

JMA's Tsunami Warning Improvement Plan

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After the devastating damage caused by the 2011 off the Pacific coast of Tohoku Earthquake, the Japan Meteorological Agency (JMA) established the Advisory Meeting for Tsunami Warning Improvement (June-September 2011) to consider the strategic plan on JMA's tsunami warning improvement, inviting tsunami experts and relevant disaster management organs. Based on the Advisory Meeting's discussion, JMA crafted the Tsunami Warning Improvement Plan in September 2011. To tailor the expression of tsunami warning messages along the context of the plan, JMA held another advisory meeting, i.e., the Advisory Meeting on Tsunami Warning Criteria and Bulletin (September 2011 to January 2012), focusing on. The Advisory Meeting summarized the recommendation on tsunami warning criteria and expression of warning messages in February 2012. In this paper, the measures to improve JMA's tsunami warning in line with the above mentioned improvement plan and recommendation are outlined.

The major issue of JMA's tsunami warning for the 3.11 event was that the 1st bulletin of tsunami warning issued three minutes after the quake was based on underestimated $M_{jma}7.9$, and thus underestimated tsunami height of 3m or 6m might have resulted in the delay of evacuation. M_{jma} , equivalent to surface wave magnitude (M_s) for shallow events, has an advantage of fast availability, but inherently saturates at around 8. To deal with this problem, JMA will introduce tools with which validity of M_{jma} estimation can be evaluated before the 1st tsunami warning issuance. If the possibility of much larger magnitude than M_{jma} estimation is detected by the tools, JMA will issue tsunami warning by replacing the magnitude by the maximum credible magnitude around the region close to the epicenter. In this case, as there is large uncertainty of tsunami height estimation, JMA will not issue tsunami height estimation numerically but qualitatively aiming at conveying emergency situation to the people.

For the 3.11 event, JMA could not calculate M_w within 15 minutes as with JMA's normal operation, because very large seismic waves went off the scale of most of JMA's broadband seismographs. And offshore tsunami observation data of cabled ocean-bottom pressure gauges deployed around Japan could not be applied for tsunami warning update. These issues led to the delay of tsunami warning upgrade for the 3.11 event. In order to deal with these matters, JMA is planning to deploy 80 new broad-band seismographs with larger measuring range to calculate M_w within 15 minutes in case of such a huge earthquake as the 3.11 event, and promote the utilization of ocean-bottom pressure gauges. In the updated tsunami warning bulletin based on M_w , tsunami height estimation is expressed numerically, because the uncertainty is diminished enough at this stage.

Tsunami height categorization will be decreased from eight (0.5m, 1m, 2m, 3m, 4m, 6m, 8m, ≥ 10 m) to five (1m, 3m, 5m, 10m, > 10 m), taking into account the realistic variation of countermeasures in time of emergency and forecast error range. Estimated tsunami height shown in the bulletin is the maximum value in the margin of error.

The above described tsunami warning improvement measures will be put into operation by the end of 2012, subject to the schedule for system modification of not only JMA but also the organs responsible for transmitting and using tsunami warning bulletin.

Keywords: Tsunami warning, Improvement plan

Table 1: Category and criteria of tsunami warning and tsunami height estimation

Category		Present	Improvement Plan		
		Expression of tsunami height	Expression of tsunami height		Estimated height
			Numerical	Qualitative	
Tsunami Warning	Major Tsunami	10 m or more, 8m, 6m, 4m, 3m	Over 10m	Gigantic *)	10m -
			10m		5m - 10m
	5m	3m - 5m			
	Tsunami	2m, 1m	3m	High *)	1m - 3m
Tsunami Advisory		0.5m	1m	(Blank)	0.2m - 1m

*) Expression in English is under consideration.

Research for Improvement of the JMA Tsunami Warning System

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1. Introduction

The 2011 off the Pacific coast of Tohoku Earthquake that is the largest earthquake of Mw=9.0 ever recorded in Japan has caused devastating damages especially by a gigantic tsunami. So many lives were lost by the tsunami, even though Japan Meteorological Agency (JMA) had issued a tsunami warning 3 minutes after the occurrence of the earthquake. So, JMA set up a committee consisting of academic and administrative experts to investigate the problems that should be solved for a better tsunami warning system. This presentation will introduce an overview of our project that aims to develop new techniques to solve the problems pointed out by the committee.

2. Problems for the Current Tsunami Warning System

The committee report says there are two major technical problems to be improved.

1) The first tsunami warning issued 3 minutes after the earthquake underestimated the tsunami heights because the magnitude was underestimated as M=7.9 at that time, and JMA could not recognize the fact of underestimation. It is crucial to develop a technique to estimate magnitude correctly for great earthquakes such as over M8.0 in a short enough time to issue the first warning.

2) The moment magnitude, which should have been calculated within 15 minutes after the earthquake, could not be calculated because of the scale out of the broad-band seismometer. Besides, the information of tsunami arrival at offshore area that was observed by ocean bottom pressure gauges (OBPGs) was not well utilized to update the tsunami warning, because the technique to utilize that information had not well been established. These prevented a prompt renewal of tsunami warning.

3. Improvement of the Tsunami Warning System

To overcome the above mentioned problems we are conducting the following researches.

1) We are developing methods to estimate the magnitude correctly for great earthquakes in a short time, or at least to judge if the magnitude becomes larger than 8.0. Four methods are proposed to estimate the magnitude and listed below.

