Recurrence of Liquefaction at the Same Site Induced by the 2011 Great East Japan Earthquake Compared with Previous Earthquakes

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SUMMARY:
The M_w 9.0 destructive earthquake that occurred March 11, 2011, in Japan was associated with widespread liquefaction within a 650-km long zone that extended in the eastern part of Japan. Based on reconnaissance surveys of the earthquake, recurrence of liquefaction at the same sites was identified at ninety sites where liquefaction had occurred during the previous earthquakes such as the 1987 Chibaken toho-oki and the 1978 Miyagiken-oki earthquakes. Comparing the extent and severity of liquefaction effects between the the former earthquakes and the 2011 earthquake, the effects of the 2011 earthquake are larger than those associated with the previous events at every site but damage patterns are very similar. Most of the repeated liquefaction sites are filled or backfilled areas on seashores, lakes, former river channels, ponds and excavated areas in the last sixty years, but old fills and natural sediments such as riverbed deposits seem to liquefy repeatedly.

Keywords: liquefaction, recurrent liquefaction; the 2011 East Japan earthquake; earthquake damage

1. 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; Yasuda and Tohno, 1988; Papathanssiou et al., 2005; and Wakamatsu, 2011). In recent, Cubrinovski et al (2011) reported that the 2010–2011 Christchurch earthquakes caused repeated liquefaction through the suburbs of Christchurch and its Central Business District. The liquefaction was very severe and widespread causing extensive damage to residential houses/properties, commercial buildings, lifelines and infrastructure.

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. The author collected 90 instances of repeated liquefaction at sites where liquefaction was induced by the March 11, 2011, Great East Japan Earthquake. This paper presents the detailed re-liquefaction map and discusses a comparison between the 2011 earthquake and previous earthquakes based on the observations made by the author and the documents for old events, with emphasis on the extent and severity of liquefaction effects. The interval between successive earthquakes for recurrence of liquefaction, land-use history, geomorphology, and geotechnical conditions of the sites are also discussed.

2. SOIL LIQUEFACTION IN THE 2011 GREAT EAST JAPAN EARTHQUAKE

At 14:46 local time on March 11, 2011, a gigantic earthquake of moment magnitude M_w9.0 struck eastern Japan including Tohoku and Kanto regions. The epicenter of the earthquake was located on the Pacific Ocean off about 130 km east-southeast of the Oshika Peninsula and at a depth of about 24 km. This earthquake induced liquefaction at a significant number of locations in 160 municipalities (cities, special wards, towns, and villages) within a 650-km long zone that extended from Aomori to Kanagawa Prefectures in the eastern part of Japan (Figure. 2.1). 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. Figure 2.2 indicates the distribution of horizontal peak ground acceleration (PGA) calculated by QuiQuake (2011). It can be seen that liquefaction occurred in the areas where the PGAs exceeded about 150 cm/s^2.

The earthquake caused repeated liquefaction in the Kanto and Tohoku regions: up to present, ninety sites plotted in Figure. 2.1 have been identified to re-liquefy. At these sites, liquefaction had previously occurred during the earthquakes listed in Table 2.1. However it is not confirmed that repeated liquefaction occurred at the exactly same place for the earthquakes of 1896, 1923 and 1962.

