The geotechnical issues of the damage caused by the great east Japan disaster and reconstruction for the Tohoku region

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ABSTRACT

The 2011 Off the Pacific Coast of Tohoku Earthquake which occurred on March 11 caused serious damage to the infrastructural facilities in the eastern area of Japan due to the strong motion of the earthquake and the subsequent tsunami. This paper includes a brief outline of the earthquake damage to various facilities in relation to geotechnical engineering, and the main geotechnical engineering problems which have emerged after this disaster, including ground subsidence caused by crustal movement, the consolidation of soft clay and liquefaction, liquefaction induced damage to river levees and tailing dams, the geotechnical damage related to Tsunami impact, and disaster waste management.

Keywords: 2011 great east Japan disaster, reconstruction work, waste management, earthquake damage, geotechnical issue

1. INTRODUCTION

The 2011 Off the Pacific Coast of Tohoku Earthquake which occurred on March 11 resulted in serious damage to the infrastructural facilities in the eastern area of Japan due to the strong motion of the earthquake and the subsequent tsunami. A brief outline of the earthquake damage to various facilities in relation to geotechnical engineering, and main geotechnical engineering problems which have emerged after this disaster are reported (Ref.1,2).

2 GROUND SUBSIDENCES

There are two main causes of ground subsidence. One is the crustal movement which occurred over a wide area. The other is surface ground deformations, in particular the liquefaction of sandy ground and the consolidation of soft clayey ground.

2.1 Wide area subsidence due to crustal movement

Wide area subsidence occurred due to crustal movement in this earthquake (Ref.3). An eastwards horizontal displacement of approximately 5.3 m and about 1 m subsidence were observed at the Oshika electronic survey point in Ishinomaki City in Miyagi prefecture. The Geospatial Information Authority (GSI) of Japan has 1240 electronic survey points, one at every 20 km distance, which observe GPS satellite continuously. Several results are listed in Table 1, and the distribution of displacement presented by the GSI is shown in Figure 1. Comparing the movement just after the earthquake and those after three years, complex but slight crustal movement was shown to have continued.

<table>
<thead>
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<th>Pref.</th>
<th>City</th>
<th>Horizontal movement (cm)</th>
<th>Vertical movement (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Just after quake</td>
<td>Just after 3 years</td>
<td>Just after quake</td>
</tr>
<tr>
<td>Miyako</td>
<td>230</td>
<td>300</td>
<td>-35</td>
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<tr>
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<td>273</td>
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<td>-29</td>
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<tr>
<td>Watari</td>
<td>280</td>
<td>368</td>
<td>-22</td>
</tr>
</tbody>
</table>

Due to subsidence, the area of land under zero meter in the Sendai plain increased from 3 km² to 16 km². Once the under zero meter area was flooded, because natural drainage cannot be expected, an artificial pumping drainage system had to be used. The short term effects of the flooding of the low land area included the difficulty of carry out searches of missing people and delay in the start of first stage restoration works. Furthermore, the long term effect is that a very fragile area was produced, extremely prone to high flood tide damage and flooding. Actually, later in 2011, coastal areas were damaged due
2.2 Ground subsidence due to the liquefaction of sandy ground and the consolidation of clayey ground

The liquefaction of surface sandy ground also caused ground subsidence. Extensive area liquefaction resulted in subsidence by as much as 50 cm in the Tokyo bay reclamation area.

In areas with soft clayey ground, it is possible that such subsidence will accelerate in the future. Figure 2 shows the accumulated subsidence observed in low land areas in Sendai City from 2001 to 2012. It is found that large subsidence occurred just after the earthquake. In addition to this, it can be seen that subsidence trend after the earthquake is larger than that before the earthquake. This can be attributed to the disturbance of the skeleton structure of the soft clayey due to cyclic shearing during the earthquake.

3 LIQUEFACTION DAMAGE

3.1 Liquefaction damage in Tokyo bay area

Severe liquefaction damage occurred around Tokyo Bay reclamation area. From the view point of external seismic force, because seismic intensity observed at the Tokyo bay area was not so large (the maximum acceleration observed at the K-NET Urayasu was 157 Gal) the long duration of seismic motion is considered to have triggered the liquefaction rather than the amplitude of seismic motion. The feature of the liquefaction damage was significant large amounts of boiling sand, as shown in Photo 2. The extensive area liquefaction and large amount of sand boiling deposits are identical to the liquefaction damage which occurred in Canterbury, New Zealand, in February 2011 even though those resulted from short duration seismic motion from an inland fault earthquake. Therefore, main cause of the large amount of sand boiling is considered to be the properties of the soil material, which includes a large fines fraction. Actually, the reclamation soils at Urayasu City were a fine silty sand containing over 50 % fines. It is known that the soil material at liquefied areas in Canterbury earthquake also contained a high fines fraction. The low permeability of fine sand contributes to maintaining the

Photo 1 State of the flooded Ishinomaki City in Miyagi prefecture after the high tide with the 2011.8 typhoon.
high excess pore water pressure and fluid state. It should be noted that the aftershock which occurred just 30 minutes after the main shock contributed to the damage in Tokyo.