- Method using the distribution of strong ground motion area
- Method to estimate Mwp using P arrival wave forms
- Method using duration times of strong ground motions
- Method comparing wave forms filtered with various frequency bands

2) In order to utilize the information of offshore arrival of tsunami waves, we are developing a new technique. The method consists of two steps. First, we estimate the initial variation of sea surface caused by an earthquake by applying the inversion method to the observed offshore tsunami waveform data. Then we forwardly calculate the tsunami waveforms along coasts using the estimated initial distribution of sea surface elevation. This method is applicable to forecasting tsunamis caused not only by earthquakes but also by marine landslides. As for enhancement of the offshore observation network, JMA is planning to deploy three buoy-type OBPGs late in 2012.

3) In the tsunami forecast using offshore data, the accuracy of observed tsunami plays an important role. But, there are two difficulties in getting precise tsunami waveforms when we use OBPG data observed near the seismic source region. The first is a problem concerning the thermal response of the pressure gauge to sudden temperature change on deep ocean floor. The second is to resolve the tsunami signals from contaminated high frequency pressure fluctuation that is caused by a nearby earthquake. To overcome the difficulties, we are estimating the characteristics of OBPG data and planning to develop a new type of OBPG.

4) JMA is planning to deploy the broad-band strong motion seismometers at 80 stations over Japan that do not scale out against strong ground motion, which will enable us to calculate Mw within 15 minutes after a great earthquake.

Keywords: Tsunami Warning, JMA, Prompt Magnitude Estimation, Offshore Tsunami Gauge, Waveform Forecast

Rapid coseismic displacement detection/estimation algorithm and its application to the 2011 Tohoku-Oki earthquake

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Real-time crustal deformation monitoring is extremely important for achieving rapid understanding of actual earthquake scales, because the measured permanent displacement directly gives us the true earthquake size (seismic moment, M_w) information. We have developed an algorithm to detect/estimate static ground displacements due to earthquake faulting from real-time kinematic GPS time series. Our algorithm identifies permanent displacements by monitoring the difference of a short-term average to a long-term average of the GPS time series [1]. We applied the algorithm to data obtained in the 2011 off the Pacific coast of Tohoku earthquake (M_w 9.0) to test the possibility of coseismic displacement detections, and further, we inverted the obtained displacement fields for a fault model. Estimated a fault model with M_w 8.7, which is close to the actual M_w of 9.0. We also applied the algorithm to data of aftershocks of the 2011 M9 earthquake. We succeed in detecting the coseismic step caused by Iwate-oki earthquake (March 11, 15:08 (JST), M_w 7.4) and Ibaraki-oki earthquake (March 11, 15:15 (JST), M_w 7.7). For the Ibaraki-oki earthquake, we evaluated the coseismic fault model estimation. The inversion estimated a fault model with M_w 7.7, which is same with the actual one determined by the seismic data [e.g. 2].

The false detection of the permanent displacement should avoid for reliable warning system. Based on the long-term varied baselines and different reference sites posterior processing, we estimated the false detection rate reached $\sim 0.25\%$ with 4-sigma confidential limit in single baseline. This false detection rate is inadequate to work for practical use in dense GPS network (many baselines) such as GEONET. We improved permanent displacement detection algorithm for reduction of the false detection rate. In the improved algorithm, the earthquake occurrence is defined as all neighboring GPS sites must be detected the displacement including oneself. We applied the improved algorithm to actual data set. The false detection rate clearly decreases with our improved algorithm, which is little more than zero. When we can use the several reference sites for the RTK-GPS data processing and compared with each reference site result, the false detection rate will become almost zero. The improved algorithm is also useful for small displacement detection because the threshold value is possible to cut down to 2 or 3-sigma confidential limit.

[1] Ohta et al., JGR, 2012 [2] Hirose et al., EPS, 2011

Global tsunami simulations from seismic CMT solutions: Developing a real time tsunami simulator

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Because the earthquake does not always occur with the anticipated magnitude, it is important to quantitatively predict tsunami height and its arrival time based on a real-time simulation with the seismic magnitude and the mechanism correctly estimated from the observed seismograms. This study develops a tsunami simulator that calculates the tsunami propagation from the seismic CMT solution estimated by the real-time seismogram analyses. The simulation is conducted with the whole earth model in order to calculate the tsunami from the earthquakes occurred in any oceans and include all the waves scattered from all the coasts and sea-bottom topography. Focusing on the tsunami in offshore regions, which does not show strong nonlinear behavior, we can rapidly synthesize the tsunami waveforms from arbitrary initial tsunami-height distributions by superposing the Green's functions loaded from the database constructed in advance.

In order to examine the validity of this simulator, we conducted a tsunami simulation for the 2011 Tohoku-oki earthquake. The moment magnitude of the CMT solution was estimated as MW 8.8 from the seismograms recorded by the velocity-type strong motion seismographs in Japan. Employing a scaling relation between the moment magnitude and the earthquake fault size, we obtained a uniform slip of 15 m on the fault of 300 km in length and 150 km in width. We calculated the initial tsunami height distribution from the fault model and simulated the tsunami propagation from the tsunami source. The simulation can successfully reproduce the tsunami height more than 4 m off the coast of Miyagi (observed height is ~5.8 m, and calculated is ~4.8 m). However, it was difficult to reproduce the detail of the waveforms because we employed a simple fault model in the simulation.

