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ABSTRACT

Tieback anchors are widely used for the stabilization of natural and manmade slopes in Japan. The interactions between tieback anchors and slopes under seismic loading need to be understood to develop rational design concepts and installation methods in earthquake prone areas. We conducted centrifuge model tests to examine the characteristics of dynamic and residual loads on tieback anchors installed in slopes subjected to seismic loads. If the model slope contained a saturated zone, circular failure occurred even with pre-tensioned tieback anchors, and the amplitude of the oscillating loads on the tieback anchors was very high. This suggested that excess pore water pressure may cause the design capacity of the anchors to be exceeded, depending on the stability of the slope and intensity of the earthquake. Additional tests were therefore conducted with model slopes with drainage pipes installed (perforated plastic tubes). The drainage pipes significantly reduced pore water pressure, which in turn enhanced the stability of the slope and reduced the loads on the tieback anchors. We conclude that installation of drainage pipes in earthfill slopes would enable the selection of smaller ground anchors and potentially reduce overall construction costs.

INTRODUCTION

Urban development of land formed from large-scale earthfill on valley slopes to meet housing demand was common in Japan during the period of high economic growth of the 1960s to 1980s. Large earthquakes in recent years, the Hanshin Earthquake in 1995, Chuetsu Earthquake in 2004, and Chuetsu-Oki Earthquake in 2007, have caused numerous rotational slope failures in such areas of earthfill. As a result, the Ministry of Land, Infrastructure, Transport and Tourism released procedures for earthquake risk evaluation of valley fill together with maps of the location of such areas of large-scale earthfill. A countermeasure project titled "Prevention of Failure of Large-scale Fill" was undertaken to reduce the damage from earthquake-related failures. Figure 1 shows a diagram of the types of construction that were conducted as part of the prevention project. These measures were installed on a slope containing houses in Kashiwazaki city, Niigata prefecture following an earthquake in 2004 and before another that occurred in 2007. One of the preventative measures shown in Fig. 1 is tieback anchors, large anchors used to hold in place retaining walls at the toe of slopes. Experiments indicate that the rise of pore water pressure caused by ground vibration in an earthquake produces a transformation in ground properties and thus a large change in the axial force of tieback anchors. We proposed a method of groundwater drainage to minimize the change in ground properties by seismic forces and associated changes in axial force of the tieback anchors. The method utilizes groundwater drainage pipes to reduce excess pore water pressure. This paper presents the experimental methodology and results of testing the proposed method by means of a centrifuge-based physical scale model and field validation.

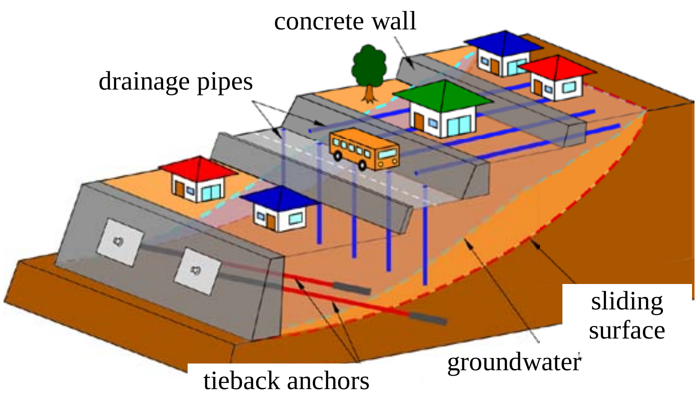

Fig. 1. Diagram of measures taken to prevent rotational failure on large-scale earthfill.

CENTRIFUGE MODEL EXPERIMENT

Purpose of experiment

Measurements of the behavior of tieback anchor works and shake experiments with centrifuge force fields show that the axial force of tieback anchors increases during earthquakes. Sometimes, tieback anchors fail during earthquakes, suggesting that phenomena not accounted for in the design occur under earthquake loads. This may be related to the phenomenon of liquefaction, whereby pore water pressure in sandy soil rises because of repeated shearing deformation in an earthquake resulting in loss of bearing strength and damage to structures. Various countermeasures to disperse excess pore water pressure have been developed to reduce damage from liquefaction.

One of the concerns on slopes with anchor works is how the ground transforms in an earthquake causing the axial force of the tieback anchor to exceed the prescribed load. We modeled this mechanism in a fill slope with tieback anchor works in a centrifuge model. We performed experiments to collect data to assist the method for designing tieback anchor works. We analyzed the collected data and considered the mechanism of deformation and the axial force of the tieback anchor works on fill slopes under various earthquake accelerations. Based on these mechanisms, we then designed drainage pipes and materials to minimize the change in fill slope properties and axial force of the tieback anchor works in an earthquake. We conducted centrifuge model tests and confirmed the effectiveness of using drainage together with tieback anchor works.

METHODS

Experimental Apparatus

The centrifuge facilities used (Fig. 2) belonged to the Research and Development Center Facility of Nippon Koei Co. Ltd. The specifications of these facilities are shown in Tables 1 and 2.

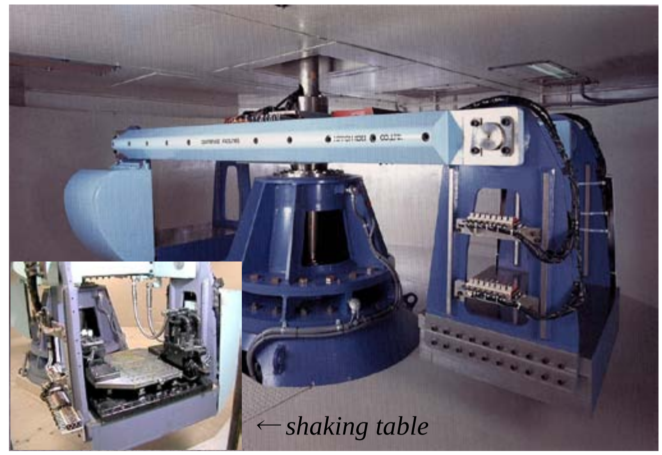

Fig. 2. The centrifuge facilities used for the experiment.

