Experimental Study on Seismic Collapse of Road Embankment considering Infiltration of Water and Condition of Compaction

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SUMMARY:
A large earthquake hit the Noto area in 2007 and after that cracks were found along the embankments of toll roads so that part of the road was closed to traffic. By previous studies it was find that the reason of embankment collapse when earthquakes happen is because of water penetration into the embankment. However, relation between the condition of compaction and collapse of the embankment is not known. In this study, we will consider the condition of compaction and the infiltration of water into the embankment as a parameter, and we will find out that which parameter have the largest effect on the intensity of the embankment collapse, from experiment. So, the purpose of this study is to find out the economical and effective countermeasure about the parameter that we should notice, when we want to resist the embankment against earthquake.

Keywords: Embankment collapse, compaction, infiltration of water, vibration model experiment

1. INTRODUCTION

Japan is one of the countries that are attacked frequently by strong earthquakes. A lot of civil engineering structures have been damaged by them. For example, road embankment is the long-distance structure. If this structure collapses over a long distance, it loses the function as a civil infrastructure because restoring the road embankment takes time. On March 25, 2007, a large earthquake hit the Noto area and after that cracks were found along the embankments of toll roads so that part of the road was closed to traffic. In addition, on August 11, 2008, a large earthquake hit the Tokai area and a road embankment of the Tomei Expressway collapsed on a large scale. Most of these earthquake-stricken embankments were built by reclaiming the valley land form collecting water. So, it is pointed out that embankment had collapsed because of water penetration.

It has been studied to increase embankments resistant to earthquakes through various vibration model experiments in past times. According to these studies, it has been reported that embankments lose stability to a large extent owing to the effects of those wet surface, and that the scale of settling and collapse expands when water level in embankment rises. Therefore, it is determined that the infiltration of water into the embankment is very closely related to the collapse. However, relation between the condition of soil compaction and collapse of the embankment is not known in foregoing studies. Soil compaction in the construction of an embankment takes the role of depression of water permeability and of the intensity increase in embankment. Therefore, it is thought that earthquake safety of embankments is affected by the infiltration of water into the embankment and the condition of soil compaction. In this study, we will pay attention to the infiltration of water into the embankment and to the condition of soil compaction as parameters that have effects on the collapse of the embankment, and we will carry out vibration model experiments of 1/60 scale in 1G gravitational field. And from experiment we will find out that which parameter has the largest effect on the intensity of the embankment collapse. Therefore, the purpose of this study is to find out the economical and effective countermeasure about the parameter that we should notice—when we want to increase the resistance of embankment to earthquake.

2. EXAMPLES OF DAMADE TO EMBANKMENT

On March 25, 2007, the 6.9-magnitude earthquake hit Noto Peninsula. The seismic center of the earthquake was about 11km underneath in the waters off Noto Peninsula. 849gal of peak ground acceleration was measured at Togi, where is at a distance of about 23km from the epicenter. After this earthquake, 11 spots where embankments had collapsed and 40 spots where cracks had been generated on the road surface were found along the Noto toll roads. Therefore, the access was blocked from Yanagida interchange to Anamizu interchange. As an example of the embankment collapse, the carriageway area collapsed for about 30m in width at the north area of Yokota interchange. When we made an on-site survey in this embankment, we found that there was a relatively affluent mountain stream at a nearby site. From the aerial photography of this scene taken in 1975 when the Noto toll road had been built, we found that this collapsed embankment had been built by reclaiming the valley land form collecting water. As other instances, the enlarged embankment collapsed for about 70m in length at the ramp of the Yokota interchange (Fig. 1). Because the top of trees on the sliding soil mass has been facing over normal direction of slope, this collapse was the typical circular slide. In addition, the discharged sediment spread out for about 200m in length and the sediment had contained so much water that someone may get mired in it. We infer that water had stood in the embankment because it had rained before collapse.

Here’s another example. On August 11, 2008, the 6.5-magnitude earthquake hit the Tokai area. Its seismic center was in Suruga Bay, about 35km far from the coast, at a depth of about 23km. The peak ground acceleration was 519gal at Nishiizu, which is located about 25km from epicenter. After this earthquake, at the part of the road embankment near Makinohara service area on up line of the Tomei Expressway, the road shoulder containing the slope and the inside lane collapsed for about 40m in length. And then, this earthquake caused a lot of cracks in the passing lane of up line and the road surface of down line widely. When we saw a contour map of the geographical features where the embankment had collapsed, we found that this collapsed embankment had been built by reclaiming the valley land form collecting water. In addition, we can see that the discharged sediment had contained much moisture as can be seen in Fig. 1.

