17th World Conference on Earthquake Engineering, 17WCEE
Sendai, Japan - September 13th to 18th 2020

ADVANCES OF REAL-TIME TSUNAMI INUNDATION AND DAMAGE FORECAST - PRESENT AND FUTURE

S. Koshimura[(1, 10)], Y. Ohta[(2, 10)], R. Hino[(3, 10)], T. Suzuki[(4, 10)], Y. Murashima[(5, 10)], A. Musa[(6, 10)], Y. Sato[(7, 10)], M. Kachi[(8, 10)], H. Kobayashi[(9, 10)]

[(1)] Professor, International Research Institute of Disaster Science, Tohoku University, koshimura@irides.tohoku.ac.jp
[(2)] Associate Professor, Graduate School of Science, Tohoku University, yusaku.ohta.d2@tohoku.ac.jp
[(3)] Professor, Graduate School of Science, Tohoku University, hino@tohoku.ac.jp
[(4)] Kokusai Kogyo Co., Ltd., takayuki_suzuki@kk-grp.jp
[(5)] Kokusai Kogyo Co., Ltd., yoichi_murashima@kk-grp.jp
[(6)] NEC Corporation, a-musa@bq.jp.nec.com
[(7)] NEC Solution Innovators, Ltd., y-sato@ts.jp.nec.com
[(8)] A2 Corporation, mark@a-2.co.jp
[(9)] Professor, Graduate School of Information Sciences, Tohoku University, koba@tohoku.ac.jp
[(10)] RTi-cast, Inc.

Abstract

A novel real-time tsunami inundation and damage forecast system was launched in 2017 and the system has been under operation as a function of the emergency response of Cabinet Office of Japan since 2018. A newly-founded spin-off technology firm RTi-cast is taking a role of offering and operating real-time tsunami inundation damage forecast services. The forecast system consists of tsunami source modeling, propagation and inundation simulation, and damage mapping with a High-Performance Computing Infrastructure. The target is the tsunamigenic earthquakes that occur along the Nankai Trough and its vicinity. Especially, the most concerned target is the Nankai Trough earthquake which is estimated to occur in next 30 years with 80 % of probability by the long-term evaluation of seismic activity in Japan. The forecasting area includes the coast line from Kagoshima to Ibaraki prefectures.

The forecast system consists of tsunami source modeling, propagation and inundation simulation, and damage mapping with High-Performance Computing Infrastructure. The vector supercomputer SX-ACE served as the core simulation architecture. To have the tsunami propagation and inundation forecasting activated, we first receive seismic information from Earthquake Early Warning (EEW) of JMA which takes only a few tens of seconds from observing seismic waves. More precise information is provided by real-time analysis of GEONET (GNSS Earth Observation Network System) data supposedly within 10 minutes after an earthquake is triggered. We use the fault rupture estimation derived by RAPiD (Ohta et al., 2012) and REGARD (Kawamoto et al., 2017) algorisms that include the estimates of the moment magnitude, fault geometry, focal mechanisms and slip distributions. Given the tsunami source model, the system automatically moves on to tsunami propagation/inundation simulation optimized on the SX-ACE to acquire the estimation of time series of tsunami at offshore/coastal tide gauges to determine tsunami travel and arrival time, extent of inundation zone, maximum flow depth distribution, and potential losses. The simulations are now optimized to be more efficient, using a new nested grid system and its MPI-parallelization (Inoue et al.,2019), and running on other HPC processors (Musa et al., 2018) to expand its capability to the other areas and users.

This paper reports advances of real-time tsunami inundation forecast methods and technologies, and discuss future perspectives for enhancing the use of real-time tsunami inundation forecast information.

Keywords: Real-time Tsunami Inundation Forecast; High-Performance Computing Infrastructure; Tsunami Damage Assessment

1. Introduction

The 2011 Great East Japan Earthquake and Tsunami disaster left many lessons to Japan's disaster management policies, and they have drastically changed to promoting initiatives for building national resilience with the aim of creating safe and secure national lands, regions, and economic society that have strength and flexibility, in any disasters.

