An experimental study on permeability of soils under shear deformation using remodeled torsional shear apparatus

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ABSTRACT

We remodeled the apparatus for torsional shear test on hollow cylindrical specimen of soils in order to examine the relationship between the shear deformation and the permeability of the impervious material for rock fill dams. As a fundamental approach concerning the permeability change of impervious materials deformed by the vertical offset, we conducted the permeability test using the apparatus.

Firstly, we conducted TEST 1 that was the permeability test method for test material deformed by turning the swivel in steps, while keeping the test pressure constant. We assumed that the coefficient of permeability obtained from TEST 1 was similar to that obtained from JIS A 1218:2009. Secondly, we conducted TEST 2 whose purpose is evaluation of water resistance of deformed test material against high water pressure as severe condition beyond realistic situation.

As the result of TEST 1, test material was not measured the increasing characteristics of coefficient of permeability under shear deformed condition.

The result of TEST 2 indicates that consolidation pressure has a influence on the increasing characteristic of coefficient of permeability of test material.

1. INTRODUCTION

The 1999 Chichi Taiwan Earthquake gave a severe damage to several dams in Taiwan. Among them, the severest was Shih-Kang Dam. Due to vertical ground offset by the fault movement, the right half slide of the dam were crushed to pieces with 7.5 m differences in level, referring to Ohmachi (2000). The event made dam engineers remind the importance to consider dam safety during an earthquake accompanied by the vertical offset.

In this study, we focus on water-tightness of the impervious core zone of the rockfill dam subject to the vertical offset, which can be deformed more complicatedly than concrete.

Because dams are structures to store water, it is important to examine the permeability change of impervious materials deformed by the vertical offset.

In order to examine the permeability change of the impervious materials of a dam deformed by the vertical offset, the element test to evaluate permeability of the impervious materials under shear displacement is needed.

As a fundamental approach concerning the permeability change of impervious materials deformed by the vertical offset, we remodeled the apparatus for torsional shear test on hollow cylindrical specimen of soils, and conducted the permeability test using the apparatus in order to examine the increasing characteristic that is a permeability of the impervious materials.

This paper shows the characteristics of the apparatus, and the test method for permeability of impervious materials which were gradually sheared, and the test results.

2. APPARATUS AND MEASUREMENTS

2.1 Apparatus

The testing apparatus is shown in Figure 1 and Figure 2. The size of the hollow cylindrical specimen is shown in Figure 3. The hollow cylindrical specimen is loaded in torsional and vertical directions independently. The vertical loading device is operated by a hydraulic actuator which is connected to the loading shaft. The torsional loading device is driven by an AC servo motor which is connected via a shaft to a horizontal and circular swivel. This device keeps a specified shear rate during torsional shear tests.

The preparing procedure of the hollow cylindrical mold is shown in Figure 4. In addition, the specifications of inner and outer rings are shown in Table 1. A hollow cylindrical specimen is placed into the hollow cylindrical mold composed of the inner and outer pipes. These pipes composed of each 3 ring equipped with 4 and 8 permeable holes attached to a porous metal and each 2 ring equipped with no holes. These rings are made of brass and acrylic for inner and outer rings, respectively.

Water pressure is applied to a hollow cylindrical specimen through porous metals attached to the inner and outer pipes. A water pressure path is connected via the pedestal to the cap.

