https://doi.org/10.20965/jdr.2018.p0453

Review:

Role of Real-Time GNSS in Near-Field Tsunami Forecasting

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[Received November 18, 2017; accepted January 31, 2018]

This short paper reviews the role of real-time global navigation satellite system (GNSS) in near-field tsunami forecasting. Recent efforts highlight that coseismic fault model estimation based on real-time GNSS has contributed substantially to our understanding of large magnitude earthquakes and their fault expansions. We briefly introduce the history of use of real-time GNSS processing in the rapid estimation of the coseismic finite fault model. Additionally, we discuss our recent trials on the estimation of quasi real-time tsunami inundation based on real-time GNSS data. Obtained results clearly suggest the effectiveness of real-time GNSS for tsunami inundation estimation as the GNSS can capture fault expansion and its slip amount in a relatively accurate manner within a short time period. We also discuss the future prospects of using real-time GNSS data for tsunami warning including effective combination of different methods for more reliable forecasting.

Keywords: real-time GNSS, near-field tsunami early warning, rapid magnitude determination, reliable forecasting, tsunami inundation

1. Introduction

Earthquakes beneath the sea-floor possibly generate tsunamis. Typically, tsunamis caused by large interplate earthquakes will strike near-field coasts within several minutes to an hour, depending on the distance between the trench and the coast.

The major earthquake that struck northeastern Japan on March 11, 2011 was named as the '2011 off the Pacific coast of Tohoku Earthquake' by the Japan Meteorological Agency (JMA) (hereafter, 2011 Tohoku-Oki earthquake). The JMA issued the first tsunami warning (a 3–6 m height) for coastal Japan three minutes after the event, based on the magnitude of the short-period seismic wave. The first warning was clearly underestimated as the estimated magnitude (M_{jma}) of 7.9, was much smaller than the actual magnitude of 9.0, which was confirmed by the actual tsunami height [1]. An offshore Global Positioning System (GPS) buoy (Kato et al., 2000 [2]) deployed off northeastern Japan then recorded a steep rise in sea level at off Kamaishi and Onahama. And then, the JMA updated the tsunami warning 28 minutes after the main shock [1] at heights upgraded to 6–10 m or more. These results clearly highlight that underestimation of the true magnitude scale immediately after the large earthquake led to an underestimation of the height of the resulting tsunami.

How can large earthquake magnitudes be accurately determined? This is one of the vital questions for reliable near-field tsunami early warning. In this review, we focus on the role of real-time Global Navigation Satellite System (GNSS) data for near-field tsunami forecasting based on the rapid understanding of the coseismic fault model estimation. Firstly, we briefly review the development of rapid coseismic fault model estimation based on GNSS data. Secondly, we introduce the recent trial for rapid estimation of tsunami inundation based on real-time GNSS data in Japan. Finally, we discuss the future of real-time GNSS in near-field tsunami forecasting.

2. Rapid Coseismic Fault Model Estimation Based on Real-Time GNSS Data and its Implementation in Japan

Several researches have utilized high-sampling (sampling interval is generally 1 Hz or larger than 1 Hz) GNSS analysis in the broadband strong motion seismometer [3–5]. General strong motion seismometers can measure acceleration, whereas GNSS seismometers can measure the displacement directly and accurately [6].

Strong motion seismometer is very sensitive and serves as a useful sensor for earthquake signals. However, the seismometer is band-limited as it is an inertial system consisting of a spring and weight. The GNSS seismometer is also an inertial system between the earth and satellites, but the system is larger than its target event, namely, the displacement generated by an earthquake. Thus, in principle, the GNSS seismometer has no band limit.

Based on these characteristics, Blewitt et al. [7] pro-

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posed that the rapid earthquake magnitude and tsunamigenic potential can be estimated within a short time period using inland GNSS data. Additionally, Blewitt et al. [8] identified the required precision and accuracy of real-time GNSS time series for rapid earthquake size estimation to avoid false tsunami warnings. Similarly, Sobolev et al. [9] proposed a GPS shield concept that used near-field GPS arrays to predict near-field tsunami forecasts. Based on numerical simulations, they suggested that the tsunami waves could be predicted with high accuracy in less than 10 minutes after a large earthquake.

After the 2011 Tohoku-Oki earthquake, several researches have stressed on the advantages of real-time GNSS data for rapid earthquake size estimation and its utilization for tsunami early warning [10–17]. For detailed information on previous researches, refer to Tsushima and Ohta [18].

