Large Scale Numerical Simulation Reproducing of Tsunami Behavior against a Station Building

Kohei MUROTANI
Computational Mechanics Laboratory, Railway Dynamics Division

The coastal area in the Tohoku region of Japan suffered serious damage from the tsunami caused by the Great East Japan Earthquake in 2011. The purpose of this research is to develop a simulator in order to predict potential damage and put in place disaster prevention measures to protect railway structures against such large scale tsunamis. For this research, a simulation was made of the tsunami generated by the Great East Japan Earthquake to evaluate the damage process that occurred at Shishiorikarakuwa station in Kesennuma city. The tsunami simulator involves a three stage zoom analysis covering a large area from the epicenter to the urban area. The results of the tsunami simulation were then used to conduct a structural analysis of the Shishiorikarakuwa station subject to the tsunami fluid pressure.

Keywords: tsunami analysis, structural analysis of railway structure, particle method, finite element method (FEM), large-scale parallel computing

1. Introduction

The 2011 off the Pacific coast of Tohoku Earthquake on March 11, 2011 was the largest earthquake on record in the area around Japan. Its epicentral area was large, 500 kilometers north to south and 200 kilometers east to west. This earthquake caused a colossal tsunami with a wave height of more than 10 meters and a maximum run-up height of 40 meters, due to which the Pacific coastal area of the Tohoku region suffered severe damage. Numerous railway structures along the JR lines in the Pacific coastal area of the Tohoku region were washed away by the tsunami, buried in debris or otherwise damaged, including 23 stations, approximately 60 kilometers of track and 101 bridge girders: a total of 1,730 structures suffered damage [1].

On comparison, the damage caused by the following tsunami was more serious than the direct damage inflicted by the Great East Japan Earthquake. As such, this research led to the development of an analysis method capable of performing structural analyses of railway structures, in which fluid pressure exerted by a tsunami is regarded as an external force, as shown in Fig. 1, in order to analyze the effects of a tsunami, caused by a large earthquake, on railway structures. This paper describes how the analysis method was validated and used in a study aimed at identifying the reasons why Shishiorikarakuwa Station in the Kesennuma urban area, though flooded by tsunami, remained almost completely intact without collapsing, despite most of the structures around it being swept away by the same tsunami.

2. Tsunami analysis simulating the Great East Japan Earthquake

2.1 Three-stage zoom tsunami analysis

The objective of this research was to analyze the effect of the tsunami caused by the Great East Japan Earthquake on railway structures. What matters in performing a three-dimensional tsunami analysis on the ground structures in urban areas is the inflow and outflow boundary conditions of a tsunami. In a real tsunami, waves which can measure a few or tens of kilometers wide come surging in for periods of time that extend to tens of minutes or more. It is difficult to accurately reproduce tsunami behavior on ground structures that are to be analyzed because of the complex web of influencing factors, such as the fault slippage at the hypocenter, the submarine and subaerial (land) topography, and the locations of ground structures. Consequently, a multi-scale analysis method composed of three stages was developed: from the tsunami source to the ground structure to be analyzed, as shown in Fig. 2.

In this research, three target domains for analysis were determined: one approximately 1,000 km square, the second 4 km by 2 km, and the third, 180 m by 150 m. A three-stage zoomed analysis [2] was performed where boundary conditions were transferred sequentially from a larger analysis domain to a smaller one. The first analysis examined tsunami propagation from the tsunami source generated at the hypocenter to the coastal area. Given the large area of approximately 1,000 kilometers square to be analyzed, a lower cost two-dimensional shallow-water long-
wave analysis was used. The inflow and outflow boundary conditions for the second analysis were generated using the evaluation results obtained in the first analysis. The second analysis examined how the tsunami, which hit the coastal area, ran onto the land, generating the inflow and outflow boundary conditions for the third analysis. The third analysis examined flooding in the urban area invaded by the tsunami. The calculations in the second and third analyses were made using a three-dimensional MPS (Moving Particle Simulation) method which facilitated the calculations required to examine how the tsunami ran onto the land. The MPS method, a type of particle method, is suitable for free surface flows and dealing with floating objects. This research used the improved Explicit MPS method, among various MPS methods, in which the semi-discretization equation of the improved SPH (Smoothed Particle Hydrodynamics) method [3] was applied to the Explicit MPS method [4]. This paper simply describes it as the MPS method. The MPS method requires the quantity of particles to be proportional to the size of the analysis domain. Therefore, the second analysis was performed using particles 1 meter in diameter, while the third analysis was performed using particles 10 cm in diameter. The third analysis reproduced how the tsunami swept over the urban area and evaluated the behavior of the railway structure as it was subjected to fluid pressure.