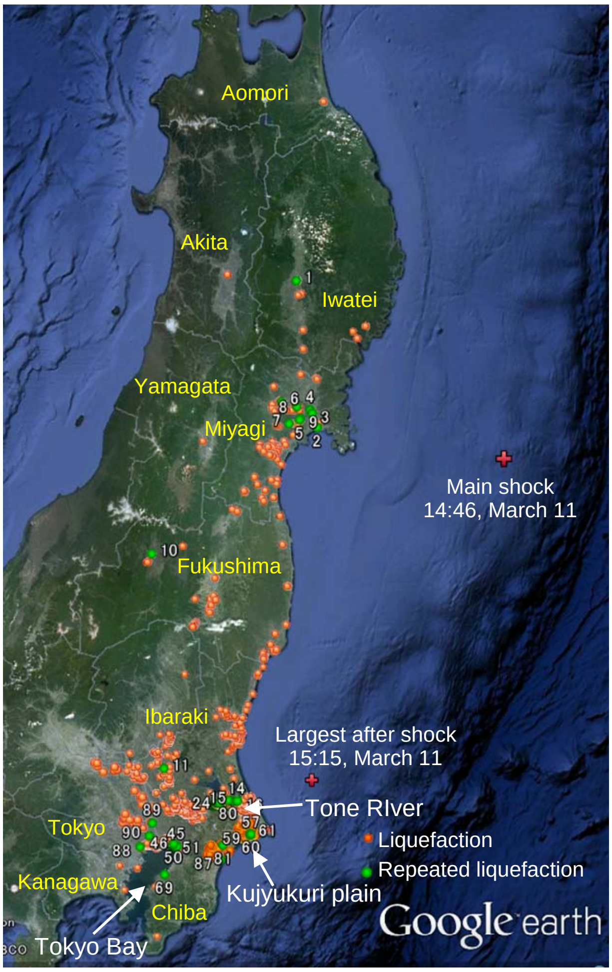


Figure 2.1. Liquefied sites and repeated liquefied sites during the 2011 Great East Japan earthquake

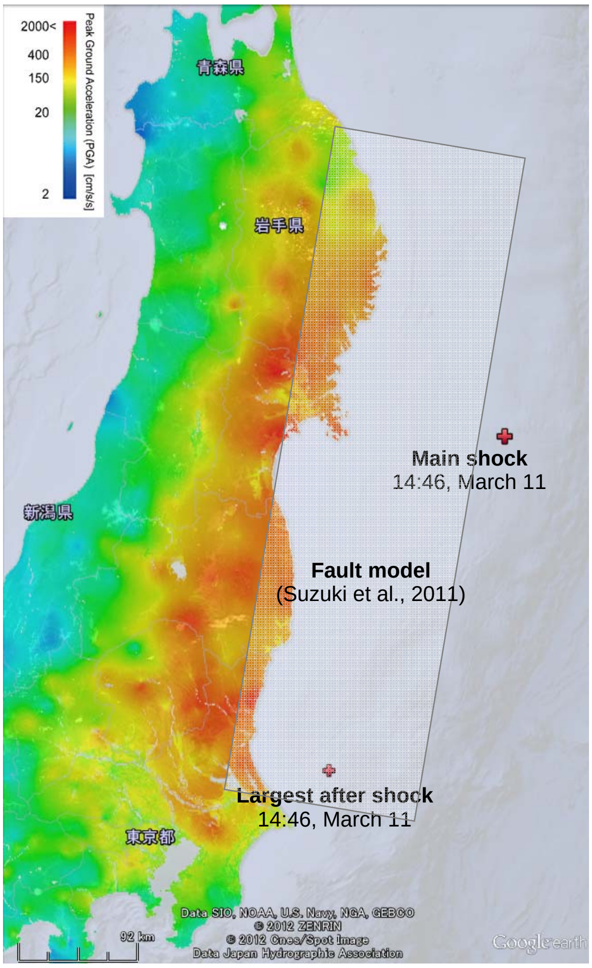


Figure 2.2. PGA map estimated by QuiQuake (AIST, 2011)

Most of the repeated liquefaction sites were located in Chiba and southern Ibaraki Prefectures in Kanto region--that is, the northern part of the Tokyo Bay area, the Kujyukuri plain and the flood plain in the lower reaches of the Tone River, where liquefaction occurred during the 1987 Chibaken toho-oki earthquake. The recurrent liquefaction was also found in 10 locations in Miyagi, Iwate and Fukushima prefectures in Tohoku region. The horizontal PGAs estimated or recorded at the repeated liquefied sites during the 2011 and the former earthquakes are summarized in Table 2.1. The PGAs during the 2011 earthquake seems to be larger than those during the previous earthquakes in each area, although the PGAs are not available for previous event.

