

# LABORATORY HYDRAULIC FRACTURING TESTS FOR CORE MATERIALS USING LARGE SIZE HOLLOW CYLINDRICAL SPECIMENS

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**Abstract:** In order to design the soil structures, we must consider the safety against seepage failure in the structures. After the failure of Teton Dam in 1976, hydraulic fracturing has been attracted a lot of attention, many experimental and analytical researches have been performed, but there are many unclear points such as mechanism and occurrence condition of hydraulic fracturing. Hydraulic fracturing is one of the major problems in embankment dams because it plays an important role in the initiation of cracks in core zone in a dam body, but there are a few examples of experimental investigation using construction materials of embankment dams that are relatively large structures among soil structures that should be secured the safety against hydraulic fracturing. We must make the researches on hydraulic fracturing of embankment dams, because 37% of failures of embankment dams are caused by seepage failure and contraction of core width has been recently investigated in the construction.

In this study, core material of rockfill dam under construction is used as material of laboratory tests. We use large size hollow cylindrical specimens with the external diameter of 30cm. We investigate the influences of  $D_{max}$  and confining pressure,  $\sigma_3$ , on the pressure at the hydraulic fracturing,  $p_f$ .

We find that it is very important to appropriately set the values of  $D_{max}$  and the size of specimens in order to produce the phenomena of hydraulic fracturing in laboratory tests. In this study, we find that the minimum size of external diameter of specimens is needed to be 15cm and large-size specimens tests constantly produce the hydraulic fracturing.

**Key words:** hydraulic fracturing, rockfill dam, core material

## 1 Introduction

In designing structures such as embankment dams and levees that use soil materials, safety has to be secured against structural fracture that is induced by a locally formed high permeability conduit. Hydraulic fracturing has attracted much attention since the failure of the Teton Dam in 1976. Although various experimental and analytical investigations on hydraulic fracturing have been performed, much remains to be discovered about the underlying mechanisms and conditions. Among all structures for which safety has to be secured against hydraulic fracturing, an embankment dam is a relatively large-scale structure, but there has been very little examination of hydraulic fracturing in experiments on embankment dam materials. Seepage failure accounts for

37% of the total number of incidents in embankment dams. Some topics that often come up in recent discussions are whether or not to reduce core zone width in the construction of rockfill dams. For these reasons, it is strongly suggested that further research on hydraulic fracturing should be carried out.

In this study, hydraulic fracturing tests were performed on large size hollow cylindrical specimens to evaluate the resistance of compacted core materials to hydraulic fracturing.

## 2 Hydraulic fracturing tests using large size hollow cylindrical specimens

### 2.1 Test method

Hydraulic fracturing tests using large size specimens have seldom been conducted due to the difficulties in installing a test equipment.

There were two types of specimen used in the tests: one consisted of rockfill dam core materials the size of which had been adjusted by eliminating grains larger than its maximum grain size of  $D_{max}=19\text{mm}$ ; and in the other, those grains larger than its maximum grain size of  $D_{max}=2\text{mm}$  were eliminated. The grain size distribution of each material is shown in Figure 1 and the following is the test procedure.