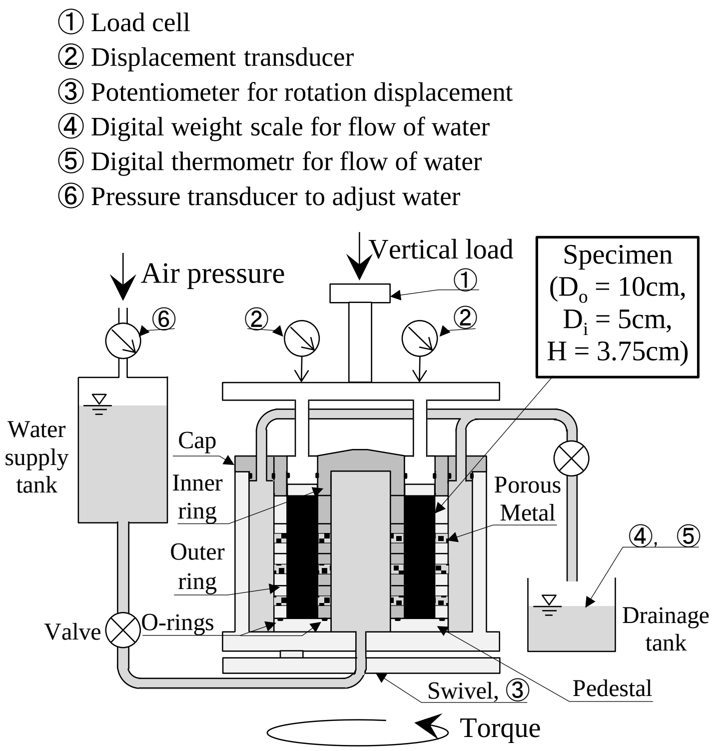


Figure 1. Cylindical torsional shear and permeability testing apparatus using hollow cylindrical specimens

