Investigation of liquefiable property and S-wave velocity distribution focused on coal ash used for rail yard embankments

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ABSTRACT

In the 2011 Great East Japan Earthquake the rail yard embankment constructed by use of coal ash was damaged by severe liquefaction, resulting in the differential settlement of railway track. In the railway the settlement is limited to ensure safety, however the evaluation method for differential settlement is not established. It is thus necessary to establish the evaluation method for the differential settlement of railway track induced by liquefaction. In this study, cyclic undrained triaxial tests for the fill material contained coal ash were performed to validate whether it was liquefied. It was found that the fill material was possibility to be liquefied sufficiently. In addition, field level survey and surface wave exploration method were conducted to examine the effect of the thickness of liquefiable layer and S-wave velocity distribution on differential settlement caused by liquefaction. The results revealed that the differential settlement is concerned with distribution of the S-wave velocity and the thickness of the liquefiable layer.

Keywords: liquefaction, differential settlement, surface wave exploration method, coal ash

1 INTRODUCTION

The 2011 Great East Japan Earthquake caused liquefaction in wide areas around Tokyo in spite of low acceleration of the earthquake (Bhattacharya, 2011). The damage was caused by the characteristics of the earthquake such as long duration time, long period of seismic wave and a few large aftershocks. The embankments which constructed on the soft clay ground were damaged by liquefaction of the embankment body. Koseki et al. (2012) and Suzuki et al. (2011) indicated that such damage cases were possible to occur in railway embankments. This mechanism is explained that the part of embankment which settles down below groundwater level caused by consolidation of the soft ground during serviceable period is liquefied during earthquake.

The rail yard embankment on soft clay ground in Mito city was liquefied in the 2011 Great East Japan Earthquake. It is considered that this damage was caused by same mechanism as liquefaction of the embankment. So that means that the fill material contained coal ash was possible to be liquefied. The reason for using coal ash in railway facilities may be suspected that the coal ash gotten by steam locomotive was used against settlement occurred during the serviceable period. It was confirmed that coal ash was deposit in some facilities. If coal ash has a possibility to be liquefied under a certain condition, the facilities were associated with a risk of liquefaction damage during earthquake.

In the Japanese railway the settlement is limited to ensure safety. The evaluation methods for settlement induced by liquefaction were proposed by Ishihara and Yoshimine (1992), Tokimatsu and Seed (1987) and Aseismic design standard (2012). However the evaluation of the differential settlement is not conducted. One reason is that the evaluation is conducted based on the results of investigation performed in a spot such as SPT and etc. Therefore it is difficult to grasp special distribution of the property of the ground.

In this study cyclic undrained triaxial tests for coal ash and the liquefaction evaluation were performed to validate whether the liquefaction of the fill material contained coal ash. In addition, field investigations were conducted to examine the effect of the thickness of liquefiable layer and S-wave velocity distribution on differential settlement caused by liquefaction. In the field investigation level survey and surface wave exploration method were conducted.

2 INVESTIGATION SITE

The investigation site was the rail yard embankment in Mito city that suffered intense liquefaction in the 2011 Great East Japan Earthquake. Fig. 1 shows a top view of the investigation site. The black, blue and red
The liquefaction evaluation for railway embankment was carried out to examine the liquefaction resistance of the fill material containing coal ash. The liquefaction evaluation based on the cumulative damage theory which proposed by Okawa et al. (1987) was carried out utilized the results of the cyclic undrained triaxial tests and the ground surface seismic motion in Mito city.

3.1 TEST CONDITION AND METHOD OF THE CYCLIC UNDRAINED TRIAXIAL TESTS

The specimens used for cyclic undrained triaxial tests were typically 75 mm in diameter and 150 mm in height. They were taken from 2.0–2.75 m deep in the rail yard embankment by a thin-walled sampler. Shown in Table 2 is test conditions for cyclic undrained tests. The earthquake. The groundwater level throughout the year was roughly -1.1 m from surface of ground in intervals of rainfall. It tended to rise significantly after rainfall or snowfall, and then fall again after a few days. Fig. 3 (b) shows the daily rainfalls in March 2011. There was not rainfall for a few days before March 11, when the earthquake occurred, and the groundwater level was estimated roughly -1.1m from the ground surface at the time of the earthquake.

The liquefaction resistance of the fill material containing coal ash, cyclic undrained triaxial tests were performed. The liquefaction evaluation based on the cumulative damage theory which proposed by Okawa et al. (1987) was carried out utilized the results of the cyclic undrained triaxial tests and the ground surface seismic motion in Mito city.