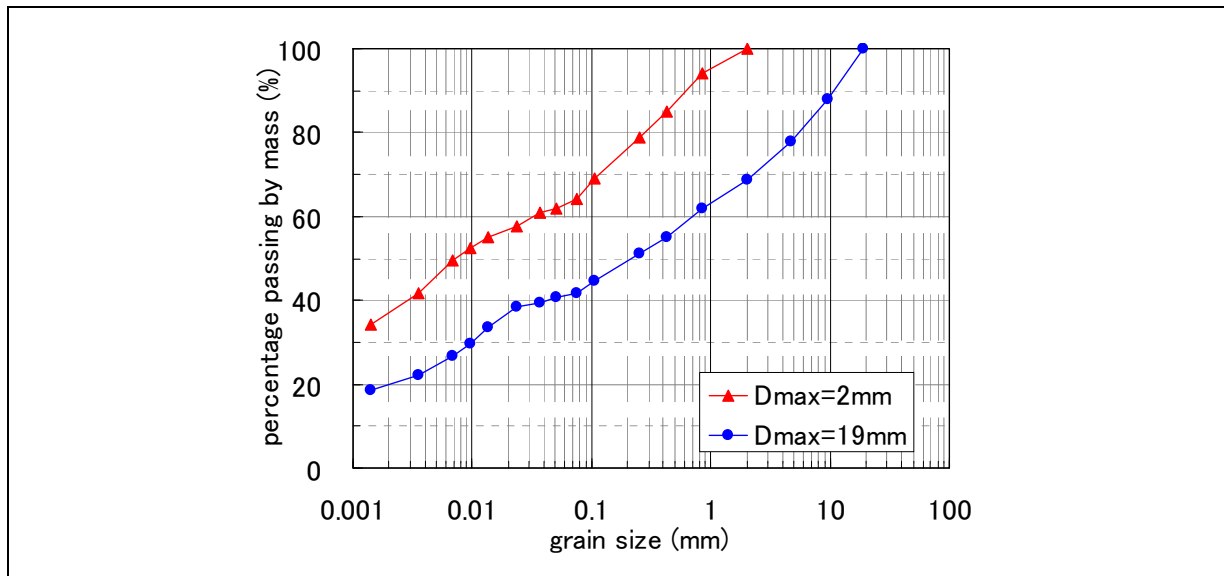


Figure 1. Grain size distribution of the test materials

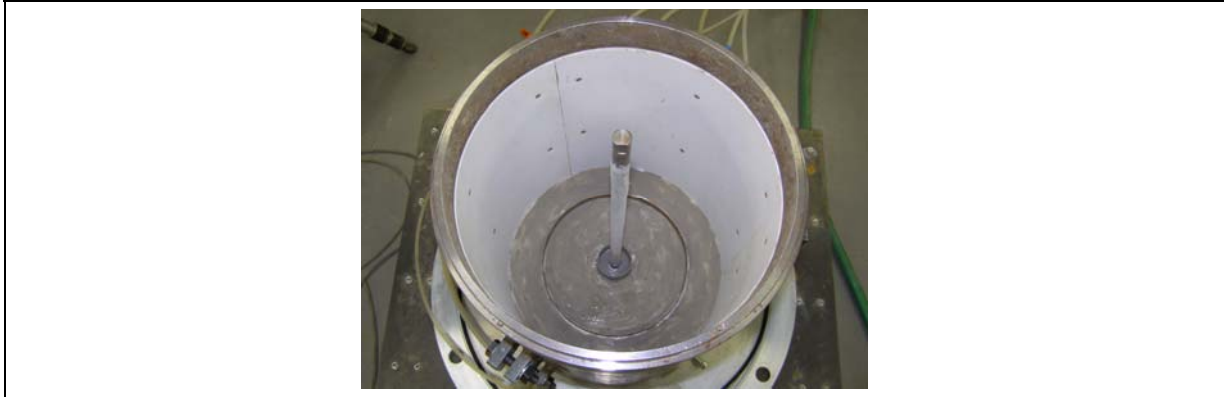


Photo 1. Mold and rod used to prepare a specimen

- (1) A rod with a diameter of 1.5cm was installed in the center of a mold with an inner diameter of 30cm and a height of 30cm (Photo 1).
- (2) To prepare a specimen, materials were compacted in the above mold with a compaction degree of 95% (1Ec) and optimum water content ratio,  $w_{opt}$ . The thickness of a compacted layer was fixed at 3cm.
- (3) After the completion of specimen, the rod was extracted, and the hollow center was filled with Toyoura sand, which features excellent permeability.
- (4) The specimen was placed in a large-scale triaxial compression test facility that had been modified for the hydraulic fracturing test. At that time, to prevent leakage from the ends of the specimens during the test, a cut off plate with a height of approximately 1.5cm was installed on the top cap and the pedestal (Photo 2), and bentonite was placed to the borders of the specimen with the top cap and the pedestal.

