ESTIMATION OF LAND SUBSIDENCE INDUCED BY A MEGA EARTHQUAKE USING WATER LEVEL DATA

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ABSTRACT

This paper investigates the land subsidence at the Kobama harbor caused by the 2011 off the Pacific Coast of Tohoku Earthquake as detected by the water level measurement data. The continuous water level measurement data were compared to the astronomical tide. It was found that before the earthquake, the recorded water level coincide well with the astronomical tide. The land subsidence caused vertical dislocation of the measurement device. Therefore, the measured water level deviates from the astronomical tide. This deviation corresponds to the subsidence. It was found that the earthquake caused an approximately 39 cm of subsidence at Kobama port. The result correlates well with the reported height change, issued by the Geospatial Authority of Japan (GSI). The water level analysis can be used to monitor the land subsidence and therefore, will be beneficial in reconstruction process concerning future disaster.

1. INTRODUCTION

The 2011 off the Pacific Coast of Tohoku Earthquake occurred at 14:46 on March 11, 2011. The earthquake was recorded at 9.0 (Japan Meteorological Agency (JMA)) with the epicenter approximately 70 km east of the Oshika Peninsula of Tohoku. The hypocenter was located at an underwater depth of approximately 30 km. The earthquake violently rocked the Tohoku Region to the Kanto Region, and triggered a massive tsunami wave that caused severe damages to the coastal area.

Imakiire and Koarai (2012) provided an overview of the crustal deformation caused by the earthquake. They had shown that both the horizontal and the vertical deformation occur along the affected regions, including in the Pacific coastal area. The subsidence of several tens of centimeters was recorded along the coast in Miyagi to the Ibaraki Prefecture. The GPS Earth Observation Network (GEONET) detected that the earthquake caused a great displacement. GSI (2011a) reported that a wide area was affected by this displacement with a maximum subsidence of 1.20 m occurred at the Oshika site in Ishinomaki City, Miyagi Prefecture, based on the GPS data, as shown in Fig. 1.

This deformation greatly changed the height of the benchmark points such as that on 14 March, the GSI decided that the control points and benchmarks were no longer usable. Their locations and elevation had greatly changed by the earthquake. Therefore, the GSI resurveyed and issued a corrected version on 31 October (2011b). The height change based on the survey is shown in Fig. 2, which correlates well with those obtained from GPS data in Fig. 1. The maximum height change was approximately -1.14 m at the same location.

The water level data in coastal area, when available, may provide an efficient way to estimate the magnitude of land subsidence, following a mega earthquake. Yeh et al. (1995) had shown that a continuous water level measurement data in coastal area could be applied to estimate the magnitude of subsidence. They analyzed the water level data at Malokurilskaya Bay during the 1994 Shikotan Earthquakes and Tsunami and found that the earthquake caused an approximately 53 cm of subsidence.

Unfortunately, the tsunami triggered by the 2011 off the Pacific Coast of Tohoku Earthquake caused damages to most of the water level measurement devices along the coast. However, Kakehi (2011) measured the water level data continuously at Kobama harbor during the earthquake. This data set can be used to estimate the subsidence at the corresponding location. In this study, the continuous water level measurement data at Kobama port were analyzed and compared to the astronomical tide provided by the Japan Meteorological Agency (JMA) at Sendai Port.

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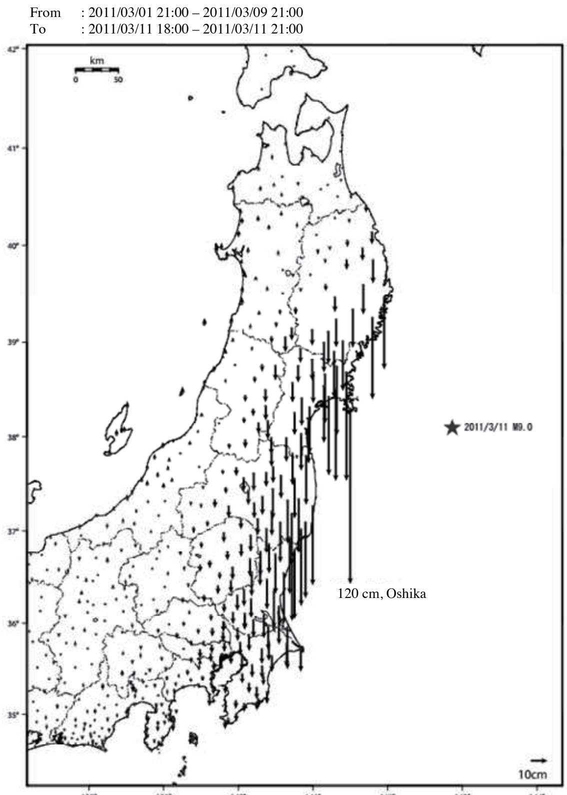

