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RECURRENT LIQUEFACTION INDUCED BY THE 2011 GREAT EAST JAPAN EARTHQUAKE COMPARED WITH THE 1987 EARTHQUAKE

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ABSTRACT: The M_w 9.0 destructive earthquake that occurred March 11, 2011, in Japan was associated with widespread liquefaction within a 500-km long zone that extended from Iwate to Kanagawa Prefectures in the eastern part of Japan. Based on reconnaissance surveys of the Great East Japan Earthquake of March 11, 2011, recurrence of liquefaction at the same sites was identified at sites where liquefaction had occurred during the M_J6.7 Chibaken Toho-oki earthquake of December 17, 1987; the surveys also compared observed liquefaction effects with those of the 1987 earthquake.

Key Words: Great East Japan earthquake, liquefaction, re-liquefaction, 1987 Chibaken Toho-oki earthquake

INTRODUCTION

Liquefaction has been known to occur repeatedly at the same site during successive earthquakes, as shown by examples from Japan, United States, and Greece (e.g. Kuribayashi and Tatsuoka, 1975; Youd and Hoose, 1978; Youd and Wieczorek, 1982; Suga et al., 1983; Yasuda and Tohno, 1988; Papathanssiou et al., 2005; Wakamatsu, 2011; and Yamada et al., 2011).

Wakamatsu (2011) revealed that recurrence of liquefaction at the same site had occurred at 150 sites, including the re-liquefaction sites identified by Yasuda and Tohno (1988) based on the GIS database analysis for approximately 16,800 liquefied sites during the period from 745 to 2008 throughout Japan. These repeated liquefactions were concentrated in areas with specific geomorphologic conditions: abandoned river channels (36 sites) artificial fills (35 sites), and lower slopes of sand dunes (26 sites).

Widespread liquefaction was generated repeatedly in natural sediments within a short period in Christchurch and adjacent areas, New Zealand, during the September 2010 Darfield (M_w 7.1), February 2010 Christchurch (M_w 6.2), and 13 June 2011 Christchurch (M_w 6.2) earthquakes, causing significant damage to residential buildings and lifelines (Yamada et al., 2011). The repeated liquefaction was often quite severe, and many residents reported that in some cases the severity increased in subsequent events.

It is important for evaluating the process of re-liquefaction and the aging effects of soils against liquefaction to investigate instances of repeated liquefaction. In addition, the locations of repeated liquefaction are considered potential areas of liquefaction in future earthquakes. In this study, the author collected more than 60 instances of repeated liquefaction at sites where liquefaction was induced by the March 11, 2011, Great East Japan Earthquake, and compares observed liquefaction effects with those associated with a previous earthquake. The land-use history, geomorphology, and geotechnical conditions of the sites are also examined.

DISTRIBUTION OF LIQUEFIED SITES CAUSED BY THE 2011 GREAT EAST JAPAN EARTHQUAKE

At 14:46 local time on March 11, 2011, a gigantic earthquake of moment magnitude M_w9.0 occurred with an epicenter located on the Pacific Ocean off the Oshika Peninsula. This earthquake induced liquefaction at a significant number of locations in 149 municipalities (cities, special wards, towns, and villages) within a 500-km long zone that extended from Iwate to Kanagawa Prefectures in the eastern part of Japan (Fig. 1). The farthest liquefied site from the epicenter of the main shock is Minami-boso Town, whose epicentral distance is approximately 440 km. Serious damage was caused to residential houses, pipelines, embankments, agricultural facilities, and port facilities as a result of the liquefaction. Liquefied sites induced by previous earthquakes are also plotted in Fig 1. It can be seen that liquefaction was induced by the 2011 earthquake in the most of the municipalities where liquefaction had occurred in the past.

According to the eyewitness testimony of local residents, sand boiling was observed during the main shock at 14:46 March 11; however, in some areas near the Pacific Ocean in northern Chiba and southern Ibaraki Prefectures, sand eruption did occur during the largest aftershock, which took place at 15:45 March 11 with an epicenter located on the Pacific Ocean off Ibaraki Prefecture. In some areas, sand boils occurred during minor aftershocks, but the dates and times were not identified precisely because a number of strong aftershocks occurred at short intervals after the main event.

