Soil Properties of Liquefied Soils in Tokyo Bay Area by the 2011 Great East Japan Earthquake

Propriétés des sols liquéfiés dans la baie de Tokyo pendant le grand séisme de l'Est du Japon en 2011

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ABSTRACT: The 2011 Great East Japan Earthquake caused severe liquefaction in artificially reclaimed lands along Tokyo Bay. These lands were constructed of soils dredged from the bottom of the bay. The dredged and filled soils were estimated to have been liquefied by the earthquake, but their liquefaction strength was not so low because they contained much fines. The very long duration of the main shock and an aftershock 29 minutes later should have induced the severe liquefaction. Two remarkable characteristics of the liquefied grounds were observed: i) much boiled sand and large ground subsidence, and ii) the buckling of sidewalks and alleys. The former must have occurred because the liquefied soils were very fine. The latter might have been induced by a kind of sloshing of liquefied ground.

RÉSUMÉ : Le Grand Séisme de 2012, à l'Est du Japon a produit des nombreux cas de liquéfaction sévère des remblais artificiels, le long de la baie de Tokyo. Ces terrains ont été construits à partir du compactage de matériaux dragués du fonds de la baie. Il était connu que ces sols avaient une certaine susceptibilité à la liquéfaction. Cependant, leur résistance à la liquéfaction avait été estimée comme supérieure, à cause de leur contenu important de fins, par rapport à celle qui s'est avérée réellement pendant le séisme. La durée très longue du séisme principal et une réplique importante survenue 29 minutes après, apparaissent comme les causes de l'ampleur de la liquéfaction. Deux particularités très évidentes ont été observées : i) Une quantité importante de sables a été éjectée à la surface, avec des tassements considérables du terrain, et ii) La contorsion-roulement par compression des trottoirs et allées. Le premier cas a peut être été le produit de la composition assez fine des sols et le deuxième cas par le « ballottement » du terrain pendant le temps d'occurrence de la liquéfaction.

KEYWORDS: liquefaction, earthquake, sandy soil

1 INTRODUCTION

During the 2011 Great East Japan Earthquake, soil liquefaction occurred in the Tohoku region of northeastern Japan and in the Kanto region surrounding Tokyo because the earthquake was huge, with a magnitude of Mw=9.0. Many houses, roads, lifelines, and river dikes were severely damaged by soil liquefaction. According to the Ministry of Land, Infrastructure, Transport and Tourism (MLIT), about 27,000 wooden houses in Japan were damaged due to liquefaction.

In the Tokyo Bay area, liquefaction occurred in a wide area of reclaimed land along Tokyo Bay, though the epicentral distance was very large, about 380 to 400 km. Large amounts of boiled sand, large settlements and a kind of sloshing of liquefied grounds were observed in the Tokyo Bay area. The author and his colleagues conducted laboratory tests, model tests and seismic response analyses to ascertain the properties of the liquefied soils and explain the remarkable behavior of the ground due to liquefaction.

2 EFFECT OF LONG DURATION OF SHAKING DURING THE MAIN SHOCK AND AN AFTERSHOCK ON LIQUEFACTION

2.1 *Liquefied area in Tokyo Bay area*

Figure 1 is a map of the liquefied zones in the Tokyo Bay area (Kanto Regional Development Bureau of the Ministry of Land, Infrastructure, Transport and Tourism, 2011). The ground surface was covered with boiled sands all around the reclaimed lands at Shinkiba in Tokyo, Urayasu City, Ichikawa City, Narashino City and western Chiba City. On the contrary, sand boils were observed only here and there on the reclaimed lands at Odaiba, Shinonome, Tatsumi, Toyosu and Seishin in Tokyo and at eastern Chiba City. The total liquefied area from Odaiba to Chiba City reached about 41 km^2. Many houses, roads, and lifelines were severely damaged in the liquefied zones. The most serious damage was in Urayasu City, where soil liquefied in about 85% of the city area.

