Seismic behavior and numerical simulation of earth-fill dam with geosynthetic clay liner in shaking table test

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ABSTRACT: In this paper, shaking table tests by using a small-scale as well as a full-scale earth-fill dams with geosynthetic clay liner were carried out in order to examine aseismicity of these earth-fill dams. Moreover, the behavior of these fully instrumented earth-fill dams subjected to seismic loading was simulated by numerical analysis. First, in the small-scale shaking table test, there observed no failure along the geosynthetic clay liner when the earth-fill dam was subjected to seismic motion. When the stability of the model dam was simulated by pseudo-static limit equilibrium analysis, and also the seismic response was simulated by FEM seismic analysis, it was successfully confirmed that the behavior of the model earth-fill dam was unaffected by the existence of the geosynthetic clay liner. Second, comparative shaking table tests by using a full-scale earth-fill dam with sloping core zone and the other with geosynthetic clay liner were carried out. The acceleration response as well as the deformation behavior was similar between these two models, both having 3m high. It should be mentioned that the acceleration response increased gradually towards the dam top and the deformation after shaking was relatively large near the foot of the slope. These observations were, to a great extent, successfully simulated by the numerical analysis.

Keywords: earth-fill dam, clay liner, shaking table test, numerical analysis, aseismicity

1 INTRODUCTION

In Japan, remedial works are underway to improve waterproof and aseismic performance of old earth-fill dams. In so doing, sloping core zone with low-permeability clay are widely used (Ministry of Agriculture, Forestry and Fisheries in Japan, 2015). But recently, a geosynthetic clay liner having an outstanding waterproofing ability is increasingly being used in earth-fill dams for preventing water leakage as well as for improving the resistance against earthquake attacks because of a shortage of low-permeability clay (Oda et al. 2015). However, geotechnical engineers are concerned with a sliding type of failure that may take place at the interface between the soft clay liner and the fill material. Yet, a better understanding is needed about the seismic behavior of the earth-fill dam with the geosynthetic clay liner. In this paper, shaking table tests by using a small-scale as well as a full-scale earth-fill dams with geosynthetic clay liner were carried out in order to examine the aseismicity of earth-fill dams. In addition, the behavior of these fully instrumented earth-fill dams subjected to seismic loading was simulated by numerical analysis.

2 SMALL-SCALE SHAKING TABLE TEST AND NUMERICAL SIMULATION

2.1 *Shaking table test*

The sliding failure type of a small-sized earth-fill dam model inside which a geosynthetic clay liner was mantled was examined in the small-scale shaking table test. Figure 1 shows the model tests performed in this study. The model fill was prepared by compacting a well-graded soil (D_{50}=0.35mm) to the degree of compaction ranging from 80% to 85%. In these tests, a sine wave (the frequency, f=5Hz) horizontal acceleration was applied for 8sec. Figure 2 shows the structure of a geosynthetic clay liner employed in this study.

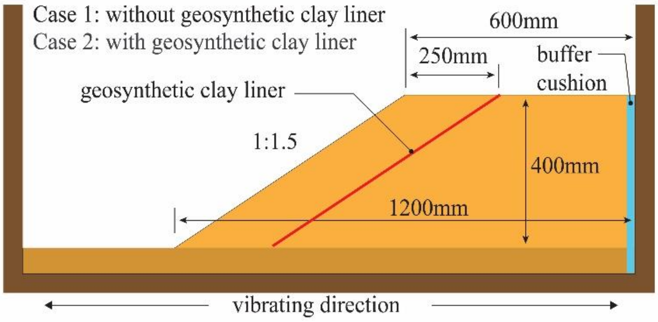


Figure 1. Cases of shaking table test and the structure of geosynthetic clay liner.