In the aftermath of devastating tsunami disasters, identifying its impacts and finding devastated areas is quite important for disaster response and relief activities. Because of the devastating damage on infrastructure and local/regional/international communication network and the failure of the emergency response, the impacted regions/countries and overall damage could not be addressed for months. Thus, the importance of developing technologies to forecast the regional impact of great tsunami disaster has been raised. However, the extensive scale of catastrophic tsunami makes it difficult to comprehend overall impact of tsunami along the long stretch of coastline, and also may disable to prioritize how the limited resources for detecting damage and emergency response should be deployed in such limited amount of time and information. Recent advances of high-performance computing and dense observations this problem and lead to understanding whole picture of the affected areas in-real time. Three approaches of real-time tsunami inundation forecast methods have been proposed as shown in Table 1. First is so-called "data-driven" approach that searches tsunami forecast data from pre-computed database connected with offshore tsunami observation[1 -3]. The second is "data assimilation" that assimilates tsunami wave field using dense offshore tsunami observation networks[4, 5]. Both are highly depend on the configuration of offshore tsunami sensors. The third is "real-time forward simulation" that runs simulations in real-time with given tsunami source models based on seismic and geodetic observations. The real-time forward approach has the most advantages in simulating tsunami inundation on land once if reliable tsunami source model is obtained.

The authors established a method of real-time tsunami inundation forecasting and damage estimation to estimate the impact of tsunami disaster. The method was verified through the case studies in the 2011 Tohoku earthquake tsunami with regard to its forecasting reliability and capability[6]. After the verification, in 2017, the system started its operation as a function of tsunami disaster response system in Cabinet Office, Government of Japan.

Table 1 – Methods of real-time tsunami inundation forecast.

Approach and Method	Key sensors	References
Data-driven, Multi-index method (Database search)	S-net	Yamamoto et al. (2016) [1]
Data-driven, Gaussian Process Regression	DONET	Igarashi et al. (2016) [2]
Data-driven and forward simulation, Near-TIF		Gusman et al. (2014) [3]
Data assimilation	S-net, DONET	Maeda et al. (2015) [4] Wang et al. (2018) [5]
Real-time forward simulation	GEONET	Koshimura et al. (2017) [6] Musa et al. (2018) [7] Ohta et al. (2018) [8]

2. Real-time Tsunami Inundation Forecast with Forward Simulation

The vector-parallel supercomputers SX-ACE and SX-Aurora served as the core simulation architectures. SX-ACE are installed at both Tohoku and Osaka Universities and are operated independently to enhance the redundancy of emergency situation. The simulation management system that achieves optimal allocation of jobs between nodes was newly established. This job management on SX-ACE supports urgent job prioritization for the real-time tsunami inundation simulation[7]. The function of urgent job prioritization executes the tsunami inundation simulation at the highest priority, while immediately suspending other active jobs. The suspended jobs automatically resume as soon as the activated tsunami inundation simulation completes.

The forecasting target is the tsunami-genic earthquakes that occur along the Nankai Trough and its vicinity (Fig. 1). Especially, the most concerned target is the Nankai Trough earthquake which is estimated to occur in next 30 years with 70 % of probability by the long-term evaluation of seismic activity in Japan. The forecasting area includes 6,000km-long coast line from Kagoshima to Shizuoka prefectures. In the operation, we verify the capability of the method as a new real-time tsunami inundation forecasting, damage mapping and response system for stakeholders and responders through the case studies of the 2011 event.

The implemented tsunami numerical model is based on the non-linear shallow-water equations discretized by staggered leap-frog finite difference method. Using SX-ACE, we accomplished "10-10-10 challenge", to complete tsunami source determination in 10 minutes, tsunami inundation modeling in 10 minutes with 10 m grid resolution (Fig. 2).