The above introduces two examples of seismic damage to embankments. We noticed a similarity that the discharged sediment had contained much moisture at the example of the collapse of embankment on the Noto toll road and at the Tomei Expressway. According to records, it had rained in the places where embankments had collapsed before the Noto Peninsula Earthquake and the earthquake centered in Suruga Bay. Therefore, we infer that collapsed embankments due to these earthquakes had contained much water in them. As we have seen throughout previous chapter and this chapter, we consider that condition of soil compaction and infiltration of water into embankments are factor affecting earthquake safety of embankments. In this study, we will pay attention to these factors as parameters that have effects on the collapse of the embankment, and we will carry out vibration model experiments.

Figure 1. Collapsed embankment at Yokota IC (left photo) and discharged sediment (right photo)

3. VIBRATION MODEL EXPERIMENTS

In this chapter, we will pay attention to the condition of soil compaction and the infiltration of water into embankments as parameters that have effects on the collapse of the embankment, and we will carry out vibration model experiments.

Last year, Mr. Karasawa who had belonged to our laboratory already carried out the vibration model experiments of 1/60 scale. In this experiment, he paid attention to the soil moisture content and water level that infiltrated into model embankment as parameters. When we carry out vibration model experiments, it is impossible to replicate and measure all real phenomena because model embankment differs in scale from actual-size embankments. Therefore, we decide the point to be focused. In our experiment, we will focus attention on acceleration, relative density, moisture content, water level that infiltrated into model embankment, infiltration direction of water, condition of soil compaction and visual behavior observation of model embankment. Then, we will carry out our experiment and consider the results including the experiment carried by Karasawa.

3.1. Experimental Methodology

We use an earth tank, of which inside dimension is 1000mm wide, 1800mm in length, and 600mm high. Then, we make a model embankment of 1/60 scale, of which dimension is 400mm wide at crown, 450mm high and slope with a gradient of 1:1.5. In this study, we make a model embankment by reference to the enlarged embankment built on hard ground which stands at the place where embankment collapsed called Tate-6. (It is located close to Toyota-colony of Nakajima-cho in Nanao city.) The material to use for experiments is cohesive soil which is collected at Tate-6. Its properties are shown in Table1. Fig. 2 shows the cross-section view of model embankment and location of acceleration.

Table 1. The Properties of Test Sample

maximum grain size(mm)	soil particle density(g/cm^3)	maximum dry density(g/cm^3)	optimum water content(%)
9.5	2.747	1.251	40.2

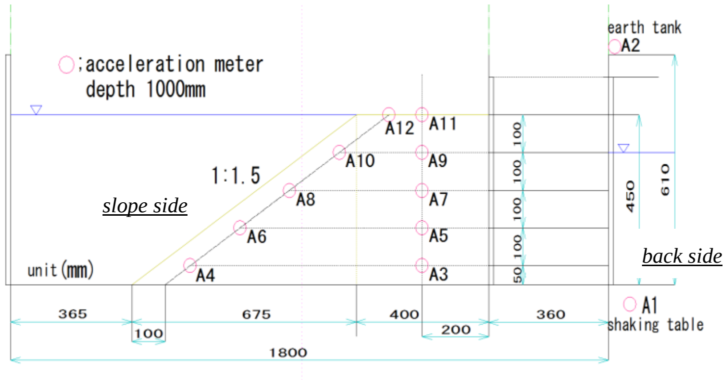

Figure2. The cross-section view and location of acceleration meter

3.2. The Result of Experiment Considering Water Content

Karasawa had carried out three patterns of vibration model experiments considering water content as a parameter, and had compared them. Experiment case and input acceleration when the model embankment collapsed are shown in Table2. In each case, he vibrated the compacted model embankment in which water content of soil was fixed. The input waveform was sinusoidal wave, and model embankment was vibrated for 30 seconds at its natural frequency, with 100gal amplitude.

