Real-time Prediction Method of Tsunami Inundation for Railway Line

Seiji TSUNO

Seismic Data Analysis Laboratory, Center for Railway Earthquake Engineering Research

To evaluate the influence of tsunami inundations on railway lines and implement measures for evacuation, it is necessary to predict the depth of tsunami inundations at sites of railway facilities. The author therefore developed a real-time prediction method of tsunami inundations for railway lines, immediately after large earthquakes occur at sea. This method first predicts tsunami water levels in the coastal areas, using tsunami water levels at sea and the tsunami propagation functions. Secondly, the method predicts the depth of tsunami inundations for the target railway line, using a database of tsunami inundations for scenario earthquakes, created in advance.

Keywords: real-time prediction method of tsunami inundation, tsunami propagation function, scenario earthquake, tsunami inundation map, database, railway line

1. Introduction

To evaluate the influence of tsunami inundations on railway lines and rapidly implement measures for evacuation, it is necessary to predict the depth of tsunami inundations at sites of railway facilities immediately after the occurrence of an earthquake. The author developed a real-time prediction method of tsunami inundations for railway lines, using tsunami data observed at sea and tsunami simulation results prepared in advance. Since the 2011 off the Pacific coast of Tohoku earthquake, water-pressure gauges have been installed on the ocean floor off the Pacific coast of the Tohoku region [1]. Real-time tsunami prediction methods which apply the assimilation theory to tsunami data [2] and interpolate into tsunami simulation results [3] have been developed. These methods however, do not satisfy both the immediacy and stability for tsunami warning. This study therefore uses tsunami data at one observation point to improve the immediacy of tsunami warning. A database of tsunami propagation functions and tsunami inundation maps were compiled in advance to improve the stability of tsunami warning. Based on these results, the real-time prediction method, which in-

tegrates the prepared tsunami simulation results with the observed tsunami data, was developed. This paper also presents an example of this method being applied to predict the depth of tsunami inundations along an actual railway line.

2. Outline of the method

The real-time prediction method of tsunami inundations for railway lines proposed in this study consists of two steps: first, a real-time prediction of tsunami water levels in the coastal areas, and second, a real-time prediction of the tsunami inundation areas. Figure 1 shows an overview of this method. Tsunami water levels in the coastal areas, for the first step in this method, are predicted by multiplying the tsunami data recorded at one observation point at sea with the tsunami propagation function prepared using the 2-D tsunami simulation in advance. In the second step, the tsunami inundation areas that are expected by the predicted tsunami water levels in the coastal areas, are extracted from the inland tsunami inundation maps due to possible scenario earthquakes stored in the database.

Fig. 1 Real-time prediction method of tsunami inundations for railway lines

3. Scenario earthquakes and database of tsunami inundations for the target area

3.1 Scenario earthquakes and target area

This section describes the compilation of the database used in the second step. For the fault model, 96 earthquake source faults with a magnitude of more than 8, according to the combination of segments (Fig. 2), were set at the plate boundary of the Japan Trench, from off Tokachi to off the Boso Peninsula. In this fault model, the inhomogeneity of the slip amount is characterized. Twice slip amount as large as the average slip amount is arranged in the large slip region and four times slip amount as large as the average slip amount is arranged in the super large slip region, according to the scale of magnitude [4]. Figure 3 shows examples of the scenario earthquake fault models (No. 1: single segment rupture, No. 22: 4 segments-linked rupture including a large slip region).

Tsunami inundation simulations of the scenario earthquakes at the plate boundary of the Japan Trench were performed for Ishinomaki City. Figure 4 shows the detailed seafloor topographical model around Ishinomaki City (for an area with a grid size of 15 m).

3.2 Database of tsunami inundations for the target area

The linear long-wave theory was applied to the 2-D tsunami simulation from the deep sea area to the coastal area, and the shallow water long-wave theory [5] was applied to the 2-D tsunami inundation simulation from the coast area to the inland with the boundary condition of run-up [6]. The various conditions for the 2-D tsunami inundation simulation were set as shown in Table 1. Figure 5 shows examples of the results of the tsunami inundation simulations for Ishinomaki City by scenario earthquake fault models (No. 1 and No. 22) at the plate boundary of the Japan Trench. The scenario earthquake fault model of No. 1 has a small tsunami inundation area, because the slip region is located far from Ishinomaki City (Fig. 3 left). On the other hand, the fault model of No. 22 has a large tsunami inundation area, because the slip region is located near Ishinomaki City (Fig. 3 right). In this way, a database

Fig. 2 Fault segments at the plate boundary of the Japan Trench

Fig. 3 Scenario earthquake fault models of No. 1 and No. 22 (■: large slip region)

Fig. 4 Detailed seafloor topographical model around Ishinomaki City (grid size: 15 m)

