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SOIL SUBSIDENCE MAP OF THE TOKYO BAY AREA LIQUEFIED IN THE MARCH 11th GREAT EAST JAPAN EARTHQUAKE

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ABSTRACT: The March 11th 2011 East-Japan Earthquake has caused sand-liquefaction over a long stretch of landfills along the coast of Tokyo Bay. An attempt was made to detect soil subsidence from airborne LiDAR (**Li**ght **D**etection **a**nd **R**anging) images before and after the earthquake. To cancel out deep-seated tectonic displacements and systematic errors of LiDAR, the template matching technique is used for the end-bearing pile-supported buildings chosen as the template in the source image of the target area of Urayasu. The obtained subsidence map describes the spatial distribution of soil subsidence in great detail.

Key Words: Great East Japan Earthquake, liquefaction, soil subsidence, LiDAR, digital surface model, rehabilitation

INTRODUCTION

Tokyo Bay area is a home to millions of people as well as the port/factory zone to support urban lives. The March 11th 2011 Off the Pacific Coast of Tohoku Earthquake (known as the Great East Japan Earthquake) has caused sand-liquefaction over a long stretch of landfills along the coast of Tokyo Bay, leaving many houses tilting and lifelines cut off on and in loosened sediments of sands. 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 exposed sidewalks. The liquefied areas along the coast of 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 16 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). Alaska area of Aringay (at around 16.385614, 120.3263) has subsided by 1 to 3m such that sea water touched roofs of houses at high tide (Yanagisawa et al., 1993a). In the 1964 Niigata Earthquake, similar problems were reported. About a 640m 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 those previous examples, it is very important for relevant organizations to have quantitative information of the soil subsidence to cope with the post-earthquake problems.

Images from an airborne Light Detection and Ranging (LiDAR) system, namely digital surface models (DSMs hereafter), were obtained on April 20th and September 6th 2011 for Urayasu and Funabashi-Mihama areas, respectively, and an attempt is being made to compare the imageries with those before the earthquake (Konagai K. et al, 2011a). From those analyzed, this paper describes the overall features of soil subsidence in Urayasu.

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 three airborne devices, (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) 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 Ichkawa City, Funabashi City and Mihama area of Chiba City) are 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 difference in flight altitudes may also yield different errors such as false increase in elevation of pixels away from nadir of the sinusoidal scanning, etc. In addition to the above-mentioned system-correlated anomalies, the effect of deep-seated tectonic deformations caused by this earthquake was really remarkable over the entire stretch of the Pacific coast areas of the eastern Japan (Geospatial Information Authority of Japan, 2011). However liquefaction-induced shallow soil subsidence can be simply measured with reference to roof elevations of pile supported buildings such that any potential horizontal or vertical biases can be eventually canceled out. Therefore, to find the best matching depth for DSMs to minimize the effect of both the system-correlated anomalies and the tectonic deformations, template matching technique is used for the end-bearing pile-supported buildings chosen as the template in the source image of target areas.

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, Funabashi and Mihama	December 2006 to January 2007	0.792 points/m^2
Ichikawa, Funabashi and Mihama	September 6th 2011	1.786 points/m^2

Table 2.RC buildings for template matching

Template building	Latitude (degree)	Longitude (degree)	Elevation (m) in 2011	Elevation (m) in 2006	Increment (m)
A1	35.645125	139.920240	31.1023	31.3083	-0.2060
A2	35.645125	139.920571	31.1292	31.3419	-0.2127
B1	35.647987	139.913904	112.9577	113.1900	-0.2323
B2	35.647906	139.914026	112.9761	113.2367	-0.2606
B3	35.647951	139.914092	112.9663	113.1745	-0.2082
B4	35.653619	139.901497	112.9464	113.1917	-0.2271
C1	35.653457	139.901585	20.9227	21.1300	-0.2074
C2	35.653952	139.901696	20.9132	21.1199	-0.2067
C3	35.653682	139.901806	16.9115	17.1025	-0.1910
C4	35.647951	139.913949	13.5811	13.7840	-0.2029
D1	35.651817	139.899839	14.3769	14.5829	-0.2061
D2	35.651592	139.900280	14.3778	14.5738	-0.1959
E1	35.639417	139.895500	13.6783	13.8505	-0.1722
E2	35.638109	139.897155	14.2482	14.4560	-0.2078
F1	35.644944	139.891650	13.6680	13.8642	-0.1962
F2	35.644673	139.892025	13.6488	13.8733	-0.2245
F3	35.645052	139.892445	13.4727	13.6934	-0.2207
				Average	-0.2078
				Standard deviation	0.0193

