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Evaluation of Embankment Material Properties Affected by Circular Slip Failure Mode due to a Large-Scale Earthquake

Tomohiro Shiono, Akira Takahashi & Kazunori Takasawa
Tokyo Electric Power Co Inc, Tokyo, Japan
shiono.tomohiro@tepco.co.jp

Tomokazu Suzuki
Tokyo Electric Power Services Co., Ltd, Tokyo, Japan

ABSTRACT:
There is a keen interest in dam stability against a large-scale earthquake. In case of an embankment dam, embankment plastic deformation may occur in the event of a large-scale earthquake. Failures to be considered are mainly reservoir overtopping and seepage of an embankment dam. Embankment dam is required to maintain a reservoir during and after the earthquake. For the overtopping failure mode, dam stability can be evaluated by comparing the dam's freeboard and the settlement examined by an analysis. On the other hand, evaluation of the stability against seepage is rather complex in case a circular slip is predicted in the embankment. The circular slip may cause the positive dilatancy of the embankment material along the circular shear plane. The positive dilatancy increase permeability which may affect pore pressures and dam stability after the earthquake. The seepage stability, therefore, should be evaluated in consideration of such property change by the circular slip. As to laboratory tests, ring shear test method is applicable to measure a permeability coefficient along the shear plane. We conducted ring shear tests to examine the permeability of embankment material which is subject to a circular slip due to the earthquake. Furthermore, box shear tests were additionally conducted since it represents more accurate shear mechanism. According to the material used for this study, the ring shear test method is practical to evaluate the permeability up to 8% strain level, where both the ring shear tests and the box shear tests showed the consistent dilatancy characteristics. The coefficient of the permeability is approximately 1 to 3 times when the shear strain becomes 8%. The test results did not show a significant permeability change in such shear strain level. It indicates the predicted strain in the embankment material up to approximately 8% is unlikely to cause a seepage failure just after the earthquake excitation.

Keywords: Fill dam, circular slip, dilatancy, permeability property along a shear plane.

1. INTRODUCTION

Ministry of Land, Infrastructure and Transport of Japan released a guideline to examine seismic resistant performance of dams against a large-scale earthquake (MLIT, 2005). Dams are required to maintain reservoirs during and after an earthquake from the downstream safety view point. In case of an embankment dam, plastic deformation may occur in the event of a large-scale earthquake. Stability against seepage of the embankment dam should be examined in case the following failures are predicted.

- A circular slip in a homogeneous earthfill dam. And the upstream side of the circular plane is below reservoir water level.
- A circular slip crossing a center core of the rockfill dam

In case of the circular slip, it will cause positive or negative dilatancy of the embankment material along the shear plane. The positive dilatancy increases permeability which may affect pore pressures and dam stability after the earthquake. This study was aimed to examine such property changes affected by a circular slip, which is applicable to examine the seepage stability of the embankment dam.

2. APPLIED SHEAR TEST METHOD

The shear tests are generally divided into indirect or direct shear tests. The indirect shear test is a test to examine the shear strength from compressive strength indirectly, such as triaxial compression test. A shearing plane is formed in [45 degrees +φ/2] in the test material, which causes difficulty to measure the permeability along the shear plane.

On the other hand, the direct shear test is a test to examine the shear strength along a specific shear plane directly, such as box shear test and torsion shear test. The box shear test, however, causes a gap between upper part and lower part of a test specimen due to the shear strain, which causes difficulty to maintain water tightness for conducting a permeability test.

Firstly, both torsion shear tests and box shear tests were conducted under several conditions. Results of the torsion shear tests were compared with the box shear tests which are considered to represent more accurate shear mechanism. And, applicable conditions of the torsion shear test were identified to examine the permeability along the shear plane. Later, permeability coefficients along the shear plane were examined during a shear process by the torsion shear tests.

2.1. Ring shear test, shearing torsionally

A holly cylindrical specimen was used for a ring shear test. The shearing devise was modified with reference to the applicable study paper, Matsui et al in 1978, so that water permeability could be directly measured along a shear plane as shown in Fig.2. The ring shear tests were conducted as following manners.

