Subsidence Map of Tokyo Bay Area Liquefied in the March 11th Great East Japan Earthquake

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SUMMARY:
The March 11th, 2011 Off the Pacific Coast of Tohoku Earthquake, also known as the Great East Japan Earthquake, has caused sand-liquefaction over a long stretch of landfills along the coast of the Tokyo Bay. An attempt was made to detect soil subsidence from raster images converted from airborne LiDAR (Light Detection and Ranging) data before and after the earthquake. To cancel out deep-seated tectonic displacements and systematic errors of LiDAR surveys, the template matching technique is used for the end-bearing pile-supported buildings and bridge piers chosen as templates in source images of the target areas. The obtained subsidence maps describe the spatial distribution of soil subsidence in great detail.

Keywords: Liquefaction, Great East Japan Earthquake of 2001, Soil subsidence, Tokyo Bay Area

1. INTRODUCTION

Tokyo Bay area is a home to millions of people as well as the port/factory zone to support urban lives. Intensive flows of people and goods make the Tokyo Bay Area the world renowned commercial and consumption hub. All the more because the area has been the center of the economics and urban lives, the impact of the sand-liquefaction over a long stretch of landfills along the coast of the Tokyo Bay in the March 11th, 2011 Off the Pacific Coast of Tohoku Earthquake was serious leaving many houses tilting and lifelines cut off. After almost all sands were cleared up for rehabilitation, subsidence of the liquefied area was observed as clear differences in level between ground floors of pile-supported RC buildings and surrounding sidewalks. The liquefied areas along the coast of the Tokyo Bay reportedly reaches 42 km^2 (Yasuda, 2011), and there yet remain serious long-lasting concerns about sewage treatment and possible inundations inside levees. In the July 16th, 1990 Luzon Earthquake for example, the city center along the meandering river trace of the Pantal was one of the most seriously liquefied areas where drainage systems were clogged up by the accumulated sand causing temporary flooding. Some RC buildings along Pelez Boulevard have sunken in the liquefied sand with their surrounding soils remained underwater for several months (Yanagisawa et al., 1993a). In the 1964 Niigata Earthquake, similar problems were reported. About a 640m long stretch of Akashi Avenue has subsided due to liquefaction and remained underwater by about 60cm. The area along Tsusen River was flooded by tsunami, and remained underwater for about a month (Hokuriku Regional Development Bureau, 2007). These areas have been frequently inundated in heavy rains since then. One of the more notorious of these floods was the record rainfall on Aug. 4th 1988, which later led the Niigata Prefectural Government into the construction of a new drainage pump station at Yamanoshita lockage (Niigata Regional Development Bureau, 2007). With all these previous examples, it is very important for relevant organizations to have quantitative information of the soil subsidence to cope with post-earthquake problems.

Raster imageries converted from an airborne Light Detection and Ranging (LiDAR) data, namely digital surface models (DSMs hereafter), were obtained on April 20th and September 6th 2011 for Urayasu and Ichikawa-to-Chiba areas, respectively, and an attempt was made to compare the

imageries with those before the earthquake (Konagai K. et al, 2011a, 2011b, 2012). This paper describes the overall features of soil subsidence in all target areas.

2. DETECTION OF SOIL SUBSIDENCE FROM LIDAR IMAGES

A Light Detection and Ranging (LiDAR) system is capable of rapid and accurate collection of topographic and elevation data. It consists of (1) a laser scanner, (2) a kinematic airborne Global Positioning System (GPS), (3) an interfaced Inertial Measurement Unit (IMU), and (4) a fixed, ground-based reference GPS station for detecting the difference between its position indicated by satellites and a known fixed position for correcting positioning errors. The laser scanner emits fast pulses from a focused infrared laser which are beamed toward the ground surface with an oscillating mirror for fast scanning in a sinusoidal pattern. The kinematic GPS measures the spatial position of the platform aircraft, while the IMU records the pitch, roll, and heading of the aircraft.

