Tsunami inundation forecast development and usage for NOAA Tsunami Warning System

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Tsunamis are coastal disasters that in many cases allow only minutes of warning before initial impact. Since the 2004 Boxing Day tsunami, there had been significant advancements in tsunami forecast methodology, pre-disaster preparedness and basic understanding of tsunami physics. Yet, the destruction resulted from the 2011 Japan tsunami underscored the difficulties of implementing the advances in tsunami science into practical applications. The capability of tsunami inundation forecast has immence potential for increasing coastal resilience and reduce loss of lives during the tsunami. However, realization of such potential requires new standards of robustness and accuracy for practical application of such capability. The presentation describes methodologies of the real-time tsunami flooding forecast, its testing and implementation for the U.S. Tsunami Warning System and lessons learned from initial use.

S-net Utilization for Real-Time Tsunami Inundation Forecast System

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NIED is constructing S-net (Seafloor Observation Network for Earthquakes and Tsunamis along the Japan Trench) that consists of about 150 ocean bottom observation stations and covers wide area of the offshore Kanto, Tohoku, and Hokkaido. S-net successfully observed the 2016 Fukushima-oki earthquake and tsunami propagation from the offshore toward the land. Such records are useful for obtaining additional lead time for earthquake and tsunami early warning. Recently NIED developed a new methodology of realtime tsunami inundation forecast system using S-net, which will provide flow depth in addition to the tsunami arrival time and heights. In the system, the Tsunami Scenario Bank (TSB) that contains offshore tsunami pre-calculated waveforms, coastal tsunami heights, flow depth maps, and others is constructed in advance along the Pacific coast of Chiba prefecture in the Kanto region. When a tsunami is generated with an earthquake, several appropriate tsunami scenarios that can explain offshore tsunami observations are quickly selected from the TSB. The tsunami inundations are estimated explicitly without any source information, which may contain large estimation error. The system is evaluated and improved through the demonstration experiments with local governments. The performance of the system is validated for the simulated data of the 1677 historical Boso earthquake as well as the observed data of the 2016 Fukushima-oki earthquake.

Keywords: tsunami inundation forecast, realtime forecast, S-net

Synthesis of Tsunami Waveforms Including Dynamic and Static Pressure Change: Practical tests of tFISH

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Most tsunami studies neglected the effects of seismic waves in synthesizing tsunami waveforms. This is not a serious problem when using coastal tide-gauges and sensors deployed far from the tsunami source. However, when the records obtained inside or near the source are used, this becomes a significant problem because seismic waves contaminate tsunami signals. Therefore, in order to correctly evaluate the performance of tsunami forecasting methods, it is necessary to take into account the effects of seismic waves in addition to tsunami. In this study, we propose a synthesis method for ocean-bottom pressure records including both seismic waves and tsunami (Saito and Tsushima 2016 JGR). The method conducts seismic-wave and tsunami simulations in synthesizing the pressure records. First, a linear seismic-wave simulation is conducted with a kinematic earthquake fault model. Then, a nonlinear tsunami simulation is conducted using the sea-bottom motion calculated in the seismic-wave simulation. By using these simulation results, we synthesize realistic ocean-bottom pressure records including both seismic wave and tsunami. We synthesized the ocean-bottom pressure records of S-net for a simplified Tohoku-Oki earthquake fault model. Then, the performance of a tsunami source estimation method of tFISH was examined. Even though the synthesized records contain large dynamic pressure change, which is not considered in the algorithm, tFISH successfully worked with expected performance: tFISH correctly estimated the tsunami source when 5 min elapsed after the earthquake occurred. The pressure records synthesized in this study, including both seismic wave and tsunami, are more practical for evaluating the performance of our tsunami monitoring ability, whereas past tsunami studies usually neglected the seismic wave contribution.