Table 2.1 Comparison of PGA at repeated liquefied sites during the 2011 Great East earthquake and previous earthquakes

Area of repeated liquefaction	Site No. in Figure 2.1	PGA during the 2011 main shock (cm/s^2)	Year and magnitude of the previous earthquakes	PGA during the previous earthquakes (cm/s^2)
Hanamaki city, Iwate Prefecture	1	389*	August 31, 1896 (M_J7.2)	None
Miyagi Prefecture	2-9	321-554*1	April 30, 1962 (M_J6.5) June 12, 1978 (M_J7.4) May 26, 2003 (M_J7.1) July 26, 2003 (M_J6.4)	None 294*2 244*1 207*1
Aizu-bange Town, Fukushima Prefecture	10	176*1	June 16, 1964 (M_J7.5)	None
Shimotsuma City, Ibaraki Prefecture	11	358*1	January 18, 1895 (M_J7.2)	None
Lower reaches of the Tone River	12-29, 71-80, 82-86	219-399*1	January 18, 1895 (M_J7.2) December 17, 1987 (M_J6.7)	None 185*2
Tokyo Bay area	30-51, 62-69, 88	142-244*1	December 17, 1987 (M_J6.7) Sept 1, 1923 (M_J7.9)	153-171*2 None
Kujyukuri plain of Chiba Prefecture	52-61, 70, 81, 87	158-176*1	December 17, 1987 (M_J6.7) Sept 1, 1923 (M_J7.9)	None
Tokyo Lowland	89, 90	142-231*1	Sept 1, 1923 (M_J7.9)	None

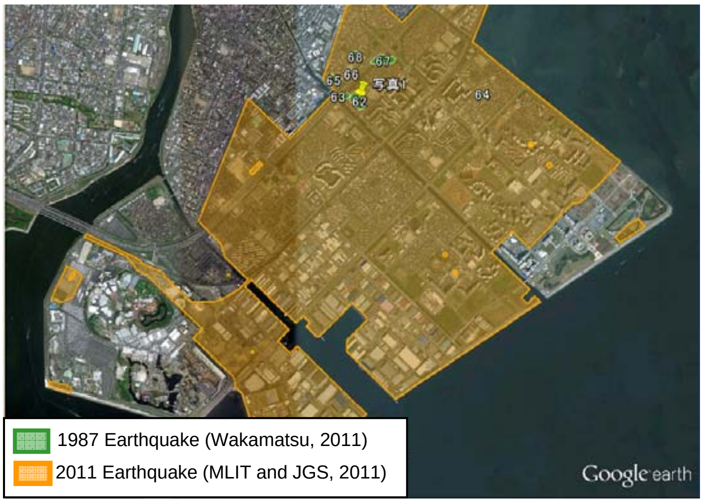
*1: Estimated value calculated by QuiQuake, *2: Recorded value at the station within 10 km from the liquefied sites (National Research Center for Disaster Prevention Science and Technology Agency: 1978; 1988)

3. REPEATED LIQUEFACTION AND THEIR LAND-USE HISTORY, GEOMORPHOLOGY, AND GEOTECHNICAL CONDITIONS

3.1. 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 7 sites in Mihama 3-chome, Kairaku 1-chome, and Irifune 4-chome, as shown in Figure 3.1, 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 (Figure 3.2 (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 (Figure 3.2 (b)). Figure 3.3 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 fills composed of loose fine to very fine sands and silty sands. The groundwater level is as high as around GL-3 m. The loose fill at a depth of 3 to 8 m seems to have liquefied in this area.

Repeated liquefaction at the same site was also identified to occur at total of 22 sites in Mihama-ku, Chiba City. 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 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 1961 and 1980 and were mainly composed of loose fine sand and silty sand fills with SPT N-values less than 10 from the surface to a depth of about 7 m. The groundwater level is as high as around GL-2 m. The loose sandy fills at a depth of 2 to 7m presumed to have liquefied during the earthquakes.