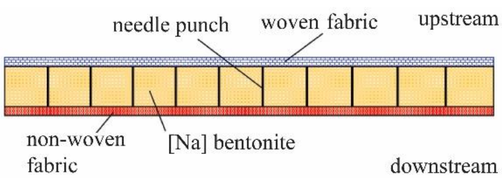
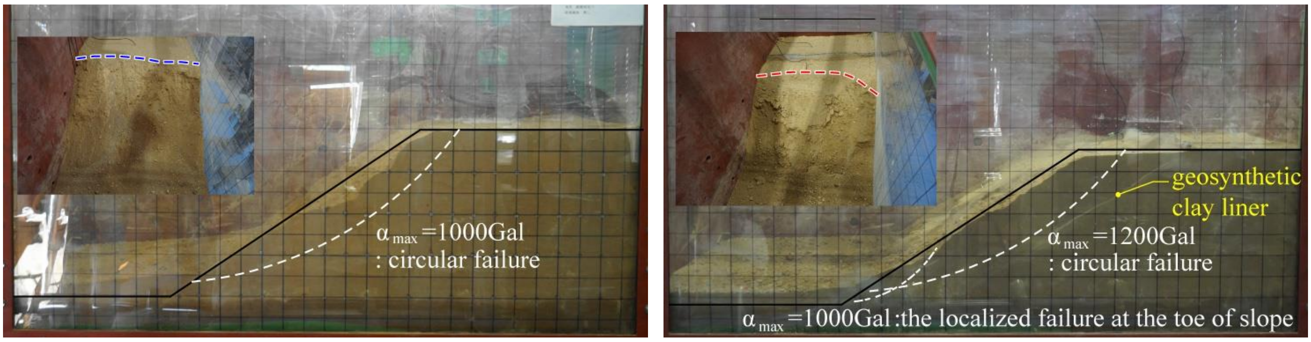


Figure 2. The structure of geosynthetic clay liner employed (refer to Takashi et al. 2016).

As seen in Fig. 3, when the maximum acceleration of 1000Gal was applied, a shallow circular failure developed over the central portion of the fill slope in Case1 without the geosynthetic clay liner. On the other hand, only a localized failure occurred at the toe of slope in Case 2 with the geosynthetic clay liner. In Case 2, the failure at the toe of slope gradually expanded when the maximum acceleration was increased to 1200Gal and the circular failure eventually occurred above the geosynthetic layer. However, no slip was observed at the interface between the geosynthetic clay liner and the fill.



(a) without the geosynthetic clay liner (Case 1) (b) with the geosynthetic clay liner (Case 2)
Figure 3. Results of shaking table test.

2.2 *Numerical analysis*

In order to examine the seismic behavior and the shape of failure surface of earth-fill dams with and without the geosynthetic clay liner, 2D-FEM eigenvalue analysis, together with dynamic analysis as well as pseudo static limit equilibrium analysis were carried out for the two cases (see in Fig. 1). The material properties used in this analysis are shown in Table 1. More details of the numerical simulation of a small-scale earth-fill dam in shaking table test have been described by Jeong et al. (2016).

Table 1. Material properties.

	Model	γ_t (kN/m^3)	E(kN/m^2)	ν	c (kPa)	ϕ(°)
Frame	Linear elastic	20.0	100,000	0.20	-	-
earth-fill dam	Mohr-Coulomb	18.5	5,000	0.34	0.5	38
Geosynthetic clay liner	Mohr-Coulomb	16.0	15,000	0.35	15.0	28

At first, in the eigenvalue analysis, the free vibration analysis was carried out by assuming the property of the test fill being the linear elastic. As a result, the time history of horizontal displacement at the top of slope was obtained. Figure 4 shows a time history of horizontal displacement during the free vibration analysis, suggesting that the natural frequency of both cases was approximately 20 Hz. It was manifested that there observed no difference in terms of the natural frequency for these two cases with and without the geosynthetic clay liner.