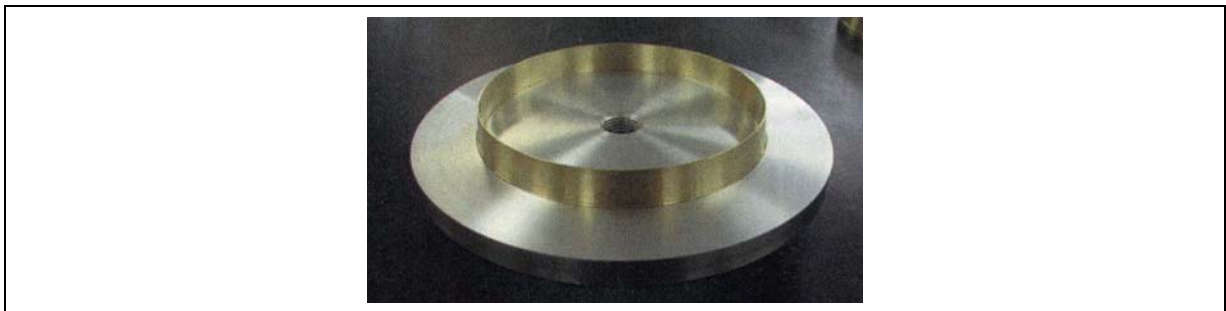


Photo 2. Cut off plate

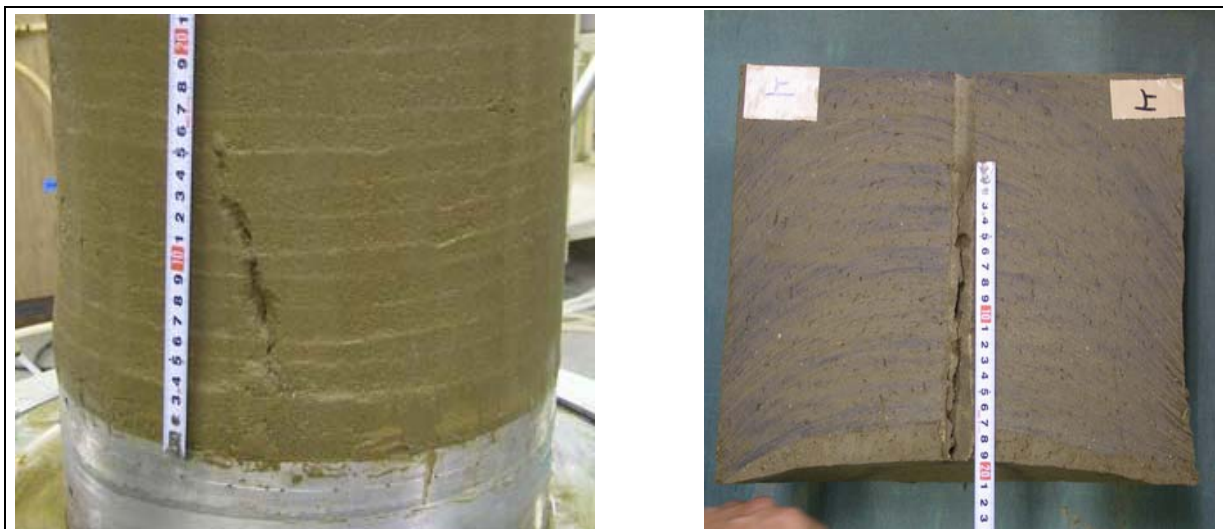
- (5) The specimen was saturated and consolidated by the 3t method at required confining pressures,  $\sigma_3$  (98kN/m<sup>2</sup>, 196kN/m<sup>2</sup> and 392kN/m<sup>2</sup>).
- (6) The pressure of water injection was increased at the rate of 9.8kN/m<sup>2</sup>/min through the water filler containing the Toyoura sand.
- (7) The test was halted when the amount of water injected rapidly increased. Photo 3 is an exterior view of the test device.



Photo 3. Exterior view of the test device

## 2.2 Test results

Photos 4 and 5 demonstrate the appearance of cracks formed in the specimens with  $D_{max}=2\text{mm}$  and 19mm, respectively. After the tests on large hollow specimens, several cracks were detected outside and inside both specimens. This indicates the strong possibility of distinct hydraulic fracturing being generated in each test using large hollow specimens. Linear cracks occurred in a vertical direction on the inside and outside of both specimens with  $D_{max}=2\text{mm}$  and 19mm, but the shape of the cracks running on the outside of the specimen with  $D_{max}=19\text{mm}$  was complex in some cases.

