Shaking table test of large-scaled slope model subjected to horizontal and vertical seismic loading using E-Defense

Essai sur table vibrante de talus de grande taille soumis à des accélérations verticales et horizontales

Shinoda M., Nakajima S.
Structures Technology Division, Railway Technical Research Institute, Tokyo, Japan

Nakamura H.
Seismic Safety Division, Japan Nuclear Energy Safety Organization, Tokyo, Japan

Kawai T.
Department of Civil Engineering, Tohoku University, Sendai, Japan

Nakamura S.
Department of Civil Engineering, Nihon University, Fukushima, Japan

ABSTRACT: This paper describes a series of shaking table test of a large slope model subjected to vertical and horizontal seismic loading. The slope model was constructed using mixed material with silica sand and bentonite clay. A number of accelerometers and displacement transducers were set to measure the response characteristics of the slope model. Input waves used in the shaking table tests were sinusoidal and observed waves recorded near an actual nuclear power plant. The test results clearly show that a critical direction of the vertical and horizontal accelerations exists, which is a factor to decrease the slope stability.

RÉSUMÉ : Cet article décrit une série d'essais sur table à secousses de modèles de gros talus soumis à une accélération verticale et horizontale. Les modèles de talus ont été construits à l'aide d'un mélange de matériaux incluant du sable siliceux et de l'argile colloïdale. L'installation de divers accéléromètres et capteurs de déplacement a permis de mesurer les caractéristiques de réponse des modèles de talus. L'onde incidente utilisée dans les essais sur la table à secousses était une onde sinusoïdale et l'onde observée a été mesurée près d'une centrale nucléaire. Le résultat des essais montre clairement qu'il existe une direction critique de l'accélération verticale et horizontale qui entraîne une déstabilisation du talus.

KEYWORDS: slope, stability, shaking table.

1 INTRODUCTION

In 2006, the geguralory guideline for aseismic design of nuclear power reactor facilities was revised in 2006. In this regulatory guide, it is specified that the facilities shall be designed about the phenomenon accompanying an earthquake after having considered the collapses which can be assumed at a slope around the facilities and tsunami enough. Both of them were made the target of the judgment already as before, but it is specified in the new regulatory guide newly this time. Therefore, it is necessary particularly to evaluate a slope stability subjected to an earthquake.

In the current regulatory guide, slopes to be carefully considered are within 50 m distance between the toe of the slope and the interest nuclear power plant and having within 1.4 times height of a slope which possibly cause the nuclear power plant damage when occurring failure. In Japan, there are 54 nuclear power reactor plants constructed at 18 areas. Among all of the nuclear power reactor plants, the number of the related slopes to be carefully considered becomes 13 areas with various slope heights ranged from 10 m to 200m of the order magnitude.

Conventionaly, for stability evaluation of natural slopes around a nuclear power plant, a safety factor based on a limit equibirium method has been used to check the safety of the natural slope against a design seismic excitation. Even though the calculated safety factor exceeds 1.0, a degree of collpase varies a great deal depending on physical properties, mechanical properties, geometry of the natural slope. Under the above instructions of the revised guideline, the stability evaluation of the natural slope around the facilities should be developed to considered a degree of a displacement due to instability of the natural slope subjected to a seismic load in addition to the conventional evaluation based on the limit euqilibrium method with the safety factor.

This paper describes a series of shaking table test of a large slope models subjected to vertical and horizontal acceleration using a three dimensional full-scale earthquake testing facilities named E-Defense to develop the above evaluation method.

2 FAILURE MODE OF SLOPE

Our research group conducted over 20 cases of shaking talele test to investigate deformation and response characteristics of several types of slopes subjected to seismic load. From the past investigation, it is revealed that a slip surface coule be observed in the following pattern:

1) Slip surface is generated from top to bottom of the slope.
2) Slip surface is generated in the surface layer.
3) Slip surface is generated at the tip of the slope.
4) Slip surface is generated at the top of the a slope.

