Soil Dynamics and Earthquake Engineering 53 (2013) 240–253

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

journal homepage: www.elsevier.com/locate/soildyn

Maps of soil subsidence for Tokyo bay shore areas liquefied in the March 11th, 2011 off the Pacific Coast of Tohoku Earthquake ☆

Kazuo Konagai [a,*], Takashi Kiyota [a], Shota Suyama [a], Toru Asakura [b], Kenichi Shibuya [c], Chikako Eto [c]

[a] *Institute of Industrial Science, University of Tokyo, Tokyo 153-8505, Japan*
[b] *CTI Engineering International Co. Ltd., Tokyo 136-0071, Japan*
[c] *Aero Asahi Corp., Saitama 350-1165, Japan*

ARTICLE INFO

Article history:
Received 2 October 2012
Received in revised form
21 June 2013
Accepted 25 June 2013
Available online 13 August 2013

Keywords:
Liquefaction
Great East Japan earthquake of 2011
Soil subsidence
Tokyo bay area

ABSTRACT

The March 11th, 2011 Off the Pacific Coast of Tohoku Earthquake, also known as the Great East Japan Earthquake, has shown that a long stretch of landfills along northeastern shorelines of the Tokyo Bay had very high susceptibility to liquefaction, causing concerns about re-liquefactions of the area in the scenario earthquake expected in the capital's metropolitan area. 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 eliminate deep-seated tectonic displacements and systematic errors of LiDAR surveys, the template matching technique is used for clusters of 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.

1. Introduction

Tokyo Bay Area, which was formerly used for seaweed collection, fishing, and resorts, is now a part of the great Tokyo–Yokohama–Chiba metropolitan area. By the mid-1970s, production of heavy metals and chemicals in the eastern bay area was the highest among Japan's industrial regions [1]. Intensive flow of people and goods has made the Tokyo Bay Area a world renowned commercial and consumption hub. All the more because the area has been the center of the economy 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 and power poles tilting and lifelines cut off [2]. After almost all sands were cleared up for rehabilitation, clear differences of level between ground floors of pile-supported RC buildings and surrounding sidewalks were noted. The liquefied areas along the coast of the Tokyo Bay reportedly reached 42 km^2 [3], and there yet remain serious concerns about sewage treatment and possible inundations inside levees. According to the census data, the population of Chiba Prefecture has fallen by 7724 residents since the beginning of 2011 for the first time since record keeping began in 1920 [4]. Cases of modern liquefaction illustrate that soil subsidence caused by sand liquefaction can cause long-lasting problems. In the July 16th, 1990 Luzon Earthquake for example, the city center of Dagupan 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 sunk in the liquefied sand with their surrounding soils and remained underwater for several months [5]. In the 1964 Niigata Earthquake, similar problems were reported. About a 640 m long stretch of Akashi Avenue has subsided due to liquefaction and remained about 60 cm underwater. The area along Tsusen River was flooded by tsunami, and remained underwater for about a month [6]. These areas have been frequently inundated in heavy rains since then. One of the more notorious of these floods was the record rainfall on August 4th, 1988, which later led the Niigata Prefectural Government into the construction of a new drainage pump station at Yamanoshita lockage [7].

In addition, what should not be forgotten is that the liquefied areas are considered to be at high risk of re-liquefaction. Wakamatsu has confirmed that sand deposits, which were once liquefied in past earthquakes, did liquefy again in the March 11th Earthquake in at least 145 municipalities in both Kanto and Tohoku Regions, including Urayasu City [8]. The Earthquake

* Corresponding author. Tel.: +81354526142, +81453394034; fax: +81354526144.
E-mail addresses: konagai@ynu.ac.jp, kaz_kon@ll.em-net.ne.jp (K. Konagai).

0267-7261/$ - see front matter © 2013 The Authors. Published by Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.soildyn.2013.06.012

Research Institute of the University of Tokyo predicted that there would be a 70% probability that the capital's metropolitan area would experience a magnitude-7 quake within 4 years and a 98% probability within the next 30 years [9].

