Liquefaction damage in the Kanto region caused by the 2011 off the Pacific coast of Tohoku Earthquake in Japan, and the land condition of damaged areas detected by time-series geospatial information

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Abstract

The 2011 off the Pacific coast of Tohoku Earthquake in Japan caused liquefaction in large parts of the Kanto Region, especially in the Tokyo Bay side area and the lower reaches of the Tone River. Liquefaction was concentrated in areas of land reclamation and former river channels, where it is easy to recognize using time-series geospatial information such as old topographical maps and old aerial photographs. The author conducted a field survey about the disaster situation at liquefaction sites in the middle and downstream areas of the Tone River, and conducted research about geographical conditions of the remarkable area affected by liquefaction damage using time-series geospatial information. The time-series geospatial information that was mainly utilized was old French style maps "Rapid Survey Maps", old topographical maps, past aerial photos, Land Condition Maps and Landform Classification Maps for Flood Control. It is effective to use land historical information detected by time-series geospatial information for mapping of areas of vulnerability.

1. Introduction

"The 2011 off the Pacific coast of Tohoku Earthquake" caused heavy liquefaction damage to buildings, public facilities and lifelines in large parts of the Kanto District, especially in the Tokyo Bay area and the lower plains along the Tone River (Ministry of Land, Infrastructure, Transport and Tourism, Kanto Regional Development Bureau and the Japanese Geotechnical Society, 2011; Research Institute of Environmental Geology, Chiba, 2011).

Conditions under which liquefaction occurs are as follows: strong earthquake motion, high ground water level and loosely deposited sand. Places with the highest possibility of liquefaction are reclaimed land, former river channels, and lowlands between sand dunes and sandbars. To know the potential for liquefaction, it is important to determine the history of the land. The Geospatial Information Authority of Japan (GSI) has archived time-series geospatial information, such as old topographical maps and old aerial photos, and it provides these archived data to the general public. It is possible to understand the history of the land and liquefaction-prone locations from time-series geospatial information.

We surveyed the damage at the liquefaction sites and researched geographical conditions of areas remarkably damaged by liquefaction using time-series geospatial information. We mainly used time-series geospatial information, such as old maps called "Rapid Survey Maps (Japanese: Jinsoku-Sokuzu)", old topographical maps, previous aerial photos, Land Condition Maps, and Landform Classification Maps for Flood Control.

2. Useful geospatial information for detection of land history

It becomes possible to grasp beforehand the area which liquefaction tends to occur by getting to know the history of land using time-series geospatial information. The information below outlines the said time-series geospatial information.

2.1 Old topographical maps

The GSI and Japanese Imperial Land Survey in the General Staff Office of the Imperial Army (which

was the former National Mapping Agency) had published 1/50,000 and 1/25,000 scale topographical map series data for the whole of Japan from the middle Meiji Era. These old edition topographical maps can be perused in GSI, and anyone can obtain them by carrying out a copy.

2.2 Old aerial photos

The U.S. Army took aerial photos of all of Japan area with scale of 1/40,000 in late 1940's, and GSI has taken aerial photos of all of Japan from after the 1960's. In addition, large scale color aerial photography (about 1/10,000) has been taken for all of Japan after the second half of the 1970's. These aerial photos are being digitized as a national land change archive project, and it can be viewed from the GSI website, where one can search and inspect maps and aerial photos from the search functionality available in the system.
(http://mapps.gsi.go.jp/maplibSearch.do).

2.3 Rapid Survey Maps (Jinsoku-Sokuzu)

"Rapid Survey Maps" is a map series which the General Staff Office of the Imperial Japanese Army created on the Kanto Plain Region including Boso and Miura Peninsula in the early Meiji Era (1880-1886). The features shown in the diagrams were similar to a style used in France at the time, and it is easy to grasp the landscape of that period. The original drawings of the Rapid Survey Maps can be perused in GSI, and anyone can obtain them by carrying out a copy, and also the reprinted edition for every area is available for sale from the Japan Map Center. Moreover, it can be also be perused through the "Historical Agricultural Environment Inspection System" website, (http://habs.dc.affrc.go.jp/) of the National Institute for Agro-Environmental Sciences. This system is very effective to grasp the changes of landscape, because it is able to display the seamless Rapid Survey Map with the Fundamental Geospatial Data published by GSI in this system.

2.4 Thematic map (Land Condition Map, Landform Classification Map for Flood Control)

In order to know the history of land, it is effective to read about the landform classification, and see the evolution of landforms in the targeted area. As thematic maps include landform classification, there are Land Condition Maps and Landform Classification Maps for Flood Control. Although the covered area of these thematic maps is restrictive, the area of artificial geographical features, such as former river channels, reclaimed land and embankments, for which liquefaction may easily occur is shown in these thematic maps. These thematic maps can browse from the GSI website (Land Condition Map;

Fig.1 Index map of the reported area (base map by GSI Maps)

http://www1.gsi.go.jp/geowww/themap/lcm/; Landform Classification Map for Flood Control; http://www1.gsi.go.jp/geowww/themap/lcmfc/index.html).