Moreober, a sliding failure mode of slope subjected to seismic load was classified as quick sliding mode, slow sliding mode and quick sliding mode after slow sliding mode as those intermidiate.

From the past shaking table tests, only horizontal acceleration were applied to the slope models due to the specification of the shaking table. Ling el al. (1997) pointed out the vertical acceleration has a significant effect on the calculated factor of safety and yield acceleration of steep slope. Therefore, in this research, a large shaking table test was conducted to evaluate the effect of vertical seimic load against the dynamic response and failure mode with an unique slope model under the horizontal and veritcal seismic loading condition.

3 SPECIFICATION OF E-DEFENSE

Table 1 shows a specification of E-Defense. E-Defense is the world's largest shaking table having the size of 20 m by 20 m, which can simulate high level ground motions. The maximum payload is reaced to 12 MN so that various full-scale models can be tested by this equipment.

4 LARGE SLOPE MODEL

Two large slope models having one layer and three layers were constructed for the shaking table test. One layered slope model was constructed to evaluate the response characteristics during seismic excitation. Three layered slope model was constructed to evaluate the deformation characteristics during seismic excitation and confirm the failure mode. In this paper, only the shaking table test using one layered slope model is described. Figure 1 shows the slope model configuration and arrangement of measurement equipments. The height and width of this model are 3.8 m and 4.5 m, respectively. This model was consists of general soil and reinforced soil layers assumed as weathered layers on the hard rock layer as shown in Table 2. The hard rock layer was constructed using cement-mixed gravel which consisted of a weight ratio of 100:4:7 of gravel, cement and water. The target wet density was 19.6 kN/cm^3. The general layer consisted of a weight ratio of 100:7:10 of silica sand, bentonite and water. The target wet density was 16.2 kN/cm^3. The reinforced layer consisted of a weight ratio of 100:10:10 of silica sand, bentonite and water. The target wet density was 16.2 kN/cm^3. In this test, the slip surface was ssumed to be generated in the general soil layers so that geogrids having strength of 30 kN/m were installed in the reinforced layers.

5 INPUT WAVES

At first, the shaking table tests were carried out with the sinusoidal wave having only the horizontal component and both the horizontal and vertical components in series to investigate the basic effect of vertical acceleration against the dynamic

Table 1. Specification of E-Defense.

Table size	20 m × 15 m	
Payload	12 MN	
Shaking direction	Horizontal	Vertical
Max. acceleration	900 gal	1,500 gal
Max. velocity	200 cm/s	70 cm/s
Max. displacement	± 100 cm	± 50 cm

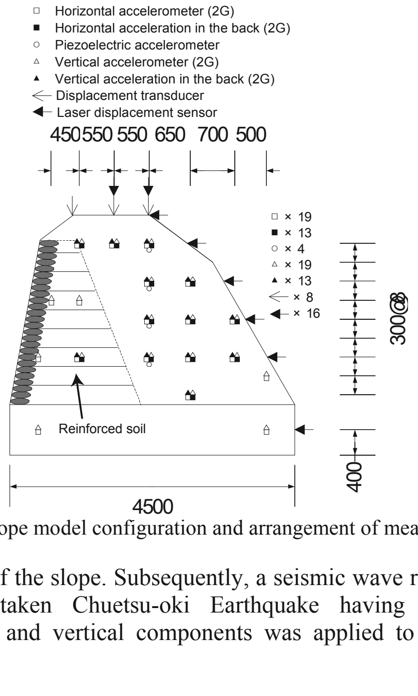


Figure 1. Slope model configuration and arrangement of measurement equipment.

