Investigation of Liquefaction-induced Damage to Wooden Houses in Urayasu City Caused by the Great East Japan Earthquake

15 WCEE
LISBOA 2012

Kohji Tokimatsu & Kota Katsumata
Tokyo Institute of Technology

SUMMARY:
Based on field reconnaissance carried out after the Great East Japan Earthquake, overview of liquefaction-induced damage to buildings is presented focusing on the city of Urayasu adjacent to Tokyo. Extensive soil liquefaction occurred in most areas reclaimed after 1968, with numerous sand boils and significant ground settlement up to 60 cm, broadly accompanied by settlement/ tilting of wooden buildings and reinforced-concrete structures supported on spread foundations. The extent and distribution of damage were greatly affected by local soil conditions including thickness of reclaimed fills, groundwater table, depth to bedrock (or natural site period), and structure-soil-structure interaction effects as well as whether remedial measures had been taken to mitigate future geotechnical hazards. Certain pile foundations then under construction in the liquefied area also incurred damage. Borehole camera and inclinometer surveys reveal liquefaction-induced permanent ground displacement to have been the major cause of damage.

Keywords: Liquefaction, Settlement, Spread foundation, Pile foundation, Great East Japan Earthquake

1. INTRODUCTION

The “11th March 2011 Great East Japan Earthquake” (M9.0) triggered an unprecedented tsunami, that overwhelmed many towns and swept away several tens of thousands of houses and other buildings along the coastline of northeast Japan, leaving about 20,000 people dead or missing. This earthquake also caused extensive ground problems including soil liquefaction, leading to extensive damage to buildings and infrastructures including roads, bridges, railways and ports, as well as to lifelines (Architecture Institute of Japan, 2011; Tokimatsu et al., 2011, 2012). Such liquefaction-induced damage was particularly significant in the city of Urayasu, affecting more than 9,000 private houses. This paper reports on liquefaction-induced damage to buildings in the city.

2. GOELOGICAL AND GEOPHYSICAL SETTING

Figure 2.1 shows a map of Urayasu city, Chiba Prefecture, with the years when reclamation work was done for each area. The city consists of three towns, Moto-machi, Naka-machi and Shin-machi. The later two towns were in turns reclaimed after 1964 outside levees along the old coastline of the Moto-machi area. In the Naka-machi areas reclaimed in the first phase of the project through 1975, many houses, commercial buildings and public facilities have been built. Meanwhile, the Shin-machi areas completed in the second phase through 1980 have many high-rise condominium buildings, universities, hotels and storehouses. Vacant lots still dot areas near the coast. Sand excavated from the seabed off Urayasu was mainly used to fill the reclamation sites. A magnitude-6.7 quake that occurred off eastern Chiba Prefecture on Dec. 17, 1987 (Chibaken Toho-oki Earthquake) reportedly caused liquefaction in some parts of the city, including Kairaku, Mihama and Irifune. The altitude is 0 to 2 meters north of the old coastline of 1964, 2 to 4 meters between the 1964 coastline and the 1971

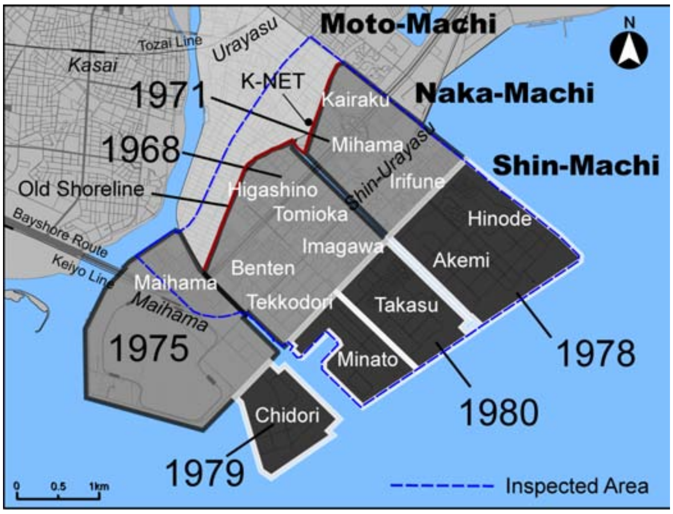

Figure 2.1. Map showing Urayasu city with reclamation year (Tokimatsu et al., 2012)

coastline to the south, and 3 to 7 meters in land reclaimed in or after 1979. The altitude is especially high in a park near a coastal levee in Akemi.