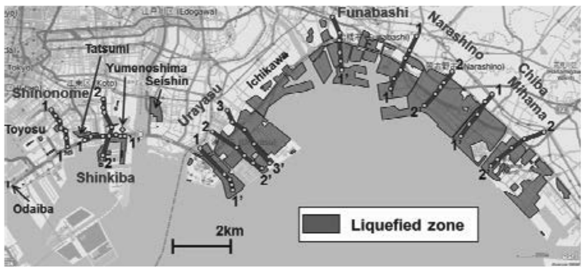


Figure 1. Liquefied areas from Odaiba in Tokyo to Chiba (Kanto Regional Development Bureau of MLITT)

2.2 *Cyclic torsional tests to demonstrate the effect of the long duration of shaking during the main shock and an aftershock*

The most remarkable characteristic of the liquefaction in the Tokyo Bay area was that widespread serious liquefaction was induced even though the recorded accelerations were not large and the liquefaction strength of the reclaimed soils was not low. Figure 2 shows ground surface accelerations measured by K-net

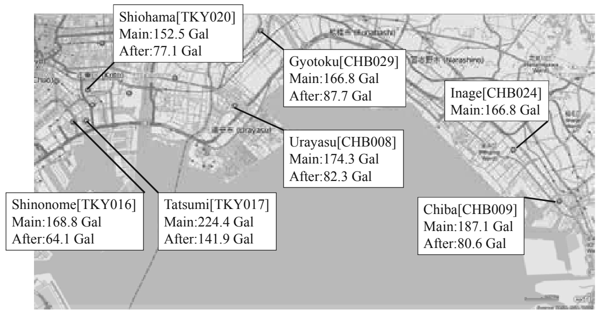


Figure 2 Ground surface accelerations measured by K-net (NIED, 2011) during the main shock and an aftershock 29 minutes later

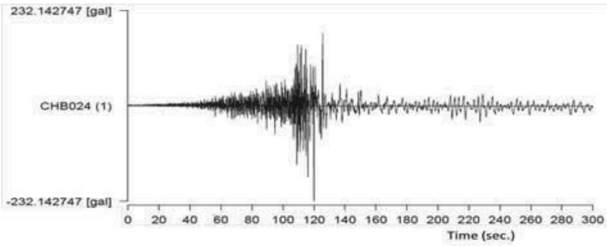


Figure 3 Acceleration wave measured by K-NET Inage during the main shock

(NIED, 2011) during the main shock and an aftershock 29 minutes later. Surface accelerations were not high, around 160 cm/s^2 to 300 cm/s^2, in the liquefied zones. Figure 3 shows the accelerograph at Inage, where boiled sand was observed. The frequency fell to low values after two peaks at 120 sec. and 126 sec. This means that a long duration of shaking, around 1 minute, might have caused liquefaction at the K-NET Inage site. Shaking continued for a long time after the occurrence of liquefaction. According to inhabitants of the area, the boiling of muddy water was not intense after the main shock, somewhat like an oozing out. However, boiling intensified during the aftershock (Yasuda et al., 2012). Some inhabitants testified that boiling did not occur during the main shock but occurred during the aftershock. The authors conducted cyclic torsional shear tests and some simple analyses to evaluate the effect of the long shaking on the occurrence of liquefaction.