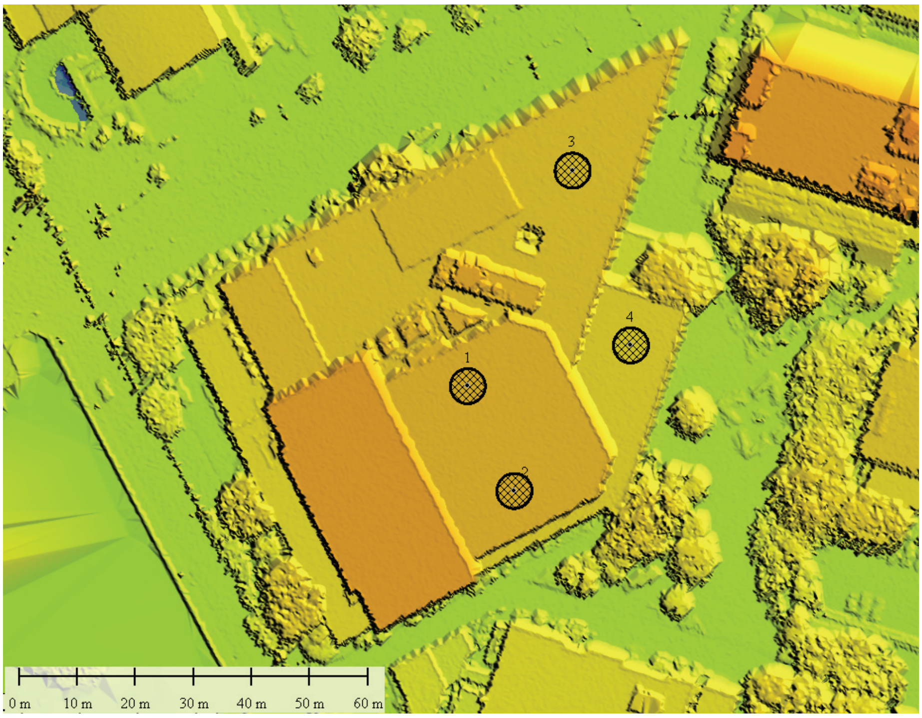


Fig. 1 Template points on a pile-supported RC building

It is to be noted that LiDAR returns (reflections) from water surfaces are known to be of suspect accuracy, because water has a number of physical properties that vary tremendously and make it a poor reflector of light. Moreover the area has a great tidal range of 1.8 to 2m. Therefore the discussion hereafter only deals with on-shore soil subsidence.

In Urayasu City, 17 points on flat roofs of total 6 buildings (Table 2) were taken as templates to find the best matching depth. 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 (Fig. 1). As shown in Table 2, 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. This standard deviation of 1.93cm is considered to be small enough to discuss large soil subsidence that appeared as clear several tens centimeters difference in level between ground floors of pile-supported RC buildings and sidewalks.

For canceling lateral biases, we need to extract Lagrangian components of displacements. However, Comparing DSMs at different times only allows 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 motion 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. (2010, 2011b) 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 nodes 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 Fig.2, 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 undergo a rigid-body-translation movement $\{\Delta y \quad \Delta z\}^T$, their Lagrangian components that represent the rigid body movement of the roof can be obtained by solving the following simultaneous equations.

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

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 (g, f, k1, k2 and k3 in Fig. 3) are taken among the others as templates.