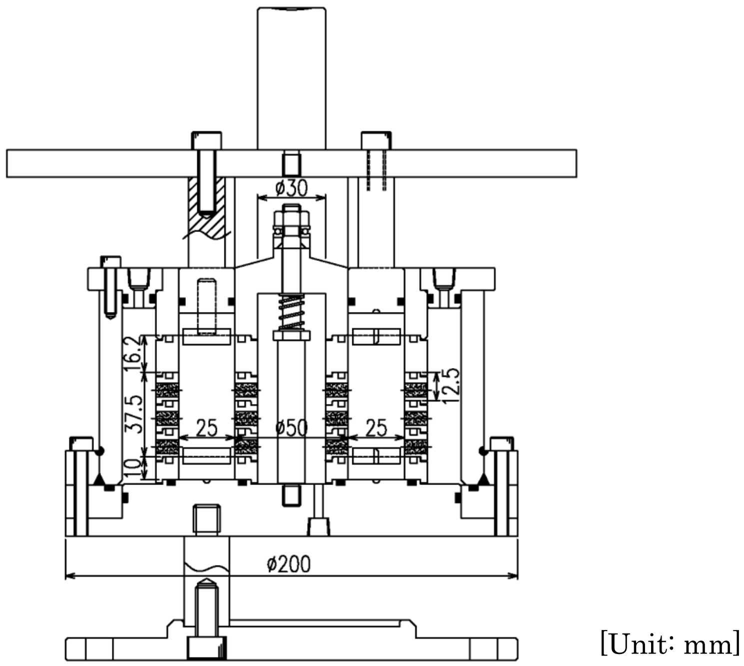


Figure 2. Structure of hollow cylindrical mold and circular swivel

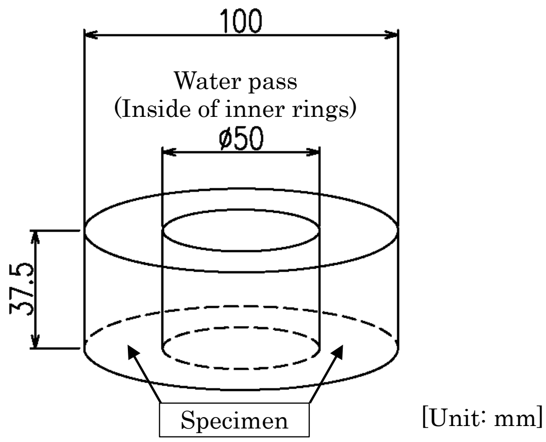


Figure 3. Size of hollow cylindrical specimen

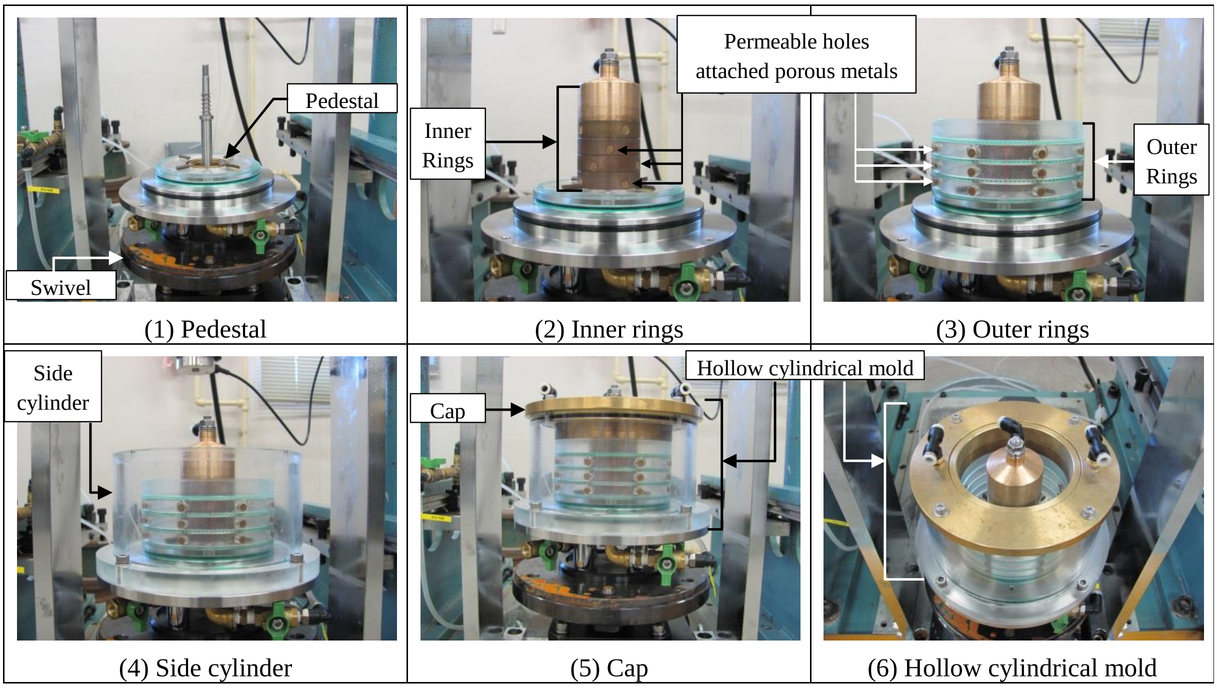


Figure 4. Preparing procedure of hollow cylindrical mold

Table 1. Specifications of Inner rings and outer rings

		Inner rings	Outer rings
Outer diameter (mm)		25	60
Inner diameter (mm)		15	50
Height (mm)			
Equipped with permeable holes		12.5	12.5
Equipped with no permeable holes	(Top)	16.2	16.2
	(Bottom)	10	10

Permeable hole diameter (mm)	6	6

2.2 Measurements

The measurements of this test are as follows:

- Vertical stress in a specimen
- Vertical displacement in a specimen
- Shear strain in a specimen
- Flow rate of water through a specimen
- Temperature of water thorough a specimen

The vertical stress was measured by a load cell installed below the vertical loading parts. The vertical displacement was measured by a displacement transducer. The shear strain was obtained by measuring the rotational displacement with a potentiometer, installed into the horizontal and circular swivel. The flow rate and temperature of water through a specimen were measured by the digital weight scale and the digital thermometer, respectively.

The data acquisition procedure is shown in Figure 5.

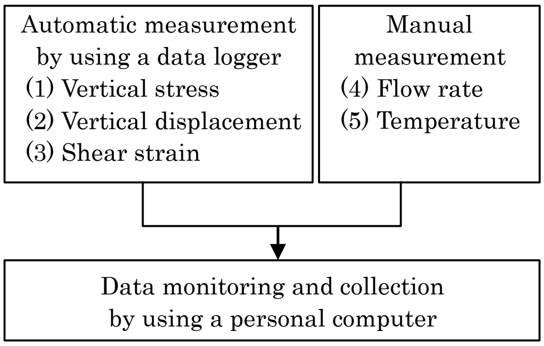


Figure 5. Data acquisition procedure

3. TEST MATERIAL AND PREPARATION OF SPECIMEN

3.1 Test material

For preparing the test material, we applied a grain size analysis to the weathering granite and cohesive soil brought from the vicinity of a borrow pit of an existing dam, and mixed them. This is referred to as material A hereafter. The grain size distribution of the material A is shown in Figure 6. It is similar to that of the impervious materials of an existing dam, and the maximum grain size of material A is set to be 2mm or less in consideration of a thickness of the specimen of 25mm.

Physical test results for material A are summarized in Table 2. The results of compaction and permeability test for material A are shown in Table 3 and Figure 7. The permeability test was conducted based on the “Test methods for permeability of saturated soils (JIS A 1218: 2009)”, which provided by Japanese Industrial Standards(JIS).

