Soil liquefaction and slope failures during the 2011 Tohoku, Japan Earthquake

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ABSTRACT: 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 large-scale tsunami and damage to nuclear power plants. Many slope failures occurred in hilly areas, such as in residential lands on valley fills in Miyagi Prefecture close to the epicentre. Moreover, although located about 380 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 deformations. This paper discusses the results of the damage investigation conducted in the area after the earthquake, with emphasis on slope failures in valley fills and 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.

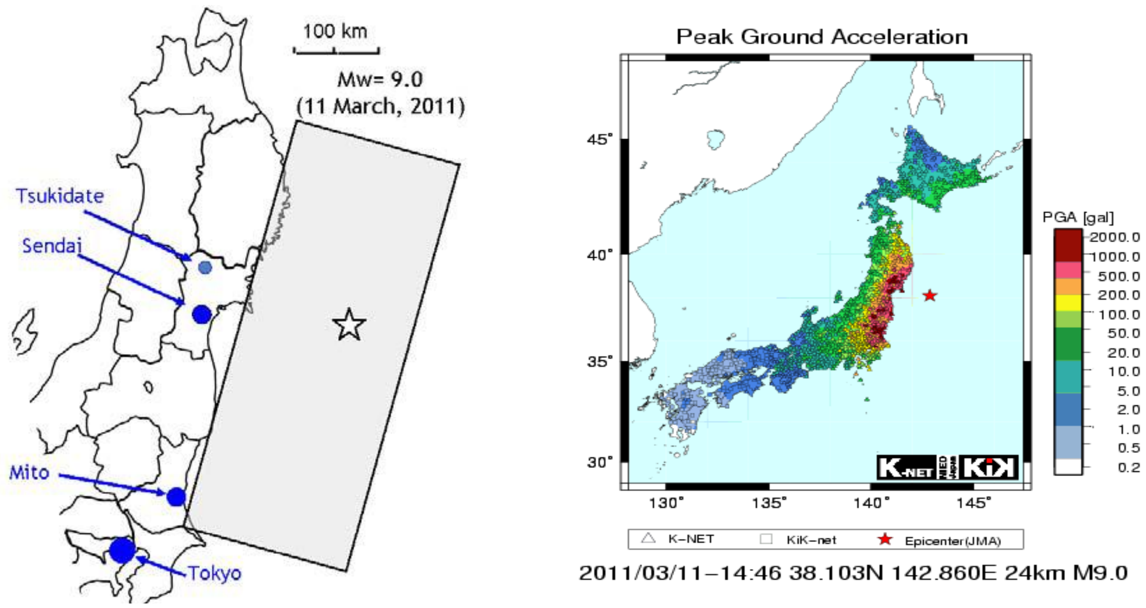
1 INTRODUCTION

At 2:46 pm (local time) on 11 March 2011, a gigantic earthquake with moment magnitude Mw 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 large-scale tsunami generated by the earthquake. Aside from wreaking havoc to residential houses near the coasts, the tsunami also damage the Fukushima Daiichi nuclear power plants, 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).

The author was able to visit some of the earthquake affected sites four months after the earthquake while on study and research leave in Japan. Emphasis of the visits was on areas affected by soil liquefaction and on residential embankments in valley fills where slope failures occurred. Although most of the damaged infrastructure have been repaired when the visits were made, many of the affected structures remained in their damaged state. Some of the findings observed are reported in this paper, focusing on the effect of ground deformations on the response of residential structures. 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 and sites near river channels and on the slope failures that occurred in residential lands on valley fills.

2 THE EARTHQUAKE

Considered as the largest in recorded history worldwide, the March 11, 2011 earthquake struck along the subduction zone interface plate boundary between the Pacific and North America plates. The size of the causative mechanism was about 500 km long in the NS direction and 200 km wide (See Figure 1a). The huge scale of the earthquake produced strong shaking across a broad region and triggered many strong motion recorders installed throughout the affected area. Figure 1(b) illustrates the



(a) (b)

Figure 1: (a) Location of causative mechanism and major damaged areas (after Towhata et al., 2011); and (b) distribution of peak ground accelerations recorded by KyoshinNet (Note: 1 gal = 1 cm/s^2)

distribution of peak ground accelerations (PGA) recorded in various strong motion sites operated by the National Research Institute for Earth Science and Disaster Prevention (NIED). The maximum PGA recorded during this earthquake was in station MYG004 (Fault distance =75 km), where 2425 and 1150 cm/s^2 were monitored in NS and EW directions, respectively.

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 2 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 as much as 180 seconds, caused extensive damage not only to superstructures but to the ground as well.

