted in this study. it is preliminary determined that the stresses at all levels are 0.4 MPa, 0.8 Mpa, 1.2 Mpa, 1.6 Mpa and 2.0 Mpa. The actual normal load varies with the area of the specimen, but it does not affect the final test results (reference). The corresponding shear stress was obtained by tests under various normal stresses, and then the mechanical parameters of shear strength were obtained. The field test photos are shown in Fig. 8.

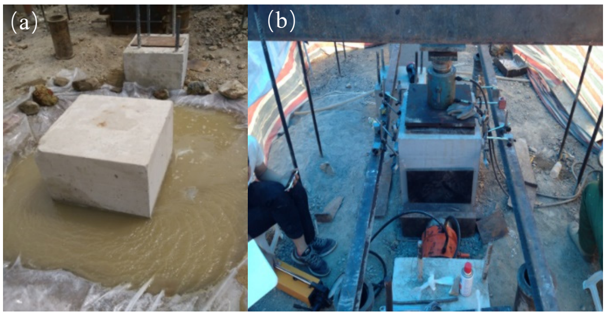

Fig. 8 In-situ direct shear test.

(a) Artificial water immersion. (b) Test in progress.

According to the “Rock Test Regulations for Hydropower and Water Conservancy Engineering” (DL/T 5368-2007), the test results were comprehensively sorted, and the corresponding curve charts were drawn and listed.

4 Results

4.1 Deformation test results

According to the summary table of test results and the relationship curve between pressure and deformation at each test point of the argillaceous zone (Fig. 9), the relationship between the pressure and deformation (or elastic) modulus of the argillaceous zone can be obtained (Figs. 10 and 11).

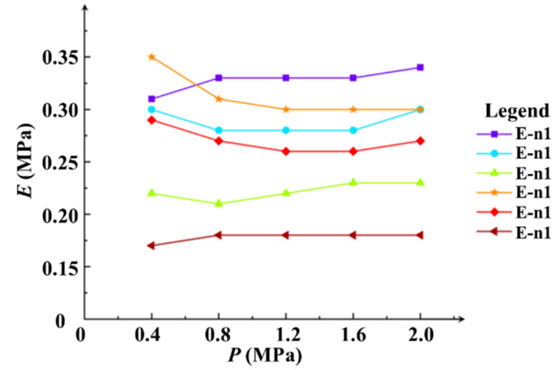

Fig. 10 Relation curve of deformation modulus for the F67 fault argillaceous zone.

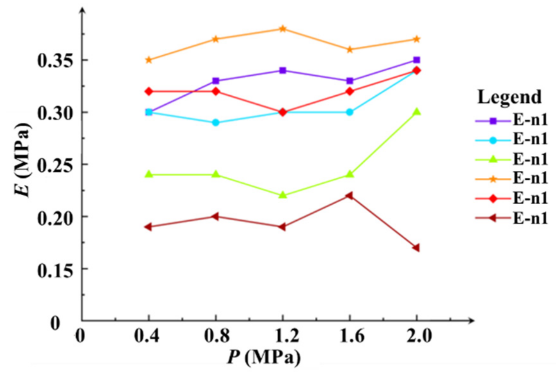

Fig. 11 Relation curve of elastic modulus for the F67 fault argillaceous zone.

According to the “Rock Test Regulations for Hydropower and Water Conservancy Engineering” (DL/T 5368-2007), the relationship curve between pressure and deformation of each test point can be determined. The results are shown in Table 1.

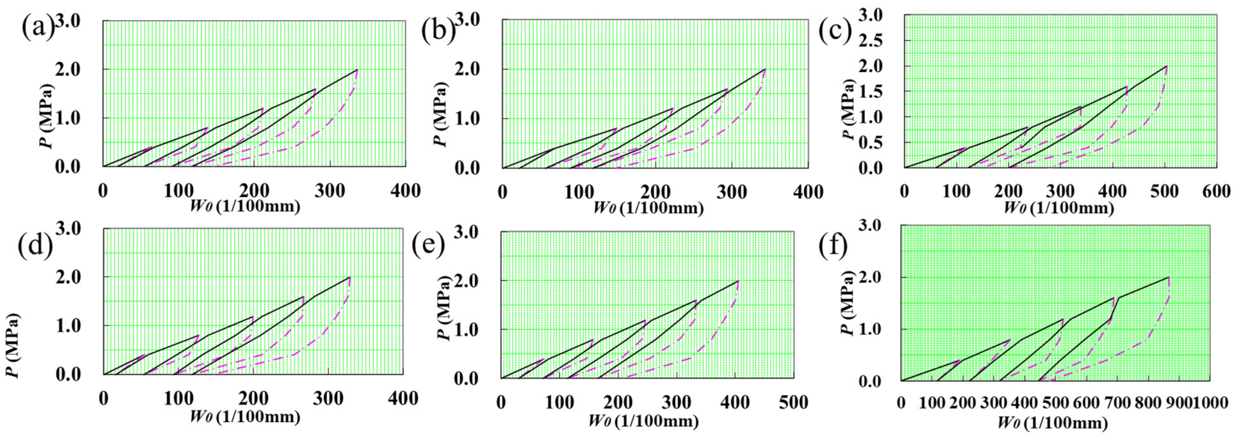

Fig. 9 Pressure-deformation curve. (a-f) Test point n1-n6.

