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ABSTRACT

An overview of the geotechnical aspects of the building damage in the 2011 Tohoku Pacific earthquake is presented, based on field reconnaissance made after the quake. It is shown that: (1) Extensive soil liquefaction occurred along the coast of Tokyo Bay and around the Tonegawa River floodplain. Liquefaction primarily occurred within relatively new reclaimed area, with large ground settlement up to 60 cm, accompanied by settlement/tilting of wooden and reinforced concrete buildings supported on spread foundations; (2) Numerous houses in Sendai's hilly residential areas constructed with cut-and-fill methods were badly damaged not only by simple collapse of retaining walls, but also by slope failures of fill; (3) Several pile-supported buildings tilted and settled not only in the Tohoku region but also in the Kanto plain, implying damage to pile foundations; and (4) Several steel and reinforced concrete structures in Onagawa were knocked over by tsunami surges, probably after having suffered damage to their pile foundations.

INTRODUCTION

The Tohoku Pacific Earthquake (M9.0), occurring of the coast of the Tohoku area (Fig. 1) at 2:46 p.m. on March 11, 2011, was the strongest event ever recorded in Japan. The earthquake triggered giant tsunami, which caused huge damage mainly in the Tohoku region, leaving over 18,000 people dead or missing. Furthermore, soil liquefaction and other ground problems have left extensive damage to infrastructure, lifelines, houses and other structures.

The significant features related to geotechnical problems caused by the event include: (1) settlement and tilting of buildings and houses with spread foundations and failures of piles and buildings supported on pile foundation, all occurred in liquefied area; (2) damage to pile foundations due to inertial force from superstructures, (3) slope failures of manmade fills and associated damage to residential houses in Sendai's hilly residential area, (4) tsunami-induced overturning of several buildings supported on pile foundations in the Tohoku coastal region, and (5) damage to buildings and houses caused by the vertical gap of the causative fault. We carried out geotechnical reconnaissance surveys after the quake with emphasis placed on liquefaction-induced damage to residential houses in Urayasu city that has been developed in the reclaimed waterfront of Tokyo Bay. This paper summarizes the results of our survey.

LIQUEFACTION DAMAGE AND SEISMIC MOTIONS

Table 1 summarizes the number of liquefaction-induced damage to residential houses by prefecture. Liquefaction occurred in 90 cities and towns in 9 prefectures in the Tohoku and Kanto regions, having affected almost 27 thousands houses, most of which concentrated in the Kanto region

Fig. 1. Epicenter of the Tohoku Pacific Earthquake

including Chiba and Ibaraki prefectures. Figure 2 shows a map of the Kanto region together with the locations at which soil liquefaction was observed. The figure clearly indicates that liquefaction occurred along the coastline of Tokyo Bay as well as the lower reaches of the Tone River.

Figure 3 is a map of the Tokyo Bay area in which location of reclaimed lands (and years of reclamation work; Kaizuka, 1993) and of the liquefied sites in the 2011 event. The figure clearly indicates that liquefaction occurred only in the reclaimed lands in the Tokyo Bay area.

Figure 4 shows correlations between the depth of the alluvial basement and liquefaction sites (Bureau of Port and Harbor, Tokyo Metropolitan Government, 2001; Kanto Regional Development Bureau, Ministry of Land, Infrastructure, Transportation and Tourism, 2011; Ministry of Land, Infrastructure, Transportation and Tourism, 2011). It is interesting to note that most of the extensively liquefied sites are located in areas where the basement depth is 35-40 meters or more.

Table 1. Number of liquefaction-induced damage to residential houses

Tohoku	Iwate	3
	Miyagi	140
	Fukushima	1,043
Kanto	Ibaraki	6,751
	Gunma	1
	Saitama	175
	Chiba	18,674
	Tokyo	56
	Kanagawa	71
Total		26,914

Fig. 2. Map of Kanto region
(Kanto Regional Development Bureau, Ministry of Land, Infrastructure, Transportation and Tourism, 2011)

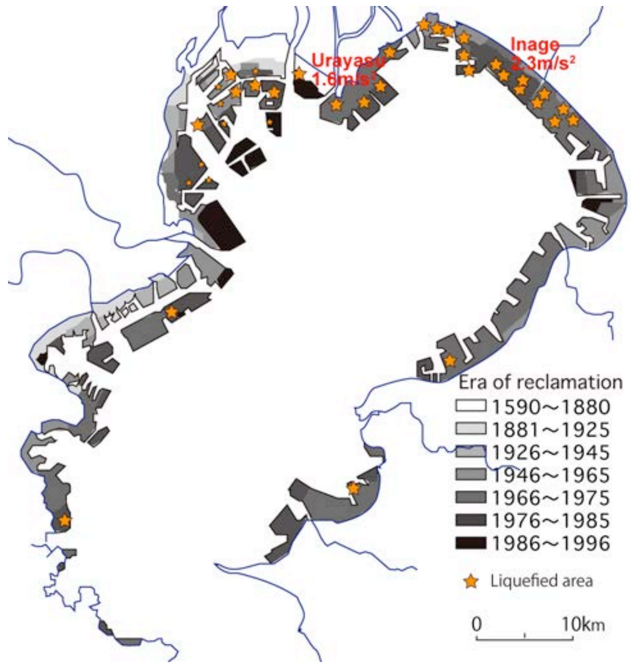

Fig. 3. Reclaimed lands of Tokyo Bay area
(Kaizuka, 1993)

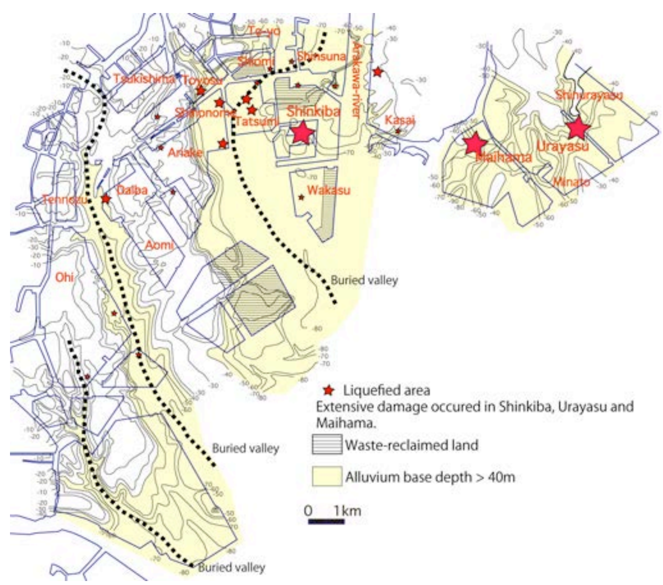

Fig. 4. Map showing depth of alluvium deposit
(Bureau of Port Harbor, Tokyo Metropolitan Government, 2001 and Urayasu City, 2011b)

Figures 2 and 3 also show selected peak accelerations recorded in the Kanto area. Among the K-NET strong motion stations 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 observed in the neighborhood of K-NET Urayasu (CHB008), which is located north of the old coastline in Urayasu city.