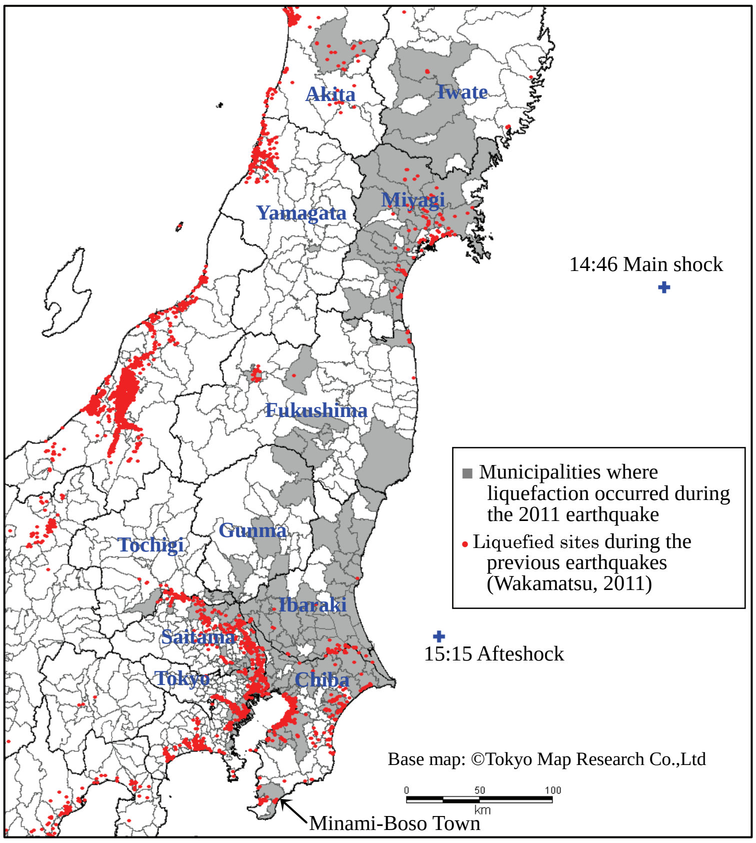


Fig. 1 Distribution of cities, special wards, towns, and villages where liquefaction occurred during the Great East Japan earthquake and liquefied sites in past earthquakes

SITES OF REPEATED LIQUEFACTION AND THEIR LAND-USE HISTORY, GEOMORPHOLOGY, AND GEOTECHNICAL CONDITIONS

Figure 2 shows distribution of sites where repeated liquefaction was identified during the 2011 Great East Japan earthquake in Kanto. Most of the sites were located in Chiba and southern Ibaraki Prefectures--that is, the northern part of the Tokyo Bay area, northern areas of the Kujyukuri plain and the flood plain in the lower reaches of the Tone River, where liquefaction occurred during the M_J6.7 Chibaken toho-oki earthquake of December 17, 1987. Following the 1987 earthquake, the author conducted extensive reconnaissance investigation in the affected areas, and consequently liquefied sites were specified precisely (Kotoda and Wakamatsu, 1989).

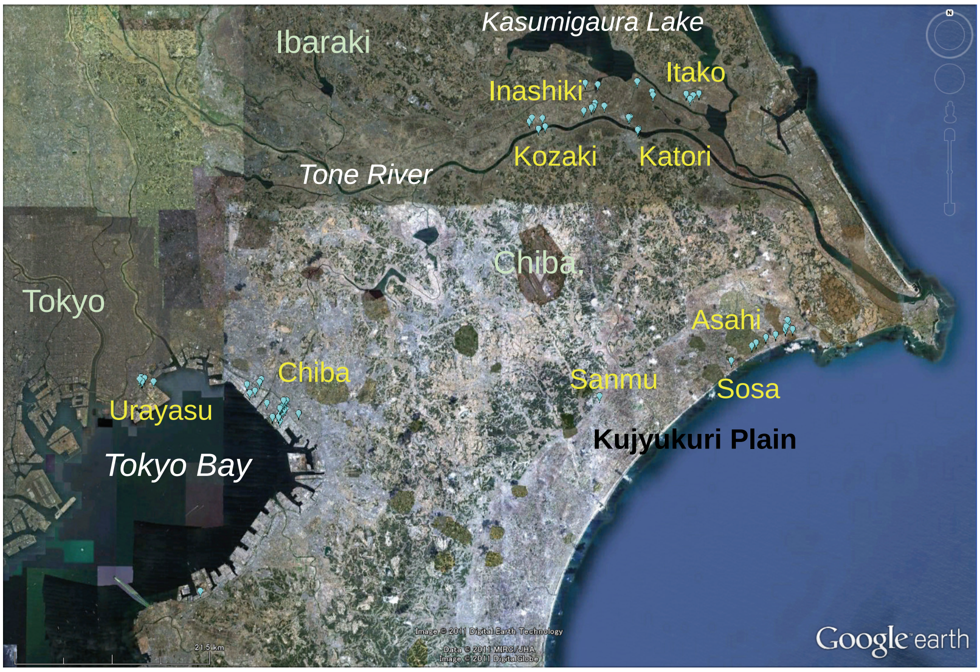


Fig. 2 Distribution of sites where repeated liquefaction was identified during the 2011 Great East Japan Earthquake