To have the tsunami propagation and inundation forecasting activated, we first receive seismic information from Earthquake Early Warning (EEW) of JMA which takes only a few tens of seconds from observing seismic waves. More precise information is provided by real-time analysis of GEONET (GNSS Earth Observation Network System) data supposedly within 10 minutes after an earthquake is triggered. We use the fault rupture estimation derived by RAPiD[9] and REGARD[10] algorithm that includes the estimates of the moment magnitude, fault geometries, focal mechanisms and slip distributions. Given the tsunami source information, the system moves on to tsunami propagation/inundation simulation running on SX-ACE and SX-Aurora to acquire the estimation of time series of tsunami at offshore/coastal tide gauges to determine tsunami travel and arrival time, extent of inundation zone, maximum flow depth distribution, and potential losses. The implemented tsunami numerical model is based on the non-linear shallow-water equations discretized by staggered leap-frog finite difference method. Using SX-ACE, we accomplished "10-10-10 challenge", to complete tsunami source determination in 10 minutes, tsunami inundation modeling in 10 minutes with 10 m grid resolution. The simulations are now optimized to be more efficient, using a new nested grid system and its MPI-parallelization[11], and running on other HPC processors[12] to expand its capability to the other areas and users (Fig. 2).

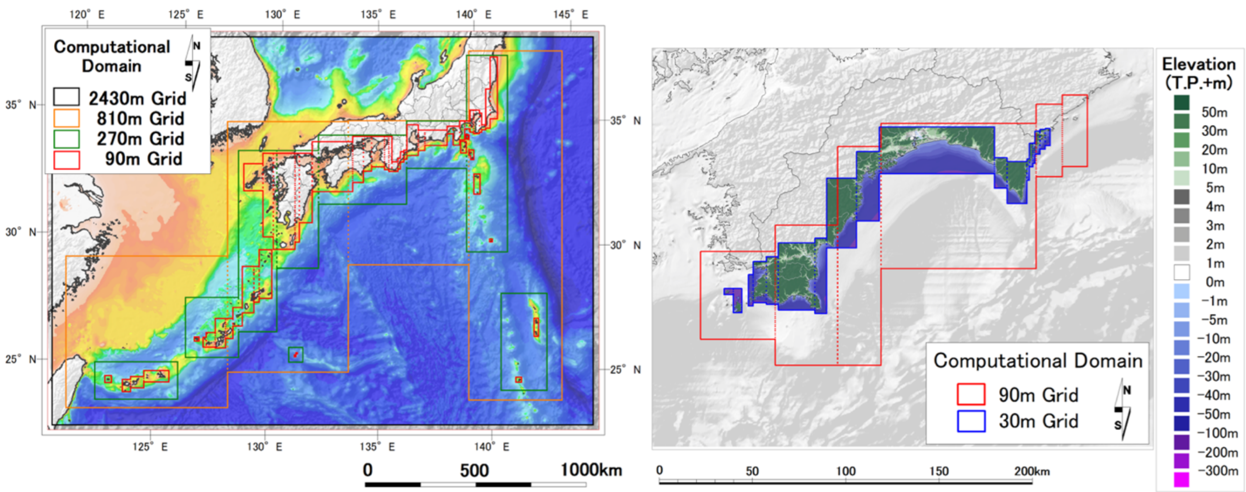

Fig. 1 – Computational domains for Nankai Trough earthquake tsunami[11]. Left:Nested grid system, Right:Grid configurations for Kochi Prefecture.