Figure 5 shows acceleration time histories at K-NET Inage (a duration of 100 seconds including principal motions). The peak acceleration was 2.34m/s^2 in the north-south direction and 2.03m/s^2 in the east-west direction. Spiky waves occurring around 120 seconds suggest a possibility of cyclic mobility of sand in a liquefaction process.

Figure 6 presents similar data during the main shock and the largest aftershock in K-NET Urayasu, where no liquefaction occurred. Unlike that at K-NET Inage, the acceleration time history at K-NET Urayasu does not show any spiky waves. The peak accelerations during the main shock and aftershock were 1.71m/s^2 and 0.80m/s^2, respectively. The largest aftershock (M7.6) occurring of the coast of Ibaraki Prefecture (Fig. 1) about 30 min after the main shock, could have induced re-liquefaction and worsened the damage caused by the main event, although the PGA in the Tokyo Bay area was about a half of the main shock.

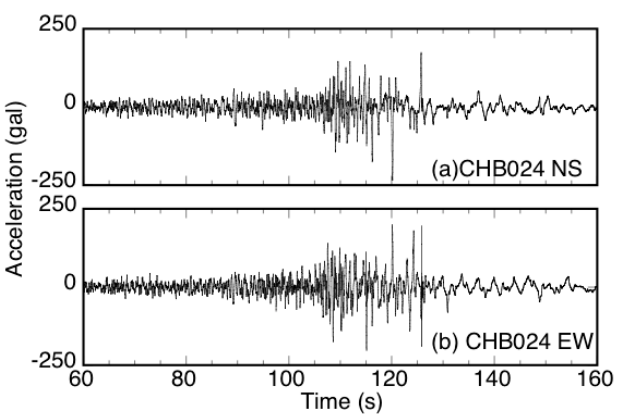

Fig. 5. Acceleration time histories at K-NET Inage

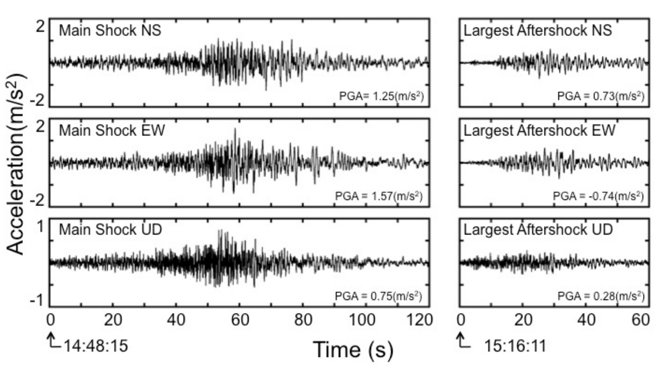

Fig. 6. Acceleration time histories at K-NET Urayasu

LIQUEFACTION-INDUCED DAMAGE IN URAYASU

Figure 7 shows a map of Urayasu city, Chiba Prefecture, as well as the years when reclamation work was done for each area. The work in the city started in around 1964 outside levees of the oldtown, Moto-machi. In the area reclaimed by 1975 (Naka-machi), many houses, commercial buildings and public facilities have been built. Meanwhile, the areas completed by 1980 (Shin-machi) 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. In Urayasu city, a magnitude-6.7 quake that occurred off eastern Chiba Prefecture on Dec. 17, 1987 (Chibaken Toho-oki Earthquake), reportedly caused less extensive soil liquefaction in such areas as Kairaku 1-chome, Mihama 3-chome and Irifune 4-chome.

Figure 8 shows the distribution of peak ground acceleration (PGA) within the city. The peak ground acceleration varied within the city from 1.5-2.7m/s^2, probably depending on the soil condition including the thickness of soft soil and the occurrence or nonoccurrence of soil liquefaction at each site.

Figure 8 also 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, 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

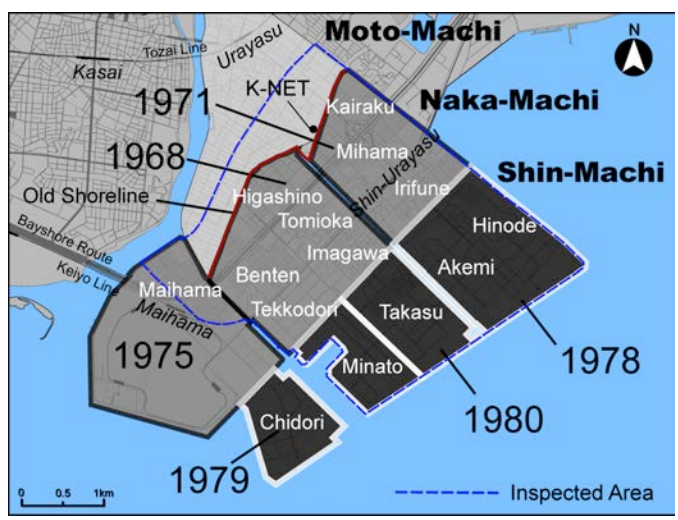

Fig. 7. Map showing Urayasu City with reclamation year (Tokimatsu et al., 2012, Urayasu, 2011b)

(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.

Our geotechnical reconnaissance survey was carried out in the area circled with the dotted line in Fig. 7. Figure 9 shows a damage 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

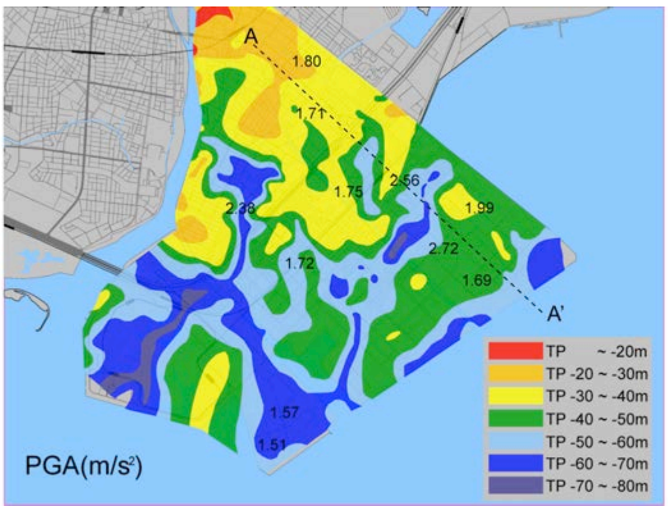

Fig. 8. Map showing thickness of soft soil overlying Pleistocene deposit (Tokimatsu & Katsumata, 2012, Urayasu City, 2011b)