Fig. 1 Vertical displacement caused by the 2011 off the Pacific Coast of Tohoku Earthquake (GPS), GSI (2011a)

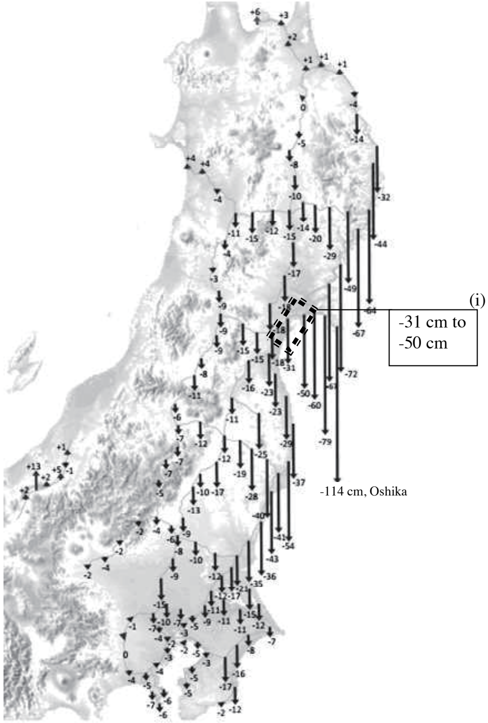

Fig. 2 Height change along the leveling survey, GSI (2011b)

2. STUDY AREA AND DATA

The study area is the Kobama harbor, which is located in Sendai Bay, Miyage Prefecture as shown in Fig. 3. This harbor is located at the north east of the Sendai Port. Kakehi (2011) measured the water level at this location. Although this area was severely damaged by the tsunami, the measurement device in Kobama harbor did not suffer from any significant damages and continued to record the water level data continuously with a 10 minutes interval. It was confirmed that the measurement device was still secured in its position after the tsunami with no significant damages (Kakehi, 2011). On the other hand, the measurement device at the Sendai Port was damaged by the tsunami and the tidal level was not measured continuously. Nevertheless, the astronomical tide at Sendai Port is available. Further discussions in this study will be based on these two sets of water level data.

Fig. 3 Study area

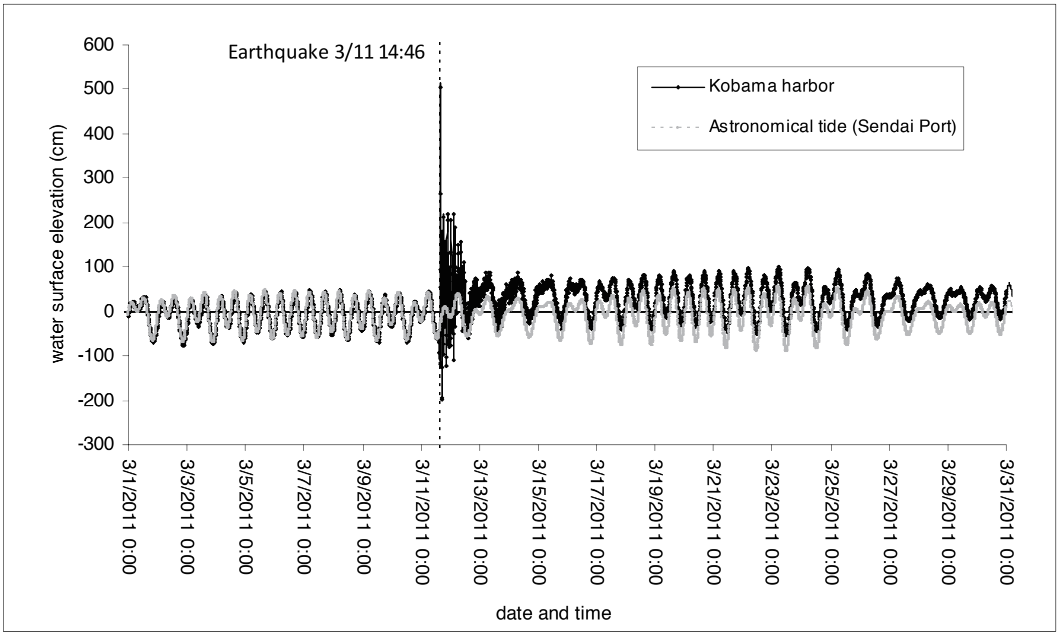

Fig. 4 Water level data (Kobama) and astronomical tide (Sendai Port), GMT +09:00

In this study, the measurement data at Kobama harbor, starting from 14 January to 6 April was obtained and used for analysis. The measurement device here was not tied to any control points or benchmarks. Therefore, the data were converted based on the average water level from 15 January 2011 00:00 to 11 March 2011 00:00. The mean sea level is estimated at +2.08 m. The astronomical tide was obtained at the nearest location, Sendai Port, given at an hour interval (JMA, 2011). The mean sea level at Sendai port is +0.90 m. The measurement data at Kobama harbor were obtained with an interval of 10 minutes. Thus, the astronomical tide at Sendai Port was interpolated.

