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LIQUEFACTION-INDUCED DAMADE TO BUILDINGS IN URAYASU CITY DURING THE 2011 TOHOKU PACIFIC EATHQUAKE

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ABSTRACT: An overview of the liquefaction-induced damage to buildings in Urayasu city during the 2011 Tohoku Pacific earthquake is presented, based on field reconnaissance made after the quake. It is shown that extensive soil liquefaction occurred in most of the areas reclaimed after 1968, accompanied by numerous sand boils and large ground settlement up to 60 cm as well as settlement/tilting of wooden and reinforced concrete buildings supported on spread foundations. The extent and distribution of the damage were significantly affected by local soil conditions including the thickness of reclaimed fills, the depth to the bedrock or natural site period, and whether remedial measures were taken against soil liquefaction, as well as structure soil structure interaction effects.

Key Words: Tohoku Pacific earthquake, soil liquefaction, ground settlement, tilting and settlement of building

INTRODUCTION

The “11th March 2011 Tohoku Pacific 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[1),4)]. 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.

GOELOGICAL AND GEOPHSICAL SETTING

Figure 1 shows a map of Urayasu city, Chiba Prefecture, with the years when reclamation work

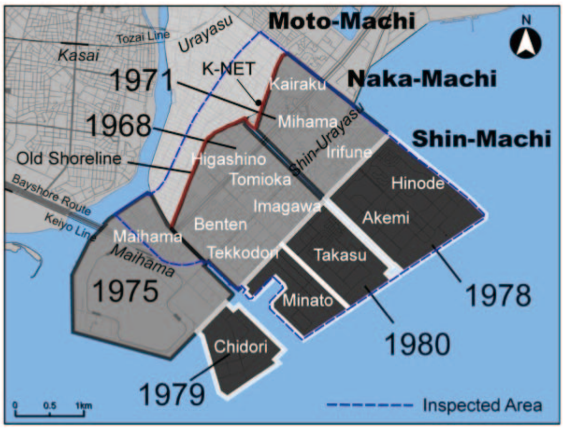

Fig. 1 Map showing Urayasu city with reclamation year[4),5)]

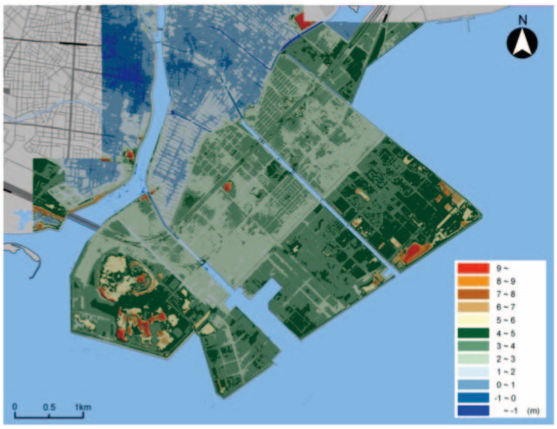

Fig. 2 Map showing elevation in 2006

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 1-chome, Mihama 3-chome and Irifune 4-chome.

Figure 2 shows altitudes based on a digital elevation model with 2x2 m data spacing that was determined with an airborne scanning laser survey made before the quake (December 2006). 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 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 3 shows depth distribution for the sedimentation of soft soils overlying the Pleistocene deposit. Figure 4 is a cross section of the ground of Urayasu city along the A-A' survey line in Figure 3. 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. It can also be seen by comparing Figures 3 and 4 that the depth of Pleistocene deposit (Ds), with N-values of 50 or

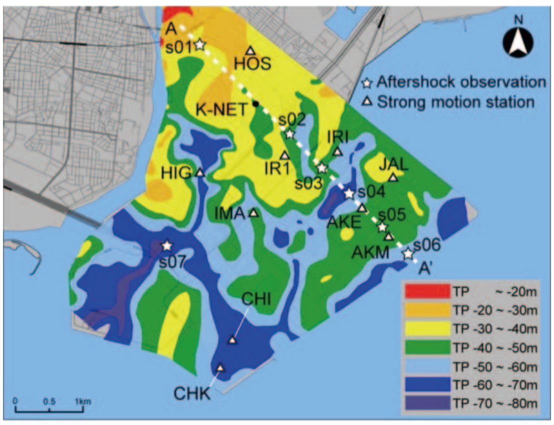

Fig. 3 Map showing thickness of soft soil overlying Pleistocene deposit[6),7)]

