the model boundaries, which will cause disturbance. Therefore, the viscoelastic dynamic artificial boundary is adopted for the boundaries of the bottom, left, and right of the model, and other boundaries are set as the free boundary.

INFLUENCE OF RAINFALL DURATION ON SLOPE PORE WATER PRESSURE AND DEFORMATION

The influence of rainfall duration on pore water pressure: Take 20 mm/d moderate rain as the rainfall intensity. Rainfall time is taken as a single variable. Assuming that the rainfall and rainfall seepage continues, the simulation of pore water pressure and slope safety factor in each stag is carried out. In order to know more about the influence of rainfall duration on the pore water pressure, the slope monitoring sites are set up in different locations, thus the pore water pressure of different monitoring points can be obtained. The monitoring point locations are shown in Figure 4.

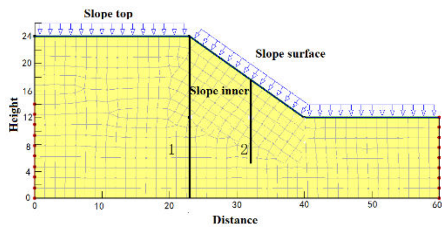


Figure 4. Monitoring points at different locations of slope

The Figures 5 and 6 show that under the condition of the constant rainfall intensity, the longer rainfall duration leads to the greater pore water pressure. In Figure 6, arch area at the middle-lower part of slope surface is found. The pore water pressure changes in a higher level, where the pore water pressure equipotential line appears inflection. The reasons is that the point was close to underground water level, and the underground water level in this region increased due to the rainfall, and the pore water pressure also increased.

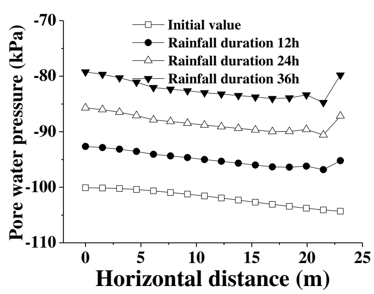


Figure 5. Influence of rainfall duration on pore water pressure on top of slope

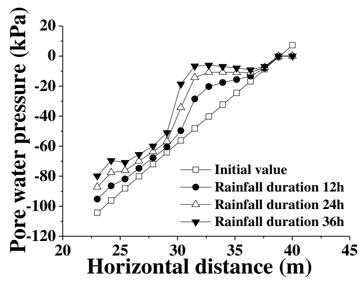


Figure 6. Influence of rainfall duration on pore water pressure on slope surface

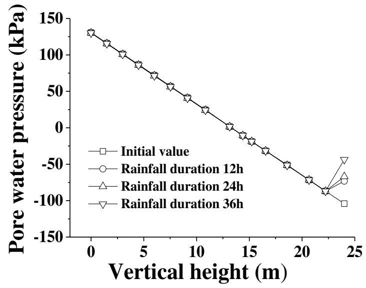


Figure 7. Pore water pressure of monitoring line 1

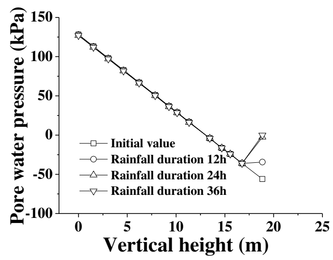


Figure 8. Pore water pressure of monitoring line 2

It is shown in Figures 7 and 8 that within the 36 hours of rainfall duration, because the increase of the depth of rainfall seepage was little, the soil water stress of the same depth had little change. Latter than 36 hours, because the outermost slope soil fully saturated, a water line is formed, while pore water pressure under the water line is still negative. The pore water pressure of slope surface position changed much more. There is a discount near the slope surface of lines 2 and 3.

The influence of rainfall duration on slope deformation: To analyze the influence of rainfall duration on the slope deformation, the horizontal displacements and vertical displacements of slope top, slope surface, and slope toe are calculated supposing the rainfall duration is 36 hours.

It is shown in Figures 9~14 that the longer of the rainfall duration is, the bigger of the slope deformation accumulation will be. And the vertical displacements of slope top, surface and bottom are larger than the horizontal displacement. At the slope top, with the increase of horizontal distance, the horizontal displacement increases at first and then decreases. The vertical displacement changed a little, and the displacement of central slope position becomes larger. At the slope surface, the horizontal displacement and vertical displacement increased with the increase of distance, and the rate reaches 50% and 75%. At the slope bottom, with the increase of horizontal distance, the horizontal displacement decreased, but the change of vertical displacement is not obvious. The maximum of horizontal and vertical displacement are in the slope toe position, which is the position of the slope that can be most easily damaged.