Table1. Summary of deformation test results for the fault argillaceous zone.

Lithology	Loading direction	Project	Test results (GPa)					
Argillaceous zone	Vertical	Test point	E-n1	E-n2	E-n3	E-n4	E-n5	E-n6
		Deformation modulus	0.24	0.21	0.13	0.20	0.17	0.08
		Elastic modulus	0.35	0.38	0.30	0.37	0.34	0.18

From the analysis of Fig. 9, Fig. 10, Fig. 11 and Table 1, it can be seen that the test results have a certain degree of discreteness, but they are all in the same order of magnitude, with little difference. The loading curve of the test rock mass is gentle, indicating that the stiffness of the rock mass is low. After unloading, the deformation of the rock mass can only partially recover, and there are obvious plastic deformation and slow hysteresis. It indicates that the structure of the test rock mass is loose and broken, but its composition and structure are relatively uniform. The measured values of deformation modulus at each test point ranged from 0.08 to 0.24 GPa with an average of 0.17 GPa, and the elastic modulus ranged from 0.18 to 0.38 GPa with an average of 0.32 GPa.

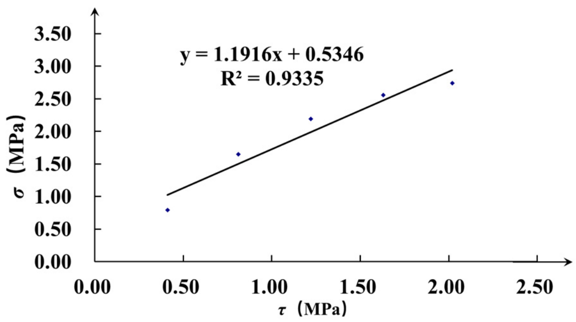

Fig. 13 Normal stress-shear stress curve for shear strength of rock for the fault argillaceous zone.

4.2 Direct shear test results

6 test points, numbered τ-n1 ~ τ-n6, were set up in the direct shear test of the argillaceous zone. The relation curves between shear stress and shear displacement for each point are shown in Fig. 12. In the process of sorting out the test results, based on the comprehensive analysis of the shear surface characteristics, this study used the least square method to determine the shear of rock (rock joint) peak and the corresponding strength parameters. The test results are shown in Table 2, and the fitting curves of normal stress-shear stress are shown in Figs. 13 and 14.

From the test results in Fig. 13, Fig. 14 and Table 2, it can be seen that the results of this group are relatively regular, which is consistent with the geological situation.

As can be seen from the stress-displacement curve in Fig. 12, the specimen basically belongs to plastic destruction type.

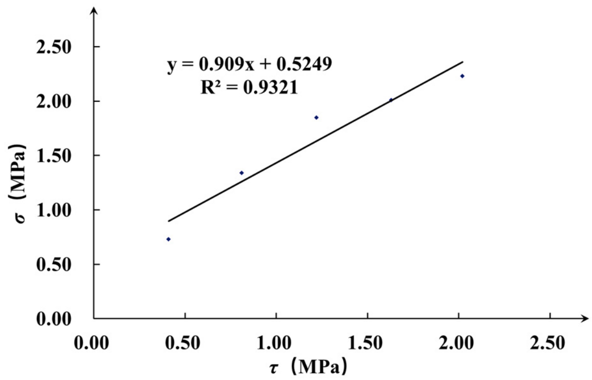

Fig. 14 Normal stress-shear stress curve for shear strength of rock joint for the fault argillaceous zone.

Table2. Summary of shear test results for the fault argillaceous zone.

Test point	Pile number			σ(MPa)	τ(MPa)		Shear strength of rock		Shear strength of rock joint	
	X	Y	H		Shear of rock	Shear of rock joint	tg φ’	C’ (MPa)	tg φ	C’ (MPa)
τ-n4	611.915	-35.963	178.101	0.41	0.79	0.73	1.191	0.534	0.909	0.524
τ-n2	616.862	-37.573	178.309	/	/	/				
τ-n3	616.398	-39.881	178.642	0.81	1.65	1.34				
τ-n1	616.429	-34.892	178.439	1.22	2.19	1.85				
τ-n6	611.358	-41.431	178.290	1.63	2.56	2.01				
τ-n5	611.634	-38.520	178.237	2.02	2.74	2.23				