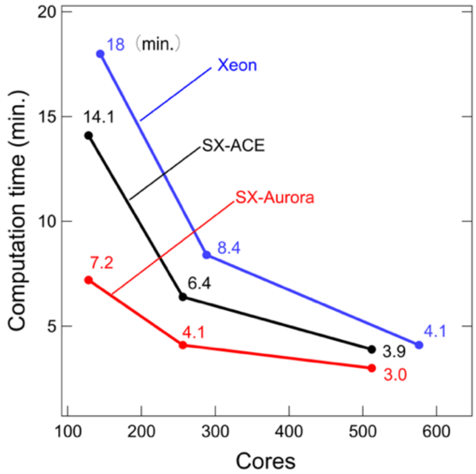

Fig. 2 – Performance of real-time tsunami inundation forecasts with multi-computational platforms[12].

3. Damage Estimation and Mapping

Identifying the tsunami impacts and finding devastated areas is quite important for disaster response and relief activities. Only the tsunami inundation forecasting results don't determine the exposure information. Given the maximum flow depth distribution, the system performs GIS analysis to determine the numbers of exposed population and structures using census data, then estimates the numbers of potential death and damaged structures. The key is a tsunami fragility curve[13], which represents structural damage probability as a function of tsunami flow depth to perform quantitative estimation of washed-away buildings (Fig.3).

The results are disseminated as mapping products (Fig.4) to responders and stakeholders, e.g. national and regional municipalities, and private sectors to be utilized for their emergency/response activities, e.g. identifying the number of exposed population, potential damage on houses, road networks, critical infrastructures, search and rescue, and recovery.

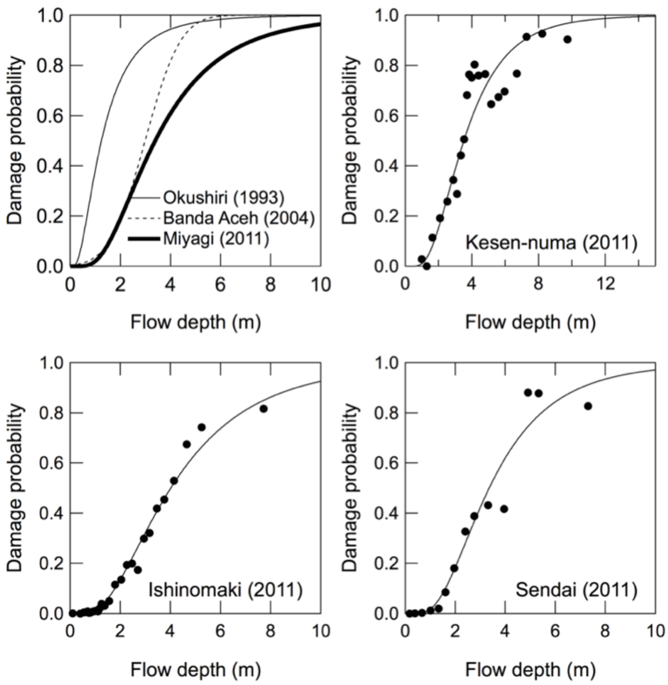

Fig. 3 – Tsunami fragility curves for estimating structural damage[13].

4. Summary

With use of modern computing power and advanced monitoring capabilities, we established a new system of real-time tsunami inundation forecasting, damage estimation and mapping to enhance society's resilience in the aftermath of major tsunami disaster. After an earthquake is triggered along Nankai Trough, the tsunami source estimation is performed with earthquake early warning information and GEONET data analysis, and is designed to complete the tsunami source estimation within 10 minutes. Then the real-time tsunami inundation forecasting system is activated to execute the jobs on vector super computer SX-ACE within 10 minutes. The spatial resolution of the tsunami inundation forecasting is up to 10 meters to perform precise tsunami inundation forecasting and damage estimation using tsunami fragility curves. The results are disseminated as mapping products to responders and stakeholders, e.g. national and regional municipalities, to be utilized for their emergency/response activities. The system has started its operation since November 2017 as a function of tsunami disaster response system of the government of Japan. Enhancement of rapidity and reliability of tsunami inundation forecast technology leads a new tsunami warning that includes survival information.