Figure 2.2 shows depth distribution for the sedimentation of soft soils overlying the Pleistocene deposit. Hidden valleys of about 60 meters deep exist directly below Minato, Imagawa, Akemi and Irifune areas, causing complicated changes in the thickness of soft clayey deposit in those areas. The depth of Pleistocene deposit (Ds), with N-values of 50 or greater, along the A-A' line (northwest to southeast) is about 20 meters below the sea level near the old coastline on the north side, and about 50 meters below the sea level in the area closest to the sea, showing that the depth becomes greater toward the sea (in the southeast direction). In contrast, along the northeast to southwest line, which is perpendicular to the A-A' line, the depth becomes greater towards the southwest. The reclaimed fills in the Naka-machi and Shin-machi areas are mostly deposited between the sea level and a depth of 4-8 meters.

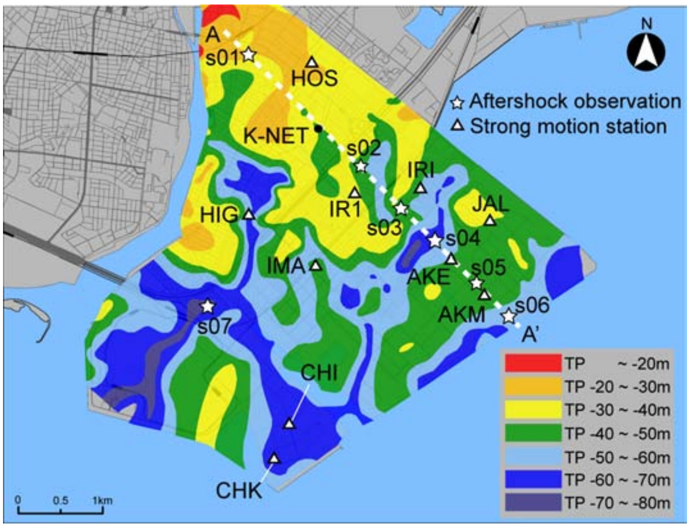

Figure 2.2. Map showing thickness of soft soil overlying Pleistocene deposit (Urayasu city, 2011b)

3. STRONG MOTION CHARACTERISTICS

A considerable number of strong motion accelerograms recorded in the city are available. These include one at a K-NET station in Urayasu (CHB008) located north of the old coastline (see Figure 2.1) as well as those obtained with the strong motion network operated by Keiyo Gas Co. Ltd (Urayasu city, 2012).

Figure 3.1 shows the acceleration time histories at K-NET Urayasu during the main shock and the largest aftershock (M7.6) that occurred in about 30 min after the main shock. The peak accelerations during the main shock and aftershock were 1.71m/s^2 and 0.80m/s^2, respectively. No liquefaction was spotted in the neighborhood of K-NET Urayasu (CHB008).

Figure 3.2 shows the distribution of peak ground acceleration (PGA) within the city. The peak ground acceleration varied within the city, with tendency where it is largest in the Naka-machi area.

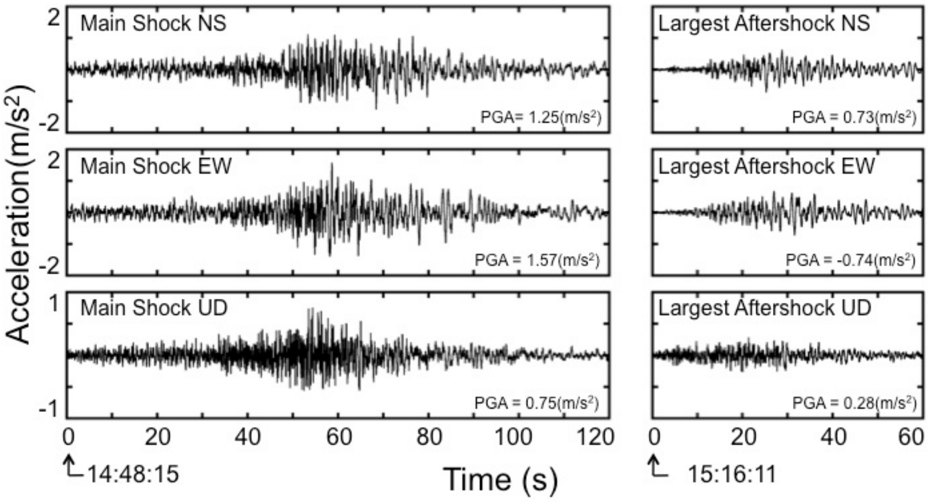

Figure 3.1. Acceleration time histories at K-NET Urayasu during the main shock and the largest aftershock