Table. 1. Specifications of the centrifuge and related facilities used for the experiment

Table	Value
Type	Beam
Effective Radius	R=2.6m
Max. Acceleration	250 G
Max. Payload	1,000 kg
Data Acquisition	40 ch

Table. 2. Specifications of the shaking table used used for the experiment

Table	Value
Shaking Control System	Electrohydraulic Servo Control
Max. Centrifugal Acceleration	100 G
Max. Shaking Acceleration	25 G (1/30 model 818gal)
Max. Payload	250kg
Max. Displacement	±3.0mm
Frequency Range	10 - 400Hz
Max Velocity	40 cm/s

The centrifuge model used for the experiment is shown in Fig. 3. For ground material we used Toyoura Standard Sand (Toyoura Keiseki Kogyo Co. Ltd., Shimonoseki, Yamaguchi, Japan), a standard silica sand, and kaolin clay at a ratio of 4:1, 92% compaction, and slope gradient of 1:1.5. We placed gravel at the toe of the slope to hold in the particles of media. The basic physical properties and grain size accumulation curve of the model ground media are shown in Table 3 and Fig. 4.

Four anchors made of stainless steel wire attached to an anchor plate were arranged at intervals of 75 mm on the slope in this model. Three drainage pipes as shown in Fig. 5 were set between the anchors (see Fig. 6). The drainage pipes were formed from alternating sections of soft bellows tube and aluminum tube of 6 mm diameter with open strainers on the sections of tube located below groundwater level in the model. The purpose of the bellows tube was to enable the tube to follow the expected shearing deformation of the model ground. As shown in Fig. 1, groundwater drainage works are usually set with a slight gradient, and their purpose is to control the rise in pore water pressure during an earthquake. Therefore, the drainage pipes were set parallel to the anchors.

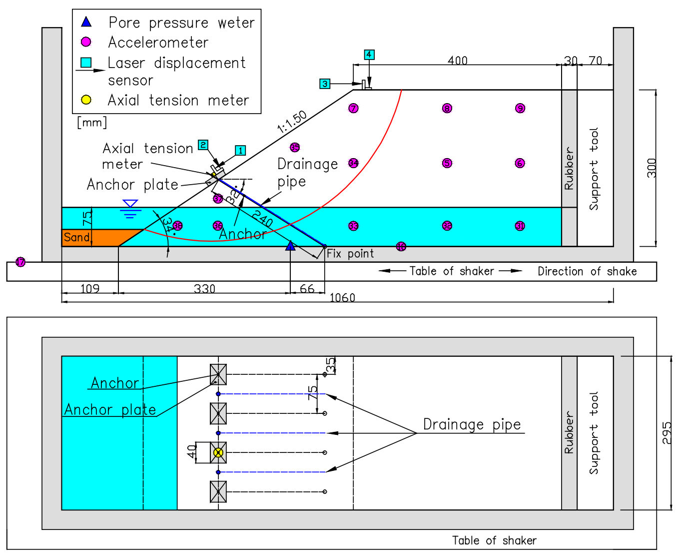

Fig. 3. The model used for the experiment and arrangement of the axial tension sensors.

Table. 3. Basic physical properties of model ground.

Table	value
Particle density(ρ_s)	2.668 g cm^{-3}
Maximum dry bulk density(ρ_{dmax})	1.880 g cm^{-3}
Optimum moisture content(w_{opt})	11.7%
Degree of compaction(D_c)	92.0%
Coefficient of permeability(k)	4.6×10^{-4}cms^{-1}
Cohesion (c')	2.01 kN m^{-2}
Internal friction angle (ϕ')	34.1°

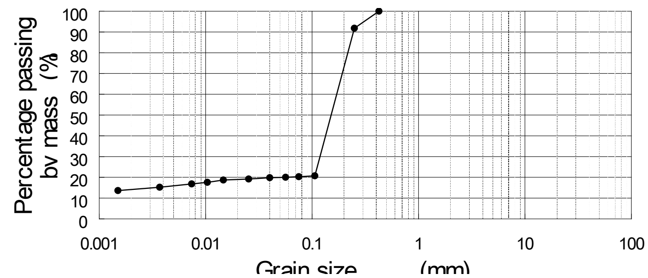

Fig. 4. The grain size accumulation curve of material used in the model ground.

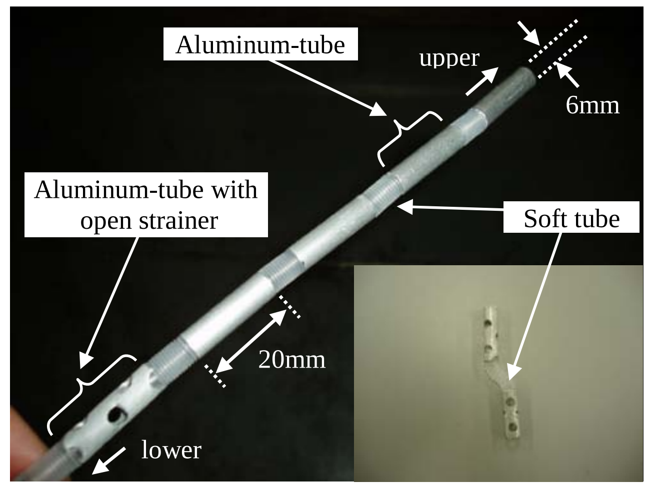

Fig. 5. The drainage pipes used in the model.

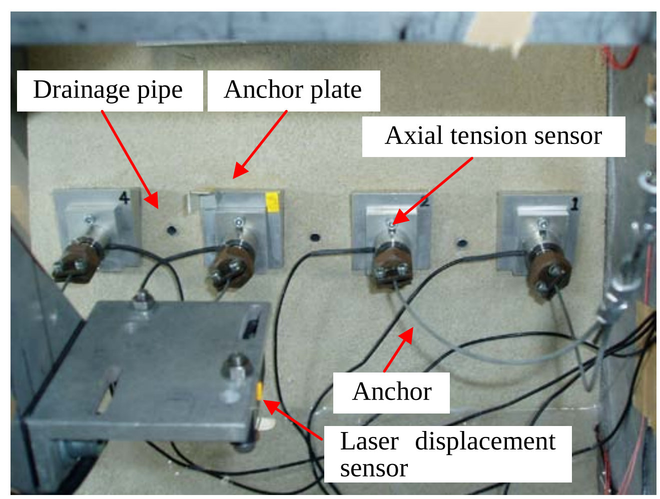

Fig. 6. The drainage pipes between the anchors.