Tokyo Bay area

Along the shoreline of Tokyo Bay, land reclamation has been performed since the Edo Era, especially since the 1950s. Extensive violent sand boils occurred in artificial fill along the Tokyo Bay, particularly in the areas from Urayasu to Chiba, during the 2011 earthquake in places where surface effects of liquefaction occurred during the 1987 Chibaken toho-oki earthquake. Repeated liquefaction was identified to occur at a total of 6 sites in Mihama 3-chome, Kairaku 1-chome, and Irifune 4-chome, located in seaside areas of Urayasu City that were filled in between 1965 and 1971. During the 1987 earthquake, a lot of sand boils erupted and water flowed out from the ground in the roads, parks, and residential lots; minor damage took the form of settlement and cracks to pavement, walls, and gateposts, but no effects of liquefaction occurred in houses and buildings (Photo 1 (a)). In contrast, liquefaction effects were severe during the 2011 earthquake: huge quantities of sand erupted and accumulated to depths of several dozen centimeters; single-family houses settled and tilted perceptibly and lifelines were damaged severely (Photo 1 (b)). Figure 3(a) shows the soil profile and SPT N-value in Mihama 3-chome, where severe sand boils were observed. The soil from the ground surface down to a depth of 8m is fill composed of loose fine sand and silty sand with silt seams A silt layer of sea bed sediment lies beneath the fill. The groundwater level is as high as around GL-3 m. The loose fill up to around 8 m seems to have liquefied in this area.

Repeated liquefaction at the same site was identified to occur at total of 19 sites in Mihama-ku, Chiba City (Photo 2 (a) (b)). Many sand boils and ground cracks were observed in schoolyards, parks, and the yards of housing complexes, but no damage to houses and buildings occurred during the 1987 Chibaken toho-oki earthquake. The effects of liquefaction induced by the 2011 earthquake were severe: huge amounts of sand erupted, single-family houses settled and tilted substantially, and lifelines were damaged, as was seen in Urayasu. The areas had been filled in between 1966 and 1975 and were mainly composed of loose fine sand fills with SPT N-values less than 10 from the surface to a depth of about 7 m as shown in Fig. 3(b). The loose sandy fills at a depth of 2 to 7m presumed to have liquefied during the earthquakes.

(a) 1987 earthquake

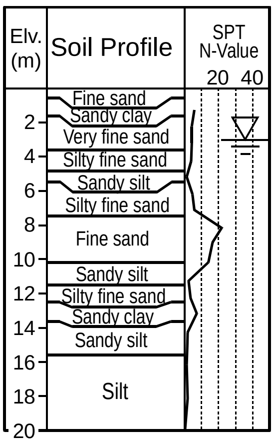
(b) 2011 earthquake (Urayasu City, 2011)

Photo 1 Sand boils due to repeated liquefaction in 3-chome of Urayasu City

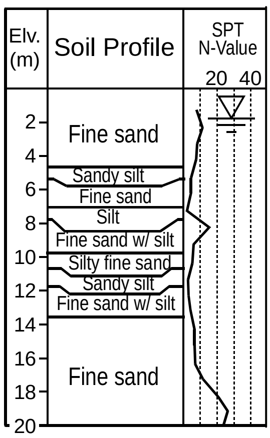
(a) 1987 earthquake

(b) 2011 earthquake (Onizuka et al., 2011)

Photo 2 Sand boils due to repeated liquefaction at Takasu-daisan elementary school, Mihama-ku, Chiba City



(a) Mihama, Urayasu City



(b) Mihama-ku, Chiba City

Fig. 3 Soil profile and SPT N-value in Tokyo Bay area

Kujyukuri plain of Chiba Prefecture

Kujyukuri plain is located in the south-easternmost part of Chiba Prefecture facing the Pacific Ocean and is a typical coastal plain consisting of sand bars (including partial sand dunes developed on the bar) along the shoreline and inland marshes behind and between bars.

Liquefaction occurred in residential areas and farms in the Kujyukuri plain during the 2011 earthquake. Liquefaction effects were most clearly observed in the northern half of the plains closer to the epicenter: the cities of Asahi, Sosa, Togane, Sanmu, and Kujyukuri Town. Among them, liquefaction-induced damage was the most extensive and serious in Asahi City, where 757 houses were damaged due to liquefaction (Asahi City, 2011).