Keywords: Tsunami, Theory, Simulation

Improvement of tsunami-forecasting method based on tsunami inversion: small-size and large-amplitude tsunamis

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Since 2000, real-time tsunami forecasting methods based on inversion of offshore tsunami data have been proposed for tsunami disaster mitigation (e.g., Titov et al., 2005; Tsushima et al., 2009). In the previous studies, we developed a tsunami-forecasting method based on inversion for initial sea-surface height distribution, named tFISH (Tsushima et al., 2009, 2012). In the tFISH algorithm, tsunami source that is initial sea-surface height distribution is expressed by a linear superposition of elementary tsunami sources. The size of elemental sources is about 20 km that can well express tsunami sources of moderate to large interplate earthquakes. However, tsunamis that affect coastal communities are sometimes generated by a spatially small-size source. For example, a Mw 6.9 intraplate normal-faulting earthquake occurred off Fukushima prefecture, northeastern Japan, on 22 November 2016, and the 1.4-m-height tsunami was observed at coastal tide gauge. The area of the source is comparable or smaller than that of elemental source, and thus the tFISH may not resolve the source and decrease accuracy of tsunami forecasting. Considering that the tsunami height at the coast was large (> 1 m) enough to cause the disaster, the accurate forecasting for this event is important. In this study, we try to improve the tFISH algorithm for accurate forecasting of small-size and large-amplitude tsunamis.

I performed numerical simulation of tsunami forecasting assuming the 2016 Nov. off Fukushima earthquake. An earthquake faulting of the 2016 earthquake is assumed by referring the aftershock distribution, and then the resultant tsunami was calculated numerically to obtain tsunami waveforms at offshore and coastal tsunami observing points. The obtained waveforms are regarded as observation data and used in the tFISH inversion.

Firstly, to know the tFISH performance for the event, the tFISH was applied to the synthetic data. Tsunami waveform data at S-net and GPS buoys from the origin time to 30 min of the earthquake were fed into the tFISH inversion. As a result, the estimate of initial tsunami height distribution did not resemble to the assumed one (i.e. true source in the simulation): long-axis of the estimated source is north-south direction, although the true one is northeast-southwest direction. The difference of the long-axis direction directly leads to the difference of tsunami-energy directivity, resulting in degrading tsunami-height prediction along the coast. The cause of the source misestimation is that the spatial size of the elemental source is too large to express the true source. Actually, short-period tsunami waveforms observed at S-net are less modeled in the inversion.

Then, to solve the problem, a two-steps inversion is proposed in this study: at the first step, the conventional tFISH inversion is performed. Then, we consider that if the estimated source is expressed by extremely small number of elemental sources (e.g., one source only), the true source may be smaller than the elemental one. When this criterion is satisfied, we go to the next step. At the second step, we perform tsunami-waveform inversion with elemental sources whose sizes are much smaller than the original ones (here, 4 km size, the one-fifth of the original). In the inversion, the small-size elemental sources are distributed to sea area where tsunami source is imaged in the first-step inversion, in order to reduce the number of unknown parameters. After that, we decide whether or not the source model at the second step is chosen as the final solution by using the following criterion: the comparison between observed tsunami waveforms and the calculations in the inversion shows the better agreement than in the first-step inversion. We used tentative values for two criteria in the new approach and applied this algorithm to synthetic data from the 2016 Nov. off Fukushima earthquake and succeeded in avoiding the misestimation of long-axis of the source that is critical for tsunami directivity.

Keywords: Tsunami, Real-time forecasting, Inverse problem

Observations of sea surface heights using an airborne radar altimeter for great tsunamis early detection

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Most tsunami forecasting systems rely on the predicted magnitude and epicenter of an earthquake. This system sometimes underestimates the tsunami, especially when the magnitude of associated earthquake is large and the tremor continues for a long time. Recently, attempts to detect the tsunami directly by satellite radar altimeter have been proposed (e.g., J. Gower, 2007). The studies suggest that satellite radar altimeters are capable of detecting the tsunami, however real-time detection is still difficult due to the low frequency of sampling possessed by satellite systems. In this study, we suggest to detect tsunami directly by airborne radar altimeters.
We performed nadir pointing observations using Frequency Modulated Continuous Wave (FMCW) radar, which is attached to the bottom of an airplane body. The radar observation procedure is basically similar to the present satellite radar altimeter. However, in airborne observation, airplane altitude is changing by a few meters at any time during the flight. Thus, a precise prediction of airplane positions by Global Navigation Satellite System (GNSS) is also important. We estimated the position and altitude by a baseline kinematic analysis. We then estimated the averaged sea surface height (SSH) by the radar altimeter observation and the GNSS analysis result.
We conducted airborne observations once in June 2016, and twice in December 2016. To check the precision of SSH measurements, the flight days and paths were decided according to the satellite SSH altimeter Jason-2 and Jason-3 schedules. We measured the SSH several times and compared with the Jason results. After correcting the geoid and tidal changes, we confirmed that our observation error is less than 10 cm in average, which is sufficient to capture large tsunamis offshore. In the future, we expect to form a dense observation network by using multiple commercial airplanes equipped with the same radar altimeter, which enables real-time tsunami detections. We also expect that future developments of the radar technology can lead to a low operational and maintenance cost compared to the existing tsunami observing systems.