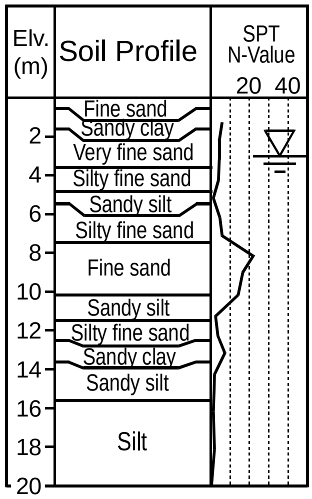
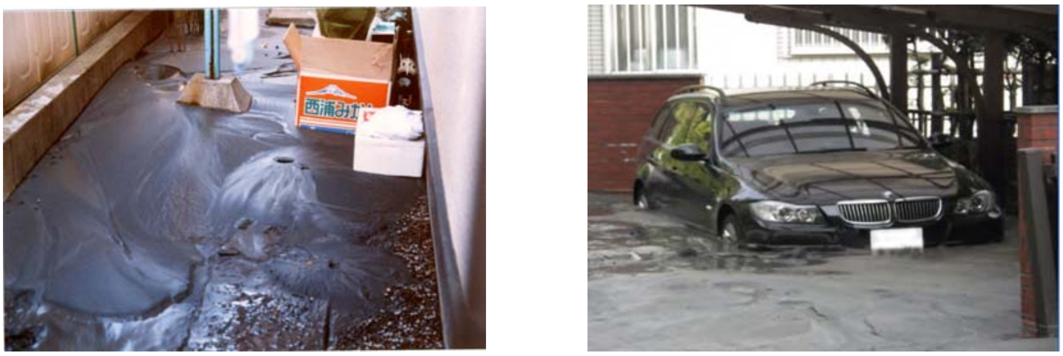


Figure 3.1. Distribution of liquefied areas during the 2011 and the 1987 earthquakes in Urayasu City

Figure 3.3. Soil profile and SPT N-value in Mihama 3-chome, Urayasu City



(a) 1987 earthquake **(b) 2011 earthquake (Urayasu City, 2011)**

Figure 3.2. Sand boils in Mihama 3-chome, Urayasu City (35.6503N, 139.9062E)

3.2. Kujyukuri plain of Chiba Prefecture

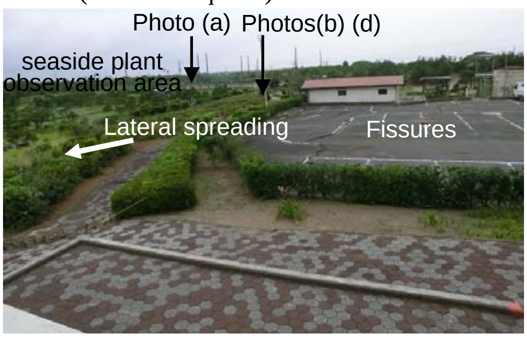
Kujyukuri plain is located in the south-easternmost part of Chiba Prefecture facing the Pacific Ocean and is a typical coastal plain consisting of sand bars (including partial sand dunes developed on the bar) along the shoreline and inland marshes behind and between bars. Liquefaction occurred in residential 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 is identified to recur at total of 13 sites in this plain: 10 sites in Asahi City and one site each in Sosa City, Sanmu City and Kujyukuri Town, respectively. In Idono-hama, Ashikawa, Nakayari, Shiinauchi, Nonaka, and Sangawa in Asahi City, houses damaged during the 1987 earthquake were repeatedly affected due to liquefaction during the 2011 earthquake.

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). According to interviews with city government officials and local residents, all of the repeated liquefactions occurred in areas formerly excavated and backfilled for iron mining.

Figure 3.4 (a) shows a 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 Figure 3.4 (a) 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 Figure 3.4 (b). 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 Figure 3.4 (c). Figure 3.4 (d) indicates the crack in a walking path with about a 85 cm slump which occurred at the same point as in Figure 3.4 (b). 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.

(a) Sand boils in multipurpose open space (1987 earthquake)

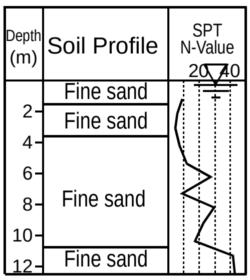
(b) Slump of the walking path (1987 earthquake)



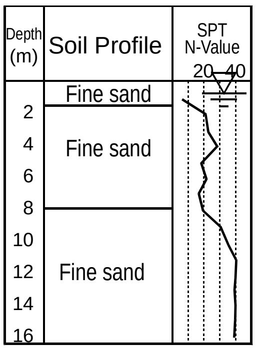
(c) Lateral spreading in the athletic park (2011 earthquake)

(d) Slump of the walking path (2011 earthquake)

Figure 3.4. Liquefaction effects of the athletic park in Yoshizaki-hama, Sosa City (35.6733N, 140.6189E)



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



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

Figure 3.5. Soil profile and SPT N-value in Yoshizaki-hama

3.3. 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 found, which were created as a consequence of the shortcut channeling projects which were conducted from the 1900s to the 1930s. These ponds and abandoned meanders 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 28 sites in Inashiki City and Kwachi Town, Ibaraki Prefecture, and Katori City and Kozaki Town, Chiba Prefecture (Figure 3.6).