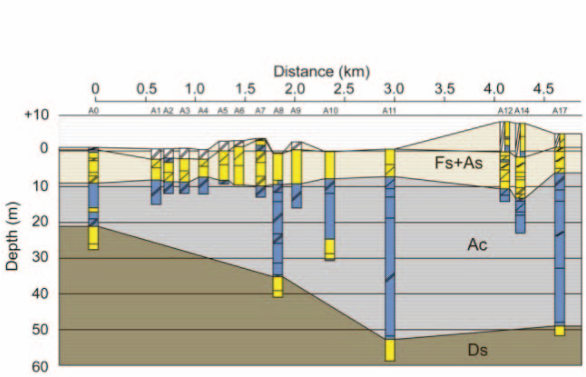

Fig. 4 Geological cross section along A-A'[4)]

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). By comparison, along the northeast to southwest line, which is perpendicular to the A-A’ line, the depth becomes greater in the southwest direction. Figures 3 and 4 shows that 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 5 shows the distribution of H/V spectral peak period in the city. The H/V peak period varies significantly from 0.7s to 2.5s within the city in such a way that it becomes longer with increasing thickness of soft soil.

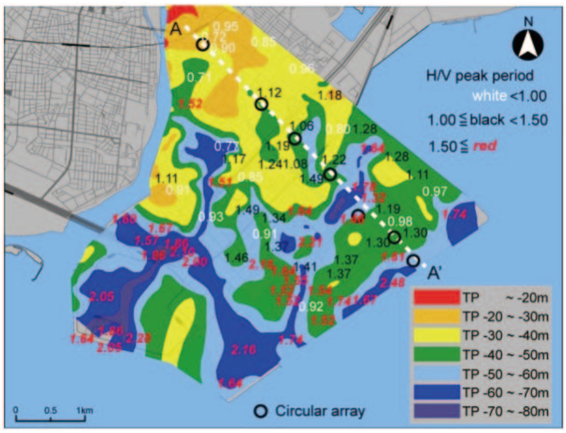

Fig. 5 Map showing H/V spectral peak period

STRONG MOTION CHARACTERISTICS

Among the K-NET strong motion stations in and around Urayasu city along the Tokyo Bay coast at which digitized time-history data of the main shock are available (National Research Institute for Earth Science and Disaster Prevention, 2011), soil liquefaction was observed near two stations: at K-NET Inage (CHB024) and K-NET Tatsumi (TKY017). No liquefaction was spotted in the neighborhood of K-NET Urayasu (CHB008), which is located north of the old coastline in Urayasu city.

The acceleration time history at K-NET Inage (a duration of 100 seconds including principal

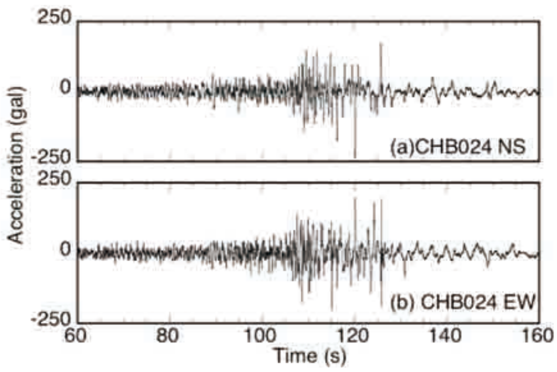

Fig. 6 Acceleration time histories at K-NET Inage during the main shock[4)]

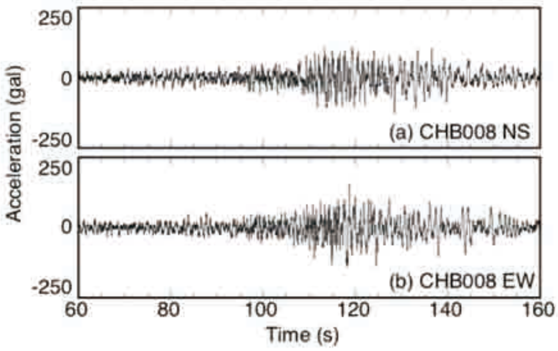

Fig. 8 Acceleration time histories at K-NET Urayasu during the main shock[4)]