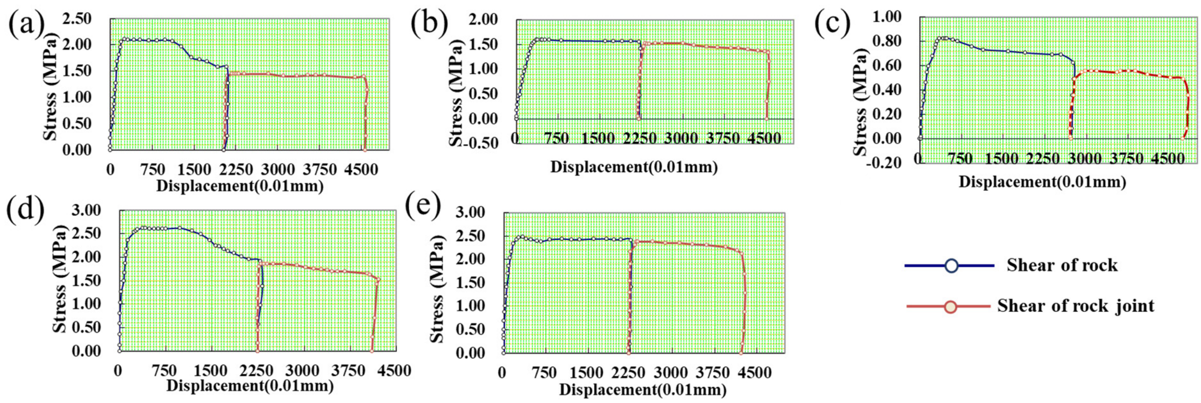

Fig. 12 Shear stress-displacement curve. (a-e) Test point n1and n3-n6.

5 Discussion

The F67 fault at the dam foundation is the largest developed fault zone with the worst engineering geological conditions in the dam site area. It is an important research object in the field of engineering geology. Its strength parameters are particularly important, and are affected by complex factors such as lithology, genesis, and occurrence environment. Therefore, in the investigation of dam construction area, the testing and survey of faults are put in the first place. At present, there are two main methods for selecting rock mass deformation and shear strength parameters in fault fracture zones. One of them is the engineering analogy method, which is generally used in the planning and feasibility study stage for small and medium-sized projects or large-scale projects with insufficient data. The other is the field investigation method, which is mainly used for large-scale projects and is carried out in geological exploration tunnels or on the foundation surface of dam foundations.

The rock mass deformation tests (6 test points) and the rock mass direct shear tests (6 test points) were carried out in the argillaceous zone of the F67 fault. On the whole, the deformation law of each test point is good, which is basically consistent with the actual condition of the measured rock mass. Besides, the deformation parameters obtained are reasonable in order of magnitude. However, due to the influence of site construction, geological structure, lithology distribution, etc., the selection of test sections and the arrangement of test points are limited to some extent. Therefore, the number of measurements is limited at the dam site. As a result, the macroscopic representation of test results in the whole project area has some limitations.

The results of this test are different from the in-situ test results of rock mass of the F67 fault zone in the exploration tunnel 189 and the foundation of the lower dam site in 1973, 2008, and 2009 [15]. This is mainly due to the different excavation mode, different elevation, different overlying mountain, and the existence of fracture zone, weathering zone and unloading zone in the test area. Moreover, the hydrological environment is also quite different, especially in the deformation test area. The elevation of this test section is 174 m, which is the lowest point of several nearby dam sections. Therefore, both groundwater and surface water gather here. Considering the effect of artificial drainage and natural evaporation, the test rock mass gradually changes from relatively dense structure to loose irregular structure after the repeated soaking and drying cycles [16, 17].

Due to the incomplete grasp of the geological data of the entire project, the current research is difficult to in-depth. Therefore, the above is mainly from an experimental point of view. The design and calculation indexes of different rock masses in the dam site area are suggested to be selected on the basis of multiple test results and in combination with other relevant data of the project and engineering analogy.

6 Conclusion

It is very important to understand the shear and deformation properties of the fault gouges in hydroelectric engineering. In this rock mass deformation test, a group (6 test points) of rock mass deformation tests were carried out on the fault gouges for the F67 fault. On the whole, the deformation law of each test point is good, which is basically consistent with the actual situation of the measured rock mass, and the deformation parameters are reasonable in the general order of magnitude. The deformation modulus of fault gouges ranged from 0.08 to 0.24 GPa with an average of 0.17 GPa, and the elastic modulus ranged from 0.18 to 0.38 GPa with an average of 0.32 GPa. A group (6 test points) of rock mass direct shear tests have been carried out on the fault gouges for the F67 fault. In general, the regularity of the test results is good. The peak strength of the fault gouges is tgφ' = 1.191 and C = 0.534 MPa, with correlation coefficient R^2 = 0.933. The peak intensity tgφ = 0.909 and C = 0.524 MPa, with correlation coefficient R^2 = 0.932.

However, due to the geological structure and lithology distribution and other reasons, the selection of test sections and the arrangement of test points are limited. Therefore, the macroscopic representation of test results in the whole project area has some limitations.

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