Silty sand taken from the boiled sand in Urayasu City was used for the cyclic torsional shear tests. The fines content, maximum void ratio and minimum void ratio were 36%, 1.477 and 0.828, respectively. The silty sand was poured into a mold with a relative density of 90 %. Two types of shear wave were applied to the specimen, a sine wave of 20 cycles and the seismic wave recorded during the main shock and the aftershock at the K-NET Urayasu site. In the case of seismic wave, excess pore water pressure increased gradually with shear stress as illustrated in Figure 4. The relationships between the stress ratio R (τ_d/σ') for the sine wave or R_{max} (τ_{max}/σ') for the seismic wave and residual excess pore water pressure u/σ_c' are plotted in Figure 5. As R=0.27 for u/σ_c'=1.0 and R_{max}=0.31 for u/σ_c'=1.0, the correction factor C_w according to the JRA standard (JRA, 1996) becomes 0.82. The safety factor against liquefaction F_L and the liquefaction potential P_L were evaluated from the data gathered from boring sites along the 11 soil cross sections shown in Figure 1, under the conditions of C_w=0.82 and 1.0. In the estimation, R_L was estimated from SPT N-values and fines content Fc, using the formula proposed by the technical committee of Urayasu City (Urayasu City, 2012). Figure 6 shows the F_L values evaluated from boring data from Urayasu, where liquefaction occurred. If the C_w is assumed be 1.0, most of F_L are estimated to be greater than 1.0, whereas F_L are less than 1.0) if C_w is assumed to be 0.82. Figure 7 compares

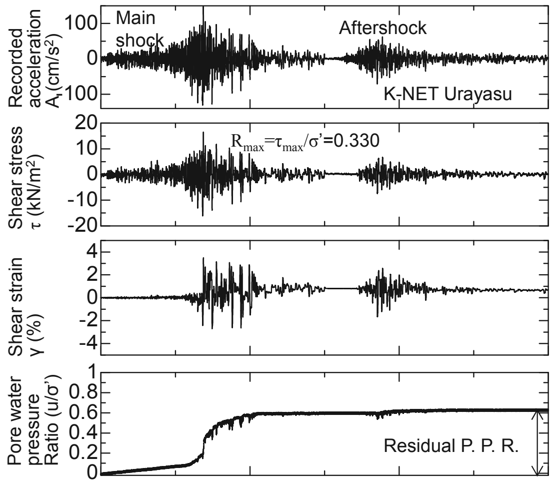


Figure 4 Time histories of shear stress, shear strain and excess pore water pressure

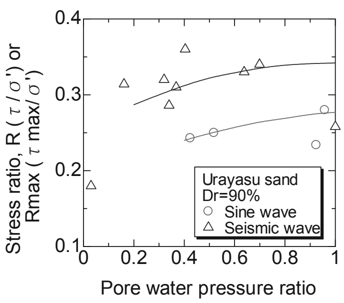


Figure 5 Relationship between shear stress ratio and excess pore water pressure

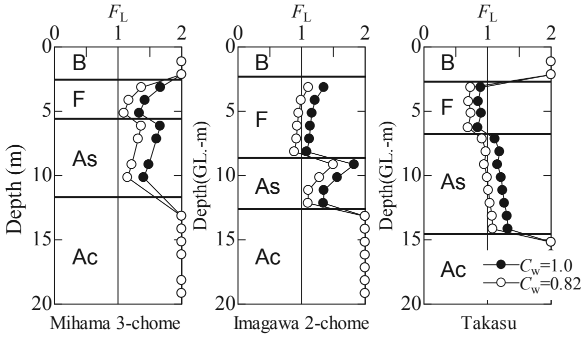


Figure 6 Analyzed F_L at liquefied sites in Urayasu City

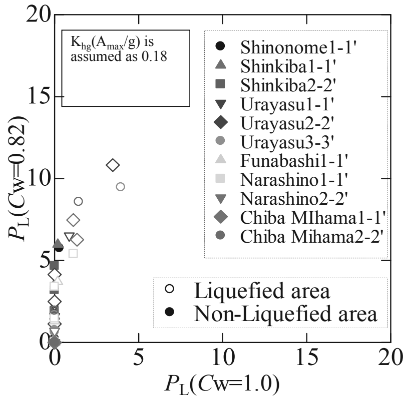


Figure 7 Effect of C_W on P_L

P_L for all boring data under the assumption of C_w=0.82 and C_w=1.0. If Cw=0.82, P_L for liquefied sites are calculated to be greater than about 10 and the severity of liquefaction can be demonstrated.

