Disaster prevention measures for expressway embankment

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ABSTRACT

Expressway embankments have collapsed in many locations in Japan recently because of torrential rains and earthquakes striking the areas. Because the soil from collapsed embankments contains much water, we have assumed that penetrating rain and groundwater affected the embankments, in some way, and led to the collapse. To reinforce the slopes and prevent such disasters, we have dug slits where are excavated at the foot of the slope and filled with crushed stones to reduce the water content ratio of the slope. To verify the effectiveness of this measure, we have conducted the following two tests. First, we conducted laboratory tests, changing the water content ratio, to examine the changes in the strength characteristics of the embankment soil. This test confirmed that soil strength weakens as the water content increases, even if compaction of the soil remains the same. For the second test, we made a 1/50-scale model embankment and carried out large-scale dynamic centrifugal force loading tests to verify the reinforcement effects of this measure. The test confirmed that embankments reinforced with the drainage works held down deformation to half of that of embankments which were not reinforced.

Keywords: embankment, slope, water content, dynamic centrifugal force loading model test

1. INTRODUCTION

Expressway embankments (hereinafter embankments) have collapsed in many locations in Japan recently because of torrential rains and earthquakes striking the areas. Because the soil from collapsed embankments contains much water, we have assumed that the embankments were affected, in some way, by penetrating rain and groundwater, which led to slope failure. To prevent such disasters, we have reinforced slopes where high water content, such as welling of water, has been observed. This measure, called the “crushed-stone vertical drainage works i),” is designed to drain inflowing water from the embankment. In this paper, we will report on the effectiveness of the crushed-stone vertical drainage.

2 DISASTER CAUSED BY COLLAPSED EMBANKMENT

Figure 1 shows an embankment that has collapsed when the Great East Japan Earthquake struck Japan in 2011. The location is near the 92.4KP on the inbound lane on the Joban Expressway in the northeastern region of Japan. Around this area, the expressway has four lanes with each two lanes for the inbound and outbound traffic and is built on an embankment. The lay of the land is mostly flat, so a trapezoidal embankment built on a level ground continues for some distance. The embankment is a 9 meter high single-layer embankment. The embankment had been in-service for 27 years when the slope-failure disaster struck.

Fig. 1. Collapse disaster case of embankment

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As you can see in Figure 2, the overtake lane and hard-shoulder of the inbound lanes collapsed along the length of the expressway for about 110 meters and created a maximum level difference of about 2 meters. When we squeezed the soil from the collapsed embankment with our hands, water dripped out indicating high water content. Because there were no cut-and-fill borders, where water could penetrate, or groundwater source nearby, we assumed that rain entered the embankment through cracks or other defects in the pavement and drainage pipes crossing the road.

3 EFFECTS OF WATER PENETRATING EMBANKMENT

In order to find out how infiltrating water affects embankment strength, we collected soil from an embankment of an expressway in service, and conducted the following test using the sampled soil. The soil was collected from around the 92.4KP on the inbound lane of the Joban Expressway, where the embankment had collapsed by the 2011 Great East Japan Earthquake. The physical properties of the sample are shown in Table 1.

<table>
<thead>
<tr>
<th>Item</th>
<th>Physical properties</th>
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<tr>
<td>Soil grain density $\rho_s$</td>
<td>2.70 g/cm$^3$</td>
<td>Gravel 2mm or more</td>
<td>0.9 %</td>
</tr>
<tr>
<td>Natural water content ratio $w_n$</td>
<td>34.3 %</td>
<td>Sand 75mm or more</td>
<td>45.0 %</td>
</tr>
<tr>
<td>Plasticity index $I_p$</td>
<td>28.5</td>
<td>Silt 75 $\mu$m~5 $\mu$m</td>
<td>25.8 %</td>
</tr>
<tr>
<td>Stones 75mm or more</td>
<td>0.0%</td>
<td>Clay 5$\mu$m or under</td>
<td>28.3 %</td>
</tr>
</tbody>
</table>

Sixteen types of soil samples with different degrees of water content was made out of the collected soil by compacting the soil into 4 different degrees ($D_c=85, 90, 95, 100\%$) and giving each 4 different degrees of air space ratios ($V_a=5, 10, 15, 20\%$). We carried out the uniaxial compression test on them. The tests results are shown in Figure 3. In all density ratios ($D_c$), strength ($q_u$) lowered as the water content ($w$) increased. This tendency is stronger when the density ratio is higher. The collapsed embankment did not show signs of bulging (swelling) or sinking (contraction) until just before slope-failure. Therefore, we assumed that the compaction at the time of construction was maintained (density ratio remained steady) till just before the collapse. In other words, we assumed that although compaction remained the same, water entering the void in the embankment caused soil strength to lower.

4 EMBANKMENT REINFORCEMENT MEASURES BY DRAINING WATER

The crushed-stone vertical drainage has been constructed around the 92.4KP area on the inbound lane of the Joban Expressway to drain water and lower the water content ratio.