3.2 Preparation of specimen

Test specimens were prepared as follows. Material A with optimum water content (w_{opt}) of 31.9% was placed into a hollow cylindrical mold. It is spread into a layer with a thickness 37.5mm by tamping with a 2.5kg rammer.

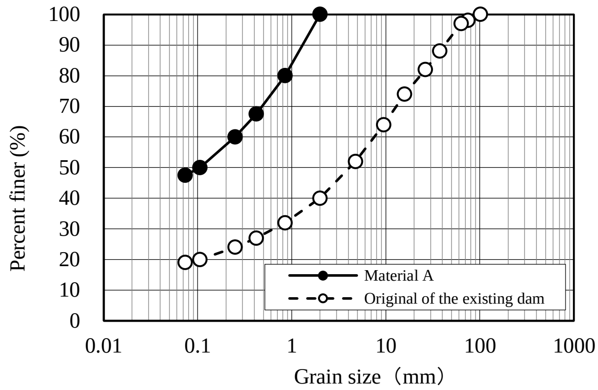


Figure 6. Grain size distribution of Material A

Table 2. Physical test results of material A

Item	Material A
Specific gravity G_s	2.614
Liquid limit W_L (%)	69.6
Plastic limit W_p (%)	39.4
Plasticity index I_p	30.2

Table 3. Results of compaction and permeability test for material A

	W_{opt} (%)	ρ_{dmax} (g/cm³)	k_{100} (cm/s)	k_{95} (cm/s)
Material A	31.9	1.353	4.2×10^{-7}	5.4×10^{-7}

where, W_{opt} = Optimum water content, ρ_{dmax} = Maximum dry density, k_{100} = Coefficient of permeability at W_{opt} and ρ_{dmax}, k_{95} = Coefficient of permeability at W_{opt} and ρ_{d95}, $\rho_{d95} = 0.95\rho_{dmax}$.

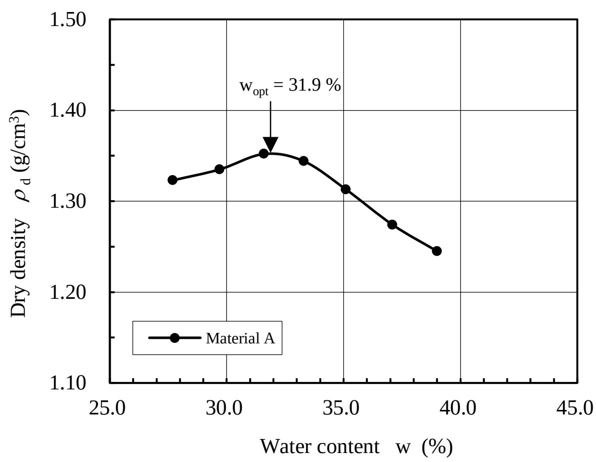


Figure 7. Results of compaction test

4. EXPERIMENTAL STUDY

4.1 Procedures of test

The procedure of permeability test under shear deformed condition using the apparatus is shown in Figure 8.

After setting the specimen into the hollow cylindrical mold, it was permeated from the bottom end by water for about 12hours. Subsequently, the specimen was one dimensionally consolidated under the test pressure for about 1hour. After one dimensional consolidation, a permeability test was initiated at no deformed condition, and a shear deforming process was proceeded by turning the swivel in steps, while keeping the test pressure constant (TEST 1). The hydraulic gradients in all test conditions was set for each shear strain based on the method and the test results of JIS A 1218:2009 in consideration of laminar flow. Therefore, we assumed that the coefficients of permeability obtained from TEST 1 were similar to that obtained from test methods of JIS A 1218:2009. After TEST 1 was finished, a permeability test for checking the critical hydraulic gradient by applying to the water pressure at the shear strain of 50% was conducted (TEST 2).