The converted data for water level at Kobama harbor and astronomical tide at Sendai Port are shown in Fig. 4. The raw data clearly shows the tsunami wave that was caused by the 2011 off the Pacific Coast of Tohoku Earthquake. It is also shown here that both data overlaps each other well prior to the earthquake. However, the water level at Kobama port shows a consistent shift from the astronomical tide after the tsunami. Hence the elevation of the measurement device was lower in the period after the earthquake than in the before. This suggests that land subsidence occurred at this location, which will be discussed further in the next section.

3. RESULTS AND DISCUSSIONS

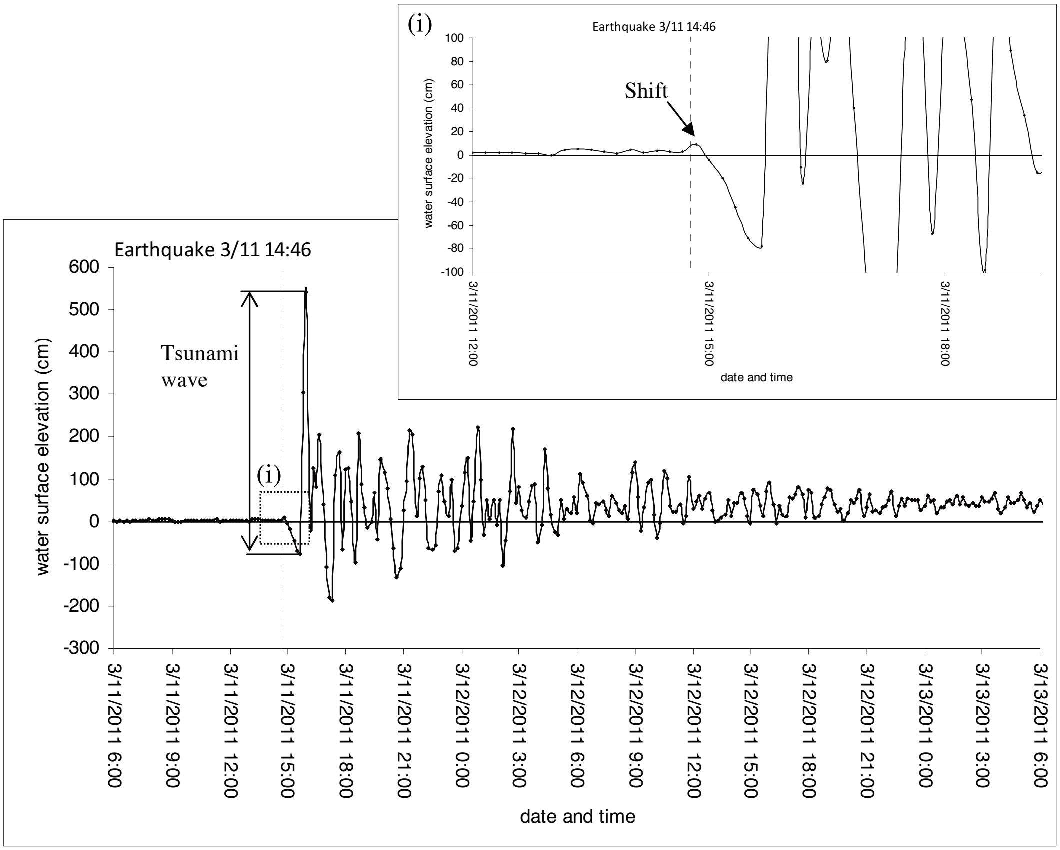

Fig. 5 Water level data (Kobama) after removal from the astronomical tide, GMT +09:00

