SOIL LIQUEFACTION IN TOKYO BAY AREA DUE TO THE 2011 TOHOKU (JAPAN) EARTHQUAKE

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SUMMARY

A devastating earthquake hit the Tohoku and Kanto regions of Japan on 11 March 2011, causing extensive damage to life and property as a result of a large-scale tsunami and damage to nuclear power plants. Although located about 400 km away from the epicentre, many residential and commercial buildings and lifeline facilities in Tokyo Bay area suffered extensive damage due to soil liquefaction and associated ground deformation. This paper discusses the results of the damage investigation conducted in the area after the earthquake, with emphasis on liquefaction-induced damage to buildings, roads, lifelines and other infrastructure. In addition, the performance of ground improved by various remediation techniques is discussed. Finally, lessons learned from the event are summarised.

INTRODUCTION

At 2:46 pm (local time) on 11 March 2011, a gigantic earthquake with moment magnitude M_w 9.0 shocked the Tohoku and Kanto regions in eastern part of Japan. Considered as the biggest to hit the country in modern times, the earthquake, officially called the "2011 off the Pacific coast of Tohoku Earthquake" (JMA, 2011), had an epicentre located 130 km off the coast of Sanriku in the Tohoku region at a depth of 24 km. More than 15,000 people were killed and thousands more were reported missing (NPA, 2011) as a result of a large-scale tsunami generated by the earthquake. Aside from wreaking havoc to residential houses near the coast, the tsunami also damaged the Fukushima Daiichi nuclear power plant, triggering a nuclear crisis. Following the main shock, many more aftershocks were recorded, with more than 500 aftershocks having magnitude greater than 5 and at least 5 having magnitude greater than 7 (JMA, 2011).

In Tokyo, located about 400 km away from the epicentre, a Japan Meteorological Agency (JMA) intensity 5 was reported, with peak accelerations ranging from 0.1- 0.2g and significant duration of shaking of 100-200 sec. Such long duration of shaking triggered soil liquefaction at many sites in the reclaimed areas located in Tokyo Bay, such as in Urayasu, Shin-Kiba and Odaiba. Most of the sites were recalimed as recently as the 1970s, although reclamation works in Tokyo Bay dated as far back as the 1800s. Many residential and commerical buildings in these reclaimed islands were affected by the ground deformation (lateral spreading and settlement) induced by liquefaction. Road pavements buckled, manholes were uplifted and lifeline facilities were damaged..

Following the earthquake, the second and third authors, together with their colleagues, conducted field investigation in the affected areas in Tokyo Bay and documented the damage caused by widespread liquefaction. The first author was able to visit the affected sites four months after the earthquake while on a research visit to Japan. Although most of the damaged infrastructure have been repaired by that time, many of the damaged structures, especially houses and manholes, remained in their damaged state. During the reconnaissance, focus was made on the effect of liquefaction and ground deformation on structures as well as the performance of improved ground. Details of the seismological aspects of the earthquake are presented in many other reports and publications; hence this paper focuses only on the liquefaction damage in reclaimed lands along Tokyo Bay.

TECTONIC SETTING

The earthquake occurred off the coast of Miyagi Prefecture in the eastern coast of Japan. The hypocentre is located on the boundary of the North American plate along the Japan Trench and Pacific plate (see Figure 1). The Pacific Plate is subducting under the North America plate at a rate of about 85 mm/yr in the west direction, making this zone one of the most seismically active regions in Japan. Many large earthquakes have occurred in this zone with an average recurrence of about 30 years. In 1896, an earthquake with magnitude estimated

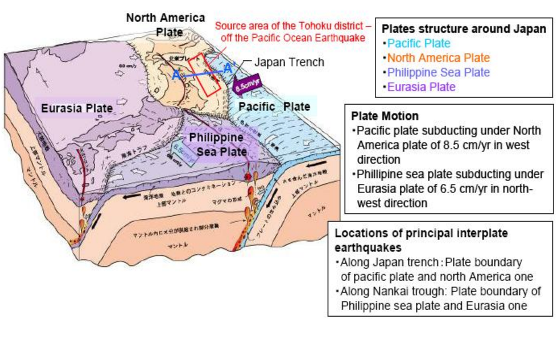

Figure 1: Plate tectonics around Japan and source area of the 2011 earthquake (Source: http://www.kantei.go.jp/foreign/kan/topics/201106/iaea_houkokusho_e.html).