The obtained high-resolution digital elevation maps (Digital Surface Models: DSMs hereafter) before the earthquake (in December 2006-January, 2007 for the entire target areas) and after the earthquake (on April 20th 2011 for Urayasu City and September 6th for the area from Ichikawa to Chiba) are raster graphic images of pixels having information of their elevations. These images have different spatial pixel densities as shown in **Table 1** for different areas and times, depending on the safe flight altitudes allowed for the aircraft to fly near the Haneda and Narita International Airports. The increase in flight altitudes can also yield increase of errors because the laser-light beam can spread transversely as it propagates. In addition to the above-mentioned system-correlated errors, the effect of deep-seated tectonic deformations caused by this earthquake was remarkable over the entire stretch of the Pacific coastal areas of the eastern Japan (Geospatial Information Authority of Japan, 2011). However liquefaction-induced shallow soil subsidence can be simply measured with reference to elevations of top ends of pile supported buildings and bridge piers such that any potential horizontal or vertical biases can be eventually canceled out. Therefore, to find the best matching depth for DSMs before and after the earthquake, template matching technique is used with end-bearing pile-supported structures chosen as templates.

17 points on flat roofs of 6 buildings and 121 points on piers for the Bay-shore Route of the Tokyo Metropolitan Expressway were taken as templates for Urayasu and Ichikawa-to-Chiba areas respectively to find the best matching depths for both areas. At each template point, a circle with radius of 3m is drawn around it, and elevations of pixels within this circle are averaged for the representative value of the point's elevation (**Figure 1**). As for Urayasu area, the elevations of the chosen points after the earthquake are 20.78cm lower than those before the earthquake in average with the standard deviation of 1.93cm. The Ichikawa-to-Chiba area was divided in two sub-areas, west and east of Edogawa Diversion Channel. For the west and east subareas, 3D-planes that best-fit into the spatial elevation changes of the chosen template piers along the expressway viaducts were obtained with the standard deviations 2.47cm and 4.75cm, respectively. Though the errors for the two sub-areas are a little larger than that for Urayasu because of the higher flight altitude, they are considered to be small enough to discuss large soil subsidence that appeared as clear several tens centimeters differences in level between ground floors of pile-supported RC buildings and the surrounding sidewalks.

Table 1. Spatial resolutions of DSMs at different times and areas

Area	Date of LiDAR survey	Spatial Resolution
Urayasu	December 2006 to January 2007	0.792 points/m^2
Urayasu	April 20th 2011	4.089 points/m^2
Ichikawa-to-Cjiba	December 2006 to January 2007	0.792 points/m^2
Ichikawa-to-Chiba	September 6th 2011	1.786 points/m^2