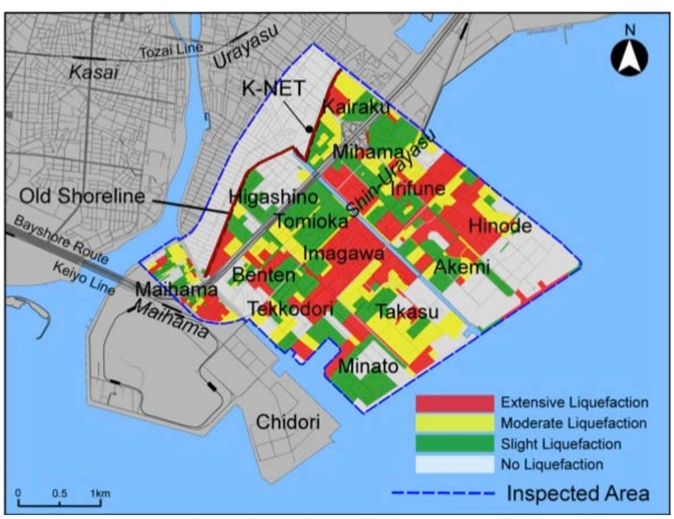

Fig. 9. Map showing extent of liquefaction damage (Tokimatsu et al, 2011)

re-liquefy. Summarized below are the typical findings in the reclaimed area:

1) In the area where liquefaction occurred, many sand boils (Photo 1) and ground settlements were obnserved. Underground facilities, such as manholes, emergency water tanks and parking lots were uplifted (Photos 2 and 3), tapping water and sewerage systems.

2) Many buildings and houses on spread foundations (Photos 4-6) tilted and settled without any damage to superstructure.

Photo 1. Boiled sand and large settlement of house (Tokimatsu et al., 2011)

Photo 2. Uplifted manhole (Tokimatsu et al., 2011)

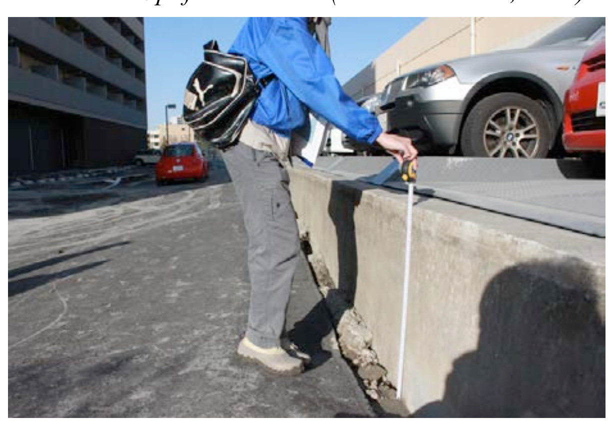

Photo 3. Lifted parking lot (Tokimatsu et al., 2011)

This is because many buildings had adopted mat foundations or highly rigid foundations enough to prevent damage resulting 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 relatively large settlement, probably because their ground contact pressure was greater.

4) Many pile-supported buildings suffered large gaps as much as 50 cm, (Photos 6 and 7) which resulted from liquefaction-induced ground settlement.

5) In many areas where no liquefaction occurred in the reclaimed areas including the Tokyo Disneyland, ground improvement work of some kind has been carried out. This has confirmed the effectiveness of ground improvement work against earthquake shaking with a peak ground acceleration of $2.0 m/s^2$ caused by the M9 earthquake.

LIQUEFACTION-INDUCED DAMAGE TO RESIDENTIAL HOUSES IN URAYASU

Figure 10 shows the distribution of damaged houses in terms of inclined angle, based on the survey on about 9,000 houses conducted by Urayasu city government. Figure 11 shows the distribution of average inclination angle of residential houses in each district. Figures 10 and 11 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 Fig. 9.

Figure 12 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 Fig. 12 with Figs. 9 and 10 suggests that the area with larger ground settlements experienced more severe liquefaction damage to buildings.

Figure 13 shows the distribution of inclination angle of

Photo 4. Largely tilted building (Tokimatsu et al., 2011)

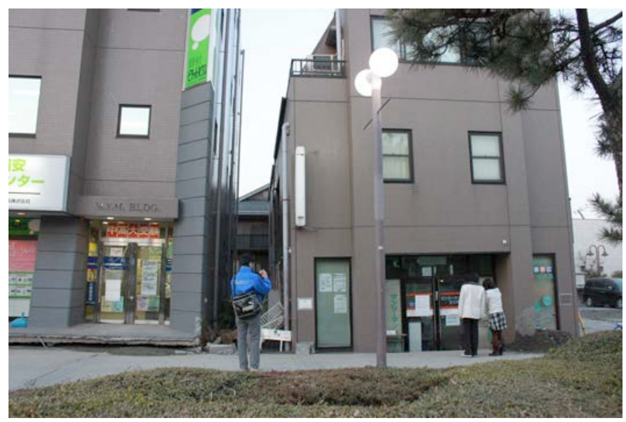

Photo 6. Pile-supported building and settled building (Tokimatsu et al., 2011)

Photo 5. Tilting houses (Tokimatsu et al., 2011)

Photo 7. Pile-supporting building suffering large settlement (Tokimatsu & Katsumata, 2012)

residential houses with respect to ground settlement, prepared from Figs. 10 and 12. Figure 13 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.

A close inspection of the damage to houses suggests that, when two buildings stand closely together, they often tilt toward each other, as in Photo 4 and Fig. 14. This is supposed to occur because the ground settlement between the two structures is greater due to their combined weight loads. When buildings face a street, they tend to tilt backward as shown in Photo 5 and Fig. 14, probably because they tended to incline toward the closer buildings located behind them.

Many residential houses adopted cement column piles or steel pipe piles for reducing uneven settlement caused by very soft surface soils. Figure 15 summarizes the performance of such 151 houses located in the heavily damage area with thickness of reclaimed fill greater than 8 m. The damage to houses tends to decrease with increasing length of pile, regardless of pile type.