3. Liquefaction damage on Tone River area caused by the 2011 off the Pacific coast of Tohoku Earthquake

In this chapter, we introduce site-locations with typical liquefaction damage, which have a clear relationship between liquefaction and land history using time-series geospatial information. The positions of site-locations are shown in Fig.1.

3.1 Liquefaction damage in the Hinode area of Itako City, Ibaraki Prefecture

Although liquefaction occurred at many places in Itako City, Ibaraki Prefecture, which is in the lower reaches of the Tone River, liquefaction damage was especially serious in the Hinode area. Typical liquefaction damage in the Hinode area is shown in Fig.2. Although the main roads were restored to some extent by June 2011, leaning utility poles were left as is (photo A in Fig.2). The school buildings showed an apparent relative uplift of about 25 cm at Hinode Junior High school (photo B in Fig.2). The extent of the damage tended to be more severe in the southern areas. Street-level water-drainage gutters were deformed by lateral spreading; cave-in and other damage. The surface covers of street-level water-drainage gutters can be seen in photo C and D in Fig.2. Some piles were up-lifted by liquefaction (photo E in Fig.2). The Rapid Survey Maps published by the Imperial Japanese Army about 130 years ago shows that the Hinode area is land that was reclaimed by the drainage of a small bay (Fig.3), which means the area is susceptible to liquefaction.

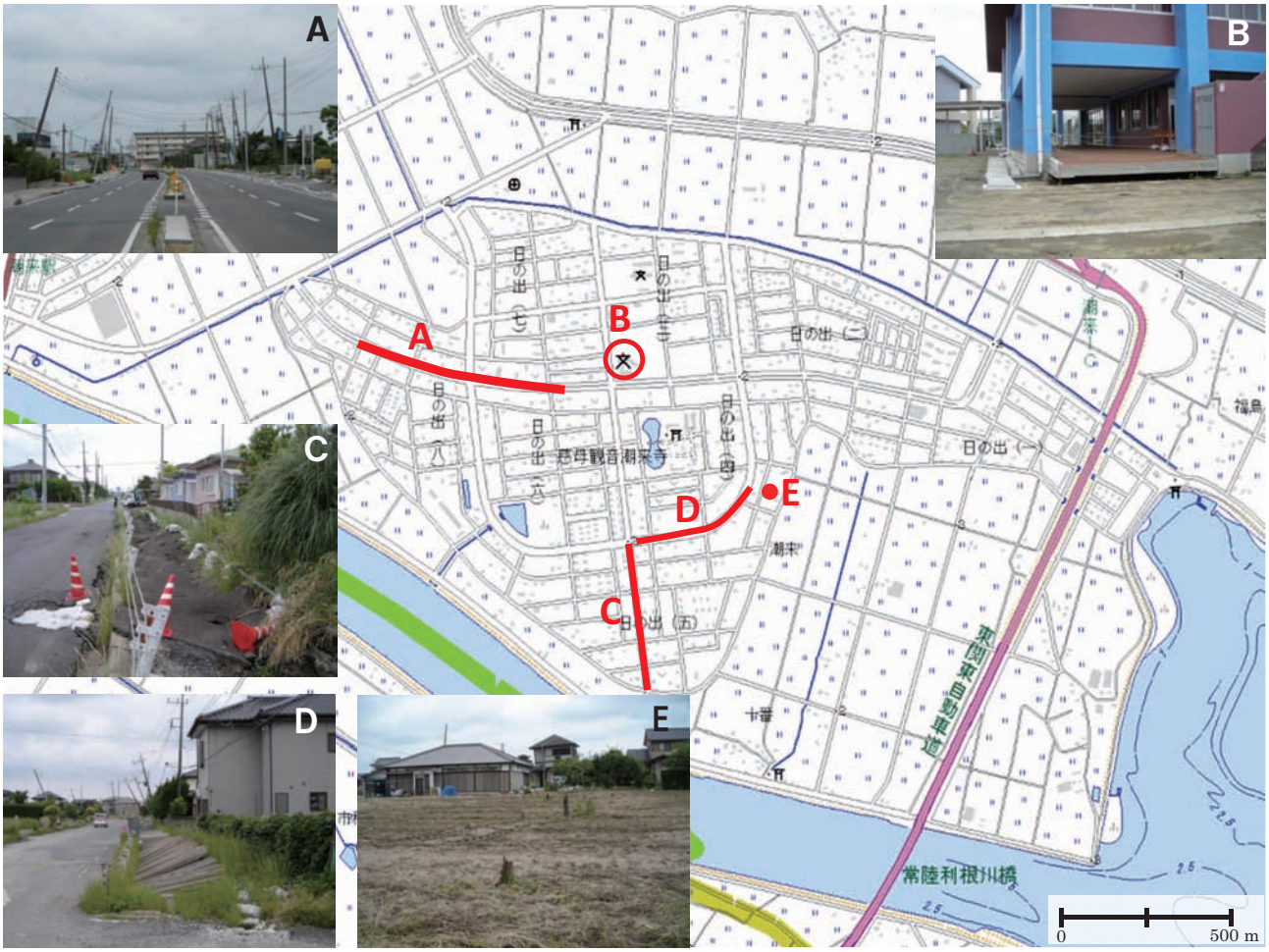

Fig.2 Liquefaction damage in the Hinode area, Itako City (base map by GSI Maps) and ground photo of a field survey done on 16th June, 2011