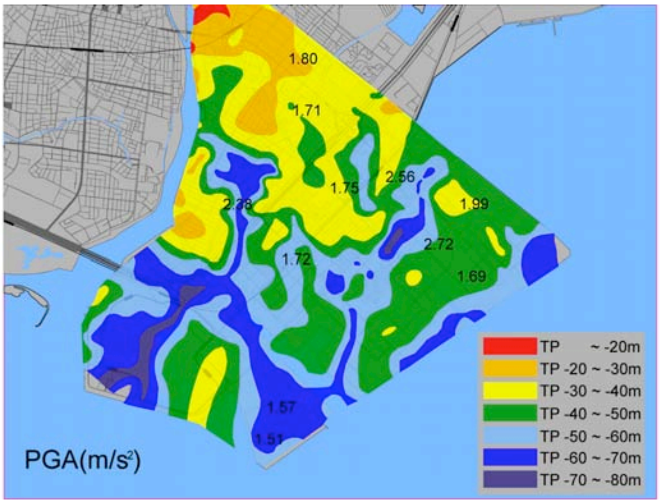

Figure 3.2. PGA recorded during the main shock (Urayasu city, 2012; Tokimatsu &Katsumata, 2012)

4. LIQUEFACTION-INDUCED DAMAGE TO BUILDINGS

Figure 2.1 also shows with dotted line the area within which our initial reconnaissance survey was made. The survey area covers not only a part of the natural deposit on the northwest of the old coastline, including the neighborhood of Urayasu Station and K-NET Urayasu site, but also most of the reclaimed land in the city.

Figure 4.1 shows a damage distribution map in which the extent of soil liquefaction is classified into four categories (i.e., no, slight, moderate, and extensive), based on the field performance of soils and buildings including ground settlements as well as settlements and tilting of houses. It can be confirmed that, liquefaction-induced damage was not seen on the north of the old coastline as of 1964 but was widely developed in the area reclaimed after that year. The areas that had experienced liquefaction in the 1987 Chiba-ken Toho-oki Earthquake did re-liquefy. The degree of damage varied from place to place within the reclaimed areas. In particular, some of the reclaimed zone escaped any liquefaction damage probably due to ground treatment including remedial measures against soil liquefaction.

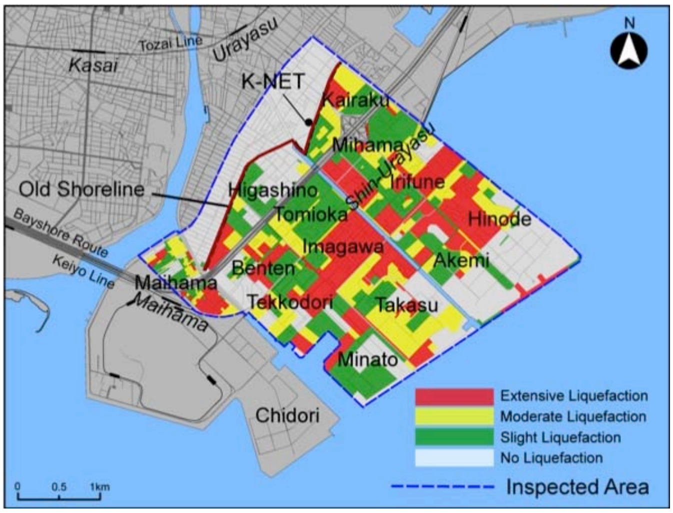

Figure 4.1. Map showing extent of liquefaction Damage (Tokimatsu et al., 2011, 2012)

Our initial and follow-up reconnaissance survey including measurements of tilting angle and direction of houses, partly using a 3D laser scanner, leads to the following findings.

1) In areas where liquefaction occurred, many sand boils, ground settlements up to 60 cm as well as settlements and tilts of building and houses on spread foundations (Figure 4.2) were observed

Figure 4.2. (a) Buildings suffering large settlement and tilting (left) and **(b)** buildings experiencing different gaps against subsiding ground (right) (Tokimatsu et al., 2011)

Figure 4.3. (a) Pile-supported buildings suffering large ground settlement (left) and **(b)** uplifted underground parking garage (right) (Tokimatsu et al., 2011)

everywhere. Vertical gaps were created around pile-supported structures due to ground settlements (Figures 4.2(b) and 4.3(a)), causing damage to piping and other facilities. Underground facilities, such as manholes, emergency water tanks and parking lots were uplifted (Figure 4.3(b)), damage was done to tap water and sewerage systems, roads had dents and utility poles were toppled. But little or no damage to superstructures induced by seismic force was observed.