![Fig. 2 Illustrated overview of three-stage zoom tsunami analysis [2]](image1)

2.2 State of Kesennuma after the Great East Japan Earthquake

This section examines the state of Kesennuma after the Great East Japan Earthquake. Figure 3 shows the aerial photos [5] of Kesennuma in the wake of the Great East Japan Earthquake taken by the Geospatial Information Authority of Japan (GSI) on May 26, 2011. Figure 3 (a) shows the damage caused by the tsunami to Kesennuma as a whole, and Fig. 3 (b) shows the 60 m-long (200 ft) vessel Kyotoku-maru No. 18, cast ashore to within about 50 meters of Shishiorikarakuwa Station. Figure 3 (a) shows that many ground structures were destroyed by the flood. On the other hand, Fig. 3 (b) illustrates that Shishiorikarakuwa Station remained intact though it suffered flood damage [5].

![Fig. 3 Aerial photos of Kesennuma after the Great East Japan Earthquake [5]](image2)

2.3 First analysis of Kesennuma

This section describes the first analysis. Figure 4 shows the results of the first analysis, which was a shallow-water long-wave analysis conducted using a two-dimensional finite difference method, that was performed by using TSUNAMI-K, a tsunami simulator developed by Kozo Keikaku Engineering Inc. TSUNAMI-K is a tsunami wave height / run-up calculation software using the shallow-water long-wave analysis method [6] applying the two-dimensional finite difference method, which was developed by Prof. Imamura of Tohoku University. The initial water level was calculated from the 55 sub-fault model Ver. 8.0 of Fujiji and Satake, and the time of tsunami occurrence was set to 14:47. Figure 4 (a) shows the propagation of the tsunami at 15:07, 1,200 seconds after it started, while Fig. 4 (b) shows the tsunami propagation at 15:27 (2,400 seconds after it began). Figure 5 compaes the GPS (Global Positioning System) wave meter observation results [7] based on the
observations of the Ports and Harbours Bureau, Ministry of Land, Infrastructure, Transport and Tourism (MLIT), and processing by The Port and Airport Research Institute (PARI), and the results of the shallow-water long-wave analysis using TSUNAMI-K. This research shows that they agree well, where 5 to 1,350 meter long meshes were used.

Since the second analysis required both Kesennuma Bay and the Kesennuma urban area to be included in the analysis range, the range was set to an area of 4 km north to south and 2 km east to west, centering on the mouth of the Shishiori River in Kesennuma Bay. Figures 6 and 7 show the results of the second analysis started at 15:27 (2,400 seconds after the tsunami appeared), using the particle simulator developed by RTRI [2]. The particle simulator, which enables particle collision analysis, is a software under development for the MPS method. In the second analysis, 130 million particles of 1-m in diameter were used. The computer used for the analysis was RTRI’s supercomputer XC30. It took 88 hours for a 1,800 second analysis using 100 nodes.

2.4 Second analysis of Kesennuma

Since the second analysis required both Kesennuma Bay and the Kesennuma urban area to be included in the analysis range, the range was set to an area of 4 km north to south and 2 km east to west, centering on the mouth of the Shishiori River in Kesennuma Bay. Figures 6 and 7 show the results of the second analysis started at 15:27 (2,400 seconds after the tsunami appeared), using the particle simulator developed by RTRI [2]. The particle simulator, which enables particle collision analysis, is a software under development for the MPS method. In the second analysis, 130 million particles of 1-m in diameter were used. The computer used for the analysis was RTRI’s supercomputer XC30. It took 88 hours for a 1,800 second analysis using 100 nodes.
It can be seen from Figs. 6 and 7 how the tsunami which entered Kesennuma Bay first flowed up the Shishiori River first, and then ran up, corkscrewing through the structures in the Kesennuma urban area as if it were following the first run-up. Figure 8 shows the result of a comparison between the flooded area observed by GSI [8] and the flooded area in the second analysis. Figure 8 confirms that the inundated area in the second analysis is almost in agreement with the one that appears in the observation data. The Kesennuma urban area used for this analysis was a mountainous area, which means that so long as inflow and outflow volumes were properly processed the flooded areas identified through observation data and from the analyses would easily agree. Were the terrain to be mainly made up of flatland widely extending inland, with dominant land attributes, such as asphalt and fields, then agreement between analysis results and observed data would be more difficult to achieve.

2.5 Third analysis of Kesennuma

This section describes the third analysis. Figure 9 shows the results of the third analysis of the area in vicinity of Shishiorikarakuwa Station, started at 15:37 (3,000 seconds after the tsunami appeared), where a particle simulator developed by RTRI was used. The area used for the analysis was 180 m north to south and 150 m east to west. 180 million particles 0.1 m in diameter were used. The computer used for the analysis was RTRI’s supercomputer XC30. It took 2 weeks for a 400 second analysis using 50 nodes. Figure 9(a) confirms that the tsunami began to break over the embankment at around 15:39 and overwhelmed the embankment flooding the platform located at the highest level in the station area, after 15:40 as shown in Fig. 9(b).