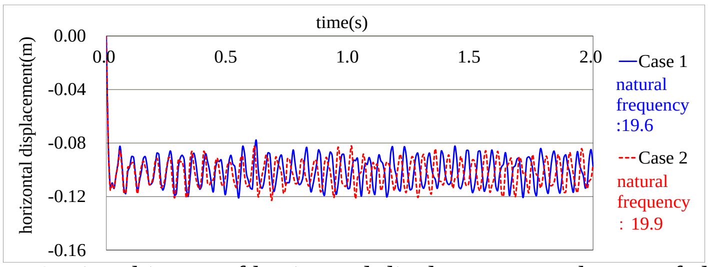


Figure 4. Time history of horizontal displacement at the top of slope.

Second, time history seismic response analysis was performed in order to examine the response characteristics of test fills by using PLAXIS2D. In this analysis, a sine wave (the frequency, *f*=5Hz) horizontal acceleration was input at the base boundary, which was similar to the shaking table test. The amplification ratio (i.e., response acceleration / input acceleration) of horizontal acceleration at the top as well as the toe of slope is summarized in Table 2. In this numerical simulation of the small-sized earth-fill dam in shaking table test, it is verified that the geosynthetic clay liner does not affect the seismic response characteristics. In addition, it should be mentioned here that the effects of amplification are insignificant for both cases.

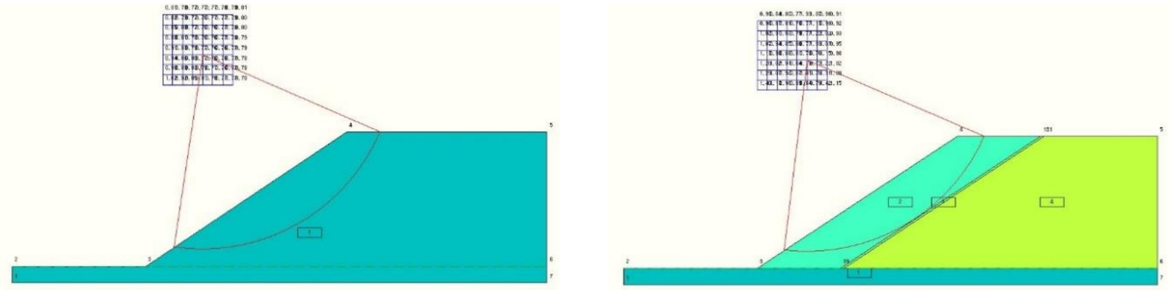
Table 2. Amplification ratio of Horizontal response acceleration.

	Case	600Gal	1000Gal
Top of slope	Case1(without geosynthetic clay liner)	1.02	0.99
Toe of slope	Case2(with geosynthetic clay liner)	1.02	1.02
Top of slope	Case1(without geosynthetic clay liner)	0.97	0.97
Toe of slope	Case2(with geosynthetic clay liner)	0.98	0.97

A pseudo-static limit equilibrium analysis was performed to compare failure shapes and the factor of safety by COSTANA program (Jeong et al. 2016), in which the geosynthetic clay liner was modeled as a solid element. Table 3 shows the results, suggesting no difference at all for both the cases. Similar to the result of shaking table test, there observed no sliding at the boundary of ground and the geosynthetic clay liner, since the circular sliding surface formed well above the geosynthetic clay liner (Fig. 5).

Table 3. Factor of safety.

Lateral seismic coefficient	k_h=0.15	k_h=0.30	k_h=0.60	k_h=1.00
Case1(without geosynthetic clay liner)	1.54	1.19	0.76	0.46
Case2(with geosynthetic clay liner)	1.54	1.19	0.77	0.46



(a) without the geosynthetic clay liner (Case 1) (b) with the geosynthetic clay liner (Case 2)

Figure 5. Circular sliding surface in the case of k_h=0.6.

