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EFFECT OF THE SOIL MOISTURE DISTRIBUTION AFTER RAINFALL ON SEISMIC STABILITY OF EMBANKMENT SLOPE

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ABSTRACT: Recent studies of sediment disasters have indicated that slope failure due to earthquakes was affected by precipitation before the earthquake. Here, we focus on the effects of variation in soil moisture conditions due to antecedent rainfall on slope failure due to earthquakes. To clarify the relationship between the volumetric water content of soil with elapsed time after rainfall and the scale of slope failure, we conducted a series of vibration loading experiments under different soil moisture conditions. In the experiments, 'rainfall' was applied to the model slope using an artificial rain simulator, and the model slope was subjected to seismic wave loading using a shaking table. Soil moisture and laser displacement sensors were used to measure the volumetric water content of soil and displacement of the slope, respectively. The results indicated that the top of slope collapsed and sliding failure occurred when the volumetric water content of the soil was low. The crest of the model slope settled considerably without eroding the sliding surface when the volumetric water content of soil was high. Our study indicated that the soil moisture distribution has a significant influence on the scale of slope failure.

Keywords: Slope Failure, Antecedent Rainfall, Vibration Loading Experiments, Sliding Failure

1. INTRODUCTION

Many slope failures happen in Japan each year and inflict enormous damage. Rainfall and seismic movements are major factors in slope failures. Studies have examined the effects of topography on landslides triggered by earthquakes [1]-[3] and proposed a prediction method for risk assessment of seismic slope failure in mountainous areas based on local topographical and mechanical conditions [4]. Although these studies pointed out the potential effects of topography and geology on seismic slope failure, they did not focus on the influences of soil moisture on seismic responses and the damage to embankment slopes due to the earthquake. The Niigata Chuetsu earthquake in 2004 was an example showing how soil moisture and groundwater conditions affected the slope failure. Reference [5] reported that the soil moisture and groundwater conditions were significant factors in controlling the strength of the slope in seismic slope failures and the movement of colluvial soils after the collapse. However, few studies have investigated the effects of soil moisture (groundwater) conditions on seismicity using in situ measurements [6] or laboratory experiments [7], [8].

In this study, we focused on the variation in soil moisture conditions due to antecedent rainfall. We also conducted a series of loading experiments under different soil moisture conditions to clarify the relationship between variation in the volumetric water content of soil and seismic slope failures.

2. EXPERIMENTS

2.1 Experimental Method

We focused on the relationship between soil moisture conditions and the displacement of a model slope. Experiments were conducted using an artificial rain simulator (Daiki Rika Kogyo, DIK-6000S) and a shaking table (Shinken, G-9210). We made a model slope with granite soil (Masa soil) in a tank. Table 1 shows the properties of the soil. We applied vibration loading to the slope model via a shaking table after artificial rainfall and examined the failure configuration. To clarify the collapse processes, we took videos during the vibration loading experiments. A 1000 mm long, 600 mm wide, and 700 mm high, stainless steel tank was mounted on top of the shaking table. Figure 1 shows an image of the model slope and points where soil moisture and displacement were measured. The model slope measured 656 mm long, 600 mm wide, and 400 mm high. Ten soil moisture sensors (Decagon Devices, S-SMx-M005) were used to measure the variation in the volumetric water content of the soil and six laser displacement sensors (Micro Epsilon, ILD1300-200) were used to measure the displacement of the model slope. The vertical and horizontal displacements were measured by the laser displacement sensors SV1-3 and SH1-3, respectively.