A saturated zone (equivalent to groundwater) was established in the lowermost 75 mm of the model ground. Viscous fluid is usually used in centrifuge model tests to achieve accurate scaling. However, the purpose of this experiment was to examine the role of groundwater on ground deformation and the effect of the drainage pipes, so water was used instead of viscous fluid.

Axial tension meters were set up at the head of anchors to measure the axial force of the anchor and pore water pressure meters were placed in the bottom of the model. In addition, targets for laser measurement of displacement were installed on the shoulder of the slope and accelerometers were installed in the model. Measurements from these meters were recorded by a logger together with timestamp data.

The procedure for centrifuge model tests is shown in Fig. 7. First of all, an initial pre-stress force of 2 kgf was applied to the anchor, and initial consolidation by the self-weight of the material was produced by a centrifugal acceleration field of 40 G. The centrifuge was stopped once, then the initial pre-stress force was again set to about 10 kgf after which simulated seismic waves were generated by shaking the model bottom in a sinusoidal waveform as 15 waves with a frequency of 1.5 Hz (see Fig. 8). The maximum acceleration amplitudes were 100, 200,and 300 gal which were applied in succession.

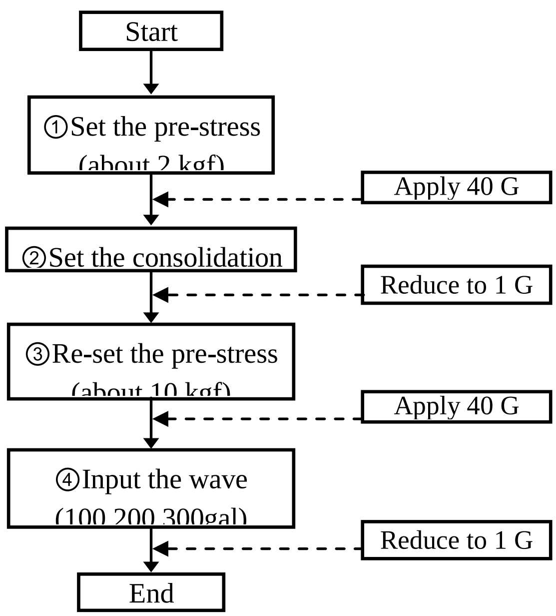

Fig. 7. The procedure used for the centrifuge model tests.

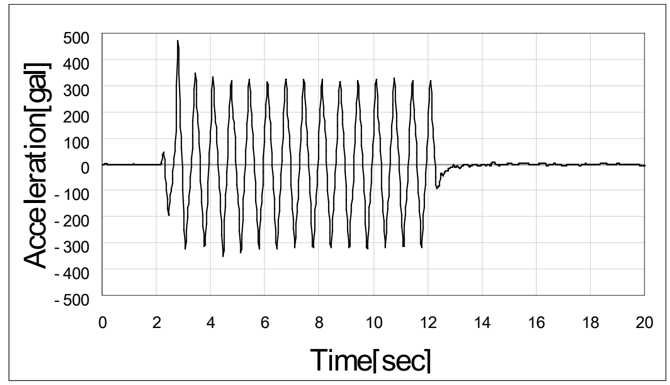

Fig. 8. Input waves for the maximum acceleration amplitude of 300 gal.

<u>Experimental cases</u>

Three experimental cases were used as shown in Fig. 9. Case 1 was for the anchor set entirely in unsaturated ground. Case 2 set the anchor within saturated ground. Case 3 was as for case 2 with the addition of drainage pipes. Cases 1 and 2 were compared to determine the influence of groundwater. Cases 2 and 3 were compared to determine the effect of the drainage pipes.

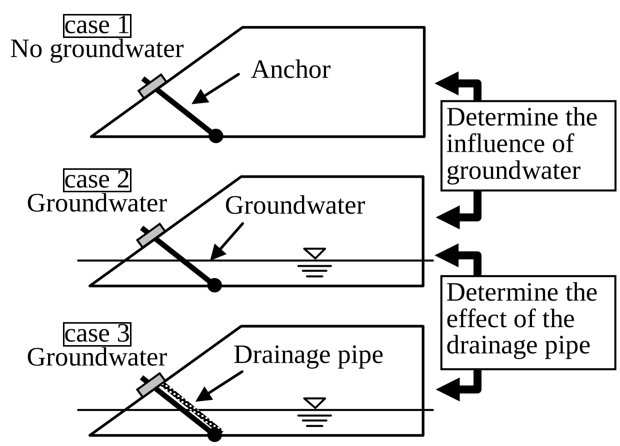

Fig. 9. The three experimental cases used for the centrifuge model tests.

RESULTS

Displacements and axial forces of anchors, in this section, are reported in terms of field scale, which are obtained by multiplying the displacements and forces of the model by the magnitudes of centrifugal acceleration. As well, input waves are shown in terms of field scale.

<u>The influence of groundwater</u>

The results of experiment case 1, without groundwater, and case 2, with groundwater, are shown in Fig. 10 and Fig. 11. The maximum acceleration amplitudes in this figure are 300 gal. Figure 10 shows the time series of the horizontal and vertical displacement on the shoulder of the slope of the model, and Fig. 11 shows the axial force of the anchor.

To show the amount of change after shaking, the values are shown relative to the initial position. Fig. 10 shows that horizontal displacement accumulated gradually. The amplitude of each shake can be seen in the displacement curve as the model was shaken back and forth. Figure 10 shows that the vertical displacement caused by each shake (Fig. 10B) was much less than the horizontal displacement (Fig. 10A). However, the residual vertical displacement (Fig. 10B) was much larger than the residual horizontal displacement (Fig. 10A).