Liquefaction had been generated at many sites in the Kujyukuri plain lying in the epicentral region during the 1987 Chibaken toho-oki earthquake. Single-family houses were damaged by liquefaction, but number of the damaged houses was smaller than in the 2011 earthquake because this area was sparsely populated at the time of the 1987 earthquake, and the liquefaction was confined to smaller local areas.

In the coastal area of the Kujyukuri plain, iron sand mining had been in operation on a large scale up to the 1970s: excavation was done by open cuts to depths ranging from 5 to 10 m. Iron was extracted by iron concentrators from excavated sand at the site; the remaining sand was backfilled into the excavated ground, and finally the land was returned to its owners and used as paddy field (Iioka Town, 1976; Asahi City, 1988).

Liquefaction is identified to recur at total of 12 sites in this plain: 10 sites in Asahi City and one site each in Sosa City and Sanmu City, respectively. In Idono-hama, Ashikawa, Nakayari, Shiinauchi, Nonaka, and Sangawa in Asahi City, houses damaged during the 1987 earthquake were repeatedly damaged due to liquefaction during the 2011 earthquake. According interviews with city government officials and local residents, all of the repeated liquefactions occurred in areas formerly excavated and backfilled for iron mining.

Photo 3 shows damage to a house in Ashikawa, Asahi City, due to repeated liquefaction. The house in Photo 3 (a) settled about 30 cm and tilted northward (toward the front of the photo), and the base of the house was separated from the foundation during the 1987 earthquake; two nearby houses were also affected by liquefaction. Water bubbled up in the surrounding farms and flooded them for a while. The house in Photo 3 (a) was rebuilt after the 1987 earthquake, but the ground of the lot sank as a result of the repeated liquefaction during the 2011 earthquake and the newly-built house was severely damaged again (in Photo 3(b)). Seven nearby houses, including the two houses damaged during the 1987 earthquake, were severely affected by liquefaction. According to the owner of the house in Photo 3, his lot had been excavated for sand iron mining around 1960, and then backfilled, and had been used as paddy field. Around 1975, the land was filled up by about 1 m to be used for housing lot.

At a farmland plot adjoining a factory in Sangawa, Asahi City, sand erupted during both the 1987 and 2011 earthquakes (Photo 4). The factory building settled differentially, and the floor slab showed a crack about 3 cm wide after the 1987 earthquake. The settlement of the factory building increased and

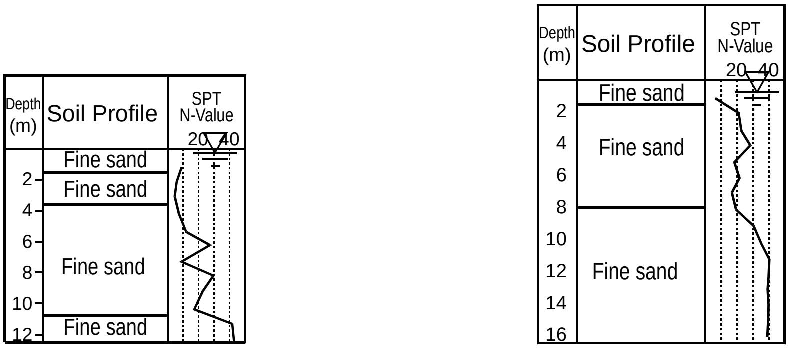
(a) 1987 earthquake

(b) 2011 earthquake

Photo 3 Damaged to a residential house due to repeated liquefaction in Ashikawa, Asahi City

(a) 1987 earthquake (b) 2011 earthquake

Photo 4 Sand boils and damage to a factory due to repeated liquefaction at Sangawa, Asahi City



(a) Excavated and backfilled areas for iron mining (Liquefied)

(b) Natural ground of coastal plain (No effect of liquefaction)

Fig. 4 Soil profile and SPT N-value in Sangawa, Asahi City

the frames of the windows were distorted substantially in the 2011 earthquake. Around the factory, 17 single-family houses were severely damaged due to liquefaction. According to a resident, no houses were damaged during the 1987 earthquake and small cracks appeared in the pavement.

Figure 4 (a) shows the soil profile and SPT N-value survey conducted in the formerly excavated and backfilled areas. The upper 4 meters is loose fine sand with SPT N-value less than 10 with high potential to liquefy, which is presumed to have been backfilled after excavation for iron sand mining. Ground water level is as high as 0.25 meters. Whereas Fig. 4 (b) shows the soil profile and SPT N-value in the natural ground at near by site (a), where no effects of liquefaction was observed. It shows a typical soil profile for coastal plain, that is, upper 9 meters is moderately-dense fine sand with SPT N-value around 20, which is sand bar origin.