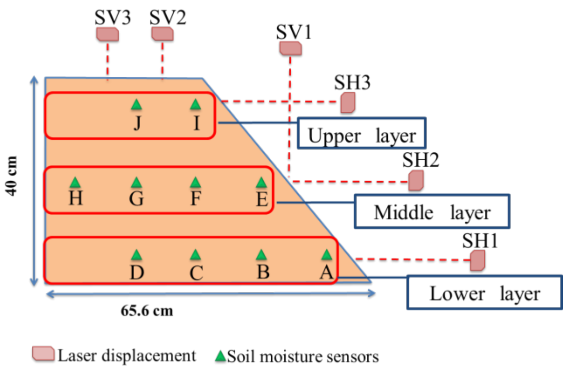

Fig.1 Schematic diagram of the embankment and the measurement points

Table 1 Properties of Masa soil

Relative density, D_r	78%
Initial moisture content, w	10%
Dry density, ρ_d	1.60g/cm^3
Wet density, ρ_t	1.76g/cm^3
Coefficient of permeability, k	2.09×10^{-5}m/s
Void ratio, e	0.631
Porosity, n	38.7%

2.2 Experimental Conditions

In this study, six case experiments were conducted. Table 2 shows the rainfall conditions. We set a different elapsed time from the end of the artificial rainfall to provide loading to create differences in the volumetric water content of the soil. In all experiments, the rainfall intensity was maintained at 30 mm/h. The rainfall duration, was 1 h in Cases 1-3 and 3 h in Cases 4-6. The bottom, rear, and sides of the tank were undrained, and the slope angle was set at 50°. Figure 2 shows the waveform of acceleration. The Maximum acceleration was set for about 600 gal and the frequency was set at 5 Hz. Figure 3 shows the initial volumetric water contents of the soil in Cases 1-6. These values were obtained by calibrating each soil moisture sensor. Although the volumetric water contents at the beginning of experiments should have been 16%, as calculated from the initial moisture content and dry density, the actual values ranged from 12% to 22%. To compare the responses of the volumetric water content for all cases, we corrected the observed initial volumetric water content to 16% as the actual initial condition. We treat the modified volumetric water content in the Results and Discussion.

Table 2 Experimental conditions

	Amount of rainfall per hour	Rainfall duration	Elapsed time after rainfall
Case1			no time
Case2		1hour	1hour
Case3	30mm/h		1day
Case4			no time
Case5		3hour	1hour
Case6			1day

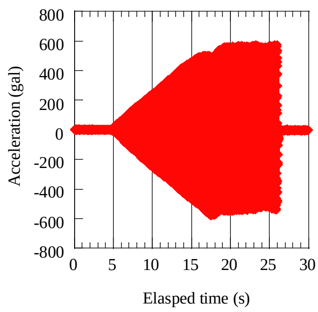

Fig.2 Waveform of acceleration

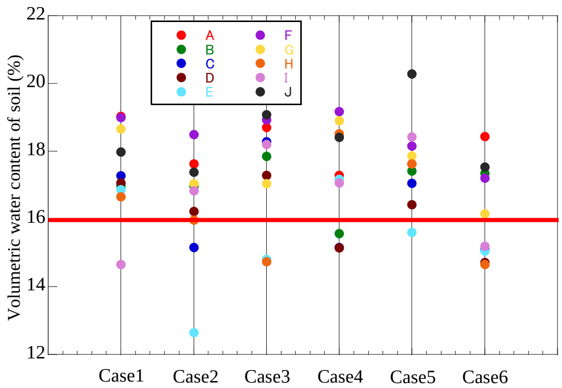

Fig.3 Initial volumetric water contents of the soil (Cases 1-6)

3. RESULTS AND DISCUSSION

3.1 Small Rainfall before Loading

Figure 4 shows the final longitudinal profile of the slope failure and Fig.5 shows photographs of the final slope shape in Case 1. During rainfall, the increase in the volumetric water content of the soil from the initial value was about 8% in the lower layer and about 4% in the other layers. After the rainfall ended, the decreases in the volumetric water content of soil in the upper and middle layers were larger than those in the lower layer. At point D in the lower layer, the decrease in soil moisture changed little after the rainfall ended. This resulted because there was less infiltration of water from the lower layer to the deeper area of the slope due to the undrained condition of the bottom of slope (Fig.6). The displacements in Case 1 were larger than those in Cases 2 and 3 (Fig.7). The time until collapse after loading in Case 3 was longer than in the other cases. Although collapse with a sliding surface in the model slope was confirmed in Cases 2 and 3, it was not in Case 1. Following settlement of the crest after providing the loading in Cases 2 and 3, the top of the slope collapsed, forming the sliding surface. In Case 1, not only the surface but also the back of the model slope collapsed.