What are the advantages of real-time GNSS for near-field tsunami warning? The most important advantage is the estimation of the unsaturation magnitude for the large event. In Japan, the Geographical Information Authority of Japan (GSI) established GEONET, a nationwide GNSS network composed of more than 1300 stations. Before the 2011 Tohoku-Oki earthquake, GEONET did not implement nation-wide real-time GNSS data analysis for rapid coseismic fault model estimation. However, following the 2011 Tohoku-Oki earthquake, the GSI and Tohoku University developed the real-time GEONET Analysis system for Rapid Deformation monitoring (REGARD) to maximize the performance of the dense GEONET network. The primary purpose of the REGARD system was to estimate unsaturated magnitude for earthquakes larger than M8, based on finite coseismic fault model estimation [19]. From April 2016, the REGARD system commenced crustal deformation monitoring and automatic modeling for most GEONET stations. The 2016 Kumamoto earthquake (M_j7.3) occurred on April 16, 2016 (Japan standard time, GMT +9) in southwestern Japan, which was the first large earthquake with $M_j > 7$ in Japan after the launch of the REGARD system. The REGARD system successfully modeled coseismic displacements and estimated finite single coseismic fault models, which were consistent with post-processed ones (Kawamoto et al. [20], this issue). This was the first result of the REGARD for a large earthquake; this result is expected to accurately estimate coseismic fault models for interplate large earthquakes.

Similar to the REGARD system, real-time GNSS can estimate the finite fault model accurately with comparative ease because the spatial pattern of coseismic displacement strongly depends on the expansion of the coseismic fault.

In contrast, many techniques for rapid earthquake size estimation deduced from the seismometer data adopt point source assumption. The estimated point source can be translated to the finite fault model experimentally by applying the scaling law between fault dimension and magnitude [21].

However, the heterogeneity of the slip distribution and the possible aspect ratio of the coseismic fault may be significantly diverse between each event and the each subduction zone. Especially, it will be difficult to assume the heterogeneity of the slip distribution before the event. Such fault model expansion and amount of slip contribute to timely and accurate tsunami warnings as the initial sea-surface distribution strongly depends on the spatial distribution of the crustal deformation in the sea-floor. Thus, the estimation of the magnitude as well as the coseismic fault model expansion is extremely important for near-field tsunami forecasting.

In the next section, we briefly introduce the impact of the rapid coseismic fault model estimation on tsunami inundation forecasting.

3. Rapid Estimation of Tsunami Inundation Based on Real-Time GNSS Analysis

3.1. Approaches of Estimating Rapid Tsunami Inundation

The rapid tsunami inundation method was developed following sustained efforts. The pre-computed scenario database is extremely useful as estimation of the tsunami inundation can be determined as soon as the hypocenter and magnitude information are identified. For example, Abe and Imamura [22] proposed a strategy for real-time inundation forecasting of near-field tsunamis, which calculated numerous tsunami inundation scenarios before earthquakes occurred. Following an earthquake, several possible scenarios were selected from pre-calculated inundation scenarios by referring to the information available in real-time. The Center for Tsunami Research (NOAA) has developed a short-term inundation forecasting scheme [23]. Gusuman et al. [24] developed a methodology called the Near-field Tsunami Inundation Forecasting (NearTIF), which requires pre-computed tsunami inundation and pre-computed tsunami waveform databases. Tsunami waveforms at near-shore points can be simulated in real-time after information about a tsunami source is estimated. The accuracy of the pre-computed scenario database type approach, however, will strongly depend on the precomputed scenarios. If the unexpected event occurs in the database, the accuracy of the tsunami inundation will be limited.

An alternative approach is the "forward" type, which means that the initial sea-surface distribution will be assumed on the basis of external seismological, geodetical, and other geophysical techniques. Tsunami propagation and its inundation can be calculated when initial sea-surface distribution is obtained. If the initial sea-surface distribution data is reliable, the reliability of calculated tsunami inundation results will also be high. This is the one of the advantages of the "forward" approach. However, the accuracy of the calculated tsunami inundation will strongly depend on the assumed coseismic fault model for the initial sea-surface distribution, which can serve as a disadvantage. Additionally, the computation

time for rapid tsunami inundation with high spatial resolution is also a problem as the computational cost of nonlinear shallow water equations is high for quasi real-time purposes. If we can overcome these disadvantages, the "forward" modeling approach will play an important role for the near-field tsunami forecasting because we can consider the diversity of the coseismic fault and/or the heterogeneity of the its distribution of each events. Thus, we adopted the "forward" modeling approach. In the next section, we will briefly describe quasi real-time tsunami inundation forecasting systems based on the "forward" approach.