For the 2006 Kuril earthquake, tsunami warning/advisory was issued at the Japanese coast of the Pacific Ocean and canceled the warning/advisory 5 hours after the earthquake occurrence. But, the maximum tsunami height arrived at some parts in northeastern Honshu, Japan after the cancelation. The tsunami scattered from the Emperor seamounts constitutes the maximum tsunami height [e.g. Koshimura et al. 2008 GRL]. The ocean-bottom pressure gauges located at Sagami bay recorded the leading tsunami and the maximum-height tsunami at 2 hours and 8 hours after the earthquake occurrence, respectively. Our tsunami simulator can successfully simulate the arrival times of both the leading wave and the maximum wave, whereas it was impossible to simulate the maximum tsunami arrival if we limit the simulation area to around Japan.

Keywords: tsunami, simulation, CMT solution

Tsunami simulation using submarine displacement calculated from simulation of ground motion due to seismic source model

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Since fault fracturing due to an earthquake can simultaneously cause ground motion and tsunami, it is appropriate to evaluate the ground motion and the tsunami by single fault model. However, several source models are actually used independently according to whether the ground motion is evaluated or the tsunami, because of difficulty in evaluating both phenomena simultaneously.

Many source models for the 2011 off the Pacific coast of Tohoku Earthquake are proposed from the inversion analyses of seismic observations or from those of tsunami observations. Most of these models show the similar features, which large amount of slip is located at the shallower part of fault area near the Japan Trench. That indicates that the ground motion and the tsunami can be evaluated by the single source model.

In this study, we try to carry out the tsunami simulation using the displacement field of oceanic crustal movements, which is calculated from the ground motion simulation of the 2011 off the Pacific coast of Tohoku Earthquake. First, the large-scale ground motion simulation based on the voxel type finite element method is performed for the whole eastern Japan. The fault model based on the teleseismic body wave, which is constructed by the Japan Meteorological Agency, is assigned to the source region. The synthetic waveforms by the simulation are generally consistent with the observation records of K-NET and KiK-net. Next, the tsunami simulation is performed by the finite difference calculation based on the shallow water theory. The initial wave height for tsunami generation is estimated from the vertical displacement of ocean bottom due to the crustal movements, which is obtained from the ground motion simulation mentioned above. Although the results of tsunami simulation show that synthetic waveforms are fairly consistent with the observations of the GPS wave gauges, the comparisons of synthetics and observation show that the tsunami simulation in this study underestimates the maximum wave height in most observing stations.

Although the results of these simulations generally indicate the possibility that a phenomenon of tsunami can be evaluated using the source model from seismic analysis, there remain difficulties in evaluation of the tsunami maximum wave height, which is one of the most important issues in disaster prevention.

Keywords: the 2011 off the Pacific coast of Tohoku Earthquake, tsunami, ground motion, source model, simulation

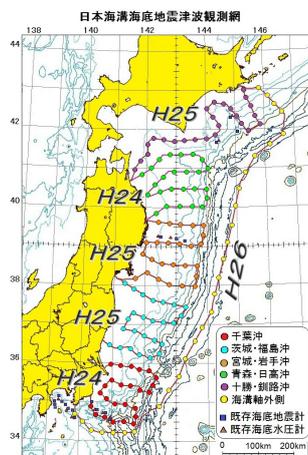
Ocean bottom seismic and tsunami network along the Japan Trench

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Huge tsunami, which was generated by the 2011 off the Pacific Coast of Tohoku Earthquake of M9 subduction zone earthquake, attacked the coastal areas in the north-eastern Japan and gave severe casualties and property damages in the areas. The present tsunami warning system, based on land seismic observation data, did not work effectively in the case of the M9 earthquake. It is strongly acknowledged that marine observation data is necessary to make tsunami height estimation more accurately. Therefore, new ocean bottom observation project has started in 2011 that advances the countermeasures against earthquake and tsunami disaster related to subduction zone earthquake and outer rise earthquake around Japan Trench and Chishima Trench. A large scale ocean bottom cabled observation network is scheduled to be deployed around Japan Trench and Chishima Trench by 2015. The network is consisted of 154 ocean bottom observation stations. Ocean bottom fiber optic cables, about 5100 km in total length, connect the stations to land. Observation stations with tsunami meters and seismometers will be placed on the seafloor off Hokkaido, off Tohoku and off Kanto, in a spacing of about 30 km almost in the direction of East-West (perpendicular to the trench axis) and in a spacing of about 50 - 60 km almost in the direction of North-South (parallel to the trench axis).

Keywords: Ocean bottom cable, Realtime observation, the Japan Trench, Tsunami monitoring, Ocean bottom seismic observation, Warning



An Offshore Experiment of Tsunami Monitoring System using GPS Buoy

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In the process of development of a GPS tsunami meter, the basic experiment in the Sagami bay, the utilization experiment off Ofunato, and the actual proof experiment off Muroto have been conducted. Five tsunamis were observed by a series of experiments. These observation results proved that the measurement accuracy of tsunami height was an order of cm. The Ministry of Land, Infrastructure, Transport and Tourism utilized the development result of the GPS tsunami meter, and started national deployment of the GPS buoy. The system has been adopted as a part of the nationwide ocean wave information system for port and harbors (NOWPHAS). The real-time tsunami records of 11th March 2011 Tohoku-Oki earthquake tsunami observed by GPS buoy of NOWPHAS. Over 6m tsunami height is observed at the Off South Iwate (Kamaishi). The Japan Meteorological Agency which observed this data updated the level of the tsunami warning to the greatest value.