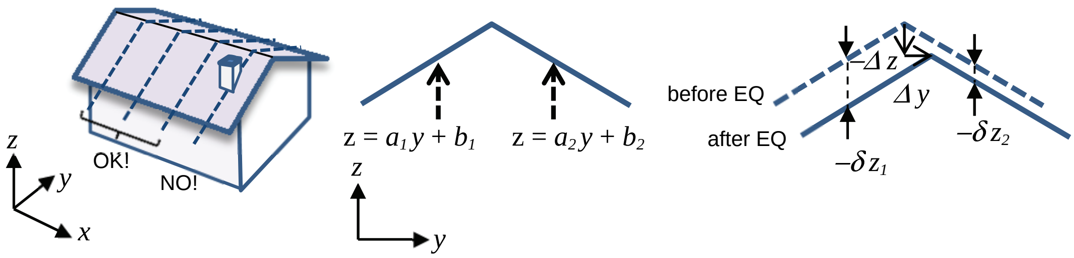


Fig. 2 Template building with sloping roofs for adjusting

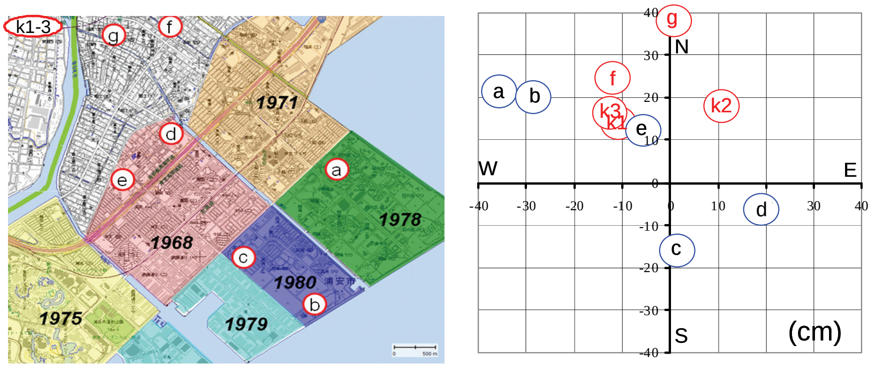


Fig. 3 Locations of template buildings in Urayasu (left) and Lagrangian components of lateral shifts for these buildings (right).

Fig. 3 shows the obtained Lagrangian components of lateral displacements. 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.

OBTAINED MAP OF SOIL SUBSIDENCE

Fig. 4 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.