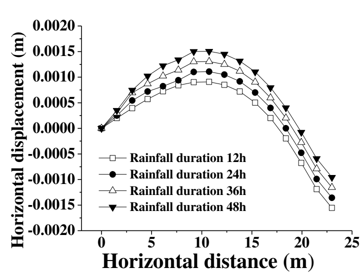


Figure 9. Influence of rainfall duration on horizontal displacement of slope top

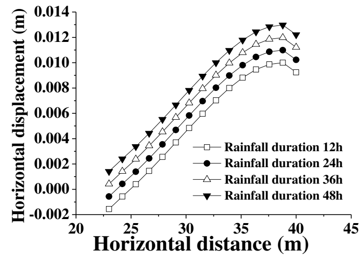


Figure 10. Influence of rainfall duration on horizontal displacement of slope surface

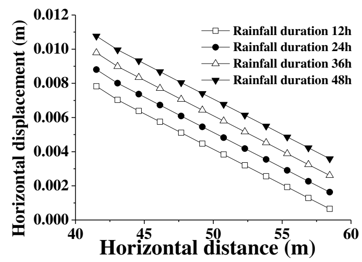


Figure 11. Influence of rainfall duration on horizontal displacement of slope toe

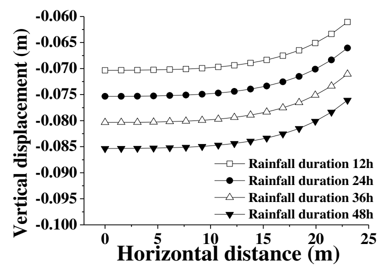


Figure 12. Influence of rainfall duration on vertical displacement of slope top

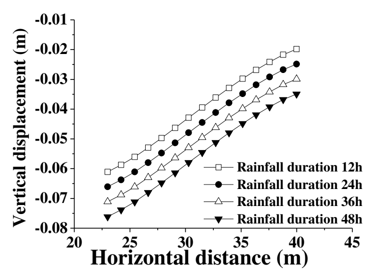


Figure 13. Influence of rainfall duration on vertical displacement of slope surface

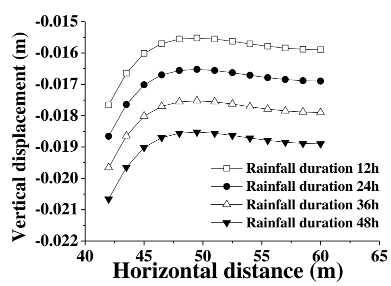
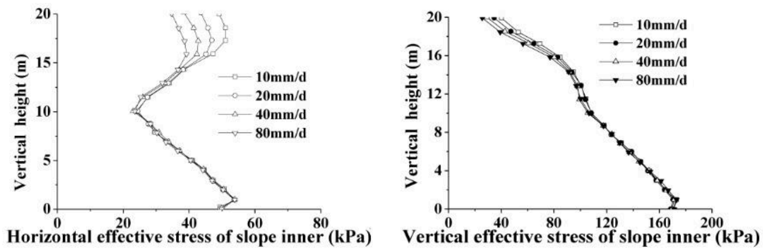


Figure 14. Influence of rainfall duration on vertical displacement of slope toe

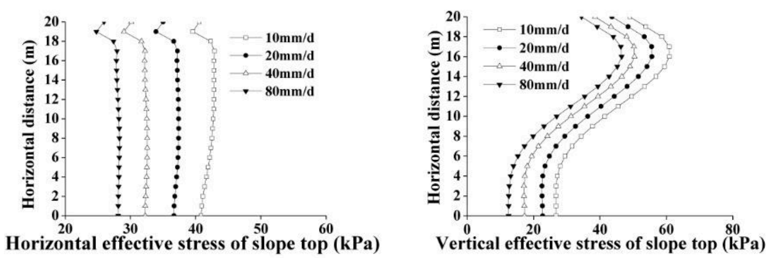
INFLUENCE OF RAINFALL INTENSITY ON STRESS AND DISPLACEMENT OF SLOPE

Influence of rainfall intensity on slope stress: In order to analyze the influence of rainfall intensity on slope effective stress, rainfall intensity of 10mm/d, 20mm/d, 60mm/d and 80mm/d are considered and then the horizontal and vertical effective stress at different positions of slope are calculated. The results are shown in Figures 15~17.