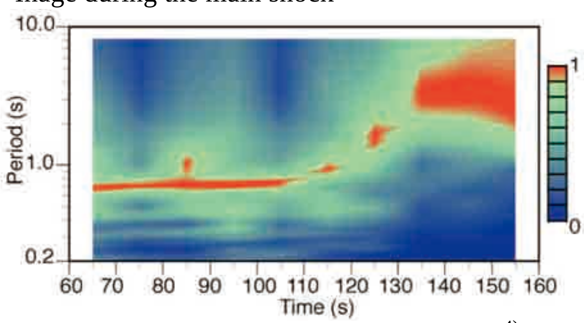

Fig. 7 Normalized running spectra at Inage[4)]

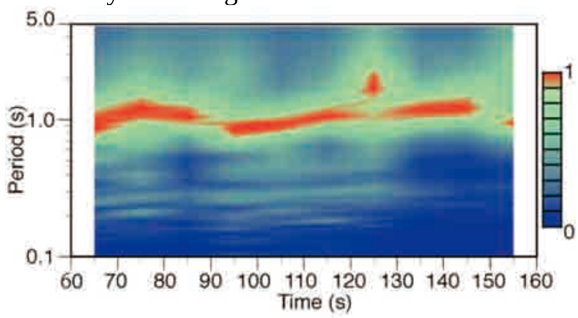

Fig. 9 Normalized running spectra at Urayasu[4)]

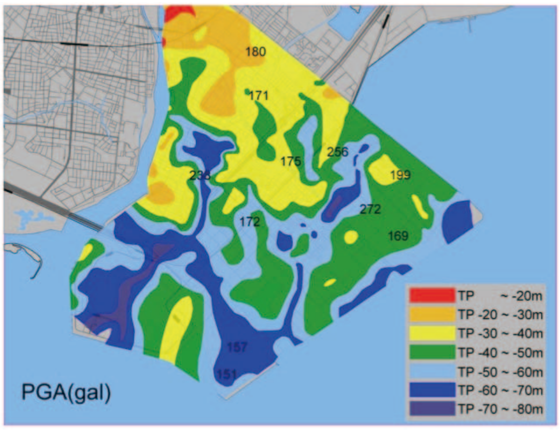

Fig. 10 PGA recorded in the city during the main shock

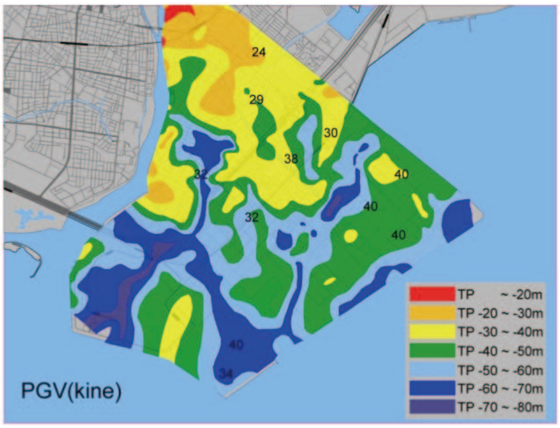

Fig. 11 PGV recorded in the city during the main shock

motions) is shown in Figure 6. The peak acceleration was 2.34m/s2 in the north-south direction and 2.03m/s2 in the east-west direction. Spiky waves occurring around 120 seconds suggest a possibility of cyclic mobility of sand in a liquefaction process. Figure 7 shows the running spectra at K-NET Inage, normalized at the spectral peak of each 10-second interval. The periods become elongated from 0.7 s to about 4 s between 110 seconds to 140 seconds. This suggests that the ground liquefied gradually with cyclic loading during the 30 seconds. Figures 8-9 present similar data for K-NET Urayasu, where no liquefaction occurred. Unlike that at K-NET Inage, the running spectra at K-NET Urayasu shows no apparent changes in the spectral peak period. Considering the fact that the principal motion with accelerations greater than about 1 m/s2 at the non-liquefied Urayasu site lasted about 30 s from 110 to 140 seconds, complete liquefaction at Inage likely to have occurred in the latter part of the principal motion.