3 PLENTY OF BOILED SAND AND LARGE SETTLEMENT

Much eruption of sands and large ground subsidence occurred in the liquefied area. The maximum thickness of the erupted sand and the maximum ground subsidence observed by the author were about 30 cm and 50 cm, respectively, as shown in Figure 8. This was the first time the author had seen such thickly deposited boiled sand in Japan. However, much eruption and large subsidence also occurred in Christchurch, New Zealand during the main shock in September 2010 and the aftershock in February 2011. Erupted sands in Christchurch and Tokyo Bay were silty sands or sandy silts with much fines, as shown in Figures 9. A model test was carried out to demonstrate how very fine sandy soils cause much eruption and large ground subsidence.

Two sets of testing devices, schematically shown in Figure 10, were prepared, one for a silty sand erupted in Urayasu and the other for a clean sand named Toyoura sand which had no fines. Water tanks and acrylic cylinders 30 cm in diameter were connected with pipes. Testing soils were filled in the acrylic cylinders to a thickness of L=10 cm, then concrete blocks, which were models for road pavement, were placed on the surfaces of the soils. Water was flowed from the water tanks to the soils for three minutes to heights of H=10 cm, 12.5 cm, 15 cm or 17cm. Figure 11 (a) shows the surface of the model pavement before (left) and after (right) the water flow for Toyoura sand with the hydraulic gradient H/L=1.5. Only a few soil particles erupted onto the pavement even though water had passed through the soil and stood on the pavement. On the contrary, for Urayasu sand, many soil particles erupted onto the pavement, as shown in Figure 11 (b). The deposited Urayasu sand was about 3 cm thick.

It is estimated that fine soil particles were easily lifted above the ground surface by the ejecting water and that the removal of the deposited soils by inhabitants accelerated the settlement of the ground surface. Moreover, from the very fine sandy soils, water was ejected for a long time because of the low permeability of these soils.

Figure 8. Large settlement induced at Shin-urayasu station

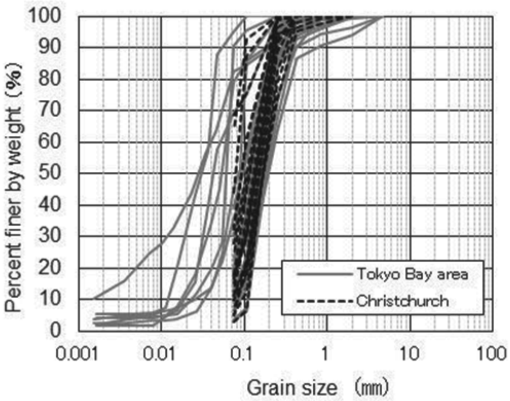


Figure 9. Grain size distribution curves of boiled sands in Tokyo Bay area and Christchurch

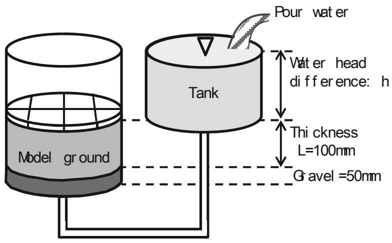
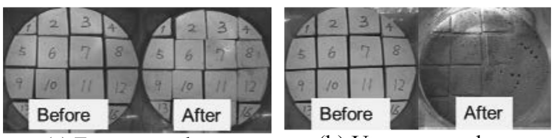


Figure 10. Testing device for eruption of sand



(a) Toyoura sand (b) Urayasu sand

Figure 11. Surface of the model pavement before and after the water flow

4 A KIND OF SLOSHING OF LIQUEFIED GROUND AND ITS EFFECT ON ROAD AND BURIED STRUCTURES

Strange heaving, buckling or thrust was observed at several footways and alleys, as shown in Figure 12. Some boundaries existed besides the footways and alleys, such as banks of old sea walls and elevated bridges. Therefore, some thrust might have occurred at these boundaries due to a kind of sloshing of liquefied ground, as schematically shown in Figure 13 (1), because shaking continued for long time after the occurrence of liquefaction, as mentioned above. On the other hand, the heaving of a footway was observed even though there was no such boundary as shown in Figure 12. The locations of heaved footways and alleys in Urayasu City, with and without