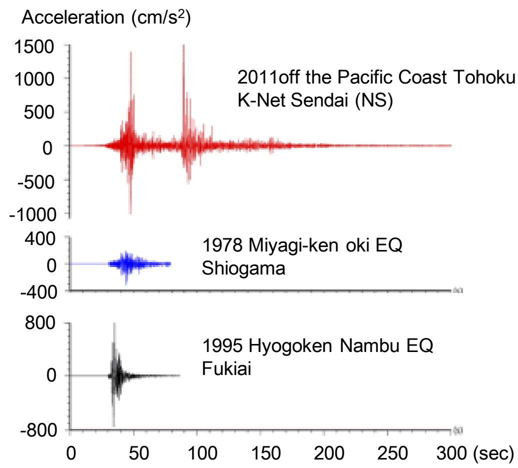


Figure 2: Comparison of recorded strong motions at K-Net Sendai (NS) station during the 2011off the Pacific Coast of Tohoku Earthquake with those from previous destructive earthquakes (modified from Shimizu Corp, 2011).

3 LIQUEFACTION-INDUCED DAMAGE IN KANTO REGION

Liquefaction-related damages were primarily observed around the northern and northeastern shorelines of Tokyo Bay (such as the reclaimed portions of Shin-Kiba, Urayasu City and Mihama) and at sites along the Tone River (such as Itako, Katori, Kamisu, and Kashima). Figure 3 indicates the areas where liquefaction was observed in the Kanto Region.

Figure 3: Observed liquefied sites in Kanto Region, denoted by red circles (after of Houkoku Engineering Ltd).

In Tokyo, located about 380 km away from the epicentre, 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. The long duration of shaking triggered soil liquefaction at many sites in the reclaimed areas located adjacent to Tokyo Bay. Most of the sites were reclaimed as recent as the 1970s, although reclamation works in Tokyo Bay dated as far back as the 1800s. Many residential and commercial buildings in these reclaimed islands were affected by ground deformation (lateral spreading and settlement) induced by liquefaction. Road pavements buckled, manholes were uplifted and lifeline facilities were damaged (See Figure 4a). Ground subsidence was also observed, especially near buildings supported by pile foundations (see Figure 4b). More detailed description of liquefaction-induced damage in Tokyo Bay is presented elsewhere (Orense et al. 2011).

(a) (b)

Figure 4: Observed liquefaction-induced damage in Urayasu City: (a) uplifted manholes over a section parallel to the road; and (b) ground settlement adjacent to pile-supported building.

(a)

(b)

Figure 5: (a) Excellent performance of SCP-improved ground in Tatsumi; and (b) an undamaged building resting on improved ground in Shin-kiba while adjacent to it, sand boils were everywhere.

Many sites near Tokyo Bay, especially those in the reclaimed areas, were remediated during the economic bubble in the 1980s. Sites improved by sand compaction piles (SCP), gravel drains, and cement deep mixing method performed well in the earthquake. Figure 5(a) shows a medical centre building in Tatsumi whose foundation ground was improved by non-vibratory SCP method (or SAVE compozer method). It can be seen that although liquefaction-induced damage, such as ground settlement and sand boils, occurred outside the improved area, no damage was observed within the improved zone. The foundation ground of the building shown in the background of Figure 5(b) was remediated against liquefaction and the building was undamaged. Just a few meters away, sand boils were evident in the unimproved ground.

In Kamisu City located adjacent to Tone River, ground subsidence and distorted pavements were observed in many places. Figure 6(a) shows a stretch of road which subsided by about 50 cm. Buckled pavements, sand boils and popped-up manholes were seen in the vicinity. Another area of extensive liquefaction was observed in Hinode, Itako City, which was formerly a lake. Many residential houses suffered damage as a result of uneven settlement and lateral spreading (see Figure 6b). Electric poles were tilted, buried water pipelines were compressed and buckled, and many roads were damaged. When the visit was made four months after the earthquake, the community remained in its damaged state. Basic necessities, such as electricity and water supply, have not been restored to some houses making life difficult to those who decided to stay in the area. The ground adjacent to the primary school building settled by about 30 cm, and this necessitated the installation of ramps to enter the building. The building itself was on pile foundation and suffered very little structural damage.

(a)

(b)

Figure 6: (a) A portion of the road in Kamisu City which settled due to liquefaction; and (b) damaged house as a result of liquefaction in Itako City.

Soil liquefaction was generated over a very wide region quite far from the epicentre. Because of the large area affected, disaster recovery and restoration work took quite some time, prolonging the suffering of the affected residents. In Tokyo Bay, for example, thousands of residential houses underwent some degree of damage, such as tilting and subsidence. Although these houses can be readily restored (by jacking, for example), the possibility of re-liquefaction during future aftershocks would require the application of economical ground remediation techniques which ordinary householders can shoulder.

