Development of Real-time Prediction Method of Tsunami Water Level in Coastal Zone, Using Tsunami Propagation Effect

Seiji TSUNO
Seismic Data Analysis Laboratory, Center for Railway Earthquake Engineering Research

Satoru FUJIHARA
Nuclear & Engineering Department, Science & Engineering System Division, ITOCHU Techno-Solutions Corporation

In order to rapidly predict tsunami water levels in coastal zones where the water depth is deeper than 50 m, a method is proposed which convolutes tsunami water levels observed in the sea and tsunami propagation effects excited by a small fault. To predict tsunami water levels in coastal zones where the water depth is shallower than 50 m, a method is proposed which uses a small-scale tsunami numerical simulation. This study investigates the validity of the proposed methods, by applying these methods to numerical simulation data for the 2011 off the Pacific coast of Tohoku earthquake (Mw 9.0).

Keywords: real-time prediction, tsunami water level, propagation effect

1. Introduction

Tsunami water levels predicted in coastal zones during the 2011 off the Pacific coast of Tohoku earthquake (Mw 9.0) were underestimated, due to real-time reports, from the earthquake early warning system using seismic data, underestimating the scale of the earthquake [1]. Therefore, to obtain more appropriate predictions of tsunami water levels in coastal zones right after a tsunami has been induced by an earthquake, the S-net (Seafloor observation Network for Earthquakes and Tsunamis along the Japan Trench) was installed on the ocean floor off the East Japan Pacific coast [2]. Tsunami water levels in the sea can thus be observed by virtue of water-pressure gauges installed on the ocean floor, right after the occurrence of a tsunami; this is expected to offer a real-time prediction technique, which directly predicts tsunami water levels in coastal zones using water levels observed on the ocean floor [3-6].

A real-time prediction method was developed through this study, for tsunami water levels in coastal zones right after the occurrence of a tsunami, using tsunami water levels observed in the sea and tsunami propagation effects due to submarine topography. The validity of the proposed real-time tsunami prediction method was investigated using data from numerical tsunami simulation of the 2011 off the Pacific coast of Tohoku earthquake (Mw 9.0).

2. Tsunami simulation of the 2011 off the Pacific coast of Tohoku earthquake

The tsunami simulation of the 2011 off the Pacific coast of Tohoku earthquake was performed using a Finite Difference Method (FDM) scheme, using the fault slip model proposed by the Headquarters for Earthquake Research Promotion, Cabinet Office, Government of Japan [7] (Fig. 1). 4 different grid-sizes were used (1215, 405, 135, and 45 m) in the areas from the sea to coastal zones, setting about 20 grids for one wave-length [8]. A time sampling of 0.81 seconds and 0.09 seconds are adopted in the linear long-wave theory and in the shallow water long-wave theory, respectively. A submarine topography mesh-model was constructed, attaching a water depth and a height above the sea level to the center of the grid in each area (Fig. 2). Digital data of submarine topography was used from the Japan Coast Guard [9] and digital data with a mesh height of 5m above sea level was used from the Geospatial Information Authority of Japan [10]. Initial tsunami water levels induced by the fault slip of the 2011 off the Pacific coast of Tohoku earthquake were estimated by crustal deformations for a vertical motion in a half space elastic medium [11]. The shallow water long-wave theory [12] applied to this study was shown in the equations (1) to (3).

\[
\frac{\partial \eta}{\partial t} + \frac{\partial M}{\partial x} + \frac{\partial N}{\partial y} = 0
\]
### 3. Real-time prediction method of tsunami water levels

#### 3.1 Outline

A real-time prediction method has been developed to give tsunami water levels in coastal zones right after the occurrence of a tsunami, using the tsunami water levels observed in the sea and tsunami propagation effects due to submarine topography. The conceptual diagram of the proposed method is shown in Fig. 4. Tsunami water levels in coastal zones were predicted following 2 steps: (step 1) water levels are predicted in coastal zones where the water depth is shallower than 50 m, using the tsunami water levels observed in the sea and tsunami propagation effects due to the submarine topography. (step 2) Water levels were predicted in coastal zones where the water depth is shallower than 50 m, by small-scale simulation using tsunami water levels calculated in step 1.