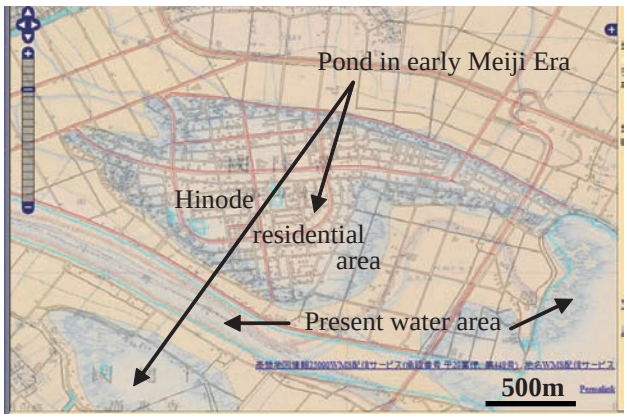

Fig.3 The overlay of Rapid Survey Map published by the Imperial Japanese Army in the early Meiji period and Fundamental Geospatial Data published by GSI on present day in the Hinode area, Itako City (by Historical Agriculture Environment Inspection System of the National Institute for Agro-Environmental Science). Blue colored areas are water areas in the early Meiji Era, and the blue solid lines represent present water boundaries.

3.2 Liquefaction damage in Kessa area of Inashiki City, Ibaraki Prefecture and Kokuno area of Katori City, Chiba Prefecture

The region from the Kessa of Inashiki City, Ibaraki Prefecture to Kokuno of Katori City, Chiba Prefecture, is land that consists of an old buried channel of the Tone River, and many colonies locate on a natural levee along old channel (Fig.4). In this region, liquefaction occurred by the Chiba East off Earthquake in 1987.

In the northwest side of the Kami-kessa area and Rokkaku area, residential inclination, residential subsidence and undulated road deformation by liquefaction were observed (Fig.5; A). There are many traces of sand volcanoes in a paddy field that was once a river channel. In residential areas that has been filled up paddy fields, inclinations of houses and cracks in the land due to collapse of fill up mound were observed. Because of land subsidence over a large area, houses and roads became submerged under water. This area was swampland according to the Rapid Survey Map published in the 1880's and the topographical map published in 1950's showing scale of 1/25,000.

In the former river channel between the Nomayawara area and the Kokuno area of Katori City and the Naka-shinden area of Inashiki City, there are many traces of sand volcanoes in wide area making up paddy fields (Fig.5; B-B'). At an apartment located there, a little less than 20cm relative rise of the building structure was observed (Fig.5; B). On the other hand, evidence of liquefaction such as sand volcanoes were not observed in the Nomayawara area, the Kokuno area (Fig.5; C), and Naka-shinden area (Fig.5; D) which were land areas going back as early as the Meiji Era at least.

This area was a river channel of the Tone River in the Rapid Survey Map published in the1880's (Fig.6). At that time, although the Tone River's channel was diverted, this place still serves as a border between Chiba Prefecture and Ibaraki Prefecture.

In the topographical map with a scale of 1/25,000

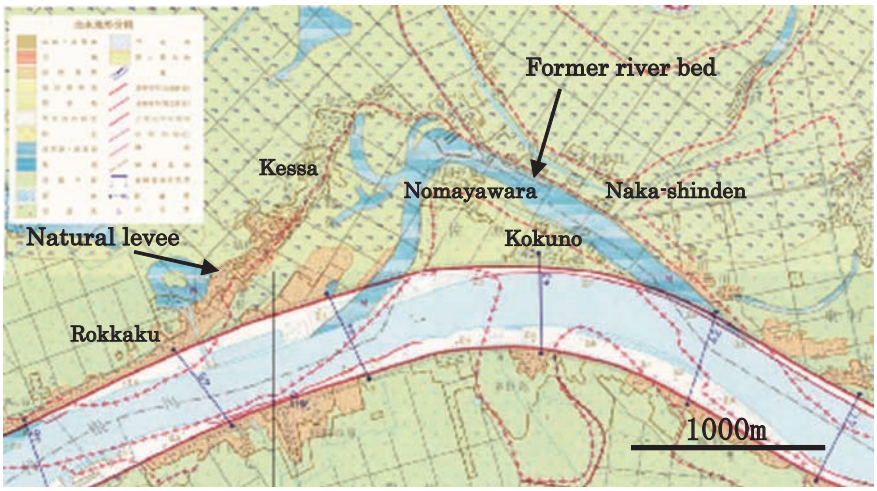

Fig.4 Part of Landform Classification Map for Flood Control "Asou" and "Sawara-seibu" published by GSI in 1977

