Seismic behavior of model embankment affected by seepage water and frozen surface

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ABSTRACT

The 2011 off the Pacific coast of Tohoku Earthquake occurred on March 11. When the earthquake occurred, there were a number of frozen subsurface zones in cold districts, such as Hokkaido. However, any experimentally-verified case of deformation and collapse modes of embankment was not available in respect to the seismic performance of a frozen embankment. This study examined the earthquake resistance of embankment in cold districts by providing shake to a model embankment on which the surface layer had been frozen after adding seepage water. Additionally, a similar experiment was conducted for a model embankment on which the surface had not been frozen.

Keywords: seismic behavior, embankment, frozen surface

1 INTRODUCTION

In the Mid Niigata Prefecture Earthquake in 2004, it was reported that the strength of the soil was decreased due to the raised degree of saturation in the embankment caused by the rainfall immediately before the earthquake occurrence, and that the extent of the damage in the embankment became larger because the seismic ground motion was applied to the soil under such conditions (Matsumaru et al. 2006). For this reason, the more study examples with the aim of examining the influence of the water level appearing in the embankment and the rainfall history on the earthquake resistance have been conducted (e.g. Kawajiri et al. 2014, Matsumaru et al. 2014). Additionally, Cases where the valley fill ground collapses by the raised water level in the embankment along with the increased snowmelt water at the early spring were reported in the snowy cold regions. Moreover, the 2011 off the Pacific coast of Tohoku Earthquake occurred on March 11, and if this had occurred in a cold region like Hokkaido, Japan, a lot of frozen zones in the ground would have been formed.

In addition, after March, the decrease in earthquake resistance would be expected by the raised water level in the embankment due to the increased snowmelt water. The analytical results of studies concerning the vibrational property under an actual travelling train about the seismic performance of such frozen embankments have been reported (Chen et al. 2014). However, there was no study example that experimentally examined the deformation and the collapse of the embankment with the focus on dynamic behaviors including the pore water pressures. In this study, the earthquake resistance of the embankment in the cold region was examined by exciting the model embankment on which the surface had been frozen after adding seepage water. The qualitative influence of the presence of freezing condition on the dynamic behavior of the embankment when shaking is applied was examined.

2 TEST PROCEDURE

2.1 Test soil and model embankment

In this study, the sample that mixed the Toyoura sand and the Fujinomori clay at a rate of 8.5:1.5 in the weight ratio was used. Figure 1 shows the grain size distribution.
distribution of the soil sample. Figure 2 shows the compaction curve.

Figure 3 shows the general description of the model embankment used for this experiment. The model embankment was prepared in the earth tank of 550 mm (length) × 300 mm (height) × 150 mm (width). First of all, the supporting stratum of 25 mm in height was prepared. Afterwards, the embankment with the 1:1.5 slope gradient and 200 mm in height was prepared on the supporting stratum. The degrees of compaction, $D_c$, were set to $D_c = 90\%$ and $D_c = 75\%$ for the supporting stratum and the embankment part, respectively. The layer thickness of embankment part was set to be 25 mm and compaction was applied until the prescribed embankment height was reached. $D_c = 90\%$ was set for the supporting stratum so as not to cause the subsidence or the liquefaction by the shaking. Moreover, $D_c = 75\%$ was set for the model embankment to reproduce the actual low density embankment condition. The optimum water content, $w_{opt}$ was set to be the target for the water content, $w$.

The embankment condition can be observed because the front side of the earth tank used for the transparent acrylic. Water was poured to maintain the water level, $h_w$ of 50 mm in the embankment model. In addition, to prevent the deformation of the toe of slope by the seepage water, the gravel of about 10 mm diameter was placed along the toe of slope. The measurement items included the pore water pressure in the embankment and the vertical displacement at the top of slope.

### 2.2 Test cases

The experiments were conducted under two cases of different surface freezing conditions of the embankment. The surface of the embankment was not frozen in Case 1. The shaking was applied after confirming that the prescribed water level was established by providing the seepage water. In Case 2, the embankment surface was frozen by a freezing spray after confirming that the prescribed water level was established. Afterwards, the shaking was applied. Shaking of the sinusoidal wave of 5Hz, 20 waves was applied with the inputted acceleration, $g_s$ which was increased in 100 gal incremental steps from 300 gal. This shaking was continued until the embankment collapsed.