Table 2 summarizes the performance of 136-engineered buildings owned by Urayasu city. The buildings in the non-liquefied Moto-machi did not suffer any significant damage not only to structure itself but also to lifelines, while

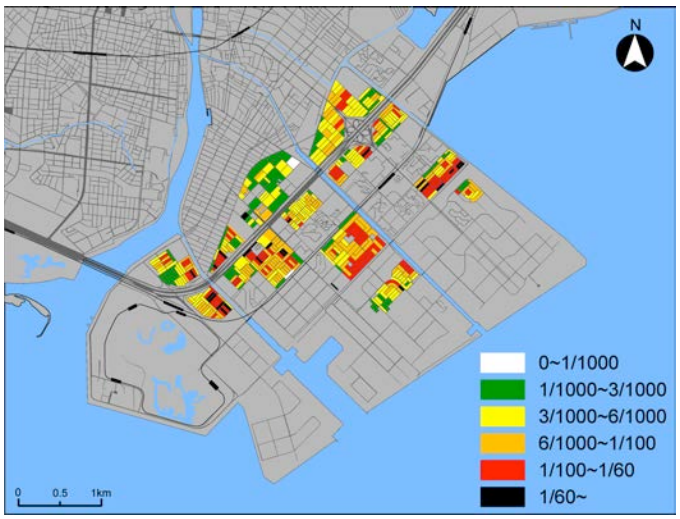

Fig. 10. Distribution of inclination angle of houses (Urayasu City, 2012)

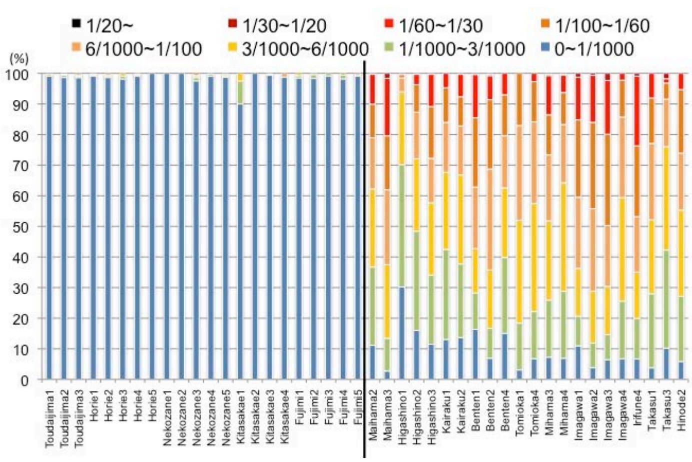

Fig. 11. District by district distribution of inclination angle of houses (Urayasu City, 2012)

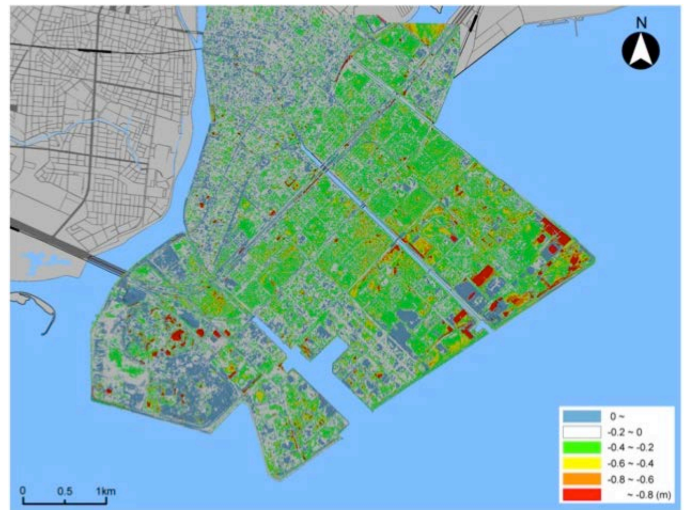

Fig. 12. Map showing vertical ground settlement between 2006 and 2011 (Tokimatsu & Katsumata, 2012)

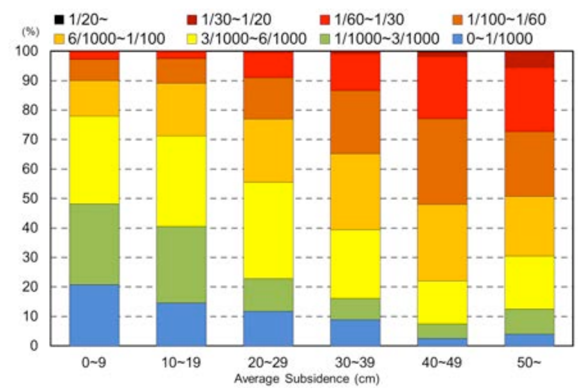

Fig. 13. Relation between ground settlement and angle of inclination (Tokimatsu & Katsumata, 2012)

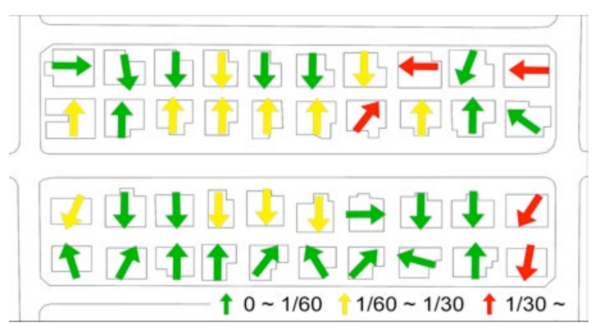

Fig. 14. Typical result of tilting angle and direction of houses in a district (Urayasu City, 2012)

Table 2. Occurrence of ground settlement around pile-supported building (Urayasu City, 2012)

	Point Bearing Piles		Friction Piles	
	Without ground treatment	With ground treatment	Without ground treatment	With ground treatment
Moto-Machi	0/26	0/4	0/13	0/0
Naka-Machi Liquefied Area	3/4 Max 60cm	6/16 Max 20cm	18/36 Max 30cm	0/3
Shin-Machi Liquefied Area	10/12 Max 70cm	2/4 Max 30cm	8/12 Max 60cm	0/0

(Number of buildings with gap against the ground surface/ Number of investigated buildings)

about a half of the buildings in liquefied Naka-machi and Shin-machi experienced large gaps and damage to lifelines due to ground settlement, irrespective of the foundation type. The vertical gaps created around a building were as much as 60-70 cm for point bearing piles and 30-60 cm for friction piles. The vertical gaps around a building on treated ground were smaller.

COMPARISON OF FIELD PERFORMANCE WITH SPT-BASED LIQUEFACTION EVALUATION PROCEDURE

Figure 16 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 17 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 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

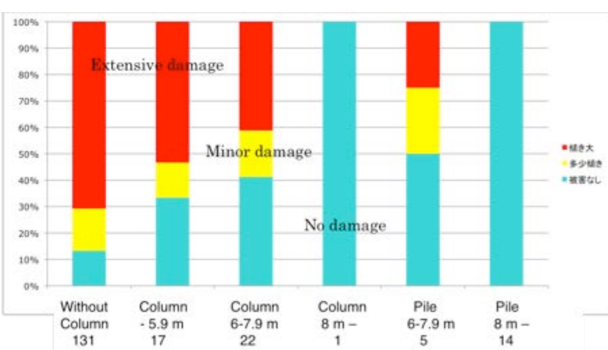

Fig. 15. Relation of depths of cement column piles or steel pipe piles with damage to houses (Urayasu City, 2012)