Fig.5 Liquefaction damage in Kessa and Kokuno area (base imagery by Google Earth), and ground photos in a field survey on 16th June, 2011

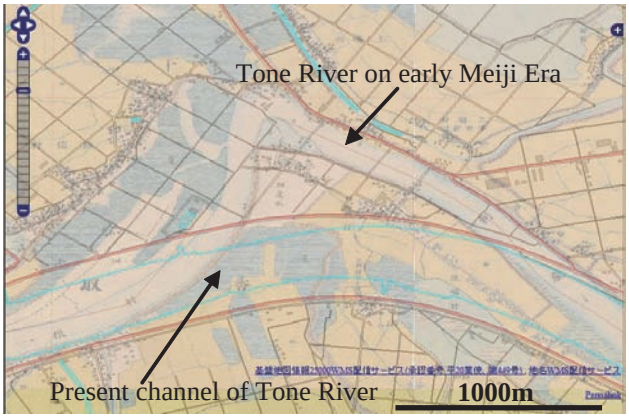

Fig.6 The overlay of the Rapid Survey Map published by the Imperial Japanese Army in the early Meiji period and Fundamental Geospatial Data published by GSI on present day Kessa area, Inashiki City and Kokuno area, Katori City (by Historical Agriculture Environment Inspection System of the National Institute for Agro-Environmental Science). The light blue colored areas are water areas and dark blue colored areas are wetlands in the early Meiji Era, and blue solid lines represent present water boundaries.

Fig.7 Part of an old 1/25,000 scale topographical map "Sawara" published by GSI in 1946 and "Asou" published by GSI in 1954

published in 1950's (Fig.7), you can see the former river stream which is not the main stream of the Tone River. Liquefaction occurred in this area of the old Tone River channel which was marshland.

3.3 Liquefaction damage in Kozaki Town, Chiba Prefecture

In the east side of Kozaki Town, Chiba Prefecture, there is the zonal land reclamation area comprising part of the Tone River's old channel. In this region, liquefaction occurred due to the Chiba East off Earthquake in 1987. The photographs of the field survey are shown in Fig.8.

The area which sand volcanoes occurred over a wide area is consistent with the area of the old river channel (Fig.8; A). In the park along the edge of the north part of the old river channel, the central part of the river was buried with sand by a sand volcano rising up from the river bottom (Fig.8; B). An intense crack and surge occurred in a parking area, and a public toilet facility was elevated by 50 cm or more (Fig.8; C).

According to the Rapid Survey Map published in the 1880s, this area was the main stream of Tone River (Fig.9). Using aerial photo taken in 1947 by the U.S. Army (USA-R 391-23; Fig.10), it is easy to understand the process in which the old river channel was blocked and how the water dried up. Since it became the same ground height as a surrounding paddy field due to land reallocation, and the form of landscape was modified by human intervention, now, it is difficult to recognize the existence of the old river channel there. But it is possible to decipher the edge of the old river channel from the difference in a color tone in the color aerial photo taken in 2005 by GSI (CKT-2005-3X C10-22; Fig.11).

3.4 Liquefaction damage in Fusa area of Abiko City, Chiba Prefecture

Liquefaction was observed in the neighborhood of JR Fusa station in Abiko City, Chiba Prefecture. The heavy damaged area due to liquefaction is located within a limited narrow area (circled dashed line portion of Fig.12). Liquefaction damage, such as sand volcanoes, inclination