2) Even where foundations settled or tilted, few superstructures suffered damage. This was because many buildings had adopted mat foundations or highly rigid foundations to prevent damage to superstructures from liquefaction or uneven settlings.

3) RC buildings and houses with the first floor or semi-basement made of reinforced concrete, suffered larger settlement, probably because their ground contact pressure was greater.

4) When buildings face each other across a street, they tend to tilt backward, away from each other, as in Figure 4.4. When two buildings stand closely together, they often tilt toward each other, as shown in Figures 4.2(a) and 4.4. Such unique tendency was probably caused by building-soil-building interaction effects in which the combined loads of the two adjacent buildings increased their settlements on the neighboring side.

5) Several pile foundations, including some under construction during the main shock, suffered severe damage probably due to dynamic and/or permanent lateral ground displacement caused by soil liquefaction.

6) In many areas located in the reclaimed area but unaffected by soil liquefaction, including the Tokyo Disneyland, ground improvement work of some kind had been carried out. This has confirmed the

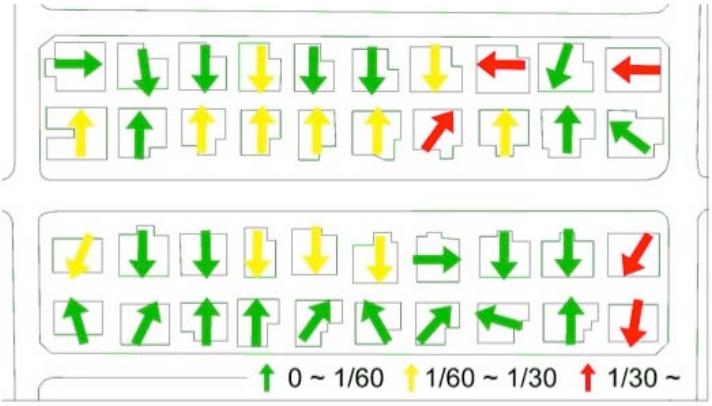

Figure 4.4. Typical result of tilting angle and direction of houses in a district (Urayasu city, 2012)

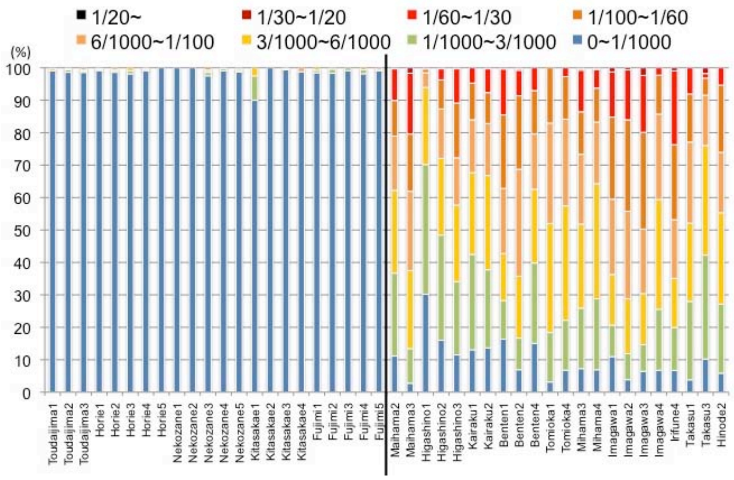

Figure 4.5. District by district distribution of inclination angle of houses (Urayasu city, 2012)

effectiveness of ground improvement work against the ground shaking with a peak ground acceleration of the order of 2.0m/s^2 caused by the M9 long duration earthquake.

Figure 4.5 shows the distribution of average inclination angle of residential houses supported on spread foundations in each district, based on the survey on about 9,000 houses conducted by Urayasu city government. Figure 4.6 summarizes the district-by-district distribution of damaged houses in terms of inclined angle. The figures show that the houses located on the non-liquefied north side of the old coastline had no damage, while those located in the reclaimed area suffered extensive damage. In particular, about 1/3-1/2 of the houses in the residential areas of Maihama 3-chome, Benten 1-chome, Imagawa 1 to 3-chome, and Irifune 4-chome tilted more than 1/100. These areas are classified in the category of extensive damage in Figure 4.1.