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| Soil particle density, ρs (g/cm³) | 2.326 ~ 2.484 |
| Wet density, ρ (g/cm³) | 1.284 ~ 1.3093 |
| Dry density, ρd (g/cm³) | 0.843 ~ 0.949 |
| Maximum dry density, ρdmax (g/cm³) | 1.171 ~ 1.295 |
| Optimum water content, wopt (%) | 28.6 ~ 41.4 |
| Fine grain content rate, Fc (%) | 9.0 ~ 19.0 |

**Table 1. Results of physical tests of the fill material containing coal ash**
Table 2. Test conditions for cyclic undrained triaxial tests

<table>
<thead>
<tr>
<th></th>
<th>Wet density ρ (tf/m³)</th>
<th>CSR</th>
<th>Confining stress(tf/m²)</th>
<th>Frequency (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1.</td>
<td>1.489</td>
<td>0.20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Case 2.</td>
<td>1.470</td>
<td>0.40</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Case 3.</td>
<td>0.978</td>
<td>0.23</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Case 4.</td>
<td>0.981</td>
<td>0.30</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 6 The liquefaction resistance curve of the fill material properties of loose density fill material were mainly evaluated. For isotropic consolidation, the specimens were saturated by applying back pressure up having a Skempton’s B value greater than 0.95 under an effective confining pressure of 25 kPa. The cyclic loading was characterized by a sin wave with a frequency of 0.1 Hz. Table 2 shows the test condition of the cyclic undrained triaxial test. Each test was conducted until the double amplitude axial strain exceeded 10%.

3.2 TEST RESULTS

Fig. 4 shows the relationships between axial strain and deviatoric stress in Case 3 and 4. In general, a structure of a soil is stronger on the compressive side than the tensile side. In each case axial strains in the tensile side were larger than the compressive side with increase of the number of cycles. The Stress paths are shown in Fig. 5. In each case effective mean stress didn’t reach zero. The gradient of failure lines in the tensile side were different from it in the compression side, the fill material exhibited strong anisotropy.

Fig. 6 shows the liquefaction resistance curve of the fill material containing coal ash. Owing to different densities of specimens sampled in the rail yard embankment, it was difficult to evaluate the liquefaction resistance. However the liquefaction resistance in loose specimens was evaluated roughly. The liquefaction resistance ratio in the loose specimens was determined to be 0.245 for a double amplitude axial strain of 10% and 20 cycles. On the other hand, the liquefaction resistance in dense specimens was less than 0.4 for a double amplitude axial strain of 10% and 20 cycles. The liquefaction evaluation was conducted to use this result.

3.3 LIQUEFACTION EVALUATION USING CUMULATIVE DAMAGE THEORY

In the liquefaction evaluation for coal ash layer the ground surface seismic motion and the result of laboratory tests were used. The ground surface seismic motion was calculated using the earthquake wave observed in Mito city as obtained by an attenuation model of the stratum structure in the investigation site. Fig. 7 shows the acceleration time history of the ground surface seismic motion used for liquefaction evaluation. In the seismic wave the maximum acceleration was 785
Fig. 7 The acceleration time history of the ground surface seismic motion used for the liquefaction evaluation.

Table 3. The results of liquefaction evaluation for fill material

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>Factor of safety for liquefaction ( F_L )</th>
<th>Probability of liquefaction ( P_L )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.00</td>
<td>0.25</td>
<td>0.25</td>
</tr>
<tr>
<td>2.00</td>
<td>0.18</td>
<td>21.09</td>
</tr>
<tr>
<td>3.00</td>
<td>0.15</td>
<td></td>
</tr>
</tbody>
</table>

Table 3 shows the result of liquefaction evaluation for fill material contained coal ash. This examination was based on assumption, liquefaction resistance ratio in liquefiable layer is close to the same despite the difference in depth. The factors of safety for liquefaction \( F_L \) (Iwasaki, 1984) were evaluated to be less than 1.0. The results mean the fill material had the potential of the liquefaction in the 2011 Great East Japan Earthquake. In addition, the probability of liquefaction \( P_L \) was over 20. It means that the degree of liquefaction is extensive if the material is liquefied.

4 FIELD INVESTIGATIONS

In this section, we derived the relationship among the thickness of the fill material layer, the S-wave velocity distribution, and the settlement of the railway track.

4.1 INVESTIGATION CONDITION

The surface wave exploration method was conducted to evaluate the thickness of liquefiable layer and S-wave velocity distribution. In surface wave exploration method to estimate S-wave velocity is based on the close relationship between the dispersion characteristic of surface wave and the S-wave velocity of earth materials, and S-wave velocity is estimated by an inverse analysis of the dispersion of the observed surface wave. The surface wave exploration method used in this investigation has 24 pieces of the wave receivers, and they are able to measure in 23 m at one hit by mallet. The thickness of the liquefiable layer was estimated based on the S-wave velocity in the boundary between the fill material layer and the organic silt layer.

The level survey was conducted at the critical damaged point and at 5 m intervals in minor damaged area to grasp the level of the top of the railway track.