Figure 3.6. Distribution of liquefied areas during the 2011 and 1987 earthquakes in the area along Tone River

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

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

Figure 3.7. Damage due to liquefaction in Rokkaku, Inashiki City (35.9183N, 140.4408E)

Violent sand eruptions and numerous large sand craters were observed with diameters of 1 to 3 meters in the paddy fields and residential houses, water pipes and farm road were damaged due to liquefaction during the 1987 earthquake. The effects of liquefaction were more severe and widespread during the 2011 earthquake than during the 1987 earthquake. These effects predominantly developed within the filled channels and ponds as shown. Huge quantities of sand erupted and accumulated to depths of several dozen centimeters; single-family houses and telephone poles settled and tilted perceptibly and road, water supply and sewage systems were damaged severely.

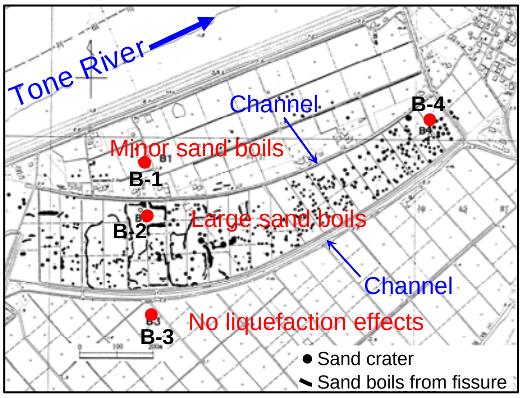
Figure 3.7 (a) to (c) show liquefaction-induced damage in Rokkaku, Inashiki City, during the 1987 earthquake, and Figure 3.7 (d) to (f) show the damage at the exactly same sites during the 2011 earthquake. Rokkaku had been a small pond named “Guru-gawa”, with a depth of about 2 meters, that was filled 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 Figure 3.7 site: telephone poles sank, with their height reduced to around 2 m, and the road subsided below the surface of the adjacent paddy field (Figure 3.7 (a)); gateposts tilted slightly (Figure 3.7 (b)); a small truck parked in a yard was buried by boiled sand (Figure 3.7 (c)).

Liquefaction-induced damage was also the most serious at the Figure 3.7 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 (Figure 3.7 (d)); gateposts settled by more than 20 cm (Figure 3.7 (e)); a house built on the lot shown in Figure 3.7 (c) sank up to 1 m (Figure 3.7 (f)).

Figure 3.8 (a) shows the distribution of sand boils observed in the former river course in Kozaki Town during the 1987 earthquake, as identified by field survey and aerial photographs taken after the earthquake. Numerous large sand boils were formed on the former channel; it seemed that the surficial ground had completely liquefied. 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 south of the former river channel.

Figure 3.8 (b) shows an aerial photograph taken eighteen days after the 2011 earthquake. There was widespread and very large thickness fine sand ejecta covering the former river channel: the small stream flowing at the northern end of the former river channel was completely filled with boiled sand. According to a 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 river channel was severely affected by liquefaction: most of the single-family houses, walls, and telephone poles were settled and tilted, and the roads were covered with boiled sand. Bridge piers of Kozaki Bridge across the Tone River and river dike were damaged due to liquefaction. No such effect of liquefaction had occurred in this residential area during the 1987 earthquake.

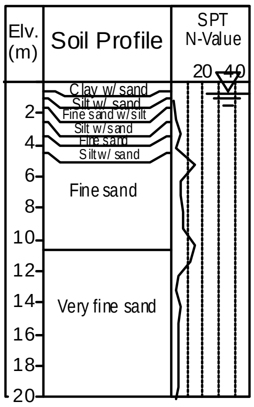
The author conducted boring explorations at four sites in the area of Figure 3.8 two months after the 1987 earthquake. Figure 3.9 shows the soil profiles and SPT N-value at B-1 through B-4 in Figure 3.8 (a). The borings disclosed that there were five types of loose sand deposits at the site: clayey sand 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 approximately 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 Figure 3.9.