Photo 4. Example of crack formation (specimen with  $D_{max}=2\text{mm}$ ) (left: outside, right: inside)

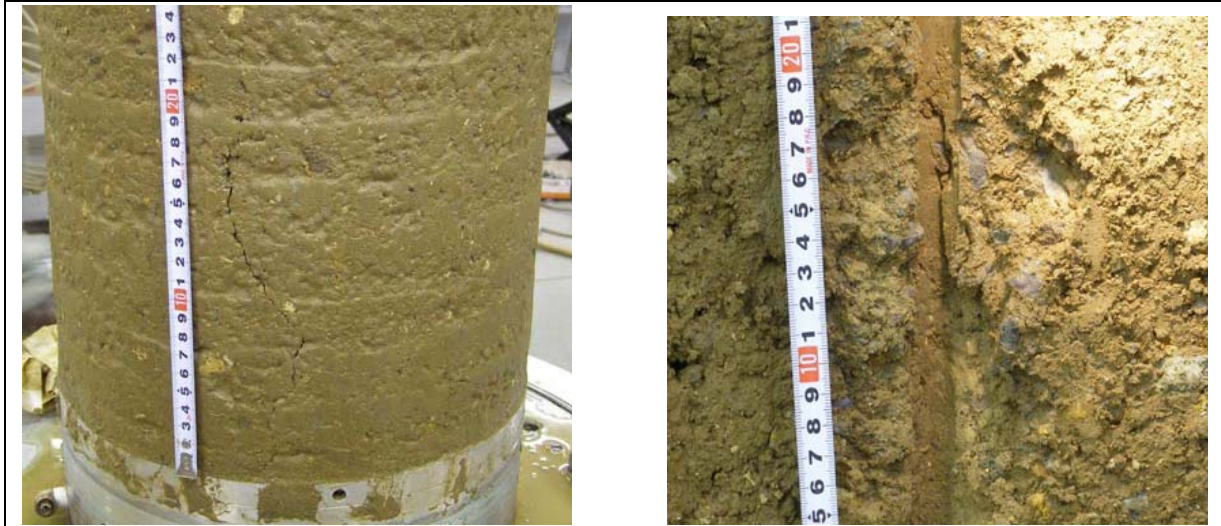


Photo 5. Example of crack formation (specimen with  $D_{max}=19\text{mm}$ ) (left: outside, right: inside)

### 3 Hydraulic fracturing tests using medium size hollow cylindrical specimens

#### 3.1 Test method

There were two types of specimen used in the tests: one consisted of rockfill dam core materials the size of which had been adjusted by eliminating grains larger than its maximum gain size of  $D_{max}=19\text{mm}$ ; and in the other, those grains larger than its maximum grain size of  $D_{max}=4.75\text{mm}$  were eliminated. The size distribution of each material is shown in Figure 2 and the following is the test procedure.grain