4.2 EXAMINATION OF ACCURACY OF SURFACE WAVE EXPLORATION METHOD

In general the accuracy and the resolution of surface wave exploration method are lower than PS-logging. Therefore the comparison of the S-wave velocity measured by PS-logging with it measured by surface wave exploration method was conducted to examine the accuracy and the resolution of the surface wave exploration method in damaged area. The site conducted by PS-logging and surface wave exploration method is shown in Fig. 1. The surface wave exploration method was performed in the site where roughly 5 m away from the hole used for PS logging. Fig. 8 shows the result of the comparison of S-wave velocities. The result reveals that the S-wave velocity measured by surface wave exploration method was almost same as it measured by PS-logging.

The threshold S-wave velocity in the boundary between the fill layer and the organic silt layer was determined to grasp the thickness of the liquefiable layer. The S-wave velocity in the fill layer was higher than 100 m/s in Fig.8. The S-wave velocity of the silt layer below the fill layer was measured in the range of 55–70 m/s. Based on the results, the threshold S-wave velocity was determined to be 100 m/s. Using this threshold S-wave velocity, the thickness of the liquefiable layer were estimated at 0.5 m intervals.
the thick liquefiable layer such as Fig. 9 (c) and Fig. 9 (d), the thicker the liquefiable layer at certain spots is the weak correlation between the average S-wave velocity and the level of the track. One reason for the weak correlation between them is considered that the S-wave velocity distribution in depth direction was unevenness such as Fig. 10 (a). Therefore the degree of liquefaction at the spots where the liquefiable layer is thin has possibilities to be also unevenness during earthquake. Other reason is that the direction of the displacement induced by liquefaction is not only in one direction. Especially in cases where the boundary between the liquefiable layer and the organic silt layer inclines, the lateral flow of the liquefiable layer was possible to occur during earthquake.

Fig. 10 shows the results of surface wave exploration method in the severe damage area and minimal damage area. The red circles in Fig. 10 (a) indicate the places observed the sand boils. In severe damage area the S-wave velocity distribution is lower than that in minimal damage area. In particular, the S-wave velocity below the places observed the sand boils was lower than it below other places. Nakazawa et al (2010) reported that the occurrence of the sand boils decreased the S-wave velocity by the comparison of S-wave velocity before the occurrence of the liquefaction with S-wave velocity after it. In the damaged area, S-wave velocity before earthquake is unknown. So that means that it is possible to induce the occurrence of the sand boils due to lack of the S-wave velocity distribution before earthquake. In minimal damage area it is difficult to identify the part of the boundary between the liquefiable layer and the organic silt layer due to the greater S-wave velocity in the organic silt layer than threshold value to presume the boundary between them. One reason why the S-wave velocity in minimal damage area is greater than it in severe damage area is that the number of train running in severe damage area is greater than it in severe
damage area. Fig. 11 shows the results of level survey in the severe damage area and minimal damage area. In Fig. 11 (a), black line indicates the soil layer boundary obtained by surface wave exploration method. The relative level of the track is drawn as zero in the starting point. In severe damage area the level of the rail track distribution is not flat. In particular, at the place where S-wave velocity was low such as the place from 90 m to 120 m in the distance the level of the rail track distribution is irregularly. On the other hand, at the place of the high S-wave velocity such as the place from 160 m to 180 m in the distance the level was relatively high. It is deduced that the differential settlement induced liquefaction was caused by the unevenness of the S-wave velocity. The level of the rail track distribution is affected by the shape of the boundary between liquefiable layer and organic silt layer in the places from 40 m to 50 m and 100 m in distance.

In minimal damage area the level of the rail track is flat. One of the reason is that the S-wave velocity in liquefiable layer is higher than it in the critical damage area. So that means the value of the liquefiable layer is possible to be concerned the degree of the liquefaction and the deformation induced by liquefaction.

5 CONCLUSIONS

In this study a series of cyclic undrained triaxial tests was performed to validate whether the fill material contained coal ash is liquefied in rail yard embankment in the 2011 Great East Japan Earthquake. In addition, the investigations were conducted to examine the effect of the thickness of liquefiable layer and S-wave velocity distribution on differential settlement caused by liquefaction. The results reveal the following.

(a) The liquefaction strength ratio of the fill material contained coal ash was 0.245. In the result of the liquefaction evaluation the fill material has potential to liquefy in the earthquake.

(b) There is a good correlation between the average S-wave velocity in the liquefiable layer and the level of the track at the places where the liquefiable layer is thin. The reason of it is suspected that the liquefaction strength ratio is low due to the loose density of liquefiable material in the cases where the average S-wave velocity in liquefiable layer is low.

(c) In the cases of the thick liquefiable layer, the correlation of them is weak. One reason is that the unevenness of the S-wave velocity distribution in the depth direction is larger, and the settlement induced by liquefaction is smaller depending to the thickness of the liquefiable layer.

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