Physical Modelling in Geotechnics

Dynamic centrifuge model tests of soil-bentonite vertical cut-off walls with earthquake-proof performance

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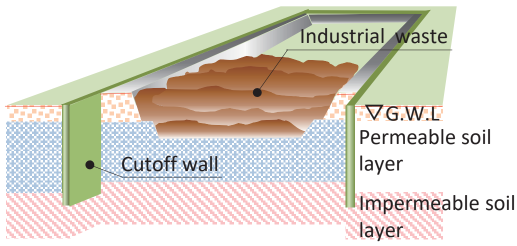
ABSTRACT: Vertical cut-off walls using low permeable materials are often constructed at contaminated sites to contain the contaminants and to prevent their migration in the aquifer. It is also needed to the leakage control of river embankment and regulating pond. The usual countermeasure is to construct the soil-cement cut-off walls. However, it is pointed out that the soil-cement cut-off walls are damaged during the earthquake. The purpose of this study is to develop the soil-bentonite vertical cut-off walls with earthquake-proof performance. In this study, dynamic centrifuge model tests were performed to confirm the earthquake-proof performance. The following findings were obtained from this study. 1) It is concluded that the soil-bentonite vertical cut-off wall which was developed in this study has the high earthquake-proof performance because the deformation of soil-bentonite vertical cut-off wall follows the model ground deformation during the shaking. 2) The failure of soil-bentonite cut-off wall does not occur although that of soil-cement mixing wall is confirmed.

Keywords: Dynamic Centrifuge Model Test, Vertical Cut-off Wall, Earthquake-proof Performance

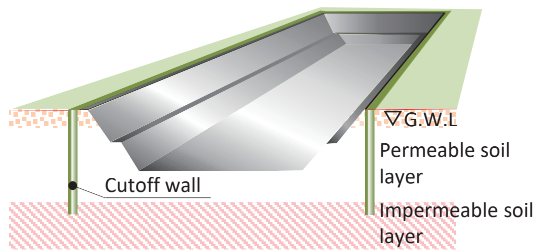
1 INTRODUCTION

Vertical cut-off walls using low permeable materials are often constructed at contaminated sites to contain the contaminants and to prevent their migration in the aquifer. It is also needed to the leakage control of river embankment and regulating pond. Figure 1 summarizes the concept of applicability on vertical cut-off walls. The usual countermeasure for the migration and the leakage control is to construct the soil-cement cut-off wall. However, it is pointed out that the soil-cement cut-off wall is damaged when the earthquake happens. Moreover, the barrier performance of cut-off wall decreases as the crack of cut-off wall occurs.

The purpose of this study is to develop the soil-bentonite vertical cut-off walls with earthquake-proof performance. The soil-bentonite vertical cut-off wall which is developed in this study is a rather flexible material compared with other typical barrier materials such as soil-cement mixing material. There are some previous researches to examine the performance of soil-bentonite cut-off walls (Evans et al., 2008, Yao et al., 2009, Takai et al., 2012). These researches are subjected to construct the vertical cut-off walls by mixing powdered bentonite and in-situ soil. The results of previous researches are reported as follows;



(a) Containment of waste soil



(b) Leakage control of regulating pond

Fig. 1 Concept of vertical cutoff walls.

1. It is possible to construct the low permeable cut-off walls as bentonite and in-situ soil are mixed.
2. The damage of cut-off walls does not occur when the large deformation happens in the ground.
3. Corrosion and degradation does not occur because

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it is stable that the major component of bentonite is inorganic substance such as montmorillonite.

4. Sludge amount due to the construction of cut-off walls decreases as bentonite and in-situ soil are mixed in the construction process.

The soil-bentonite vertical cut-off walls with earthquake-proof performance was developed. The following findings (Watanabe et al., 2019);

1) The hydraulic conductivity showed the high value and decreased with the confining pressure from the triaxial hydraulic conductivity tests.

2) According to the in-situ full scale test, it is confirmed from the results of CPT that the soil-bentonite vertical cut-off wall can be constructed the constant quality along to the depth direction by using TRD (Trench cutting Re-mixing Deep wall) method.

3) It is examined that the soil-bentonite vertical cut-off wall has the high hydraulic conductivity from hydraulic conductivity test for the core sampling specimen of in-situ full scale test.

In this study, the dynamic centrifuge model tests were performed to confirm the earthquake-proof performance and the impermeable performance of the developed cut-off wall. Four kinds of step-wise shaking using sine wave were conducted for the soil-bentonite vertical cut-off wall and the soil-cement mixing vertical cut-off wall.