1) Make a test specimen.
2) Mount a specimen in a ring shear test instrument, and compact it by loading.
3) Measure permeability before shearing
4) Rotate the ring device to shear the specimen torsionally.
5) Measure permeability coefficient along the shear plane.

The torsion shear stress, strain and permeability along the shear plane were expressed by Eq.1, Eq.2, and Eq.3 respectively.

2.1.1 Torsion shear stress

$$\tau = \frac{2}{A} Q = \frac{2}{\pi \; (r_3^{\,2} - r_1^{\,2})} \times Q$$

$$= \frac{2}{\pi \; (r_3^{\,2} - r_1^{\,2})} \times \frac{r_4}{r_2} \times F \qquad (1)$$

Where:

τ	:	Shear stress
A	:	Area of the shear plane
r_3	:	Outer radius of the specimen
r_1	:	Inner radius of the specimen
Q	:	Shear stress at the center of the specimen of gravity position
r_4	:	Gyration radius of the test devise
r_2	:	Gyration radius at the test specimen center of gravity position
F	:	Arm tip reaction by the torsion

2.1.2 Torsion shear strain

$$r = \frac{\Delta\theta}{2H} \times \frac{r_3 + r_1}{2} \times 100 \qquad (2) \quad \text{(EPCEA, 1981)}$$

Where:

r	:	Torsion shear strain
$\Delta\theta$	:	Rotation angle
r_3	:	Outer radius of the specimen
r_1	:	Inner radius of the specimen
H	:	Height of the specimen

2.1.3 Permeability coefficient

$$k = 0.842 \times \frac{a}{H\ (t_2 - t_1)} \times \log\left(\frac{r_3}{r_1}\right) \times \log\left(\frac{h_2}{h_1}\right) \qquad (3)$$

Where:

k	:	Permeability coefficient
a	:	Inner area of the standpipe
r_3	:	Outer radius of the specimen
r_1	:	Inner radius of the specimen
h_1	:	Water pressure at time t_1
h_2	:	Water pressure at time t_2
H	:	Height of the specimen