response of the slope. Subsequently, a seismic wave recorded at the Niigataken Chuetsu-oki Earthquake having both the horizontal and vertical components was applied to the slope model to investigate the effect of iregular motion having both the horizontal and vertical components. Figure 2a) shows orbits in cases of sinusoidal seismic waves without phase difference and with a phase difference of 180 in degrees. Figure 2b) shows the orbit of recorded seismic excitation used in this study. For positive and negative direction of accelerations, a forward of slope is positive in the horizontal direction and a upward is positive in the vertical direction. Here, the sliding failure probably occures along the slope inclination, therefore it can be considered that the most effective direction in the inertia force caused by seismic load against the sliding failure is the parallel direction of slope inclination. This means that the phase difference between the horizontal and vertical directions becomes 180 in degrees as shown in Figure 2a). Figure 3 shows time histories of horizontal and vertical accelerations of the recorded seismic excitation. The target horizontal and vertical acceleration were 700 and 470 gal, respectively. In the shaking table tests, the horizontal acceleration was applied with a step of 100 gal from the start of the horizontal acceleration level of 100 gal.

Table 2. Strength property.

Material	Peak state		Residual state	
	Friction angle (in degrees)	Cohesion (kPa)	Friction angle (in degrees)	Cohesion (kPa)
General soil	31.4	11.06	32.8	4.45
Reinforced soil	29.3	13.38	31.4	5.55

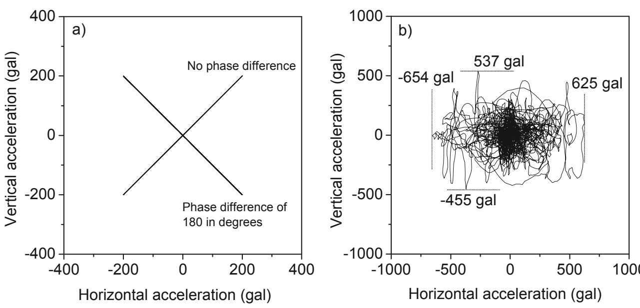
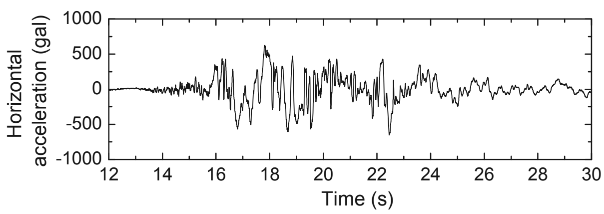
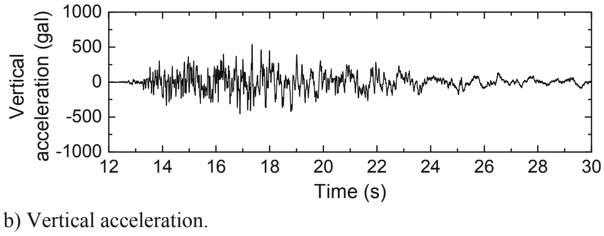


Figure 2. Orbits between horizontal and vertical accelerations on the shaking table; a) sinusoidal excitation, b) recorded seismic excitation.



a) Horizontal acceleration.



b) Vertical acceleration.

Figure 3. Record seismic wave with amplitude adjustment.

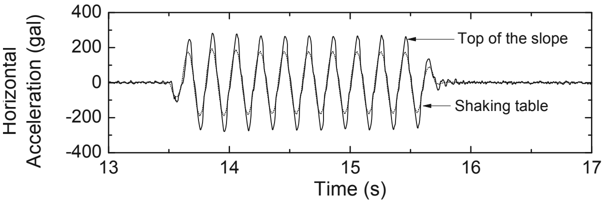


Figure 4. Representative time histories of horizontal acceleration measured at the shaking table and the top of the slope under the sinusoidal excitation.

6 TEST RESULTS

6.1 Shaking table test results under sinusoidal excitation

Figure 4 shows a representative time histories of horizontal acceleration measured at the shaking table and the top of the slope under the sinusoidal excitation having only the horizontal component. There was clear amplification at the top of the slope from 1.5 to 1.9 times as compared to that of the shaking table. This trend can be seen in other similar cases.