2 DYNAMIC CENTRIFUGE MODEL TEST

2.1 Centrifuge apparatus

The beam type centrifuge apparatus was used to the model test as described in this paper. This beam type centrifuge has a pair of parallel arms that hold platforms on which the model container and a weight for counterbalance are mounted. Radius of rotation is 7.01m, which is the distance from the rotating shaft to the platform base. The surface of swinging platform is always normal to the resultant acceleration of the centrifuge acceleration, nG, and earth's gravity. The shaking table platform was used in dynamic centrifuge model tests.

2.2 Material used in centrifuge model tests

Figure 2 indicates the grain distribution curve of Silica sand No. 7, and the physical properties of that are also shown in Table 1. The model ground is prepared by air-pluviation method using Silica sand No. 7.

The compounding conditions of model soil-bentonite cut-off wall are proposed in Table 2. The constitutional materials are sand (Silica sand No. 5), Kaolin clay (only Case 2), Ca-bentonite, water and ion-exchange material. In addition, the composite soil means the soil including a fine content such as Kaolin clay. The making process of model soil-bentonite cutoff wall is described as follows;

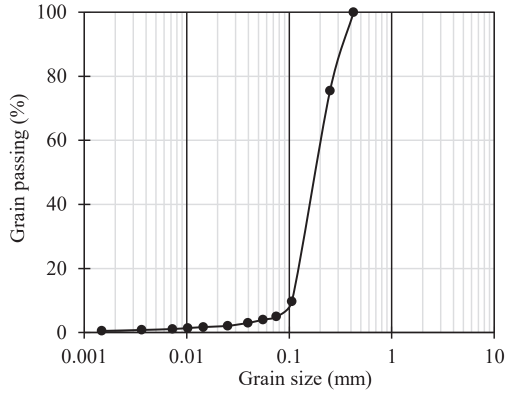


Fig. 2. Grain size distribution of silica sand No.7.

Table 1. Physical properties of silica sand No. 7.

Soil particle density ρ_s (g/cm^3)	2.654
Mean diameter D_{50} (mm)	0.185
Maximum void ratio e_{max}	1.193
Minimum void ratio e_{min}	0.698

Table 2. Compounding condition of cut-off wall.

	Soil type	Sand (g)	Kaolin clay (g)	Water (g)	Ca-bentonite (g)	Ion-exchange material (g)
Case 1	Sandy soil	1713	-	480.4	122.6	4.4
Case 2	Composite soil	1486.6	165.2	541.6	122.6	4.4

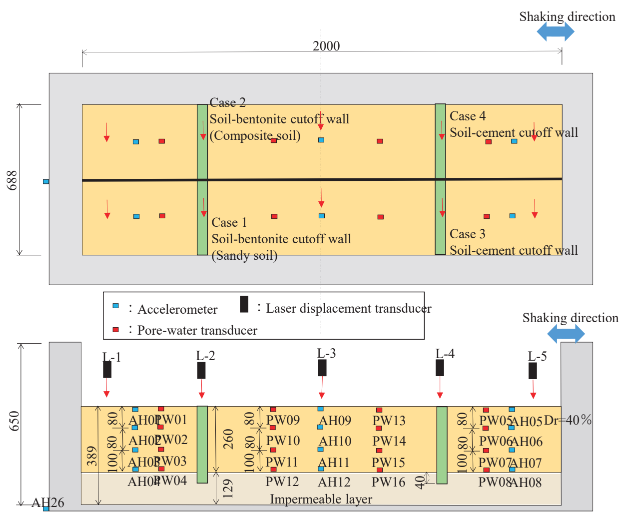


Fig. 3. Schematic view of centrifuge shaking table test.

1. The predetermined sand and water are mixed homogeneously by the rotary-type mixer. (i.e. model ground material) Here, the predetermined Kaolin clay is added in the Case 2.