For the tsunami water levels observed in the sea in step 1, simulation data were used through linear long-wave theory for the fault slip of the 2011 off the Pacific coast of Tohoku earthquake. The tsunami propagation effects in step 2 were obtained by dividing tsunami water levels in coastal zones by those in the sea, using the simulation data in the linear long-wave theory for the main fault slip of the 2011 off the Pacific coast of Tohoku earthquake (Fig. 1 and Fig. 5). The validity of the proposed method was investigated using the simulation data for the 2011 off the Pacific coast of Tohoku earthquake.

#### 3.2 Tsunami propagation effects

Tsunami propagation effects $G_2(\omega)$ were estimated by dividing tsunami water levels in coastal zones $X_2(\omega)$ by those in the sea $S_2(\omega)$ in the frequency domain, for the main fault slip of the 2011 off the Pacific coast of Tohoku earthquake (Eq. 4). Tsunami water levels $X_1(\omega)$ were predicted in coastal zones for the 2011 off the Pacific coast of Tohoku earthquake, by convoluting the tsunami water levels in the sea $S_1(\omega)$ for the 2011 off the Pacific coast of Tohoku earthquake by the tsunami propagation effects $G_2(\omega)$ (Eq. 5).

$$G_2(\omega) = X_2(\omega) / S_2(\omega)$$

$$X_1(\omega) = S_1(\omega) \cdot G_2(\omega)$$

Here, $\omega$ indicates angular frequency.

The tsunami water levels and the tsunami propagation effects were processed, as follows. To remove high frequency signals, for example, the low-pass filter with a corner frequency of $f_c$ (Hz) was applied to signals by the moving average of the time-window $M$.

$$f_c = 0.443 \cdot f_s / M$$

Here, $f_c$ and $f_s$ indicate the corner frequency of low-pass filter and the sampling frequency, respectively. $M$ is the time-window for the moving average. $f_s$ is 1 Hz. $M$ is 180 for incidental tsunami waves, 60 for tsunami output waves, and 200 for tsunami propagation functions, in this study.
3.3 Prediction of tsunami water levels in coastal zones

Tsunami water levels at point 846 and at point 895 (Fig. 5) simulated by the fault slip of the 2011 off the Pacific coast of Tohoku earthquake are shown in Fig. 6. Tsunami water levels at point 893 convoluting the tsunami water levels at point 846 and point 895 for the 2011 off the Pacific coast of Tohoku earthquake are shown in Fig. 6. Tsunami water levels predicted in the coastal zone of the Ojika Peninsula is shown in Fig. 8 (left). The maximum of tsunami water levels could be predicted appropriately in coastal zones where the water depth is deeper than 50 m, using the tsunami propagation effects by the main fault of the 2011 off the Pacific coast of Tohoku earthquake.

3.4 Tsunami simulation in coastal zones

In step 2, the small-scale simulation area around the Ojika Peninsula is shown in Fig. 8 (left). The maximum of tsunami water levels were predicted along the shoreline of the Ojika Peninsula. Tsunami water levels predicted in step 1 were used, as the incidental tsunami waves to the east boundary in step 2. Tsunami water levels from simulations and predictions at 4 points (944, 919, 893, and 866) along the east boundary are shown in Fig. 9. The tsunami water levels at these 4 points were quite similar to each other both in amplitude and in phase; therefore, tsunami water levels at point 919 were adopted as the uni-
Fig. 6  Tsunami water levels at incident points 846 and 895 in the sea

Fig. 8  Maximum tsunami water level along the shoreline of the Ojika Peninsula

Fig. 7  Tsunami water level at evaluation point 893 in the coastal zone

Fig. 9  Tsunami water levels at points 944, 919, 893, and 866 in the coastal zone, predicted by incidental tsunami wave at 846
form tsunami water level along the east boundary, in step 2. Boundaries in the north, south, and west have release boundary conditions. A simulation was performed using a time sampling of 0.09 seconds and grid size of 45 m in the shallow water long-wave theory.

The maximum tsunami water level along the shoreline of the Ojika Peninsula predicted in step 2 is shown in Fig. 8. The predictions along the shoreline of the Ojika Peninsula showed the same tendencies as the simulations. On the other hand, the low approximation along the north boundary between predictions and simulations indicates that the contribution of incident tsunami waves was ignored due to the release boundary conditions of the north boundary. The proposed method could predict the tsunami water levels as being higher than 10 m along the shoreline of the Ojika Peninsula; therefore, this method using the tsunami water levels in the sea is a useful technique to predict tsunami water levels along the shoreline in real-time.