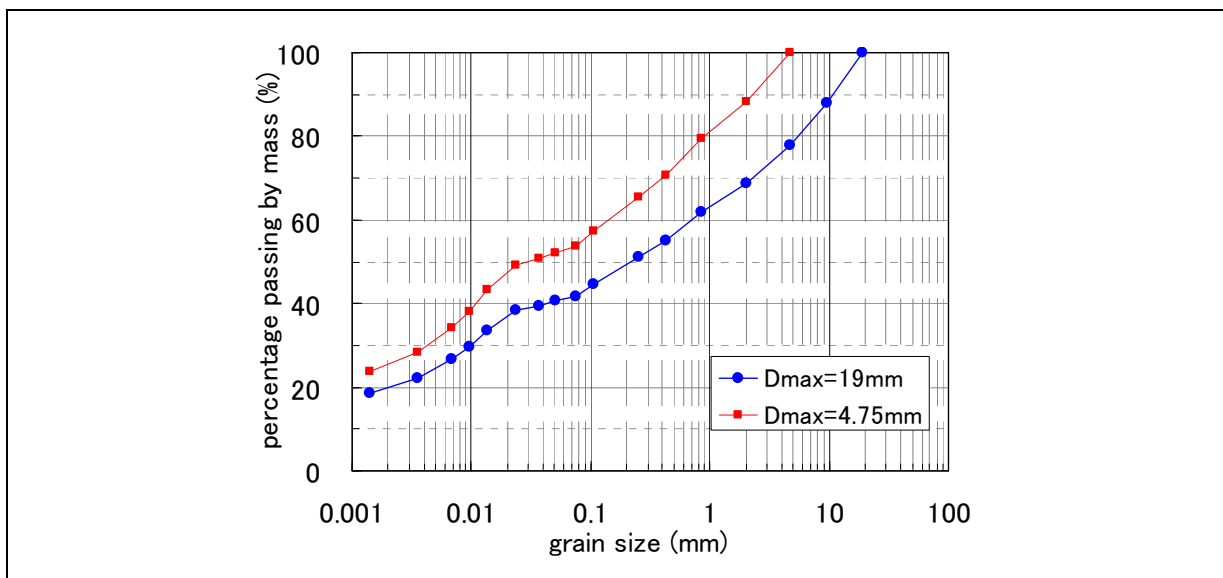


Figure 2. Grain size distribution of the test materials

(1) A cylindrical rod was installed in the center of a mold with an inner diameter of 15cm and a height of 15cm (Photo 6).



Photo 6. Mold and rod to prepare a specimen (a rod with a diameter of 5cm)

(2) To prepare a specimen, materials were compacted in the above mold with a compaction degree of 95% (1Ec) and optimum water content ratio,  $w_{opt}$ . The thickness of a compacted layer was fixed at 3cm.

(3) After the compaction of specimen, the rod was extracted, and the center hollow was filled with Toyoura sand, which features excellent permeability.

(4) The specimen was placed in a middle-scale triaxial compression test facility that had been modified for the hydraulic fracturing test. At that time, to prevent leakage from the ends of the specimens during the test, a cut off plate with a height of approximately 1.5cm was installed on the top cap and the pedestal, and bentonite was placed to the borders of the specimen with the top cap and the pedestal.

(5) The specimen was saturated and consolidated using the 3t method with required confining pressures,  $\sigma_3$  (98kN/m<sup>2</sup>, 196kN/m<sup>2</sup> and 392kN/m<sup>2</sup>).

(6) The pressure of water injection was enhanced at the increasing rate of  $\Delta p/\Delta t$  through the water filler containing the Toyoura sand.

(7) The test was halted when the amount of water injected rapidly increased.

### 3.2 Test results

Photo 7 illustrates an example of a crack formed in the specimen in the hydraulic fracturing test.

The appearance of a crack tended to be more obvious with the smaller  $D_{max}$ , the smaller rod diameter,  $\varphi$  (or the longer penetration distance) and the higher confining pressure,  $\sigma_3$ . In the case of the specimen with  $D_{max}=19\text{mm}$  and  $\sigma_3=98\text{kN/m}^2$ , no crack was detected.

Based on these test results, it is assumed that hydraulic fracturing cannot be generated on the materials used in this study unless the specimens are produced in a mold with an outer diameter of at least 15cm.