With all mentioned above, it is very important for relevant organizations to have quantitative information on the soil subsidence to cope with post-earthquake problems. Raster images converted from airborne Light Detection and Ranging (LiDAR) data, namely digital surface models (DSMs hereafter), were obtained on April 20th, September 6th and November 27th, 2011 for Urayasu, Funabashi–to–Chiba and Ichikawa areas, respectively, and an attempt was made to compare the images with those before the earthquake [10], [11], [12]. 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 correcting positioning errors [13]. 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) before the earthquake (in December 2006–January, 2007 for the entire target areas) and after the earthquake (on April 20th, 2011 for Urayasu, September 6th for the area from Funabashi to Chiba, and November 27th for Ichikawa)

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

Area	Date of LiDAR survey	Spatial resolution (points/m^2)
Urayasu	December 2006 to January 2007	0.792
Urayasu	April 20th, 2011	4.089
Ichikawa-to-Chiba	December 2006 to January 2007	0.792
Ichikawa-to-Chiba	September 6th, 2011 and Nov. 27th, 2011	1.786

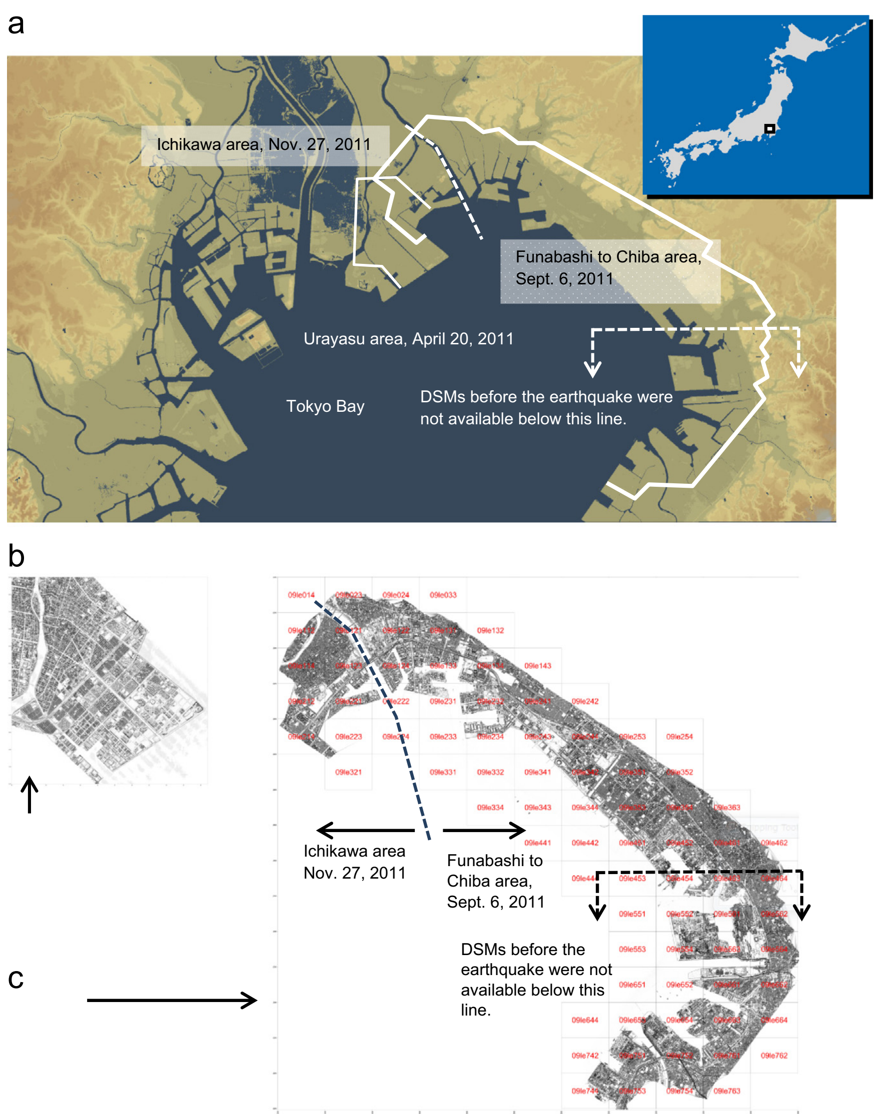

Fig. 1. DSMs obtained for the Tokyo bay shore area. (a) Air-borne LiDAR surveyed areas (b) Urayasu area, April 20, 2011 and (c) DSMs of Ichikawa area (November 27, 2011) and Funabashi to Chiba area (September 6, 2011)