The axial force of the anchor during shaking displayed an amplitude similar to the horizontal displacement shown in Fig. 10. The axial force reached a maximum just before the end of shaking. The actual axial force in case 2 (with groundwater), was 227.1 kN before shaking commenced, and the maximum value reached during shaking was 805.2 kN. Therefore, the shaking generated about 3.5 times the initial axial force.

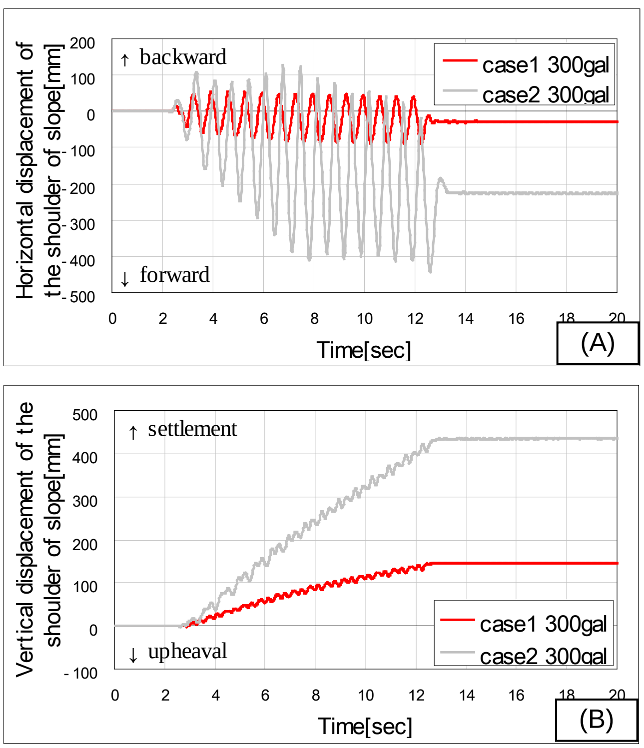

Fig. 10. Time series data of the horizontal (A) and vertical (B) displacement at the shoulder of the slope of the model for experimental cases 1 and 2.

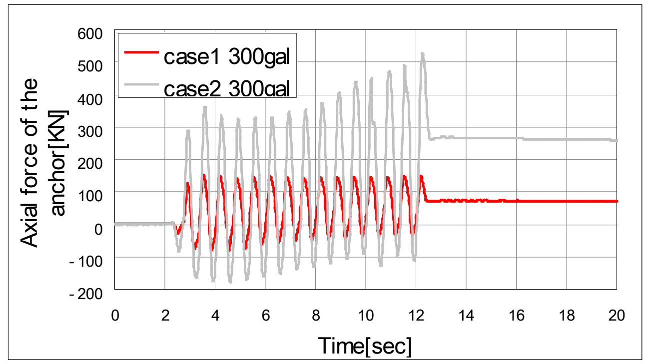

Fig. 11. The time series data of the axial force of the anchor for experimental cases 1 and 2.

Comparing case 1 and case 2 shows that both vertical and horizontal displacements were greater in the presence of groundwater (case 2). The differences in the deformation of the model in cases 1 and 2 are shown in Fig. 12. Moreover, it was demonstrated that the increase in axial forces corresponded with the amount of deformation.

Figure 13 shows the horizontal versus vertical displacement of the shoulder of the model slope at each maximum acceleration amplitude, and Fig. 14 shows the maximum value of the axial force of the anchor during shaking. Figures 13 and 14 show that the existence of groundwater produced about 3 to 8 times greater displacement of the shoulder of the slope and about 2 to 3 times greater axial force on the anchor, depending on the size of the acceleration.

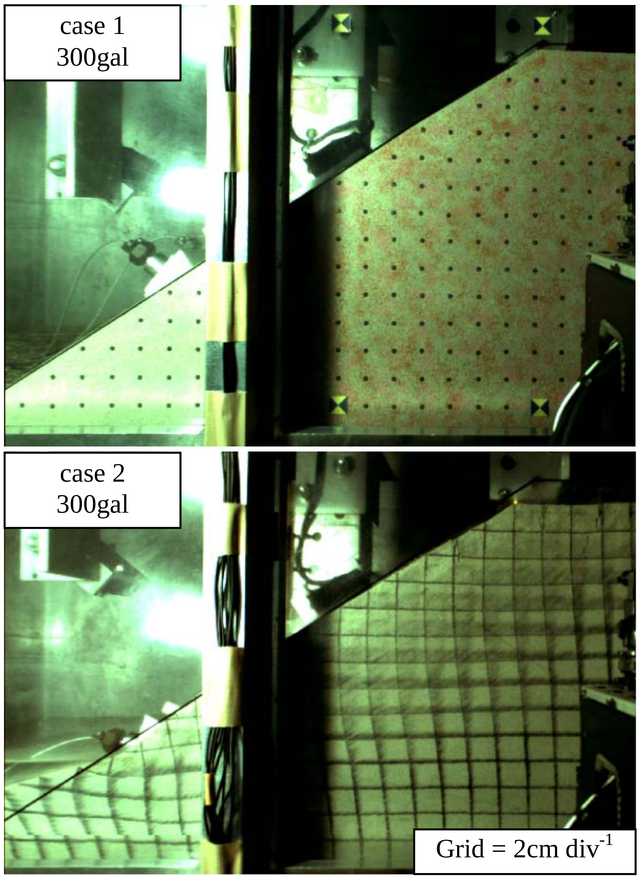

Fig. 12. Side views of the models of cases 1 and 2 after shaking at 300 gal.