Figures 10 and 11 show the distribution of peak grand acceleration and velocity (PGA and PGV) obtained with strong motion network operated by Keiyo Gas Co. Ltd (Urayasu city, 2012). Both peak ground acceleration and velocity varied in the city, with tendency where PGA is largest in the Naka-machi area and PGV increases towards the sea.

LIQUEFACTION-INDUCED DAMAGE TO BUILDINGS

Figure 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.

Based on the field performance of soils and buildings including ground settlements as well as settlements and tilting of houses, a damage distribution map was drawn in which the extent of soil liquefaction is classified into four categories (i.e., no, slight, moderate, and extensive) as shown in Fig. 12. It can be confirmed that, liquefaction-induced damage was not seen on the north of the old coastline

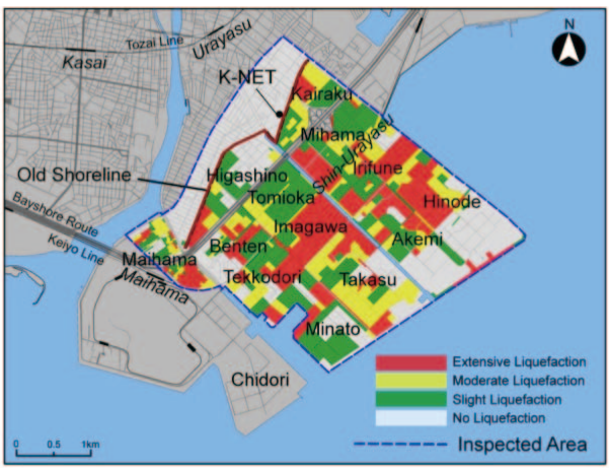

Fig. 12 Map showing extent of liquefaction damage[4]


Photo 1 Sand boils stacked over the road


Photo 2 Wooden house suffering large settlement


Photo 3 Buildings suffering large settlement and tilting[4)]


Photo 4 Buildings supported on pile (left) and spread (right) foundations[4)]

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, however, varies 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.

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 (Photo 1), ground settlements up to 60 cm as well as settlements and tilts of building and houses on spread foundations (Photos 2-4) were observed everywhere. Vertical gaps were created around pile-supported structures due to ground settlements (Photos 4-5), causing damage to piping and other facilities. Underground facilities, such as manholes, emergency water tanks and parking lots were uplifted (Photo 6), damage was done to tap

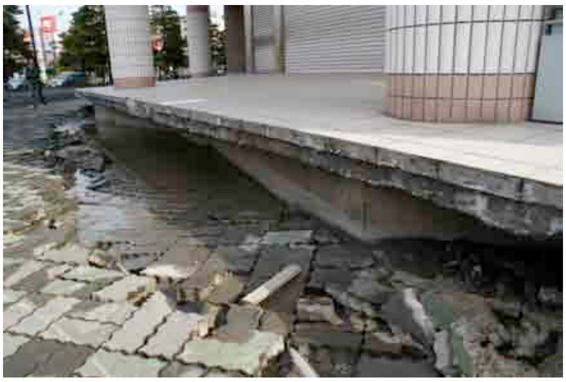
Photo 5 Pile-supported buildings suffering large ground settlement[4)]


Photo 6 Uplifted underground parking garage[4)]