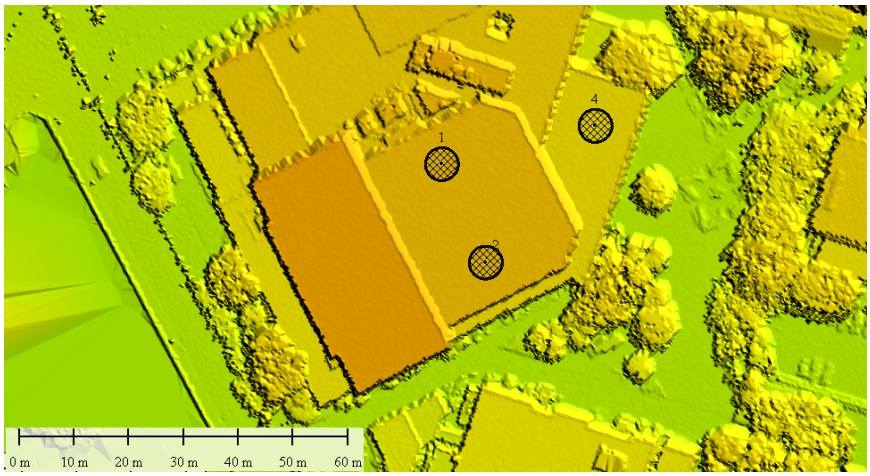


Figure 1. Template points on a pile-supported RC building

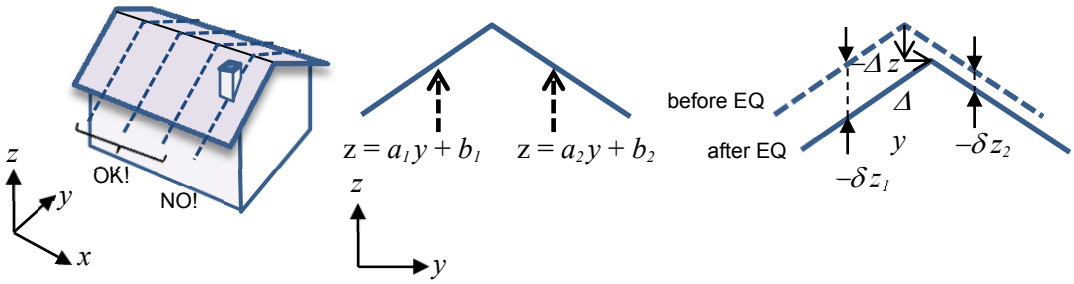


Figure 2. Template building with sloping roofs for adjusting

Given the higher density of pixels for Urayasu, an attempt was made to extract lateral components of Lagrangian displacements for template matching. Comparing DSMs at different times only allow us to detect displacements in the Eulerian description, in which the description of motion is made in terms of the spatial coordinates which does not follow the motion of a particular target. One practical method to deal with this problem is to detect edges of buildings where elevation changes sharply, and keep tracking the motions of the detected edges. However, as described previously, the DSMs have a spatial resolution of 4 pixels/m^2 at most, which is a little to sparse for sharp edge detection. After the 2004 Mid-Niigata Prefecture Earthquake, Konagai et al. (2009, 2011c) estimated Lagrangian components of tectonic displacement induced within a mountainous terrain of Yamakoshi Village by assuming that tectonic displacement varies gently in space, and therefore three adjacent pixels of DEM would have the same Lagrangian displacements. The same method is applied here for detecting lateral Lagrangian displacements of roofs with sloping surfaces towards walls. As illustrated in **Figure2**, several cross-sections of a roof are taken first, and after those with outshooting objects are excluded, they are averaged for the representative roof shape with two sloping surfaces towards walls on both sides. If two points on the two sloping surfaces of a roof undergo a rigid-body-translation movement $\{\Delta y \quad \Delta z\}^T$, their Lagrangian components $\{\Delta x \quad \Delta z\}^T$ can be obtained by solving the following simultaneous equations.

$$\begin{Bmatrix} \delta z_1 \\ \delta z_2 \end{Bmatrix} = \begin{bmatrix} -a_1 & 1 \\ -a_2 & 1 \end{bmatrix} \begin{Bmatrix} \Delta y \\ \Delta z \end{Bmatrix} \tag{2.1}$$

where, $\{\delta z_1 \quad \delta z_2\}^T$ are Eulerian displacements at these two points. It is noted that even a pile-supported building may not be an appropriate target for lateral template matching, because piles are laterally flexible enough to be easily deformed by the movements of the surrounding side soils. Therefore five buildings in areas with no evidence of liquefaction are taken among the others as templates. The points on a stable ground have shifted about 22.45cm north and 4.92cm west in average with the standard deviations of 9.69cm and 10.35cm, respectively. The DSM after the earthquake was thus moved sideways to cancel the measured biases. It is noted that the standard deviations for the case of lateral template matching are larger than that for the vertical case. However

these standard deviations of about 10cm are at least much smaller than the error expected from the edge detection method.

3. SOIL SUBSIDENCE MAPS

3.1 Urayasu Area

Figure 3 shows the obtained soil-subsidence map of Urayasu. The aerial photograph of the same area on the upper right of the figure was taken in 1948 by the US Army (Geospatial Information Authority of Japan, 2011b), clearly showing that it was post-World War II when the majority of land reclamation in Urayasu was undertaken, and the greater part of the city today spreads over the reclaimed land of sand dredged from the Tokyo Bay. On this map, subsidence can be seen over the entire stretch of the reclaimed land. In particular, remarkable subsidence is seen where the aerial photo of 1948 shows darker black indicating the presence of deeper water. On the other hand, on the long-existing natural land of Urayasu before the time of land-fills, no or slight subsidence less than 0.1m is seen.