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between 8.2 – 8.5 triggered a tsunami which killed more than 21,000 people. In 1933, a M8.1 earthquake claimed more than 1,500 lives. Because of such activity, a warning of a possible large earthquake in the near future has been issued in Sendai, one of the biggest cities in eastern Japan, in anticipation of the plate subduction in this zone (Cabinet Secretariat, 2011). However, the size of the 2011 earthquake was more than the expected one, with the actual causative mechanism being 500 km long in the NS direction and 200 km wide.

RECLAMATION WORKS IN TOKYO BAY

Reclamation work in Tokyo Bay started way back in the Edo period (1603-1868) and continued up to the present time, peaking during the economic boom of the 1970s. The total reclaimed land were about 249 km^2, which is about 20% of the original area of the bay (Morita, 2005). Figure 2 illustrates the history of reclamation works within the Tokyo Metropolitan region. One of the first reclamation works in the Koto sea region was the reclamation of Hibiya Irie in the 1590s to build a town and farming estate and the Onagi channel was excavated in the shallow sea for transporting food and salt (Endoh, 2004). The soil dredged from Onagi channel was used for filling the northern part of the channel. Since that time, reclamation works have continued in the Koto sea region not only for industrial and commercial purposes, but also as a result of garbage disposal. Because of these reclamation works, the sea area of the Koto region has been replaced by man-made islands, with the exception of some ship routes.

The city of Urayasu is located in Chiba Prefecture, east of Tokyo. It is best known as the home of Tokyo Disney Resort. In 1948, Urayasu, then a town, had a total area of 4.43 km^2 and consisted mainly of the fishing village. After the prefecture was chosen as the site for a major Kawasaki Steel factory in 1950, the prefectural government embarked on a large-scale land reclamation program that dredged up large plots of waterfront property for factories, warehouses, and docks. As a result of these reclamation works, Urayasu's area grew to 6.67 km^2 in 1968. A history of the reclamation works in the area is available at the website of the Urayasu City government (www.city.urayasu.chiba.jp/menu2863. html) and re-produced in Figure 3. Maihama, the present site of Tokyo Disney Resort (Disneyland and Disneysea) was reclaimed in 1975. By 1981, Urayasu's land area quadrupled to 16.98 km^2.

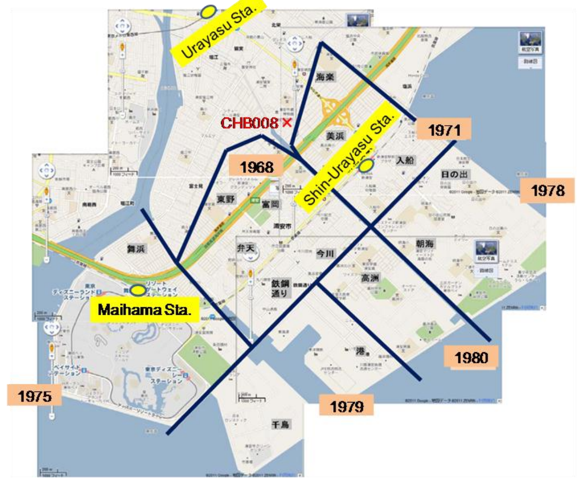

***Figure 3:** History of reclamation in Urayasu City (adapted from Urayasu city website and Google map).*

The new landfill section was called "Shin-Urayasu" (New Urayasu), and has an "American" inspired layout, with a grid-like map of wide streets, large sidewalks, parks and palm trees. Tall buildings and modern apartments characterise this area, highlighted by very nice views of Tokyo Bay.

STRONG MOTION RECORDS

The huge scale of the 2011 earthquake produced strong shaking across a broad region and triggered many strong motion recorders installed throughout the affected area. Figure 4 illustrates the distribution of peak ground accelerations (PGA) recorded in 697 K-Net and 515 KiK-Net stations, which are operated by the National Research Institute for Earth Science and Disaster Prevention (NIED). The main difference between these two networks is that K-Net is an observation network which records data only on the free surface, while KiK-Net has boreholes with installed sensors located both at the bottom of the borehole and on the surface. The maximum PGA recorded during this earthquake was in station MYG004 (Fault distance = 75 km), where 2,425 and 1,150 cm/s^2 were monitored in NS and EW directions, respectively.

