Hydraulic Fracturing Test of Clay Core in Earth-Rock Fill Dam with the Potential Weak Links

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Abstract: Hydraulic fracturing is of great concern in earth-rock dam engineering and is also one of the hot research issues in earth core dams. Hydraulic fracturing can cause the destruction of the dam's anti-seepage body and cause catastrophic consequences. This paper uses a triaxial hydraulic splitting test to quantitatively describe the shape of hydraulic fractures in clay core, and further demonstrates the occurrence mechanism of hydraulic fracturing from a microscopic perspective. Hydraulic fracturing is ultimately a deformation problem. Due to the compressive deformation of the soil, the initial fracture takes an elliptical shape in the two-dimensional space, thus producing a wedge splitting effect on the fracture tip.

1 INTRODUCTION

In earth-rock fill dam engineering, accidents caused by hydraulic fracturing often lead to the destruction of the dam's anti-seepage body, thus causing catastrophic consequences. (Seed et al., 1976) and (Wilson et al., 1984) both pointed out that hydraulic fracturing is the occurrence and development of cracks in soil.

There are many reasons for hydraulic fracturing of the clay core in earth-rock fill dam. (Lowe et al., 1970) classified cracks in dams into vertical cracks caused by uneven settlement, horizontal cracks caused by arching effects, shrinkage cracks caused by water loss in the dam body, etc. (Sherard et al., 1973) pointed out that cracks are a common problem in earth-rock dams, which can occur during the construction of the dam or after it is built. Based on the assumption that there is a splitting failure zone in the core wall, Lo and (Kaniaru et al., 1990) analysed the hydraulic fracturing characteristics of five earth-rock dams including Balderhead, Hyttejuvet, Viddalsuatu, Teton and Yard's Creek. (Alfaro et al., 2001; Wong et al., 2001) pointed out that hydraulic fracturing pressure is not only related to the overlying pressure at the location where hydraulic fracturing cracks occur, but also related to the strength of the soil and inherent cracks or defects. (Murdoch et al., 2002) pointed out that the characteristics of shallow hydraulic fractures obtained through excavation and drilling cannot meet the needs of predicting the development of hydraulic fractures. (Au et al., 2003) used a modified consolidation instrument to conduct hydraulic fracturing tests on kaolin samples. Hydraulic fracturing tests were conducted with liquids of different viscosities under different consolidation states was analysed. The influence of factors such as ratio and boundary conditions on hydraulic fracturing. These scholars have studied the quantitative relationship between hydraulic pressure and various influencing factors during hydraulic fracture failure, but most of them focused on drilled cylinders or square specimens.

In view of the potential weak links in the clay core of earth-rock fill dam, this paper conducts

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experimental simulations through pre-existing cracks to study the hydraulic fracture of the clay core, and establishes the influence of various physical, mechanical and other factors on the hydraulic fracturing characteristics, including hydraulic pressure, various factors and fracture dimensions.

2 TRIAXIAL HYDRAULIC FRACTURING TEST

2.1 The Properties of Clay

The material used in this paper is low plastic clay, with the liquid limit of 36% and the plastic index of 21%. The maximum dry density of light compaction is 1.78 g/cm^3 and the optimum moisture content is 16.6%. The specimen was prepared with the compaction degree of 98%, and the permeability coefficient is 1.1×10^{-6}cm/s. Particle-size distribution and constitutive parameters are shown in Figure 1 and Table 1.

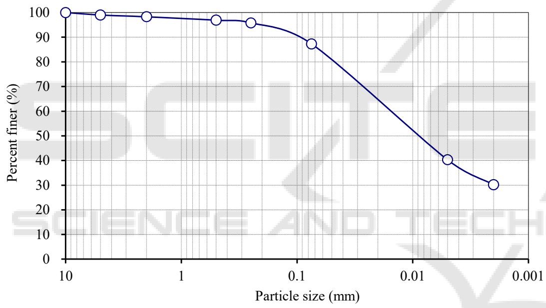

Figure 1: Particle-size distribution curve of clay.

Table 1: The parameters of Duncan-Chang model for clay.

c_{CD} (kPa)	φ_{CD} (°)	K	n	K_b	m	F	G	R_f	D
60.7	19.6	139.9	0.338	52.3	0.185	0.126	0.296	0.836	3.513

2.2 Triaxial Hydraulic Fracturing Test

The aim of triaxial hydraulic fracturing test is to study the law of hydraulic fracturing of soil under confining pressure and to obtain the failure mode of hydraulic fracturing. The effects of saturation, compactness, consolidation ratio, confining pressure, dimension of pre-existing fracture and loading rate of hydraulic pressure are studied.