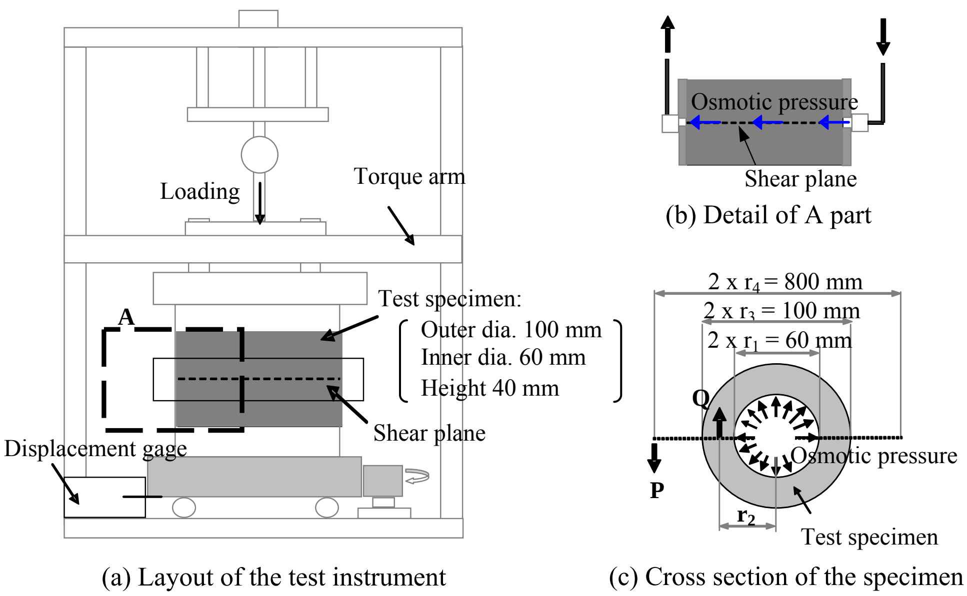


Figure 1. Ring shear test instrument

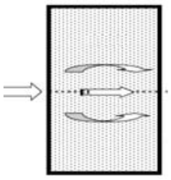


Figure 2. Image of the permeability measurement by the ring shear test

2.2. Box shear test, shearing directly

The size of the specimen is 20 cm-long and 10 cm of diameter. A test specimen was set in a shear box as shown in Fig.3. The box shear test is generally applicable to measure the shear strain up to 5 cm by using a shear box. The box shear tests were conducted as following manners.

1) Make a test specimen, and set the specimen in a shear box.
2) Mount the shear box in a test instrument.
3) Compact the specimen by loading.
4) Strain the shear box horizontally.

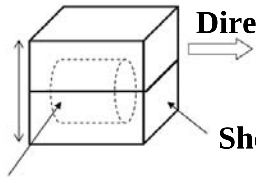


Figure 3. Box shear test

3. IDENTIFICATION OF THE DILAYTANCY CHARACTERISTICS BY DIFFERENT SHEAR TESTS, AND CONDITIONS

3.1. Shear test conditions and test materials

Earthquake causes a load for a short term by excitation. Therefore, the shear strain due to the earthquake could be considered under the un-drained and constant volume condition. In this study, the shear tests were conducted under the un-drained and constant volume condition with loading control. Shear strain rate was determined to be 0.3% per minutes referring to the guideline (JGS, 2010).

Properties of the original material used for the tests, fine and sand material, were tabulated in Table 1. The sand material was prepared for 2 types. One is the original material which grain distribution has 37.5 mm of maximum grain, and the other is the material that the grain greater than 2.0 mm was excluded from its grain distribution. Those materials were mixed in order to adjust the grain distribution for the tests. The test materials were prepared for fine, average and coarse in consideration of a typical grain distribution of a homogeneous earthfill dam. The grain distribution considered in this study as a typical homogeneous earthfill dam is shown in Fig.4.

Table 2 shows the mixing ratio to obtain the adjusted test materials. Since instruments of the torsion shear test and the box shear test are applicable to the material composed of the grain smaller than 4.75 mm or 19 mm respectively, gravel fractions of the test materials were modified so that the grain greater than 4.7 mm or 19 mm were excluded. Dry density and water content of the modified test materials were determined as shown in Table 3 based on Eq.4 and Eq.5 proposed by Waller-Holtz. The grain distribution of the test materials were adjusted to the target distribution as shown in Fig.5

$$\rho_d = \frac{1}{\dfrac{(1-P)}{\rho_{d1}} + \dfrac{(1+w_2 \cdot G_{s2})}{G_{S2}\,\rho_w}} \qquad (4)$$

$$w = w_1(1-P) + w_2 P \qquad (5)$$

Where:

ρ_d	:	Dry density after modification of gravel fraction
w	:	Water content after modification of gravel fraction
ρ_{d1}	:	Dry density of soil, 0.71 g/cm^3 of fine material
P	:	Gravel ratio
G_{s2}	:	Gravel density, 2.66 g/cm^3 of sand
ρ_w	:	Water density
w_1	:	Water content of soil, 96.2 % of fine material
w_2	:	Water content of gravel, 3.9 % of sand

Table 1. Properties of the test material

Item		Material	
		Fine	Sand
Density	(g/cm^3)	2.64	2.71
Water content	(%)	88.8	3.7
Liquid limit	(%)	122.7	
Plasticity limit	(%)	71.1	
Plasticity index		51.6	
Absolute dry density	(g/cm^3)		2.66
Water absorption rate	(%)		0.7

Table 2. Mixing ratio of the adjusted materials

Test materials	Dry weight ratio		
	Fine	Sand -1	Sand-2
Fine material	1.0	–	–
Average embankment material	1.0	0.70	0.20
Coarse embankment material	1.0	2.50	0.20
Coarse foundation	1.0	5.00	0.20