Fig. 8 Comparison of flooded areas appearing through observation data and analysis results

In the third analysis, two models were created: Model Op, with all the windows and doors of the station building open, and Model Cl, with all the windows and doors closed. A structural analysis of the station building was made for both models, focusing on the tsunami wave pressure being exerted on the building. Figure 10 (a) confirms how the tsunami entered the station building through the openings, such as doors and windows, and filled the building with sea water as the tsunami surged its way through. It can be seen from Fig. 10 (b) that the sea water did not enter the station building when there was no way in for the tsunami, despite the surge, because the doors and windows were closed.

Figures 11 (a) and (b) show the distributions of water pressure around the station building when there was no way in for the tsunami, despite the surge, because the doors and windows were closed. A comparison between Figs. 11 (a) and (b) shows that they are similar to each other in that the water pressure on the exterior walls of the station building varied according to the water level. However, it can be seen from Fig. 11 (a) that water pressure was acting on the inside of the station building, while Fig. 11 (b) shows that no water pressure was acting on the inside of the station building.

3. Reproduction of tsunami behavior around railway structure

3.1 Distribution of water pressure around station building

Fig. 9 Third analysis
shows that no water pressure was acting on the inside of the station building. However, it can be seen from Fig. 11 (a) that water pressure was similar to each other in that the water pressure on the exterior walls of the station building varied according to the water level. In Fig. 15, the maximum equivalent stress values at the other nodes A, B and D occurred because they were in the concave areas behind areas facing the tsunami surges, which are structurally the weakest points. From Fig. 15, the results indicate that the equivalent stress when the windows and doors were “closed” was 5.5 times higher at 15:43:40, and 3.5 times higher when equivalent stress peaked in the time series, than when the windows and doors were “open,” because of the support from inside the station building due to the water pressure.

Thus it is considered that one of the reasons Shishiorikarakuwa Station remained almost intact despite the majority of structures around it being swept away, was that Shishiorikarakuwa Station has an open structure with open windows and doors, which allowed the tsunami through the station building, thus preventing a buildup of stress around the building.

3.2 Equivalent stress distribution on station building

Figure 12 shows the results of equivalent stress distributions by structural analysis using the tsunami wave pressure as the external force. ADVENTURE_Solid 1.2 was used for the structural analysis. The mesh size was 5 centimeters, and secondary tetrahedral elements were used. The nodes on the bottom were fixed, and the water pressure in Fig. 11 was converted into nodal loads. The wall thickness of the station building was set to 20 centimeters. A static elastic analysis was performed by applying the Young’s modulus and Poisson’s ratio of concrete to the physical properties. The actual Shishiorikarakuwa Station is a wooden building. However, we need to perform an analysis with its form retained (intact state) in order to evaluate the stresses on the station building. Therefore, a robust concrete structure was chosen instead of a wooden structure for the analysis. A comparison between Figs. 12 (a) and (b) shows that larger stresses were generated on Model Cl than on Model Op because of the support from inside the station building due to the water pressure.

Figure 13 shows the positions of the nodes showing maximum equivalent stress in Fig. 12. Figures 14 and 15 respectively show the time series of the maximum pressure and the maximum equivalent stress on the station building. In Fig. 14, the maximum pressure applied to both station building models increase in the same way as time passes. Since the water pressure of a tsunami is greatly affected by static water pressure, lower elements tend to be subject to higher water pressure.

Figure 16 shows the time series of the equivalent stress at nodes A and B of Model Op, and nodes C and D of Model Cl. In Model Op, the equivalent stress at node A peaked between 15:39:26 and 15:42:12, while the equivalent stress at node B peaked between 15:42:13 and 15:43:40. In Model Cl, the equivalent stress at node C peaked between 15:39:52 and 15:40:33, while the equivalent stress at node D peaked between 15:40:34 and 15:43:40. The reason node C displayed the maximum equivalent stress is thought to be because it was directly hit by the tsunami. The maximum equivalent stress values at the other nodes A, B and D occurred because they were in the concave areas behind areas facing the tsunami surges, which are structurally the weakest points. From Fig. 15, the results indicate that the equivalent stress when the windows and doors were “closed” was 5.5 times higher at 15:43:40, and 3.5 times higher when equivalent stress peaked in the time series, than when the windows and doors were “open,” because of the support from inside the station building due to water pressure.
Tsunami flow direction

(a) Model Op (Windows and doors are open)