As shown in Figure 2, the test device consists of three parts: a triaxial apparatus in the middle, a water intake measuring device for fracturing pressure on the left and an external variable measuring device for confining pressure on the right. The specimen with fracture is installed in the triaxial apparatus, the specimen is wrapped in rubber membrane, the pressure chamber is linked with the confining pressure device, and the base of the specimen is linked with the pressure water inlet device.

The triaxial hydraulic fracturing test can simulate the stress state such as confining pressure and consolidation ratio of the specimen, and it is an ideal research method. The triaxial fracturing tests are carried out in the aspects of saturation, compactness, consolidation ratio, confining pressure, dimension of pre-existing fracture and hydraulic pressure loading rate. The test program is shown in Table 2, with a compaction degree of 98%; the dimensions of pre-existing fracture are shown in Figure 3.

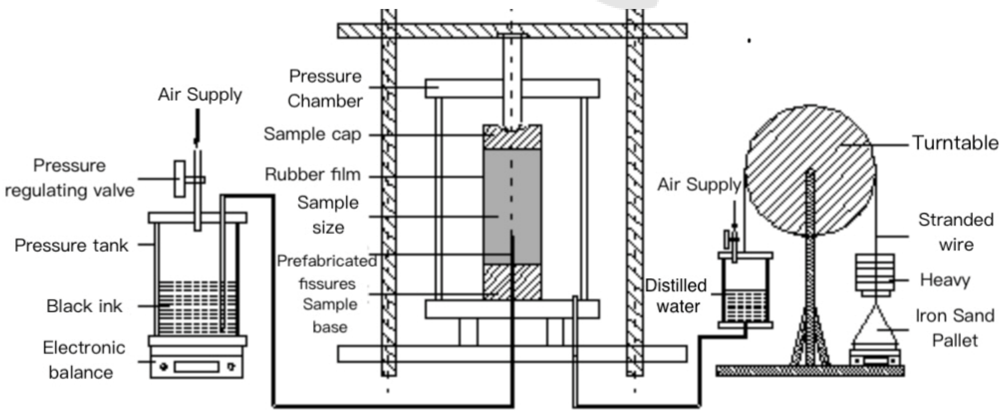

Figure 2: Diagram of triaxial hydraulic fracturing test device.

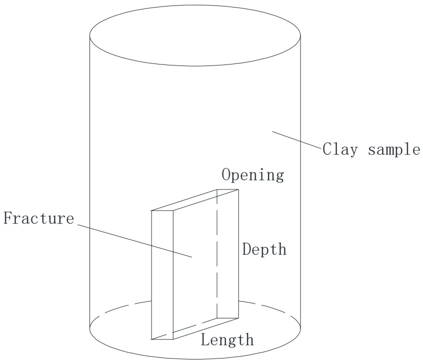

Figure 3: Dimensions of pre-existing fracture in specimens.

Table 2: Testing program of triaxial hydraulic fracturing for clay with pre-existing fracture.

No. of sample	Dimension of fracture			Confining Pressure (kPa)
	Depth (mm)	Length (mm)	Opening (mm)	
SLPL-11	50	20	2	50
SLPL-12	50	20	2	200
SLPL-13	50	20	2	350
SLPL-14	50	20	2	100
SLPL-15	50	20	2	350
SLPL-16	50	20	2	200
SLPL-17	100	20	2	200
SLPL-18	150	20	2	200
SLPL-19	50	35	2	200
SLPL-20	50	50	2	200
SLPL-21	50	20	4	200

2.3 Results Analysis

The development of hydraulic fracture in SLPL-15 specimen is shown in Figure 4. The sample size is φ101 mm × H200 mm, and the pre-existing fracture dimension is 50mm in depth × 20mm in length × 20mm in opening. Consolidate for 48 hours under a confining pressure of 350kPa. After starting the test, the pore pressures are 50, 80, 120, 160, 200, 230, 270, 310, 350, and 390kPa. Each level of pressure lasts for 10 to 15 minutes until the change rate of the balance. At 430 kPa pore pressure for 4 min, the specimen was destroyed, ink gushed from the splitting crack, the valve was closed, and the test was stopped. There are three distinct long fractures and several small fractures around the specimen. The apparent fracture length of the sample is about 11 cm, which is larger than the ink length inside the sample, and greater than the depth of the pre-existing cracks by 5 cm. And the depth of ink staining directly above the pre-existing fracture is about 2 cm, which is shown that hydraulic fracturing occurred to some extent along the fracture depth.