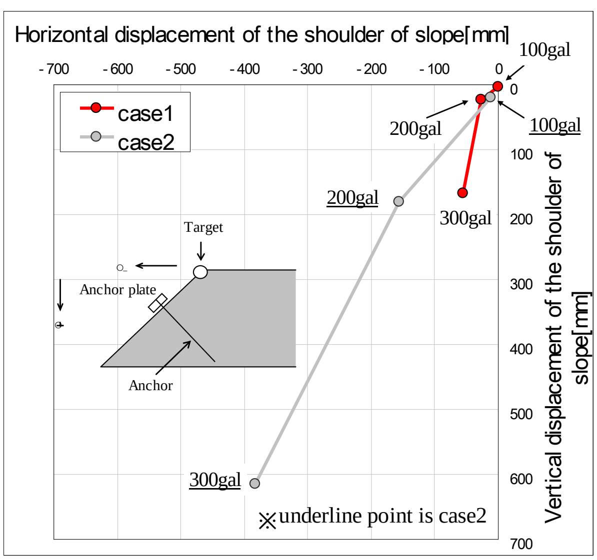

Fig. 13. The displacement of the shoulder of the slope of the model at each maximum acceleration amplitude for experimental cases 1 and 2.

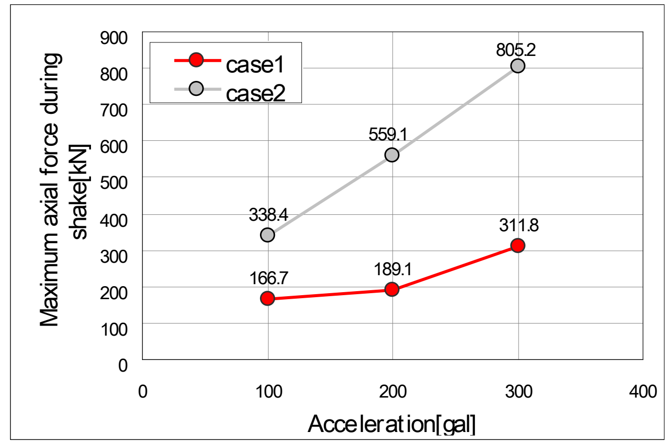

Fig. 14. The maximum value of the axial force on the anchor during shaking for experimental cases 1 and 2.

These results clearly demonstrate that groundwater influenced the deformation of the model and the axial forces of the anchor.

The mechanism of deformation of the model fill slope

The deformation mechanism in the presence of groundwater appears to have been roughly similar to liquefaction. Shear displacement and dilatancy of the saturated and nearly saturated ground material probably occurred as a result of the cyclic shear forces. Water in the pores spaces of the ground material was subjected to pressure from the movement of surrounding particles causing a rise in pore water pressure, a similar process as liquefaction.

Figure 15 shows time series of pore water pressure from the sensor at the bottom of the model for case 2, i.e., with groundwater present. It shows that pore water pressure rose repeatedly during shaking. Displacement of the shoulder of the slope increased gradually during shaking and with each shake (Fig. 10). It is thought that the repeated rise in pore water pressure is central to the mechanism. As one shake causes a rise in pore water pressure, the shear strength is lowered and the next shake generates greater deformation. This repeated rise in pore water pressure and deformation of the fill slope is shown in Fig. 10 and Fig. 15.

The rise in pore water pressure will reduce the effective stress and shear strength of the material of the fill slope. Figure 16 shows the results of a non-drained cyclic triaxial test that we conducted to obtain the deformation characteristics of the material. The stiffness of the material represented by Young's modulus decreased gradually as deformation increased, which is consistent with the progress in deformation caused by shaking.

We considered if the mechanism of ground deformation in the model was the rise in pore water pressure, then deformation of the model slope could be controlled by suppressing the rise in pore water pressure. To verify this mechanism we conducted the case 3 experiment with drainage pipes.

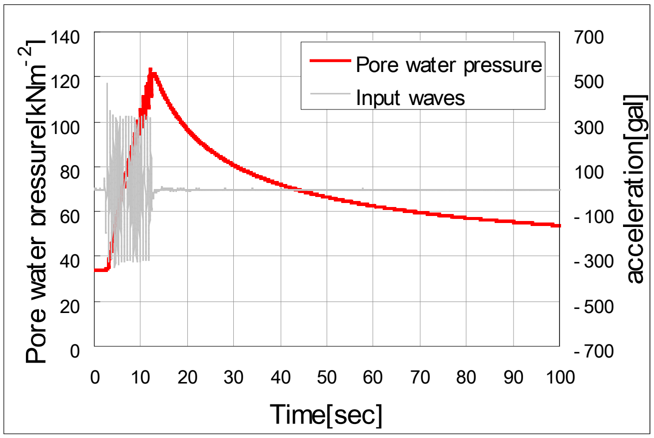

Fig. 15. Time series of pore water pressure for experimental case 2 (with groundwater, maximum acceleration amplitudes are 300 gal).

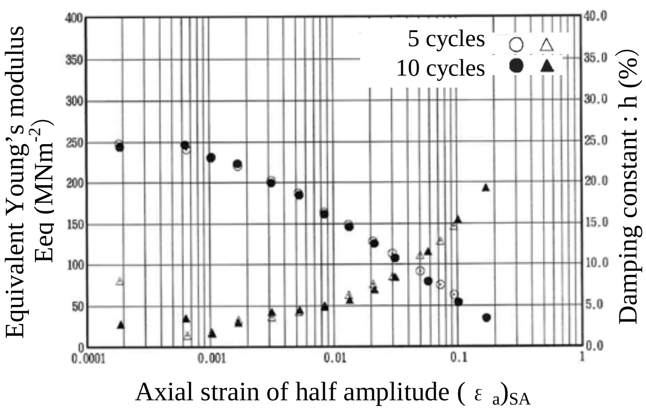

Fig. 16. The result of the undrained cyclic triaxial test.

The effect of drainage pipes

The results of the experiments for cases 2 and 3 are shown in Figs. 17–23. Displacement of the shoulder of the model (Fig. 17), axial forces of the anchor (Fig. 18), pore water pressure (Fig. 19), deformation of the model (Fig. 20), displacement of the shoulder of the slope at each maximum acceleration (Fig. 21), maximum axial force of the anchor at each maximum acceleration (Fig. 22), and maximum pore water pressure during shaking (Fig. 23) were all considerably lower in case 3 than in case 2. As a result, it can be said that the drainage pipe had a pronounced effect on lowering the amount of deformation.