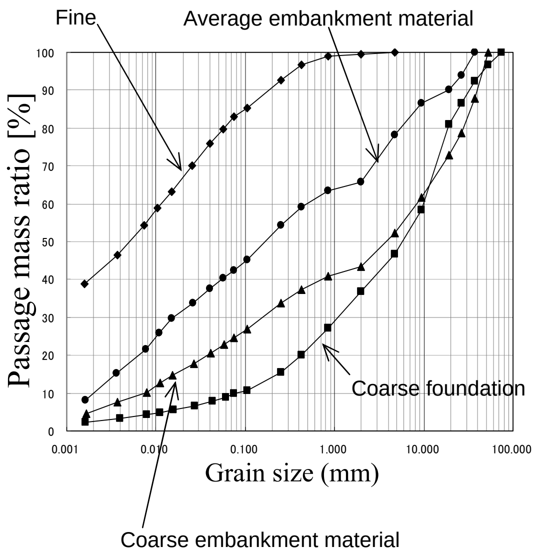


Figure 4. Grain size distribution of a homogenous earthfill dam

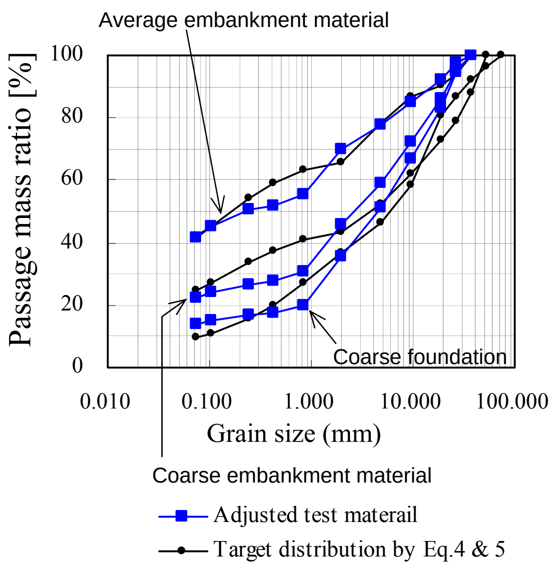


Figure 5. Grain size distribution of the adjusted test materials

Table 3. Dry density and water content of the modified test materials

Item	Test material, determined based on Eq.4 and 5			Reference, material shown in Fig. 4	
Material	Sand rate (%)	Dry density (g/cm^3)	Water content (%)	Dry density (g/cm^3)	Water content (%)
Average, fill embankment	45	1.04	55.0	1.12	51.7
Coarse, fill embankment	70	1.40	32.0	1.70	21.3
Coarse, foundation	80	1.67	22.0	1.47	25.3

3.2. Identification of the dilatancy characteristics by different shear tests

Test conditions are tabulated in Table 4. Each shear test was conducted under the un-drained and constant volume condition with loading control. Fig.6 shows comparison between the box shear tests and the ring shear tests, and relations between shear strain, stress and vertical loading.