3.2. Quasi Real-Time Estimation of Tsunami Inundation System Based on the "Forward" Approach

Based on the REGARD system developed by GSI and Tohoku University and the high spatial and temporal resolution tsunami inundation modeling technique based on the high-performance computing developed in Tohoku University, "The research group of real-time estimation for tsunami inundation" (Principle Investigator: Prof. Koshimura from Tohoku University) was launched in 2014. The group consists of Tohoku University, Osaka University, Kokusai Kogyo Corp., NEC Corp., and A2 Corp. The several authors of this paper are also members of this research group. Our group has been developing rapid tsunami inundation system based on the "forward" modeling approach. The flow chart of the system is illustrated in **Fig. 1**.

For the accurate tsunami inundation prediction, we employed either the finite fault model (single rectangular fault model and/or slip distribution in the plate interface) from REGARD issued by GSI or finite coseismic fault model using EEW information issued by JMA as the backup system. In the REGARD system, Green's function using a triangular dislocation element in a homogeneous elastic half-space [25] was adopted for coseismic slip distribution in the plate interface.

Original source code of Meade [25] was identified using MATLAB. However, the code was insufficient performance for our quasi real-time purpose as high spatial density of initial sea-surface is required for accurate tsunami inundation forecasting. Thus, we approximated the slip distribution in the triangular dislocation elements estimated by REGARD using many small rectangular faults [26].

For the fault model deduced from the EEW information, the fault dimension and slip amount were assumed using the scaling law proposed by Wells and Coppersmith [21]. Interplate reverse fault mechanism was assumed when the hypocenter was located near the plate interface. The fault geometry (dip angle, strike direction, rake angle) for other regions was assumed on the basis of tectonic setting and/or past earthquake catalog. Once obtained the coseismic fault model and/or slip distribution in the plate interface, we calculated the initial sea-surface distribution.

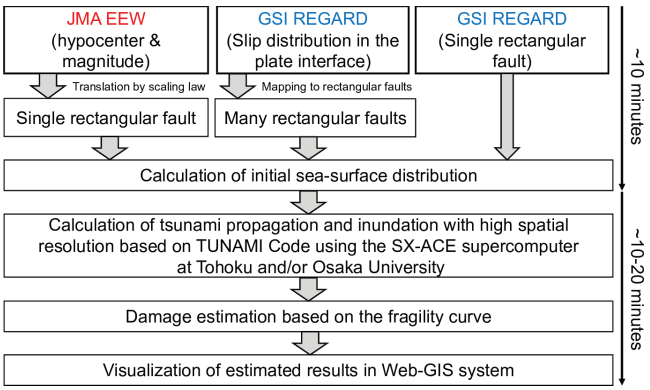

Fig. 1. Flow chart of the rapid tsunami inundation estimation system developed by "The research group of real-time estimation for tsunami inundation."

We utilized the vector-parallel supercomputer SX-ACE, at the Tohoku University and/or Osaka University for calculations. For the calculation of tsunami propagation and its inundation, we used the TUNAMI (Tohoku University's Numerical Analysis Model for Investigating Tsunami), which can solve non-linear shallow water equations and uses the staggered leap-flog finite difference method as the numerical scheme.

Computation time strongly depended on the size of the calculation grid. Although grid size all along the Nankai trough was 30 m, with calculation period of 6 hours after the event, the computational time was less than 10 minutes. Finally, structural damage caused by the tsunami inundation was estimated using the fragility curve proposed by Koshimura et al. [27]. Total computation time for the estimation of the tsunami inundation from finite fault model estimation, the damage estimation and the visualization of the result was approximately less than 20 to 30 minutes after the event origin.

In November 2017, the Cabinet Office, Government of Japan, commenced operation of the system for estimation of tsunami inundation and damage. The system is to be adopted as part of the Disaster Information Systems (DIS) operated by Japan's Cabinet Office. The system has been developed based on the results from "The research group of real-time estimation for tsunami inundation" including utilization of the results from the REGARD system. The system will use information generated for the initial response of the Government after a tsunamigenic earthquake.

In the next section, we will discuss the impact of rapid coseismic fault model deduced using real-time GNSS on the estimation of tsunami inundation.