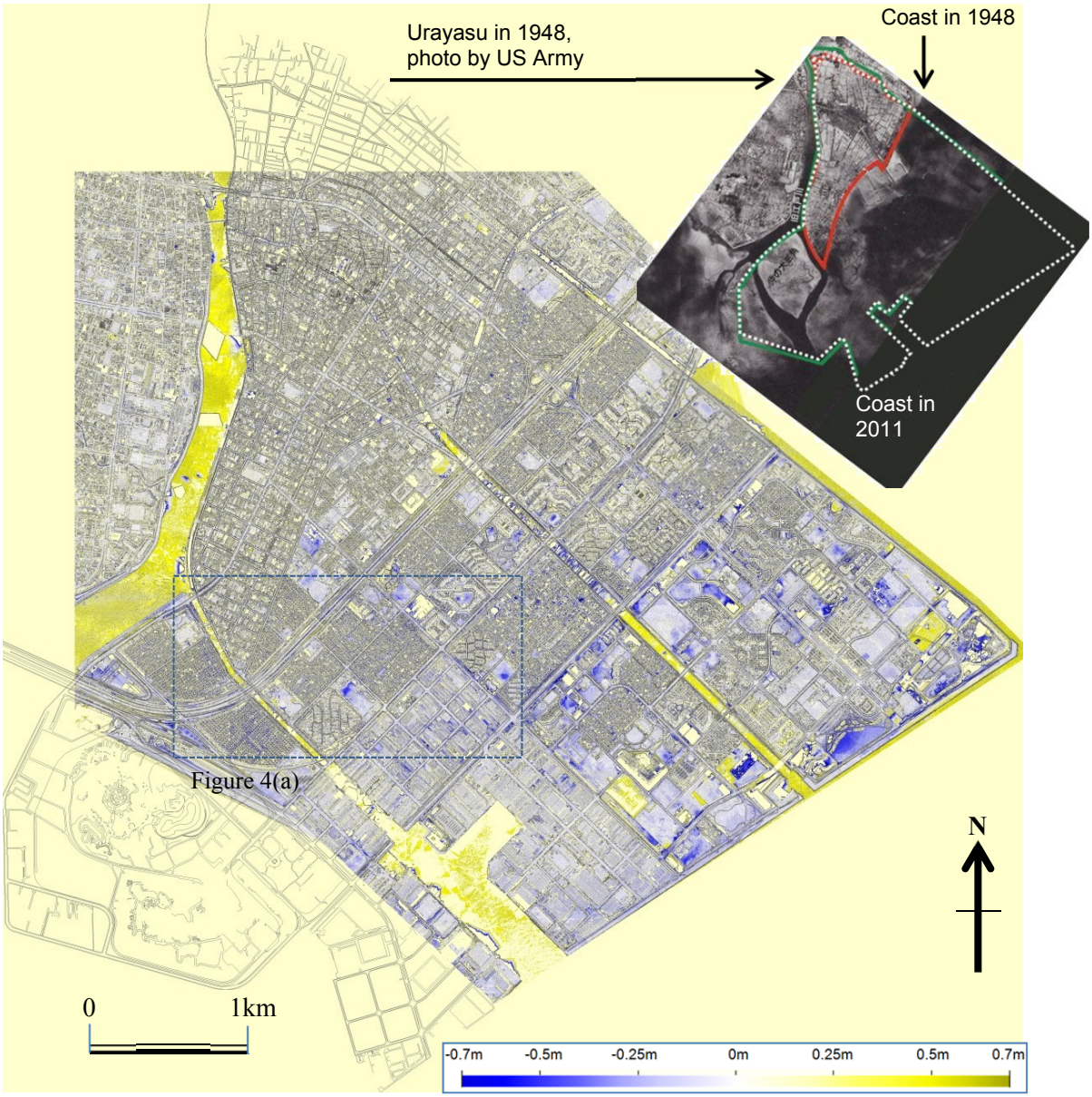
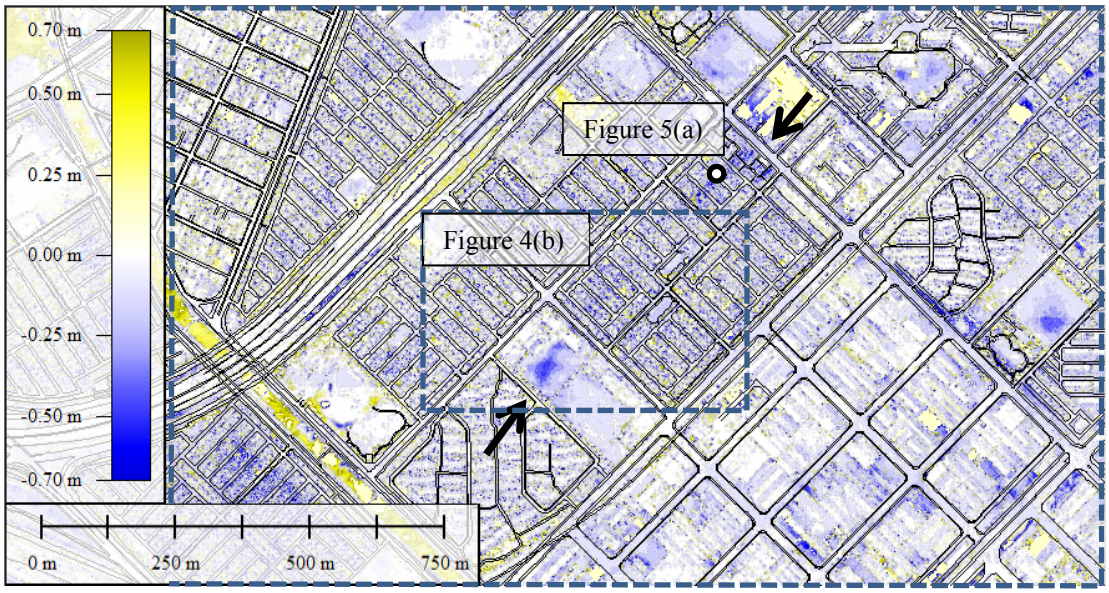