2. The predetermined Ca-bentonite and water are mixed homogeneously. (i.e. injection liquid)

3. The predetermined ion-exchange material and

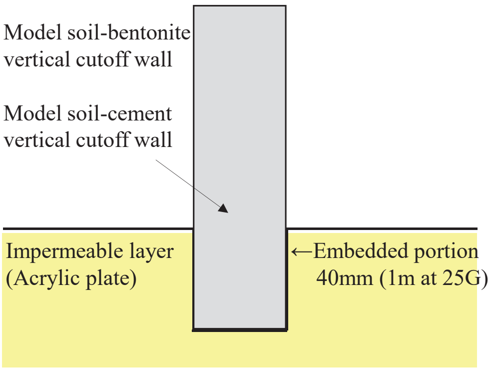


Fig. 4. Detail of embedded portion for model.

water are mixed homogeneously. (i.e. injection activating agent)

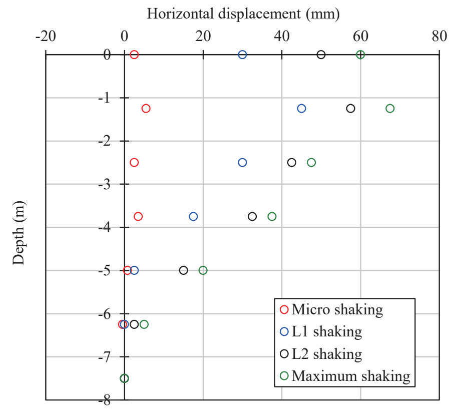
4. The injection liquid and injection activating agent are added to the model ground material.

5. The model soil-bentonite cutoff wall is made by injecting the model ground.

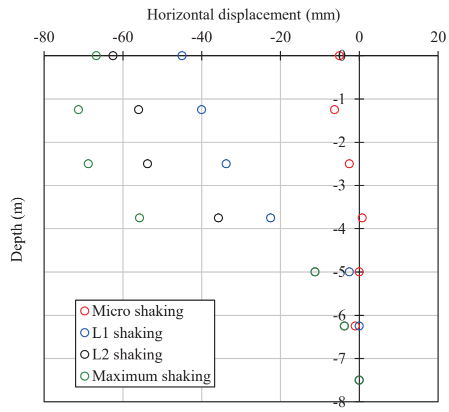
2.3 Experimental condition

Figure 3 shows the schematic view of centrifuge shaking table test. A rigid soil container was used in the shaking table test, and the model ground was created using air-pluviation method such that the relative density of the D_r was 40%. Silica sand No. 7 (Specific gravity of soil, G_s=2.645) was used in preparing the model ground. The bottom layer was the impermeable layer which was made by the acrylic plate. The detail of embedded portion for the model vertical cutoff wall is shown in Fig. 4. For the vertical cutoff wall, the sandy soil-bentonite cutoff walls was simulated using compounding condition of Case 1 as described in Table 2, whereas composite soil-bentonite cutoff wall was simulated using compounding condition of Case 2 as described in Table 2. The model soil–cement mixing walls (Cases 3 and 4) are made by Silica sand No. 5 and cement. The target strength of soil-cement mixing walls are unconfined strength q_u=500kN/m^2. It is confirmed that the strength of soil-cement is almost q_u=500kN/m^2 from the unconfined compression test. The dimension of model cutoff wall are width 20mm, depth 340mm and length 300mm. As the model scale ratio was 1:25, a centrifuge acceleration of 25G was used in the shaking table tests. The model ground is saturated after preparing the dry sand ground by using the metolose water which has 25 times larger viscosity than water. All the tests were conducted to the saturated sand conditions under 25G centrifuge acceleration field.

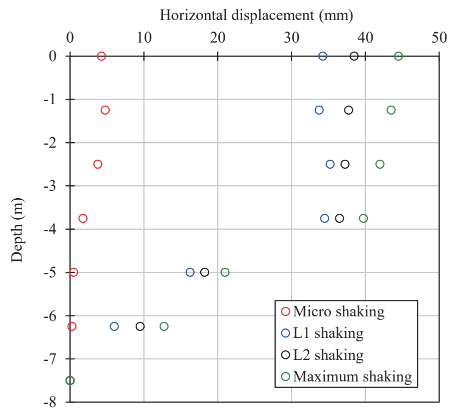
The frequency and amplitude of acceleration were varied using sine wave as input to generate stepwise shaking. The frequencies of sine wave used in this experiment are 60Hz and 120Hz to examine the dynamic behavior due to the difference of frequency. Thus, the prototype frequencies of sine wave are 2.4Hz and 4.8Hz respectively. The parameters measured in the