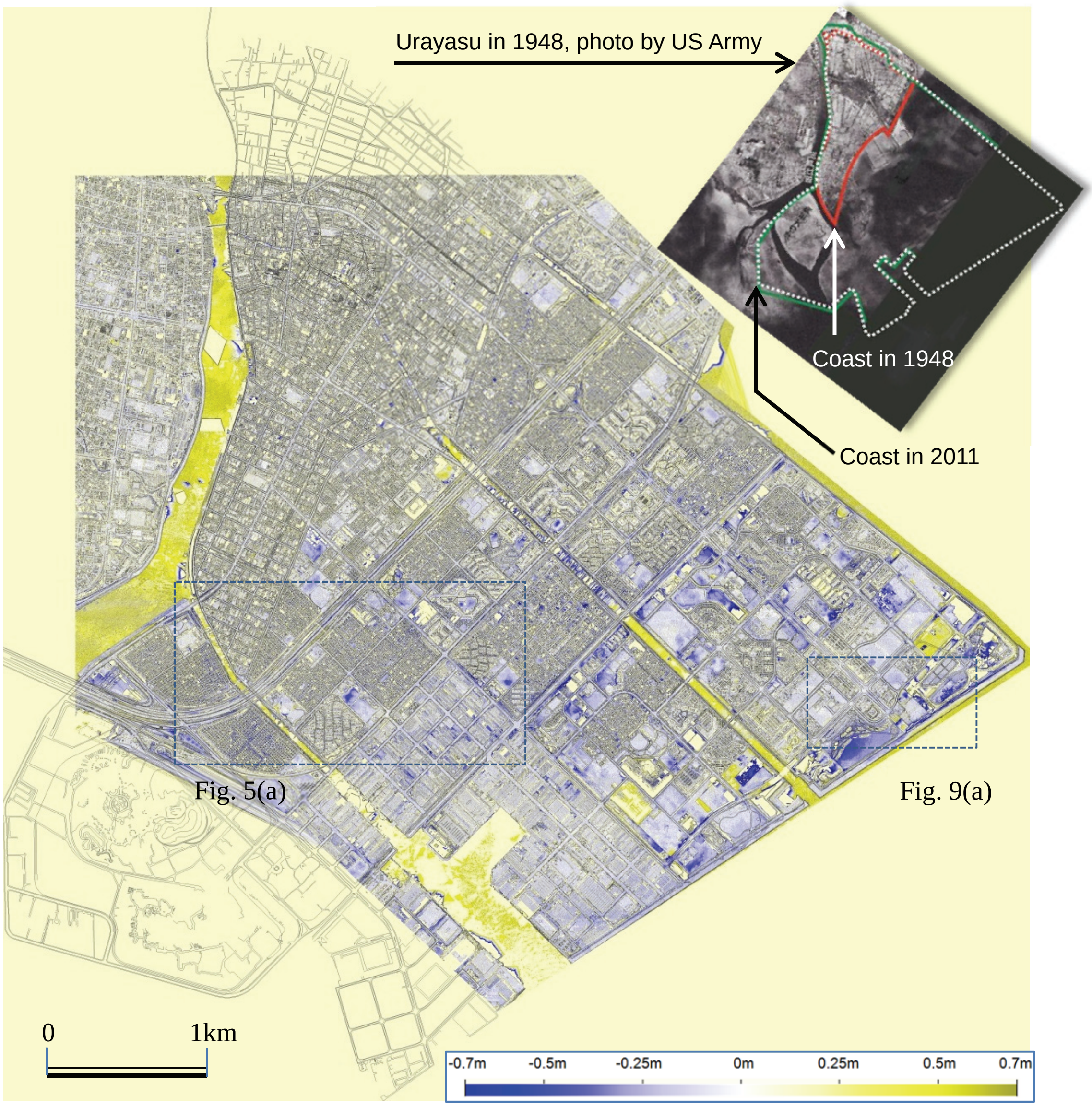
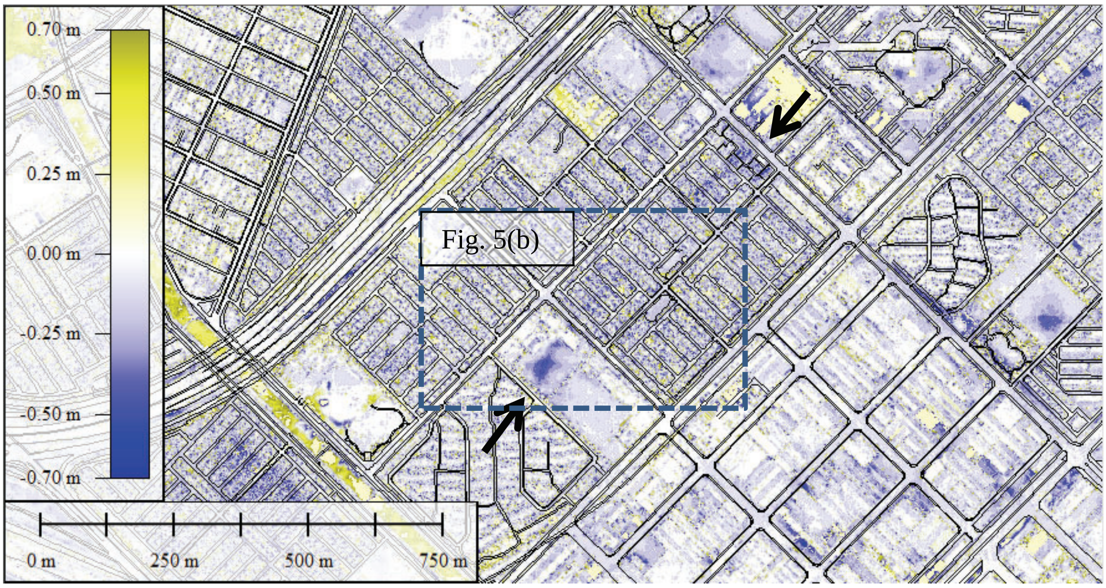