3.3. Impact of Using Real-Time GNSS Data in the Finite Fault Model for Estimation of Tsunami Inundation

In this section, we assess the impact of use of real-time GNSS for the estimation of tsunami inundation. The selected scenario was the 2011 Tohoku-Oki earthquake. We

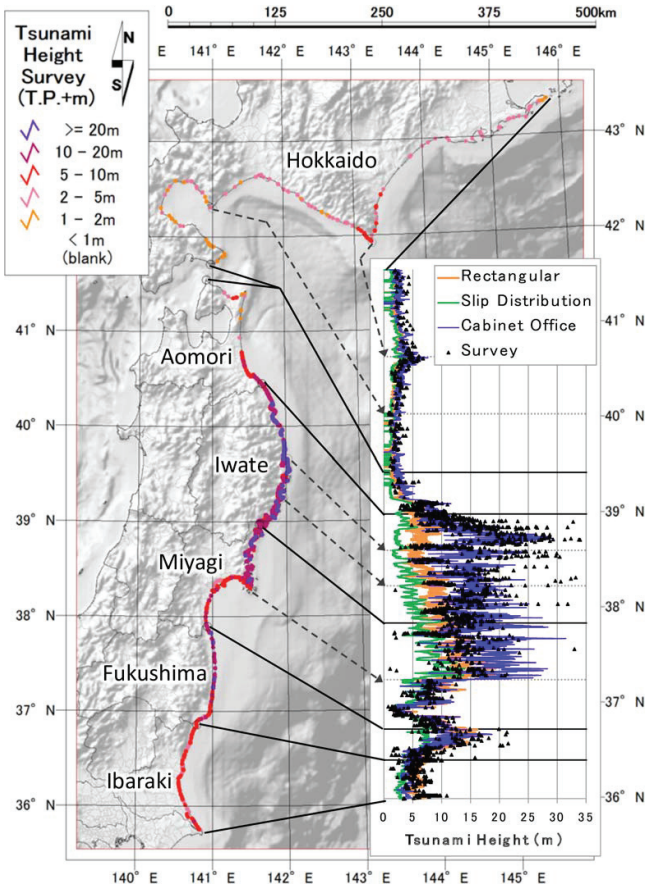

Fig. 2. Estimated tsunami height along the coastline in northeastern Japan and tsunami trace observation results. Orange, green, purple, and black indicate the single rectangular fault model, slip distribution model in the plate interface, result from "the Cabinet Office model," and tsunami trace results compiled by the 2011 Tohoku Earthquake Tsunami Joint Survey Group, respectively.

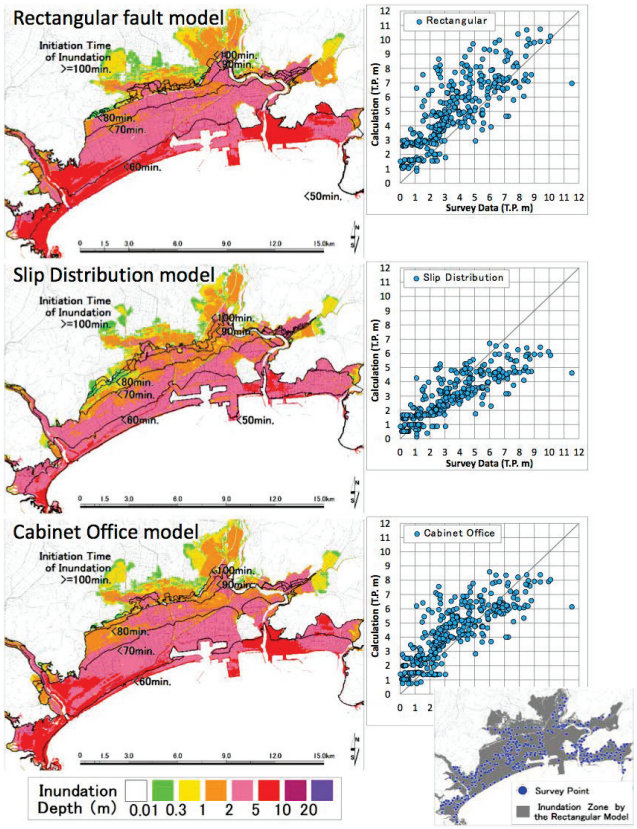

Fig. 3. Comparison of different models used for estimation of maximum tsunami inundation depth in Ishinomaki-Matsushima, Miyagi prefecture. Each row figures represents the result of single rectangular fault model using real-time GNSS [15], slip distribution in the plate interface by REGARD [28], and coseismic slip model proposed by Cabinet Office, government of Japan, respectively. Left column represents estimation results of maximum tsunami inundation depth with the starting time of the tsunami inundation by the contours. Right column represents the correlation between calculated maximum tsunami inundation depth (vertical axis) and in-situ survey results (horizontal axis) at each site in small circles which place is denoted in the right bottom inserted figure.