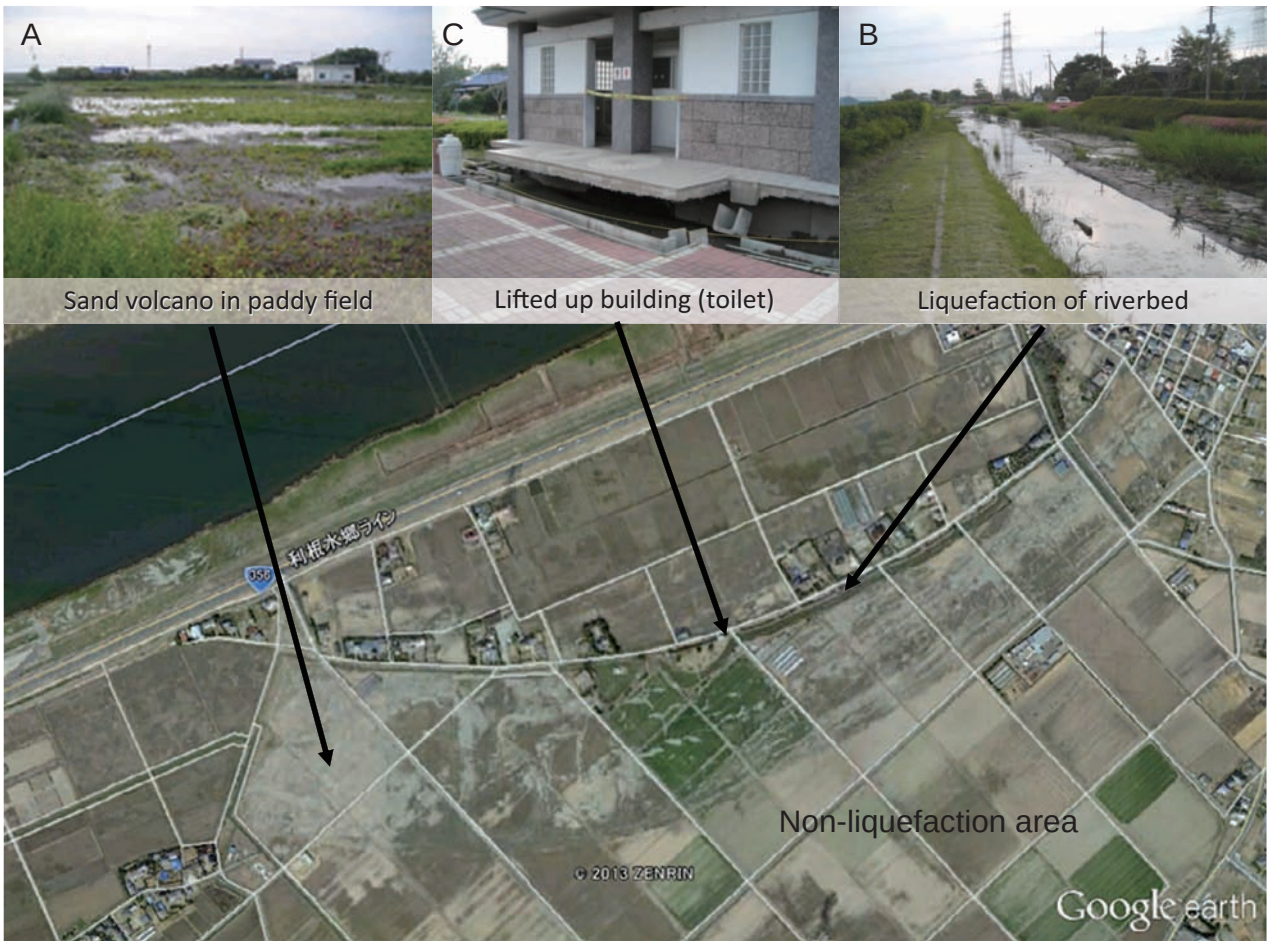

Fig.8 Liquefaction damages in Kozaki Town (base image by Google Earth), and ground photos in field survey on 3rd June, 2011

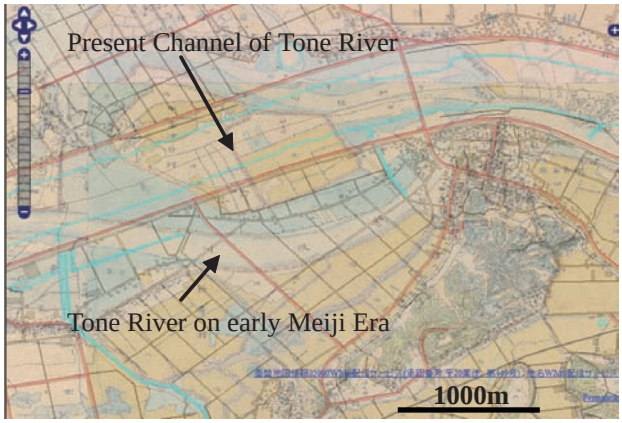

Fig.9 Overlay of the Rapid Survey Map published by the Imperial Japanese Army in the early Meiji period and Fundamental Geospatial Data published by GSI for present day Kozaki Town (by Historical Agriculture Environment Inspection System of the National Institute for Agro-Environmental Science). The light blue colored areas are water areas and dark blue colored areas are wetlands in the early Meiji Era, and blue solid lines represent present water boundaries.

Fig.10 Aerial photo of Kozaki Town taken by the US Army in 1947 (USA-R391-23)

Fig.11 Aerial photo of Kozaki Town taken by GSI in 2005 (CKT-2005-3X C10-22)

and subsidence of electric poles, concrete block walls and houses, and damage to roads was observed (Fig.12). This area had not reported liquefaction damage at the time of the Chiba East off Earthquake in 1987.

The Landform Classification Map for Flood Control shows that the place whose liquefaction damages were serious is the land reclaimed area from the swamp of the old river channel (Fig.13). The olden aerial photo taken by the U.S. Army in 1947 (USA-M 675-1) shows that two water part with long shaped existent in the direction of northeast to southwest (Fig.14a). The zonal part along the prefectural road whose liquefaction damages were serious in this earthquake is in agreement with the part of the long shaped water part. That long shaped water part had become a residential area by land reclamation, in the aerial photo taken by GSI in 1962 (MKT-62-1 C11-17), (Fig.14b).