4. Conclusions

A real-time prediction method was developed for tsunami water levels in coastal zones right after the occurrence of a tsunami, using tsunami water levels observed in the sea and tsunami propagation effects due to submarine topography. To rapidly predict tsunami water levels in coastal zones where the water depth is deeper than 50 m, a method has been proposed which convolutes tsunami water levels observed in the sea and tsunami propagation effects excited by a small fault. To predict tsunami water levels in coastal zones where the water depth is shallower than 50 m, a method has been proposed which uses a small-scale tsunami numerical simulation. This study investigated the validity of the proposed methods, by applying them to data from numerical simulations of the 2011 off the Pacific coast of Tohoku earthquake (Mw 9.0).

References

[1] Hoshiba, M. and Ozaki, T., “Earthquake early warning and tsunami warning of JMA for the 2011 off the Pacific coast of Tohoku earthquake,” Zisin, Vol. 64, No. 3, pp.155-168, 2012 (in Japanese).
[2] Uehira, K., Kanazawa, T., Mochizuki, M., Fujimoto, H., Noguchi, S., Shimbo, T., Shiomi, K., Kunugi, T., Aoi, S., Matsumoto, T., Sekiguchi, S., Okada, Y., Shinohara, M., and Yamada, T., “Seafloor observation network for

earthquakes and tsunamis along the Japan Trench (S-net) (3),” Japan Geoscience Union Meeting, STT53-01, 2015.
[3] Tanioka, T., “Method for a tsunami numerical simulation started from tsunami observed data near a tsunami source area,” SSJ Fall Meeting, S17-05, 2015 (in Japanese).
[4] Tsuno, S., Fujihara, S., Korenaga, M., and Hashimoto, N., “Investigation of the estimation method of tsunami, using tsunami propagation effects,” SSJ Fall Meeting, S17-03, 2015 (in Japanese).
[5] Yamamoto, N., Hirata, K., Aoi, S., Suzuki, W., Nakamura, H., and Kunugi, T., “Rapid estimation of tsunami source centroid location using a dense offshore observation network,” Geophysical Research Letters, 16, pp.4263-4269, 2016.
[6] Yamamoto, N., Aoi, S., Hirata, K., Suzuki, W., Kunugi, T., and Nakamura, H., “Multi-index method using offshore ocean-bottom pressure data for real-time tsunami forecast,” Earth, Planets and Space, 68, 128, 2016.
[7] Headquarters for Earthquake Research Promotion, Cabinet Office, Government of Japan, http://www.bousai.go.jp/jishin/index.html, 2012.
[8] Hasegawa, K., Suzuki T., Inagaki, K., and Shuto, N., “A study on the mesh size and time increment in the numerical simulation of tsunamis,” Journal of JSCE, Vol. 381/II-7, No. 2, pp.111-120, 1987 (in Japanese).
[9] Japan Coast Guard, “M7000 Digital bathymetric chart.”
[10] Geospatial Information Authority of Japan, “5m Digital Elevation Model.”
[11] Okada, Y., “Internal deformation due to shear and tensile faults in a half-space,” Bull. Seismol. Soc. Am., Vol. 82, No. 2, pp.1018-1040, 1992.
[12] Imamura, F., Shuto, N., and Goto, C., “Numerical simulations of the transoceanic propagation of tsunamis,” 6th Congress APD-IAHR, pp.265-272, 1988.
[13] Fujihara, S., Hashimoto, N., Korenaga, M., and Tamiya, T., “Tsunami simulation of 2011 Tohoku-Oki Earthquake: Evaluation of difference in tsunami wave pressure acting around Fukushima Daiichi nuclear power station and Fukushima Daini nuclear power station among different tsunami source models,” Transactions of the Atomic Energy Society of Japan, doi:10.3327/taesj.J14.025, Vol.15, No. 1, pp.1-11, 2016.
[14] Ports and Harbours Bureau, Ministry of Land, Infrastructure, Transport, and Tourism (MLIT), “The Nationwide Ocean Wave information network for Ports and HArbourS (NOWPHAS), Tsunami waveform data,” http://www.mlit.go.jp/kowan/nowphas/.

Authors

Seiji TSUNO, Dr. Eng.
Assistant Senior Researcher, Seismic Data Analysis Laboratory, Center for Railway Earthquake Engineering Research
Research Areas: Earthquake Engineering

Satoru FUJIHARA, Dr. Sci.
Nuclear & Engineering Department, Science & Engineering System Division, ITOCHU Techno-Solutions Corporation
Research Areas: Earthquake Engineering