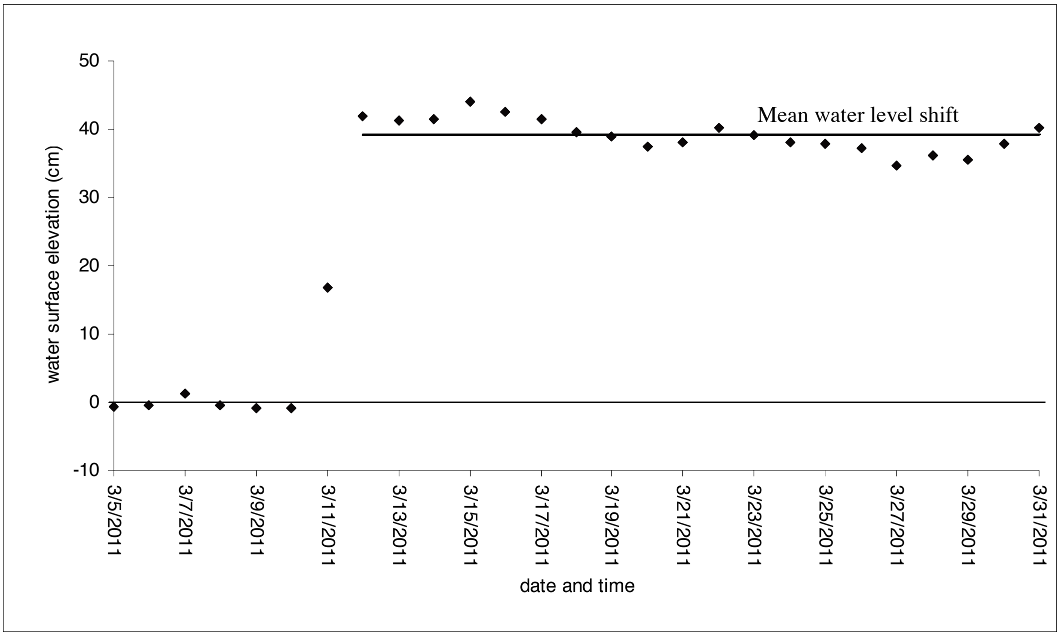

Fig. 6 Daily average data, GMT +09:00

The data were analyzed in details to estimate the subsidence in the study area. The water level data were separated from the astronomical tide and the result is shown in Fig. 5. According to this figure, the first tsunami wave peak arrived at 16:00, or approximately 74 minutes after the earthquake. The water level at this time was approximately 5.42 m. The water level drops prior to this peak was approximately 0.78 m at 15:40. Thus, the incoming tsunami wave height is approximately 6.19 m, measured from the lowest water level before the peak. This agrees well with the results obtained by Kakehi (2011).

Figures 4 and 5 both show that this shift appears after the initial wave. However, the initial subsidence occurrence might be earlier than the tsunami wave. A closer look at Fig. 5 at the period (i) shows a vertical shift occurred almost immediately after the initial shock from the earthquake. The water level recorded at 14:40, 6 minutes before the earthquake was approximately +2.89 cm. The water level suddenly increased to +9.22 cm at 14:50, 4 minutes after the earthquake. This suggests that the subsidence process may have started although it has not reached the maximum value. It should be noted that the subsidence in coastal area might occur due to the shock from the earthquake itself and the pore water pressure, in which the later is usually larger. Thus, the initial subsidence immediately after the earthquake can be lower. Unfortunately, the sudden drop of water level due to the incoming tsunami wave soon followed this shift. Thus, the gradual increased of the subsidence cannot be further analyzed.

Daily averaged water level data were computed based on the measurement data and further adjusted by eliminating the daily variations caused by astronomical tide. The results are presented in Fig. 6. It was confirmed that the daily averaged water level before the earthquake did not show significant deviation to zero. However, their values were greatly increased after the earthquake. This figure shows the shifting of the mean water level of approximately 39 cm after the earthquake and tsunami. This vertical shift correlates well within the range of the surveyed height change by GSI around Sendai Bay (Fig.2 (i)), from 31 cm to 50 cm. This value also agrees well with the reported seabed subsidence at the nearby southern end of Suzaki Coast (Tanaka et al., 2014). It is also shown here that after the earthquake on 11 March, there were no significant deviations to the new value of mean water level. This suggests that there were no additional subsidence in the following days after the major earthquake although there were several major aftershocks occurred. Interesting to note that this mechanism is different to the subsidence occurred at Malokurilskaya Bay. There, the subsidence occurred gradually which lasted for several days in which the main subsidence was followed by smaller ones due to the aftershocks as reported by Yeh et al. (1995).

4. CONCLUSIONS

The water level data at Kobama harbor has been successfully used to estimate the subsidence caused by the 2011 off the Pacific Coast of Tohoku Earthquake at the corresponding location. The magnitude of the land subsidence was estimated by computing the mean water level shift from the astronomical tide. In addition, the water level analysis also shows that the first tsunami wave arrived at approximately 74 minutes after the earthquake with a wave height of approximately 6.19 m.

The water level data at the Kobama harbor correlate well with the astronomical tide prior to the earthquake. However, the water level data shifted from the astronomical tide after the earthquake. The subsidence started immediately after the initial shock. It was found that the Kobama harbor area suffered from an approximately 39 cm of subsidence, which corresponds well to the general range of subsidence in this area.

The methods has shown that the water level data can be used to assessed the subsidence in coastal area that can be very useful in the early stage of recovery process concerning future disasters. The method should be applied and verified with other data set in various locations.

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