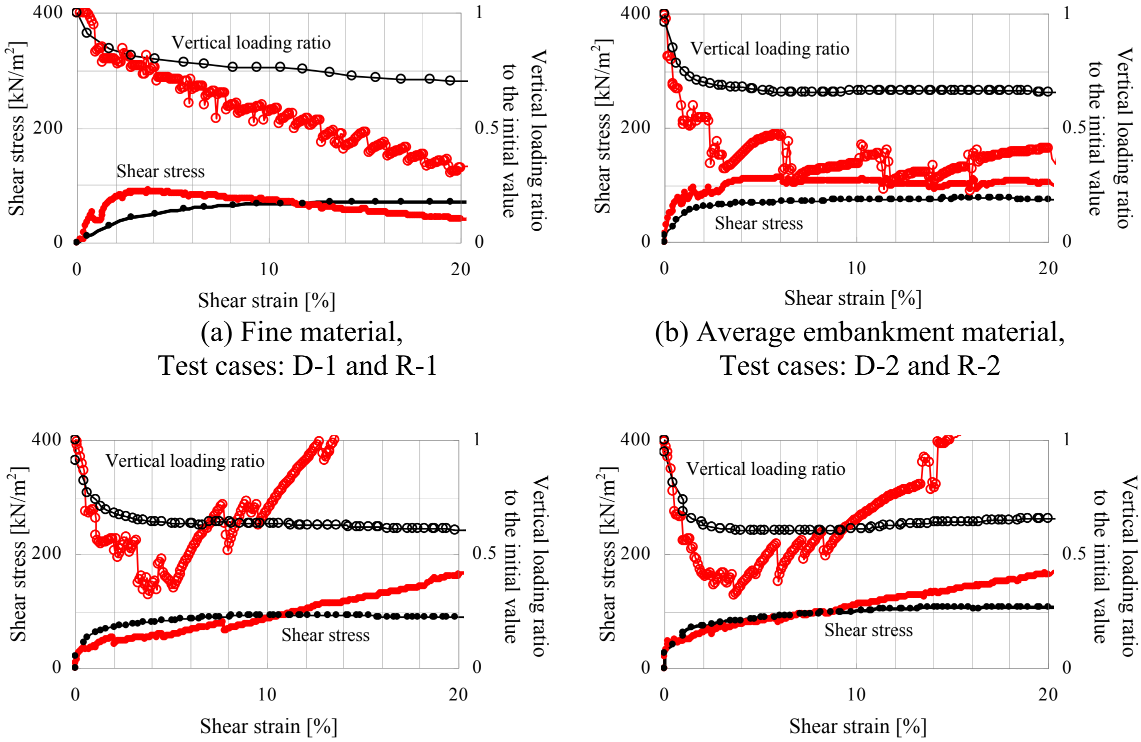
In case that the vertical loading trend during a shear process shows a change of plus or minus sign of the inclination in Fig.6, it means the dilatancy of the material changes from negative to positive or from positive to negative. Test results are summarized as followings.

- As to the fine and the average embankment materials, vertical loading values continued to decrease gradually during a shear process as shown Fig.6 (a) and (b). The material continues to show the negative dilatancy during a shear process by both the ring shear tests and the box shear tests.
- As to the coarse grain materials, a discrepancy of the dilatancy characteristics was observed between the ring shear tests and the box shear tests as shown in Fig.6 (c) and (d). Results of the box shear tests show negative dilatancy up to approximately 5 % of the shear strain, and then it turns to positive dilatancy. On the other hand, the ring shear tests continued to show negative dilatancy during a shear process.

Table 4. Test cases

Test case	Test method	Material	Max. grain size (mm)	Constant volume condition
D-1	Box shear test (Direct shear test)	Fine material	19	Constant volume condition by loading control. Initial loading was set to 100 kN/m^2
D-2		Average embankment material		
D-3		Coarse embankment material		
D-4		Coarse foundation		
R-1	Ring shear test	Fine material	4.75	
R-2		Average embankment material		
R-3		Coarse embankment material		
R-4		Coarse foundation		

Note: Shear strain rate is 0.3% per minute.



(a) Fine material,
Test cases: D-1 and R-1

(b) Average embankment material,
Test cases: D-2 and R-2

(c) Coarse embankment material,
Test cases: D-3 and R-3

(d) Coarse foundation,
Test cases: D-4 and R-4

Figure 6. Results of the ring shear tests and the box shear tests,
Red: Box shear test, Black: Ring shear test

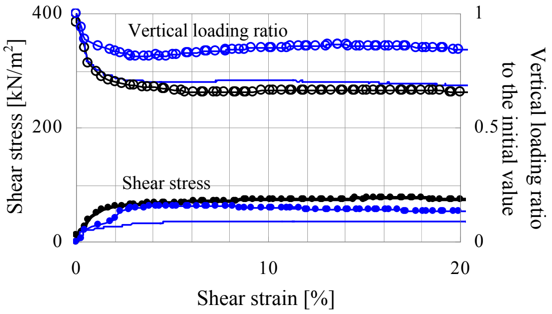
4. INDENTIFICATION OF THE DYLATANCY CHARACTERRISTICS BY DIFFERENT VERTICAL LOADING AND DENSITY CONDITIONS