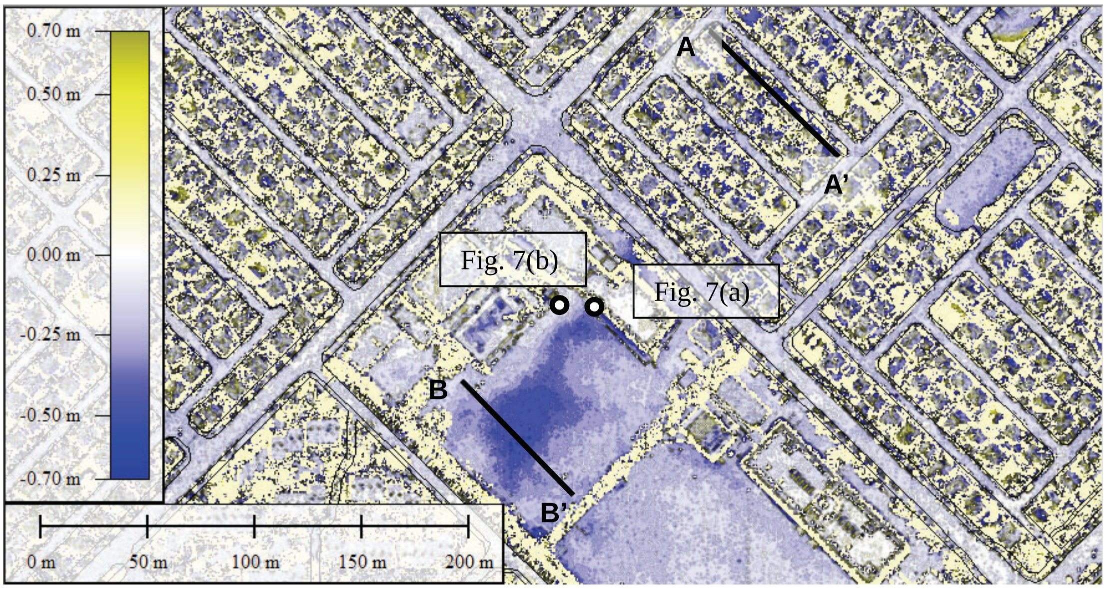
Fig. 4. Soil subsidence map of Urayasu.

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 at that time. 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.

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 Fig. 5. 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 as shown in Fig. 6(a). The southwestern extension of the brush appeared as sand blows lined up in the schoolyard of Miakegawa Primary School (Fig. 7(a)). Later, on April 24, there appeared a puddle as shown in Fig. 7(b) due to a heavy rain of April 23rd 2011. Fig. 7(b) shows a cross-section of this school yard where the deepest subsidence of about 0.5m was reached.