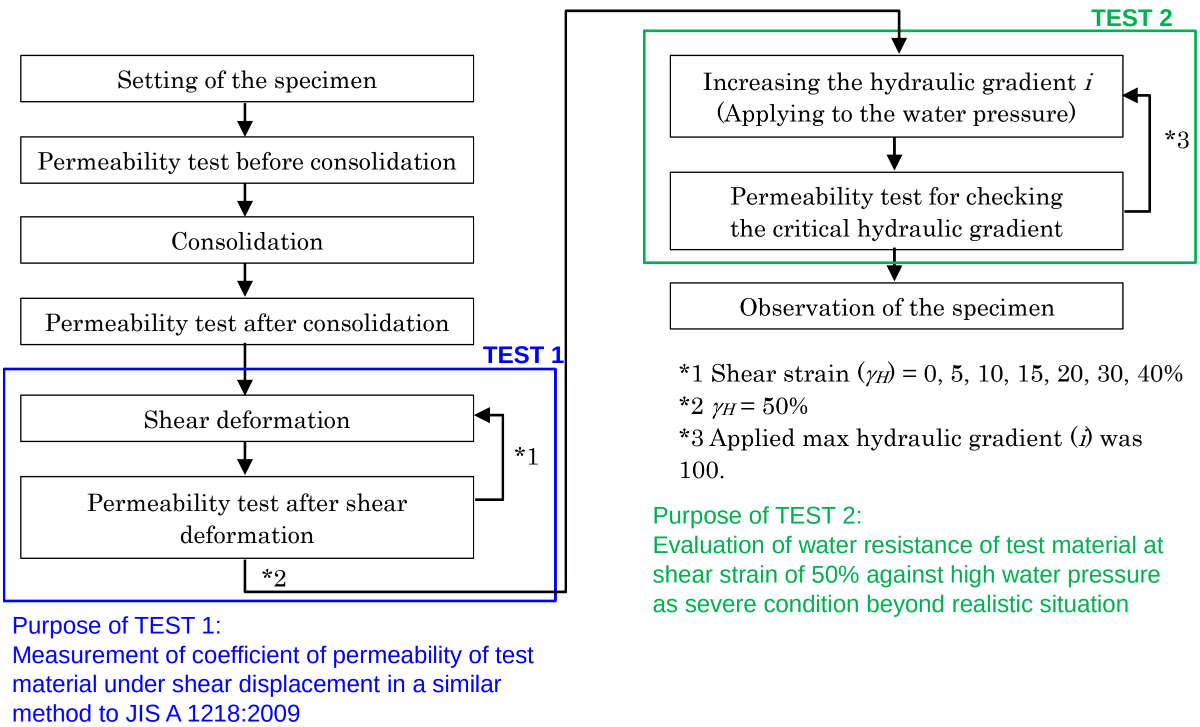


Figure 8. Procedure of permeability test under shear deformed condition

4.2 Determination of coefficient of permeability and shear strain

The flow in the hollow cylindrical specimen is regarded as the two dimensional seepage flow occurring horizontally throughout the specimen. Under this assumption, the permeability of the soil forming the hollow cylindrical specimen can be evaluated using Equation (1) based on Darcy's law, referring to Sakai & Kawakita (1958).

$$k_h = 0.366 \frac{Q}{Lh(t_2 - t_1)} \log\left(\frac{r_2}{r_1}\right) \tag{1}$$

where, k_h (cm/s) = the horizontal coefficient of permeability, Q (cm^3) = the total flow rate through the surface area of the specimen except the top and the bottom area, L (cm) = the height of the specimen, h (cm) = the head loss, $t_2 - t_1$ (s) = the total measurement time, r_1 (cm) = the inner diameters of the hollow cylindrical specimen, r_2 (cm) = the outer diameters of the hollow cylindrical specimen.

The hydraulic gradient at the outer diameter of the specimen is evaluated by the following relationships (Equation (2)):

$$i = 0.434 \frac{h}{r_2 \times \log(r_2 / r_1)} \tag{2}$$

In this study, the relationship between water pressure and water head were defined as 10kPa = 1m.

The shear strain of this test was determined by the Equation (3).

$$\gamma_H = \frac{H_\theta}{L} \tag{3}$$

where, H_θ = the amount of rotating displacement of the specimen.

4.3 Conditions of test

Test conditions are shown in Table 4 and Table 5. The loading conditions were determined by associating with the earth pressure of a 100m high class dam.

Table 4. Test conditions (common to all the tests)

Dry density	Consolidation and drainage condition	Water pressure (hydraulic gradient *i*)	Shear rate	Max shear strain
ρ_{d95} = 1.285	Consolidated-drained (CD)	0.1 kPa – 400 kPa (0.3 — 1,150)	0.0015 rpm	50 %

Table 5. Test conditions

Test name	Loading condition	Equivalent dam height concerning loading condition	Sample of specimen
Ex_2-000	0kPa	0m	Material A
Ex_2-005	100kPa	5m	Material A
Ex_2-020	400kPa	20m	Material A
Ex_2-060	1,200kPa	60m	Material A
Ex_2-080	1,600kPa	80m	Material A

5. RESULTS AND DISCUSSIONS

Figure 9 shows the comparison of vertical displacement obtained from different loading conditions. The findings obtained from Figure 9 are summarised below.