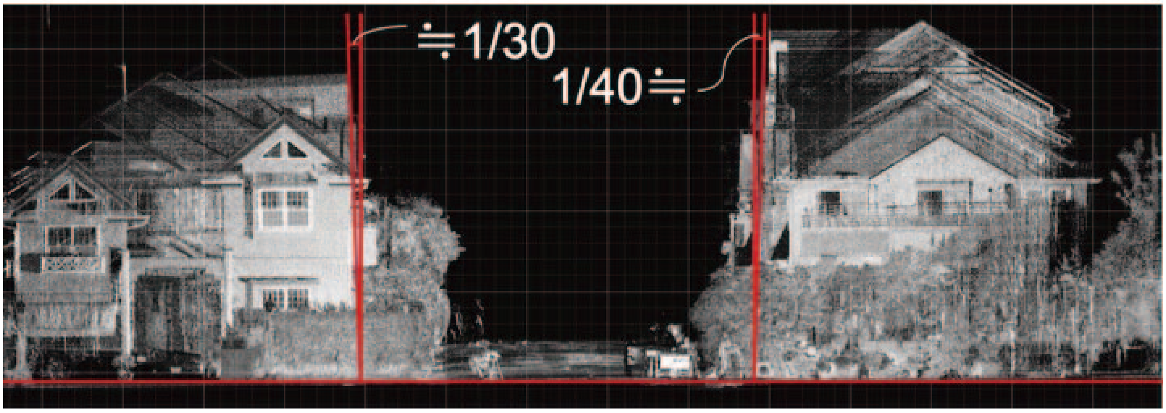

Fig. 13 Typical result of 3D laser scanning of buildings

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 houses, and houses whose first floor or semi-basement was made of reinforced concrete to prevent flood damage, suffered larger settlement, probably because their ground contact pressure was greater.

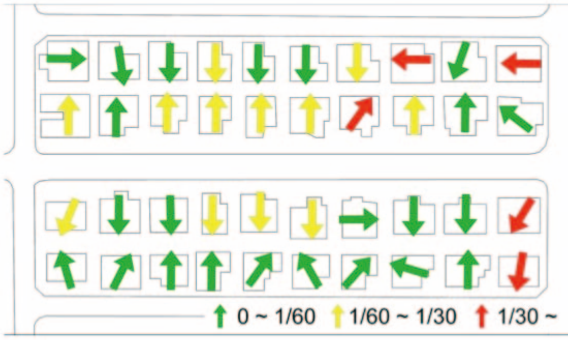

Fig. 14 Typical result of tilting angle and direction of houses in a district

4) When buildings face each other across a street, they tend to tilt backward, away from each other, as in Photo 1 and Figures 13 and 14. When two buildings stand closely together, they often tilt toward each other, as in Photo 3 and Figures 13 and 14. 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 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 effectiveness of ground improvement work against the ground shaking with a peak ground acceleration of 2.0m/s2 caused by the M9 long duration earthquake.

Figure 15 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.

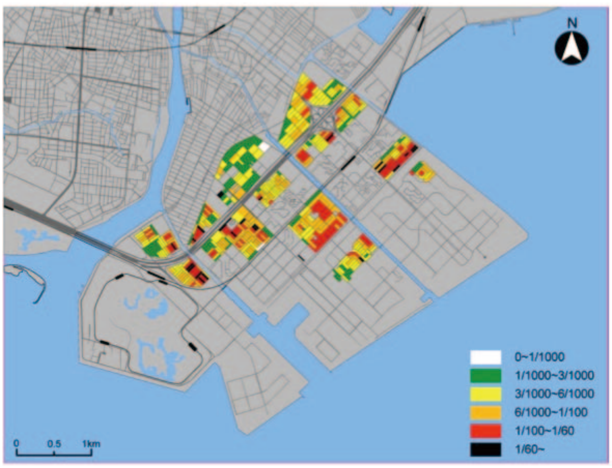

Fig. 15 Map showing distribution of average inclination angle of houses[7)]

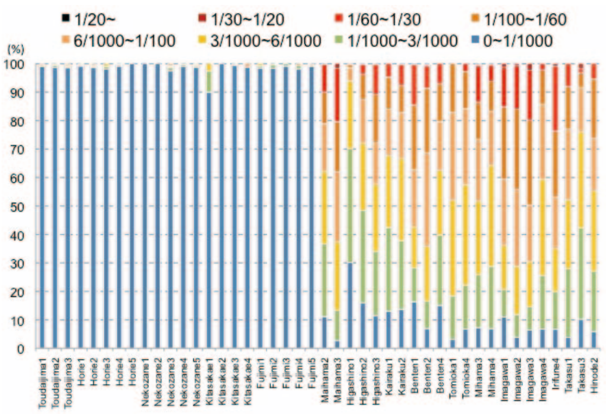

Fig. 16 District by district distribution of inclination angle of houses[7)]