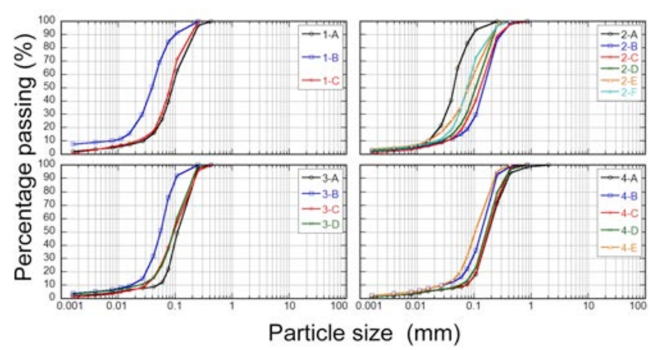

Fig. 16. Grain size distribution of boiled sand (Tokimatsu et al., 2011)

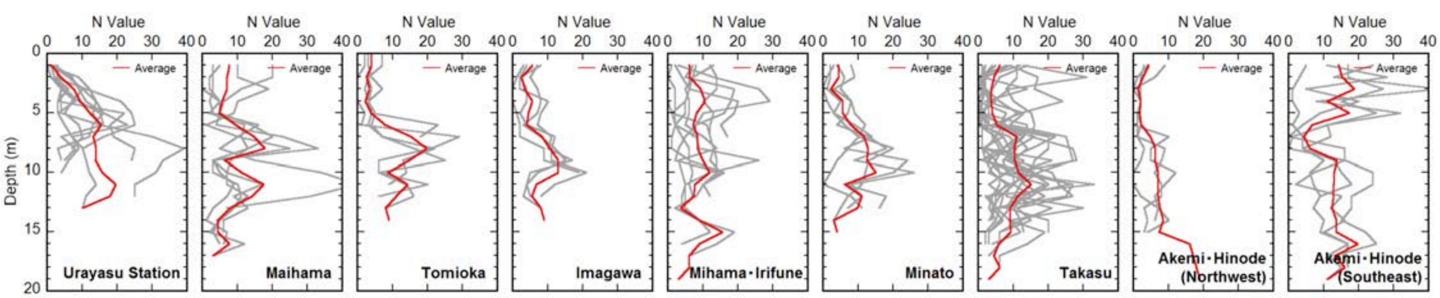

Fig. 17. Distribution of SPT-value with depth at selected districts (Tokimatsu et al, 2011)

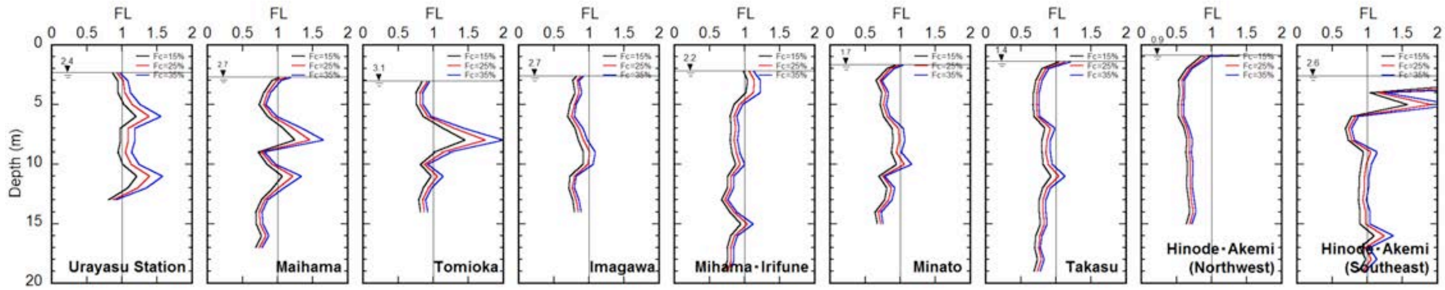

Fig. 18. Result of SPT-based liquefaction evaluation at selected districts (Tokimatsu et al., 2011)

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 Figs. 8, 9 and 10 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 18 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 (Fig. 17), a peak ground acceleration of $2.0 m/s^2$ 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 3 shows comparison of the average figure of estimated ground settlement based on N-value distribution in each area in Figure 17 (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.

Table 3. Comparison between estimated and observed settlements (Tokimatsu et al., 2011)

	Estimated (mm)			Observed (mm)		
	Fc=15%	Fc=25%	Fc=35%			
	Av.	Av.	Av.	Max.	Av.	Min.
Neighborhood of Urayasu Station (Nekozane, Todaijima, Kitasakae)	90	60	50	0	0	0
Maihama	250	180	140	-	-	-
Tomioka	180	130	100	300	260	150
Imagawa	230	160	120	500	220	50
Mihama, Irifune	320	230	180	450	190	70
Minato	260	190	150	600	220	50
Takasu	380	280	230	500	230	20
Akemi, Hinode (Northwest area)	440	330	270	650	320	30
Akemi, Hinode (Southeast area)	170	110	90	150	80	20

LIQUEFACTIONINDUCED DAMADE IN THE TONE RIVER REGION

Soil liquefaction occurred around the Tone River basin, as shown in Figure 2 (Kanto Regional Development Bureau, Ministry of Land, Infrastructure, Transportation and Tourism, 2011). Houses suffered damage due to liquefaction in Kuki city and Satte city, Saitama Prefecture, and in various places in Chiba and Ibaraki Prefectures.

Katori City, Chiba Prefecture

Waterways leading to the Tone River crisscross the Sawara area of Katori city. A comparison with a 1955 map shows that much of the area and its waterways used to be marshes and river channels. Liquefaction damage was particularly conspicuous in reclaimed land, including land along the waterways. Settlement and tilt of spread foundation buildings, settlement of ground adjacent to pile-supported buildings, uplift of buried structures, and road surface irregularities and slumps were observed in many places. Along waterways, liquefaction-induced lateral spreading occurred, and the following damage was also observed.

1) Due to liquefaction-induced lateral spreading, the stream became narrow and the riverbed lifted (Photo 8). The ground behind the embankment also settled greatly and shifted horizontally, causing damage to a bridge across the stream.

2) Houses and other structures near the embankment had their foundations tilted, as if pushed toward the stream, and some collapsed (Photo 9). Most of the collapsed houses were generally old with low foundation rigidity. A gap of up to 50 cm emerged between pile supported buildings and the ground surrounding them.

Itako City (Hinode area), Ibaraki Prefecture

In the Hinode area of Itako city, extensive soil liquefaction occurred accompanied by numerous sand boils, which caused spread foundation buildings to tilt or settle, ground to settle around buildings supported by a pile foundation, buried structures to be uplifted and roads and sidewalks to have dents and bumps as a result of ground settlement, which also left utility poles tilted. Water supply and sewer systems were both blocked in the entire Hinode area immediately after the earthquake. Liquefaction damage was larger in the southern part of the area, through which the Hitachi-Tone River, a tributary of the Tone River flowing out of Lake Kasumigaura, runs. The degree of ground settlement was accordingly larger in the south, at 40-50 cm near the Itako Sewage Treatment Plant, than in the north at 10 cm or less.