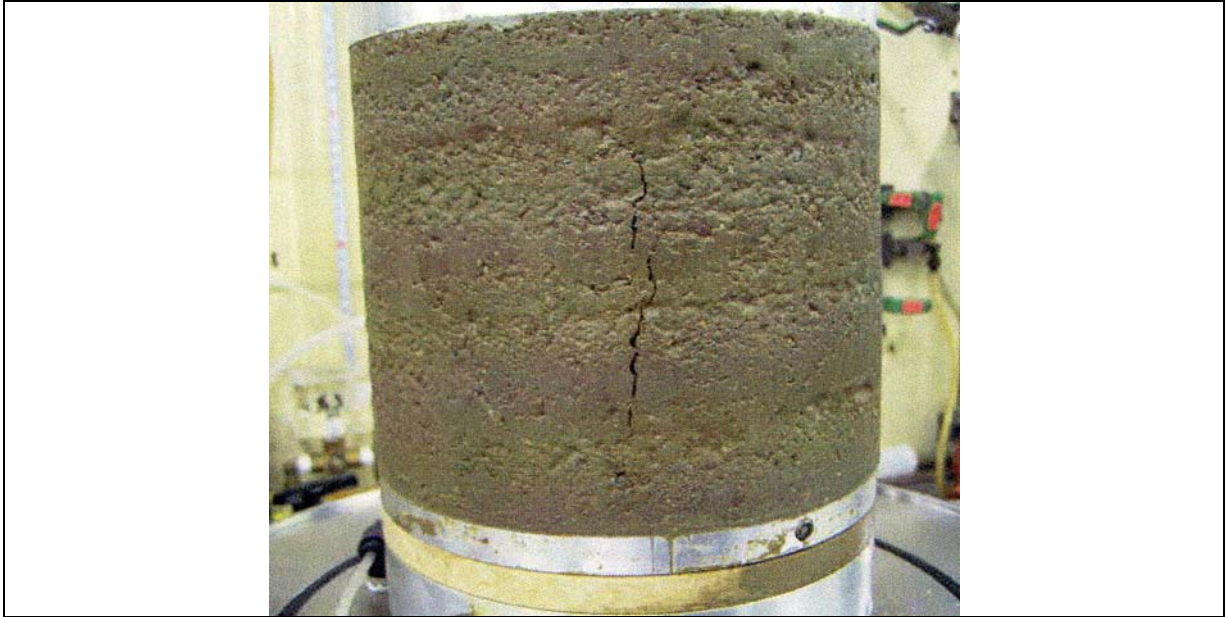


Photo 7. Example of crack formation

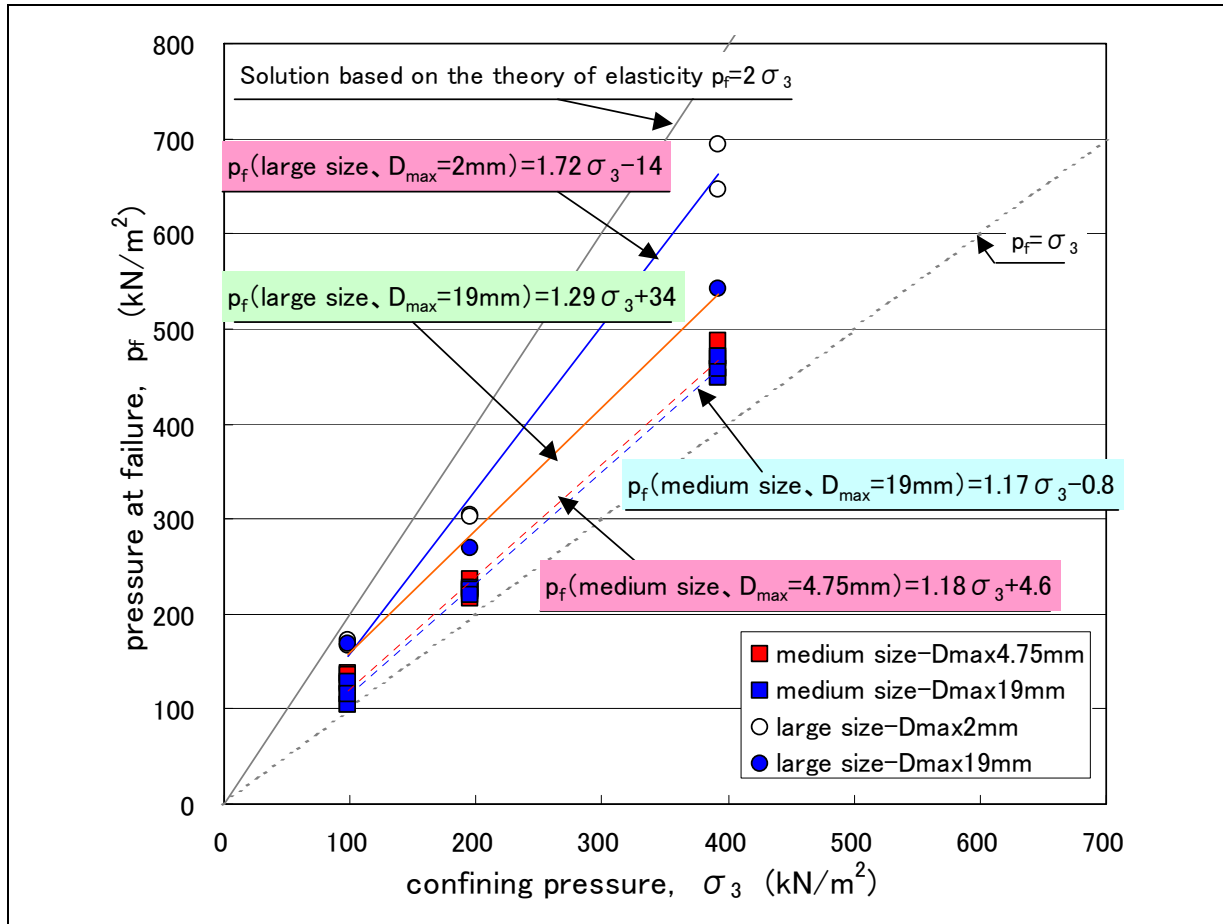
#### 4 Relation between confining pressure, $\sigma_3$ , and pressure at failure, $p_f$