Table 1 Various conditions for the 2-D tsunami simulations in this study

	Conditions for 2-D tsunami simulations
Grid size	Gradually setting a finer grid size: 1215 m, 405 m, 135 m, 45 m, 15 m Setting a grid size of 45 m, 15 m for inland Setting a grid size of 1215 m, 405 m, 135 m and 405 m at sea
Time sampling	Setting 0.9 to 0.1 seconds based on a grid size under the CFL conditions grid size of 1215 m: 0.9 second, grid size of 405 m: 0.9 second, grid size of 135 m: 0.3 second grid size of 45 m: 0.3 second, grid size of 15 m: 0.1 second
Theory	Linear long-wave theory (depth of 50 m -), Shallow water long-wave theory (- depth of 50 m)
Initial condition	The crustal deformation calculated by the method [7] is applied as the initial water level
Boundary condition	Sea area: Perfect transmission conditions Inland: In the area with a grid size of 45m and 15 m, boundary conditions of run-up [6]
Frictional coefficient	Sea area: Manning's roughness length of $0.025 \text{ m}^{-1/3}\text{s}$ Inland: Based on the condition of land use
Duration	6 hours after the occurrence of earthquake

(a) Scenario earthquake fault model of No. 1

(b) Scenario earthquake fault model of No. 22

Fig. 5 Tsunami inundation area in Ishinomaki City caused by scenario earthquake fault models of No. 1 and No. 22 (□: area with a grid size of 15 m)

of tsunami inundation maps in Ishinomaki City, which stores inundation areas for various types of tsunamis, was created for 96 scenario earthquakes at the plate boundary of the Japan Trench.

4. Real-time prediction of tsunami inundations for a railway line

4.1 Real-time prediction of tsunami water levels in a coastal area

As shown in the first step of Fig. 1, the tsunami water levels in the coastal areas were predicted in real-time, using the tsunami water levels observed at sea and the tsunami propagation functions depending on the seafloor topography [8]. The following shows the specific procedure

of this method, which was verified using the example of the 2011 off the Pacific coast of Tohoku earthquake that occurred at the plate boundary of the Japan Trench.

- As the observed tsunami water levels at sea, the tsunami water level at the incident point was calculated by 2-D tsunami simulation using the Japanese Cabinet Office model [9] for the 2011 off the Pacific coast of Tohoku earthquake (Mw 9.0).
- The tsunami propagation function was estimated by de-convoluting the waveform from the 2-D tsunami simulation results at the incident point and the waveform from the 2-D tsunami simulation results at the evaluation point for the fault element. Figure 6 shows fault elements of 50 km^2 set at the plate boundary of the Japan Trench (from off Tokachi to off the Boso Peninsula). Figure 7 shows an example of an incident point and an evaluation point for fault element of No. 56 as shown in Fig. 6.
- To estimate the waveform of the tsunami water level at evaluation point in the coastal area, both immediately and stably, the waveform of the tsunami water level is obtained by multiplying the tsunami water level at the incidence point at sea by the tsunami propagation function between the tsunami incidence point and the evaluation point for the fault element.

The results of the real-time prediction shown in Fig. 8 indicate that this method can accurately estimate the waveform of tsunami water levels at the tsunami evaluation point in coastal areas with respect to the 2011 off the Pacific coast of Tohoku earthquake.

4.2 Real-time Prediction of Tsunami Inundations for an inland area

As shown in the second step of Fig. 1, the tsunami inundation area was predicted in the real-time, using the predicted tsunami water levels in the coastal area and the tsunami inundation maps based on scenario earthquakes. The specific procedure of this method is described below, and was verified using data from the tsunami of the 2011 off the Pacific coast of Tohoku earthquake that occurred at the plate boundary of the Japan Trench.

- A scenario earthquake was selected, by a matching method on the similarity between the predicted tsunami water level at the evaluation point in the coastal

Fig. 6 Fault elements of 50 km² set at the plate boundary of the Japan Trench

area obtained from the first step, and the tsunami water level at the same evaluation point based on scenario earthquakes [2].

- The tsunami inundation area in the target area based on the selected scenario earthquake is extracted from the database.

Figure 9 shows a scenario earthquake (amount of slip in the large slip region: 8.74 m, amount of slip in the background slip region of the scenario earthquake: 5.35 m) selected from the tsunami water level at the evaluation point in the coastal area shown in Fig. 8 and the Cabinet Office model as the correct answer. Although the fault area of the selected scenario earthquake was consistent with the Cabinet Office model, the fault area of the selected scenario earthquake was located in slightly south of the Cabinet Office model, and the detailed slip distribution was different. A comparison of the tsunami inundation area in Ishinomaki City obtained through the selected scenario earthquake and the tsunami inundation area by the Cabinet Office model are shown in Fig. 10. The inundation area (76 km²) based on the selected scenario earthquake, matched the inundation area (81 km²) in the Cabinet Office model by more than 90% with a good agreement.