adopted the single rectangular coseismic fault model deduced using real-time GNSS [15] and the slip distribution model from the REGARD system [28]. Kawamoto et al. [28] estimated the slip distribution using the REGARD system for the same situation under real-time conditions. For comparison, we also calculated the tsunami inundation based on the coseismic slip distribution model proposed by an investigative committee held by the Cabinet Office of the Japanese government (hereafter, "the Cabinet Office model") which was estimated using tsunami inversion after the event. For detailed information regarding processing, see Inoue et al. [26].

Figure 2 illustrates the tsunami height along the coastline obtained using single rectangular fault model (orange), slip distribution model (green), and the Cabinet Office model (purple). We also plotted the in-situ tsunami survey result compiled by the "2011 Tohoku Earthquake Tsunami Joint Survey Group" [29]. The single rectangular fault and slip distribution models underestimated the tsunami height compared to the observed height. This may have been caused by the deviation in the estimated location of high coseismic patch in the plate interface. When only coseismic displacement field in onshore GNSS data was used, the maximum coseismic patch was estimated towards a landward portion compared to the actual position, and the amount of coseismic slip was also underestimated [30, 31].

Figure 3 shows the maximum tsunami inundation depth in Ishinomaki-Matsushima area in the Miyagi prefecture and comparison with tsunami height measured by in-situ survey. The Cabinet Office model showed good agreement with the observation because the model was estimated using inversion based on actual tsunami data. The results of single rectangular fault and slip distribution model using GNSS data also exhibited good correlation with the observation, although slight underestimation was noted in the slip distribution model for the place of high tsunami inundation area (**Fig. 3**). The area of the tsunami inundation depends on the tsunami wave length.

Although the coastal tsunami height was underestimated in the single rectangular fault and slip distribution model using real-time GNSS data, the models succeeded in representing the characteristics of long wave length during this event.

As mentioned in Section 2, one of the advantages of real-time GNSS is the estimation of coseismic fault expansion along with the earthquake magnitude. Accurate estimation of fault expansion will lead to accurate estimation of tsunami inundation. This may be an extremely important functionality of real-time GNSS for near-field tsunami warning. In the next section, we discuss the future prospects of near-field tsunami forecasting and its utilization for disaster mitigation based on real-time GNSS analysis.

4. Future Prospects of Real-Time GNSS for Near-Field Tsunami Warning

Real-time GNSS can provide relatively accurate coseismic fault expansion and slip amount in the fault plane compared to the seismometer. It is clearly more suitable for near-field tsunami forecasting. In contrast, we also pointed out the limitations of onshore real-time GNSS data for the estimation of the coseismic fault in Section 3.3.

Tsushima and Ohta [18] highlighted the importance of combination approaches as they are expected to overcome the disadvantages of individual sensor types. For example, Tsushima et al. [32] proposed the combined use of onshore GNSS data and offshore tsunami data. In their algorithm, initial sea-surface height distribution estimated using onshore real-time GNSS data was modified using offshore tsunami data.

Japan already possesses offshore tsunami networks such as the Nationwide Ocean Wave information network for Ports and HArborS (NOWPHAS [33]), S-net and DONET [34]. Furthermore, the quasi real-time ocean bottom crustal deformation by GPS-Acoustic measurement have been developing in few research groups. For example, Takahashi et al. [35] have developed a new system for real-time observation of tsunami and crustal deformation using seafloor pressure sensors, and array of seafloor transponders and a real-time Precise Point Positioning (PPP) based on the moored buoy system. Imano et al. [36] assessed and improved the accuracy of quasi real-time GPS-Acoustic measurement using moored buoy system based on the actual sea-trial data. For the future, these offshore network data should be used with onshore seismic and geodetic data for more robust near-field tsunami forecasting. Further, new methodology employing combination of different sensors will be critically important. Individual sensors types have advantages and disadvantages, suggesting that multiple sensors should be used in combination to maximize the advantages of individual data sources. Thus, real-time GNSS should be used as one of the sensors for more robust near-field tsunami forecasting.