Figure 3 illustrates the relationship between  $\sigma_3$  and the pressure at failure,  $p_f$ . The definition of  $p_f$  was given as the pressure of water injection when the amount of injected water rapidly increases. According to Figure 3, the  $p_f$  displays the same tendencies with the test result of the medium size hollow cylindrical specimen, remaining within  $\sigma_3$  and the solution based on the theory of elasticity, and increasing in proportion to  $\sigma_3$ . Differing from the results of the medium size hollow cylindrical specimen, the test result of the large size hollow cylindrical specimen reveals that the smaller  $D_{max}$  is associated with the greater  $p_f$ . Also, that the  $p_f$  of the large size specimen is greater than that of the medium size specimen.

The pressure at failure,  $p_f$ , is considered to have a linear relationship with the confining pressure,  $\sigma_3$ , as expressed with  $p_f = m \times \sigma_3 + n$ . Figure 3 indicates the values of  $m$  and  $n$  derived from the hydraulic fracturing test results,  $p_f$ , of large size and medium size hollow cylindrical specimens through the least square method. In the hydraulic fracturing test on medium size hollow cylindrical specimens,  $m=1.17$  was attained regardless of  $D_{max}$ , whereas the test on large size hollow cylindrical specimens resulted in  $m(D_{max}=2\text{mm})=1.72$  and  $m(D_{max}=19\text{mm})=1.29$ , suggesting the dependency of  $m$  on  $D_{max}$ . The opposite (positive or negative) nature of the sign for  $n$  between  $n(D_{max}=2\text{mm})=-14$  and  $n(D_{max}=19\text{mm})=34$  may be attributed to dispersion due to the small number of tests.

#### 5 Colclusion

As for the core materials used in this study, the value of  $D_{max}$  was set so as to include gravel. In some hydraulic fracturing tests using medium size hollow cylindrical specimens with an outer diameter of 15cm, no hydraulic fracturing cracks were clearly identified. Therefore, in order to generate hydraulic fracturing in the specimens under the test conditions employed in this study, the creation of specimens with an outer diameter of at least 15cm is required.

Figure 3. Relationship between  $\sigma_3$  and  $p_f$ 

In Figure 3, the value of  $m$  tends to decrease as the size of a specimen becomes smaller. However, in the hydraulic fracturing tests on medium size hollow cylindrical specimens with an outer diameter of 15cm which is considered to be the size of minimum requirement to generate hydraulic fracturing in specimens of  $D_{max}=2\text{mm}$ , the value of  $m$  is 1.17 and independent of  $D_{max}$ . In view of the small size of the pinhole damage that is assumed in the hydraulic fracturing tests to be the cause of hydraulic fracturing, the core zone in an actual rockfill dam can be regarded as a massive specimen. Thus, as for the core materials used in these tests, the  $m$  value at the time of hydraulic fracturing is expected to exceed the value of at least 1.17, which was obtained in the test on medium size specimens.

## References

- [1] H. Tagashira, On the proportional coefficient and constant of linear approximate equation between hydraulic fracturing pressure and minimum confining pressure based on literature review, Symposium on mechanism and evaluation method of hydraulic fracturing, pp.141-148, 1988.(in Japanese)