Non-plastic fines silt is the most susceptible material to seismic liquefaction because of the reason given above. This points to the high liquefaction potential of young reclamation ground. It should be understood that reducing the fines content of non-plastic silt does contribute to improve liquefaction potential. We should also pay attention to the origin of the ground; for example, whether the soil comes from natural deposits or artificial reclamation, such as hydraulic fill or other methods, impacts susceptibility to liquefaction.

3.2 Liquefaction damage in Tohoku district

The liquefaction damage in the Tohoku-district has not been subject to as much discussion as that in the Tokyo Bay area. This is because much of the sand boiling caused by the liquefaction which occurred in the coastal area was destroyed by the Tsunami which followed the earthquake. The traces of sand boils cannot be used as evidence of the occurrence of liquefaction. However, based on the many photographs and images taken of sand boils caused by liquefaction before the tsunami and the liquefaction that occurred during the aftershocks, liquefaction certainly occurred. Photo 3 shows the re-liquefaction at Onahama Port caused by the earthquake that occurred at Hama Dori in Fukushima prefecture on April 11.

3.3 Liquefaction Countermeasure at Sendai airport

Sendai Airport was constructed as a beach airport on a natural levee consisting of sand. The SPT for the stiff sand deposit was over 20 in most places, and the possibility of liquefaction was thought to be low. Even so, liquefaction countermeasures (permeation solidified processing, the cross jetting method and the compaction grouting method) were carried out in the part indicated by a pink hatch on Figure 3 due to fear that liquefaction might occur in back filling soils in the underground structure neighborhood where the runway is crossed. The effectiveness of liquefaction countermeasure was confirmed because liquefaction damage was observed only in the non-countermeasure areas, according to the damage investigation of Sendai Airport.

An airport, however, cannot be used when only its runway is safe and capable of functioning. When just one thing goes wrong, the function of the terminal building, the control function of the airport and the access function to the airport aerial transport function cannot be 100%. Even though the main runway did not experience fatal damage due to the earthquake at Sendai Airport, the terminal building was flooded by the tsunami and thus deprived of its function. The relief role the airport was expected to play in the case of the expected Miyagiken-oki earthquake was not possible. It is hoped that a disaster prevention measure of both the hard and software is developed, one that is capable of restoring the function of the system as quickly as possible.

At present, the trend is to pay attention to the concept of the BCP (Business Continuity Plan). This requires making assumptions about the degree of the accident in deciding a plan of an action. While this seems easy, it is actually quite difficult. Finally, the facilities themselves become earthquake-resistant, and, of when it comes to the concept of business as usual, it all boils down to being stubborn. When we have no choice, we simply have to persevere.
3.4 River levee damage due to liquefaction

The cause of most of the river levee damage in inland areas in the Tohoku district was liquefaction. Among the various damage, there was some that requires particular attention. Photo 4 shows the overview of the damaged river levee in the Naruse-river midstream area, where an embankment collapsed completely and was torn apart like a strip of paper. Traces of liquefied river levee sandy earth material on the soft clayey soil foundation ground were found during an excavation investigation after the event (see photo 4). Also, a penetration scar of the sand pulse to the embankment upper part was observed, with a liquefied sand layer approximately 1 m thick. It is thought that the sandy earth material of the bank body liquefied, and that this material was under the saturated condition due to consolidation settlement in the foundation ground and was in a loose state due to stress relaxation.

![Photo 4 Liquefaction damage of embankment at Shimo-nakanome district in Naruse River by Tohoku construction bureau.](image)

A similar case has been reported: river levee sandy soils built on peat ground liquefied during the 1993 Kushiro-oki earthquake. At the time, the consensus was that this was an atypical case; however, the mechanism involved should be considered the main mechanism of damage to river levees built on the soft foundations. From such a knowledge, the Ministry of Land, Infrastructure and Transport listed up the following points for checking and verification, as illustrated in Figure 4.

1. Embankment material is sandy soils: In case of significant damage caused by embankment material liquefaction, the materials were sandy soils with low plasticity.

2. Water level of the river levee interior: It is considered that the deformation is more pronounced when the saturated zone large. There is an example of a clear contrast between the water level in the river levee between the damaged area and the non-damaged area in the next section.

3. Quantity of consolidation settlement: The range of the loose saturated river levee body increases. A decline in the density and a decline in shear strength are possible: in a state of reduced density and shear strength, the soil is susceptible to liquefaction.

4. Soft foundation ground condition: Water from diffusion due rainwater tends to remain.

For the above reasons, it is most important that earthquake resistance is improved by reducing the degree of saturation of river levee material. Particular attention needs to pay to the susceptibility to liquefaction of the lower part material of the embankment. Furthermore, attention should be paid when there is a high degree of saturation condition due to capillary force should be considered.