Currently, the GPS buoy system uses a RTK-GPS which requires a land base for precise positioning of the buoy. This limits the distance of the buoy from the coast to, at most, 20km. In order to overcome this problem, introducing a new algorithm of precise point positioning with ambiguity resolution (PPP-AR) method and point precise variance detection (PVD) method are planned for 100km offshore observation. Also, an open source program package (RTKLIB) for super-long baseline is applicable for this purpose. So, the new experiment at off Muroto is started just now using these GPS positioning methods. The positioning results will be exhibited in real time on the internet (<http://www.tsunamigps.com/>) after tuning the system. In this experiment, the fish float buoy named Kuroshibokujou borrows for the GPS buoy under the cooperation of Kochi Prefecture.

Keywords: GPS, Tsunami-meter, PVD, PPP-AR

Sea-level observation with ultra-low power radio telemetry for the last minutes tsunami warning

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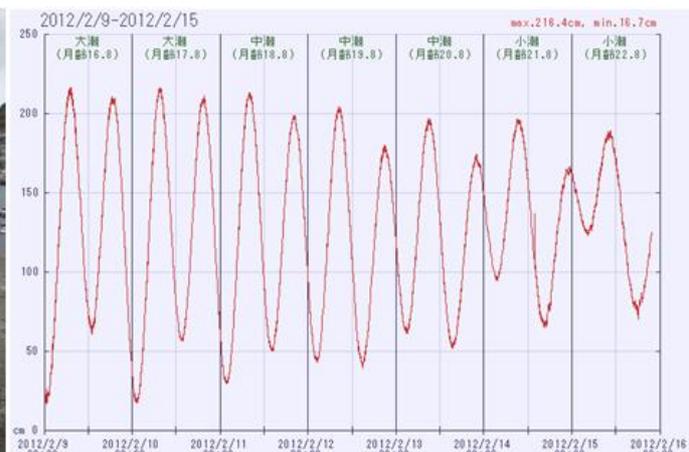
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One of the reasons why many people have lost their lives by the Great East Japan Earthquake of March 11, 2011 is that the people could not realize the approaching massive tsunami due to various problems. If accurate information of tsunami, even only several minutes before arrival, was provided to the people, number of casualties would have been smaller. A network of ocean bottom cables and buoys to directly measure the sea level will be deployed along the Japanese coast to improve the early warning system. If tsunami approaching the coast, propagating in bays is monitored in the last some tens of minutes until it hits cities, people would be able to take more appropriate action of evacuation.

For such purpose we have to install tide gauges on near-shore islands, tip of a cape, and along the coast line of a bay. We develop a system which enables such installation using MAD-SS, a very slow but ultra-low power spread spectrum radio developed by Mathematical Assist Design Laboratory. It transmits only 1 byte per second, over the distance of 100km line of sight with only 10mW VHF radio. It can be operated more than several months by a pack of dry-cell batteries or a small solar panel. Unlike using cell-phone system, the radio telemetry is reliable even during a crisis and free of charge. The system consists of a water pressure sensor, a digitizer, and a radio transmitter built in a pipe, and easy to install.

We installed a system for testing at a breakwater on Kamishima Island located at the mouth of Ise-bay to transmit the data to Mie University campus in Tsu city 45 km away. Another system was tested at Hasaki Oceanographic Research Station of PARI, in Ibaraki Prefecture, for the purpose of developing installation method at sand beach, which gives more freedom to the location of installation. Deployment of the systems to Albay Gulf and Manila Bay of the Philippines, and Pandang Island off Padang, West Sumatra Indonesia are planned. Installing the system to Pacific Island Countries will contribute to enhance monitoring capabilities of distant tsunamis for the whole Pacific.

(We are grateful to Prof. Hanazato of Mie University and Dr.Nakamura and Mr. Yanagishima of Port and Airport Research Institute for providing their facilities for the observation.)



Tsunami induced ionospheric disturbances detected by GPS-TEC observation after the 2011 Tohoku earthquake

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All the details of the commencement and evolution of ionospheric disturbances after the 2011 off the Pacific coast of Tohoku Earthquake were revealed by the high-resolution GPS total electron content observation in Japan. The initial ionospheric disturbance appeared as sudden depletions by about 6 TEC unit (20%) following small impulsive TEC enhancements around 05:54UT, about seven minutes after the earthquake onset, near the epicenter. At 06:00UT, zonally extended enhancements of TEC appeared in the west of Japan, and traveled to the southwest direction. From 06:00UT to 06:15UT, large-scale circular waves with two peaks propagated in the radial direction in the propagation velocity of 3,457 m/s and 783 m/s for the first and second peak, respectively. Following the large-scale waves, medium-scale concentric waves appeared to propagate at the velocity of 138-423 m/s after 06:15 UT. In the vicinity of the epicenter, shortperiod oscillations with period of about 4 minutes were observed after 06:00 UT for 3 hours or more. We focus on the the circular and concentric waves in this paper. The circular or concentric structures of the large- and medium-scale waves indicate that these ionospheric disturbances had a point source. The center of these structures was located around 37.5 deg N of latitude and 144.0 deg E of longitude, 170 km far from the epicenter to the southeast direction. We termed this center of the coseismic ionospheric variations as "ionospheric epicenter". According to the propagation velocities, the large-scale waves would be caused by the acoustic waves generated from the propagating Rayleigh wave for the first peak and from the sea surface near the epicenter for the second peak. The wavelength and the propagation velocity of the medium-scale concentric waves tended to decrease with time. This characteristic is consistent with the result of a numerical model of the coseismic atmospheric wave, indicating that these medium-scale waves were caused by the atmospheric gravity waves. The amplitude of the large- and medium-scale circular waves were not uniform depending on azimuth of their propagation direction, much larger in the north and west directions than other directions. This directivity could not be explained by the previously proposed theory.