Figure 12. Thrust of an alley in Urayasu City

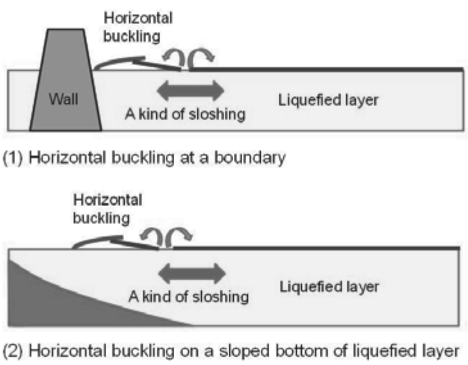


Figure 13 Two possible mechanisms of thrust or heaving

boundaries, are plotted in Figure 14. By comparing the locations

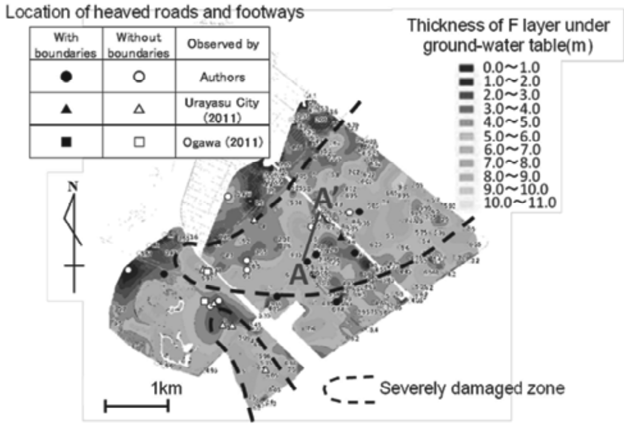
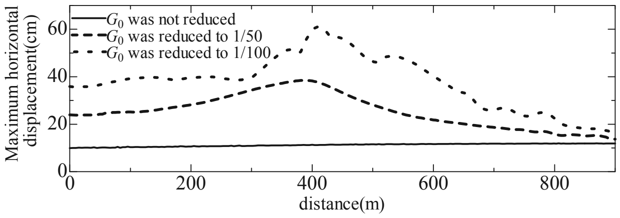
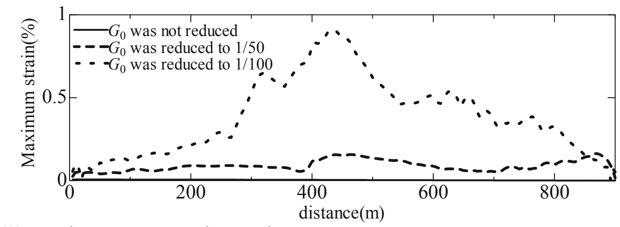


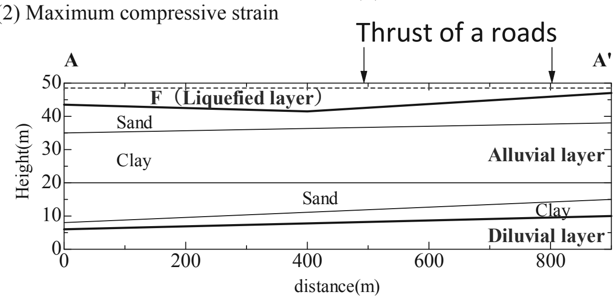
Figure 14 Estimated thickness of dredged and filled layer under water table (Quoted from the report by the Technical Committee organized by Urayasu City, 2012) and locations of heaved roads and footways



(1) Maximum horizontal displacement



(2) Maximum compressive strain



(3) Soil cross section along A-A' line

Figure 15. Results of seismic response analyses to estimate the concentration of horizontal compressive strain

of heaved footways and alleys without boundaries with the contour lines of the thickness of the dredged and filled (F) layer under the ground water table, it is seen that heaving occurred at sites where the bottom of the dredged and filled layer, in other words, the liquefied layer, was sloped. This implies that a kind of horizontal buckling of the surface layer might have occurred due to the concentration of horizontal compressive stress, as schematically shown in Figure 13 (2).