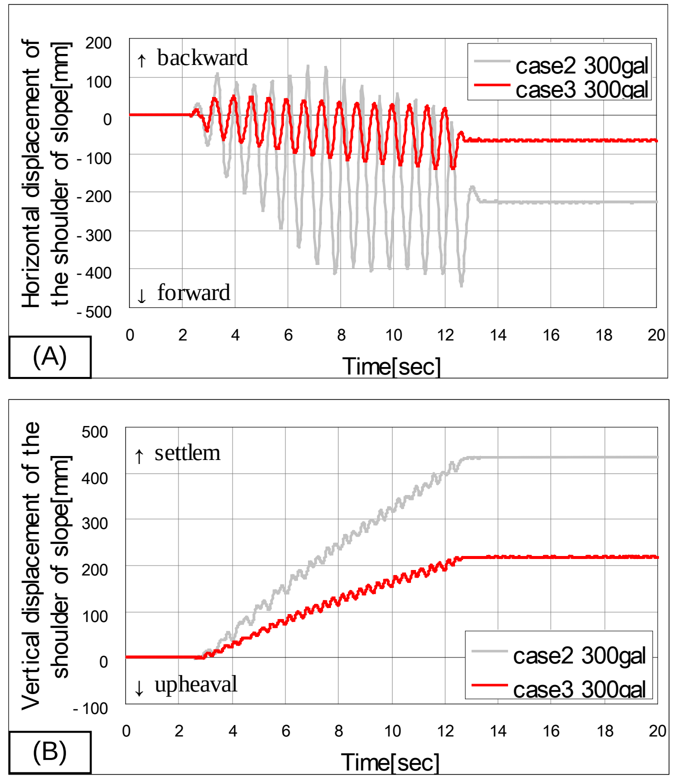

Fig. 17. Time series data of the horizontal (A) and vertical (B) displacement at the shoulder of the slope of the model for experimental cases 2 and 3.

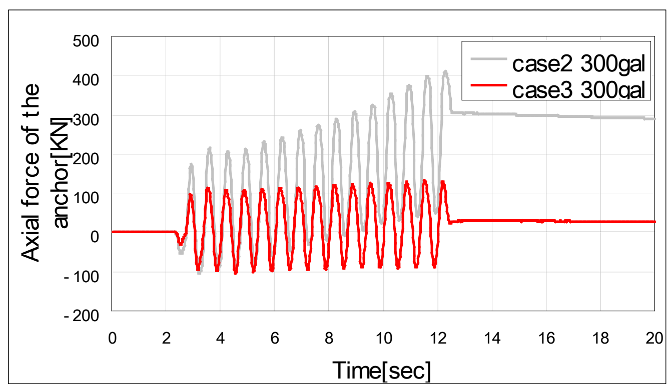

Fig. 18. Time series of the axial force of anchor for experimental cases 2 and 3.

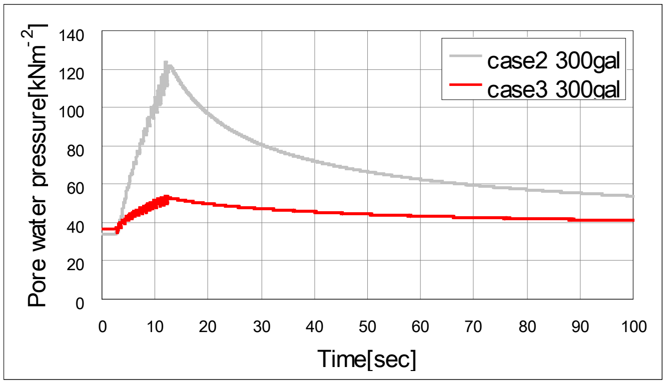

Fig. 19. Time series of pore water pressure for experimental cases 2 and 3.

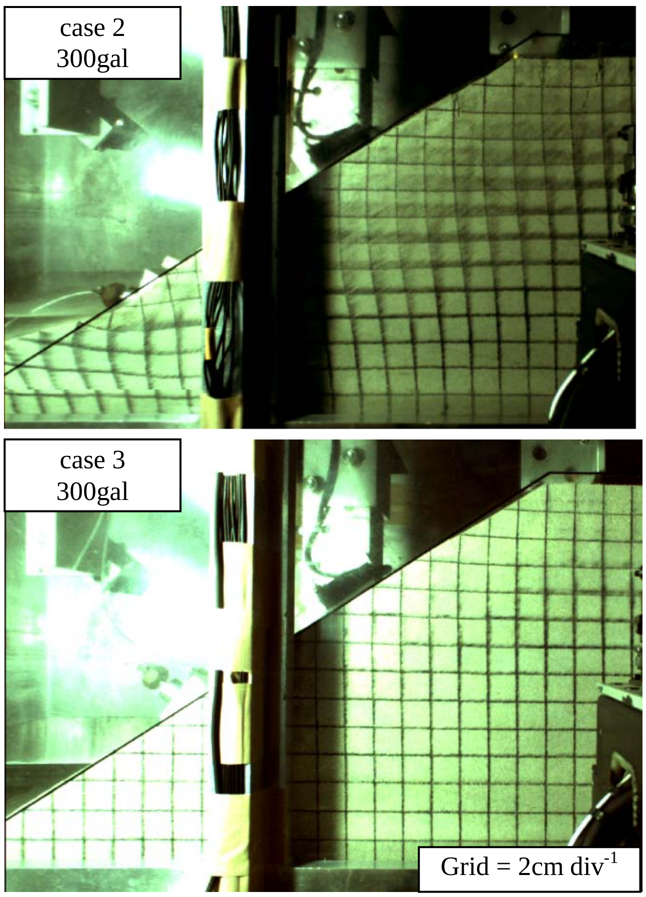

Fig. 20. Side views of the models of cases 2 and 3 after shaking at 300 gal.

Figure 21 shows the displacement of the shoulder of the slope of the model for each maximum acceleration amplitude. Also the maximum value of the axial force of the anchor and pore water pressure under shake was indicated in Figure-22, Figure-22. These results show that displacement, the axial tension, and the pore water pressure increase, when the maximum acceleration amplitude grows.However, the amount of an increase is small when there are a drainage pipe. These results show the effect of the drainage pipe, too.