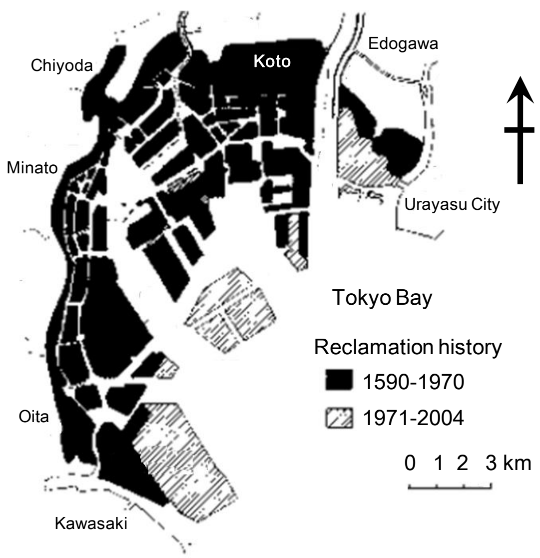

***Figure 2:** Reclaimed lands in Tokyo Bay as part of Tokyo City (modified from Endoh, 2004).*

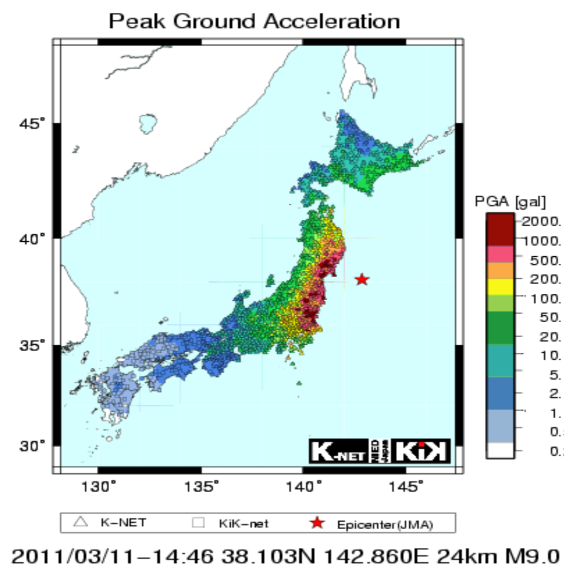

***Figure 4:** Distribution of peak ground accelerations recorded by KyoshinNet (Note: 1 gal = 1 cm/s^2).*

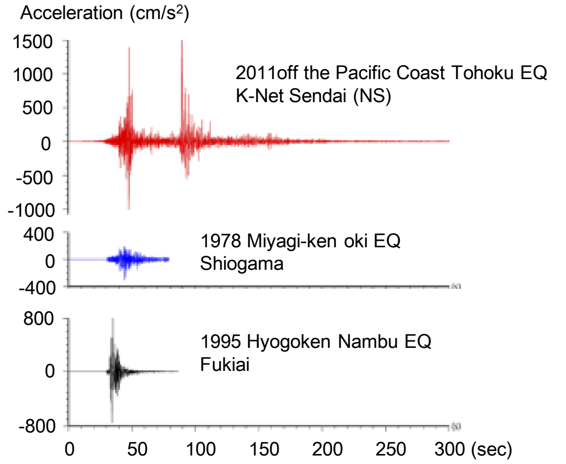

Figure 5: ***Comparison of recorded strong motions at K-Net Sendai (NS) station during the 2011 off the Pacific Coast of Tohoku Earthquake with those from previous destructive earthquakes (modified from Shimizu Corp, 2011).***

Two distinct features of the observed ground motions during the 2011 earthquake are: (1) the coupled co-seismic rupture of fault segments within the rupture zone, resulting in not one but several earthquake shaking; and (2) the long duration of significant shaking associated with the large scale of the fault plane. Figure 5 compares the recorded strong motion in Sendai during the 2011 earthquake and those of some previous destructive earthquakes. The long duration of significant shaking, lasting by as much as 180 seconds, caused extensive damage not only to superstructures but to the ground as well.

In areas adjacent to Tokyo Bay, located about 400 km away from the epicentre, the PGAs recorded were in the order of 100-200 cm/s^2. The time history of ground acceleration recorded in Urayasu (CHB008 – see Figure 3 for location) is shown in Figure 6, where it can be seen that the duration of significant shaking is about 120 sec; with such long duration, the number of cyclic load reversals is high. Coupled with the soft saturated deposits in the reclaimed areas, these conditions are recipe for soil liquefaction to occur.