Photo 5 shows an aerial plan view of an athletic park in Yoshizaki-hama of Sosa City, with an area of 27,541 m^2 near the Pacific Ocean. In the 1987 earthquake, sand boils with diameters of about 6 m were observed at nine sites in multipurpose open space with an area of 2879 m^2 as shown as Photo 6 and liquefaction-induced lateral spreading occurred in seaside plant observation area. Many fissures were observed in the slope of the area. The pavement of a walking path located on the ridge of the slide was cracked vertically and settled, and moved slightly downward as shown in Photo 7 (a). No damage occurred in the administration building of the park, which was supported by a pile foundation. Similar but more extensive liquefaction effects recurred during the 2011 earthquake: a large quantity of sand erupted; numerous ground cracks and subsidence occurred everywhere in the park; and liquefaction-induced lateral spreading recurred in the seaside plant observation area in the same manner as during the 1987 earthquake (Photo 5). Photo 7 (b) shows the crack in a walking path with about a 85 cm slump which occurred at the same point as in Photo 7 (a). The damage mode is remarkably-similar to that in 1987. According to the Yokaichiba City (the former city name before a municipal merger in 2006) government at the time of the 1987 earthquake, the lot on which the park was created had been an iron mining field, and then had been used as paddy field before being filled in 1981 for construction of the park.

Photo 5 View of an athletic park in Yoshizaki-hama, Sosa City (taken in June, 2011)

Photo 6 Sand boils in multipurpose open space generated by the 1987 earthquake

(a) 1987 earthquake (b) 2011 earthquake

Photo 7 Damage to a pavement of walking path of the athletic park due to repeated liquefaction in Yoshizaki-hama (see Photo 5 for location)

Lower reaches of the Tone River

The Tone River is the second longest river and has the largest drainage area in Japan. Along the banks of the lower reaches of the river, numerous ponds and abandoned river channels were created as a consequence of the shortcut channeling projects which were conducted from the 1900s to the 1930s, as shown in Fig. 5. These ponds and former river channels were sequentially filled up with the dredged sand of the Tone River from the 1950s to the 1960s in order to increase rice production (Editorial Committee of A Hundred Year's History of the Tone River, 1987). The greater part of the filled area has been used as paddy fields, but some was turned into residential lots.

Repeated liquefaction at the same site in this area was identified to occur at total of 20 sites in Inashiki City and Kwachi Town, Ibaraki Prefecture, and Katori City and Kozaki Town, Chiba Prefecture. The effects of liquefaction were more severe and widespread during the 2011 earthquake than during the 1987 earthquake

Violent sand eruptions and numerous large sand craters occurred with diameters of 1 to 3 meters in the paddy fields during the 1987 earthquake. These effects predominantly developed within the filled channels and ponds. Figure 6 (a) shows the distribution of sand boils observed in the former river course in Kozaki Town, as identified by field survey and aerial photographs taken after the earthquake. Numerous large sand boils were formed on the former channel, as shown in Photo 8 (a) and (b); it seemed that the surficial ground had completely liquefied, but no effects of liquefaction were observed on the small channels flowing along both ends of the former river channel. A few small sand boils were also formed on the point bar in the convex bank of the former channel where the dredged sand had not been filled, whereas no surface effect of liquefaction were observed in the concave bank.

These observed facts imply that river bed deposits might have liquefied and generated sand boils in addition to artificial fill.

Figure 6 (b) shows an aerial photograph taken eighteen days after the 2011 earthquake. The greater part of the former channel was covered with thick sand boil deposits, and the small channel flowing at the northern end of the former river channel was completely filled with boiled sand, as shown in Photo 8 (c). According to a local resident, a road north of the channel was flooded by water ejected after the earthquake. A number of large sand boils, with a maximum hole-diameter of 4m, occurred on the point bar in the convex bank along the former channel, in places where a few small sand boils were formed during the 1987 earthquake, but no surface effects of liquefaction were observed in the concave bank as was the case during the 1987 earthquake. A residential area located at the lowest end of the former