Furthermore, the arrival time of tsunami in Ishinomaki City after the occurrence of the selected scenario earthquake is shown in Fig. 11. It is found that extra time of more than one hour could have been secured in Ishinomaki City after the 2011 off the Pacific coast of Tohoku earthquake, against a computation time within one minute for extracting the tsunami inundation area from the database.

Fig. 7 Incident point and evaluation point for the fault element of No. 56 as shown in Fig. 6

Fig. 8 Comparison of predicted tsunami water level to 2-D tsunami simulation result in the coastal area

4.3 Real-time prediction of tsunami inundation for a railway line

As an example of the application of this method to railways, Fig. 12 shows a real-time prediction of the depth of tsunami inundations along the railway line (Fig. 10) for the 2011 off the Pacific coast of Tohoku earthquake. As a result, some sections have depths of tsunami inundation more than 5 m. On the other hand, there are sections where the tsunami does not arrive because of the higher altitude.

Fig. 9 Comparison of the selected scenario earthquake (left) to the Cabinet Office model (right)

Fig. 10 Tsunami inundation area in Ishinomaki City by the selected scenario earthquake and the Cabinet Office model (thick line: railway line, □: area with a grid size of 15 m)

Fig. 11 Tsunami arrival time in Ishinomaki City after the occurrence of the selected scenario earthquake (thick line: railway line)

Fig. 12 Depth of tsunami inundation along the railway line (A-A' line in Fig. 11)

Therefore, evacuating a moving train towards such a section ensures the tsunami resistance of the railway. This method is expected to be able to transmit sections identified for evacuation to the moving train before the tsunami arrives, by presenting the prediction result for the depth of tsunami inundation along the railway line immediately after the tsunami was observed at sea. As described above, this method can predict immediately and stably tsunami inundation depth along railway lines at an early stage.

5. Conclusions

To reduce tsunami damage of railways, the author developed the real-time prediction method of tsunami inundation, which integrates the prepared tsunami simulation results with the observed tsunami data, for railway lines. This method has the unique features of improving the immediacy of tsunami warning by using tsunami data at one observation point and improving the stability of tsunami warning by compiling a database of tsunami propagation functions and tsunami inundation maps prepared in advance. The proposed method was applied to the tsunami of the 2011 off the Pacific coast of Tohoku earthquake, and its performance was verified with the tsunami inundation area in the Cabinet Office model. As a result, it was confirmed that tsunami inundation area by the proposed method matched over 90% of the tsunami inundation area in the Cabinet Office model. Immediately after the tsunami observation at sea, this method can present the prediction results for the depth of tsunami inundations along railway lines.

Acknowledgement

This work was financially supported by the Japanese Ministry of Land, Infrastructure, Transport and Tourism.

References

- [1] Kanazawa, T., "Japan Trench earthquake and tsunami monitoring network of cable-linked 150 ocean bottom observatories and its impact to earth disaster science," *2013 IEEE international underwater technology symposium (UT)*, pp.1-5, 2013.
- [2] Yamamoto, N., Aoi, S., Hirata, K., Suzuki, W., Kunugi, T., and Nakamura, H., "Multi-index method using off-shore ocean-bottom pressure data for real-time tsunami forecast," *Earth, Planets and Space*, 68:128, 2016.
- [3] Tanioka, Y. and Gusman, A.R., "Near-field tsunami inundation forecast method assimilating ocean bottom pressure data: A synthetic test for the 2011 Tohoku-oki tsunami," *Physics of the Earth and Planetary Interiors*, Vol.283, pp.82-91, 2018.
- [4] Fujiwara, H., Hirata, K., Nakamura, H., Osada, M., Morikawa, N., Kawai, S., Ohsumi, T., Aoi, S., Matsuyama, H., Toyama, N., Kitou, T., Murashima, Y., Murata, Y., Inoue, T., Saito, R., Akiyama, S., Korenaga, M., Abe, Y., and Hashimoto, N., "An approach to tsunami hazard assessment along the northeastern coastal area in Japan -method and preliminary results," *Technical Note of the National Research Institute for Earth Science and Disaster Prevention*, No. 400, 2015.
- [5] Imamura, F., Shuto, N., and Goto, C., "Numerical simulations of the transoceanic propagation of tsunamis," *6th Congress APD-IAHR*, pp.265-272, 1988.
- [6] Kotani, M., Imamura, F., Shuto, N., "Tsunami run-up simulation with GIS and damage estimation method," *Proceedings of Coastal Engineering, JSCE*, Vol.45, pp.356-360, 1998.
- [7] 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.
- [8] Tsuno, S. and Fujihara, S., "Development of real-time prediction method of tsunami water level in coastal zone, using tsunami propagation effect," *QR of RTRI*, Vol. 57, No. 4, pp. 275 - 279, 2016.
- [9] Headquarters for Earthquake Research Promotion, Cabinet Office, Government of Japan, <http://www.bou-sai.go.jp/jishin/index.html>, 2012.

Author

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