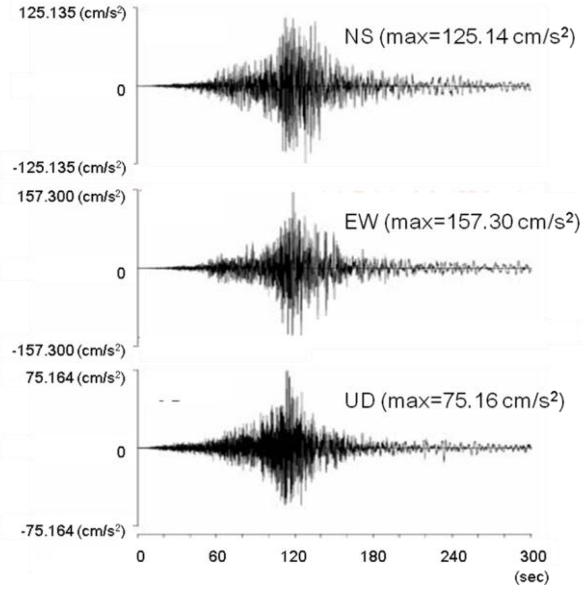

Figure 6: ***Time history of acceleration recorded in Urayasu (CHB008 station); data from K-net.***

LIQUEFACTION-INDUCED DAMAGE OBSERVED IN TOKYO BAY AREA

As mentioned earlier, although Tokyo Bay is about 400 km away from the epicentre, liquefaction was observed in many places adjacent to the bay. The major sites visited during the reconnaisance work are illustrated in Figure 7. The visit was limited to the reclaimed islands of Urayasu, Shin-Kiba, Wakasu, Odaiba, Haneda Airport and Mihama, all located along the coastline of Tokyo City and Chiba Prefecture

Possibly the worst area in terms of liquefaction-induced damage is the the newly reclaimed sites in Shin-Urayasu. Having been reclaimed only in the second half of the 20th century, the soil deposits in Shin-Urayasu are relatively young, and with the high water table and long duration of shaking, the soil is susceptible to liquefaction.

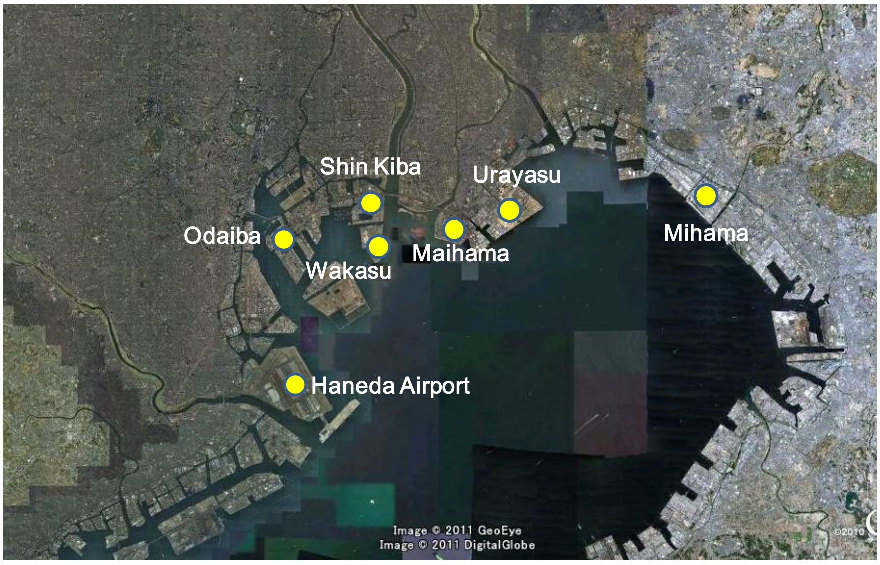

Figure 7: ***Locations of sites visited adjacent to the Tokyo Bay area (photo from Google Maps).***

Figure 8: ***A section of the road which underwent settlement as a result of liquefaction.***

During the reconnaissance visit, many roads in Shin-Urayasu were still under repair due to liquefaction-induced subsidence and buckling of road pavements. Figure 8 shows a road section which settled as a result of liquefaction.

As mentioned earlier, Shin-Urayasu is home to many tall buildings, most of which were supported by pile foundations. Needless to say, these buildings were unscathed following the earthquake (see Figure 9a). However, the ground adjacent to these buildings subsided due to liquefaction, resulting in gaps between the buildings and the adjacent ground. In some buildings, man-made ramps were constructed to fill the gap, as in Figure 9b. Differential settlement, such as those between fire stations and the surrounding ground, as well as in bridge approaches, became a very important issue in the days following the earthquake because fire engines were not able to get out of the stations to respond to emergency cases.