Figure 5 shows orbits between the horizontal and vertical accelerations measured at the shaking table and the top of the slope. The directions of accelerometers were simultaneously depicted in Figure 5a). Figure 5a) and b) show the test results under only the horizontal seismic excitation, Figure 5c) and d) show the test results under seismic excitation without phase difference, and Figure 5e) and f) show the test results under seismic excitation with a phase difference of 180 in degrees.

From Figures 5a) and b),the amplification of the horizontal acceleration measured at the top of the slope became 1.5 times as compared to that of the shaking table regardless of the direction of the horizontal acceleration. This indicates that the slope uniformly responded due to small plastic deformation under the sinusoidal excitation with the maximum horizontal acceleration of 200 gal. From Figure 5c) and d), the amplification of the horizontal acceleration measured at the top of the slope became 1.64 times as compared to that of the shaking table regardless of the direction of the horizontal acceleration.

Here, the following is a discussion about a contribution of the vertical acceleration to the horizontal amplification focused on the negative acceleration. In this case, the minimum horizontal acceleration became -200 gal of the shaking table as shown in Figure 5c) so that the horizontal amplification would be 1.5 times as compared to that of the shaking table which is equal to -300 gal . In the meantime, the actual horizontal acceleration measured at the top of the slope reached -327 gal. This means that the difference of the 27 gal is the contribution of the vertical acceleration to the horizontal amplification. Consequently, it is revealed that a percentage of the above contribution is 9% which can be obtained to be normalized by the amplified minimum horizontal acceleration (-300 gal) without the effect of vertical acceleration as mentioned before. Moreover, Figures 5c) and 5d) show that the vertical amplification increased when the vertical acceleration exhibited to the upward (positive) direction. The range of the vertical amplification exhibited from 1.24 to 1.27 times.

From Figures 5e) and 5f), the amplifications of the horizontal and vertical accelerations depended on those direction. More specifically, the amplifications of the horizontal acceleration became 1.67 times in the positive direction and 1.88 times in the negative direction. In addition, the amplifications of the vertical acceleration became 1.23 times in the positive direction and 1.14 times in the negative direction.

Similar to the above, the following is a discussion about a contribution of the vertical acceleration to the horizontal amplification focused on the negative acceleration. In this case,