Keywords: ionosphere, earthquake, tsunami, acoustic wave, atmospheric gravity wave, concentric wave

Generation and propagation of the 2011 Tohoku earthquake tsunami inferred from the OBEM array in the North-West Pacific

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The 2011 Tohoku earthquake tsunami caused a destructive damage along the shoreline from the Tohoku to Kanto districts. Because many of the tide gauge stations along the Tohoku coast were damaged by the tsunami, source process of the tsunami has not been well determined yet. After the Tohoku earthquake, several cruises of JAMSTEC research vessels recovered Ocean Bottom ElectroMagnetometers (OBEMs) from the seafloor sites in the North-West Pacific area, where the OBEMs had been installed before the earthquake. These sites are BM14 (39.058N, 144.808E, 5830m; recovered by NT11-08), NWP (41.103N, 159.952E, 5816m; recovered by KR11-07), and NM04 (38.211N, 154.190E, 5940m; recovered by KR11-10). OBEMs from these sites clearly recorded the ElectroMagnetic(EM) tsunami signals.

Seafloor measurement of the EM signals due to tsunamis had not been attained until very recently (Toh et al., 2011) because of their low signal levels. However, recent advances in technology enabled the seafloor measurements of the tsunami EM signals by using OBEMs. First simultaneous measurements of EM signals and bottom pressure during the passage of 2010 Chile earthquake tsunami in the French-Polynesia region (Hamano et al., 2011), proved that seafloor observation of EM signals is powerful tool to investigate the generation and propagation of tsunamis in the open sea, in which temporal variations of the vertical magnetic field, B_z , reproduce the variations of the sea level change due to the passage of tsunami wave, and two horizontal magnetic fields, B_x and B_y , indicate the propagation direction of tsunamis. As for the Tohoku earthquake, combination of the three OBEM stations with the tsunami monitoring stations ST2418 (38.718N, 148.698E, 5500m), ST21413 (30.528N, 152.123E, 5874m), and ST21419 (44.455N, 155.735E, 5285m) operated by NOAA, comprises an observational network for the tsunami located in the east of the fault plane of the Tohoku earthquake, which provides valuable information on the generation and propagation of the 2011 Tohoku earthquake tsunami. Among the network stations, the OBEM at site BM14 recorded the tsunami arrival after 4 minutes of the origin time of the Tohoku earthquake. This early observation at the closest place to the tsunami source enable reliable estimate of the source process of the tsunami (Ichihara et al., 2011). Here, we report the propagation process of the tsunami inferred from this tsunami observational network. By taking cross-spectra of the 24 hours signals of sea level change from each station correspond to the signals from BM14 (closest site to the tsunami source), dispersion relations of the tsunami wave across the network were calculated. The result indicates that the tsunami generated just west to site BM14 propagates across the line from BM14 through ST21418 to NM14. This west to east propagated tsunami wave shows a dispersion relation consistent with the theoretical estimate of gravity waves corresponding to the water depth of 5500 m. The dispersion shows that the decrease of phase velocity by about 15 % from the period of 20 minutes to 3 minutes. Cross-spectra of the records from ST21413 and ST21418 to that from BM14 indicate that the tsunami arrived at these sites propagate along west-east direction, suggesting the sources for the tsunami passing through these two stations are different from the source responsible for the tsunami propagated along the BM14-ST21418-NM14 line.

Keywords: tsunami, electromagnetic observation, sea floor observation, ocean dynamo effect, 2011 Tohoku earthquake

Magnitudes of the Aleutian Tsunamis in Nov. 2003 and Jun. 2011 – Deviation of Tsunami Heights on the Pacific Region

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The Aleutian earthquakes occurred on November 17, 2003 (51.40N, 178.60E, Mw7.7) and June 24, 2011 (52.008N, 171.860W, Mw7.2), US accompanying with tsunamis. The 2003 tsunami was observed in the whole Pacific tidal stations (double-amplitude 52cm at Shemya). Semi-amplitude of the 2011 tsunami was 6cm at Adak. Source area of the 2003 tsunami estimated by the inverse refraction diagram with the aftershock area, lies along the depth counter of 3000m, extending 130km located in the source area of the 1965 tsunami. The source of 2011 lies 60km in the S-N direction in the 1957 tsunami source. Judging from the author's method based on the attenuation of tsunami height with distance, magnitudes of tsunamis in 2003 and 2011 are determined to be $m=1$ and $m=0$, respectively. It is well known that the Hawaiian Islands have suffered severe damage by the 1946 Aleutian tsunami, and Crescent City, California also inundated by the 1964 Alaska tsunami.

The locality of tsunami height deviation from the average tsunami magnitude is discussed for the five Aleutian-Alaska tsunamis. The deviated magnitude values in California, Chile and Hawaiian Islands are the 1-3 grades (tsunami height- 2-to times) larger than the mean magnitude. Tsunami heights in Japan are the mean values or less. The deviated heights at each region are different from the epicenter location, because of the directivity effect.