Keywords: tsunami forecast, airborne observations, radar altimeter, GNSS

Temporal variability of tsunami detection distance revealed by virtual tsunami observation experiments using HF radar

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We statistically examined the tsunami detection distance based on virtual tsunami observation experiments by using receiving signals of the Nagano Japan Radio Co., Ltd. (NJRC) HF radar during February 2014 installed on the Mihama coast, Japan and numerically simulated velocities induced by a M_w 9.0 Nankai Trough earthquake (Japan Cabinet Office's fault model case 3). In the experiments, the Doppler frequencies associated with the simulated tsunami velocities were superimposed on the receiving signals of the radar by the method developed by Gurgel et al. (2011), and the radial velocities were calculated from the synthesized signals by the fast Fourier transform. Tsunami arrival was then detected based on the temporal change in the cross correlation of the radial velocities, before and after tsunami arrival, between two range cells 3 km apart along beam 04. Combinations of HF radar systems and tsunami detection methods should be assessed as the onshore-offshore distribution of tsunami detection probability, because the detectability of tsunami wave will be affected by the signal-to-noise ratio and the tsunami magnitude in addition to the radar system specifications. We found that the detectability with a combination of NJRC radar system and our detection method primarily depends on the kinetic energy ratio between tsunami- and shorter-period background current- (BGC) velocities. In the onshore-offshore direction, the monthly average detection probability is over 90% when the energy ratio exceeds 5 (offshore distance: 9 km L 36 km and water depth: 50 m $< h <$ 600 m) and is about 50% when the energy ratio is approximately 1 (L = 42 km, h = 1,200 m). The probability reduced over the continental shelf slope with decreasing tsunami-induced velocities. For a certain range cell on the radar beam, the energy ratio temporally varied in accordance with the variations of ocean surface wave height, ionospheric electron density and also with the shorter-period BGC physics. The energy ratio significantly decreased when the extremely large wave height exceeded 5 m and/or the ionospheric electron density became greater. From statistical analyses of the Wakayama-Nanseioki GPS wave gauge, significant wave heights are smaller from spring to summer, that is to say, the receiving signals would be more intense in this season. Meanwhile, the ionospheric electron density of the F2 layer generally becomes greater in the season, which would lead to greater receiving noise in the daytime. In addition, the energy ratio also varies depending on the tsunami magnitude. When a weaker (greater) tsunami occurs, the energy ratio becomes small (large) and the maximum detection distance is thus expected to become shorter (longer). In the experiments, the tsunami detection distance found to be dependent on the energy ratio between tsunami- and shorter-period BGC velocities and sea surface state as well as receiving noise. This demonstrates that the virtual tsunami observation experiments for other seasons and/or for another coastal regions with varying tsunami magnitude are required to understand the tsunami detection performance of HF radars comprehensively. This study is the first step towards a comprehensive understanding of variability of the maximum tsunami detection distance and development of real-time detection methods.

Keywords: HF radar, Tsunami arrival detection, Detection probability, Virtual tsunami observation experiment, Energy ratio, Signal-to-noise ratio

A global assessment of tsunami hazards over the last 400 years

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This work is our contribution towards World Tsunami Awareness Day, which was proposed by the United Nations (UN) in 2015. We conducted a global tsunami hazard assessment for local regions, including low tsunami risk areas, based on a 400-year database which allows insight on potential future tsunamis based on the seismic gap. The resulting tsunami hazard could be displayed on a global map and enable us to easily observe the local effects of tsunamis. Two criterions were selected to represent the past 100 major earthquake generated tsunamis: first, the earthquakes must be larger than magnitude 7.5 and secondly, occurred after the year 1600. Based on the results of the simulation, the locations of modern tsunamis (from the periods of 1970 to 2016) greater than 2 meters in height, are limited to areas affected by the 2004 Indian Ocean Tsunami, and the 2011 Great East Japan Tsunami. Regardless, damaging tsunamis have been witnessed everywhere in the world, especially along the Pacific Rim. This observation shows the importance of assessing or knowing the hazards based on historical events beyond our memory. Comparisons between tsunami height and wave force show that only using the tsunami height might underestimate the building damage. We wish that as a part of the World Tsunami Awareness Day related activities, our results and findings will increase tsunami awareness at the global scale, especially in comparatively low tsunami risk areas, and reduce human loss from future tsunamis.