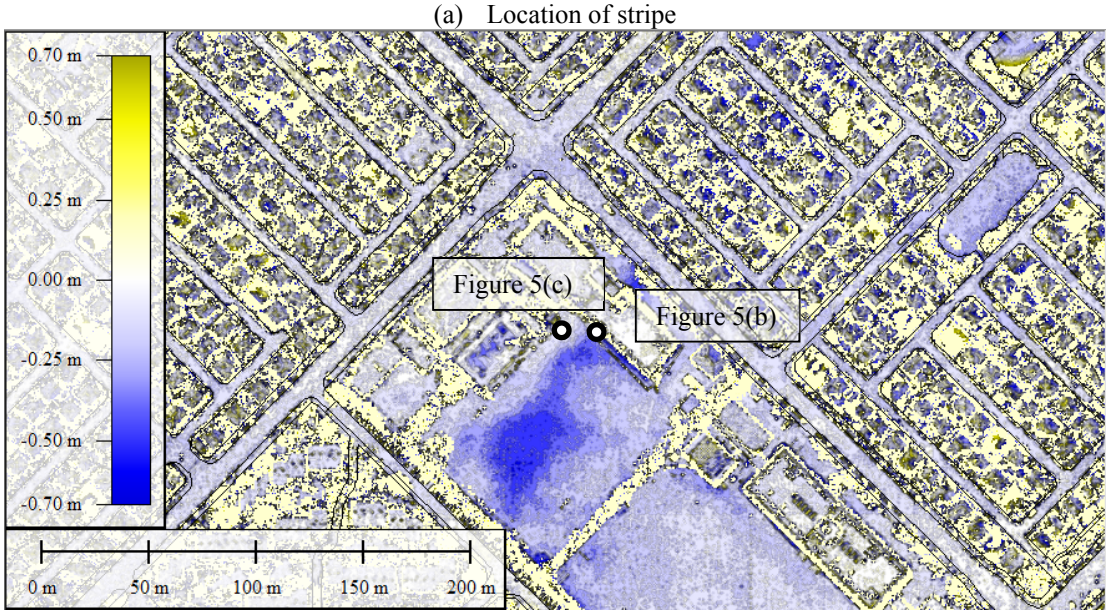