At first, Karasawa carried out case 2 and case 3. Water contents of soil are different from each other. As a result, he found that model embankment of case 3 with 31% water content of soil easily collapsed than that of case 2 with 18%. This is because the higher water content of soil, suction between soil particles got lower, and the rigidity of model embankment decreased. In addition, he saw the soil of case 3 moving to the side of slope than that of case 2 prominently. The displacement vector of soil in each case is shown in Fig. 3. In the second chapter, we stated that the discharged sediment of collapsed embankments during earthquakes had contained much moisture. Therefore, we consider that those embankments had been in danger of collapse because the water content of soil had been extremely high as case 3 in this experiment.

Table 2. Experiment Cases

	water level(mm)	water content(%)	natural frequency(Hz)	input acceleration(gal)
case1		18	15	270
case2	300	18	17	250
case3	300	31	24	150

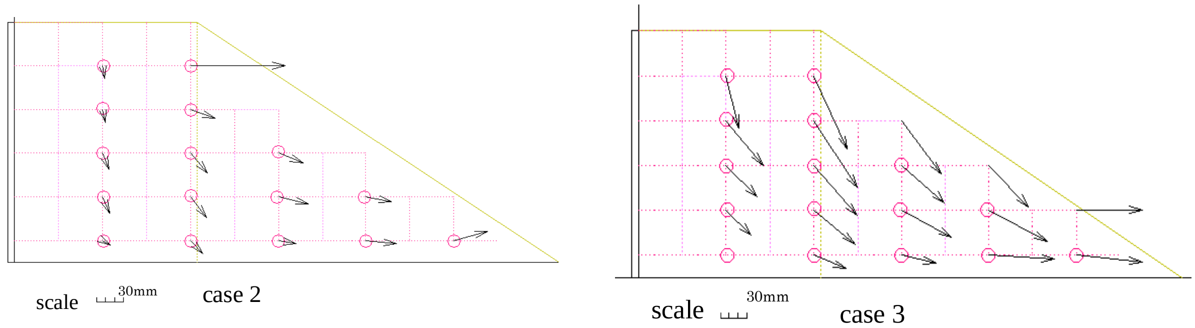

Figure 3. Displacement vector

3.3. The Result of Experiment Considering the Water Level Infiltrating into Model Embankment

Karasawa carried out three patterns of experiments considering water level that infiltrated into model embankment (It'll be written as 'water level' afterward.) as a parameter, and compared them. The experimental procedure is as explained in preceding section. Each experiment case and input acceleration when the model embankment collapsed are shown in Table3.

At first, Karasawa carried out case 2 and case 4. Their water level is different from each other. As a result, he found that model embankment of casa4 with 350mm high in water level easily collapsed than that of case 2 with 300mm high in water level. In addition, he found that at the higher water level, the soil of model embankment moved longer distance to the toe of slope. This is because the soil near crown of model embankment was pulled by the downside soil which had moved to the toe of slope in the area where water had penetrated. We infer from these experimental results that the higher the water level is, the greater the displacement of soil becomes. The displacement vector of soil in case 4 when model embankment collapsed is shown in Fig. 4.

Table 3. Experiment Cases

	water level(mm)	water content(%)	natural frequency(Hz)	input acceleration(gal)
case1		18	15	270
case2	300	18	17	250
case4	350	21	16	200

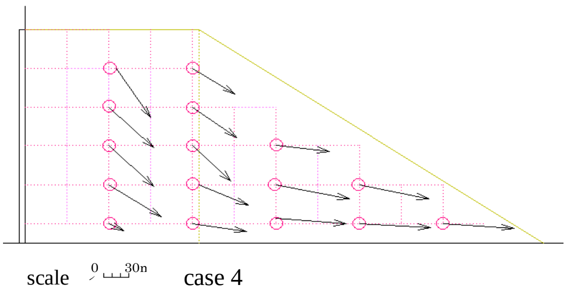

Figure4. Displacement vector

3.4. The Result of Experiment Considering Infiltration of Water and Condition of Soil Compaction

In this section, we discuss the result of experiment considering infiltration of water into model embankment and condition of soil compaction. In the experiments ranging from case 1 to case 4, Karasawa had adjusted the water content of soil, however he had not adjusted the condition of soil compaction. Therefore in the experiments ranging from case 5 to case 10, we adjust the air-dry degree of porosity of the model embankment to consider a parameter of the condition of soil compaction based on the quantitative index.