### 3 RESULT AND DISCUSSION

Figure 4 shows the water level condition in the embankment before the shaking. The water level was calculated from the water pressure that had been obtained from the pore water pressure gauge. The difference of the water level condition between Case 1 and Case 2 was small. Because the water level is lower than the position of PW03, it is considered that the effect to the behavior of the excess pore water pressure during shaking is slight. Moreover, in either of the experiment cases, the occurrence of deformation and/or cracks in the model embankment before the shaking could not be found. Based on this, it was judged that the water level of the model embankment had simulated the seepage water condition acting always from the back of the embankment.

Figure 5 shows the conditions of the models of embankment inputted acceleration applied in Case 1 and Case 2. The targets are placed in the model embankment at intervals of 25 mm in a reticular pattern.
At 600 gal in Case 1, cracking occurred in the vicinity of the center of the face of slope. In addition, the deformation of the circular slip type from the toe of slope part to the top of slope occurred. At 700 gal, the deformation from the toe of slope part was extended, and a large-scale collapse occurred. The large quantity of water gushed out from the toe of slope part as shown in Figure 6 at the end of shaking. On the other hand, a small-scale sliding failure occurred in the vicinity of the top of slope at 500 gal in Case 2. At 600 gal, the deformation of the embankment progressed in the part above the embankment height, H of about 100 mm, and a large-scale collapse occurred at 700 gal. However, the mode at the occurrence of the deformation is different from that observed in Case 1. The deformation was

Fig. 5. Photograph of embankment after shaking (a) Case1, b)Case2)

Fig. 6. Photograph of toe of slope after shaking in Case1
hardly identified in the toe of slope. Based on this, the deformation and the collapse behaviors when the shaking is applied varies considerably depending on the freezing condition of the embankment surface part.

Figure 7 shows the comparison of the relationship between the inputted acceleration at the shaking step and the vertical settlement at the top of slope. The vertical settlements for both Case 1 and Case2 started to increase at 500 gal. The settlement in Case2 progressed significantly at 600 gal to become about 4 times as large as that in Case1. However, as previously noted, the notable deformation at the toe of slope of the embankment could not be observed. The deformation in Case2 occurred only in the upper part of the embankment, and it can be indicated that a deformation larger than that in Case1 occurred at the top of slope.

Next, the difference of the deformation and the collapse modes depending on the freezing conditions of the embankment surface is discussed from the viewpoint of the pore water pressure behaviors during the shaking. Figure 8 shows the changes of the pore water pressure and the vertical displacement under the shaking in the embankment. The displacement increment in the vertical direction and the pore water pressure increment in the figure are incremental values by assuming the value in each shaking step before the shaking to be zero. The displacement in vertically downward direction is considered as positive (+) value. Here, our attention was focused on behaviors during the shaking at gs of 500 gal, 600 gal, and 700 gal when clear deformations and collapses in Case 1 and Case 2 were observed. For the change in the pore water pressure increment in Case1, the pore water pressure occurred at 500 gal in the toe of slope (PW01). At 600 gal, increases of pore water pressure in PW01 and PW02 are clear. At 700 gal, the pore water pressure occurring when the shaking was applied is even a larger value. The vertical displacement was increased in concordance with the rise of pore water pressure. Based on this, it is inferred that the progress of deformation of the embankment associated with the shaking is caused by the decreased effective stress accompanied by the increased pore water pressure. As for PW03, the pore water pressure during the shaking of 600 gal had not been increased because the location of the pore pressure meter installed was above the water level in the embankment. However, it is thought that, at 700 gal, some amount of pore water pressure increase was generated due to the changed location of the pore pressure meter caused by the deformation accompanied by the shaking, and due to the influence of increased water content around the pore water pressure meter which was caused by the capillary negative pressure increased with the increase in density because of the deformation.

Some amount of pore water pressure increase occurred in PW01, PW02, and PW03 at 500 gal in Case 2. A small sliding collapse occurred at 500 gal. However, any significant pore water pressure increase could not be observed. Based on this, it is thought that the plasticization by the shaking has more influence on this small collapse than that caused by the pore water pressure increase. Moreover, it is thought that a clear sliding did not occur because it became dilation behavior in Case 1 due to the small density of the embankment at the occurrence of the soil element shearing accompanied by the shaking. However, it is thought that a clear sliding failure was observed because brittle and contraction behaviors occurred at the shearing since the condition similar to overconsolidation existed by freezing in Case 2 where the freezing condition was provided.