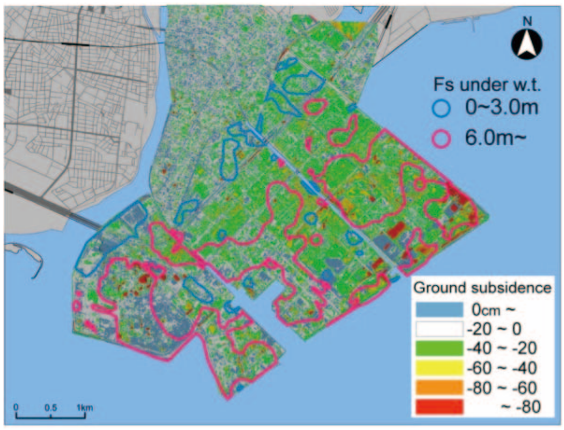

Fig. 17 Map showing vertical ground settlement between 2006 and 2011

Figure 16 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 12.

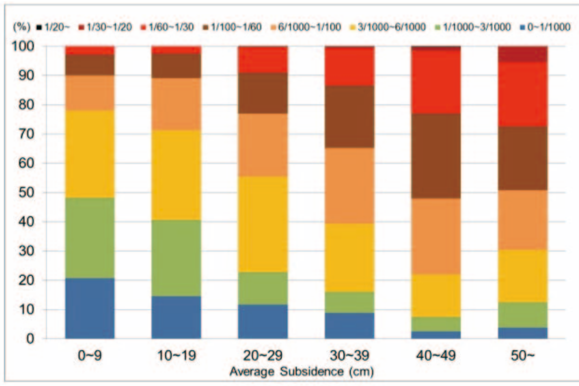

Fig. 18 Relation between average ground settlement and average angle of inclination

Figure 17 shows ground subsidence estimated from the difference between the altitudes obtained before and after the quake. 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. It seems that the area with larger ground settlements experienced more severe liquefaction damage to buildings.

Figure 18 shows the distribution of inclination angle of residential houses with respect to ground subsidence. The figure apparently shows that the inclination angle tends to increase with increasing liquefaction-induced ground settlement. For example, houses titled more than 1/100 are about 10% if the liquefaction-induced settlement (S) is less than 20 cm, whereas it becomes about 50% when S becomes greater than 40 cm.

COMPARISON OF FIELD PERFORMANCE WITH SPT-BASED LIQUEFACTION EVALUATION PROCEDURE

Figure 19 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 20 shows depth distributions of the N-value of earth filling or sand layers at each area of Urayasu in gray. The average is shown in red. The data was obtained from the Chiba prefectural government[2)] and the authors' own survey. For the 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 in altitude. 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.

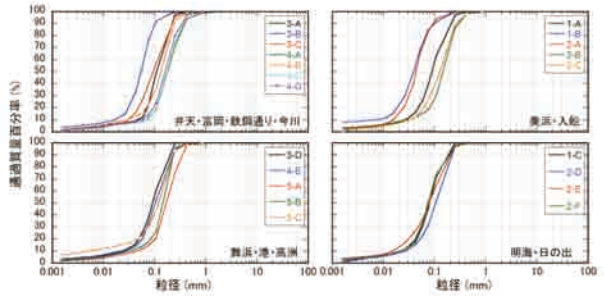

Fig. 19 Grain size distribution curves of boiled sands[4)]

Comparison of these findings with liquefaction damage suggests the following:

1) On the land side 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. And in this area, the N-value 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.

3) Comparison of Figures 8 and 13 shows that major liquefaction damage tended to occur just above or near buried valleys. Therefore, it cannot be denied that differences in ground surface response due to differences in thickness of alluvial deposits could have affected the occurrence and extent of soil liquefaction.

Figure 21 are the results of liquefaction evaluation made with a method specified in the Architectural Institute of Japan's guidelines for basic structural design (2001), using the average N-value for each area (Figure 20), a peak ground acceleration of 2.0m/s2 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%.