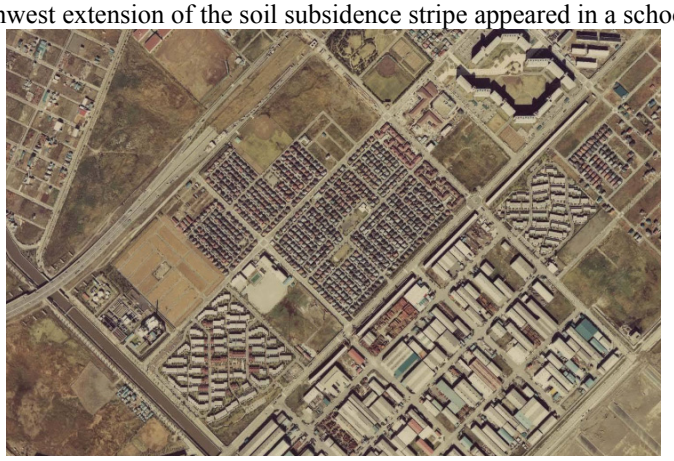
Figure 3. Soil subsidence map of Urayasu



(a) Location of stripe



(b) Southwest extension of the soil subsidence stripe appeared in a school-ground



(c) Benten area in 1979: The area was developed in late 1970s.
Geospatial Information Authority of Japan (2011b)

Figure 4. Stripe of soil subsidence of across Benten residential area

(a) Inclined and sunken houses
Photo by Kiyota T., at 35.641895, 139.89886

(b) Sand blows lined up in school ground
Photo by Kiyota T., on March 19th
at 35.638933, 139.895619

(c) Puddle appeared in school ground
Photo by Konagai K., on April 24th
at 35.639117, 139.895471

Figure 5. Extension of the subsidence stripe appeared in a school-ground of Miake Primary School

Zooming in on one of residential areas, Benten, a clear blue brush of large soil subsidence is found running across several town blocks as indicated with arrows in **Figure 4**. In these residential town blocks, where strip footings and mat foundations are the most common, houses have sunken in the soil by about 0.5m in average (**Figure 5(a)**). The southwestern extension of the brush appeared as sand blows lined up in the school ground of Miakegawa Primary School (**Figure 5(b)**). Later, on April 24, there appeared a puddle as shown in **Figure 5(c)** due to a heavy rain of April 23rd 2011.

3.2 Ichikawa-to-Chiba Area

Figure 6 shows the obtained soil-subsidence map of Ichikawa-to-Chiba area. An about 1 to 2 km wide stripe of subsided area extends all along the Tokyo Bay. Excluding two conserved tidal flats in Ichikawa and Narashino, seriously subsided spots are found clustered in Makuhari area of Chiba City (**Figure 7**). This area had been a tidal flat until 1960th. The first landfilling project was completed in 1964 as shown in **Figure 7(a)**, and followed by the 2nd three-years landfilling project for a Makuhari new city complex in 1973. **Figure 7(b)** shows the aerial photo of the new-city complex in 2006 with the original coast line a few kilo meters inland. These subsidence spots included Makuhari-Kaihin Park and the areas in front of JR Kaihin-Makuhari Station, where manholes were found sticking out (**Figure 8(a)**) and buildings next to the pile supported JR Kaihin-Makuhari Station fell forward (**Figure 8(b)**).