- Except for the loading condition of 0kPa, when the shear strain increases, the vertical displacement gradually decreased. Therefore, the volumes and the void ratio of the specimen of the loading condition of 100kPa, 400kPa and 1,600kPa were predicted to decrease, and those of 0kPa were not to increase also.
- The volume of the specimen gradually decreased under shear deformed condition on the whole.

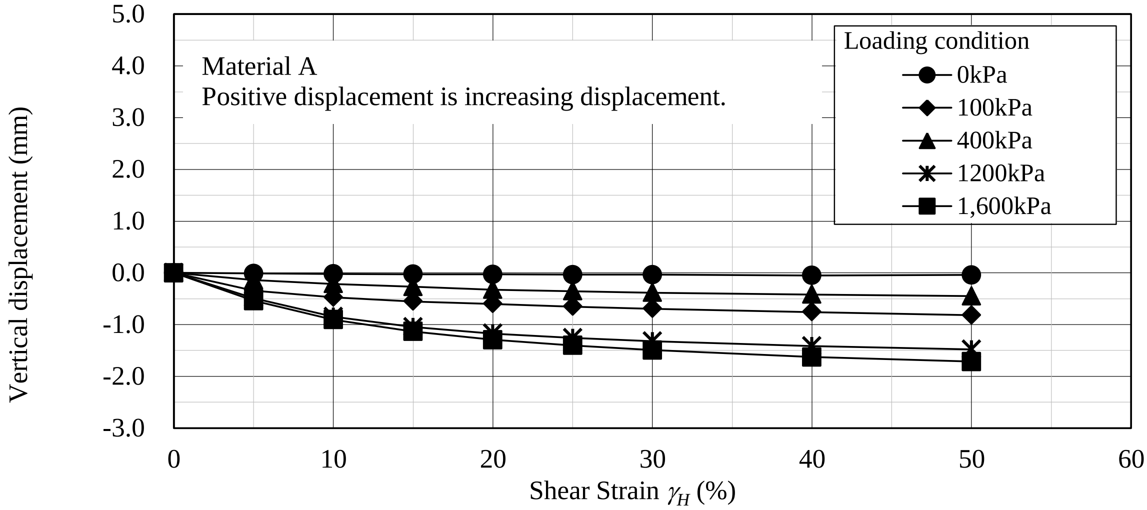


Figure 9. Comparison of vertical displacement obtained from different loading conditions

The comparison of coefficients of permeability (k_h) for each shear strain (γ_H) obtained from different loading conditions, obtained from TEST 1, is shown in Figure 10. Figure 11 shows the example of the observation result of the specimen consolidated under 100kPa at shear strain of from 0% to 50%. Note that the hydraulic gradient (*i*) was changed in consideration of the flow rate of water through the specimen. The findings obtained from Figure 10 and Figure 11 are summarized below.

- The coefficients of permeability after consolidation decrease in the order 100kPa, 400kPa, 1,600kPa and 1,200kPa.
- When the shear strain increases, the coefficient of permeability tends to decrease gradually.
- The increasing characteristic of coefficient of permeability of material A due to shear displacement was not measured on the whole.
- After the swivel initiated to turn, the specimen was uniformly deformed until the shear strain was 5.0%. When the shear strain of the specimen was reached approximately 10%, the specimen initiated to be non-uniformly deformed. That phenomenon was observed by all test specimens in this study.