3.5 Liquefaction damage in the Kinu area of Shimotsuma City, Ibaraki Prefecture

There is a low lying former river channel in a band across the Kinu area of Shimotsuma City, Ibaraki Prefecture. This landform is shown on the “Mitsukaido” Land Condition Map published by GSI (Fig.15). This former river channel sank, and land subsidence and relative ground water level rise are presumed to have

Fig.12 Liquefaction damage in the Fusa area, Abiko City (base map by GSI Maps), and ground photos taken in a field survey on 3rd June, 2011

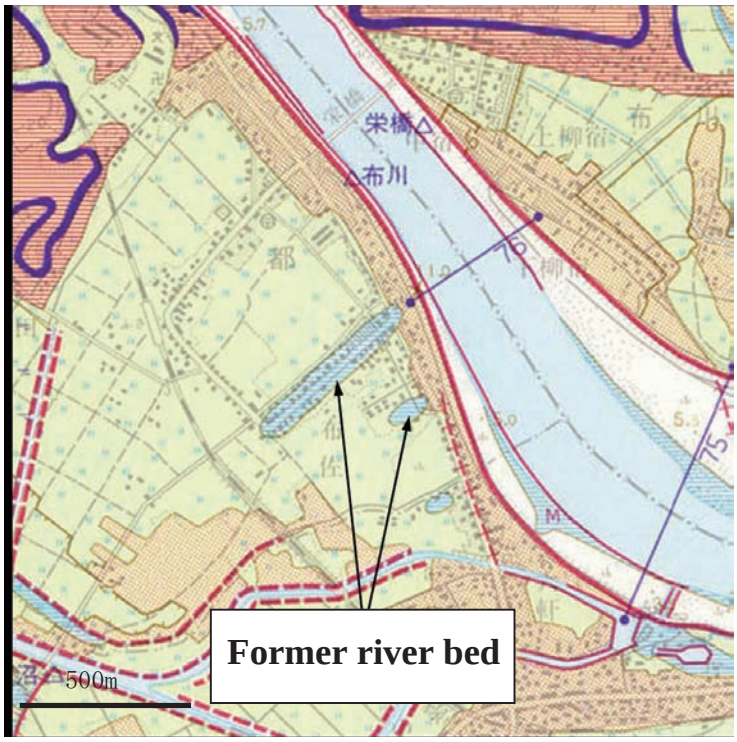

Fig.13 Part of Landform Classification Map for Flood Control "Ryugasaki" published by GSI in 1977

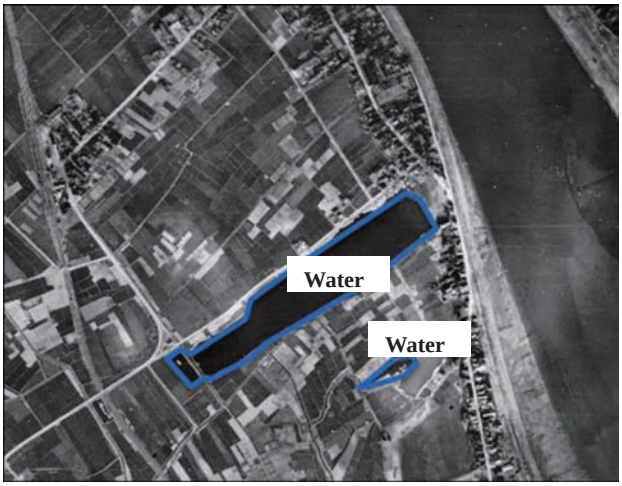

Fig.14a Aerial photo of the Fusa area taken by the US Army in 1947 (USA-M675-1)

Fig.14b Aerial photo of the Fusa area taken by GSI in 1962 (MKT62-1 C11-17)

occurred (photo A in Fig.16). Service on neighboring roads was suspended as a result of intense cracking and undulation of the road (photo B in Fig.16). Liquefaction damage, such as cracking, differential settlement and the tilting of buildings occurred even in the new residential area in the former river channel. The houses were destroyed by the severe subsidence of reclaimed land and the collapse of foundations (photo C and D in Fig.16).

The main stream of the Kinu River was shown as meandering water channel in the Rapid Survey Map published about 130 years ago (Fig.17a). A new river channel was under construction in the old topographical map "Mitsukaido" with a scale of 1:50,000, published by GSI about 80 years ago (Fig.17b). In a U.S. Army aerial photo, it is clear that the former river channel was turned into a paddy field about 65 years ago (Fig.17c).