We compact the soil which is adjusted to optimum moisture content in advance at intervals of 5cm height (9 layers in all) to make a model embankment. In constructing model embankment, the method to regulate the quality of embankments in terms of the air-dry degree of porosity is used. In this method, if the air-dry degree of porosity of embankments lies within a defined area, the compacted soil is stable state. In case that embankments are made of cohesive soil, their air-dry degree of porosity have to lie between $2\% \leqq n \leqq 10\%$ (n;air-dry degree of porosity). Therefore, as a parameter of our experiments, we considered that 2% which is minimum air-dry of porosity in stipulated range corresponds to a case of strong compaction of soil and 10% which is maximum air-dry of porosity corresponds to a case of weaker compaction. After the model embankment is completed, we infiltrate water into model embankment from back side and from slope side separately. After water is infiltrated into model embankment fully, the model embankment is vibrated for 30 seconds at sinusoidal wave with 100gal amplitude. At the same time, we observe the movement of the model embankment and measure the acceleration. If the model embankment does not display cracks or collapse, we increase the input acceleration by 100gal and vibrate it in the same way. We carried out six patterns of these experiments. Each experiment case and input acceleration when the model embankment collapse are shown in Table 4.

Table 4. Experiment Cases

	frequency(Hz)	air-dry(%)	infiltrated water from__.	input acceleration(gal)
case5	20	10	not infiltrated	not collapse
case6	20	10	back side	700
case7	20	2	back side	1100
case8	20	2	slope side	not collapse
case9	20	10	slope side	900
case10	2	10	slope side	not collapse

At first, we carried out case 5. Case 5 was a pattern of weaker compaction of soil, and we did not infiltrate water into the model embankment. As a result, the model embankment did not display cracks or collapse, although we vibrated it at 1100gal which is output bound of vibration generator. According to damage examples of embankments that we said in the second chapter, the seismic external force was less than or equal to 1000gal. Therefore, we considered that we did not have to vibrate the model embankment at more than 1100gal. Then, we carried out case 7. Case 7 was a pattern of strong compaction of soil, and we infiltrated water into the model embankment from back side. As a result, the model embankment cracked near the back side, and collapsed in the small. When we saw the part of underneath crack, there was a cavity which had much water. Therefore, we consider that the model embankment displayed cracks because soil which had contained much water had sunk due to vibration and the bearing capacity had decreased. The amplification ratio and the state of collapse of case 7 after vibration are shown in Fig. 5. We can see that the response near the crown of model embankment is increasing at 7 seconds into vibration as can be seen Fig. 5. The model embankment cracked in 7 seconds, and its maximum breadth was about 24mm. The model embankment of case 7 collapsed due to infiltration of water in spite of the fact that we had been compacted the soil of case 7 more strongly than case 5. From this we could see that the infiltration of water into the embankment has larger effect on the intensity of the embankment collapse than the condition of soil compaction.