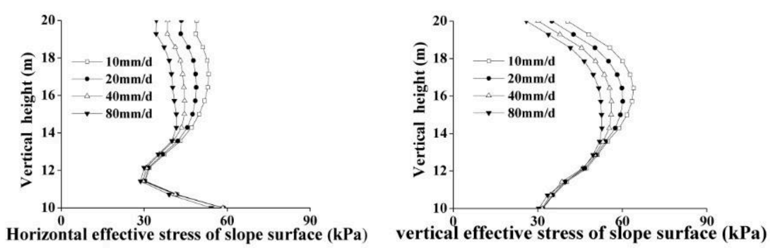
(a) Horizontal effective stress (b) Vertical effective stress

Figure 15. Effective stress of slope inner



(a) Horizontal effective stress (b) Vertical effective stress

Figure 16. Effective stress of slope top

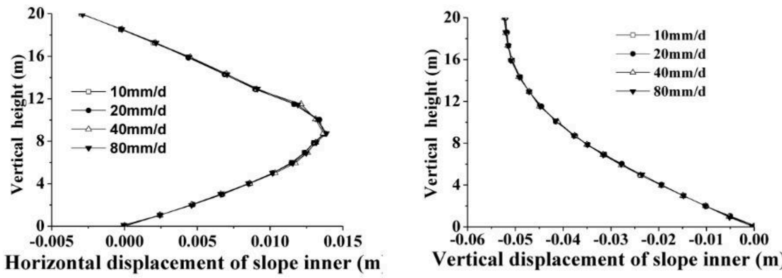


(a) Horizontal effective stress (b) Vertical effective stress

Figure 17. Effective stress of slope surface

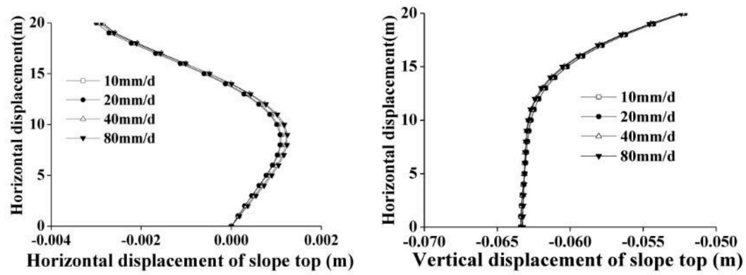
It can be seen in Figures 15~17 that the rainfall intensity effect to effective stress of slope is less than the effect of groundwater rising when the rainfall intensity increases from 10mm/d to 80mm/d. The horizontal and vertical effective stress decreases with the increase of rainfall intensity and it is shown that pore water pressure in the slope increases and the corresponding effective stress decreases with the increase of rainfall intensity. With the increase of the height of slope, the horizontal effective stresses of inner and surface of slope increase and the vertical effective stress decreases. The horizontal and vertical effective stresses of the slope top increase with the increase of the horizontal distance.

Influence of rainfall intensity on slope displacement: In order to analyze the effect of rainfall intensity on slope displacement, rainfall intensity of 10mm/d, 20mm/d, 60mm/d and 80mm/d are considered, and the horizontal and vertical displacements of slope are calculated. The results are shown in Figures 18~20.



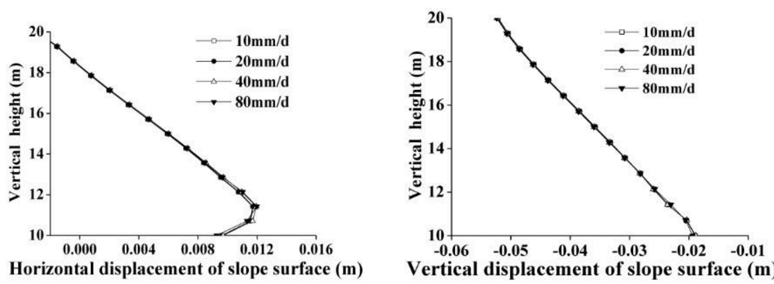
(a) Horizontal displacement (b) Vertical displacement

Figure 18. Displacement of slope inner



(a) Horizontal displacement (b) Vertical displacement

Figure 19. Displacement of slope top



(a) Horizontal displacement (b) Vertical displacement

Figure 20. Displacement of slope surface

It can be seen in Figures 18 and 19 that the rainfall intensity effect to displacement of slope is not obvious, and it is less than effect of the rising of groundwater level, when the rainfall intensity increases from 10mm/d to 80mm/d. The horizontal displacement increases at first and then decreases, with the increase of rainfall intensity. It shows that a large deformation occurs at the slope toe and the vertical displacement increases. In addition, according to the change of the horizontal displacement of the slope surface along the vertical height, it can be seen that a mutation of the horizontal displacement occurs at slope toe and then the horizontal displacement decreases gradually. It shows that the larger horizontal displacement occurs at slope toe which is the position should be concerned about mostly. And the vertical displacement increases along the vertical height.