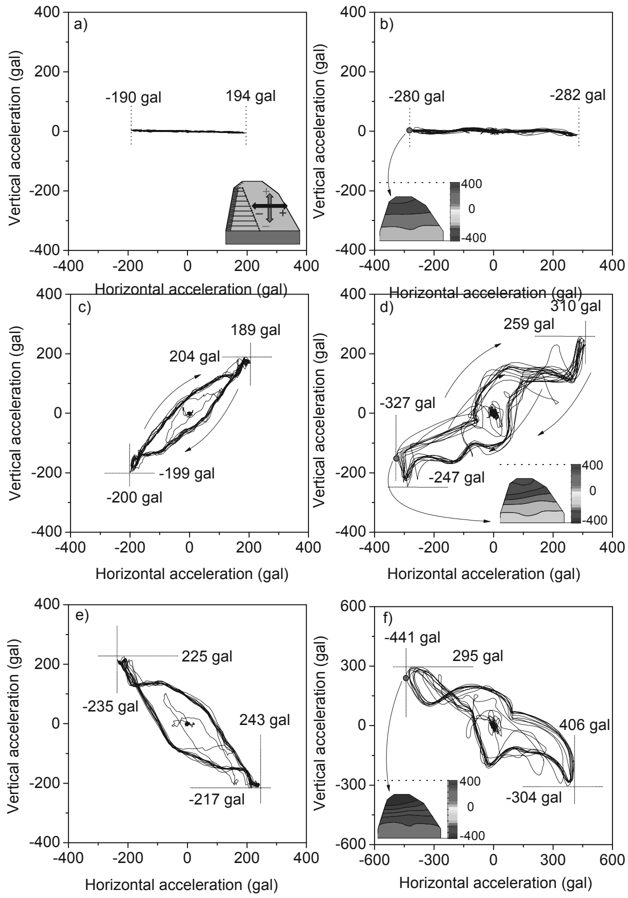


Figure 5. Orbits between the horizontal and vertical accelerations measured at the shaking table and the top of the slope: a) shaking table under only the horizontal seismic excitation, b) top of the slope under only the horizontal seismic excitation, c) shaking table under seismic excitation without phase difference, d) top of the slope under seismic excitation without phase difference, e) shaking table under seismic excitation with phase difference of 180 in degrees, f) top of the slope under seismic excitation with phase difference of 180 in degree.

the minimum horizontal acceleration is -235 gal as shown in Figure 5e) so that the expected horizontal acceleration without effect of vertical acceleration would be -353 gal. In the meantime, the actual minimum horizontal acceleration became -441 gal, which indicates that the contribution of the vertical acceleration is 88 gal. Consequently, it is revealed that a percentage of the above contribution is 25% which can be obtained to be normalized by the amplified minimum horizontal acceleration (-353 gal) without the effect of vertical acceleration.

As a result, the amplification of the acceleration increased under both the horizontal and vertical sinusoidal excitation when the inertia force applies in the parallel direction to the slop inclination.

6.2. Shaking table test results under recorded seismic excitation

Figure 6 shows the orbit between the horizontal and vertical accelerations measured at the top of the slope. A contour map at the time of minimum acceleration recorded is simultaneously depicted in Figure 6. As compared to the orbit as show in Figure 2b), the horizontal amplifications in the positive and negative directions are 1.30 and 1.28 times, respectively. In addition, the vertical amplifications in the positive and negative directions are 1.39 and 1.49 times, respectively. Moreover, as shown in Figure 6, the vertical acceleration on the shaking table exhibited zero at the time exhibiting the minimum horizontal acceleration on the shaking table. Contrary, the vertical acceleration exhibited a positive value at the similar time due to the phase difference. This indicates that the inertia force apply to the slope in the parallel and downward direction of the slope inclination.

Figures 7 and 8 show the time histories of horizontal and vertical accelerations measured at the shaking table and the top of the slope. The horizontal and vertical accelerations measured at the top of the slope increased and exhibited remarkable phase difference as compared to those of the shaking table. Figures 9 and 10 show time histories of horizontal and vertical displacements measured at the shaking table and the top of the slope. The horizontal and vertical displacements measured at the top of the slope increased in the forward and downward directions, respectively. Here, the horizontal and vertical accelerations exhibited -834 gal and 437 gal respectively at 19.03 s from the start of the shaking. From the test results under the sinusoidal excitation, the horizontal acceleration increased due the effect of the vertical acceleration when the direction of the inertia force was the same of the slope inclination. Therefore, due to the above trend, it is considered that the horizontal displacement increased at 19.16 s from the start of shaking. At 19.03 s from the start of shaking, the vertical displacement exhibited a large value due to the effect of the vertical acceleration.

This slope model collapsed at the surface layer as shown in Figure 11. This is probably due to the phase difference between the shaking table and the slope caused by the large amplification of the acceleration.

CONCLUSION

This paper describes an effect of vertical acceleration against dynamic response and deformation characteristics of the slope model subjected to horizontal and vertical sinusoidal and irregular excitation using a large-scaled shaking table. From the test results, it is revealed that there is a instability situation that a direction of inertia force applyed to the slope model in the parallel direction of the slope inclination.

For more precise evaluation of the slope exhibiting large response and phase difference, an appropriate method to evaluate the effect of horizontal and vertical accelerations such as dynamic finite element method should be used. Subsequently, the slope stability can be evaluated to calculate the safety factor at each time step using the analytical response and phase difference calculated by the above dynamic finite element analysis. This method will be reported in the near future.