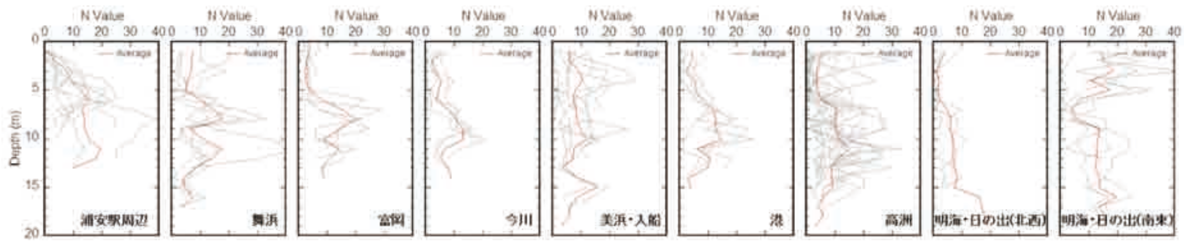

Fig. 20 Distribution of SPT-Value with depth at selected districts[4)]

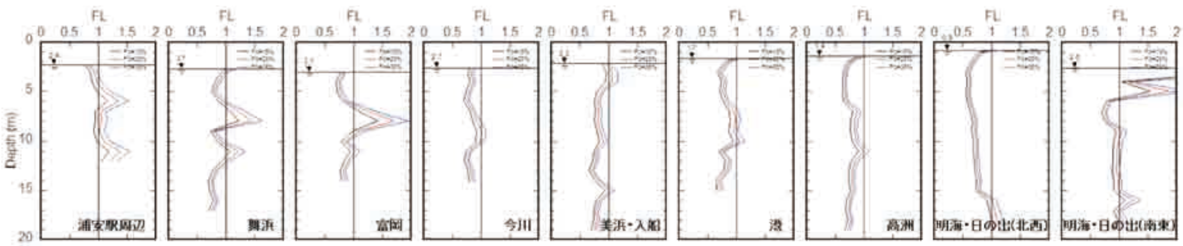

Fig. 21 Result of SPT-based liquefaction evaluation at selected districts[4)]

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 are a sequence of layers with the FL-value of lower than 1 until the depth of nearly 20 meters. These results agree with the actual damage situation.

Table 1 Estimated and Observed Settlements in Urayasu[4)]

	Estimated (cm)									Observed (cm)		
	Fc=15%			Fc=25%			Fc=35%					
	Max.	Av.	Min.	Max.	Av.	Min.	Max.	Av.	Min.	Max.	Av.	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

Table 1 shows comparison of the average figure of estimated ground settlement based on N-value distribution in each area in Figure 21 (calculation made under the AIJ guidelines), and the actual, measurements. Because fine-grain content ratio was not clear in many areas, estimates were made for 15%, 25% and 35%.

With fines content at 25%, the estimated settlement was 6 centimeters near Urayasu Station and 11 cm in Akemi-Hinode (southeast). But in other areas where liquefaction was severe, the estimate was 16 to 33 cm, with the highest figure for Akemi-Hinode (northwest). These estimates were generally in agreement with the tendency in actual figures. Even though a review is necessary after clarifying fines content for each area and each depth, it can be said that the current design guidelines were able to predict, with a reasonable degree of accuracy, the possibility of liquefaction and degree of damage.

CONCLUSIONS

Field surveys on liquefaction-induced damage to buildings in Urayasu city during the 2011 Tohoku Pacific Ocean 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.

2) Degree of liquefaction differed from place to place even within the same city, and may depend on such factors as the thicknesses of reclaimed fill and alluvial deposit, the altitude or groundwater table, and the presence of ground improvement, as well as the reclamation year, and the method and material used for reclamation.

3) Some of boiled sand samples collected had high fines content, indicating that fine grained sands had liquefied.

4) The currently available liquefaction evaluation procedure appeared to have performed well in predicting the occurrence of soil liquefaction as well as the degree of resulting ground settlements. But there is need to obtain more detailed data on ground and scrutinize the adequacy of those methods.

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