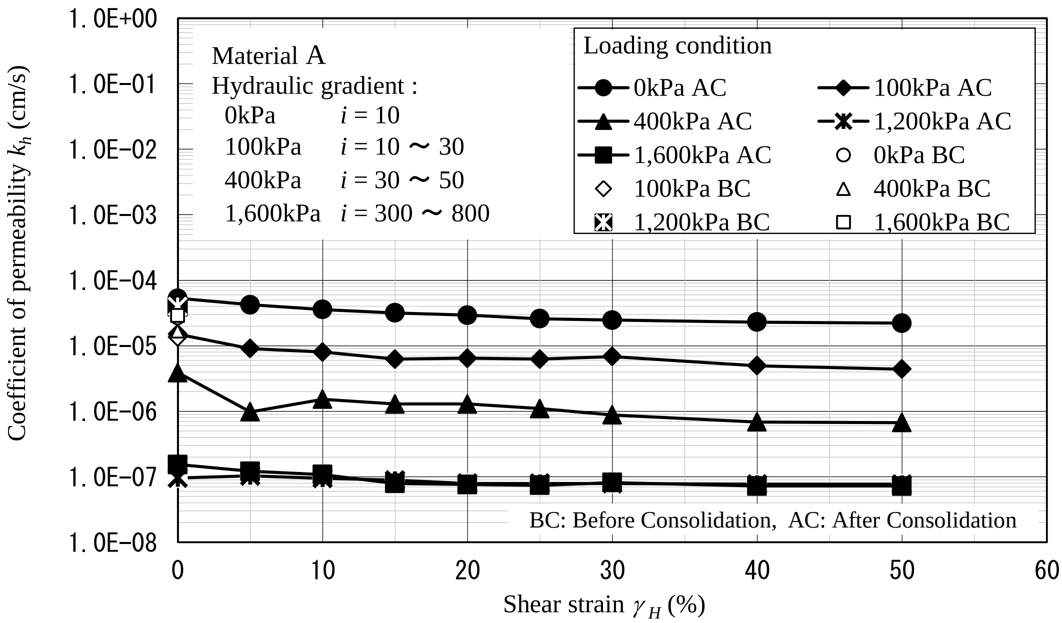
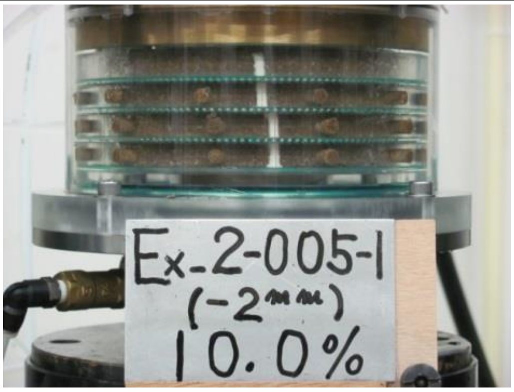


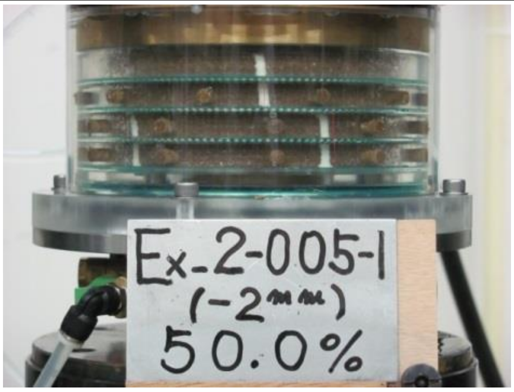
Figure 10. Comparison of coefficients of permeability for each shear strain obtained from different loading conditions (Result of TEST 1)

γ_H = 0%

γ_H = 5%



γ_H = 10%



γ_H = 50%

Figure 11. Test results of the specimen under loading condition of 100kPa

As the result of TEST 1 (see Figure 10), the coefficient of permeability of Material A under shear deformed condition did not increase. In other words, Material A had the water resistance against progressive failure of the specimen. However, if high water pressure is applied to the deformed specimen, there is a possibility that water pass will be formed along the shear zone of the specimen. In addition, it is assumed that the water pass is more likely to be formed under low loading condition in consideration of effect of constraint pressure.

From above assumption, in order to evaluate the water resistance of the deformed specimen, whose shear strain was 50%, against high water pressure, we conducted TEST 2 on the specimen under low loading conditions (the vertical load of 0kPa, 100kPa and 400kPa). For the safety side evaluation, we applied the maximum hydraulic gradient of 100 as the high pressure to the deformed specimen. The hydraulic gradient of 100 means that an impervious core zone whose thickness is 1m supports water head of 100m. When the coefficient of permeability of Material A sharply increased, we judged that Material A under each loading condition did not have the water resistance against high water pressure.

The Permeability changes of Material A at shear strain of 50% with increasing water pressure under low loading conditions is shown in Figure 12. The findings obtained from Figure 12 are summarized below.