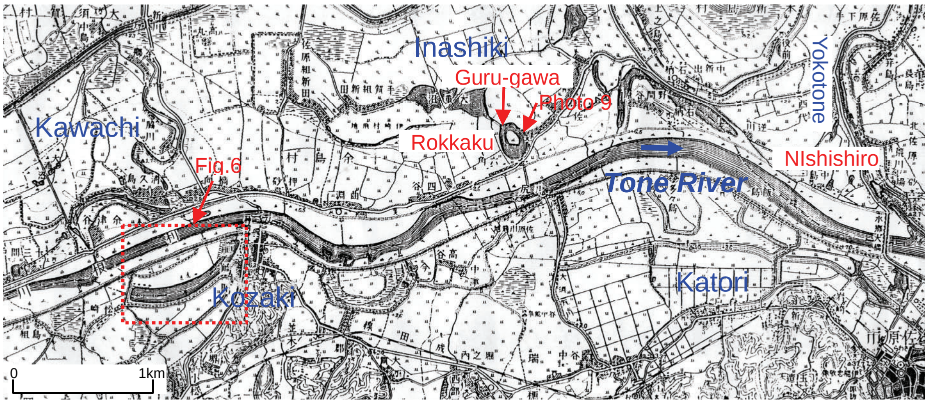
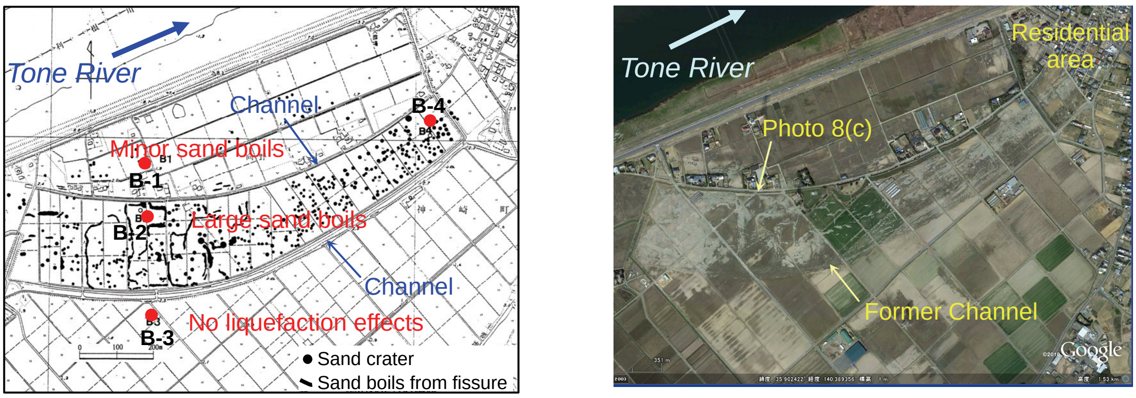


Fig. 5 Ponds along the Tone River in 1952 (Modified from 1/50,000 topographic map of Sawara)



(a) 1987 earthquake (modified from Kotoda and Wakamatsu, 1989)

(b) 2011 earthquake (satellite image taken on March 29, 2011 by Google Earth)

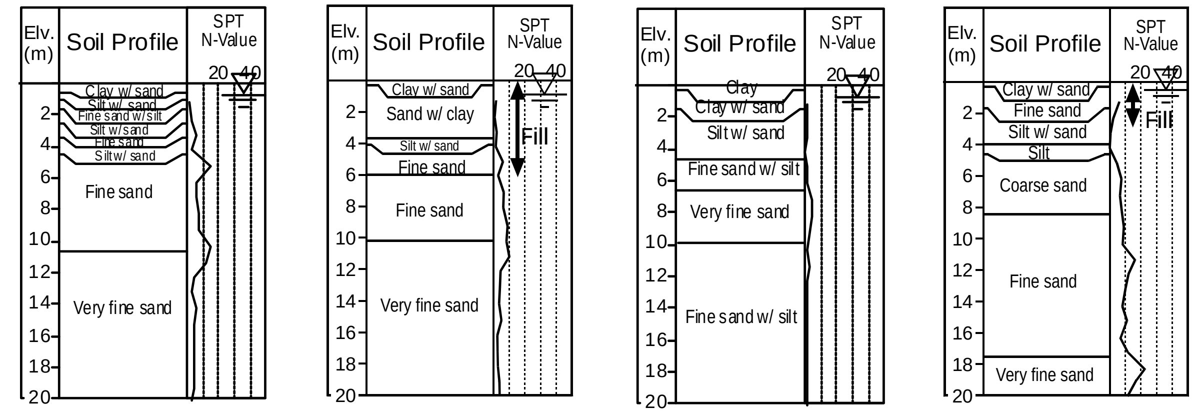
Fig. 6 Distribution of sand boils in former river course in Mukouya, Kozaki Town, Chiba Prefecture due to repeated liquefaction