REFERENCES

JEAG4601-1987, *Technical Guidelines for Aseismic Design of Nuclear Power Plants*, 1987.

Ishimaru, M. and Kawai, T.: "Basic study of the evaluation of seismic stability of rock slope using centrifuge model test", *Journal of Japan Society of Civil Engineers*, Ser. C, Vol. 67, No. 1, pp.36–49, 2011 (in Japanese).

Ling, H. I., Leshchinsky, D. and Mohri, Y.: Soil Slopes under Combined Horizontal and Vertical Seismic Accelerations, *Earthquake Engineering and Structural Dynamics*, Vol. 26, pp.1231-1241, 1997.

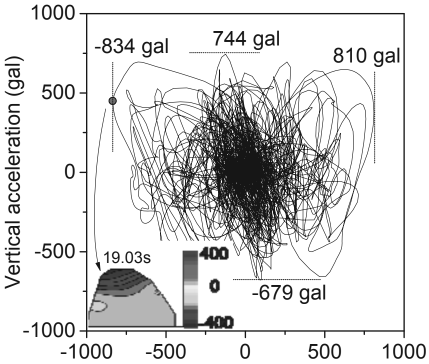


Figure 6. Record seismic wave with amplitude adjustment.

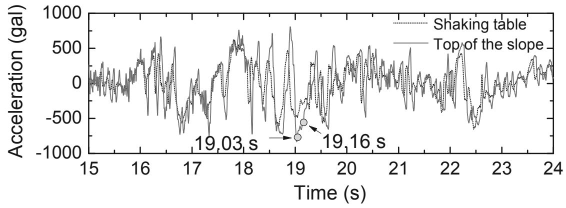


Figure 7. Time histories of horizontal acceleration measured at the shaking table and top of the slope.

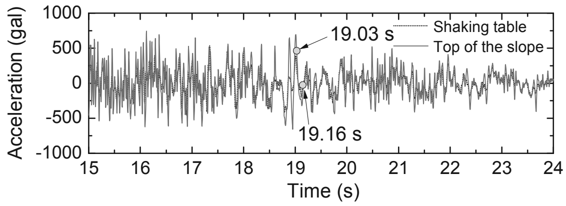


Figure 8. Time histories of vertical acceleration measured at the shaking table and top of the slope.

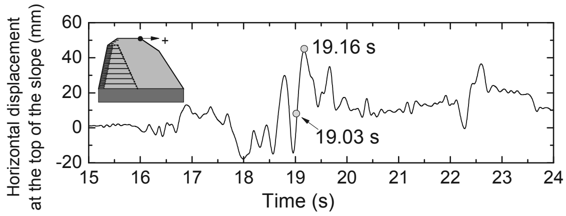


Figure 9. Time histories of horizontal displacement at the top of the slope.

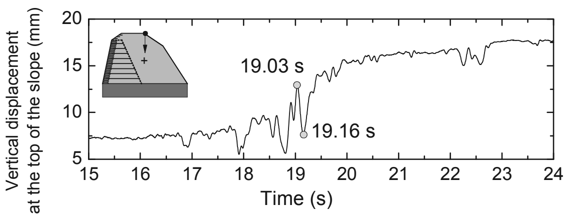


Figure 10. Time histories of vertical displacement at the top of the slope.

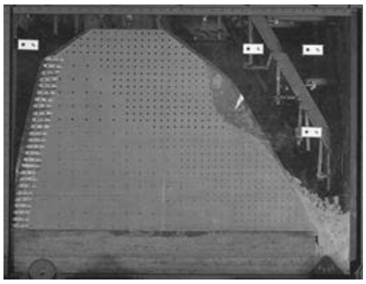


Figure 11. Slope failure under recorded seismic excitation.