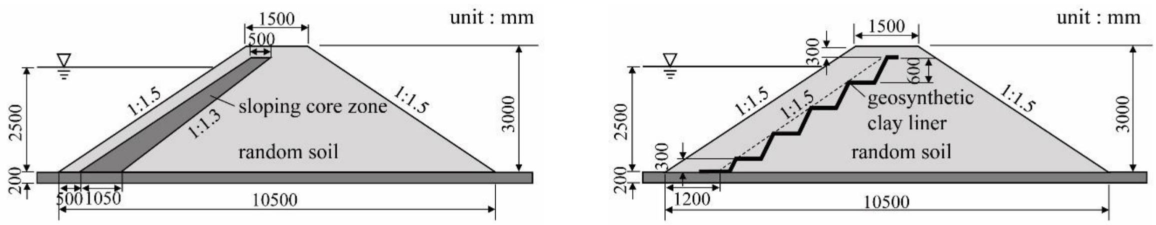
3 FULL-SCALE SHAKING TABLE TEST AND NUMERICAL SIMULATION

3.1 *Outline*

Shaking table tests by using a full-scale earth dam with a sloping core zone and with a geosynthetic clay liner were carried out by using a huge shaking table at Hyogo earthquake engineering research center E-defense. The numerical simulation was also performed in order to examine the aseismicity of these earth-fill dams.

3.1.1 *Test model*

Figure 6 shows a set of full-scale model fills with 3m in height. The water level in the upstream was maintained 0.5m below the fill top. The model fills were constructed by compacting to the degree of compaction above 95%. The cohesive soil was employed as the material of sloping core zone, and the random soil mixed clean sand with the cohesive soil was employed in the shaking table test. Figure 7 shows the grain size distribution curves of the materials used. In these tests, two type of sine waves (the frequency, *f*=5Hz) of the maximum acceleration of 177Gal and 471Gal, which correspond to Level 1 and Level 2 earthquake motions, respectively, were applied (see Fig. 8). The full-scale shaking table test has been described in detail by Sawada et al. (2016).



(a) without the geosynthetic clay liner (Case 1) (b) with the geosynthetic clay liner (Case 2)

Figure 6. Cases of full-scale shaking table test (Sawada et al. 2016).

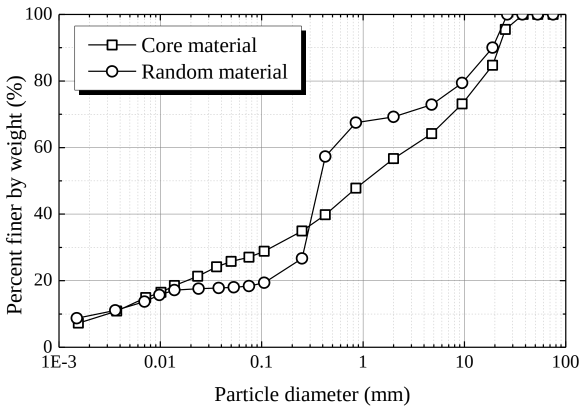


Figure 7. Grain size distribution curve (Sawada et al. 2016).

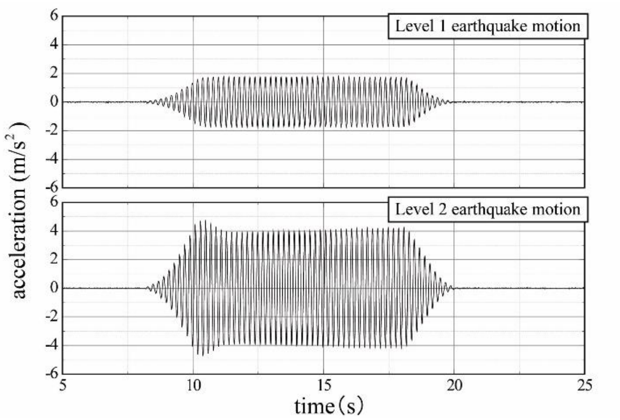


Figure 8. Input Sine waves acceleration data (Sawada et al. 2016).