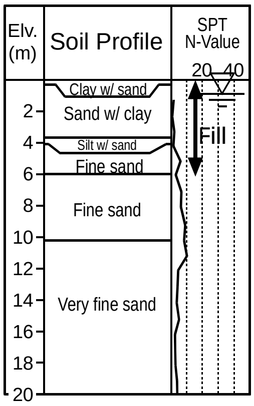
(a) 1987 earthquake (modified from Kotoda and Wakamatsu, 1989)

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

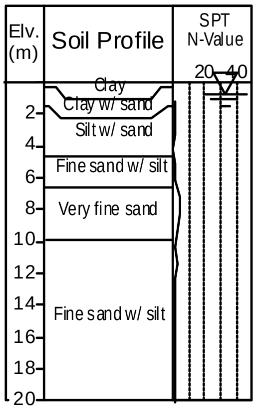
Figure 3.8. Distribution of sand boils in former river channel in Mukouya, Kozaki Town, Chiba Prefecture due to liquefaction (35.9026N, 140.3910E)



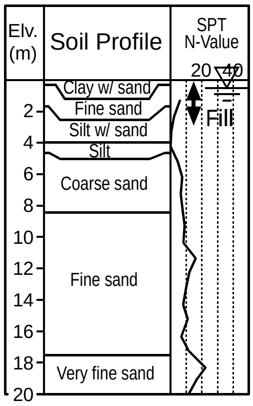
(a) B-1 (Minor sand boils in 1987)



(b) B-2 (Large amount of sand boils from fissures in 1987)



(c) B-3 (No effect of liquefaction in 1987)



(d) B-4 (Large amount of sand boils from craters in 1987

Figure 3.9. Soil profile and SPT N-value in Mukouya, Kozaki Town (see Figure 3.8 (a) for location)

According to 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 %. The fine contents for sand boils deposits in 2011 earthquake are also below 10 % (Koseki et al., 2012).

3.4. Tohoku Region

In the coastal areas of Tohoku region hit by the March 11 tsunami, occurrence of liquefaction was hardly identified; however liquefaction was observed at about 230 sites in inland areas of Aomori, Iwate, Miyagi, Akita, Yamagata and Fukushima prefectures, mainly along rivers. Repeated liquefaction was identified at ten sites in Iwate, Miyagi and Fukushima prefectures.

In Hanamaki city (No.1 point in Figure 2.1), Iwate Prefecture, liquefaction damage to houses, roads and lifelines occurred in several towns during the 2011 earthquake, where Kitakami River had meandered until 1678 shortcut channelling work for flood countermeasure as shown in Figure 3.10. After the width of abandoned river channel becomes narrower gradually and had been used as paddy filed until the late 1960’s when the land was filled up to be used for housing lot. The 2011 liquefaction effects appeared within the former river channel and adjacent flood area (natural levee and/or point bar). Sand boiling was reported at south end or the 2011 liquefied areas named Hitohi-ichi during the 1896 Rikuu earthquake. It is noteworthy that the liquefaction recurred at more than three hundred-years-old former river channel from a standpoint of aging effect.

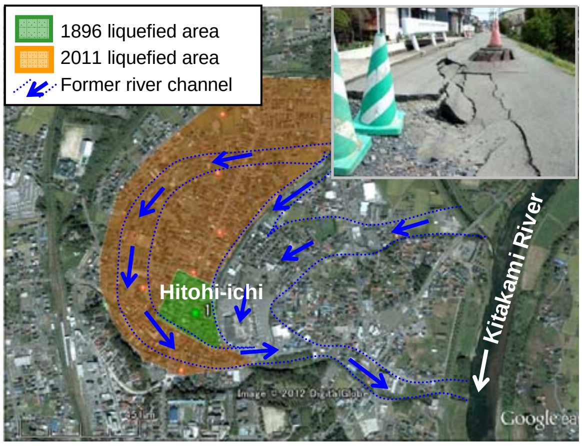


Figure 3.10. Liquefied area during the 1896 and 2011 earthquakes in Hanamaki City, Iwate Prefecture (39.3941N, 141.1158E)