Keywords: Tsunami hazard assessment, Global scale, World tsunami awareness day

Tsunami inversion for sea surface displacement from far-field data of the 2011 Tohoku tsunami

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We investigate the initial tsunami sea surface displacement of the 2011 Tohoku earthquake by performing the tsunami waveform inversion with the data of far-field stations. Tsunami travel time difference up to 15 min and polarity reversal of initial phase between observed and synthetic waveforms have been pointed out for the stations with travel time larger than 3 hours (noted as "far-field"). The differences were mostly explained by the phase correction method (Watada et al., 2014, JGR), which accounts for the dispersion effects of tsunami loadings on the Earth, seawater compression, and gravitational potential change. By applying the phase correction method, we can convert synthetic waveforms of linear long wave into dispersive waveforms.

In this study, we attempt to improve the phase correction method by including the effect of ocean density stratification and calculating the realistic tsunami ray path, not along the great circle, which minimizes the tsunami travel time from the source to the station. The characteristic ocean depth 4 km is replaced by the corresponding depths along each path. We apply the improved phase correction method to waveforms of near-field stations (travel time < 3 hours, including wave gauges, GPS stations, and OBP-type stations) and far-field stations (only DART stations) in the single and multiple time window inversions. Our results show that ocean density stratification accounts for travel time delay up to 2 minutes. In addition, replacing the great circle distance and 4 km reference depth by the non-great-circle ray path length and corresponding depth account for up to 0.8 minutes in travel time.

The inversion result of only far-field data shows a long wavelength sea surface displacement in the source area with a crest of ~6.1 meters located at the midpoint of the epicenter and the trench. Inversion with only near-field data leads to a detailed result which locates a peak displacement of ~6.4 meters near the trench. In the result of both near- and far-field data, a compact ~6.9-meter-high peak displacement appears at the midpoint of the epicenter and the trench. An improved detailed result is obtained by combining near-field stations with far-field stations. The accurate calculation of far-field stations is essential for utilizing them in tsunami source studies and trans-ocean tsunami warnings.

Keywords: tsunami inversion, far-field, phase correction, 2011 Tohoku earthquake, trans-ocean tsunami

Frontal Pop-up Structures and Tsunami Earthquakes

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Tsunami earthquakes are special class of rare earthquakes that produce exceptionally large tsunamis from relatively small earthquakes (e.g., Kanamori, 1972; Polet and Kanamori, 2000; Okal, 1988; Lay and Bileck, 2007). These earthquakes are suggested to propagate up to the subduction front with low rupture velocities and stress drops, but it is not possible to produce large tsunamis from a slip on shallow dipping megathrust. Using recently acquired high-resolution seismic reflection, bathymetry and reflectivity data here we report the presence pop-up structures, bounded by steeply dipping thrusts, near the subduction front and fresh traces of seafloor ruptures in the 2010 Mentawai tsunami earthquake rupture zone (Hill et al., 2012; Singh et al., 2011; Lay et al, 2011; Newman et al., 2011; Bilek et al., 2011), indicating that the rupture reached to the seafloor. Using tsunami modelling study, we show that the co-seismic slip on these steeply dipping conjugate thrusts can uplift the water-column, produce a large localised tsunami, and can explain the observed tsunami on the neighbouring islands. These results suggest that the pop-up structures at the subduction front might be the main cause of tsunami during tsunamigenic earthquakes, and can be used for tsunami mitigation study.

Keywords: tsunami earthquake, surface rupture, pop-up structures

A possible source model of the 1512 Eisho tsunami described in an ancient document