INFLUENCE OF RAINFALL ON SLOPE SAFETY FACTOR

To analyze the effect of rainfall seepage to slope safety factor, the rainfall of 20mm/d (medium rain) is added to the condition of groundwater seepage. The slope surface is taken as the seepage boundary. When the rainfall intensity is lower than the permeability of surface soil, the flow boundary is taken as the seepage boundary. The slope safety factors under different conditions are shown in Table 1.

Table 1. Safety factors of slope under different water conditions

Cases	No groundwater	No rainfall	Rainfall intensity 20mm/d
Safety factor	1.837	1.776	1.769

In general, the safety factors will be reduced under the cases with water. When the groundwater or rainfall seepage reaches the dangerous section of landslide, the safety factors will be decreased significantly.

The slope safety factors under the cases of the same rainfall intensity (20 mm/d) and different rainfall duration are shown in Figure 21.

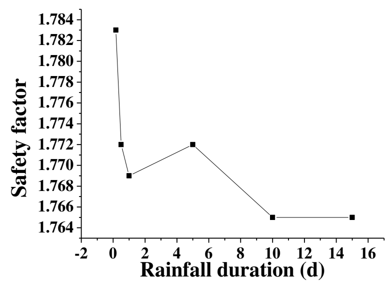


Figure 21. Effect of rainfall duration to slope safety factor

It can be seen in Figure 21 that the longer of rainfall duration is, the more effect to the slope will be, when the rainfall intensity is keep in constant. Due to the different soil materials within the range of 10d, the rainfall duration becomes larger when the slope safety factor becomes smaller. The significant effect of the rainfall seepage to the unsaturated area shows that the seepage will make the pore water pressure of unsaturated area increase and the soil effective stress reduce which causes the decrease of shear strength. And that is the main reason of the reduction of safety factor. Rainfall seepage enlarge the change of pore water pressure as time gose by, and the seepage will arrive at the weak plane of slope under the continuous rainfall of 3d to 10d. In this case, the slope is in the most dangerous situation and the calculated value of safety factor is the minimum, which also provides the reasonable explanation for the lag of landslide.

Based on the finite element simulation, the influence of different rainfall intensity and rainfall duration on the safety factor of slope is analyzed and the results are shown in Table 2.

Table 2 shows that when the rainfall intensity is less than the infiltration capacity of the soil and rainfall infiltrated completely, the rainfall intensity has a significant influence on the slope safety factor. With the same rainfall duration, the safety factor of slope stability decreases with the increase of rainfall intensity, and it has adverse influence on the stability of slope.

Table 2. Effect of rainfall intensity on safety factor of slope

Rainfall intensity mm/d	Rainfall duration/d	Safety factor
10	10	1.285
20	10	1.284
40	10	1.280
80	10	1.274

CONCLUSION

Based on the analysis of sandy slope under different rainfall intensity and duration. Study the influence of different rainfall intensity and duration on the slope displacement, pore water pressure, stress and safe factor. The conclusions can be drawn as follow:

(1) The slope pore water pressure shows the trend of increase overall when the rainfall duration increases. And the pore water pressure appear inflection at slope surface. The vertical displacements Slope top, surface and bottom are greater than the horizontal displacement. The maximum of horizontal displacement and vertical displacement are in the slope toe position.

(2) With the increase of rainfall intensity, the horizontal and vertical effective stresses of slope decrease. And with the increase of slope height, the horizontal effective stresses of slope inner and surface increase, while the vertical effective stress presents the trend of decrease. At the slope top, with the increase of X coordinate, the horizontal effective stress and vertical effective stress increase.

(3) With the increase of rainfall intensity, vertical displacement in the slope increases gradually. Horizontal displacement along with the increase of slope height shows a trend of increase at first and then decreases, the deformation at slope foot is larger, and then decreases while the slope height increases.

(4) The rainfall intensity and duration all can reduce the safe factor of slope. When the 3~10 days rainfall reaches the slope weak surface, the safe factor becomes minimum, and the slope is in the most dangerous stage. With the same rainfall duration, the safety factor of slope stability decreases with the increase of rainfall intensity.