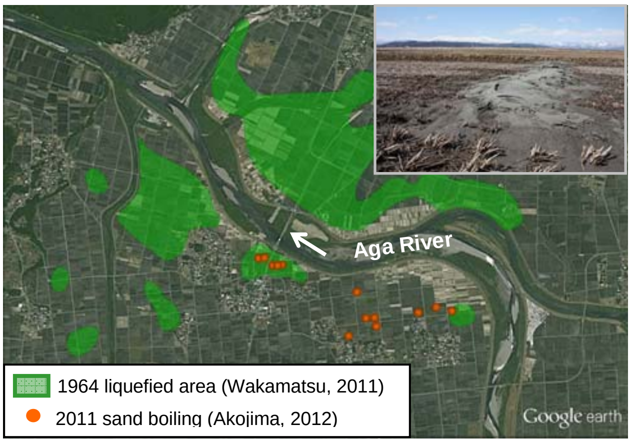


Figure 3.11. Liquefied area during the 1964 and 2011 earthquakes in Aizu-bange Town, Fukushima Pref. (37.5893N 139.8526E)

In Kitawabuchi of Ishinomaki City (No.4 point in Figure 2.1), Miyagi Prefecture located in right bank of the Eai River, the fourth time liquefaction occurrence was identified: sand boiling was observed during four successive earthquakes, 1978 (M_J7.4), May 2003 (M_J 7.1), July 2003 (M_J 6.4), and 2011 (M_w 9.0). There had been a large wetland until a hundred years ago because of the point where three rivers meet. The repeated liquefied area had been formerly river channel of the Eai River until shortcut channelling work had done in 1950'. Several houses located on the downstream of the former channel were affected by liquefaction during the 2011 earthquake. A number of sand boils occurred in the former river channel but they are also observed in the convex bank of the channel, as was found in Kozaki Town along the Tone River shown in Figure 3.8.

In Tachikawa, Aizu-bange Town (No.10 point in Figure 2.1), Fukushima Prefecture, sand boiling was observed in the paddy field on the left bank of the Aga River at the exactly same place as that during 1964 Niigata earthquake (Figure 3.11). The liquefied sites seem to be located in the flood-prone area since the channel of the Aga River turns off at a 90-degree angle. All of the 1964 liquefied areas shown in Figure 3.11 were not surveyed, because of snow accumulation after the 2011 earthquake.

Unfortunately, no borehole data is available for the above-mentioned repeatedly liquefied sites in Tohoku region for reason of sparsely-populated countryside. The key words of the land conditions for the three sites in common are former river channel and flood-prone area. This implies that the ground surface is covered with young (loose) fluvial deposits and poor drainage condition.

4. CONCLUSIONS

Second time and fourth time liquefaction was observed during the 2011 Great East Japan earthquake at a total of 90 sites in the Kanto and Tohoku regions, where liquefaction had occurred during the previous earthquakes. Liquefaction including re-liquefaction during the 2011 earthquake seems occurred in the areas where the PGAs exceeded about 150 cm/s^2. Comparing the extent and severity of liquefaction effects between the successive earthquakes, the effects of the 2011 earthquake are mostly larger than those associated with the previous earthquakes, but damage patterns are similar at every site. Most of the repeated liquefaction sites are artificially filled or backfilled areas on seashores, lakes, former river channels, ponds, and excavated areas in the last sixty years, but in some cases, old fills and natural fluvial sediments such as river bed, natural levee and/or point bar deposits seem to liquefy repeatedly. Soil profiles of the repeatedly liquefied sites located in the upper 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.

AKCNOWLEDGEMENT

The author would like to acknowledge the following people: Prof. Nozomu Yoshida of Tohoku Gakuin University; Dr. Masashi Matsuoka of the National Institute of Advanced Industrial Science and Technology; Prof. Junichi Koseki of the University of Tokyo; Mr. Chihiro Yajima of Grass Resourcing Co., Ltd.; and the students at Kanto Gakuin University who conducted reconnaissance surveys with the author after the 2011 earthquake. Mr. Tadao Numasaki, Mr. Takashi Itoga, and Mr. Kouich Sakamoto of the Inashiki City Government and Mr. Tadashi Kuroda of the City Council of Inashiki City provided information and photographs of liquefaction-induced damage and guidance through affected areas. She also thanks late Prof. Kikuo Kotoda, Mr. Takekazu Akagiri, Dr. Kazuo Watanabe and Mr. Tatsuya Mase who conducted reconnaissance surveys with the author after the 1987 Chibakentoho-oki earthquake.

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