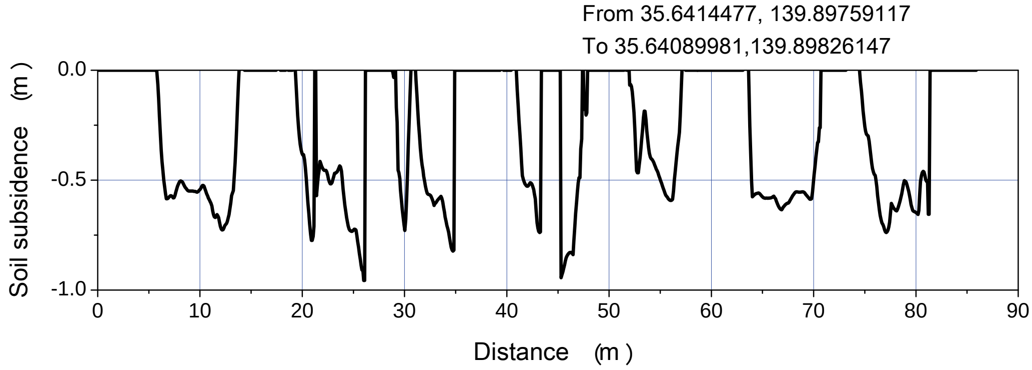


(a) Location of stripe

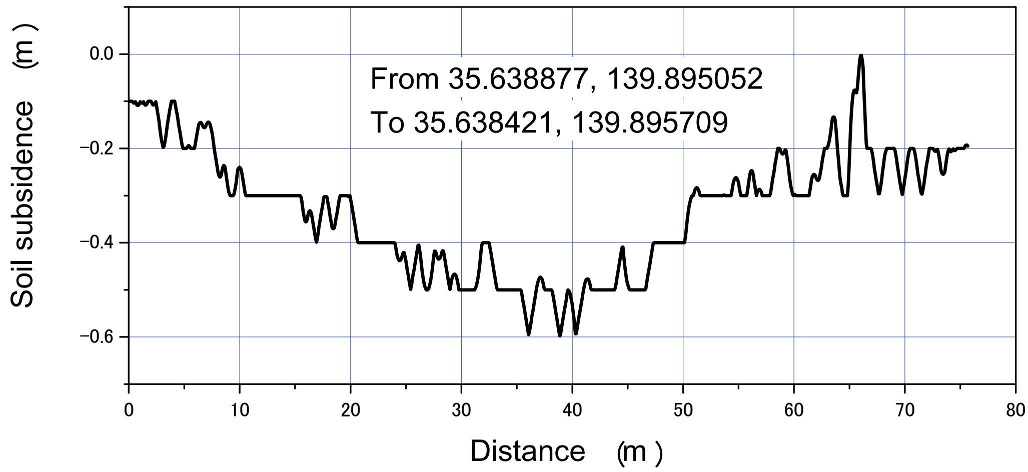


(b) Southwest extension of the soil subsidence stripe appeared in a school-ground

Fig. 5 Stripe of soil subsidence of across Benten residential area



(a) Cross-section A-A’



(b) Cross-section B-B’

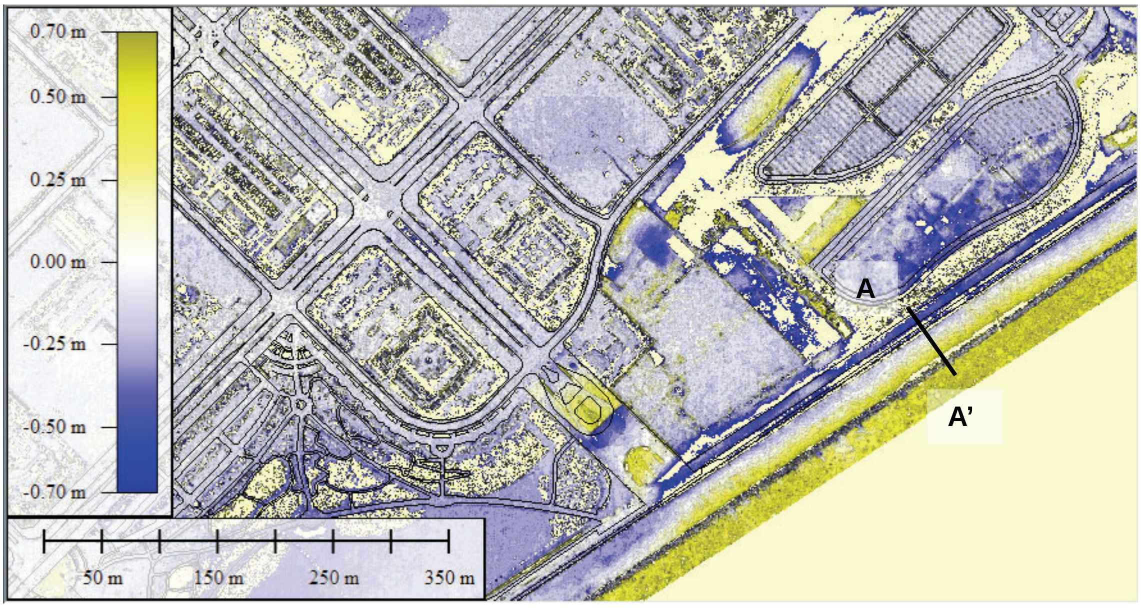
Fig. 6. Cross sections across stripe of soil subsidence that appeared in Benten residential area. Only subsidence of house roofs is shown in Fig. 6(a).