(a)

(b)

Figure 9: ***(a) Building supported by pile foundation. Note the vertical gap between the building entrance and adjacent ground; (b) A ramp constructed at building entrance due to 30 cm settlement of the adjacent ground.***

(a) (b)

Figure 10: ***(a) A manhole uplifted by as much as 2 m (photo by I. Towhata); (b) several manholes protruding up from a street in Urayasu.***

Manholes protruded above the ground, some as high as 2 m due to buoyancy effects (see Figure 10a). In other areas, such as in Hinode on the eastern side of Shin-Urayasu, the protruded height of the manhole was less severe, but almost all the manholes in the area were affected (see Figure 10b). From observation, the protruded height was affected not only by the uplift caused by buoyancy but also by the overall settlement of the surrounding ground. As a result, water and wastewater supplies to residential areas were affected, and it took several days before the services were fully restored.

Lateral spreading of the quay wall was also observed in many locations. For example, the southeast quaywall of Hinode was displaced by about 20-30 cm towards the bay. Large ground cracks parallel to the wall were observed on the concrete portion of the backfill. Although most areas of Hinode were improved following its reclamation in 1978, especially in areas where buildings were constructed, the affected area was a park and ground improvement techniques were not implemented there.

Figure 11: ***Longitudinal cracks at the backfill of the quay wall due to lateral movement of the wall towards the bay.***

Many residential houses were affected by liquefaction and ground subsidence. Some houses tilted and sank by various degrees. Voluminous amount of ejected sands covered many streets and houses, in some areas as thick as 20-30 cm, as shown in Figure 12.

Disneyland and Disneysea, both located within the Tokyo Disney Resort in Maihama, were not affected by liquefaction because ground improvement techniques were implemented there after the sites were reclaimed in 1975. However, the

Figure 12: Residential houses in Hinode, Urayasu City land covered by ejected sands immediately after the earthquake (Photo by S. Yasuda).

Figure 13: Parking areas in Tokyo Disney Resort covered by sand boils (Photo by S. Yasuda).

roads surrounding the theme parks were badly damaged sue to buckling of pavements and ground subsidence. Immediately following the earthquake, the roads were covered by ejected materials (see Figure 13).

In terms of structural failure related to buildings and bridges, there was no major damage reported. Damage to bridges include differential settlement of bridge approaches and minor cracks in the abutments. During the July visit, all damaged sections of bridges in the area were already repaired. It is worthy to mention that most of the bridges in Shin-Urayasu were seismically retrofitted prior to the earthquake and therefore were not damaged by the 2011 shaking.

NIED, which maintains the K-Net stations, also has database of the soil conditions at the station locations. Figure 14 shows the soil profile at CHB008 station located adjacent to the City Hall in the old Urayasu area, near the boundary of the reclaimed site Shin-Urayasu (see Figure 3 for location). It can be observed that the sandy deposit is about 8 m thick with shear wave velocity of 140 m/s. Ground observations indicate that this area did not undergo liquefaction. Needless to say, no traces of liquefaction were observed in the natural sand formations in the old Urayasu, a stark contrast to the extensive liquefaction in the reclaimed area of Shin-Urayasu.

Another area which suffered extensive liquefaction was Shin-Kiba, Koto Ward located to the west of Maihama. Shin-Kiba was reclaimed between 1946 and 1970, and has been the site of many industrial facilities, distribution centres and warehouses. Many roads in the area sunk as a result of liquefaction, and they were covered by ejected sand

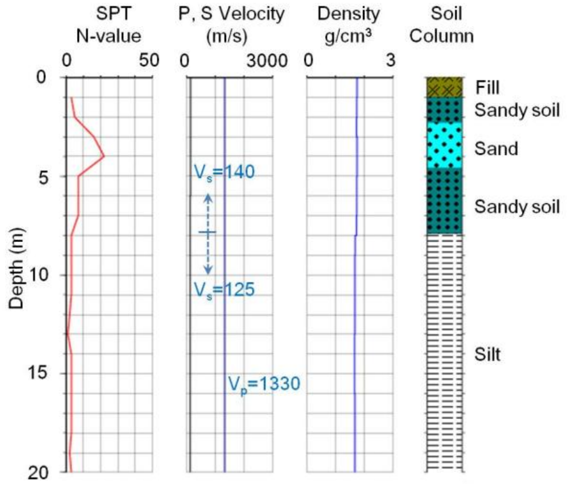

Figure 14: Boring log, P and S-wave velocity profiles and soil profile at CHB008 station (data from K-Net).