(a) Sample surface fracture

(b) Development of internal fracture

Figure 4: Development of hydraulic fracture.

The results of hydraulic fracturing tests are shown in Table 3, and the curves of fracturing pressure versus confining pressure, fracture depth, fracture length and fracture opening are shown in Figure 5. It can be obtained as follows:

(1) the law of failure pressure and confining pressure of hydraulic fracturing is the most obvious. The bigger confining pressure is, the bigger fracturing pressure is, but the increasing trend of fracturing pressure is gradually slowing down. When the confining pressure is below 200 kPa, the fracture pressure and confining pressure increase linearly, and when the confining pressure is over 400 kPa, the fracture pressure shows an asymptotical trend and does not increase linearly.

(2) the fracture pressure has little relation with fracture depth, the fracture depth varies from 50mm to 150mm, and the fracture pressure fluctuates very little, which is due to the fact that the triaxial hydraulic fracturing test is basically a failure mode of fracture propagation in the direction of fracture length, although there is fracture propagation along the depth of the fracture, the fracture in the length direction penetrates before the fracture in the depth

direction, so it shows that the fracture depth has little effect on the fracture pressure.

(3) the relationship between fracture pressure and fracture length is not significant. The deformation characteristics of the pre-placed fracture after fracturing pressure is elliptic (as shown in Figure 6) , and the two ends are the tip of the fracture, which are subjected to the tensile force caused by the fracturing pressure, and the two sides of the fracture are subjected to the total splitting tensile force, this tension is borne by a fracture-free soil.

(4) The longer the fracture, the lower the tension at the tip of the fracture, but the greater the total splitting tension on both sides of the fracture. For this test, the longer the precast joint is, the smaller the effective range of the soil which can bear the total splitting tension is, but the test result does not reflect the rule that the longer the joint is, the smaller the splitting failure pressure is, it should not belong to the simple tensile failure mode of soil. Therefore, it is proposed that the failure mode of the fracture tip is gradually tensile fracturing. Although the stress at the fracture tip is greater under the condition of the shorter fracture, the stress at the fracture tip decreases gradually with the extension of the fracture length, when the fracture is extended to a certain extent, it is close to the condition of the fracture length, and the stress at the fracture tip should be close to it.

(5) It is assumed that the equivalent fracture length after fracture propagation is the sum of the initial fracture length and the fracture length after fracture propagation, according to the Irwin equivalent fracture correction method in fracture mechanics, the displacements in this region will be released after the fracture appears, and there may be relative displacements on the upper and lower surfaces of the yield region, resulting in displacements, free water is allowed to transmit pressure inside, so the equivalent fracture length is also assumed for hydraulic fracturing of clay materials.

(6) the failure pressure of hydraulic fracturing has little relation with the fracture opening, provided that the pressure water can move freely in the pre-existing fracture. This is reflected in the clay core, no matter how big or how small the opening of the fractures, as long as the reservoir water can move freely and transmit pressure in the weak links, there is a possibility of hydraulic fracturing.

(7) when confining pressure is greater than 350 kPa, hydraulic fracturing occurs to some extent along the depth of the fracture, and the corresponding fracturing pressure is 430 ~ 440 kPa, if the deformation without restraint is large at the middle and small at the two ends, thus causing the tensile force at the fracture tip, the fracture propagation will occur not only in the direction of the precast fracture length under the larger fracture pressure, but also in the direction of the precast fracture length, in the depth direction of the fracture also appears to expand, but the length direction of the fracture first through, resulting in hydraulic fracturing did not continue to expand to the depth direction. In the core-wall Dam project, the fracture depth direction of the expansion of greater harm, more attention should be paid.

Table 3: Results of triaxial hydraulic fracturing test on clay with potential fracture.

No. of sample	**Dimensions of fracture**			**Confining pressure (kPa)**	**Fracture pressure (kPa)**
	Depth (mm)	Length (mm)	Opening (mm)		
SLPL-11	50	20	2	50	60
SLPL-12	50	20	2	200	360
SLPL-13	50	20	2	350	440
SLPL-14	50	20	2	100	140
SLPL-15	50	20	2	350	430
SLPL-16	50	20	2	200	340
SLPL-17	100	20	2	200	330
SLPL-18	150	20	2	200	360
SLPL-19	50	35	2	200	280
SLPL-20	50	50	2	200	330
SLPL-21	50	20	4	200	350