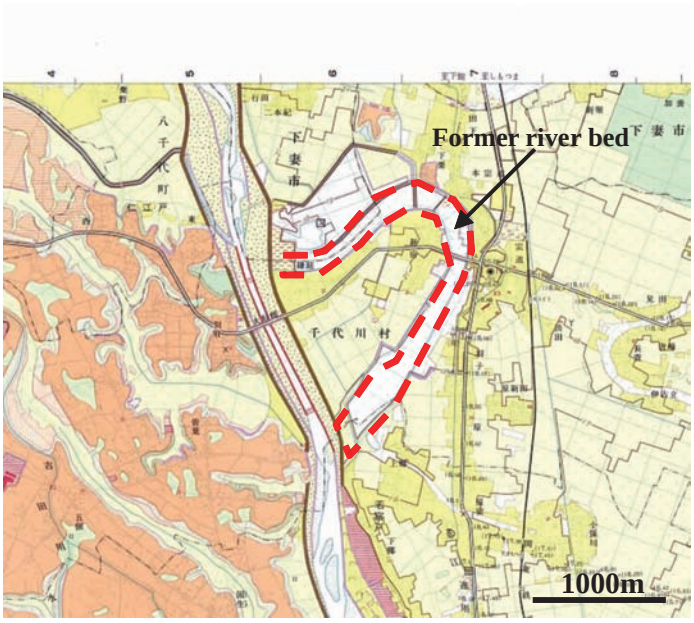

Fig.15 Part of Land Condition Map "Mitsukaido" published by GSI in 1979

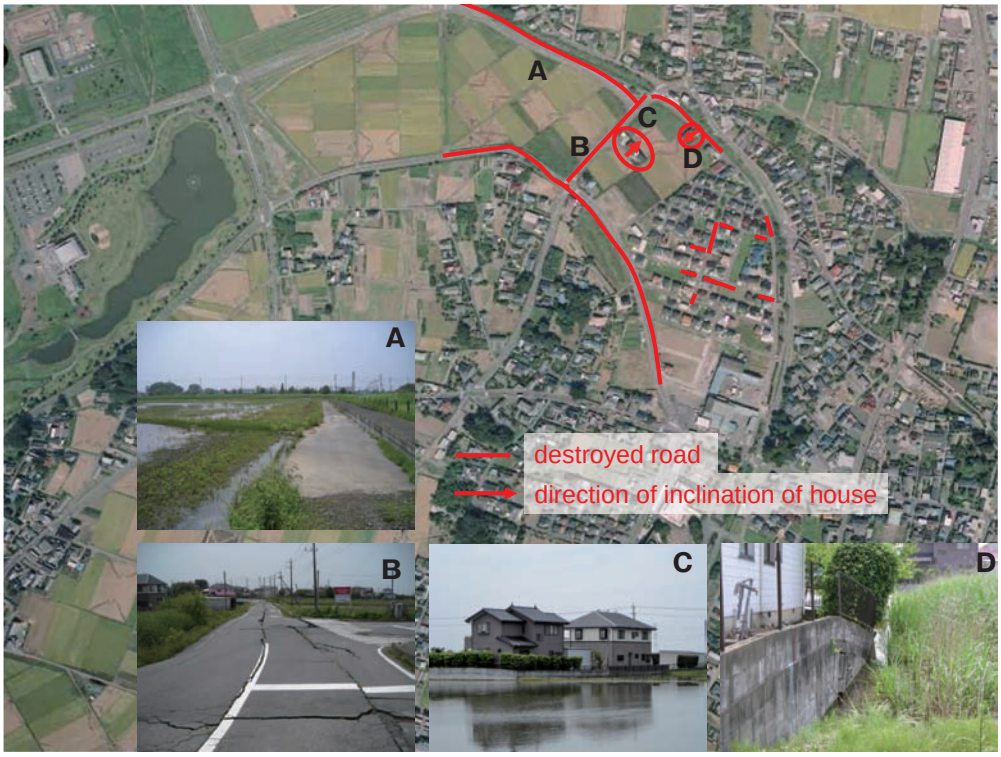

Fig.16 Liquefaction damage in the Kinu area, Shimotsuma City (Base image is an aerial photo taken by GSI in 2008 (CKT2008-2 C3-36)) , and ground photos in a field survey on 3rd June, 2011

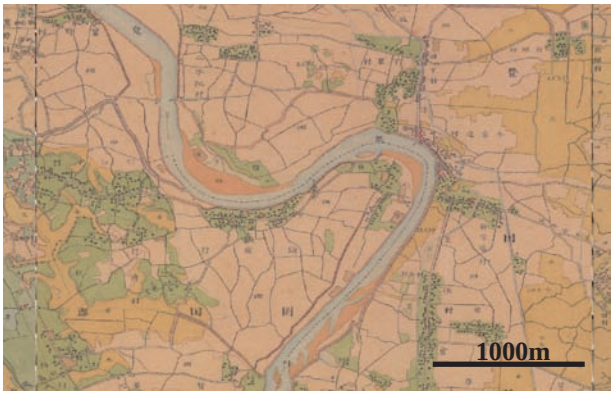

Fig.17a Rapid Survey Map of the Kinu area, Shimotsuma City published by the Imperial Japanese Army in the early Meiji period (Upper left side)

Fig.17b Part of a 1/50,000 scale old topographical map "Mitsukaido" published by the Japanese Imperial Land Survey in 1934 (Upper right side)