5. Conclusions

In this short paper, we briefly discussed the development of rapid coseismic fault model estimation based on GNSS data. Additionally, we introduced our recent trial for the development of a rapid tsunami inundation estimation system including the coseismic fault model using real-time GNSS data. Finally, we pointed out the importance of the use of a combination of multiple sensors for more reliable tsunami forecasting. Real-time GNSS data should be used as one of the sensors for near-field tsunami forecasting.

Acknowledgements

We are grateful to the GSI for providing the GEONET GNSS data. We would like to thank anonymous reviewer and the editors for their helpful comments. This study was partly supported by the JST CREST Grant Number JPMJCR1411, Japan. This study was also partly supported by the Ministry of Education, Culture, Sports, Science, and Technology (MEXT) of Japan, under its Earthquake and Volcano Hazards Observation and Research Program. This work was also supported by the Japan Society for the Promotion of Science (JSPS) KAKENHI Grant Numbers 15H03713 and 17H06108.

References:

[1] T. Ozaki, "Outline of the 2011 off the Pacific coast of Tohoku Earthquake (M_w 9.0) – Tsunami warnings/advisories and observations –," Earth Planets Space, Vol.63, pp. 827-830, doi: 10.5047/eps.2011.06.029, 2011.

[2] T. Kato, Y. Terada, et al., "Real-time observation of tsunami by RTK-GPS," Earth Planets Space, Vol.52, pp. 841-845, doi: 10.1186/BF03352292, 2000.

[3] K. M. Larson, P. Bodin, et al., "Using 1-Hz GPS data to measure deformations caused by the Denali fault earthquake," Science, Vol.300, pp. 1421-1424, doi:10.1126/science.1084531, 2003.

[4] K. M. Larson, "GPS seismology," J. of Geod., Vol.83, Issue 3-4, pp. 227-233, doi:10.1007/s00190-008-0233-x, 2009.

[5] Y. Ohta, I. Meilano, et al., "Large surface wave of the 2004 Sumatra-Andaman earthquake captured by the very long baseline kinematic analysis of 1-Hz GPS data," Earth Planets Space, Vol.58, No.2, pp. 153-157, doi: 10.1186/BF03353372, 2006.

[6] S. Miyazaki, K. M. Larson, et al., "Modeling the rupture process of the 2003 September 25 Tokachi-Oki (Hokkaido) earthquake using 1-Hz GPS data," Geophys. Res. Lett., Vol.31, L21603, doi:10.1029/2004GL021457, 2004.

[7] G. Blewitt, C. Kreemer, et al., "Rapid determination of earthquake magnitude using GPS for tsunami warning systems," Geophys. Res. Lett., Vol.33, L11309, doi:10.1029/2006GL026145, 2006.

[8] G. Blewitt, W. C. Hammond, et al., "GPS for real-time earthquake source determination and tsunami warning systems," J. of Geod., Vol.83, pp. 335-343, doi:10.1007/s00190-008-0262-5, 2009.

[9] S. V. Sobolev, A. Y. Babeyko, et al., "Tsunami early warning using GPS-Shield arrays," J. of Geophys. Res., Vol.112, Issue B8, pp. 1-18, doi:10.1029/2006JB004640, 2007.

[10] D. Melgar, Y. Bock, et al., "Real-time centroid moment tensor determination for large earthquakes from local and regional displacement records," Geophys. J. Int., Vol.188, Issue 2, pp. 703-718, doi: 10.1111/j.1365-246X.2011.05297.x, 2012.

[11] D. Melgar, B. W. Crowell, et al., "Rapid modeling of the 2011 M_w 9.0 Tohoku-oki earthquake with seismogeodesy," Geophys. Res. Lett., Vol.40, pp. 2963-2968, doi:10.1002/grl.50590, 2013.

[12] D. Melga and Y. Bock, "Near-field tsunami models with rapid earthquake source inversions from land- and ocean-based observations: The potential for forecast and warning," J. of Geophys. Res.: Solid Earth, Vol.118, Issue 11, pp. 5939-5955, doi: 10.1002/2013JB010506, 2013.

[13] D. Melgar, J. Geng, et al., "Seismogeodesy of the 2014 M_w 6.1 Napa earthquake, California: rapid response and modeling of fast rupture on a dipping strike-slip fault," J. of Geophys. Res.: Solid Earth, Vol.120, pp. 5013-5033, doi:10.1002/2015JB011921, 2015.