Photo 8. Lateral ground spreading towards the river (Tokimatsu et al., 2011)

Photo 9. House damages by lateral spreading (Tokimatsu et al., 2011)

A look at a 1955 map finds that the Hinode area corresponds to the former Uchinasakaura reclamation land (project: 1934-1949). Wakamatsu (1991) has earlier reported liquefaction damage in the Hinode area from the Chibaken Toho-oki Earthquake of 1987. In the March earthquake, liquefaction occurred on a far greater scale and affected much wider areas, bringing about more serious damage to lifelines, including tap water and sewer systems.

Kamisu city, Ibaraki Prefecture

The March earthquake severely damaged a water purification plant in Kamisu city's Wanigawa area (partly in Kashima city), maiming water pipes leading to water distribution facilities and cutting off water supply to neighboring communities.

At the Wanigawa purification plant, liquefaction induced ground settlement of up to about 50 cm and uplift of a public utility duct by up to 50 cm (Photo 10). This resulted in a gap of up to 40 cm in the vertical direction between pile supported building and the duct, which severed some of the wiring inside the duct. Horizontal gaps of up to 15 cm also emerged at many joints of the duct, leading large quantities of sand to flow into the duct, which added to the scale of ground settlement. Liquefied ground also caused lateral spreading toward a regulation reservoir at the center of the site, exacerbating ground settlement and raising the water level in the reservoir, inundating roads in the plant.

Photo 10. Uplift of buried conduit (Tokimatsu et al., 2011)

In the Fukashiba and Horiwari areas, liquefaction induced large quantities of sand boiling, causing settlement and tilt of spread foundation buildings (Photo 11), settlement of ground adjacent to buildings supported by a pile foundation, uplift of buried structures and bumps and dents in roads and sidewalks. Boiled sand in Fukashiba measured up to 50 cm thick in some places. When several structures stand close together, they tended to tilt toward the center, where settlement is larger in scale (Photo 12). Several houses located at the end of filled land tilted in the direction of lower ground (outside the land) as the earthfill collapsed due to liquefaction (Photo 11). The northern part of the Horiwari area saw serious damage—an underground drain was uplifted and houses standing along a street settled by up to 50 cm vis-à-vis the road surface or adjacent houses, but the southern part suffered only minor damage. Puddles of water had formed in all of these liquefaction areas, indicating that groundwater level was extremely shallow.

A 1955 map of the Kasumigaura area shows the Wanigawa area and the northern part of the Horiwari area correspond to the Wanigawa reclamation land at that time (project: 1928-1942). The reclaimed land was later developed into residential land, where the March temblor triggered liquefaction. The southern part of the Horiwari area, which suffered only minor damage from liquefaction, meanwhile, used to be conifer forests. In the Fukashiba area, residential districts that were once used as rice paddies suffered major damage, while land plots along an old main road and old communities suffered little damage. A stone monument in Fukashiba area shows that, to improve farmland, soil treatment including dredging was done in 1957-1959 around which extensive soil liquefaction occurred in March. This might have worsened liquefaction damage.

Photo 11. Tilted house on the edge of fill (Tokimatsu et al, 2011)

Photo 12. Larger settlement occurring in the middle (Tokimatsu et al., 2011)

PILE DAMAGE IN THE KANTO REGION

City Stadium in Urayasu City

The city stadium including the main stand, a small building for judges and illumination poles, all founded on piles in liquefied

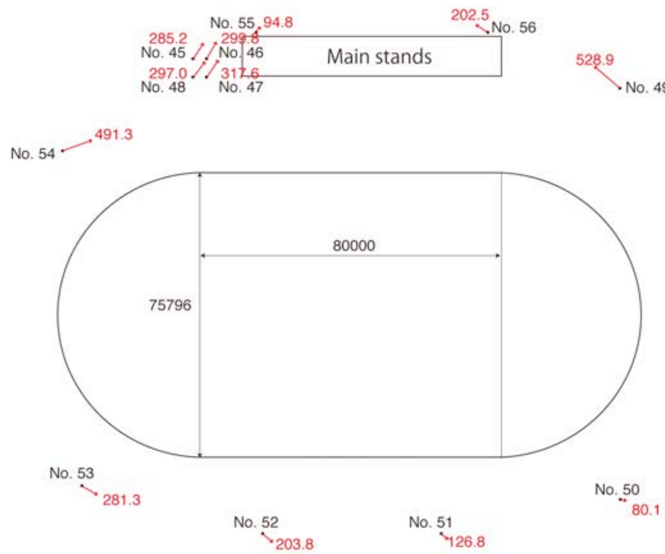

Fig. 19. Vector displacements of pile heads of City Stadium (Urayasu, 2012)

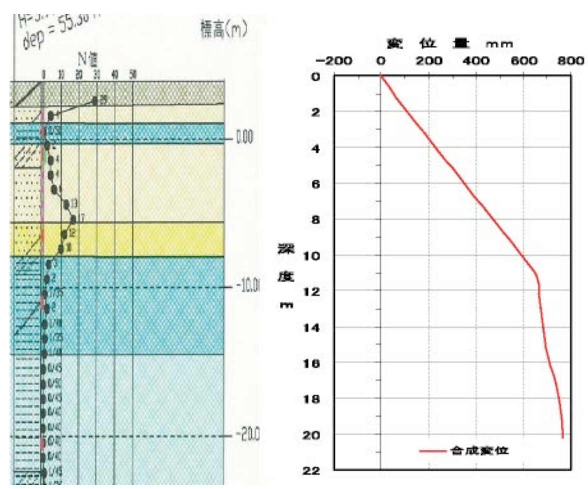

Fig. 20. Soil profile and distribution of pile deformation with depth (Tokimatsu et al., 2012)

soils in Maihama, was under construction and all the piles except for those of the main stand were extensively damaged. Figure 19 shows the horizontal vector displacements of pile head with respect to the main stand. The 2x2 group piles (Nos. 45-48) supporting the small building moved to northeast by 30 cm, while several single piles (Nos. 49-56) supporting an illuminator moved by 8-53 cm. The pile is about 48m long, having diameters of 0.6 m and consisting of a steel pipe-concrete composite pile at depths shallower than about 10 m and pre-stressed high strength concrete piles below.

Figure 20 shows the horizontal displacement profile with depth of Pile No. 49, detected from field survey using a borehole camera and an inclinometer. The pile has failed and bent at a depth of about 10 m, causing an inclined angle of about 1/15 within the surface sandy layer having a thickness of about 10 m. This confirms that the pile failed near the boundary between sand and clayey layers and immediately below the joint of pre-stressed high concrete pile and steel pipe-concrete pile.

Elementary School Building in Saitama Prefecture

An east part of a 4-story elementary school building in Omiya, Saitama Prefecture, the plan of which is shown in Fig. 21, settled by about 500 mm against the remaining west part, inducing extensive shear failures of the grade beams as well as those of the superstructure near the interface (Photo 13). The building was constructed in 1977-1978 and founded reinforced concrete piles with a length of 36 m and a diameter of 450 mm. The near surface soils around the building doe not consist of liquefiable sandy soils but humic soils, the thickness of which increases towards the north.