Figure 4.7 shows ground settlements estimated from the difference between the altitudes obtained before and after the quake using airborne laser scanning survey. The ground in the liquefied area after the quake has settled 0.2 to 0.4 m on the average, with smaller settlements on the roads. The value of subsidence reached as much as 0.6 to 0.8 m in some areas. These ground settlements from the laser scanning survey appear to be consistent with the ground settlements observed in the field. Comparison of Figure 4.7 with Figures 4.2 and 4.6 suggests that the area with larger ground settlements experienced more severe liquefaction damage to buildings.

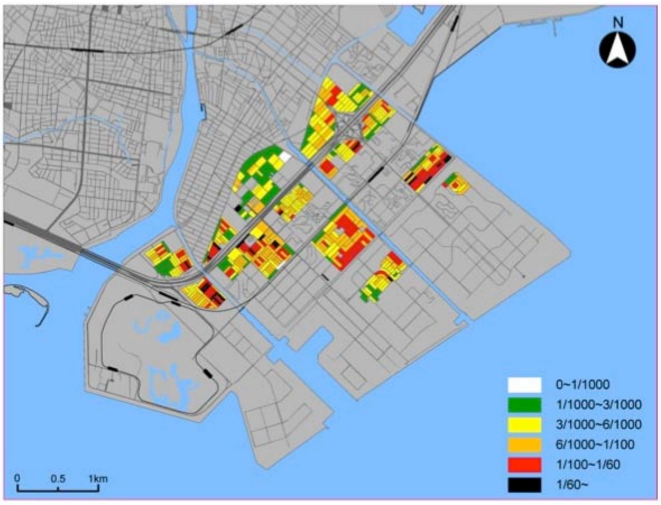

Figure 4.6. District by district distribution of inclination angle of houses (Urayasu city, 2012)

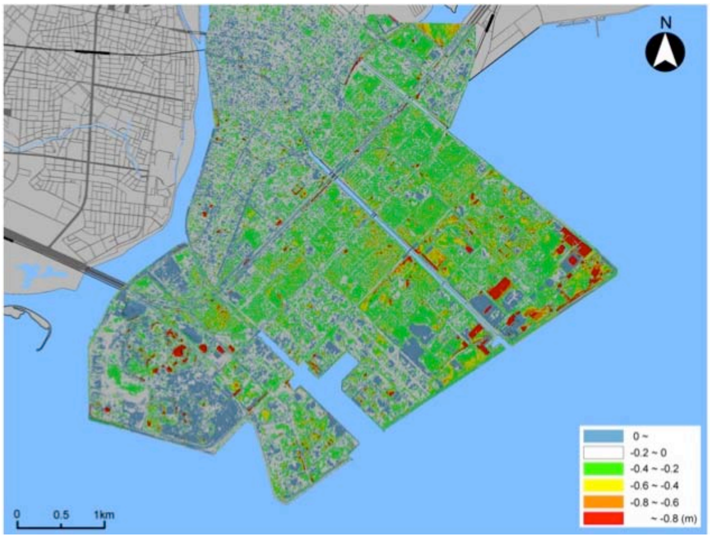

Figure 4.7. Map showing vertical ground settlement between 2006 and 2011 (Tokimatsu & Katsumata, 2012)

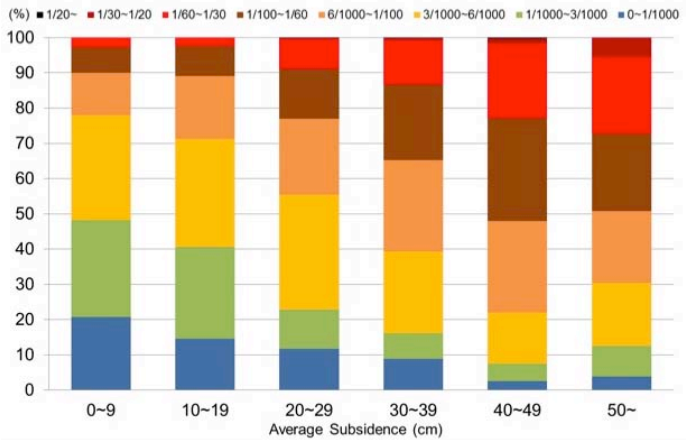

Figure 4.8. Relation between ground settlement and angle of inclination (Tokimatsu & Katsumata, 2012)

Figure 4.8 shows the distribution of inclination angle of residential houses with respect to ground settlement, prepared from Figures 4.6 and 4.7. Figure 4.8 apparently shows that the inclination angle tends to increase with increasing liquefaction-induced ground settlement. For example, about 10% houses titled more than 1/100 if the liquefaction-induced settlement (S) is on the order of 10-20 cm, whereas about 50% houses tilted when S becomes greater than 40 cm.