3.1.2 *Numerical simulation*

2D-FEM dynamic analysis using the program PLAXIS2D was carried out for the two cases as shown in Fig. 6. After setting the boundary conditions, together with the ground water condition, the time history analysis has been performed. In this analysis, two types of sine wave (the frequency, f=5Hz) of maximum acceleration of 170Gal and 400Gal were applied at the base boundary for 8 sec by simulating the dynamic motion applied in the shaking table test. The sloping core zone and the random soil was both modeled as a solid element by means of a hardening soil model with small-strain stiffness (Table 4). On the other hand, the geosynthetic clay liner was modelled using a Mohr-Coulomb model (Table 1).

Table 4. Material properties.

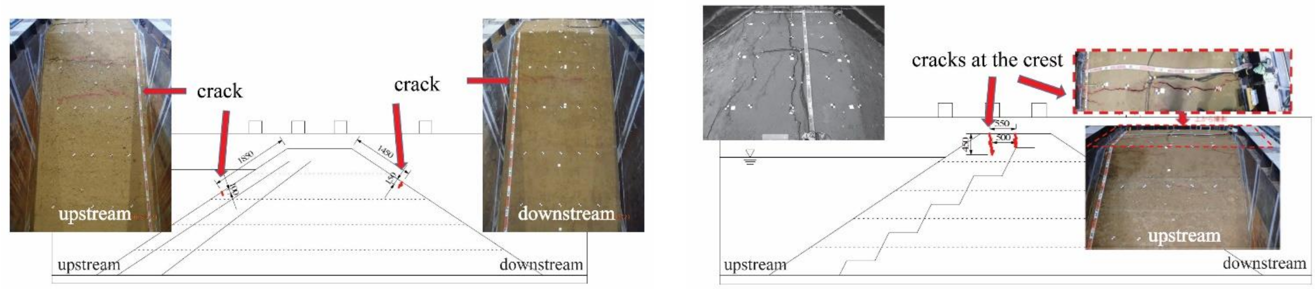
Items	Unit	Random soil	Core zone
Unsaturated unit weight, γ_t	kN/m^3	17.7	18.3
Saturated unit weight, γ_{sat}	kN/m^3	20.1	19.5
Secant stiffness in standard drained triaxial test, E_{50}	kN/m^2	11,000	11,000
Unloading / reloading stiffness from drained triaxial test, E_{ur}	kN/m^2	41,250	41,250
Poisson's ratio for unloading-reloading, ν_{ur}	-	0.2	0.2
Reference shear modulus at very small strains ($\varepsilon < 10^{-6}$), G_0	kN/m^2	63,730	74,350
Threshold shear strain at which $G_s = 0.722G_0$, $\gamma_{0.7}$	-	0.15E-3	0.15E-3
Cohesion, c	kN/m^2	6.1	38.4
Friction angle, ϕ	°	35.5	33.2

3.2 *Results and discussions*

3.2.1 *Damage and residual deformation*

In the shaking table test, the residual deformation less than 1mm developed at the crest as well as at the slope face in both cases when the maximum acceleration of 177Gal (i.e., Level 1 earthquake motion) was applied. Moreover, neither water leakage nor the crack was observed. Similar to the result of shaking table test, the crest settlement of approximately 2.5mm in the fill with sloping core zone and approximately 3.3mm in the geosynthetic clay liner case occurred in the numerical simulation. Based on these results, it can be inferred that there was no harmful deformation in both the cases.