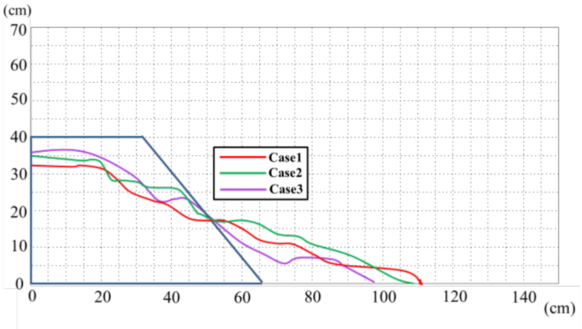

Fig.4 Longitudinal profiles of the slope failures (Cases 1-3)

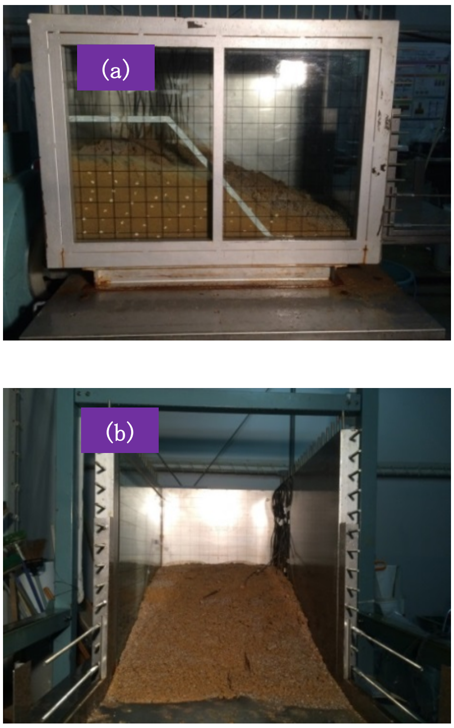

Fig.5 Photographs of the slope failure from the (a) side and (b) front (Case 1)

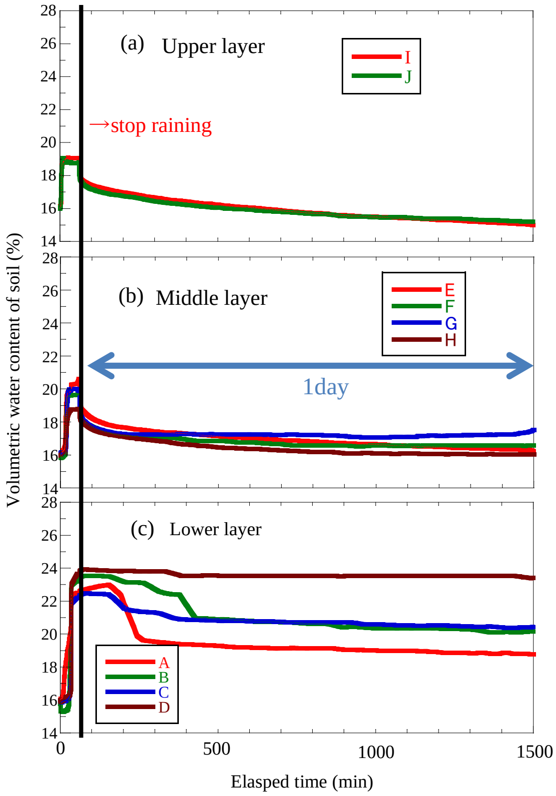

Fig.6 Volumetric water content of the soil in the (a) upper, (b) middle, and (c) lower layers (Case 3)