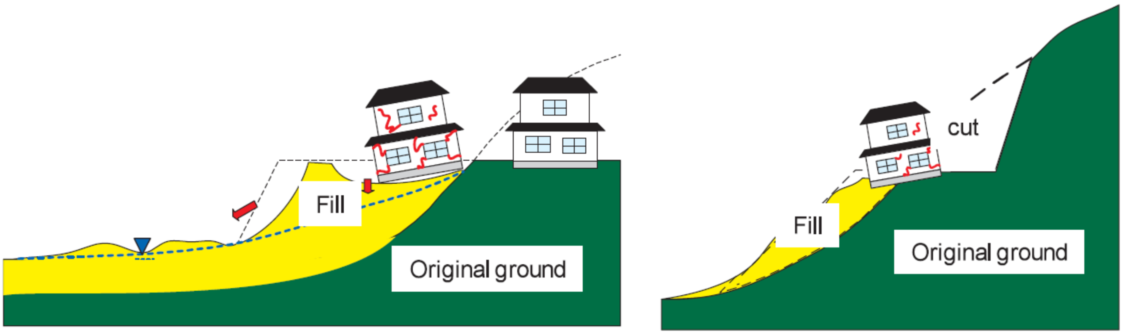
Because of the large scale and the long shaking duration, the earthquake generated large number of cycles. This may require a review of the liquefaction potential evaluation as specified in some design codes where large number of significant cycles of loading is not considered. Most of the soils that liquefied, such as those in Tokyo Bay, have high fine contents; therefore, the concept of relative density, which is the basis for estimating liquefaction resistance in many procedures adopted, may not be applicable.

4 SLOPE FAILURES IN RESIDENTIAL EMBANKMENTS

Failures of natural slopes and man-made embankments occurred in many places. However, the size of these failures was not that large. Failures of artificial earth fills for residential land development in hill areas were enormous, with 950 cases reported in 9 prefectures (Asahi Shimbun, 2011). Most heavily affected houses are often located on the land filled sites (Figure 7a) and on the boundary between land cut and fill (Figure 7b). Housing estates have been developed on suburban hills in order to meet the rapidly growing housing demand of the previous decades. The hills were chosen for housing development since the plains were already urbanized or occupied by agricultural lands that are protected by planning, while suburban hills previously used as common forest or for making charcoal lost its role in the modern city (Isoda et al, 1998).

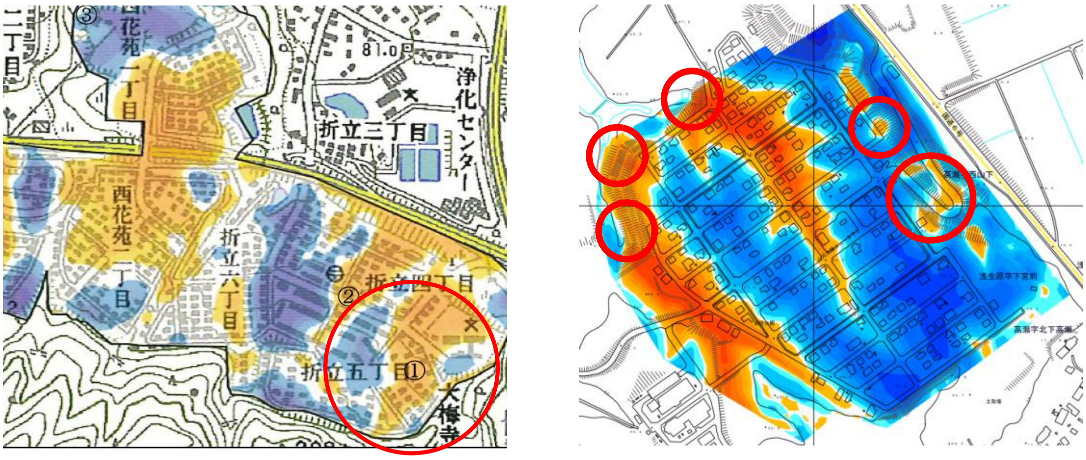
In Miyagi Prefecture alone, hundreds of slope failures were observed in many areas, such as in Oritate, Midorigaoka, Sakuragaoka and Taiyo New Town to name a few. Figure 8 illustrates the thickness distribution of cuts (darker region) and fills (lighter region) in Oritate and Taiyo New Town and the locations of observed slope failures. These sites were developed as residential areas in the 1970s by cutting and levelling off some parts of the hills and using the excavated materials as fill for the valleys, thereby creating a flat terrain with least transport of soil. To level off the residential land, cuts were made on the hills as high as 10-15m, while valley floors as deep as 15-20 m were filled up. Most of the slope failures in these areas were observed at the boundaries between fill and cut sections.