(a)Sand blows lined up in school ground March 19th at 35.638933, 139.895619

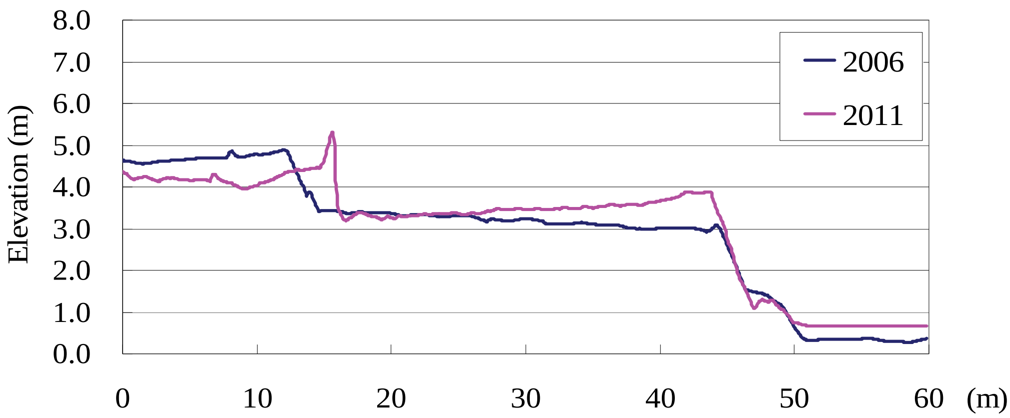

(b) Puddle appeared in school ground April 24th at 35.639117, 139.895471

Fig. 7 Extension of the subsidence stripe appeared in a school-ground of Miake Primary School

Fig. 8. Seawall pushed forward (Photo taken on Aug. 1st, 2011 at 35.63666, 139.931638)



(a) Location of AA' cross-section on the soil subsidence map



(b) Cross-sections of shore-protection work

Fig. 9 Cross-sections of shore-protection work at the southeastern end of Urayasu

All these observed features may suggest that the surface soil has spread laterally in the normal direction with respect to the brush of soil subsidence allowing liquefied sand to force its way easily through the crack, though no clear evidence was found there. Lateral spread of the ground was more clearly found near the southeast coast of the city as shown in Fig. 8. Cross-sections AA’ before and after the earthquake are compared in Fig. 9. This figure shows that the seawall was pushed about 2m forward associated with a half-meter subsidence of its backfill. A flat foot protection work, which extends over 30m distance from the seawall towards the Tokyo Bay, was also pushed toward the bay with its pavement overriding the toe of the protection work.

SUMMARY

The March 11th 2011 East-Japan Earthquake has caused sand-liquefaction over a long stretch of landfills along the coast of Tokyo Bay. The liquefied areas along the coast of Tokyo Bay reportedly reaches 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 roof elevations of pile supported buildings. Two sets of Digital Surface Models (DSMs) were compared with roofs of pile-supported RC buildings as templates for matching, and an example of the analyzed images was shown for Urayasu City. It turned out that the elevations of the chosen roofs of RC buildings after the earthquake are 20.78cm lower than those before the earthquake in average with the standard deviation of 1.93cm, thus verifying that the method allows for through discussion of liquefaction-induced soil subsidence in a quantitative manner. 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.

Maps for the other Bay Area are now being prepared, and will appear in later publications.

APPENDIX: GEOGRAPHIC REFERENCE SYSTEM

The soil subsidence map was 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 northwest corner located at 138.5°E, 36.0°N.

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