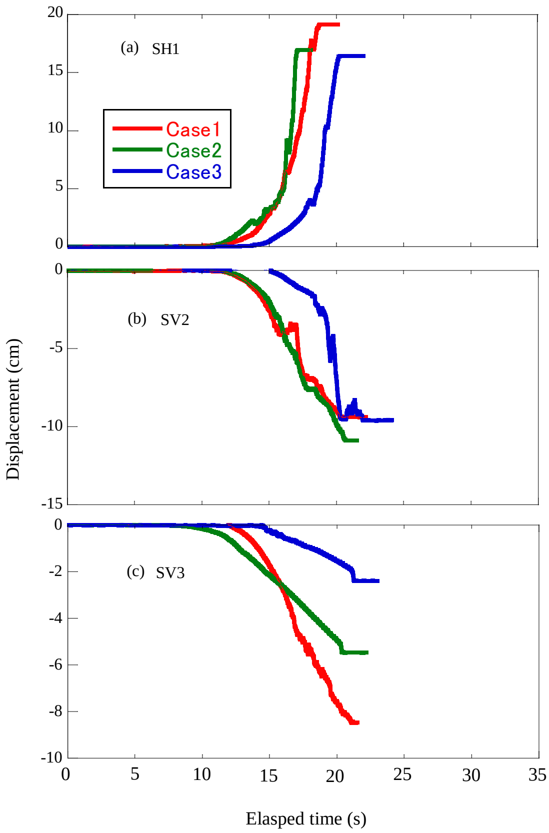

Fig.7 Displacement after loading at (a) SH1, (b) SV2, and (c) SV3 (Cases 1-3)

3.2 Large Rainfall before Loading

Figure 7 shows the final longitudinal profile of the slope failure and Fig.8 shows photographs of final slope shape in Case 4. In the lower layer, the decrease in the value of soil moisture (C and D points) showed little change (Fig.9). The decreases in volumetric water content of soil in the lower layer were similar to Cases 1-3. Although the volumetric water content of soil decreased approximately equally for both points A and B, the time to reach the minimum value was different. In Cases 4-6, settlement of the crest and collapse of the top of the slope with a sliding surface occurred, as in Cases 2 and 3. The amount of displacement in Cases 4-6 showed a large difference (Fig.10). The time to collapse in Case 6 was longer than in Cases 4 and 5.

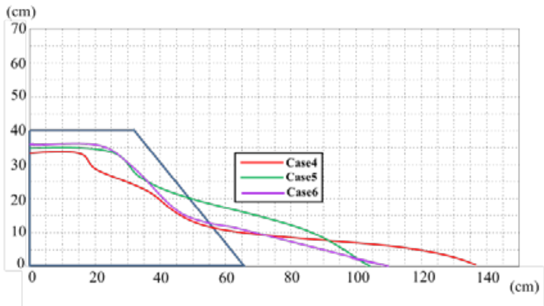

Fig.8 Longitudinal profiles of the slope failures (Cases 4-6)

Fig.9 Photographs of the slope failure from the (a) side and (b) front (Case 4)

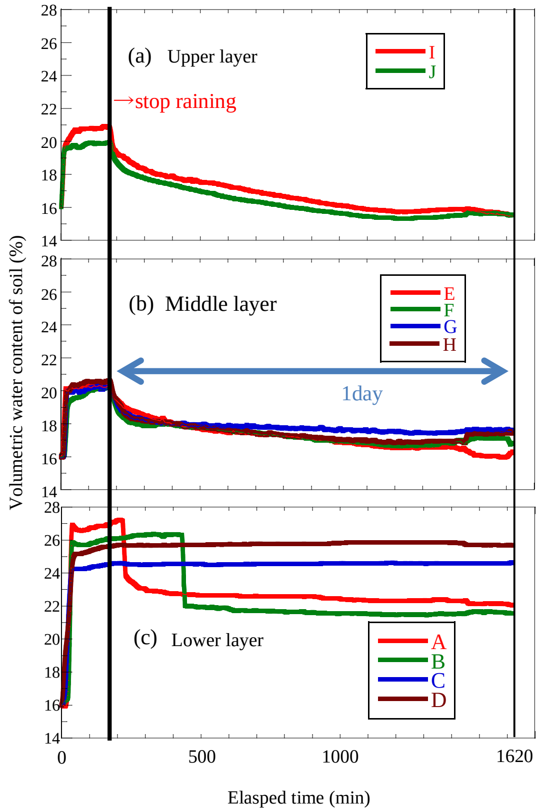

Fig.10 Volumetric water content of soil in the (a) upper, (b) middle, and (c) lower layers (Case 6)