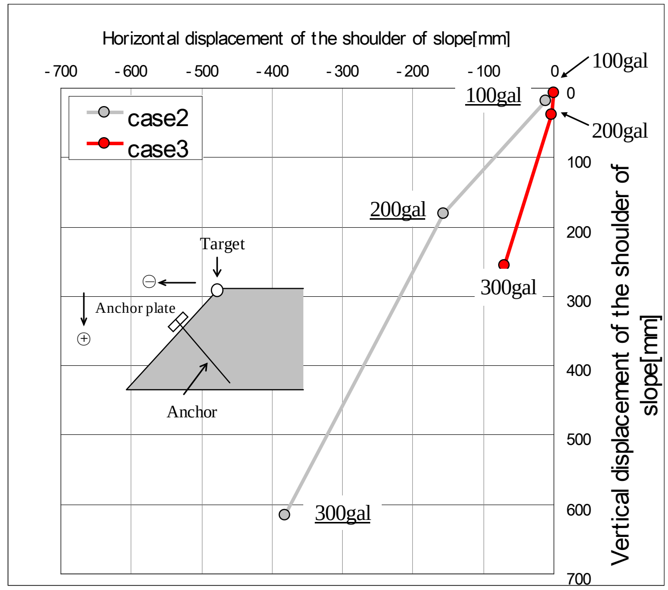

Fig. 21. The displacement of the shoulder of the slope of the model at each maximum acceleration amplitude for experimental cases 2 and 3.

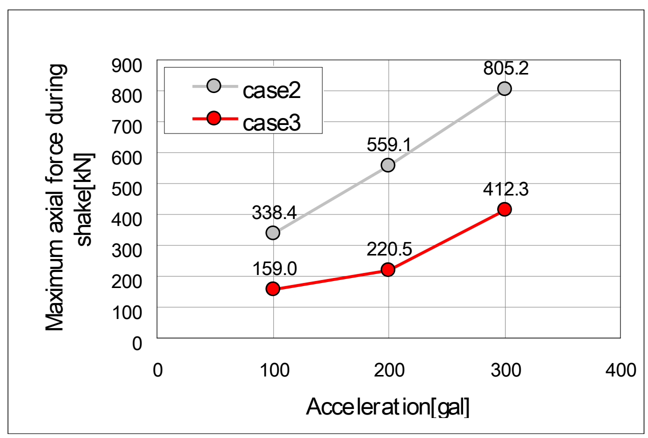

Fig. 22. The maximum value of the axial force of the anchor during shaking for experimental cases 2 and 3.

The mechanism for the reduced deformation of the model with drainage pipes installed was that the increasing pore water pressure forced free water into the highly permeable drainage pipe, preventing the accumulation of excessive pore water pressure and attendant loss of shear strength. As a result, shear deformation was controlled. Hence the experiment confirmed that the drainage pipe limited the increase in axial forces of the anchors during shaking.

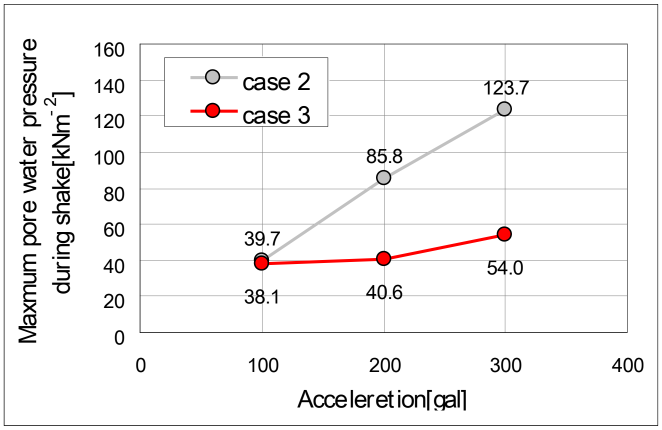

Fig. 23. The maximum value of the pore water pressure during shake.

VERIFICATION OF EXPERIMENT FOR THE ANCHOR WORKS AND DRAINAGE PIPE

Review of anchor design compared with the experiment

For anchor works on slopes such as landslides, seismic force is not often considered in the design. Therefore, it is important to examine how much seismic force affects these anchor works.

One of the methods of evaluating the effect of anchors in an experiment is the circular slide calculation. A design safety factor is first set, the necessary prevention force is calculated by the circular slide calculation, the necessary anchor force is then calculated, and finally the anchor is designed that can produce such a force. To evaluate the outcome of the experiment, the allowable tension force of a designed anchor and the axial force of the experiment were compared.

The circular slide used for calculating the maximum prevention force are as shown in Fig. 3, and the groundwater condition is controlled by prevention works. In this state, the safety factor is assumed to be 1.100, and the ground condition for the calculation is back calculated using Table 1 (cf. φ' = 29.3° is back calculated as c'=2.01 kN m^{-2}). The design then needs to be changed to raise the safety factor to 1.200 by installing anchors or other methods. The necessary force of the prevention works becomes 78.008 kN/m. If the anchor is designed for the conditions of our experiment, using one step and horizontal interval of 3 m, the design anchor force becomes 228.444 kN/unit. As a result, an anchor with allowable tension force of 297.0 kN/unit during an earthquake is selected (cf. 297.0 kN/unit = 0.90×Tys, and Tys = 330 kN/unit; Tys is yield force). The maximum value of the axial force in the case 2 experiment was 805.2 kN (Fig. 14). This exceeds the allowable axial force of 297.0 kN calculated above and indicates why large displacement of the model was observed. If the existing anchor is evaluated by the maximum value of the axial force, the effect of earthquake forces on the anchor works cannot be predicted.

Review for large-scale earthfill on valley slopes

The "Guideline for Investigation, Examination, and Measures for Earthfill" specifies a design safety factor of 1.000 or more to achieve stability of earthfill on hillsides. In accordance with this guideline, the safety factor is set to 1.000. The ground conditions used for the calculation are shown in Table 1. The circular slide used for calculating the maximum prevention force are shown in Fig. 3. The horizontal seismic coefficient is assumed to be 0.30, corresponding to an acceleration of 300 gal, the safety factor during an earthquake becomes 0.739. The necessary force for prevention works would then be 304.53 kN/m, and the design anchor force would be 815.346 kN/unit. Consequently, an anchor design with allowable tension force of 856.8 kN/unit under earthquake loading is selected, which is greater than the maximum value of the axial force of case 2. Therefore, the anchor works would not exceed the maximum value of axial force, demonstrating the effect of case 2.