5. COMPARISON OF FIELD PERFORMANCE WITH SPT-BASED LIQUEFACTION EVALUATION PROCEDURE

Figure 5.1 shows grain size distribution of boiled sand samples collected at several locations in Urayasu. The samples each have high fine-grain content ratios, at 15 to 70 percent. Those fine grains are believed to be non-plastic fine sand or silty sand, which correspond to the composition of the sand layer in reclaimed land up to 10 meters below the sea level. This suggests that the reclaimed sand layer liquefied during the earthquake.

Figure 5.2 shows depth distributions of the N-value of earth filling or sand layers at each area of Urayasu in gray (Tokimatsu et al., 2011). The average N-value at each depth is shown in red. The data was obtained from the Chiba prefectural government (2011) and the authors' personal files. For the

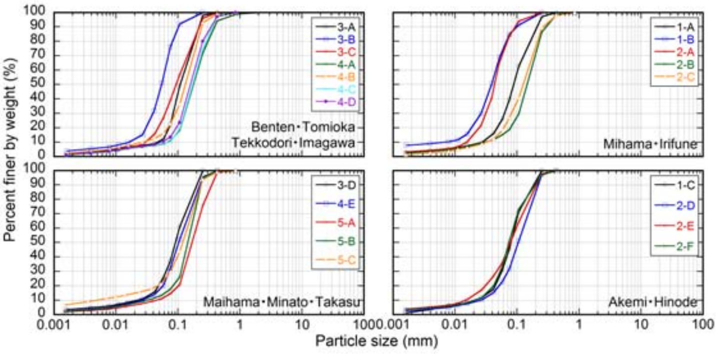

Figure 5.1. Grain size distribution curves of boiled sands (Tokimatsu et al., 2011)

Akemi-Hinode area, separate graphs were given for the northwestern and southeastern districts, because the extent of the damage was distinctively different between them. It can be seen in the figure that the N-value in the sand layer was extremely small in Tomioka, Imagawa and Akemi-Hinode (northwest), but large in the neighborhood of Urayasu Station, which is not reclaimed land, and in Akemi-Hinode (southeast), which is reclaimed land but which is the highest altitude in the city. The thickness of earth filling and sand layers was different from place to place, with Maihama, Mihama-Irifune, Takasu and Akemi-Hinode marking high figures.

Comparison of these findings with liquefaction damage suggests the following:

1) On the landside of the old coastline of 1964 or before, no liquefaction was observed even though the altitude is low and so the groundwater level is shallow. The N-value in this area is higher than in recently reclaimed land where liquefaction occurred. These facts suggest a possibility that “aging effect” of soil may have worked in mitigating liquefaction.

2) In Akemi-Hinode area (southeast), the N-value is relatively high and liquefaction damage was minor. It could be surmised that differences in reclamation materials and method of reclamation may have affected the degree of damage. Furthermore, the area’s altitude is rather high, indicating a possibility that differences in altitude may have also affected the extent of damage. This may be because, when the altitude is high, the groundwater level becomes relatively low and the consolidation of the silty sand layer below the groundwater table has progressed.

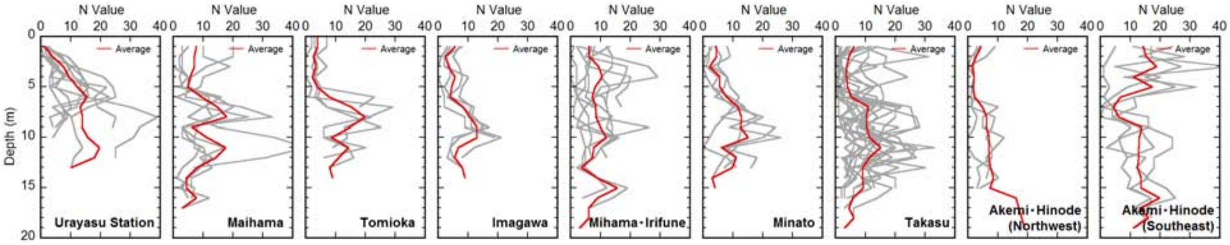

Figure 5.2. Distribution of SPT-Value with depth at selected districts (Tokimatsu et al., 2011)