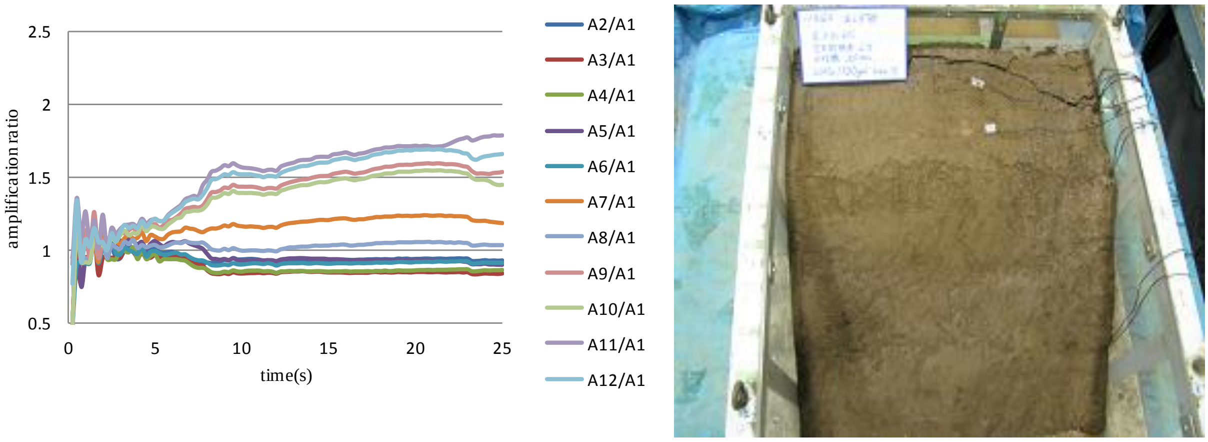

Figure 5. Amplification ratio and the state of collapse of case 7

3.5. The Result of Experiment Considering the Infiltrated Area of Water

In the preceding section, we could see that the infiltration of water into the embankment has large effect on the intensity of the embankment collapse. So in this section, we changed the infiltrated area of water in embankment to establish a relation between the infiltrated area and the collapse of embankment. As a way of experiment, we considered the case that we had infiltrated water into model embankment from back side and the case from slope side separately.

At first, we carried out case 6. Case 6 was a pattern of weaker compaction of soil, and we infiltrated water into the model embankment from back side. As a result, the model embankment cracked from toe of slope. Cracks arose up to seepage face in steps and the model embankment collapsed. We consider that bearing capacity of damaged part of model embankment decreased due to the collapse from toe of slope, and the collapse continued in the direction of top of slope in a way that soil was pulled down by self-weight. The amplification ratio and the state of collapse of case 6 after vibration are shown in Fig. 6. We can see that the amplification ratio is increasing since the vibration started as can be seen in Fig. 6. This is because as water infiltrated into the model embankment, the suction between soil particles got low, and the rigidity of model embankment declined. We infer from this experimental result that if we vibrate the model embankment again, the rigidity will decrease and the response will increase moreover. Then, we carried out case 9. Case 9 was a pattern of weaker compaction of soil, and we infiltrated water into the model embankment from slope side. As a result, the model embankment cracked near top of slope, where was estimated to be the seepage face. When we see the model embankment from side, cracks reached half its the height. The amplification ratio and the state of collapse of case 9 after vibration are shown in Fig. 7. We can see that the amplification ratio of model embankment is increasing at around 12 seconds, but after that, it overall is decreasing as can be seen in Fig. 7. We consider that since the model embankment cracked lengthways from top of slope downward, it became difficult for vibration to propagate in model embankment. The model embankment cracked when the amplification ratio peaked, and the maximum breadth of crack was about 10mm.