Keywords: Aleutian-Alaska tsunamis, Tsunami magnitude, Directivity of tsunamis

Heights of the tsunami of the Empo Boso-Oki earthquake of November 4th, 1677

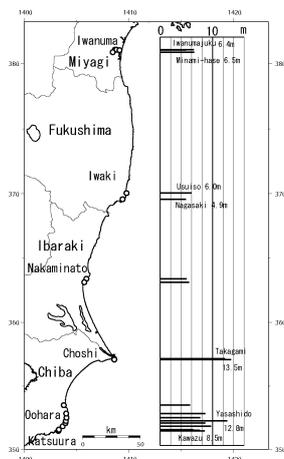
TSUJI, Yoshinobu^{1*}, KENTARO, Imai², YANUMA, Takashi³, MABUCHI, Yukio³, OOIE, Takayuki⁴, OKADA, Kiyohiro⁴, IWABUCHI, Yoko⁵, IMAMURA, Fumihiko²

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The tsunami height distribution of the Boso-Oki earthquake of November 4th, 1677 had been studied by Hatori(1975, 1979, and 2003), Tsuji(1994) and Takeuchi et al.(2007), but most of those results were estimated ones by their damage grade. In the present study we newly estimated tsunami heights with considering ratio of damages houses with total number of houses in each damaged coastal village, and we made exact measurement at all villages where description of tsunami damage was recorded in old documents. We clarified the lords who controlled each villages, and checked the configuration of residential area on the detailed map of 50,000 to one published in the period of the Meiji Era. We estimated the thickness of flooded water as 3 meters for the case that almost all houses were swept away in the residential area of a village, as 2.5 meters for the case that the number of swept away houses was about half of the total number of a village, as 2 meters for the case that the not over half of the total houses were swept away.

The highest inundation height of 13.5 meters height was measured at Takagami village in Choshi city, where sea water rushed into a pond and sea water flooded over the path whose height was 13.0 meters.

Keywords: historical earthquake, historical tsunami, Boso-oki earthquake, tsunami earthquake



Observation of azimuth dependence in dominant periods of the 2011 Tohoku Earthquake Tsunami

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Tide gage records of the 2011 Tohoku Earthquake Tsunami observed at tide stations around the Pacific Ocean were decomposed into the spectra. The records of twelve tide stations including Japanese two, Hanasaki and Chichijima, were downloaded from Internet sites, and after reducing the tidal level the spectra were calculated for time duration of 6 hours including the arrival time with time interval of 1 minute. From the energy density spectra dominant period was defined as a period of the maximum value. At the same time spectra of sea level oscillation at quiet sea condition observed at the same tide stations were calculated for time variation of 6 hours before the arrival to detect dominant periods based on the local topography.

As the result it proved that the tsunami brought a change of dominant period larger than 5 minutes in seven cases from those of the quiet sea condition. Generally, the displacement was generated toward an azimuth dependence predicted from the theory (Yamashita and Sato,1974), which is based on the assumption of constant sea depth. In the theory a reverse fault with low dip angle and the length of 450 km, the width of 200 km was assumed, and the spectra were estimated at the distance of 2000km. The theory predicts a variation of the dominant period for azimuth relative to the strike direction. Dominant periods of the tsunami and the seiche are shown in Figure 1 with a predicted curve of 6000m in sea depth. Thus, it is concluded that observed dominant periods showed an azimuth dependence characteristic to the radiation of faulting source.

Keywords: azimuth dependence, 2011 Tohoku Earthquake Tsunami, dominant period, tide gage records

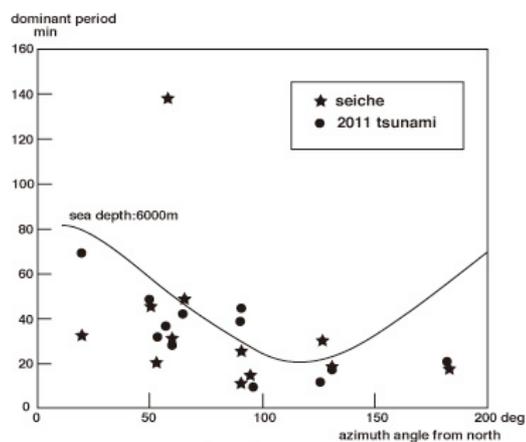


Figure 1

Origin of the reversed initial amplitude of distant tsunami

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Distant tsunami waveforms recorded at deep open sea from the 2010 Chile earthquake and the 2011 Tohoku-Oki earthquake show a reversed prolonged small initial tsunami phase arrival, which is easily identified by the reversed polarity of the large amplitude tsunami arrival following the small-amplitude initial phase arrival. The small reversed polarity before the main peak is visible in the original tidal pressure data and not introduced during the de-tide process. Thanks to the low noise DART data from large earthquakes, the arrival of the small initial phases at distant buoys are identified as early as 1 hour before the arrival of large amplitude tsunami with a reversed polarity. The small initial amplitude is as large as 10 % of the amplitude of the main phase at largest distances. Such an initial phase is not observed at buoys near the earthquakes.

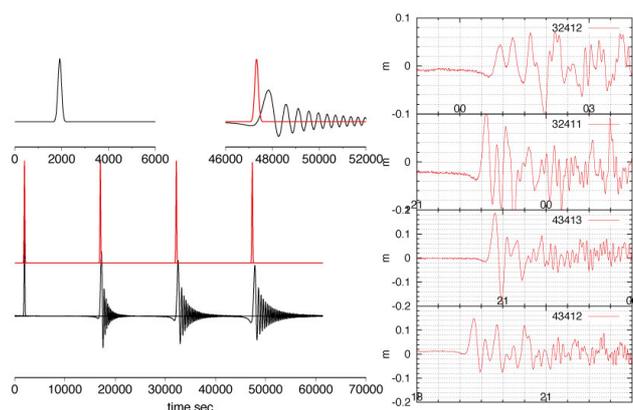
The synthetic tsunami for 1D PREM earth model including the effect of the elastic crust, mantle, and core of the earth, and the effect of the compressibility of the ocean water, and the effect of the gravity potential change caused by the motion of the mass of the water and the solid earth during the tsunami propagation, has been computed. Compared with the tsunami synthetics waveforms computed based on a conventional non-dispersive long-wavelength water waves, the tsunami for 1D earth shows a delayed arrival of the main amplitude peak of the tsunami, in addition to a prolonged small initial amplitude phase with reversed polarity before the main peak.