- When hydraulic gradient increased, coefficient of permeability increased in the order 100kPa and 0kPa.
- In case of the loading condition of 0kPa, the flow rate thorough the specimen sharply increased at hydraulic gradient of over 80. Therefore, we stopped this case before hydraulic gradient reached to 100. It was assumed that the water pass was formed in shear zone of the specimen.
- In case of the loading condition of 100kPa, the coefficient of permeability was approximately 10 times larger than the initial value after hydraulic gradient reached to 100. However, the flow rate through the specimen did not increase sharply unlike the loading condition of 0kPa.

- Coefficient of permeability at loading condition of 400kPa did not increase.
- These results indicated that the coefficient of permeability did not increase sharply even under low loading condition such as 100 kPa.
- Material A under low loading condition has water resistance against high water pressure on the whole.

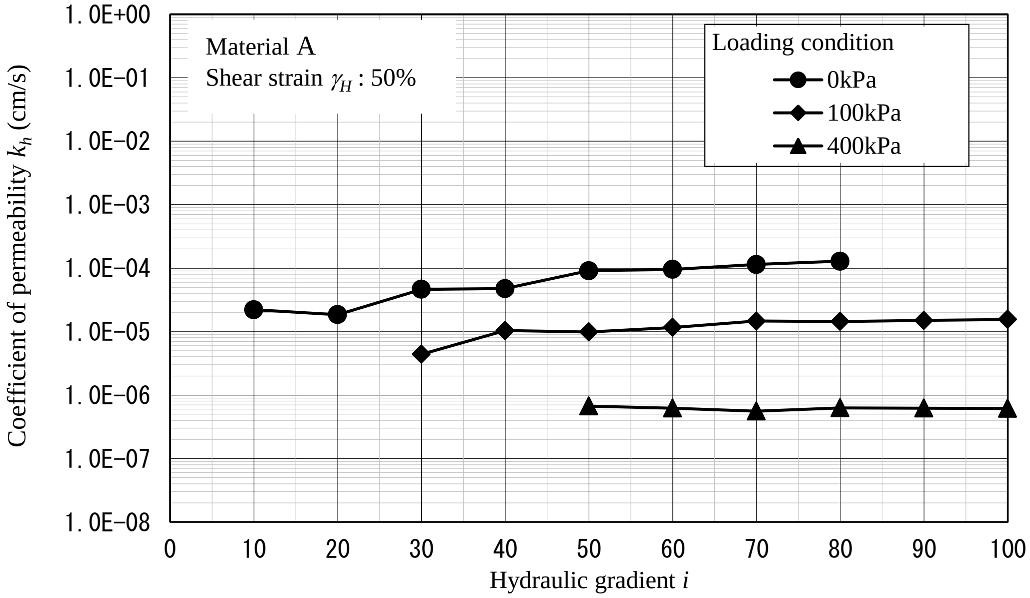


Figure 12. Permeability changes of Material A at shear strain of 50% with increasing water pressure under low loading conditions (Result of TEST 2)

6. CONCLUSION

The following findings have been obtained from the present study:

- In order to examine the relationship between the shear deformation and the permeability of the impervious material, we remodeled the apparatus for torsional shear test on hollow cylindrical specimen of soils, and conducted the permeability test for the test material which was gradually sheared. The grain size distribution of the test material is similar to that of the existing dam.
- As the result of TEST 1, test material was not measured the increasing characteristics of coefficient of permeability under shear deformed condition.
- As the result of TEST 2, test material has water resistance against high water pressure. In addition, the result of TEST 2 indicated that the coefficient of permeability did not increase sharply even under low loading condition such as 100 kPa.

The results of TEST 1 and TEST 2 indicate that deforming and deformed Material A has the water resistance against progressive failure and high water pressure, respectively. However, as the findings of this study were obtained under limited experimental conditions, continuing an examination of the relationship between the shear deformation and the permeability of the impervious material under different conditions (e.g., faster shear rate conditions than that of this study) will be necessary as a future work before practical application.

7. REFFERENCES

Ohmachi, T. (2000). *On damage to dams in Taiwan due to the 1999 Chichi Earthquake*, Journal of Japan Society of Dam Engineers, JSDE, Vol. 10, No. 2, pp. 138 – 150.

Sakai, S. & Kawakita, Y. (1958): *On the trial production of radial flow permeameter and its test*, Japan Society of Civil Engineers 1958 Annual Meeting, JSCE, pp. 39－47.