(a) 1987 sand boils from fissures near B-2 in Fig 6 (a)

(b) 1987 sand boils crate near B-4 in Fig 6 (a)

(c) 2011 sand boils filled up a channel (see Fig. 6(b) for location)

Photo 8 Sand boils in a former river course due to repeated liquefaction in Mukouya, Kozaki Town



(a) B-1 (Minor sand boils in 1987) (b) B-2 (Large amount of sand boils from fissures in 1987) (c) B-3 (No effect of liquefaction in 1987) (b) B-2 (Large amount of sand boils from craters in 1987

Fig. 7 Soil profile and SPT N-value at Mukouya, Kozaki Town (see Fig. 6(a) for location)

river channel was severely affected by liquefaction: most of the single-family houses, walls, gateposts,and telephone poles were settled and tilted, and the roads were covered with boiled sand. Bridge piers river channel was severely affected by liquefaction: most of the single-family houses, walls, gateposts, of Kozaki Bridge across the Tone River and the river dike were reported to be damaged due to liquefaction (Katori Civil Engineering Office, 2011). No such effect of liquefaction had occurred in this residential area during the 1987 earthquake.

The author conducted boring explorations at four sites in the area of Fig. 6 two months after the 1987 earthquake. Figure 7 shows the soil profiles and SPT N-value at B-1 through B-4 in Fig. 6(a). The borings disclosed that there were five types of loose sand deposits at the Mukouya site: clayey sand fill composed of hilly sand which covers the ground surface at B-2; fine sand fill composed of river bed sand, which lies beneath the hilly sand fill at B-2 and to a depth of two meters from ground surface at B-4; loose fines sands of point-bar origin which lie to a depth of four meters from the surface at B-1; fine to coarse sands of river bed deposits with SPT N-value of approximate 10, which are encountered at three holes except B-3; and very fine sand of deltaic deposits which underlies at all of holes. No distinct differences in water tables at the time of drilling (February, 1988) were found among the four boreholes as shown in Fig. 7.

According grain size analysis for sands taken from boreholes and sand boil deposits near the holes, the curves for the sand boil deposits in 1987 are very similar with three types of fine sands of river bed deposits, point bar deposits and sand fill of river bed deposits with fine contents, defined as a percentage finer than 0.075 mm in dry weight, less than 10 %. That for sand boils deposits in 2011 earthquake are also below 10 % (Koseki et al., 2012).

Photos 9 (a) to (c) show liquefaction-induced damage in Rokkaku, Inashiki City, during the 1987 earthquake, and Photos 9 (d) to (f) show the damage at the same sites during the 2011 earthquake. Rokkaku had been a small pond named “Guru-gawa”, with a depth of about 2 meters, that was filled in 1959 with dredged sand from the Tone River by the Construction Ministry. Beginning in the 1970s residential houses were built after farmland utilization. According to officials of Azuma Village (the former city name of Inashiki before municipal merger in 2005), more than 20 houses were damaged due to liquefaction during the 1987 earthquake. The most striking effects occurred at the Photo 9 site: telephone poles sank, with their height reduced to around 2 m, and the road subsided below the surface of the adjacent paddy field (Photo 9 (a)); gateposts tilted slightly (Photo 9 (b)); a small truck parked in a yard was buried by boiled sand (Photo 9 (c)).

Liquefaction-induced damage was also the most serious at the Photo 9 site during the 2011 earthquake: telephone poles sank down and became extremely tilted; roads and farms subsided and were flooded by ejected water to the extent that the former pond reappeared (Photo 9 (d)); gateposts settled by as much as 20 cm (Photo 9 (e)); a house built on the lot shown in Photo 9 (c) sank up to 1 m (Photo 9 (f)).

(a) 1987 earthquake (b) 1987 earthquake (c) 1987 earthquake

(d) 2011 earthquake (Courtesy of Inashiki City) (e) 2011 earthquake (f) 2011 earthquake

Photo 9 Damage due to repeated liquefaction in Rokkaku, Inashiki City (for location see Fig. 5)

Reclaimed land around Kasumigaura Lake

Around Kasumigaura Lake, located along the left bank of the Tone River, there had been many lakes and marshy lands up to a century ago; they had been reclaimed by the Ministry of Agriculture and Forestry during the 1920s and 1930s as part of a project to increase rice production.