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Interplate earthquakes repeatedly occur in the subduction zones such as the Nankai trough. We must learn the past earthquakes to anticipate disasters caused by the future earthquakes. Investigations by using ancient documents and geological ways are necessary for the earthquakes and tsunamis older than 100 years because the instrumental observations are limited within a period of the latest 100 years.
"SHINCHO-KI" is an ancient document that records damages caused by the 1512 Eisho earthquake, the 1605 Keicho earthquake, the 1707 Hoei earthquake and the 1854 Ansei-Nankai earthquake at Shihikui region in Tokushima, where is located along the coast of the southeastern part of Shikoku, facing to the Nankai trough. According to SHINCHO-KI, 3700 people were dead at Shishikui by the tsunami during the 1512 Eisho earthquake. However, no evidence was found for the occurrence of 1512 Eisho earthquake except for SHINCHO-KI, while the other earthquakes were recorded in many ancient documents in the southwestern Japan. Therefore, the 1512 Eisho tsunami might be a local tsunami. In this study, we suggest a possible source mechanism of the 1512 Eisho tsunami. For example, the tsunami associated with the 1998 Papua New Guiana earthquake was enhanced by a submarine mass movement. That resulted in the large tsunami up to 15 meter which was locally apparent in the Sissano lagoon.
We carefully read a bathymetric chart and found a scarp with height of about 400 m and width of about 6000 m at a position about 24 km offshore in the southeastern direction from Shishikui. We also carried out a survey by using a deep-towed sub-bottom profiler (SBP) on ROV NSS during the R/V Hakuho-maru KH-16-5 cruise. The result shows detailed structures possibly caused by a recent landslide. The vertical displacement of the strata was measured to be about 50 m. By considering these results, we constructed a model of submarine mass movement and calculated the initial sea surface displacement by a method of Watts et al. (2005). We investigated several cases by changing movement distances from 800 to 3000 m because it is unknown for one event. For the numerical tsunami simulations, we solved the nonlinear shallow water equations by a finite differential method with a nested grid algorithm which allows the spatial resolution of the study region to be easily increased. The topographic data in Shishikui was made from the present data. But we removed the artificial structures such as wave breakers and altered costal lines by referring to old map images. The numerical summations indicated that the flow depths during the 1512 Eisho tsunami described in SHINCHO-KI could be simulated by the causes using a range from 1400 to 2400 m of movement distance of the submarine mass movement. The maximum tsunami heights of 6 –9 m were calculated at Shishikui in these cases, while it was 3 m at the maximum along the Kii Peninsula located at the opposite side of the Kii Channel.

Keywords: Historical earthquake, Tsunami, Submarine land slide

Numerical modeling of tsunami inundation using upscaled surface roughness parameterization

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The importance of accurate numerical modeling of tsunami inundation in an urban area has clearly realized due to the devastating damage from the 2011 Tohoku Earthquake Tsunami and the expected high occurrence probability of Nankai Trough Earthquake. This study conducted two different upscaled surface topography parameterizations: 1) composite equivalent roughness model, and 2) drag force model, to consider the effect of structures as drag force based on detail of topographical data. Numerical results from the two surface roughness parameterizations are compared to the experimental results of a coastal city model focused on the maximum inundation depth, maximum inundation area, and its arrival time. Both the composite equivalent roughness model and the drag force model generally showed good agreement with the experimental results. The composite equivalent roughness model is superior to the drag force model in the area with low occupancy of structures. However, the drag force model shows better results of maximum inundation depth and arrival time to the experimental result at the near the edge of inundation area than the composite equivalent roughness model. The drag force model can reproduce flow direction dependency to some extent. There are several points to be improved (e.g. grid size dependency for calculating roughness parameters on the results, and of the determining the drag force coefficient).

Keywords: Tsunami, Storm surge, Bottom surface roughness, Manning, Upscaling

Tsunami Preparedness: **Is Zero Casualties Possible?**

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An important element of tsunami preparedness is the method to evacuate people from the flooding dangers of tsunamis before the tsunami arrives. The most common evacuation method is horizontal evacuation where threatened people escape to a safe area outside the tsunami hazard zone aided by well marked evacuation routes. In situations where there is insufficient time to evacuate to a safe area, some communities have established vertical evacuation procedures where evacuees seek shelter in structures that allow evacuees to rise above the flooding depth of the tsunami. These structures take several forms, including reinforced concrete building, specialized evacuation towers, or high elevation topography. Horizontal and vertical evacuation methods were put to the test during the 2011 Japanese tsunami. In general, these two methods saved about 95% of the threatened population. In order to achieve the goal of “Zero Casualties”, a third method of shelter in place option will be presented that will save the lives of people who are unable (i.e. elderly, disabled, small children) or unwilling (i.e. don’t trust the warnings, don’t want to go to an evacuation shelter with many people) to evacuate either horizontally or vertically. The shelter in place option takes the form of a survival capsule, a metal protective shell exclusively designed to survive the hostile tsunami environment.

Keywords: Tsunami Preparedness, Shelter in Place , Survival Capsule