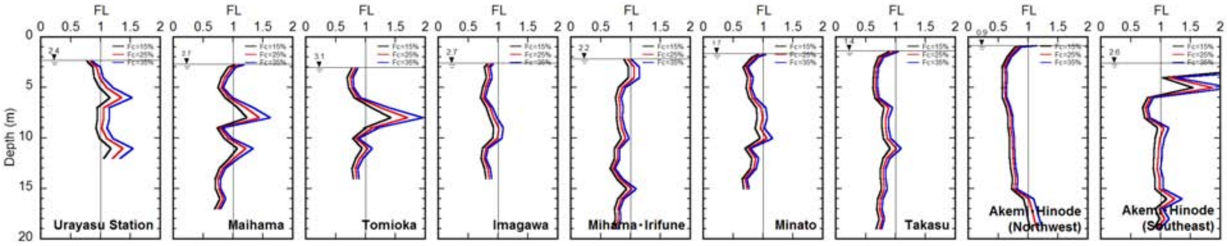

Figure 5.3. Result of SPT-based liquefaction evaluation at selected districts (Tokimatsu et al., 2011)

Table 5.1. Comparison between estimated and observed settlements

	Estimated (cm)									Observed (cm)		
	Fc=15%			Fc=25%			Fc=35%					
	Max	Ave	Min	Max	Ave	Min	Max	Ave	Min	Max	Ave	Min
Urayasu Station	19	9	3	14	6	2	11	5	2	0	0	0
Maihama	30	25	18	22	18	13	17	14	10	-	-	-
Tomioka	22	18	17	16	13	12	13	10	9	30	26	15
Imagawa	30	23	16	22	16	11	18	12	9	50	22	5
Mifune, Irifune	36	32	4	26	23	3	21	18	2	45	19	7
Minato	41	26	17	31	19	13	25	15	10	60	22	5
Takasu	49	38	9	37	28	7	30	23	5	50	23	2
Akemi, Hinode (Northwest)	56	44	45	43	33	32	35	27	27	65	32	3
Akemi, Hinode (Southeast)	23	17	15	19	11	11	15	9	9	15	8	2

3) Comparison of Figures 3.2, 4.1 and 4.6 shows that major liquefaction damage tended to occur just above or near buried valleys where PGA tended to be higher. Therefore, the differences in ground surface response due to differences in thickness of alluvial deposits might have affected the occurrence and extent of soil liquefaction.

Figure 5.3 shows the results of liquefaction evaluation made according to the Recommendations for Design of Building Foundations (Architectural Institute of Japan, 2001), using the average N-value for each area (Figure 5.2), a peak ground acceleration of $2.0m/s^2$ and at magnitude 9.0. The ground water level is set at the average for each area, and the fines content was set at three different levels—15%, 25% and 35%, as it was unknown in many areas.

The FL-value (safety factor against liquefaction) came to 1 or more at most depths in the neighborhood of Urayasu Station, where no liquefaction damage was observed, and in the Akemi-Hinode (southeast) area, where only minor damage was seen. But in other places, the FL-value turned out to be lower than 1. Especially in Mihama-Irifune, Takasu and Akemi-Hinode (northwest), there is a sequence of layers with the FL-value of lower than 1 down to the bottom of sandy soil. These results appear to be consistent with the field observation.

Table 5.1 shows comparison of the average figure of estimated ground settlement based on N-value distribution in each area in Figure 5.2 (calculation made under the AIJ guidelines: AIJ, 2001) with those observed in the field. With fines content at 25%, the estimated settlement was 6 cm near Urayasu Station and 11 cm in Akemi-Hinode (southeast), whereas is was 16 to 33 cm in other areas where liquefaction was severe, with the highest figure for Akemi-Hinode (northwest). These estimates were in fairly good agreement with the field observation. Even though a further review is necessary after clarifying effects of fines content and additional cyclic loading caused by the aftershocks on the observed ground settlements, it seems that the current design guidelines (AIJ, 2001) could have a potential capability to predict not only the occurrence of soil liquefaction but also the resulting ground settlements and thus the degree of liquefaction severity and damage.