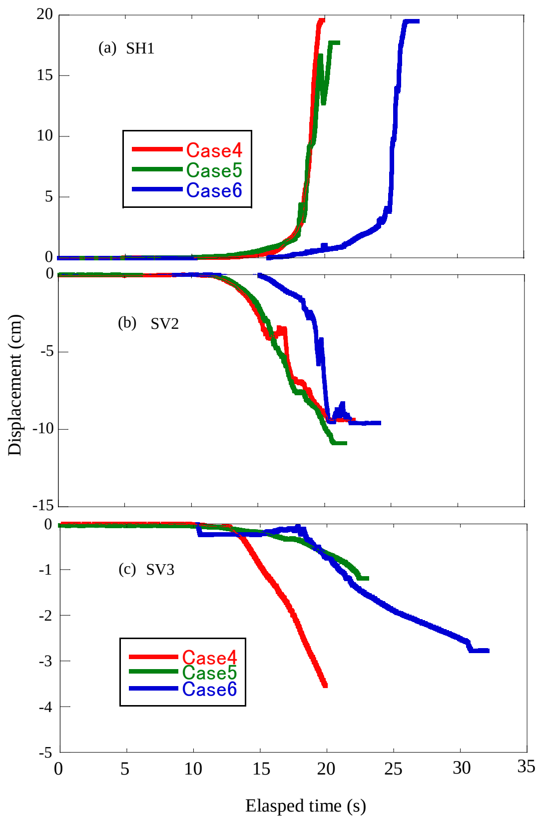

Fig.11 Displacements after loading at (a) SH1, (b) SV2, and (c) SV3 (Cases 4-6)

3.3 Effect of the Soil Moisture Conditions on Seismic Slope Failure

Figure 12 plots the spatial distributions of the volumetric water content of soil before loading and Table 3 shows the maximum, minimum and average of volumetric water contents of soil before loading in Cases 1-6. Fig.13 shows a spatial distribution of difference from initial volumetric water content of soil. In Case 1 and 2, there were no large differences in the spatial distributions of the volumetric water content relative to the other cases (Fig. 12). The increments in the volumetric water content of the soil in lower layer were larger than those in the upper and middle layers. The difference between the initial volumetric water content of the soil and that before loading in Case 1 was larger than that in Case 4 (Fig.13). This indicated that the infiltrated soil water in the lower layer flowed to the outside of the slope with the longer rainfall duration in Case 4 compared with Case 1, leading to larger increments in the volumetric water content of soil in Case 4 than in Case 1.

Table 4 and 5 show the time required for collapse and the scale. Based on the characteristics of the collapse, we categorized the collapse into three stages based on visual observations: settlement of the crest, deformation of the top of the slope, and formation of a sliding surface during collapse. We measured the time required for each of the three stages to occur. Figure 14 shows the position of the sliding surface. The position of the sliding surface became deep when the volumetric water content of soil was low. The differences in the spatial distributions of the soil moisture affected the depth of the sliding surface. Full-scale collapse occurred with a small spatial distribution of soil moisture, and partial collapse occurred with a large spatial distribution of soil moisture. Although the volumetric water content of soil near the top of the slope was high in Cases 1 and 4, the volumetric water content of soil in Case 1 was higher than that in Case 4. The sediment moved about 25cm farther in Case 4 than in Case 1. The large collapse at the top of slope in Case 1 with the small spatial distribution of soil moisture resulted in the greater distance of sediment movement relative to Case 4. Consequently, the soil moisture distribution affected the failure configuration. As a result, the amount of displacement and distance of sediment movement increased, causing collapse in a shorter time after loading when the volumetric water content of soil was high.