The seismic safety factor for earthfill on valley hillsides is selected according to the importance of preventing slope failure. Therefore, anchor designs adopted through stable computation will occasionally be exceeded when an earthquake occurs. If countermeasures are examined only in consideration of the anchor characteristics, to secure stability under earthquakes requires a large anchor.

Calculation considering the rise in pore water pressure

The effect of the drainage pipes used in our experiment was examined by substituting the values of pore water pressure in case 2 (without drainage pipe) and case 3 (with drainage pipe) into the circular slide calculation. Figure 24 shows the maximum values of pore water pressure within the saturated zone for each acceleration in case 2 and case 3. The groundwater level was set as the input data for the circular slide calculation, and the result of the calculation is shown in Table 4. The portion above the saturated zone was interpolated.

Table 4 shows that the safety factors for case 3 (saturated zone with drainage pipe) are smaller than those for case 2, indicating the effect of the drainage pipe on the safety factor. From this result, when the planned safety factor is set at 1.000 and anchors are arranged on the slope in three steps, the design anchor forces are as shown in Table 5. The design forces of standard SEEE anchors are shown as reference data in Table 5. The lower number in the table cells of the designed anchor force are the ratio of the designed anchor force to that of case 2 and acceleration of 100 gal.

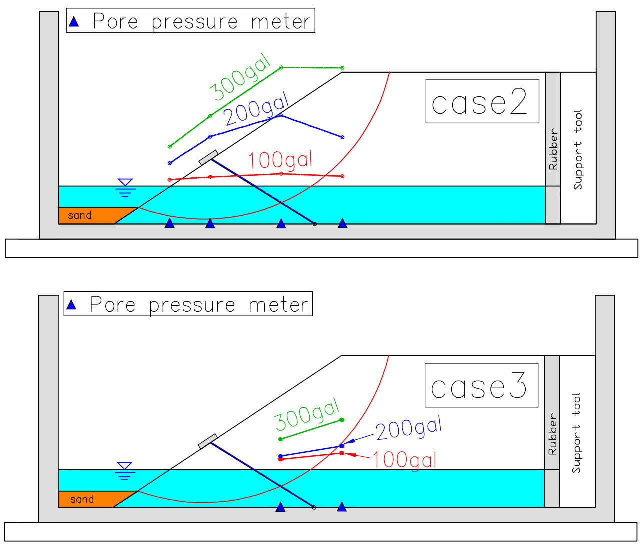

Fig. 24. Distribution of maximum pore pressure measured along the base of the model (case 2, case 3).

Table. 4. The safety factor by circular slide calculation.

Acceleration	case 2	case 3
100gal	0.680	0.705
200gal	0.426	0.697
300gal	0.154	0.619

Table. 5. The design anchor force for safety factors shown in Table 4 for the conditions of case 2 and case 3.

Accele-ration	case 2		case 3	
	Designed anchor force [kN/unit]	0.9Tys (Type)	Designed anchor force [kN/unit]	0.9Tys (Type)
100gal	333.6 (1.000)	379.8 (F50UA)	307.2 (0.921)	379.8 (F50UA)
200gal	541.9 (1.624)	547.2 (F70UA)	315.7 (0.946)	379.8 (F50UA)
300gal	936.6 (2.808)	982.8 (F130UA)	397.7 (1.192)	445.5 (F60UA)

Table 5 shows that at acceleration of 100 gal, the type of standard anchor selected is the same whether drainage pipes are installed or not. However, as acceleration increases, the design anchor force increases substantially if there are no drainage pipes. By using drainage pipes smaller anchors can be adopted, which may lead to savings in the cost of engineering measures required to provide an equivalent level of protection.

SUMMARY OF RESULTS

The centrifuge model tests compared the behavior of a model fill slope restrained by ground anchors under earthquake loads: (1) with and without a groundwater layer and (2) with a ground water layer with and without drainage pipes. The results of the experiment can be summarized as follows.

1. Displacement of the slope was much greater with groundwater than without because of a rise in pore water pressure caused by repeated shearing deformation during shaking, and slope displacement progressed gradually as shaking continued.

2. When drainage pipes were used, deformation of the model and the axial force of the anchor were greatly reduced, presumably because the drainage pipes limited the rise in pore water pressure of the model during shaking.

3. We demonstrated by design calculation that the use of drainage pipes enabled selection of a smaller anchor for the same design acceleration. Moreover, there was a suggestion that the overall cost of construction would be reduced by installation of drainage pipes.

FUTURE DIRECTIONS

The next stage of this research will be to examine methods based on the results of the experiment for designing anchors to withstand earthquake loads in valley fill, and to show the quantitative effects of applying drainage pipes to real fill slopes. It is necessary to examine the structure of the drainage pipes, construction techniques, and a practical approach to design. We believe the mechanisms can be verified by analyzing the results of the centrifuge model tests by numerical analysis in two ways: firstly, by examining the drainage mechanism in case 3, with groundwater and drainage pipes; and secondly, by examining the standard type of drainage pipe by quantitative parametric analysis using an analytical model that incorporates the effect of drainage pipes.

Following the Chuetsu Earthquake in 2004, culvert drainage works were installed on unstable slopes in Kashiwazaki City, Niigata Prefecture. The costs of these works were offset by contributions from home-owners ranging from approximately US$400 to $US18,000 equivalent, as determined by risk assessment. After the works were completed, the area was struck by another large earthquake in 2007, and no damage occurred in the areas where culverts had been installed. However, when this project was instigated, homeowners at first resisted making financial contributions towards the cost. The results of the current study may be effective in assisting to overcome the resistance of homeowners to making contributions towards the cost of drainage works on vulnerable fill slopes protected by ground anchors.

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