6. CONCLUSIONS

Field surveys on liquefaction-induced damage to houses in Urayasu city during the 2011 Great East Japan Earthquake have found the following:

1) Liquefaction occurred in areas reclaimed in relatively recent years. In some places, liquefaction caused severe sand boils and ground settlement of up to 50 cm, leading to damage such as tilt and settlement of wooden and reinforced concrete buildings with spread foundations, uplift of buried structures and slumps of roads. Liquefaction also caused a major gap between pile-supported buildings and surrounding ground, but no structural damage was observed in superstructures. Buildings with a

spread foundation that had high rigidity, such as mat foundation, did not suffer structural damage to their superstructures, even when they settled or tilted. Certain pile foundations then under construction in the liquefied area also incurred damage. The effects of long time cyclic loading induced by the M9 main shock together with additional cyclic loading caused by the aftershocks on the degree of soil liquefaction and associated damage to buildings and infrastructures should be clarified further.

2) Degree of liquefaction varied from place to place even within the city, and may depend on such factors as the thicknesses of reclaimed fill and alluvial deposit, the altitude or groundwater table, and structure-soil-structure interaction effects as well as whether remedial measures had been taken to mitigate future geotechnical hazards. Economical techniques should be developed not only to quickly level up tilted buildings but also to reduce liquefaction susceptibility of the ground beneath existing buildings.

3) Some of boiled sand samples collected had high fines content, indicating that fine-grained sands had liquefied. The currently available liquefaction evaluation procedure appeared to have performed relatively well in predicting the occurrence of soil liquefaction as well as the degree of resulting ground settlements. The damage extent of wooden houses generally increased with increasing liquefaction-induced ground settlements. Thus there is strong need to obtain more detailed field performance data in order to enhance the adequacy of the currently available liquefaction evaluation procedures.

ACKNOWLEDGEMENT

This survey was conducted jointly with Prof. Shuji Tamura, Kyoto University, Prof. Hiroko Suzuki, Tokyo Institute of Technology, Dr. Eisuke Nishikawa, a researcher at the Tokyo Institute of Technology's Global COE Program, Messrs. Youhao Zhou, Kodai Watanabe, Yoshiaki Ibaraki, Kei Inamura, Yuki Takeda, Yusuke Nakano and Kazushi Tohyama, graduate students of Tokyo Institute of Technology, Dr. Akio Abe of Tokyo Soil Research Co. and the GEER team from the United States (Profs. Ross Boulanger, Scott Ashford, Jonathan Stewart, Kyle Rollins and Steve Kramer; and Dr. Jennifer L. Donahue). Information regarding damage to building has been provided by Urayasu City. The strong motion records were provided by the National Research Institute for Earth Science and Disaster Prevention (NIED), and Keiyo Gas Company. We greatly appreciate their support and cooperation.

REFERENCES

Architectural Institute of Japan (2001). Recommendations for Design of Building Foundations (in Japanese).

Architectural Institute of Japan (2011). Preliminary Reconnaissance Report of the 2011 Tohoku-Chiho Taiheiyo-Oki Earthquake (in Japanese).

Chiba Prefectural Environmental Research Center (2011). http://www.pref.chiba.lg.jp/suiho/chishitsu.html (accessed 2011.10.27)

National Research Institute for Earth Science and Disaster Prevention (2011). Kyoshin Network K-NET, http://www.k-net.bosai.go.jp/k-net/ (accessed 2011.10.27)

Tokimatsu, K., Tamura, S., Suzuki, H. and Katsumata, K. (2011). Damage to soils in the 2011 Tohoku Pacific earthquake, *Research Reports on Earthquake Engineering,* **118**, 21-47 (in Japanese).

Tokimatsu, K., Tamura, S., Suzuki, H. and Katsumata, K. (2012). Geotechnical problems in the 2011 Tohoku Pacific earthquake, *Joint Conference Proceedings of 9th International Conference on Urban Earthquake Engineering and 4th Asia Conference on Earthquake Engineering*, March 6-8, **1**, 49-61.

Tokimatsu, K. and Katsumata, K. (2012). Liquefaction-induced damage to buildings in Urayasu City during the 2011 Tohoku Pacific Earthquake, *Proc., Intl. Symposium on Engineering Lessons Learned from the 2011 Great East Japan Earthquake*, March 1-4, Tokyo, Japan, 665-674.

Urayasu City (2011a). Project of Reclaimed Land, http://www.city.urayasu.chiba.jp/menu2863.html (accessed 2011.10.27).

Urayasu City (2011b). Geographical and Geological Features of Urayasu City, http://www.city.urayasu.chiba.jp/menu3185.html (accessed 2011.10.27).

Urayasu City (2012). Final Report, Committee on Investigation of Remedial Measures against Soil Liquefaction in Urayasu City.