An excavation survey confirmed that the piles on the northern part failed near the pile heads (Photo 14), with those on the southern part undamaged. The uneven performance of pile foundation within a building could have caused the uneven vertical displacement, and thereby inducing the shear failure of beams. The excavation survey also showed that the ground on the north settled more and induced a longer projection of piles on the north side of the building. This suggests that the difference in soil condition below the building might have induced the uneven failure of pile foundations within the building.

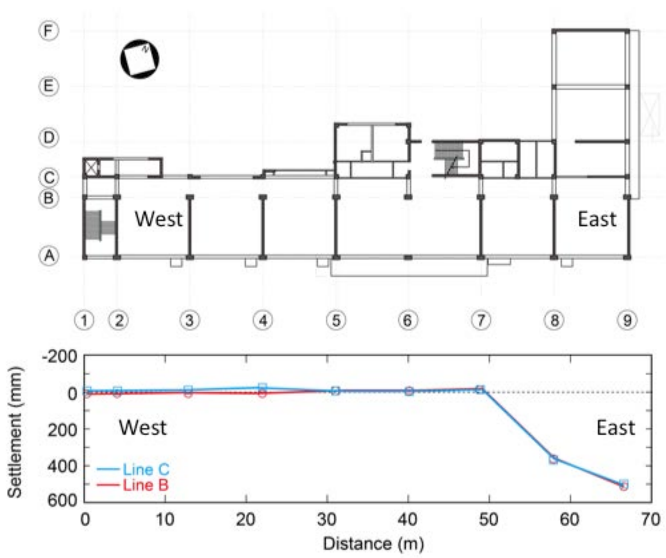

Fig. 21. Plan of elementary school in Omiya

GEOTECHNICAL PROBLEMS IN TOHOKU REGION

Pile Damage in Sendai City

In the western part of Oroshimachi-Higashi area (Fig. 22), soil liquefaction induced sand boiling, settlement of ground adjacent to structures supported by a pile foundation, uplift of buried structures, and bumps and dents in roads and sidewalks. Settlement of ground surrounding pile-supported buildings measured about 10 to 20 cm. At least two buildings apparently supported by a pile foundation tilted remarkably

Photo 13. Shear failures on beams (Tokimatsu et al., 2012)

Photo 14. Damage to pile head

(Photo 15). A similar pattern of building damage associated with pile failure involving soil liquefaction was observed in the Fukumuro area. A 14-story, steel-reinforced condominium complex, consisting of two buildings connected in an L-form with expansion joints, had pile damage (Photo16). It was completed in 1976. Along the bottom of the letter L (on the south side) runs a national highway. It has been reported that the complex's nonstructural walls suffered shear fractures in the 1978 Miyagiken-oki Earthquake. In the March quake, the southern building tilted by about 1 degree southward as its foundation on the south side settled. There were large cracks in nonstructural walls of various parts of the building, but no significant damage was observed in the major structural components. The ground settlements around the neighboring buildings were about 10 cm.

Ground Failures of Man-Made Fills in Sendai City

There are many residential lands developed with cut-and-fill in Sendai city (Fukkenn Gijutu Consultant Co., Ltd., 2008). The thickness of cut and fill in the area varies from almost zero to about 30 m. The Oritate housing complex (Fig. 22) was built in the late 1960s, and put on sale in the early the 1970s. Any geotechnical problem was not reported on the complex in the 1978 Miyagiken-oki Earthquake (the Architectural Institute of Japan, 1980; and the Tohoku branch of the Japan Society of Civil Engineers, 1980).

Figure 23 shows a damaged area in Oritate 5-chome, where many retaining walls were broken. At the lower part of a slope (P1 in Fig. 23), retaining walls had collapsed as if pushed out by backfill soil (Photo 17). Above that point, at P2, ground under a retaining wall was raised. It is believed that the

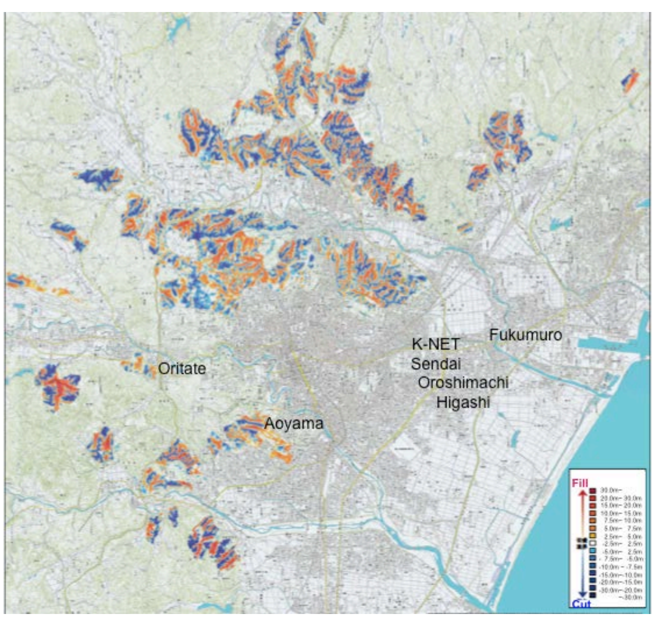

Fig. 22. Map showing cut-and-fill in Sendai City (Fukken Gijutu Cousultant Co., Ltd., 2008)

earthfill had moved toward the street, exerting a compressive force. At a somewhat high point on the slope (P3), there were major cracks in a residential land plot. At a high part of the slope, there were also retaining walls with tensile cracks. Figure 23 shows the points of tension and compression found from these examples, suggesting that landslide occurred in the hatched part in the figure. A comparison with an old topographical map (around 1964) shows that the landslide area roughly corresponds to a valley in the old landscape. The March earthquake apparently led the entire earth and sand used to fill up the valley to shift.

A house that straddles the landslide area and a cut slope was broken around the boundary (P5). Severe damage to houses concentrated at the foot of the landslide area, shown with a shade in Fig. 23 (Photo 18). Damage was greater at the end of the landslide block because ground deformation became greater in both horizontal and vertical directions.

The Aoyama housing complex there was built in the latter half of the 1960s. A number of cracks, bulges and collapses of retaining walls was observed during the 1978 Miyagiken-oiki Earthquake (Architectural Institute of Japan, 1980). According to residents' accounts, some houses that had their foundations

Photo 15. Tilt of pile-supported building (Oroshimachi) (Tokimatsu et al., 2011)

Photo 16. Tilt of pile-supported 14-story building (Fukumuro) (Tokimatsu et al., 2011)

broken in the 1978 quake had the same misfortune during the 2011 main shock.

Figure 24 shows the damaged area in Aoyama 2-chome. A major crack had formed in a housing lot in the upper part of the slope (P1 in Fig. 24). The crack was as deep as 70 cm.