5. Acknowledgements

This research was supported by JST CREST (Grant Number JPMJCR1411) and JSPS Grants-in-Aid for Scientific Research (17H06108).

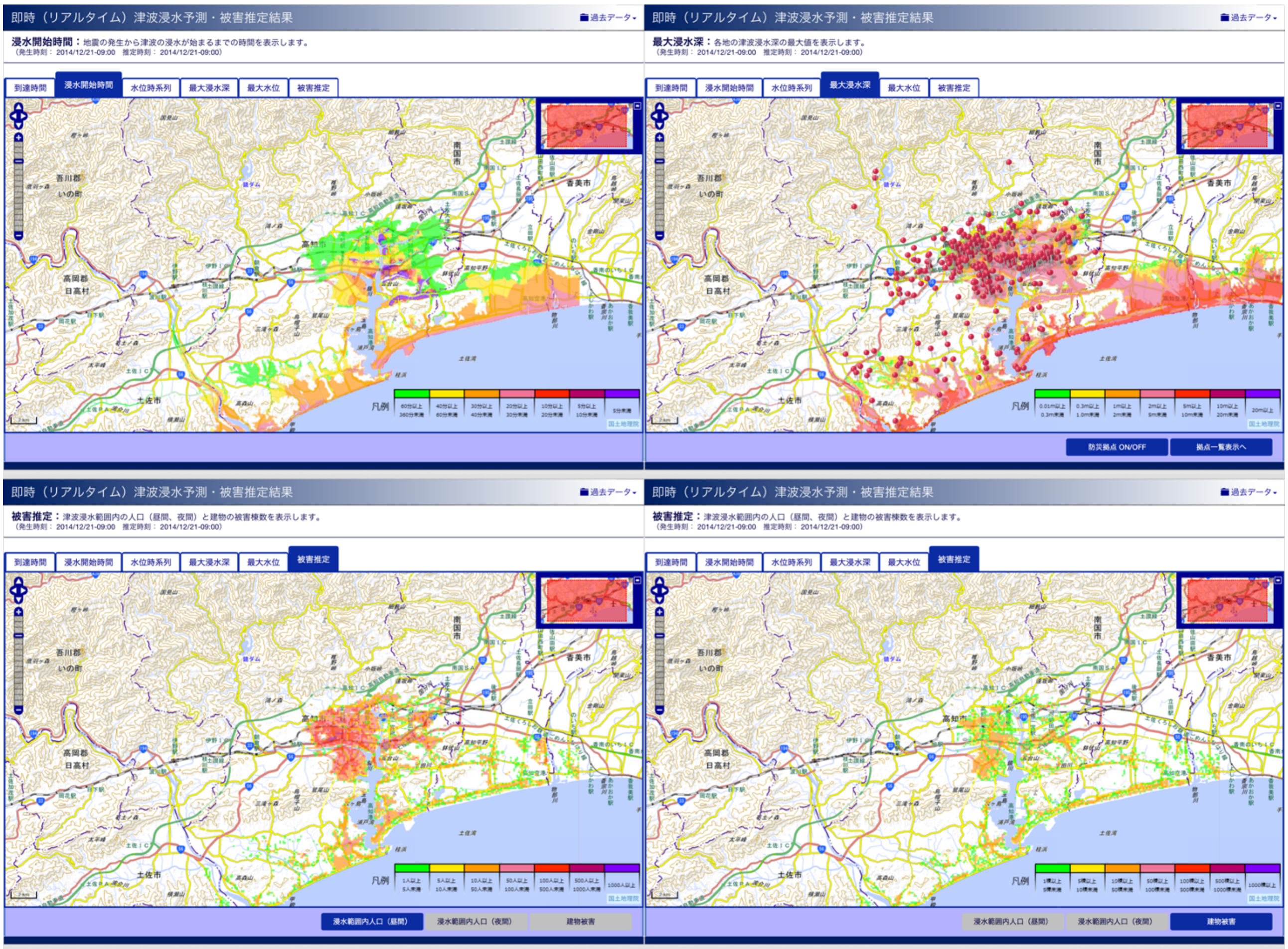

Fig. 4 – Tsunami inundation and damage forecast results. Top left:Tsunami arrival time, Top right:Maximum flow depth, Bottom left:Structural damage, Bottom right:Exposed populations.