[14] D. Melgar, R. M. Allen, et al., "Local tsunami warnings: Perspectives from recent large events," Geophys. Res. Lett., Vol.43, pp. 1109-1117, doi:10.1002/2015GL067100, 2016.

[15] Y. Ohta, T. Kobayashi, et al., "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. of Geophys. Res., Vol.117, Issue B2, B02311, doi: 10.1029/2011JB008750, 2012.

[16] Y. Ohta, T. Kobayashi, et al., "Rapid coseismic fault determination of consecutive large interplate earthquakes: The 2011 Tohoku-Oki sequence," Int. Association of Geod. Symposia 2015, Springer, doi:10.1007/1345_2015_109, 2015.

[17] B. W. Crowell, Y. Bock, et al., "Real-time inversion of GPS data for finite fault modeling and rapid hazard assessment," Geophys. Res. Lett., Vol.39, No.9, pp. 1-6, doi:10.1029/2012GL051318, 2012.

[18] H. Tsushima and Y. Ohta, "Review on Near-Field Tsunami Forecasting from Offshore Tsunami Data and Onshore GNSS Data for Tsunami Early Warning," J. Disaster Res., Vol.9, No.3, pp. 339-357, doi: 10.20965/jdr.2014.p0339, 2014.

[19] S. Kawamoto, Y. Ohta, et al., "REGARD: A new GNSS-based real-time finite fault modeling system for GEONET," J. of Geophys Res.: Solid Earth, Vol.122, pp. 1324-1349, doi:10.1002/2016JB013485, 2017.

[20] S. Kawamoto, Y. Hiyama, et al., "First Result from the GEONET Real-time Analysis System (REGARD): the Case of the 2016 Kumamoto Earthquakes," Earth, Planets Space, Vol.68, No.190, doi:10.1186/s40623-016-0564-4, 2016.

[21] D. L. Wells and K. J. Coppersmith, "New Empirical Relationships among Magnitude, Rupture Length, Rupture Width, Rupture Area, and Surface Displacement," Bull. of Seismol. Soc. of America, Vol.84, No.4, pp. 974-1002, 1994.

[22] I. Abe and F. Imamura, "Study on the evaluation of tsunami inundation in real time with database and its accuracy (in Japanese with English abstract)," J. of Japan Society of Civil Engineers, Series B2 (Coastal Engineering), Vol.66, pp. 261-265, doi:10.2208/kaigan.66.261, 2010.

[23] V. V. Titov, "Tsunami forecasting in The Sea," Vol.15: Tsunamis, chap. 12, edited by E. N. Bernard and A. R. Robinson, pp. 371-400, Harvard Univ. Press, Cambridge, Mass, 2009.

[24] A. R. Gusman, Y. Tanioka, et al., "A methodology for near-field tsunami inundation forecasting: Application to the 2011 Tohoku tsunami," J. of Geophys. Res.: Solid Earth, pp. 1-21, doi:10.1002/2014JB010958, 2014.

[25] B. J. Meade, "Algorithms for the calculation of exact displacements, strains, and stresses for triangular dislocation elements in a uniform elastic half space," Comput. and Geosci., Vol.33, Issue 8, pp. 1064-1075, doi: 10.1016/j.cageo.2006.12.003, 2007.

[26] T. Inoue, Y. Ohta, et al., "A study on methods for applying fault models rapidly estimated using real-time GNSS to tsunami simulation," J. of Japan Society of Civil Engineers, Series B, Vol.72, No.2, pp. 355-360, 2016.

[27] S. Koshimura, T. Oie, et al., "Developing fragility functions for tsunami damage estimation using numerical model and post-tsunami data from Banda Aceh, Indonesia," Coastal Engineering J., Vol.51, No.3, pp. 243-273, 2009.

[28] S. Kawamoto, K. Miyagawa, et al., "Development and assessment of real-time fault model estimation routines in the GEONET real-time processing system," Int. Association of Geod. Symposia, doi:10.1007/1345_2015_49, 2015.

[29] The 2011 Tohoku Earthquake Tsunami Joint Survey Group, "Nationwide Field Survey of the 2011 Off the Pacific Coast of Tohoku Earthquake Tsunami," J. of Japan Society of Civil Engineers, Series B, Vol.67, No.1 pp. 63-66, 2011.