Two features, delayed arrival of the main amplitude peak and the small amplitude initial phase with a reversed polarity, are successfully re-produced by the tsunami computation for 1D PREM earth model.

The small initial tsunami with a reversed polarity observed at distant locations is caused by the dispersion of the long-wavelength tsunami, and should not be misinterpreted as an evidence of a precursory crustal movement prior to the large earthquakes.

Figure Left: shows synthetic tsunami waveforms of dispersed tsunami and non-dispersive tsunami. Right: observed tsunami waveform at DART buoys after the 2011 Tohoku-Oki earthquake.

Keywords: tsunami propagation, initial amplitude anomalies, Tohoku-oki earthquake, Chile earthquake, GPS wave gauge, ocean bottom pressure gauge



Numerical modeling of Kamaishi offshore tsunami barrier against Tohoku earthquake tsunami

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At 14:46 local time on March 11, 2011, a magnitude 9.0 earthquake occurred off the coast of northeast Japan. This earthquake generated a tsunami that struck Japan as well as various locations around the Pacific Ocean. Based on the post-event tsunami survey, the regional and local scale analyses were conducted to understand the basic characteristics of this event. It is possible to verify the effectiveness of tsunami counter measure by this event. This study simulated tsunami inundation in Kamaishi bays targeting Kamaishi offshore wave barrier.

A series of numerical simulation was performed by quasi-three dimensional and full three dimensional (Navier-Stokes equation) model. The spatial resolution was 25-50m depends on the target and size of target area was 12 km by 10 km around Kamaishi and Ryoishi bays. The offshore boundary condition was given by GPS wave gage at offshore of Kamaishi bay.

The validation of numerical models was conducted against to post-event tsunami survey data on the land. Both numerical models slightly over predict against the survey data but they gave reasonable agreement with the data. The offshore barrier in Kamaishi bay reduced the tsunami height inside of Kamaishi bay about 30-40% in comparison with no-barrier case.

Keywords: The 2011 Tohoku Earthquake Tsunami, Kamaishi bay, Wave barrier, Numerical modeling, Velocity profile

Rapid magnitude estimation of great earthquakes for tsunami warning

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One of major problems in the tsunami warning for the 2011 off the Pacific coast of Tohoku Earthquake (Mw 9.0) was a lack of awareness of underestimation of the earthquake magnitude at the time soon after the occurrence. Displacement magnitude, which is usually used for the first tsunami warning a few minutes after the earthquake occurrence, could not evaluate such large magnitude due to short cutoff period (six seconds) compared to the rupture duration (about three minutes). Seismic moment could not be determined from the regional seismological network data due to over range of broadband sensor outputs, and it took longer time to estimate it from global data. To overcome these difficulties in earthquake magnitude estimation, we are developing several methods to estimate proper magnitude roughly and to understand possible magnitude underestimation soon after such large earthquakes.

Large earthquakes cause strong shaking in a wide area. Length of strong-shaking area is related to earthquake magnitude. Seismic intensity distribution in Japan can be known in a few minutes after earthquake occurrence owing to a dense on-line network of seismic intensity meter in Japan. The area of seismic intensity greater or equal to 5-upper (the Japan Meteorological Agency seismic intensity scale) reached about 700 kilometers in length. It is possible to estimate earthquake magnitude and source area roughly from the span of strong shaking.

Strong motion is observed at sites close to the source region. Maximum distance between the observation site and source area can be estimated from observed seismic intensity. If source area is assumed on the plate boundary, the fault plane could be estimated. However, the far edge of the fault is not able to be obtained from seismic intensity distribution.

The duration of the strong motion becomes also longer for larger earthquakes. Good correlation is seen between strong-motion duration and earthquake magnitude. The duration of the earthquake in March, 2011 exceeded eighty seconds, which is the largest among those of large earthquakes in and around Japan.

It takes a long time to complete a rupture of a large earthquake. Excitation of long-period seismic wave is one of features of large earthquakes. The cutoff period for the displacement magnitude was too short for the earthquake. Usage of long period components of seismic wave would help to estimate earthquake magnitude properly. A method of watching growth of magnitude from long-period seismic wave was developed. The magnitude from long-period seismic wave was estimated to reach the final value within three minutes for the earthquake in March, 2011.

Combination of these methods is expected to help us to issue a proper tsunami warning for the next great earthquake.

Keywords: magnitude determination, great earthquakes, area of strong motion, strong-motion duration

Rapid estimation of moment tensors for large earthquakes

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We have developed a method for estimating centroid moment tensor. In order to estimate it from shorter seismograms than those for the routine method in the NIED F-net and AQUA system (Matsumura et al., 2006) assuming point source and impulsive source time function, synthetic seismograms were calculated taking a simplified source time function with a duration time into consideration. We have analyzed seismograms of the 2011 Tohoku earthquake (05:46:17, March 11, 2011 in UTC) recorded by strong motion seismographs of the NIED F-net. These seismograms at 15 stations from 05:44 to 05:52 were applied by a band-pass filter (pass-band: 0.005 ~ 0.02 Hz) and inverted to estimate a moment tensor by a similar algorithm to the AQUA system with grid-searching for duration time and peak time of source time function. Time window for this inversion was selected to be 300 s from the origin time. As a result, we obtained a best model with a 60-s duration time, a peak time of 05:47:33, and Mw 8.8 under a variance reduction of 75 %, which is better than 63 % for impulsive source time function (duration time = 0 s). We have also tried to estimate the moment tensor of the same earthquake from shorter seismograms at six stations from 05:44 to 05:49. Time window for inversion was selected to be 120 s from the origin time. This result shows weak constraint for duration time; however, the estimated Mw was in a range between 8.6 (for duration time = 0 s) and 8.8 (for duration time = 60 s). Seismograms for this analysis at these six stations located in epicentral distances between 140 km and 310 km may include information of peak moment rate and half duration of the source time function. Consequently, we successfully estimated the Mw from these short seismograms.