6. References

[1] Yamamoto et al. , Multi-index method using offshore ocean-bottom pressure data for real-time tsunami forecast, Earth, Planets and Space, 68:128, 2016. doi: 10.1186/s40623-016-0500-7

[2] Igarashi et al., Maximum tsunami height prediction using pressure gauge data by a Gaussian process at Owase in the Kii Peninsula, Japan, Mar Geophys Res, 37:361–370, 2016. doi:10.1007/s11001-016-9286-z

[3] Gusman et al., A methodology for near-field tsunami inundation forecasting: Application to the 2011 Tohoku tsunami, J. Geophys. Res. Solid Earth, 119, 8186–8206, 2014. doi:10.1002/2014JB010958

[4] Maeda et al., Successive estimation of a tsunami wavefield without earthquake source data: A data assimilation approach toward real-time tsunami forecasting, Geophys. Res. Lett., 42, 7923–7932, 2015. doi:10.1002/2015GL065588

[5] Wang et al., Data assimilation with dispersive tsunami model: a test for the Nankai Trough, Earth, Planets and Space, 70:131,, 2018. doi:10.1186/s40623-018-0905-6

[6] Koshimura et al., Advances of tsunami inundation forecasting and its future perspectives, IEEE Oceans, 2017. doi:10.1109/OCEANSE.2017.8084753

[7] Musa et al., Real-time tsunami inundation forecast system for tsunami disaster prevention and mitigation, J Supercomput, 74: 3093, 2018. doi:10.1007/s11227-018-2363-0

[8] Ohta et al., Role of Real-Time GNSS in Near-Field Tsunami Forecasting, Journal of Disaster Research Vol.13 No.3, 2018. doi: 10.20965/jdr.2018.p0453

[9] Ohta, Y., T. Kobayashi, H. Tsushima, S. Miura, R. Hino, T. Takasu, H. Fujimoto, T. Iinuma, K. Tachibana, T. Demachi, T. Sato, M. Ohzono, N. Umino, Quasi real-time fault model estimation for near-field tsunami forecasting based on RTK-GPS analysis: Application to the 2011 Tohoku-Oki earthquake (Mw 9.0), J. Geophys. Res., 117, B02311, 2012. doi:10.1029/2011JB008750

[10] Kawamoto, S., Y. Ohta, Y. Hiyama, M. Todoriki, T. Nishimura, T. Furuya, Y. Sato, T. Yahagi, K. Miyagawa, REGARD: A new GNSS-based real-time finite fault modeling system for GEONET, J. Geophys. Res., 2017. DOI:10.1002/2016JB013485

[11] Inoue, T., T. Abe, S. Koshimura, A. Musa, Y. Murashima, H. Kobayashi, Development and Validation of a Tsunami Numerical Model with the Polygonally Nested Grid System and its MPI-Parallelization for Real-Time Tsunami Inundation Forecast on a Regional Scale, Journal of Disaster Research, Vol.14, No.3, pp.416-434, 2019. doi: 10.20965/jdr.2019.p0416

[12] Musa et al., Performance Evaluation of Tsunami Inundation Simulation on SX-Aurora TSUBASA. In: Rodrigues J. et al. (eds) Computational Science – ICCS 2019. doi:10.1007/978-3-030-22741-8_26

[13] Koshimura, S. and N. Shuto, Response to the 2011 Great East Japan Earthquake and Tsunami disaster, Philosophical Transactions of the Royal Society A, 2015a. doi:10.1098/rsta.2014.0373