Hinode, Itako City, where serious liquefaction-induced damage to houses and lifelines occurred during the 2011 earthquake, is one of these reclaimed land areas (Fig. 8). The district was reclaimed from Uchinasakaura Lake in 1947 and had been used as paddy field. It was developed for housing lots by being raised by an average of as much as 2.8 m with a sand dredging pump from Sotonasakaura Lake in 1971. Liquefaction effects were observed during the 1987 earthquake within the filled area, and no effects were observed in the reclaimed land without fill. In the filled area, numerous sand boils occurred, especially around Point A in Fig. 8; water spouted as high as about 5m at Point B in the figure, and sand boils and depression of the sidewalk was significant at Point C in the figure. According to Itako City, at the time of the 1987 earthquake, damage to sewage pipes buried to a depth of 3 to 4m was predominant, while no damage was suffered by pipes buried to shallower or deeper depths of less than 2 to 3m, or more than 4m. Fortunately no serious effects to houses were reported in the 1987 earthquake.

After the 2011 earthquake, severe and widespread liquefaction effects were observed in the greater part of fill-up areas including the area of the 1987 liquefaction, as shown in Fig. 8. Photos 9 (a) and (b) are a comparison of the damage at the same site in the 1987 and 2011 earthquakes. Covers of the gutter along a street were heaved up as a result of liquefaction, a number of telephone poles were dramatically inclined, and a house tilted slightly in the 2011 earthquake (Photo 10 (b)); whereas during the 1987 earthquake sand boils occurred in the farm adjacent to the street but no effects were observed on the covers of the gutter (in the front part of the photo 9 (a)).

Figure 9 shows a soil profile and SPT N-value in Hinode. The upper 4 meters is fill composed of loose fine sand, and fluvio-marine silty clay underlies the fill, in turn overlying moderately-dense sand. The water level is as high as GL-1 m. The loose fine sand fill beneath the water level seems to have liquefied during the earthquakes.

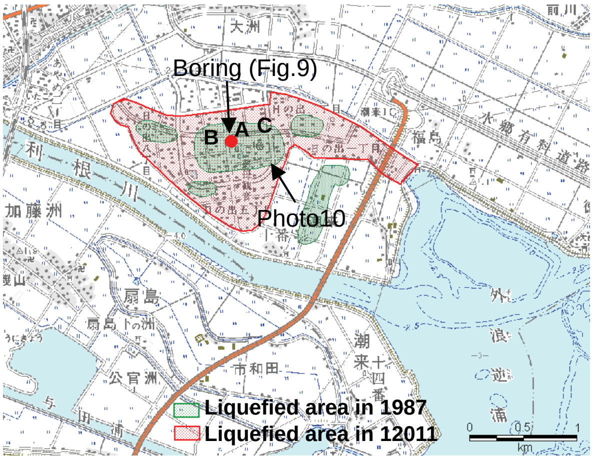


Fig. 8 Areas of liquefaction in Hinode of Itako City during the 1987 and 2011 earthquakes

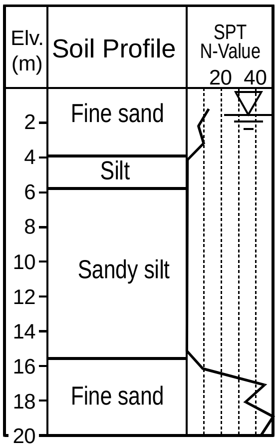


Fig. 9 Soil profile and SPT N-value in Hinode, Itako City (see Fig. 8 for location)

(a) 1987 earthquake (b) 2011 earthquake

Photo 10 Damage due to repeated liquefaction in Hinode, Itako City

CONCLUSIONS

Based on a reconnaissance survey of the Great East Japan Earthquake of March 11, 2011, recurrence of liquefaction at the same sites was identified at a total of 62 sites. As a result, the following conclusions have been reached:

1) Second time liquefaction was observed during the 2011 earthquake at a total of 62 sites in the Kanto region, where liquefaction occurred during the M_J6.7 Chibaken toho-oki earthquake of December 17, 1987.
2) Comparing the extent and severity of liquefaction effects between the successive earthquakes in 1987 and 2011, the effects of the 2011 earthquake are larger than those associated with the 1987 at every site, but damage patterns are similar at every site.
3) Most of the repeated liquefaction sites are artificially filled or backfilled areas on seashores, lakes, former river channels, ponds, and excavated areas, but natural sediments such as river bed deposits seem to liquefy repeatedly.
4) Soil profiles of the repeatedly liquefied sites located in the upper 4 to 5 meters from the ground surface showed that they were composed of loose fine to medium sand with SPT N-value less than 10. The groundwater levels are as shallow, within 3 meters from the ground surface.

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