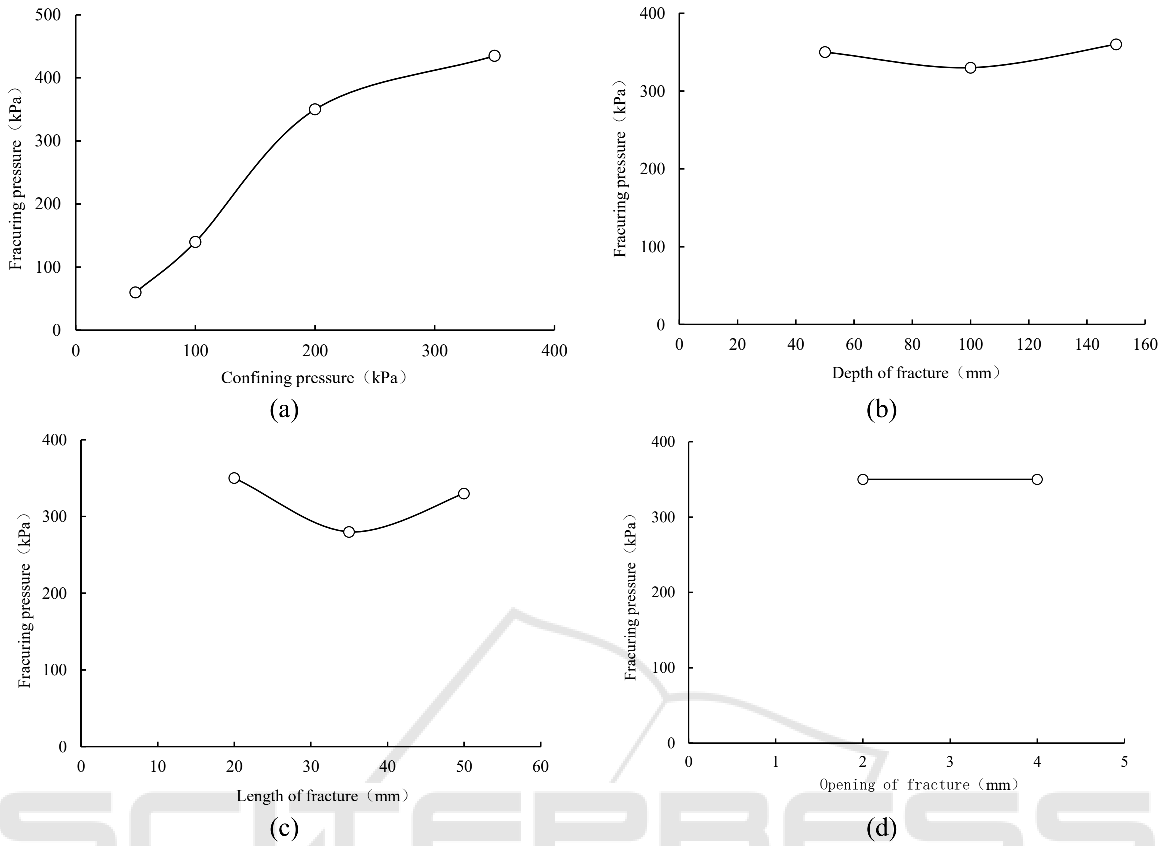

Figure 5: The curves of hydraulic fracturing pressure vs. fracture size.

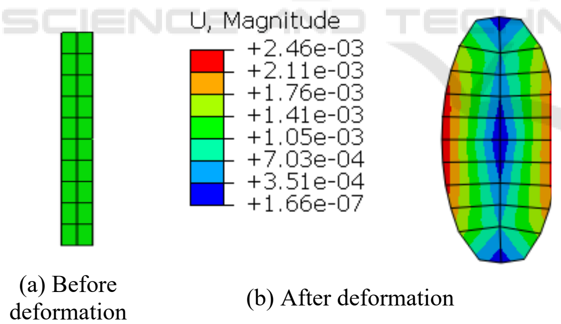

Figure 6: Deformation characteristics of fractures before and after fracturing pressure is applied.

3 CONCLUSIONS

Hydraulic splitting is ultimately a deformation problem. Due to the compressive deformation of the soil, the initial fracture takes an elliptical shape in the two-dimensional space, thus producing a wedge splitting effect on the fracture tip. The damage pressure of hydraulic fracturing has little relationship with the fracture opening. In the core wall, no matter how big or small the thickness of the fracture is, as long as the reservoir water can move freely and transmit pressure in the fracture, there is a possibility of hydraulic splitting. Define the ratio of fracture opening to equivalent fracture length as the discriminant factor of hydraulic splitting. By comparing the relationship between this factor and the critical value, you can make a process judgment on whether hydraulic splitting occurs.

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