(b) Model Cl (Windows and doors are closed)

Fig. 12 Results of equivalent stress distributions on the Shishiorikarakuwa Station building through structural analysis using the tsunami wave pressure as an external force at 15:43:40

Fig. 13 Positions of nodes A, B, C and D showing maximum equivalent stress in Fig. 12

Fig. 14 Time series of maximum pressure on station building

Fig. 15 Time series of maximum equivalent stress on station building

Fig. 16 Time series of equivalent stress of nodes A, B, C and D
4. Conclusions

This paper discussed the structural analysis made of Shishiorikarakuwa Station on the JR Ofunato Line located in the Kesennuma urban area, using the results of a three-stage zoom tsunami analysis of the Kesennuma urban area. Shishiorikarakuwa Station remained almost intact when it was flooded by the tsunami, despite most structures around it being swept away by the same tsunami on the day of the earthquake. Results of the analysis confirmed that one of the reasons Shishiorikarakuwa Station did not collapse, was that it had an open structure with open windows and doors, which allowed the tsunami to pass through the station building.

This research describes the development of a method to assess structural soundness using tsunami wave pressure on a railway structure from the results of a three-stage zoom analysis. However, tsunami damage is not only the product of wave pressure, but also the result of collisions with floating objects washed in by the tsunami. An analysis incorporating floating objects would require evaluation of fluid force, which would then be used as the external force exerted on floating objects. If the number of the floating objects increases, the impact of floating objects would also need to be considered. To take the present analysis a step further, it is necessary to deal with structural collapse and floating objects. Previous research has included floating objects and analyzed their impact. However, these methods have not been validated, and it is difficult to perform highly reproducible experiments. Since an analysis entailing destruction requires a high-resolution analysis, or an experimental/empirical method, it will be difficult to not only perform a reliable analysis, but also to perform a validity check itself. As such, the analysis method developed in this research still needs to be improved. Further research and development is expected to focus on analyses that are difficult to implement, and thus increase reproducible events while reproducing various types of tsunami damage to an extent which can be analyzed.

Acknowledgement

This work was supported in part by JSPS KAKENHI Grant Number JP26390127. This research was supported in part by the airborne laser survey data managed by the GSI, MLIT, the GPS wave meter data observed by the Ports and Harbours Bureau, MLIT, and processed by PARI, MLIT, and the Map and Aerial Photograph Browsing Service on the website of the GSI, MLIT, for all of which we are sincerely grateful.

References

[1] Tohoku District Transport Bureau, MLIT, Yomigaere! Michinoku no testudo: Higashi Nihon Daishinsai kara no fukko-no kiseki, from http://wwwtb.mlit.go.jp/tohoku/ttd/td-sub100.html (Accessed on 21 February, 2018).
[2] Murotani, K. et al., “Tsunami run-up simulation,” High-Performance Computing for Structural Mechanics and Earthquake / Tsunami Engineering, Springer Tracts in Mechanical Engineering, pp. 157-178, 2016.
[3] Tsuzuki, S., "Large-scale particle-based simulation using dynamic load balance in GPU supercomputer," Doctorial thesis, Tokyo Institute of Technology, Paper No. Ko 10097, 2016 (in Japanese).
[4] Oochi, M., Koshizuka, S., and Sakai, M., “Explicit MPS Algorithm for Free Surface Flow Analysis,” Transactions of JSCEs, Paper No. 20100013, 2010 (in Japanese).
[5] The Geospatial Information Authority of Japan (GSI), MLIT, Map and Aerial Photograph Browsing Service, from the GSI’s website, Reference No. CTO20116, Course No. C10A, Photo No. 46. (Photographed on 26 May, 2011).
[6] Imamura F., Yalciner A. C., Ozyurt G., TSUNAMI MODELLING MANUAL (TUNAMI model), from http://www.tsunami.civil.tohoku.ac.jp/hokusai3/J/project/manual-ver-3.1.pdf, 1995. (Accessed on 21 February, 2018).
[7] The Ports and Harbours Bureau, MLIT, “Tsunami observation data, The 2011 off the Pacific coast of Tohoku Earthquake,” Real-time NOWPHAS (Nationwide Ocean Wave information network for Ports and Harbours), 2011.
[8] The Geospatial Information Authority of Japan (GSI), MLIT, Tsunami Inundation Map (scale 25,000:1), Miyagi Prefecture, No. 72 (2nd ed.), 31 May, 2011.

Author

Kohei MUROTANI, Ph.D.
(Information Science and Technology)
Assistant Senior Researcher, Computational Mechanics Laboratory, Railway Dynamics Division
Research Areas: High Performance Computing, Parallel Computing, Particle Method, Finite Element Method, Computational Mechanics