Additional ring shear tests were conducted in order to examine difference of the dilatancy characteristic by test conditions, such as loading condition and density of the material. The additional test cases are tabulated in Table 5. The high compacted test specimens were also prepared in order to examine the dilatancy characteristic under different density conditions. The test results were shown in Fig.7. The positive dilatancy characteristic is more distinct under the conditions that the test specimen was high density or the initial vertical loading value was set to be smaller. The results of the ring shear tests were compared with the box shear tests in Fig.8. It was identified that the ring shear tests could simulate the dilatancy characteristics obtained by the box shear test up to approximately 8 % shear strain, when the initial loading value was set to be 50 kN/m^2 and the test specimen was high compacted.

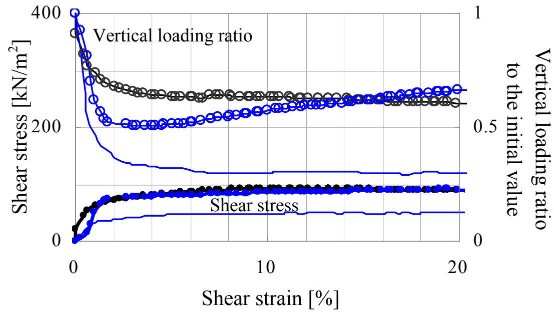
Table 5. Additional test cases

Test case	Test method	Material	Max. grain size (mm)	Constant volume condition	Note
R-5	Ring shear test	Average embankment material	4.75	Constant volume condition by loading control. Initial loading was set to 50kN/m^2	
R-6		Coarse embankment material			
R-7		Coarse foundation			
R-8		Average embankment material			Additional, high compacted
R-9		Coarse embankment material			
R-10		Coarse foundation			

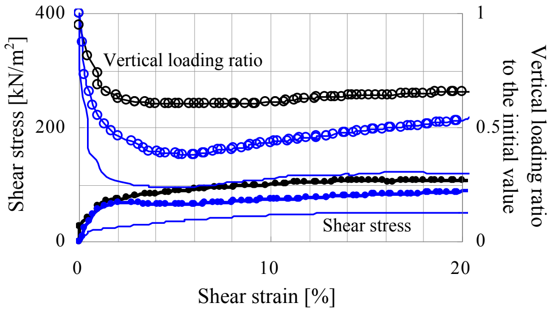
Note: Shear strain rate is 0.3% per minute.



(a) Average embankment material,
Test cases: R-2, R-5 and R-8



(b) Coarse embankment material,
Test cases: R-3, R-6 and R-9

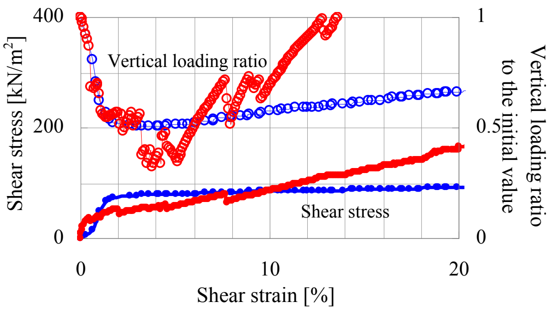


(c) Coarse foundation material,
Test cases: R-4, R-7 and R-10

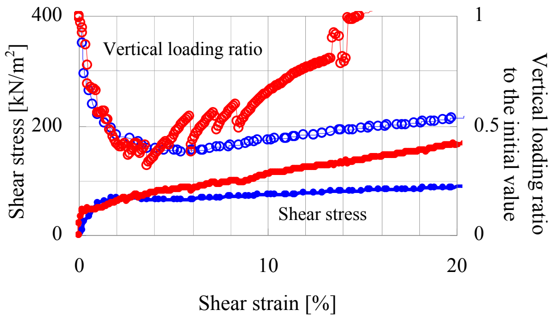
Test conditions are:

	Initial vertical loading	Note
Black with marks:	100 kN/m^2	
Blue with marks:	50 kN/m^2	High compacted specimen
Blue without marks:	50 kN/m^2	

Figure 7. Results of the additional ring shear tests



(a) Coarse embankment material



(b) Coarse foundation

Figure 8. Comparison of the ring shear tests and the box shear tests,
Red: Box shear test, Blue: Ring shear test under the indentified condition

5. EXAMINATION TO UNDERSTAND THE PERMEABILITY CHANGE AT THE FORMED SHAER PLANE

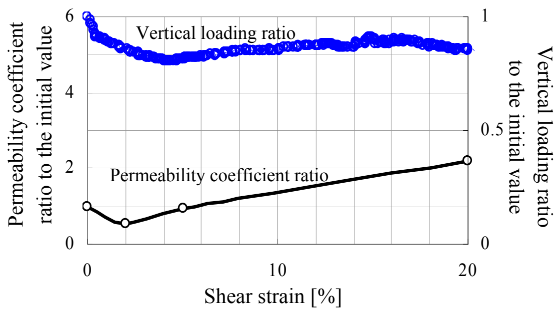
Permeability change during a shear process was examined by ring shear tests. The tests were conducted under the identified condition which could simulate the dilatancy characteristics obtained by the box shear tests as mentioned in chapter 4. Test cases and results are summarized in Table 6.

The each test shows negative dilatancy up to approximately 3 % of shear strain. As the shear process proceeds with the negative dilatancy, permeability coefficient gradually decreases up to 60-90 % of the initial coefficient. Later, the dilatancy turns into positive, and the permeability coefficient gradually increases. The permeability coefficients reach approximately 1 to 3 times of the initial values when the shear strains become 8 %. The more decrease of the permeability was observed for the smaller grain materials when the dilatancy characteristic was negative. And, the more permeability increase was observed for the coarse particle materials when the dilatancy characteristic was positive.

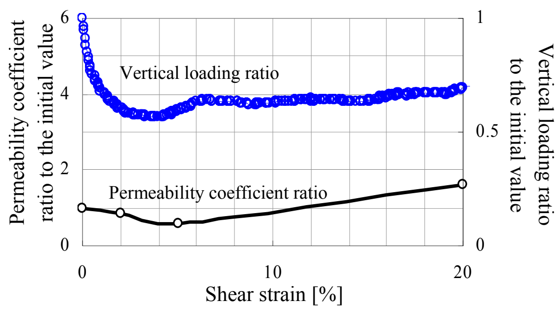
Table 6. Permeability measurements by the ring shear tests

Test case	Material	Max. grain size (mm)	Constant volume condition	Note	Shear strain (%)	Permeability coefficient (cm/s)		Ratio
						Before shear	After shear	(after/ before)
R-11	Average grain distribution	4.75	Constant volume condition by loading control. Initial loading was set to 50kN/m^2	High compacted specimen	2	2.90×10^{-7}	2.90×10^{-7}	0.52
R-12					5	2.10×10^{-7}	2.10×10^{-7}	0.95
R-13					20	2.70×10^{-7}	2.70×10^{-7}	2.19
R-14	Coarse, embankment material				2	7.00×10^{-7}	7.00×10^{-7}	0.84
R-15					5	4.40×10^{-7}	4.40×10^{-7}	0.59
R-16					20	5.60×10^{-7}	5.60×10^{-7}	1.63
R-17	Coarse, foundation				2	1.20×10^{-6}	1.20×10^{-6}	0.92
R-18					5	8.50×10^{-7}	8.50×10^{-7}	1.15
R-19					20	9.10×10^{-7}	9.10×10^{-7}	5.71