immediately after the earthquake. Traces of sand boils were still evident near the roads and in open spaces during the July visit (see Figure 15a), although most of the roads have been repaired. The damaged state of a police station remained in Shin-Kiba 1-chome, with the one-story structure tilted just as it was after the earthquake due to the liquefaction of the foundation ground (see Figure 15b). The adjacent ground also settled by 15-20 cm, causing concrete pavements near the

(a)

(b)

Figure 15: (a) Traces of ejected sands, as thick as 20-30 cm, were evident near the road; (b) Damaged police station.

structure to crack. Large undisturbed amount of sand boils were still scattered in the open field behind the station.

Except for the camping ground, the island of Wakasu to the south of Shin-Kiba was reclaimed through garbage disposal. Because of the harmful gas generated, it needed about 20 years to build the park on the island. Roughly half of the island is an industrial zone, while the other half contains a golf course and a popular camping ground. A quick drive through the island showed no noticeable traces of liquefaction, which is to be expected in an island made from dumped garbage.

Odaiba is another large artificial island connected to central Tokyo by the famous Rainbow Bridge. Initially constructed for defensive purposes in the 1850s, the area dramatically expanded during the late 20th century as a seaport district, and has developed since the 1990s as a major commercial, residential and leisure area. Most the island has been improved and therefore liquefaction was not that extensive. Among the accessible spots, a sheet pile quay wall in Shiokaze Park, located on the western end of the island, was laterally displaced towards the bay and the pavements in the backfill soil were deformed as a result of liquefaction.

Figure 16:* *Lateral displacement of sheet pile quay wall in Shiokaze Park and associated deformation of the backfill.

Mihama Ward is located in northwestern Chiba Prefecture, and consists entirely of reclaimed land from Tokyo Bay. Reclamation at this site began in 1912, with the construction of Japan’s first civilian aerodrome. Following World War II, the expanding Tokyo Metropolis created a demand for additional factory locations and public housing. Currently, Mihama is largely a regional commercial centre and home to the newly developed waterfront area of Kaihin Makuhari.

Figure 17: A tilted house in Mihama.

Unlike in Shin-Urayasu where liquefaction was extensive, traces of sand boils were observed only sporadically in Mihama. This is because most parts of the area were improved through sand compaction piles, sand drains, etc. In areas where liquefaction was observed, ground subsidence was evident, and some houses, such as that shown in Figure 17, tilted as a result of the loss in strength of the foundation ground.

PROPERTIES OF EJECTED SANDS

In all places visited, the appearance of the ejected sands as a result of liquefaction were very similar, typically grey to dark grey in colour and consisting of very fine sands. Samples were taken at various locations and the grain size distributions were obtained using sieve analysis. Figure 18 shows the grain size distribution curves of soil samples taken at Shin-Kiba, Urayasu and parking lot of Tokyo Disneyland. It can be observed that the distributions of grain sizes were fairly similar, and the fines contents were low, ranging from 2-30%.

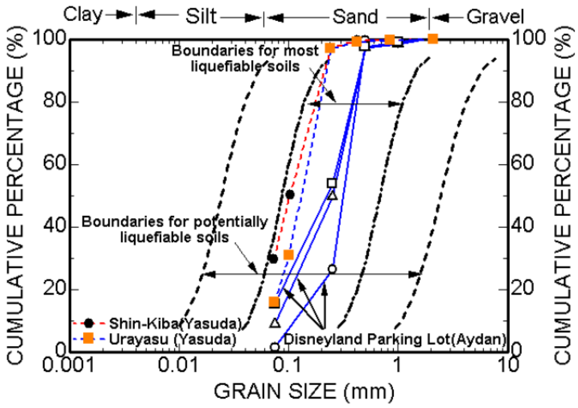

Figure 18: Grain size distribution of ejected sands taken at various locations plotted with respect to distributions observed to be susceptible to liquefaction (data provided by O. Aydan).