[30] T. Iinuma, M. Ohzono, et al., "Coseismic slip distribution of the 2011 off the Pacific coast of Tohoku Earthquake (M 9.0) estimated based on GPS data – Was the asperity in Miyagi-oki ruptured?," Earth, Planets and Space, Vol.63, No.7, pp. 643-648, doi:10.5047/eps.2011.06.013, 2011.

[31] T. Iinuma, R. Hino, et al., "Coseismic slip distribution of the 2011 off the Pacific Coast of Tohoku Earthquake (M 9.0) refined by means of seafloor geodetic data," J. of Geophys. Res., Vol.117, B07409, doi:10.1029/2012JB009186, 2012.

[32] H. Tsushima, R. Hino, et al., "tFISH/RAPiD: Rapid improvement of near-field tsunami forecasting based on offshore tsunami data by incorporating onshore GNSS data," Geophys. Res. Lett., 41, pp. 3390-3397, doi:10.1002/2014GL059863, 2014.

[33] T. Nagai, "Development and improvement of the Japanese coastal wave observation network (NOWPHAS)," J. of Japan Society of Civil Engineers, No.609 (VI-41), pp. 1-14, 1998 (in Japanese).

[34] Y. Kaneda, "Real time monitoring systems and advanced simulation researches for Earthquakes/ Tsunami disaster mitigation," AGU Fall Meeting 2013, San Francisco, NH34A-04, 2013.

[35] N. Takahashi, Y. Ishihara, et al., "New buoy observation system for tsunami and crustal deformation," Marine Geophys. Res., Vol.35, Issue 3, pp. 243-253, doi:10.1007/s11001-014-9235-7, 2014.

[36] M. Imano, M. Kido, et al., "Improvement in the Accuracy of Real-Time GPS/Acoustic Measurements Using a Multi-Purpose Moored Buoy System by Removal of Acoustic Multipath," Int. Association of Geod. Symposia, doi: 10.1007/1345_2015_192, 2015.

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Selected Publications:
- Y. Ohta, et al., "Quasi real-time fault model estimation for near-field tsunami forecasting based on RTK-GPS analysis: Application to the 2011 Tohoku-Oki Earthquake (Mw9.0)," J. of Geophys. Res., Vol.117, B02311, doi:10.1029/2011JB008750, 2012.
- Y. Ohta, et al., "Geodetic constraints on afterslip characteristics following the March 9, 2011, Sanriku-oki earthquake, Japan," Geophys. Res. Lett., Vol.39, L16304, doi:10.1029/2012GL052430, 2012.
- Y. Ohta and M. Iguchi, "Advective diffusion of volcanic plume captured by dense GNSS network around Sakurajima volcano: a case study of the vulcanian eruption on July 24, 2012," Earth, Planets and Space, Vol.67, No.1, 157, doi:10.1186/s40623-015-0324-x, 2015.

Academic Societies & Scientific Organizations:
- Geodetic Society of Japan (GSJ)
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Selected Publications:
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Selected Publications:
• Y. Bai, C. Gao, S. Singh, M. Koch, B. Adriano, E. Mas, and S. Koshimura, "A Framework of Rapid Regional Tsunami Damage Recognition From Post-event TerraSAR-X Imagery Using Deep Neural Networks," IEEE Geoscience and Remote Sensing Letters, Vol.15, No.1, 2018.
• S. Koshimura, "Fusion of real-time disaster simulation and big data assimilation – Recent progress," J. Disaster Res., Vol.12, pp. 226-232, doi:10.20965/jdr.2017.p0226, 2017.
• Y. Bai, B. Adriano, E. Mas, and S. Koshiura, "Machine learning based building damage mapping from the ALOS-2/PALSAR-2 SAR imagery: Case study of 2016 kumamoto earthquake," J. Disaster Res., Vol.12, pp. 646-655, doi:10.20965/jdr.2017.p0646, 2017.

Academic Societies & Scientific Organizations:
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Selected Publications:
• S. Kawamoto, et al., "Development and Assessment of Real-Time Fault Model Estimation Routines in the GEONET Real-Time Processing System," Int. Association of Geod. Symposia 2015, Springer, 2015.
• S. Kawamoto, et al., "First result from the GEONET real-time analysis system (REGARD): the case of the 2016 Kumamoto earthquakes," Earth, Planets and Space, Vol.68, No.190, 2016.
• S. Kawamoto, et al., "REGARD: A new GNSS-based real-time finite fault modeling system for GEONET," J. of Geophys. Res.: Solid Earth, 122, pp. 1324-1349, 2017.

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Selected Publications:
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