As described in Figure 4, slits were excavated in the slope at regular intervals, drainage pipes (perforated pipes) were placed in the slits and then the slits were filled with crushed stones (normally crusher-run stones C40-0). This works combine crushed-stone slits and basket frames to construct the reinforcement (Figure 5).
5 VERIFYING REINFORCEMENT EFFECTIVENESS BY DYNAMIC CENTRIFUGAL FORCE LOADING TESTS

In order to confirm the effectiveness of the crushed-stone vertical drainage on actual embankments, a 1/50 scale model of the embankment was used to carry out dynamic centrifugal force loading tests.

5.1 Test method

Three cases were tested as shown in Table 2. Figure 6 shows the shape of the model and the placements of various measuring instruments. Edosaki sand was used as the embankment material. The embankment was constructed so that the density ratio \((D_c)\) is about 82% of the maximum dry density \((\rho_{\text{dmax}})\) derived from mnemonic name B of JIS A 1210’s soil compaction testing method by stamping. Silica sand 4 was used as crushed-stones for the slits. As for the testing device, we used a large-scale centrifugal force loading device (effective radius of gyration: 6.6m), owned by the Public Works Research Institute.

In each test, centrifugal acceleration of 50G was applied, and then a metolose solution with 50 times the viscosity of water was seeped into the embankment through a pipe that leads from a water tank located in the hills behind the embankment. The water in the tank was kept at a constant level, and after 7 hours from the start of injection, excitation was applied. N-S waves observed at Chuo-ward, Kobe City, during the Hyogo-ken Nanbu Earthquake of 1995 were used for the excitation.

Table 2. Test cases

<table>
<thead>
<tr>
<th>Case</th>
<th>Measures</th>
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<tbody>
<tr>
<td>Case 1</td>
<td>No measures</td>
</tr>
<tr>
<td>Case 2</td>
<td>Basket frame</td>
</tr>
<tr>
<td>Case 3</td>
<td>Basket frame + Slit with crushed-stones</td>
</tr>
</tbody>
</table>

Figure 7 shows the water level (measured using piezometer) in the embankment 7 hours after the start of injection, just before the start of excitation. Compared with Case 1, we can see that the water level is lower in Case 2 and Case 3. This indicates that slits with crushed-stones is effective in draining water.

Figure 8 shows deformation in the model after excitation. In Case 1 and Case 2, the arc going through the crown of the embankment has slid down. Especially with Case 1, deformations, like large depressions of the slope top, were confirmed. But in Case 3 we can see that the deformation was small. Figure 9 shows changes over time when excitation was applied, measured by a piezometer (P2) installed at the foot of the slope. In Case 1 and Case 2, large excessive pore-water pressure is generated, but in Case 3 it is held down. We have assumed that this is because the drainage effect of slits with crushed-stones is holding down the rise of pore-water pressure. Figure 10 shows the residual vertical displacement at slope top and residual horizontal...
displacement at slope foot. We can see that deformation is held down for Case 2 and Case 3, which were reinforced, compared with the un-reinforced Case 1. And compared with Case 2, in Case 3, where slits with crushed-stones were constructed, the deformation is further held down.

From the results of the experiment, we have assumed that by constructing the crushed-stone vertical drainage the water level in the embankment lowers, and when earthquakes occur, excessive pore-water pressure is held down, keeping embankment deformations small.

Fig. 9. Time history of excessive pore water pressure (P2) at excitation

![Graph showing time history of excessive pore water pressure (P2)](image)

Fig. 10. Residual displacement of slope top and foot after excitation

![Graph showing residual displacement of slope top and foot](image)

6 CONCLUSION

Many expressway embankments have collapsed in the recent years due to torrential rains and earthquakes, but no major deformation (swelling) in the embankments at these locations have been reported, and therefore, we have assumed that the compaction of the embankment has not changed since the start of service. As explained in section 3, when we examined the strength of the embankment by changing the water content of the soil while the compaction was set at a certain level, we confirmed that the strength of the soil degraded as the water content increased even when the compaction remained the same. This indicates that soil strength relies not only on the degree of compaction but also on the water content. In many cases, water content ratio at construction and after opening of the expressway does not differ much. That means the quality (strength) of the embankment is maintained after the expressway goes into service. But if the water content ratio of the soil changes greatly after the expressway opens, especially when the ratio increases, we can suppose that soil strength lowers even if the compaction degree remains the same. As explained, we have constructed the crushed-stone vertical drainage hoping to lower the embankment’s water content because the water volume in the soil affects the strength (stability) of the embankment. As explained in section 5, lowering water level in the embankment and preventing excessive rise of pore-pressure when an earthquake strikes, we expect, will hold down deformation of embankments to half of that of embankments without any preventive measures taken.

7 CLOSING

Up to now, compared with the condition of the embankment at the time of construction, it was thought that appropriate construction, drainage, and maintenance would, maintain or improve the condition of the embankment (especially strength) over time. But we have found that the embankment strength not only relies on compaction but also on the water content. This fact points out the importance of maintaining the water content level in an embankment and indicates the value of water drainage works such as the “crushed-stone vertical drainage.” But in some cases drainage works may not be enough, so in such cases other measures must be considered.

REFERENCES