4. CONCLUSION

We conducted a series of vibration loading experiments under different soil moisture conditions to examine the relationship between the volumetric water content of soil and seismic stability.

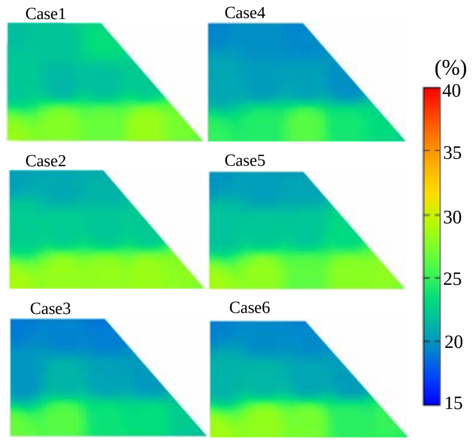

Fig.12 Spatial distribution of the volumetric water content of soil before loading

Table 3 The volumetric water content of soil before loading in Cases 1-6

	Minimum (%)	Maximum (%)	Average (%)
Case1	17.7	26.0	21.2
Case2	16.9	26.0	21.3
Case3	15.0	23.4	17.9
Case4	15.5	23.4	18.2
Case5	16.4	25.7	20.8
Case6	15.5	25.7	19.3

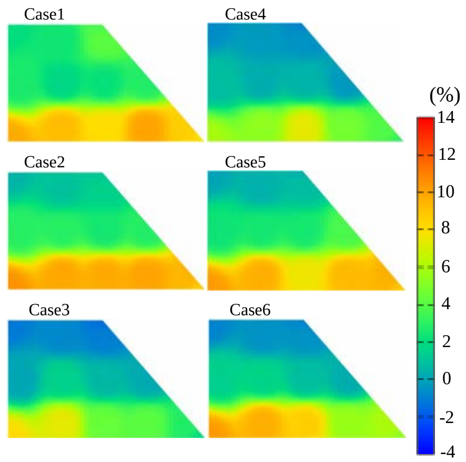

Fig.13 Spatial distribution of the difference between the initial volumetric water content of soil and that before loading

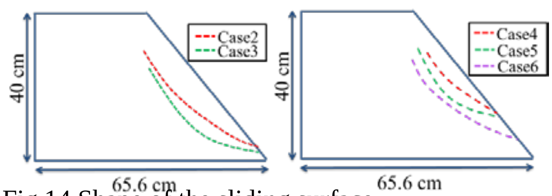

Fig.14 Shape of the sliding surface

Table 4 Time required for collapse and scale for cases involving small rainfall amounts

	Case1	Case2	Case3
Rainfall amounts	30mm (30mm/hr×1hr)		
Elapsed time after rainfall	no time	1hour	1day
Time required for settlement of crest	10s	13s	14s
Time required for collapse of top of slope	12s	15s	16s
Time required for sliding failure	no sliding failure	17s	18s
Distance of sediment movement	46.9cm	42.4cm	32.8cm

Table 5 Time required for collapse and scale for cases involving large rainfall amounts

	Case4	Case5	Case6
Rainfall amounts	30mm (30mm/hr×3hr)		
Elapsed time after rainfall	no time	1hour	1day
Time required for settlement of crest	10s	12s	16s
Time required for collapse of top of slope	14s	14s	12s
Time required for sliding failure	16s	19s	23s
Distance of sediment movement	71.4cm	37.4cm	43.4cm

We confirmed that seismic stability was impaired with increasing volumetric water content of soil using the amount of displacement and the distance of sediment movement.This study demonstrated that the difference in the soil moisture distribution affected the scale of the slope failure. We found that the soil moisture distribution was a significant predictor of slope failure. However, it is important to consider drainage conditions, rainfall conditions, and earthquake scales to predict the occurrence of slope failure. A problem is to reproduce the collapse mechanism accurately through analysis. We must compare the result of analysis with failure configurations on a model slope and the amount of displacement to the examine reproducibility of any analytical model.

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