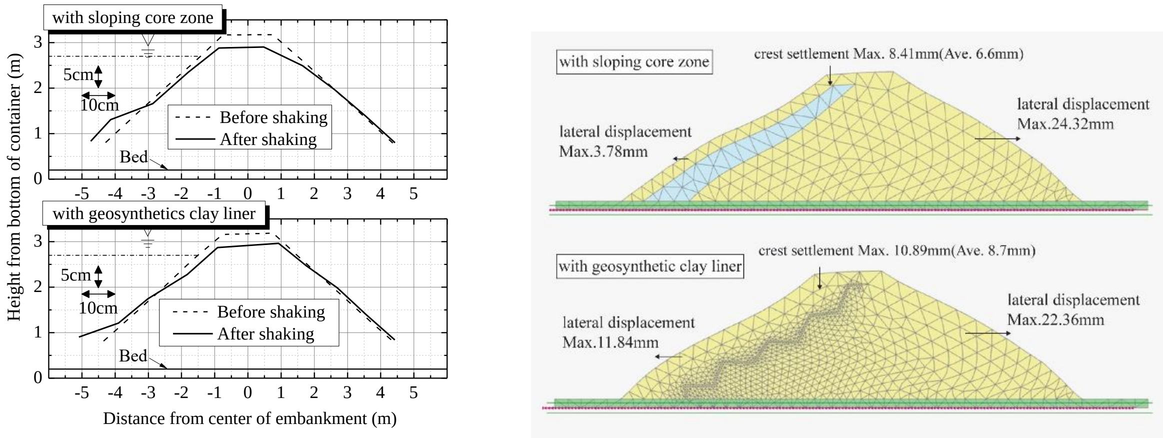
On the other hand, a couple of cracks developed at the crest as well as at the slope face in both cases when the maximum acceleration of 471Gal (i.e., the Level 2 earthquake motion) was applied in the shaking table test. As seen in Fig. 9(a), small cracks which are about 1mm width and 100mm depth have developed at both the upstream as well as the downstream slope face in the earth-fill dam with the sloping core zone. Meanwhile, as seen in Fig. 9(b), large longitudinal cracks which are about 10mm-width at the crest have developed in the earth-fill dam with geosynthetic clay liner. When the cross-section of the embankment was inspected after the shaking event, it was found that the cracks were developed due to the presence of the geosynthetic clay liner (refer to Oda et al. 2016). It would mean that the crack at the crest were developed at the interface of geosynthetic clay liner and fill materials. Nevertheless, it should be noted that no circular failure developed in both cases by showing no water leakage.



(a) with sloping core zone (b) with geosynthetic clay liner

Figure 9. Cracks observed on the surface of earth-fill dam (refer to Nakazawa et al. 2017, Oda et al. 2016).

After the Level 2 earthquake motion was applied in the shaking table test, the crest settlement as well as the lateral deformation at the toe of slope were observed (Fig. 10(a)). These residual deformations were both larger for the upstream side than the downstream side. There observed an average 21.4mm of crest settlement in the fill with sloping core zone while an average 16.7mm of crest settlement was observed in the fill with geosynthetic clay liner. Although there is some difference in the net displacement between these two cases, no appreciable difference in the deformed shape was observed. In the numerical simulation, albeit the observed residual deformation was less than that in the model tests, the crest settlement and the deformation near the toe at the upstream side of the slope were simulated as observed in the shaking table test (Fig. 10(b)). It is necessary to consider more details of strength and stiffness deterioration by applying stronger cyclic loadings in order to get more accurate simulation.



(a) results of shaking table test (b) results of numerical simulation

Figure 10. Residual deformation after shaking (modified from Sawada et al. 2016, Jeong et al. 2016).

3.2.2 *Acceleration response*

Figure 11 shows the amplification ratio of horizontal acceleration response along the vertical, noting that the height is dimensionless. As shown in Fig. 11, when the Level 1 earthquake motion was applied, the response acceleration increased gradually towards the crest, noting that the amplification of horizontal response acceleration was approximately 1.3 at the crest in both the fills, implying that the response was successfully simulated by numerical analysis (Table 5).

