Consideration on evaluation of seismic slope stability based on shaking table model test

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ABSTRACT

A series of shaking table model tests using two different size shaking tables was conducted to develop a procedure to evaluate seismic slope stability. It was found from the model tests that the type of slope failure could be categorized into two groups. One is the sliding failure, which could trigger the catastrophic failure of the slope and the other is the progressive deformation mode in which the displacement of the sliding mass of the slope would increase gradually. Based on the model test results, it was attempted in this study to propose an index to evaluate the degree of seismic slope instability. In this study, the normalized sliding displacement was applied as an index to assess the slope instability based on the observation from the shaking table model test. Based on the investigation into the correlation between the failure processes of the model slope and the values of normalized sliding displacement, it was found that the proposed index could be used to evaluate the degree of slope instability by setting the proper threshold value.

Keywords: shaking table model tests, seismic slope stability, image analysis

1. INTRODUCTION

In Japan, seismic slope stability near by the nuclear power plant has been evaluated by the factor of safety Fs calculated by comparing the driving and resistant forces mobilized along the slip surface based on the circular slip analyses (JEAG, 2007). Before conducting the circular slip analysis, possible failure planes are assumed by the relevant dynamic FEM analysis using the equivalent linear modeling of the soil. The process of the analysis is schematically illustrated in Fig.1.

In the current procedure, as illustrated in Fig. 1, target slope is judged as a suspected failure slope once the value of factor of safety becomes to be smaller than the threshold value (e.g. Fs=1.2) during the analysis. However, deformation of the slope induced by the earthquake was not only affected by the value of Fs but affected by many factors (e.g. duration of strong earthquake motion as well as the geometric configuration of the slope and the deformation and strength characteristics of the geomaterial), while the factor of safety based slope stability evaluation could not necessarily consider the above factors.

Therefore, it is required to propose an alternative index and definition of the threshold state expressing the extents of the slope instability for developing more rational slope stability evaluation procedure.

The authors conducted a series of shaking table model test (Shinoda, 2010) and relevant analyses (Abe, 2012) so as to develop an evaluation procedure of the seismic slope stability. Series of the model tests revealed that the deformation processes of the slope could be divided into three groups and the types of
Slope deformation was affected by the deformation and strength characteristics of the geomaterials, slope configuration, size of the slope model etc.

This paper begins with brief review of the previously conducted model test. The failure type of the slope observed in the model tests is introduced in second. Third, an index to express the degree of slope instability is proposed. Lastly, discussion on the threshold state of the slope using proposed index is made.

2. SHAKING TABLE MODEL TESTS

2.1 Outline of the model tests

Cross sections of the shaking table model test discussed in this paper are summarized in Fig. 2. Three different size slope models were tested. All the slope models consisted three layers named as a surface layer with moderately high strength, a weak layer with low strength and a bed rock layer with high strength, as schematically illustrated in Fig. 2.

Physical properties of the soil layers are summarized in Table 1, while the appropriate composition was examined through the relevant pseudo static circular slip analyses so as to archive the expected yielding acceleration ranging between 300 and 900 gals. In the series of the shaking table model tests, the effect of the following points on the seismic behaviour is focused.

1) Strength and deformation characteristics of the geomaterials in weak layer
2) Height of the slope model
3) Inclination of the weak layer
4) Thickness of the weak layer

Table 2 summarizes test condition discussed in the paper. Detailed test conditions are herein discussed.

2.2 Strength and deformation characteristics of geomaterials in weak layer

Three different compositions of the weak layers were used depending on the objective of the model test. Material A is the standard material used in this study and its strength was determined for achieving the expected yielding acceleration. Material B has the almost same strength with Material A, while its peaks strain was smaller than one of Material A. Material B is used in Cases 14, 27, 28 and 29.

In Case14, the effect of the deformation characteristics of the weak layer on the slope failure was investigated. In Cases 27, 28 and 29, effect of the distribution of the geomaterial within the weak layer on the seismic behaviour of the slope were investigated by changing the arrangement of Material A and Material B within the weak layer as summarized in Table 2.

The amount of bentonite was increased for preparing Material C to increase the cohesion so as to construct the slope models of Cases 20 and 22 with the height of

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Table 1: Geomaterials used in the model test

| Material          | Mixture ratio | Unit weight | Cohesion (kPa) | Internal friction angle |
|-------------------|---------------|-------------|----------------|------------------------|
| Weak layer A      | Silica sand: Bentonite: water = 100:1:10 | 17.0 | 4.0 | 44.7 |
| Weak layer B      | Silica sand: Steelgrid: Bentonite: Water = 30:70:1:2 | 21.8 | 5.5 | 34.9 |
| Weak layer C      | Silica sand: Bentonite: water = 100:70 | 17.0 | 8.2 | 31.3 |
| Bedrock layer     | Crushed stone: Cement: Water = 100:4:7 | 3.00 | 280.5 | 57.4 |
| Surface layer     | Iron sand: Bentonite: Water = 100:10:15 | 18.0 | 107.4 | 0 |