Next, at 600 gal in Case 2, the top of slope displacement of ten times or more as large as one occurred at 500 gal had occurred. While the pore water pressure increases observed for PW01 and PW02 were mild, the pore water pressure increase observed for PW03 was significant. This trend observed in the pore water pressure was similarly seen at 700 gal. Although the accurate amount of displacement cannot be examined because the vertical displacement sensor reading was in range-over, based on the collapse situation as shown on Figure 5b), it can be expected that the deformation was advanced by the shaking from 600 gal to 700 gal. The location of the pore pressure gauge installed for PW03 that showed upward trend of pore water pressure is roughly corresponding to the location of the deformation occurred in the upper part of the embankment (refer to 600 gal in Figure 5b)). Based on this, it is thought that the increase of the pore water pressure at PW03 had an effect on the deformation and the collapse of the embankment which was in the state of freezing.

Here, the reasons why the pore water pressure was increased in the upper part of embankment when the embankment surface was in state of freezing are
thought to be the following two points; 1) the effect in which the increased capillary negative pressure due to the volume change associated with the repetitive loading applied by the shaking resulted in the move of water to the upper part of the embankment and 2) the fact that because the embankment crown part was not in

![Fig. 8. Time histories of pore water pressure and displacement (a) Case1, b)Case2)](image-url)
state of freezing, the embankment crown part had better ventilation and passing water characteristics than the embankment surface which was in state of freezing. Therefore, the pore water pressure generated by the shaking was in the state that could be spread easily to the area near the embankment crown in the upper part of the embankment, and this effect created the condition where the water content could be moved more easily to the upper part of the embankment. It is thought that this caused the generation of the pore water pressure. Based on the results above, it is thought that the freezing condition of the embankment surface would have an effect on the deformation and the collapse modes associated with the strength characteristic change, and on the pore water pressure behaviors due to the changes in boundary conditions such as ventilation and passing water characteristics in embankment surface.

4 CONCLUSIONS

In this study, the shaking experiment of the model embankment was conducted to examine how the presence of freezing condition in the ground surface of the embankment where the seepage water was provided from the back side had an effect on the behavior during the shaking. The findings obtained in this study are summarized as follows.

The deformation and the collapse modes of the embankment during the shaking varied depending on the presence of freezing condition in the embankment surface. When the embankment surface was not frozen, the circular slide from the toe of slope to the top of slope occurred. On the other hand, when the embankment surface was frozen, the amount of the deformation in the toe of slope part was small, and the sliding failure occurred in the upper part of the embankment. Moreover, the amount of vertical settlement in the top of slope part along with the increase of the vibration acceleration was larger in freezing condition than in non-freezing condition. Based on this, it became clear that not only the modes of the deformation and the collapse but also the deformation magnitude vary depending on the presence of freezing condition in the embankment surface.

It was inferred that the reason why the deformation and collapse modes in the embankment surface vary depending on the presence of freezing condition was because the behaviors of the pore water pressure increased under shaking may vary. The pore water pressure was increased in the boundary part of the bearing ground and the embankment part when the embankment surface was not frozen, and the deformation progressed from the toe of slope part due to the decreased effective stress. On the other hand, the pore water pressure was increased in the embankment hillside part under the freezing condition, and the increasing trend of pore water pressure and the increasing trend of the settlement amount in the top of slope part concurred with each other. Such difference in the pore water pressure behaviors may have been caused by the changes in the boundary condition in the embankment surface including ventilation and passing water characteristics associated with freezing and non-freezing conditions.

REFERENCES

1) Chen, T., Ma, W., Wu, Z. J. and Mu, Y. H. (2014): Characteristics of dynamic response of the active layer beneath embankment in permafrost regions along the Qinghai–Tibet Railroad, Cold Regions Science and Technology, 98, 1-7, 10.1016/j.coldregions.2013.10.004.
2) Kawajiri, S., Nunokawa, O., Ito, Y., Nishida, M., Matsumaru, T., Kawaguchi, T., Ota, N. and Sugiyama, T. (2014): Experimental study of embankment collapse mechanism due to rainfall after earthquake, Japanese Geotechnical Journal, 9(2), 153-168, DOI: 10.3208/jgs.9.153 (in Japanese).
3) Matsumaru, T., Ishizuka, M., Tateyama, M., Kojima, K., Watanabe, K. and Shinoda, M. (2006): Outline of damages and rainfall infiltration analysis for the railway embankment seriously damaged in the 2004 Niigata-ken Chuetsu earthquake, Geosynthetics Engineering Journal, 21, 187-194 (in Japanese).
4) Matsumaru, T., Kojima, K. and Tateyama, M. (2014): Fundamental research about seismic behavior of embankment affected by seepage water, Journal of Japan Society of Civil Engineers, Ser. C (Geosphere Engineering), 70(1), 135-149, DOI: 10.2208/jjcsejgc.70.135 (in Japanese).