Also shown in the figure are the range of grain size distributions of most liquefiable sands and those with potential to liquefy. These ranges were obtained from past historical earthquakes in Japan and stipulated in the Japanese design code for port and harbour facilities (PHRI, 1997). Note that there are problems associated with the use of compositional criteria, as a measure of liquefaction susceptibility, because there are no generally accepted criteria and the difference between natural and reclaimed deposits. Nevertheless, using these criteria, it can be seen that the ejected sands obtained at different locations in Tokyo Bay can be said to have high potential to liquefy.

PERFORMANCE OF IMPROVED GROUND

Based on the reconnaissance works conducted at the sites mentioned, it was evident that the degree of liquefaction varied from place to place. There was a construction site in Odaiba where sand compaction piles (SCP) were being installed when the earthquake occurred. The portion of the site where SCPs were installed was unscathe while sand boils were seen in the remaining unimproved portions. SCP method is the most popular method in Japan to densify loose saturated ground as liquefaction countermeasure. Harada *et al.* (2011) described case histories of the performance of SCP-improved ground during recent gigantic earthquakes in Japan.

Figure 19: An undamaged building resting on improved foundation ground. Adjacent to it, sand boils were visible everywhere.

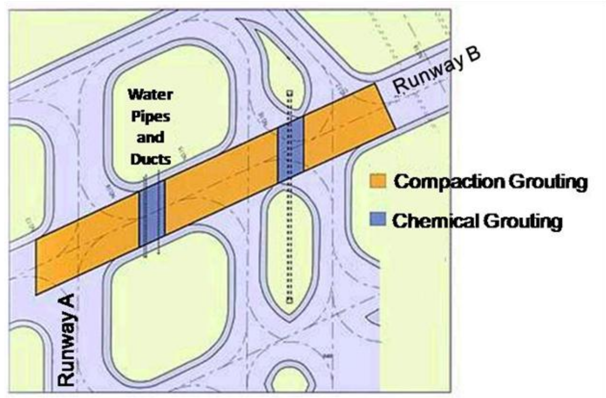

Figure 20: Portions of Haneda International Airport where compaction grouting and chemical grouting methods were implemented (figure courtesy of Sanshin Corporation).

The excellent performance of grounds remediated through SCP, sand drains and other soil liquefaction countermeasure techniques have been illustrated in many parts of Tokyo Bay. For example, the foundation ground of the building shown in the background of Figure 19 was strengthened against liquefaction and the building was undamaged. Just a few meters away, sand boils were evident in the unimproved ground.

Another example of excellent performance of improved ground is the the Haneda International Airport. In order to improve the seismic resistance of the foundation ground beneath the new runway of the airport, SCP method was employed in the late 1990s to densify the ground. As shown in Figure 20, compaction grouting was used to improve the ground at the intersection of the new Runway B and the existing Runway A, while chemical grouting was utilised near buried structures. Details of the compaction grouting implementation were discussed by Orense (2008). Needless to say, liquefaction did not occur at the airport, and the earthquake practically did not affect the airport operation, with flights resuming the very next day after the earthquake.

CONCLUDING REMARKS

The 11 March 2011 Earthquake, off the Pacific coast of Tohoku, was the largest to have struck Japan in recent years. Because of its large magnitude ($M_w = 9.0$) and large rupture zone (500 km x 200 km), the earthquake was felt over a wide area in eastern Japan. Due to the size of the earthquake, the duration of significant shaking was very long, between 100-200 sec.

Extensive liquefaction was observed on many reclaimed islands in the Tokyo Bay area, which is about 400 km away from the epicentre. The long duration of shaking which the young saturated deposits were subjected to, with amplitudes in the order of 0.1-0.2g, caused the development of excess pore water pressure and led to liquefaction. In natural deposits, liquefaction was minimal, highlighting the role of the age of the fill in liquefaction susceptibility.

The earthquake clearly showed the excellent performance of ground improved by various liquefaction countermeasure techniques. In areas where the ground conditions were remediated, there was practically no sign of liquefaction while a contrasting observation was noted on unimproved ground.

Similar to the Christchurch earthquake events, the areas affected by liquefaction were extensive and widespread, with many residential houses affected over a very wide region. Although the level of damage is not major, the number of cases involved is significant and remediating all the affected houses and buildings would require longer time and more resources to implement. The 2011 earthquake events in Japan and New Zealand have made the people realize that understanding the subsurface conditions is important. Hence, geotechnical engineers must work harder to help the people understand the importance of geotechnical engineering.

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