Table 2: Outlines of model tests

| Case number | Inclination of weak layer (degree) | Thickness of weak layer (mm) | Material of weak layer | Height of slope model (mm) | Input wave | Observed failure pattern |
|-------------|-----------------------------------|-----------------------------|-----------------------|---------------------------|------------|--------------------------|
| Case5       | 45                                | 80                          | Material A            | 1000                      | Sinusoidal wave | Catastrophic             |
| Case6       | 40                                | 80                          | Material A            | 1000                      | Sinusoidal wave | Progressive              |
| Case7       | 40                                | 160                         | Material A            | 1000                      | Sinusoidal wave | Progressive              |
| Case8       | 70                                | 90                          | Material B            | 1000                      | Sinusoidal wave | Progressive              |
| Case14      | 40                                | 84                          | Material B            | 1000                      | Irregular wave | Progressive              |
| Case27      | 70                                | 70                          | Material A            | 2540                      | Irregular wave | Progressive              |
| Case28      | 70                                | 70                          | Material B            | 2540                      | Irregular wave | Progressive              |
| Case29      | 35                                | 70                          | Material A            | 3800                      | Progressive    | Progressive              |
| Case20      | 45                                | 200                         | Material C            | 2540                      | Irregular wave | Progressive              |
| Case22      | 45                                | 400                         | Material C            | 3800                      | Progressive    | Progressive              |
2500 mm and 3800 mm.

2.3 Height of the slope model

In the series of the model tests, the height was changed among 1000mm, 2500mm and 3800mm. Model tests with height of 1000 and 2500 mm were conducted by the different shaking tables belonging to the Railway Technical Research Institute, while the model test with height of 3800 mm was conducted by the 3D full-scale earthquake testing facility (nicknamed as E-Defense) belonging to the National Research Institute for Earth Science and Disaster Prevention (Shinoda, 2013).

2.4 Inclination of the weak layer

The weak layer inclination of the slope model was set as 30, 40 and 45 degrees. Slope inclination was changed to focus on differences between the accelerations and displacement responses of the surface and weak layers, and the effect of the shear strain generation process for variable slope inclination. The boundaries between the weak layer and the rock layer were trimmed like steps to prevent failure at the boundaries and demonstrate the potential stiffness and strength of the geomaterials.

2.5 Thickness of the weak layer

The thickness of the weak layer was also changed so as to investigate into the effect of the thickness of the deformable layer on the failure process of the slope models.

2.6 Input motion

Seismic excitation was applied by shaking the soil container horizontally. Slope models with the height of 1000 mm were subjected by the ten cycles of sinusoidal excitation with the frequency of 5 Hz. Slope models of Cases 20 and 22 were shaken by using the irregular wave. Examples of time histories of the irregular shaking are shown in Fig. 3. The maximum acceleration was gradually increased while its increment was about 50 to 100 gal, until the slope model failed.

3. IMAGE ANALYSES SYSTEM

A feature of the present shaking table model tests was to use an image analyses system to measure the displacement of sliding soil mass during the shaking. The outline of the system is schematically illustrated in Fig. 4. The basic concept of the system was same as those of the system proposed by Watanabe et al.(2005), while the resolution of system was improved. In the preset study, the accuracy of the system was confirmed to be about 0.2 mm. The displacement of the target aluminum rivets with almost the same specific gravity as the geomaterials was measured using the system. Laser displacement transducers were used to measure the displacement at the surface of the slope, while deformation within the soil mass could be measureable by using the image analyses system.
4. FAILURE MODE OF THE SLOPE

4.1 Formation of slip surface in slope model

The slope model before the failure during the shaking of 400 gals is shown in Fig.5. Slip surface was generated in the weak layer. After the slip surface formation, soil mass slid along the slip surface. In present study, the slope failure was occurred due to the sliding of the soil mass after the slip surface formation in the shaking. Based on the observation, the value of the sliding displacement of the soil mass along the slip surface was adopted as an index to evaluate the extent of the instability of the slope.

4.2 Comparison of failure mode

Comparisons of the time histories of sliding displacement of soil mass in Cases 5, 6, 7 and 8 are shown in Fig. 6. The sliding displacement of the soil mass was evaluated by measuring the movement of the aluminum rivet installed in the soil mass using the image analyses system.

The sliding displacement of the soil mass in case 5 rapidly accumulated and it stopped after the soil mass reached to the bottom platen of soil container. Accumulation of the sliding displacement was increased during the shaking regardless of the direction of the inertia force. As compared with the case 5, cases 6 and 8 showed more ductile seismic behavior in which the sliding displacement was gradually increased and its increase was stopped when the shaking finished.

First part of the displacement accumulation in case 7 is the same tendencies with the cases 6 and 8. However, the displacement started to increase continuously after t = 7.25sec., and the displacement accumulation did not stop even after the shaking ended.

Based on the observations above, the failure patterns of the slope model in the present study could be divided into three patterns. First one is the catastrophic failure mode like Case 5, in which the sliding displacement increased rapidly after the soil mass started to move. This pattern of the failure is considered to be dangerous mode whose seismic stability shall be urgently improved. This pattern will be called as “catastrophic failure mode” herein.