Oritate District (Aoba Ward), located in the western part of Sendai City is a new residential development in the hills. Of the 142 houses in the area, 55 in the eastern part of the district have been damaged by slope failures. Figure 9(a) shows the slope failure directed towards the left of the photo, resulting in a portion of the road being compressed by the slide. Damage due to differential settlement under houses at the boundary between cut and fill was also significant (Figure 9b).



(a) (b)

Figure 7: Schematic diagrams of slope failures in residential embankments: (a) valley fills; and (b) partially buried slopes (after M. Kazama).



(a) (b)

Figure 8: Housing site foundation maps showing the thickness distribution of cut and fill sections (after Fukken Gijutsu Consultant, 2008): (a) Oritate District; and (b) Taiyo New Town, where circles indicate the locations of failed slopes.

(a) (b)

Figure 9: Slope failure in Oritate 5-chome: (a) damaged road; and (b) deformed house.

The Taiyo New Town housing site is located in the central part of Yamamoto, a coastal town on the southern edge of Miyagi Prefecture. It is located on the hilly region to the west of Route 6, which traverses the prefecture in an almost north-south direction. In fact, Route 6 appears to be the dividing line between the coastal plain on the east and the 40-50m high mountains on the west of the prefecture. The site has about 200 houses when the earthquake occurred. The failure shown in Figure 10(a) is located on the northern edge of the slope adjacent to a steep ravine. In this section, a portion of the road embankment collapsed over a distance of 15-20 m, and the fill materials flowed down the slope. A house adjacent to the road and located on top of the crest tilted, together with the fence and road railings. Figure 10(b), on the other hand, is located on the western section of the residential site. A 2-story house on top of the slope was damaged due to vertical offsets and extensional failure resulting from slope movement. The house was tilted, exposing its foundation. A more detailed description of the slope failures in Taiyo New Town is reported by Hyodo et al. (2011). Investigation of the local geology of the site revealed that the original ground consisted of tuffaceous sandstones of the Yamamoto Formation. Subsequent boring data showed that the sandstones were weakly consolidated and exhibited high degree of weathering towards the surface, with the surficial layer turning into sandy soil. Thus, the material used to fill up the valleys consisted of sandy soils from the weathered tuffaceous sandstones.

(a) (b)

Figure 10: Slope failure in Taiyo New Town: (a) collapsed portion of a road; and (b) house precariously hanging on top of a failed slope.

The number of failed hillside embankments (valley-filled embankments and widening embankments) has highlighted the vulnerability of these sites to very large ground accelerations, which are rarely experienced. Estimates of accelerations were in excess of 1.2g on top of the fill sections. Some failed sites manifested flow-type of failure similar to those induced by soil liquefaction; hence, the role of ground water in triggering these slides needs to be investigated.

5 CONCLUDING REMARKS

Although overshadowed by the damage caused by the large-scale tsunami and nuclear accidents, the gigantic earthquake on 11 March 2011 which hit Eastern Japan also highlighted many geotechnical problems induced by the earthquake, such as soil liquefaction of artificial fills and sites adjacent to rivers and failure of artificially modified slopes and valley fills.

In addition to the large magnitude of ground shaking, the long duration of shaking inducing larger number of significant cycles. Although located about 380 km away from the epicentre, widespread liquefaction was observed in the man-made islands and artificially reclaimed sites in Tokyo Bay. In natural deposits, liquefaction was minimal, highlighting the role of the age of the soil in liquefaction susceptibility. In areas where the grounds were remediated, there was practically no sign of liquefaction while a contrasting observation was noted on unimproved grounds.

The earthquake also showed the vulnerability of artificial embankments for housing estates. During this earthquake, many houses located on the land-filled sites and on the boundary between land cut and fill were heavily affected. The damage may be due to poor design (insufficient compaction, insufficient drainage, lack of retaining wall strength, etc.) but also the unanticipated scale of the earthquake.

Although the damage to residential houses as a result of liquefaction and slope failures are of smaller scale and most houses are restorable, the sheer number of affected houses (estimated to be in hundred thousands) and the spatially wide expanse of areas involved, the post-earthquake response and restoration works have been made difficult and delayed. Finally, the damage to residential houses made individual owners to be aware and concerned of the issues under the ground surface; hence, this is the best time for geotechnical engineers to work hard and demonstrate to the people the importance of geotechnical engineering.

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