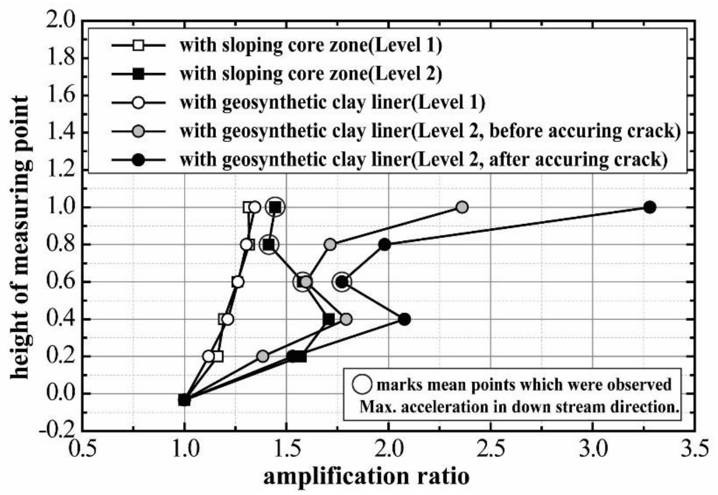


Figure 11. Amplification ratio of horizontal response acceleration (modified from Sawada et al. 2016).

On the other hand, when the Level 2 earthquake motion was applied, a large amplification characteristic was observed at a lower part of the fill in the shaking table tests (Fig.11). In addition, the amplification ratio at the crest was approximately 1.4 in the fill with sloping core zone, whereas the ratio in the fill with geosynthetic clay liner was approximately 2.3 and 3.3 before and after the crack developed, respectively. Moreover, it was manifested that the response characteristics between the upstream side and the downstream side separated by the geosynthetic clay liner were noticeably different (i.e., the phase difference of acceleration on the horizontal plane) from each other. Regarding this observation in particular, the following two points could be considered ; the difference in dynamic characteristic between saturated soil on the upstream side and the unsaturated soil on the downstream, and the strength characteristic at the interface between the geosynthetic clay liner and the fill (Oda et al. 2016). In other words, the phase difference in the horizontal acceleration would have triggered the development of the cracks at the boundary between the soil and the geosynthetic clay liner. The acceleration response then increased largely when the high level earthquake motion was applied. It should be mentioned that the phase difference of acceleration on the horizontal plane, together with the effect of tension cracks on the response characteristic were not properly simulated by numerical analysis.

Table 5. Amplification ratio of horizontal response acceleration at the crest.

	Water proof method	Level 1 earthquake motion	Level 2 earthquake motion
Shaking table test	Sloping core zone	1.3	1.4
	Geosynthetic clay liner	1.3	2.4 (before occurring the crack) 3.3 (after occurring the crack)
Numerical analysis	Sloping core zone	1.23	1.22
	Geosynthetic clay liner	1.26	1.27

4 CONCLUDING REMARKS

In this paper, shaking table tests by using a small-scale as well as a full-scale earth-fill dams with geosynthetic clay liner were carried out in order to examine the aseismicity of earth-fill dams.

Despite a concern for the geosynthetic clay liner acting as a weak layer, there observed no failure along the geosynthetic clay liner when the small-scale earth-fill model was subjected to seismic motion. It was also confirmed by the pseudo static limit equilibrium analysis. Moreover, the results of time history FEM seismic numerical simulations exhibited that seismic behaviors; i.e., the natural frequency and response characteristic, were unaffected by the geosynthetic clay liner.

When the maximum acceleration of 177Gal as the Level 1 earthquake motion was applied in the full-scale shaking table test, it was verified that there was no harmful deformation in both the fills with sloping core zone as well as geosynthetic clay liner. In addition, there was no difference in seismic behaviors such as the response characteristics as well as the residual deformation in both the fills. These observations were confirmed by the numerical analysis as well.

On the other hand, when the maximum acceleration of 471Gal as the Level 2 earthquake motion was applied in the full-scale shaking table test, a couple of cracks developed in the fills, however, no failure was observed in both cases. It was found that relatively large longitudinal cracks have developed in the earth-fill dam with geosynthetic clay liner. After the development of cracks, the amplification of the response acceleration increased further. It was also observed that there is a phase difference of acceleration on the horizontal plane between the upstream side and the downstream side separated by the geosynthetic clay liner. However, the tension cracks and the phase difference of acceleration on the horizontal occurred due to the presence of the geosynthetic clay liner were not properly simulated.

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