Fig. 23. Map showing landslide block in Oritate housing complex (Tokimatsu et al., 2011)

Photo 17. Damage to retaining wall (Tokimatsu et al., 2011)

Photo 18. Damage to wooden house (Tokimatsu et al., 2011)

Closer to a valley at P2, the retaining wall shifted about 1 meter to the valley side, causing ground to sink and leaving a void below the foundation, as in Photo 19. At the lower part of the slope, a residential land plot was destroyed as if pushed out, as in Photo 20 (At P3 in Fig. 24). Figure 24 shows the points of tension and compression found from these examples, which indicates that the landslide area was a shaded part in the figure. Comparing it with an old topographical map (around 1964) finds that the area roughly coincides with an earth cliff in the old landscape. The landslide occurred in the residential land developed by widening earthfill along the cliff. Residents

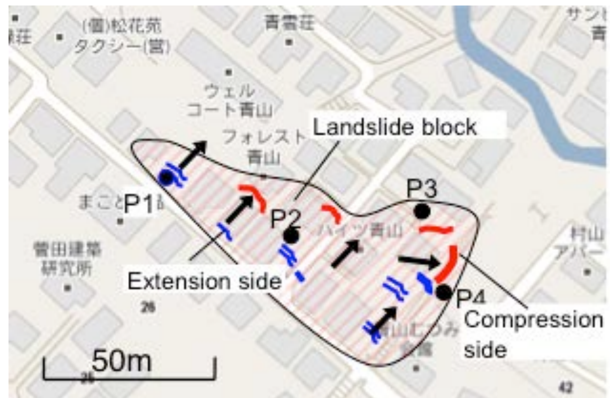

Fig. 24. Map showing landslide block in Aoyama housing complex (Tokimatsu et al., 2011)

Photo 19. Void below foundation (Tokimatsu et al., 2011)

Photo 20. Failure of reclaimed fill (Tokimatsu et al., 2011)

Photo 21. View of Onagawa from Point P1 (Tokimatsu et al., 2011)

said that the groundwater level in the neighborhood is extremely shallow at about 1 meter deep, which is considered to be a factor leading to the landslide.

Some buildings at the lower part of the landslide block suffered severe damage as a whole (P4 in Fig. 24). In Aoyama 2-chome, ground shift was large in scale in the upper part of the landslide block, severely damaging many detached houses there. Some of the entirely collapsed houses had had their superstructures reinforced against earthquakes. This fact suggests the need to make a comprehensive judgment on anti-seismic reinforcements, considering not just superstructures alone but also foundations and land plots. Residents said ground cracks and bulges of retaining walls were created initially by the main shock of March 11 and became worsen each time an aftershock hit. The April 7 aftershock, in particular, exacerbated ground deformations and destroyed foundations, suggesting a possibility of progressive failure of the ground.

Tsunami-induced Damage to Pile-Supported Buildings

Figure 25 is an aerial photo (by Google Earth) of Onagawa town. Point P1 stands for the location of Onagawa town hospital (Photo 21). The tsunami surged up to the first floor of the hospital, which stands on a hill 16 meters from the sea level. The inundation height in Onagawa was about 17 meters.

A four-story, steel-frame building, supported by a pile foundation at Point A, was swept by about 10 meters toward the mountain side and toppled sideways (Photo 22). The building apparently floated by the tsunami's force and was carried away, and then toppled. The foundation of the building had pile caps, each supported by two or three piles. The toppled building had one pre-stressed concrete (PC) pile with a diameter of 300 mm hanging from its foundation. All the other piles had broken away at their connections with the pile caps. The joints were made of filling concrete, which was weak. Most of the concrete was destroyed, with reinforcing steel alone left behind. The pile head joints were possibly damaged by the earthquake and then fractured by the ensuing tsunami.

At point B, a four-story, reinforced concrete building with a pile foundation lay on its side (Photo 23). The building used to stand at point B0, from which it was swept toward the mountainside by about 70 meters. A PC pile with a diameter of 300mm was hanging from the pile cap. The pile's head barely remained connected with the cap by reinforcing steel, but the rest of the pile suffered comparatively minor damage. Most of the other piles were found at point B0, either fractured at their heads or head joints, or pulled from the ground with damage at or near their heads. The state of destruction of these piles showed that bending and tensile forces had applied. At a neighboring five-story, reinforced concrete building (at P2), adjacent ground apparently settled, indicating soil liquefaction. It is possible that, when soil liquefaction had lowered the shear strength of the ground, horizontal and buoyant forces of the tsunami applied to the building, pulling the piles out of the ground or causing complete failures at the pile heads. At point D, a two-story, reinforced concrete building with a pile

Fig. 25. Aerial photo of Onagawa town (Google Earth)

Photo 22. Toppled building A (Tokimatsu et al., 2011)

Photo 23. RC building B carried 70 m away and toppled (Tokimatsu et al., 2011)

foundation (police box) was tipped over sideways. The adjacent ground apparently settled similarly, indicating soil liquefaction occurred in the neighborhood.

Point J is the site of the Marine Pal Onagawa (three-story, reinforced concrete building), a tourist facility on the coast. Facing the sea, this facility was apparently hit directly by tsunami. Soil was badly washed away around its foundation and part of the ground was lost, but no tilt or shift was observed. There was no damage to its structure, either.

CONCLUSIONS

Field surveys on building damage associated with geotechnical problems in the 2011 Tohoku Pacific Ocean Earthquake have found the following:

1) Extensive soil liquefaction occurred along the coast of Tokyo Bay and around the Tone River floodplain. Liquefaction primarily occurred within relatively new reclaimed area, with large ground settlement up to 60 cm, accompanied by settlement/tilting of wooden and reinforced concrete buildings supported on spread foundations. 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. Liquefaction also caused a major gap between pile-supported buildings and surrounding ground, but no structural damage was observed in superstructures.

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 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. The currently available liquefaction evaluation procedure appeared to have performed reasonably well in predicting the occurrence of soil liquefaction as well as the degree of resulting ground settlements, although further verification is definitely needed.

4) Numerous houses in Sendai's hilly residential areas constructed with cut-and-fill methods were badly damaged not only by simple collapse of retaining walls but also by slope failures of fill.

5) Several pile-supported buildings tilted and settled not only in the Tohoku region but also in the Kanto plain, implying damage to pile foundations.

6) Several steel and reinforced concrete structures in Onagawa were knocked over by tsunami surges, probably after having suffered damage to their pile foundations. The toppled buildings were rather old, and apparently were not built with seismic design. For this reason, pile-cap joints, or piles themselves, suffered a certain extent of damage from the earthquake, becoming unable to withstand the tsunami's wave pressure and buoyancy force.

7) Large-scale, newly built buildings, such as Marine Pal Onagawa, did survived direct hits by the tsunami without any structural and foundation damage.

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