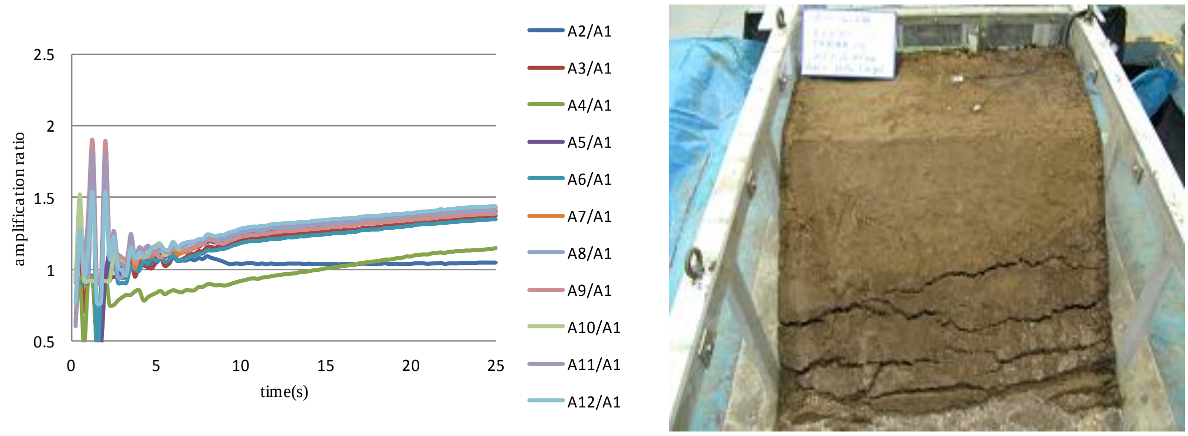

Figure 6. Amplification ratio and the state of collapse of case 6

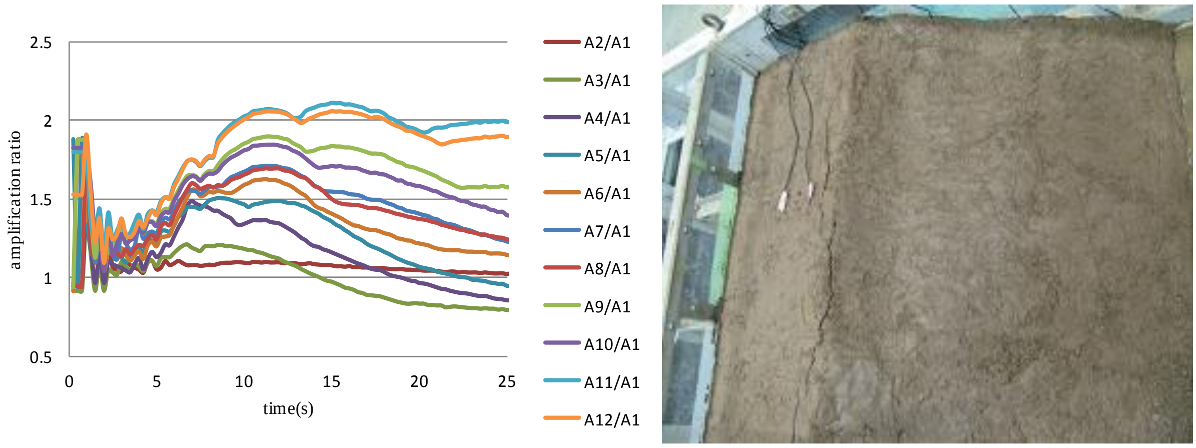

Figure 7. Amplification ratio and the state of collapse of case 9

Then, we made a comparison between case 6 and case 9. Case 6 was a pattern that we infiltrated water into the model embankment from back side. Case 9 was a pattern that we infiltrated water into the model embankment from slope side. When we vibrated case 6 at 700gal, it cracked from toe of slope and the collapse continued to half the height of the model embankment. On the other hand, when we vibrated case 9 at 900gal, it cracked near top of slope but the model embankment did not collapse. We made a comparison between case 7 and case 8 additionally. In case 7 that we infiltrated water from back side, it collapsed when we vibrated it at 1100gal. On the other hand, in case 8 that we infiltrated water from slope side, it did not crack or collapse. We infer from these experimental results that if saturated soil exists in embankment, it will collapse in a way that saturated soil can not bear the weight of unsaturated soil which is located on saturated soil because bearing capacity of saturated soil decreases. As the reason that there is a difference in experimental results between both cases that we infiltrated water from back side and slope side, we consider that there is a difference in self-weight of unsaturated soil between both cases which are located on saturated soil. In case that we infiltrated water from slope side, it is considered that self-weight of unsaturated soil which is located on saturated soil is more lightweight than self-weight of crown because saturated soil exists on slope side. So, we consider that a pattern that water infiltrate from slope side has lower effect on the intensity of embankment collapse than a pattern that water infiltrate from back side. We infer from these experimental results that if water infiltrates into actual embankment from ground due to rainfall and saturated soil exists at bottom of the back of embankment, the embankment is liable to collapse in earthquake. For this reason, we consider that it is important to drain water out from boundary with ground preferentially in order to prevent embankment from collapsing in earthquake. In these experiments, we designed slope with a gradient of 1:1.5. We consider that if we design slope of embankment with steeper gradient than these experiments, toe of slope will be subjected to larger load of unsaturated soil. In that case, we also require attention to drain water out from toe of slope.

4. CONCLUSIONS

In this study, we focused attention the infiltration of water into the embankment and the condition of soil compaction as parameters that had effects on the collapse of the embankment, and we carried out vibration model experiments in 1G gravitational field. Here are available results on experiment.

(1) An embankment cracks or collapses frequently at saturated soil and at seepage face due to vibration. One reason might be that as water infiltrates into the model embankment, the suction between soil particles gets low, and the rigidity of model embankment declines.
(2) After an embankment cracks, response at the head of damaged part or the part where loses the binding force of adjacent soil mass increases.
(3) The higher water content of soil or the higher water level makes an embankment be liable to collapse in earthquake.
(4) The infiltration of water into the embankment has larger effect on the intensity of the embankment collapse than the condition of soil compaction.
(5) A pattern that water infiltrates from back side has larger effect on the intensity of embankment collapse than a pattern that water infiltrates from slope side. It is important to put the finest focus on drainage and drain water out from boundary with ground preferentially in order to prevent embankment from collapsing in earthquake.

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