The second failure mode was observed in cases 6 and 8, in which the displacement of the soil mass was gradually increased only when the slope model was subjected to the inertia force which would induce the driving force for the slope failure. This pattern of the failure will be called as “progressive failure mode” herein.

The last failure mode was observed in case 5 where the failure mode was changed from the progressive failure mode to catastrophic failure mode. In the last type of failure mode, it was thought that the failure mode changed because the sliding displacement exceeded threshold state.

5. CONSIDERATION ON THRESHOLD CONDITION OF SLOPE MODEL

5.1 Normalized sliding displacement

In the present study, normalized sliding displacement of the slope is proposed as an index to evaluate the extent of the instability of the slope based on the observations from the model tests. The definition of the normalized sliding displacement is schematically illustrated in Fig. 7. The normalized sliding displacement
displacement was evaluated by normalizing the value of sliding displacement of soil mass along the slip surface $\delta$ by the length of the slip surface $L$.

The sliding displacement $\delta$ could be evaluated by detecting the local displacement of aluminum rivet in the sliding soil mass using the image analysis system introduced in former part of the paper. The sliding displacement of the soil mass was evaluated as the relative displacement to the stable part of the slope model as schematically illustrated in Figs 6 and 9. The length of the slip surface $L$ was measured from the models after the failure.

5.2 Evaluation of normalized sliding displacement

Different three timings are highlighted so as to discuss the relationships between the extents of the slope instability and the values of normalized sliding displacement of the soil mass.

The highlighted three timings are as follows.

1) The peak strength has been already mobilized along the slip surface while the strength reduction has not so significant yet (This state is called as Timing A).

2) The sliding soil mass has been already unstable thus the sliding displacement would increase per one cycle of loading (This state is called as Timing B).

3) The stability of the slope was completely lost thus the sliding soil mass would not stop even after the shaking ceased (This state is called as Timing C).

The value of sliding displacement at Timing A is evaluated by drawing the relationship between the response horizontal acceleration and sliding displacement as illustrated in Fig. 8. Reduction of the response acceleration of the sliding soil mass was caused by the reduction of mobilized strength along the slip surface. In the present study, the value of sliding displacement $\delta$ at the 20% reduction as compared to the peak acceleration was extracted as illustrated in Fig. 8.

The values of sliding displacement at Timing B and C are evaluated from the time history of the relative velocity of the sliding soil mass as shown in Fig. 9. The relative velocity of the sliding soil mass is evaluated by differentiate the time history of relative sliding displacement of soil mass with respect to time.

For the Timing B, the value of sliding displacement at the clear first peak was obtained because the continuous displacement accumulation would be induced in the following loading, which corresponds to the definition of the Timing B.

There is timing when the relative velocity of the sliding mass started to show the positive value continuously (i.e. sliding mass never stopped even after
the driving force ceased or the direction of the inertia force changed). By following the definition of the Timing C, the value of the sliding displacement one cycle before the above threshold value is extracted as also illustrated in Fig. 9.

5.3 Discussion on threshold state of the slope based on normalized displacement

The comparison of normalized sliding displacement in the shaking table model test presented in this study is shown in Fig. 10. The value of the normalized sliding displacement at the Timing C was the largest, while that of the Timing A was the smallest, and the Timing B was the intermediate in all the cases.

The ratios of the normalized displacement at the Timing B to the Timing C (denoted as R) and the failure pattern of the slope, which was defined before, are also indicated in Fig. 10.

By referring to the definition of the Timing B and C, the Timing B could be regarded as the beginning or the first stage of the slope instability, and the Timing C could be regarded as the threshold state because the sliding of the soil mass would not stop even after the earthquake-induced driving force becomes to zero.

The values of R in cases the slope models showed catastrophic failure mode were smaller than the ones of slope models exhibited the progressive failure mode. It was also found from the comparisons in Fig. 10 that the values of R were ranging from 2 to 32. This behavior indicates that by setting the Timing C as the threshold state of the slope, both Timings A and B could be possible to set as the “design threshold state” because a certain amount of displacement accumulation was required to reach to the threshold state from the first stage of the slope instability in every case.

Relevant simulations to evaluate all the timings reasonably and analyses of the model tests with same approach will be required for further study.

6 SUMMARY

Based on the series of shaking table model tests, it was attempted to propose an index to evaluate threshold condition of the slope. The points of discussion are summarized as follows.

Three patterns of failure mode are observed. One is the catastrophic failure mode, the other one is the progressive failure mode and in the last one, failure mode changed from progressive failure mode to catastrophic failure mode.

Sliding of the soil mass along the slip surface was observed in the process of the failure thus the normalized sliding displacement of the soil mass was adopted as an index to evaluate the extents of the slope instability.

Three different timings are proposed to trace the process of the slope failure and comparisons of the normalized sliding displacement at each timing indicated that certain amount of displacement accumulation was required from Timings A and B to Timing C, which could be regarded as the threshold state of the slope.

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