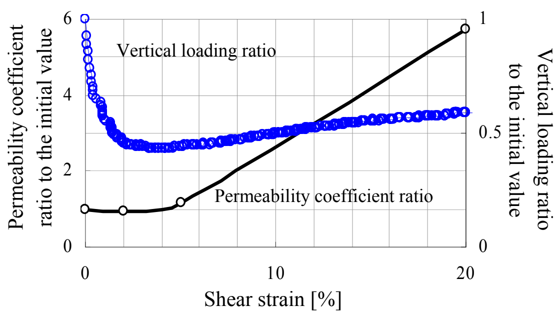
Note: Shear strain rate is 0.3% per minute.



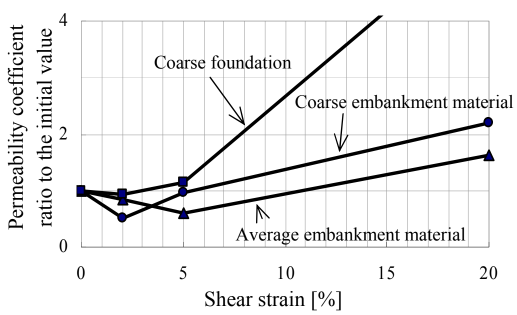
(a) Average embankment material



(b) Coarse embankment material



(c) Coarse foundation



(d) Difference by grain sizes

Figure 9. Permeability measurements by the ring shear tests

6. CONCLUSION

This study was aimed to examine the embankment material properties subject to a circular slip, which is applicable to evaluate embankment stability against seepage. Results of this study are summarized as follows.

The circular slip may cause positive dilatancy of the embankment material along the shear plane. The positive dilatancy increases the permeability which may affect pore pressures and dam stability after the earthquake. The permeability coefficients of the embankment materials were examined by shear tests.

The ring shear test was applicable to measure the permeability along the shear plane. The applicable ring shear test condition was identified by comparison with the box shear test results focusing on dilatancy characteristic. As to the material used for this study, it was evaluated that the ring shear tests with the high compacted specimen could simulate the dilatancy characteristic obtained by the box shear test up to 8 % shear strain. The ring shear test is practical up to 8 % shear strain for the test material to evaluate the permeability along the shear plane. The permeability coefficient is approximately 1 to 3 times when the shear strain is 8 %. The test results did not show a significant permeability increase. It may indicate that the predicted strain in the embankment material up to approximately 8 % is unlikely to cause a seepage failure just after the earthquake.

Equivalent linearization method is widely adopted for a seismic response analysis in order to examine seismic resistant performance of an embankment dam. The equivalent linearization method is generally considered to be applicable to the seismic response up to approximately 0.1% of strain level, Nakamura et al in 2002. The indentified strain range for evaluation of the permeability by the shear test is greater than the strain level, according to the material used for this study.

REFERENCES

1. Ministry of Land, Infrastructure and Transport (2005): *Guideline to examine seismic resistant performance of dams against large-scale earthquake,* Ministry of Land, Infrastructure and Transport, Tokyo, Japan.
2. I. Matsui, M. Ikemi, and T, Okamoto (1978): *An analysis on Stability of Core Zone Adjoining with Foundation, and an Experimental Study on the Properties of Contact Clay*, CRIEP Research Report, No. 378008, Central Research Institute of Electric Power Industry, Tokyo, Japan.
3. Japanese Geotechnical Society (2010): *Ground material examination method and interpretation,* Japanese Geotechnical Society, Tokyo, Japan
4. Electric Power Civil Engineering Association (1981): *New edition of fill dam engineering, revised edition,* Electric Power Civil Engineering Association, Tokyo, Japan
5. S. Nakamura, N. Yoshida (2002): *The proposed non-linear dynamic seismic response analysis method based on a dynamic deformation characteristic of the ground material in a frequency domain,* Proceedings of the Japan Society of Civil Engineers, No.772/III-61, pp. 169-187, Japan Society of Civil Engineers, Tokyo, Japan.