Fig.17c Aerial photo of the Kinu area taken by the US Army in 1947 (USA-R388-61) (Lower)

3.6 Liquefaction damage in the Yoshino area of Joso City, Ibaraki Prefecture

The old river channel of Kokai River is a crescent lake used as a fishing pond park called Yoshino Park in the Yoshino area of Joso City, Ibaraki Prefecture. The undercut slope side of the old river channel was only opened as a park, and part of the point bar on the opposite side of the shore closed to the public in November, 2011, because of heavy liquefaction damage. Due to the damage left by the 2011 off the Pacific coast of Tohoku Earthquake in this park, this area was very important place to study the situation of liquefaction damage. We took a ground survey of Yoshino Park in November, 2011, with Joso City Office members. The disaster situation of Yoshino Park is shown in Fig.18.

The point bar area was beginning to become enlarged toward the old river channel side, and many cracks of 40-50 cm in width and 40-70 cm in depth were observed along the river (A in Fig.18). There were many open cracks running also in the direction which intersects perpendicularly to main crack. A rest house was damaged with about 70 cm vertical displacement of its foundation by lateral liquefaction (photo B in Fig.18). The summerhouse also inclined greatly and a crack with an opening width of 40cm and depth 80cm grade had been observed on the outskirts (photo C in Fig.18). Although there is a big water area which was an old lotus field behind the park, this water area was separated from the crescent lake by a water gate. As this water gate was destroyed and caved in completely, the old lotus field was reconnected directly with the crescent lake (photo D in Fig.18).

This old river channel was a main stream of the Kokai River as shown in the aerial photo taken by the US Army in 1948 (Fig.19b). The river channel of the Kokai River shortened and became a crescent lake as seen in the aerial photo taken by GSI in 1961 (Fig.19c). The position of the river channel in the Rapid Survey Map published in the early Meiji Era (Fig.19a) is different from the position of river channel in the aerial photo taken by the US Army. The location of the river channel in the early Meiji Era is the location of the present remains of the lotus field.

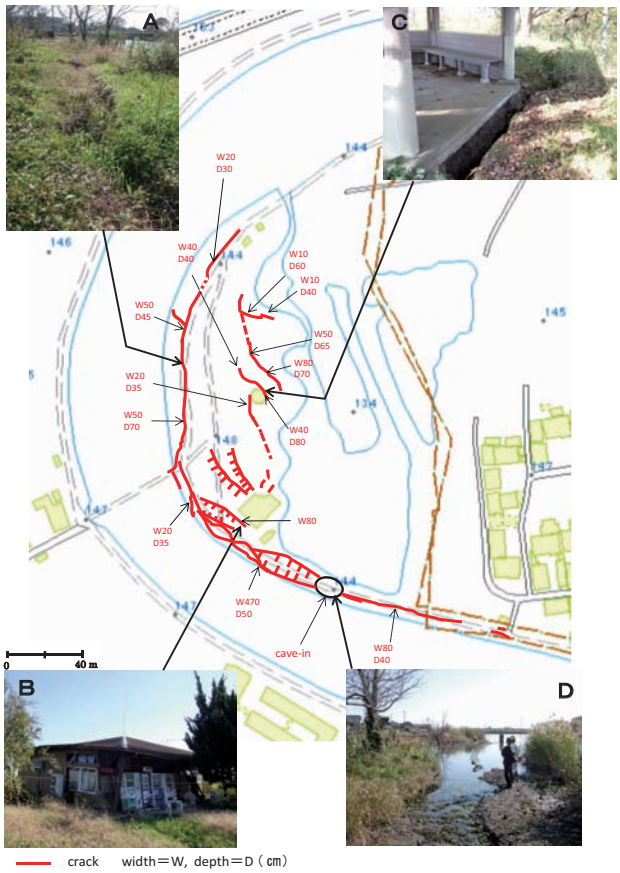

Fig.18 Liquefaction damage in Yoshino Park, Joso City (base map by GSI Maps), and ground photos in a field survey on 17th November, 2011

Fig.19a Overlay of "Jinsoku-sokuzu" published by the Imperial Japanese Army in the early Meiji period and Fundamental Geospatial Data published by GSI on the present day Yoshino area, Joso City (by Historical Agriculture Environment Inspection System of the National Institute for Agro-Environmental Science). The light blue colored areas are water areas and the dark blue colored areas are wetlands in the early Meiji Era, and blue solid lines represent present water boundaries.

Fig.19b Aerial photo of the Yoshino area taken by the US Army in 1948 (USA-R793-18)

Fig.19c Aerial photo of the Yoshino area taken by GSI in 1961 (MKT-61-3 C23-24)

4. Conclusion

The 2011 off the Pacific coast of Tohoku Earthquake in Japan caused liquefaction in large parts of the Kanto Region, especially in the Tokyo Bay side area and the lower reaches of the Tone River. The most severely affected areas by liquefaction were reclaimed land such as former river channels, which can be recognized from old maps and old aerial photos.

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