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Shaking Table Tests on a Deformation Mitigation Method for Road Embankment during Liquefaction by Using Gravel and Geosynthetics

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ABSTRACT

Small scale shaking table tests in a 1-g gravity field were carried out to evaluate the effectiveness of deformation mitigation method for road embankment during liquefaction by using gyosynthetics sandwiched between gravel. The gravel layer could dissipate the excess pore water pressure during liquefaction immediately, and restrained the shear deformation under the embankment because of its high permeability. Furthermore, the composite layer which consisted of the gravel with geosynthetics could perform as a rigid plate with high permeability. As a result, the improved layer could restrain the deformation of embankment, and this effect could keep shape of embankment.

INTRODUCTION

A settlement and deformation of road embankment was occurred due to soil liquefaction during earthquake. Because it brings a serious damage such as cracks and gap of road surface, even emergency vehicles could not pass the road after the earthquake. Photo 1 shows an example of road embankment damage during 2007 Noto-peninsula earthquake in Japan. It was considered that the damage was caused by liquefaction because the embankment consisted of loose consolidated sandy soil deposit with high water level. Ambulances and restoration work cars could not run through this road after earthquake.

A liquefaction countermeasure technique for embankment by using geosynthetics sandwiched between gravel had been proposed (Murakami et al., 2010). Because the gravel has high permeability, it will be able to dissipate excess pore water pressure rapidly. Furthermore, because the geosynthetics has high-tension strength, the gravel layer with it will have high resistance against bending deformation due to overburden load of embankment. This method does not restrain the occurrence of liquefaction completely but mitigate the excessive deformation such as settlement and lateral movement. Its performance requirement is to secure a passable road for emergency car and repair the road rapidly just after earthquake.

It had been confirmed that this method has effectiveness for countermeasure against soil liquefaction by a centrifuge model shaking test and numerical analysis (Murakami et al., 2010). However, since it was difficult to evaluate the permeability under a similarity rule in the centrifuge model test, a qualitative investigation in a 1-g gravity field was required. Therefore, shaking table tests were conducted in a 1-g gravity field in order to evaluate the effectiveness of this method during earthquake in this study.

Photo 1. Damage of road embankment during 2007 Noto-peninsula earthquake.

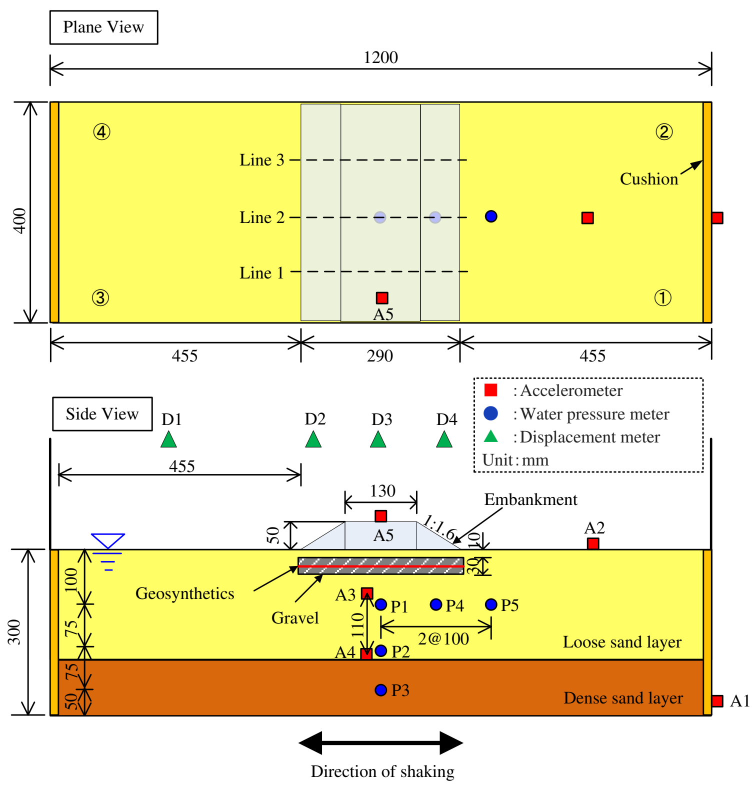

Figure 1. General view of model ground.

TEST PROCEDURE

Figure 1 illustrates a cross section of top and side view of a model ground with a location of transducers. The model ground was set up in a rigid acrylic container whose size is 1200 mm long, 400 mm wide and 500 mm high. Liquefiable loose sand layer was formed under water by pouring silica sand No.7 (ρ=2.66g/cm^3, D_{50}=0.17mm, k=4.79x10^{-3}cm) through 2mm sieve to reduce the dropping velocity and to maintain it in the loosest state as possible. The relative