![Photo 5 Squeezed trace in the sandy earth material from liquefied zone by the excavation investigation.](image)

3.5 Tailing dam damage

A tailing dam was also damaged due to liquefaction. A tailing dam bank located south of Kesennuma City broke, and the liquefied slag flowed downstream (see Figure 5). The flow state from the satellite image of 4/7 clearly confirms this. Slag is residual soil characterized as

![Fig. 5 Fluidization failure of tailing dam deposits due to seismic liquefaction, (Google earth image 2011/4/7).](image)
poorly graded fine silt which has adopted a mineral at a mining site. Slag mixes with water, and is sent by a pump to an accumulated place. Because of the loose state and poorly graded soils, the possibility of liquefaction is high. Because the water is not separate from the soil, it travels a long distance once it fluidizes. Such damage has been reported in the past from sites all over the world. It is thought that the fluidization mechanism of slag differs from that of the liquefaction of clean sand. To avoid fluidization failure, it is necessary to use solidification measures when depositing the slag.

4 DAMAGE DUE TO TSUNAMI

4.1 Damage to Port and Coastal facilities

Many ports and harbor structures were subjected to the seismic motion and the force of the subsequent tsunami. Generally speaking, breakwater damage is considered to be caused by the tsunami, and damage to quay wall structures is the result of seismic motion and liquefaction. The damage mechanism to the breakwaters located in the tsunami affected area were investigated, as shown in Fig.6. Research on the foundation design of breakwaters subjected to the overflow of tsunami wave is required. In the case of quay wall structures, research is required on the combined effects of seismic motion, liquefaction and the rapid draw down of the water level in front of the structure.

4.2 Damage to river dike at river mouse area

River mouth area in Miyagi prefecture suffered extensive damage. In one example, over 1.1 km of the right side of embankment washed away in the Shin-Kitakami-river estuary, as shown in Figure 7. Plans need to be made to rehabilitate the area which incurred tsunami damage by restoring the embankment in the estuary which do not involve simply restoring the embankment to its former state. This also applies to the restoration of an elevated railroad along the coast. As mentioned earlier, the ground subsided due to crustal movement, and this should be taken into consideration when making decisions about the infrastructure and the future plans of the community.

In a totally different take on embankments, the Sendai east expressway embankment stopped the tsunami from infiltrating the Sendai plain, which dramatically decreased the amount of damage to areas inland from it. Now, as a multiple protection policy against tsunami damage, the use of a prefectural road with a padded embankment to provide protection against another tsunami event like this one is being considered. However, from the perspective of foundation engineering, the technical requirements required to provide earth structures with tsunami-proof and erosion-proof performance have never been investigated. Research needs to be done on this point and also on mitigation in cases where over flow occurs.

4.3 Erosion of soils around bridge and building foundations

Tsunami damage to road facilities on National Route 45 where the Tohoku-district Pacific Ocean coastal area is tied to north and south was also significant. The main damage involved the washing away of a pier of a bridge and a beam. In terms of geotechnical damage to the road facilities, the soils filled behind the abutment in the bridge approach portion were eroded by the tsunami (Photo 6 left). Furthermore, there was significant scouring damage around the buildings (Photo 6 right).

4.4 Damage to buildings due to tsunami

With regard to the damage to reinforced concrete buildings and a steel structure buildings in Tsunami affected areas, attention should be paid to the damage at Onagawa town in Miyagi prefecture. Figure 8 shows the distance and the direction of building displacement. The
distances and the directions vary considerably. This involved many various foundation types, including individual foundations, spread foundations and pile supported foundations, as shown in Fig. 8. In addition to this, the liquefaction that took place before the tsunami reduced the frictional resistance of the pile foundations. These example of damage require careful attention when considering the basic design for a refuge for future tsunami events.

During the processing work, a huge amount of soils, including ash after incineration, soils included in the waste and tsunami deposition soils (see Photo 7), were generated. In order to make it possible to use such large quantities of earth and sand as resources and to use them effectively, improvements in the field of earth material management are required. From the perspective of preservation of the geotechnical environment, this disaster has provided an opportunity to rethink and improve the framework of regular waste treatment. Foundation engineering can make a significant contribution in this field.

Photo 7 Tsunami deposit, in Higashi-Matsushima City in Miyagi pref. (left) and a rice field in Soma City in Fukushima pref. (right). The characteristics of the deposited soil from the tsunami change from area to area.

6 CONCLUSIONS
The damage caused by the Great East Japan earthquake has highlighted many geotechnical issues, including ground subsidence, liquefaction, geotechnical damage due to tsunami, and the geo-environmental problem. Each of them is summarized in this paper. Rehabilitation work is ongoing and geotechnical engineers have much to contribute.

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