Seismic response analyses were carried out to estimate the concentration of horizontal compressive strain along line A-A' in Figure 14. Figure 15 (3) shows the soil cross section along line A-A'. In the analyses the "FLUSH" software program was used. The shear modulus in small strain, G_0 was estimated form SPT *N*-values, and the $G/G_0 - \gamma$ and the $h - \gamma$ relationships were estimated by the relationship proposed by Yasuda and Yamaguchi (1985). However, for the dredged and filled layer, G_0 was reduced to 1/50 and 1/100 to consider the effect of liquefaction, and G_0 was assumed to be constant regardless of shear strain γ. Many seismic records were obtained from the ground surface and from underground during the earthquake. Of these, the seismic wave recorded at Yumeno-shima, shown in Figure 1, was used for the analysis. Figures 15 (1) and 15 (2) show the distribution of the maximum horizontal displacement and compressive strain of the soil, respectively, at the depth of GL-1.5m. As shown in Figure 15 (2), large compressive strain is estimated to have been induced near the site where the thrust of a road occurred.

Many sewage manholes were cracked and sheared in a horizontal direction and filled with muddy water, whereas a few manholes were lifted or slightly settled in Urayasu City. The large horizontal displacement of liquefied ground had to cause the disconnection of pipe joints and the shear failure of the manholes, allowing the influx of muddy water into the pipes and manholes.

5 CONCLUSION

Laboratory tests, model tests and seismic response analyses were carried out to explain the remarkable behavior of the ground due to liquefaction in the Tokyo Bay area during the 2011 Great East Japan Earthquake, and the followings conclusions were derived:

(1) Seismic intensities in the liquefied zones were not high, with peak surface accelerations of 160 to 300 cm/s^2, though the liquefied ground was covered with boiled sands. The very long duration of the main shock and an aftershock 29 minutes later should have induced the severe liquefaction.

(2) It is estimated that much eruption of sands and large ground subsidence occurred because the liquefied soil had much fines and was easily lifted above the ground surface by the ejecting water.

(3) A kind of horizontal buckling of the surface layer might have occurred due to the concentration of horizontal compressive strain of liquefied ground and caused the strange heaving, buckling or thrust of the footways and alleys.

6 REFERENCES

Japan Road Association 1996. Specification for highway bridges. (in Japanese).

Kanto Regional Development Bureau of the Ministry of Land, Infrastructure, Transport and Tourism 2011. Study on the liquefaction in Kanto Region during the Tohoku-Pacific Ocean earthquake. (in Japanese)

National Research Institute for Earth Science and Disaster Prevention (NIED). K-NET WWW service, Japan (http://www.k-net.bosai.go.jp/).

Urayasu City. 2012. Report on measures against liquefaction in Urayasu City, (in Japanese)

Yasuda, S. and Yamaguchi, I. 1985. Dynamic soil properties of undisturbed samples. *Proc. of the 20th Japan National Conf. on SMFE*,539-542. (in Japanese)

Yasuda, S. 2009. Estimation of earthquake-triggered flood in a subsided area, *Proc. of the 17th International Conference on Soil Mechanics & Geotechnical Engineering*, 1686-1689.

Yasuda S., Harada K., Ishikawa K. and Kanemaru Y. 2012. Characteristics of the Liquefaction in Tokyo Bay Area by the 2011 Great East Japan Earthquake. *Soils and Foundations*, (in printing)