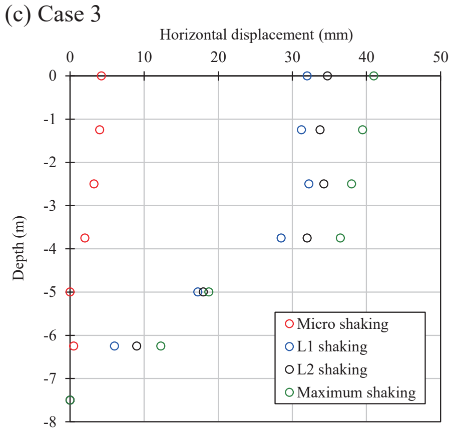
(a) Case 1



(b) Case 2



(c) Case 3



(d) Case 4

Fig. 5. Depth distribution of horizontal (Sine wave: 4.8Hz).

experiment were acceleration at various depths of the model ground, displacement of the model cutoff wall surface and at ground level, and the pore water pressure at various depth of model ground. Moreover, the image analysis such as PIV (Particle Image Velocimetry) to obtain the deformation of model cutoff wall and model ground was carried out after the experiment by tracking the model ground movement sequentially. It is possible to examine the failure mode of model cutoff wall and model ground from the results of image analysis.

3 RESULTS OF CENTRIFUGE MODEL TESTS

The results of centrifuge model tests present the prototype scale values in this chapter. The depth distributions of horizontal displacement are shown in Fig. 5. Here, the input acceleration levels are described as follows;

Micro shaking: Lower than 100gal*
L1 shaking: 200~300gal*
L2 shaking: 600~700gal*
Maximum shaking: Higher than 1000gal*
*Acceleration: 1G = 980gal

It is important to estimate the horizontal displacement of cutoff wall to obtain the earthquake-proof performance. Therefore, the horizontal displacement of cutoff wall is calculated by PIV analysis during the shaking. It is confirmed that the horizontal displacement of soil-bentonite cutoff wall as shown in Figs. 5(a) and 5(b) indicates the large value at the shallow depth of model ground. This fact implies that the horizontal displacement of model cutoff wall dominates at the shallow depth of model ground because the large horizontal force is acted to the model cutoff wall at the shallow depth of model ground. The deformation behavior of model soil-bentonite cutoff wall as described above shows the same trend regardless of the input wave frequency.

On the other hand, the horizontal displacement of soil-cement cutoff wall as shown in Figs. 5(c) and Fig. 5(d) presents that the difference of horizontal displacement at the shallow depth of model ground indicates the small value. It is said that the failure such as the cracks of cutoff wall occurs in the small shaking level. Thus, the soil-cement cutoff wall cannot follow the ground deformation during the shaking. The deformation behavior indicates the same trend regardless of the input wave frequency.

Figures 6(a) and 6(b) present the model cutoff wall after the shaking. The soil-bentonite vertical cutoff wall as shown in Fig. 6(a) does not occur the failure such as the cracks of model cutoff wall. It is concluded that the soil-bentonite vertical cutoff wall can follow the ground deformation in the large earthquake. Moreover, it is said that the impermeable performance can be kept after the large earthquake because the large failure is not examined. Figure 6(b) indicates the soil-cement cutoff wall after the shaking tests. Here, the red lines in Fig. 6(b) mean the dominant cracks. Form Fig. 6(b), the many

(a) Soil-bentonite cut-off wall (b) Soil-cement cut-off wall

Fig. 6. Model cut-off wall after shaking.

cracks of model cutoff wall are observed. This fact implies that the soil-cement cutoff wall cannot follow the ground deformation.

4 CONCLUSIONS

In this study, the dynamic centrifuge model tests were performed to confirm the earthquake-proof performance and the impermeable performance of soil-bentonite and soil-cement vertical cutoff wall. Four kinds of step-wise shaking using sine wave were conducted for the soil-bentonite vertical cutoff wall and the soil-cement mixing vertical cutoff wall. The following findings were obtained from this study.

1) It is concluded that the soil-bentonite vertical cutoff wall which was developed in this study has the high earthquake-proof performance because the deformation of soil-bentonite vertical cutoff wall follows the model ground deformation during the shaking.

2) According to the observation after the dynamic centrifuge model tests, the failure of soil-bentonite cutoff wall does not occur although the collapse of soil-cement mixing vertical cutoff wall due to the shaking is confirmed. Therefore, this fact implies that the soil-bentonite vertical cutoff wall has the high earthquake-proof performance.

3) It is needed to study the detailed mechanism of earthquake-proof performance when an eccentric earth pressure is acted to the developed soil-bentonite cutoff wall.

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