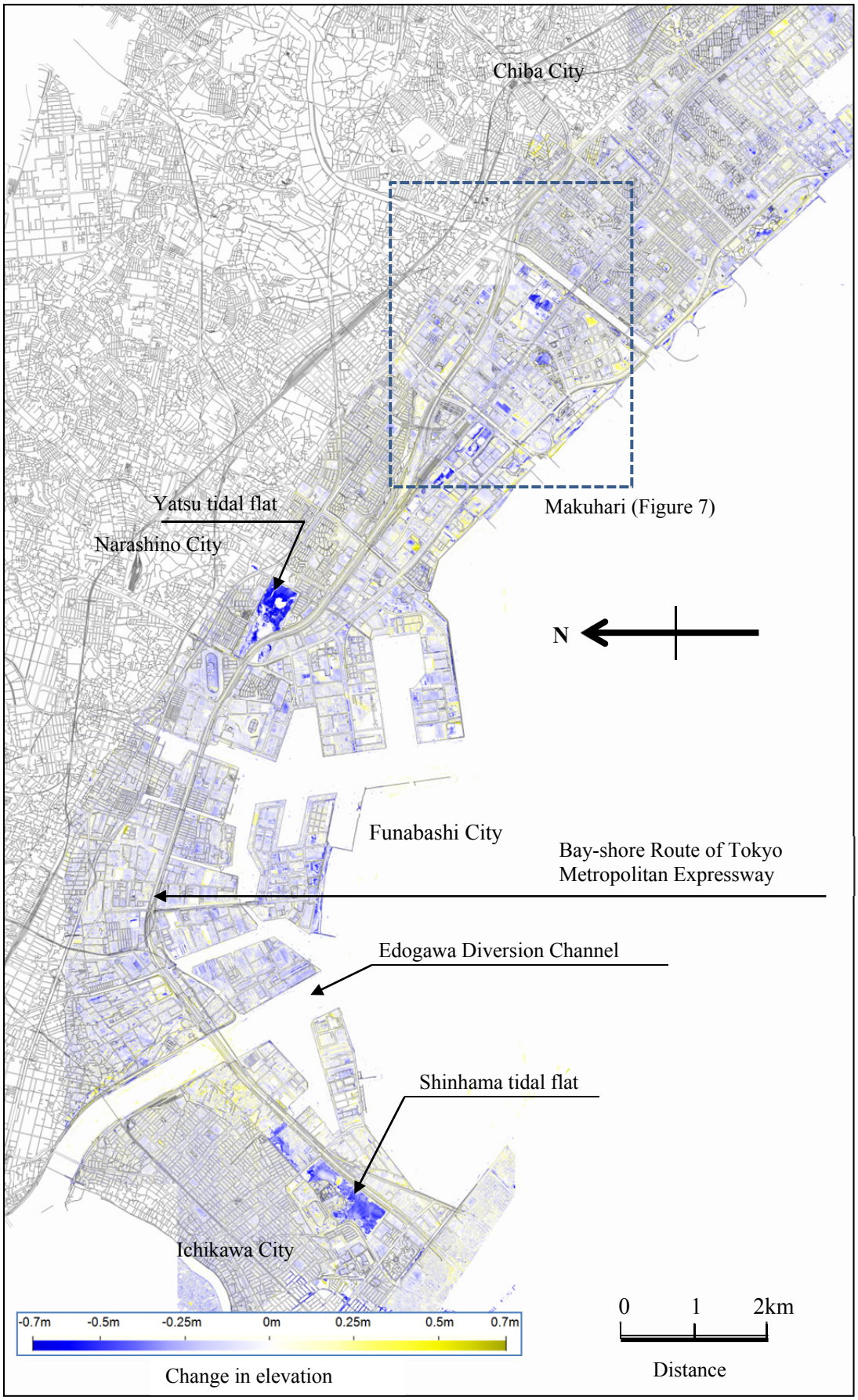


Figure 6. Soil subsidence map of Ichikawa-to-Chiba area

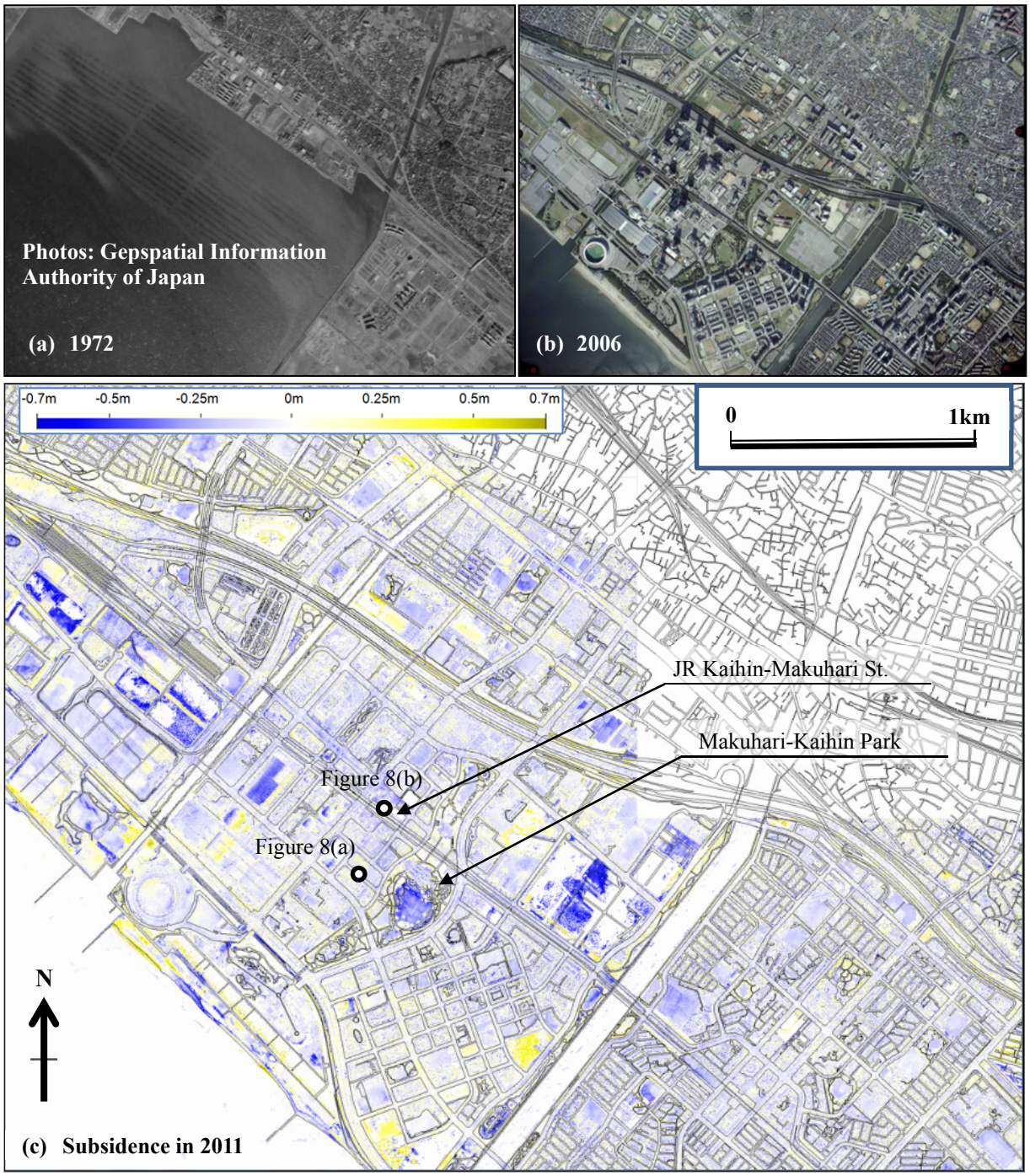


Figure 7. Soil subsidence map of Makuhari

(a) Location: 35.646337,140.040413 (b) Location 35.648773,140.04176

Figure 8. (a) Manhole sticking out of sidewalk and (b) a two story building falling forward (Photos by Kazuo Konagai on July 10th 2011)

4. CONCLUSIONS

The March 11th 2011 East-Japan Earthquake has caused sand-liquefaction over a long stretch of landfills along the coast of the Tokyo Bay. The liquefied areas along the coast of the Tokyo Bay reportedly reach 42 km^2, and there yet remain serious long-lasting concerns about sewage treatment and possible inundations inside levees, etc. An attempt was made to measure liquefied soil subsidence with reference to elevations of top ends of pile supported buildings and bridge piers. Two sets of Digital Surface Models (DSMs) were compared with pile-supported RC buildings and bridge piers as templates for matching, and examples of the analyzed images were shown for Urayasu and Ichikawa-to-Chiba areas. On the obtained map of Urayasu, subsidence can be seen over the entire stretch of the reclaimed land. In particular, remarkable subsidence is seen where the aerial photo of 1948 shows darker black color indicating the presence of deep water at that time. The obtained map of Ichikawa-to-Chiba area shows an about 1 to 2 km wide stripe of subsided area extending all along the Tokyo Bay. Seriously subsided spots were found clustered in Makuhari area of Chiba City, which had been a tidal flat until landfilling projects started in 1960s and 1970s.

APPENDIX: GEOGRAPHIC REFERENCE SYSTEM

The soil subsidence maps ware prepared on the Japanese National Grid System. The Japanese National Grid System divides Japan into a set of 19 zones assigned with Greek numerals from I to XIX in principle in a row-by-row pattern starting from the zone at the southwest corner. Exceptions (from XIV to XIX) are for isolated islands. The surveyed Tokyo Bay area is included in Zone IX with its southwest corner located at 139°50'E, 36°00'N.

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