Keywords: moment tensor, centroid moment tensor

Effects of rupture process in the source inversion of 2011 off the Pacific coast of Tohoku Earthquake Tsunami

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The 2011 off the Pacific coast of Tohoku Earthquake (Mw 9.0) and Tsunamis attacked and severely damaged the east coast of Japan. Inverse analysis on the tsunami source was conducted on the basis of sea-level observation of GPS buoys and water pressure gauges located near the source area. Observed data are inverted to determine the initial sea-surface height distribution and its time development that are generated by the rupture motion of inter-plate faults and the related sea-floor deformations. We use an inversion method of synthesizing tsunami Green's functions. To compute the Green's functions, tsunami wave propagation was calculated on the basis of the finite-difference approximation of linear long-wave equations in a spherical coordinate system. Such inversions are usually ill-posed problem mainly because of limited observation. To avoid the ill-posedness, smoothing and rupture constrains are imposed. The rupture constraint is based on a priori information about the tsunami source region. The region at a given time is estimated by the distance from epicenter and a rupture velocity. According to the seismic wave analysis by Japan Meteorology Agency, epicenter is located at N38°6.2', E142°51.6', 24 km deep and the rupture velocity and the rupture duration is assumed as 2.0 km/sec and 3 minutes respectively. The inversion result shows that the peak of surface elevation moved eastward from epicenter for first 1 minute to reach close to the Japan Trench and moved northward along the trench axis for next two minutes. The maximum elevation of tsunami source is +6.9 m in total and is located at northeast of epicenter in the west side of the trench axis. The crest of initial wave form is distributed in the west side of the trench. To investigate the effect of rupture process, we perform another inversion with the assumption of rupture velocity as infinity. A major difference between the two inversions is the location of the wave form crest. In the infinite rupture velocity case, the crest penetrates into east side of the trench. The tsunami source model of finite rupture velocity show a better accuracy for the prediction of waveforms which were temporally and/or spatially different from waveforms used in the source inversion. Therefore, it is concluded that the effect of rupture time lag is not negligible in the 2011 off the Pacific coast of Tohoku Tsunami case and the effect should be included in the validation of inundation or damage on the coastal area and the assessment for future risk.

Keywords: 2011 off the Pacific coast of Tohoku Earthquake, tsunami source inversion, rupture process

Effect of offshore tsunami station array configuration on accuracy of near-field tsunami forecast

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1. Introduction

Tsunami forecast based on offshore tsunami data is effective to adequately update tsunami warnings. Several methods have been proposed by recent studies (e.g., Baba et al., 2004; Titov et al., 2005; Tsushima et al., 2009; Hayashi, 2010). Tsushima et al. (2011) applied the tFISH algorithm (Tsushima et al., 2009) retrospectively to the offshore tsunami data from the 2011 Tohoku earthquake, and showed that tFISH is able to contribute to improvement of the forecasts for the coastal sites in the Sanriku region, northern Honshu where many offshore stations were operated at the time of the 2011 Tohoku event. They pointed out that poor azimuthal coverage of offshore stations should degrade forecasts at some coastal sites where no offshore station is located in somewhere along tsunami ray paths to there. In this study, we discuss how an array configuration of offshore tsunami stations affects coastal tsunami forecasts provided by tFISH.

2. Simulation Procedure for Forecasting Tsunami

As a test case, we simulated tsunami forecast of the 2011 Tohoku earthquake. The simulation was carried out as follows: (1) Tsunami waveforms, computed for observation points by assuming a fault model, were regarded as the observed tsunami waveforms. (2) Coastal tsunami waveforms were then estimated from offshore tsunami data by using tFISH. (3) The results of the tsunami forecast were evaluated by comparing the observed waveforms at coastal sites (100 m in water depth) with the predictions from Hokkaido to Kanto.

For calculation of the observed waveforms, we assumed the fault model of Fujii et al. (2011). In the tFISH algorithm, offshore tsunami waveform data are inverted for initial sea-surface height distribution in source region, and then prediction of coastal tsunami waveforms are synthesized by using the estimated height and pre-computed tsunami Green functions.

We here assumed three different array configurations. First consists of the cabled OBPG and GPS buoy stations that were operated during the 2011 Tohoku earthquake, called the existed array configuration. Second consists of the existed array and three additional OBPG stations that are supposed to locate on the inner slope of the Japan Trench, called the IT array configuration. These stations are distributed from off Aomori to off Fukushima with a spacing of ~200 km nearly parallel to the trench. Third consists of the existed array and three additional OBPG stations that are supposed to locate on the outer part of the Japan Trench, called the OT array configuration.

3. Results

We forecasted coastal tsunami waveforms at 20 min after the mainshock using the observed tsunami data at offshore stations in each configuration. In the case of the existed array configuration, the first peaks of the tsunamis were observed at the two OBPG stations, resulting in a good agreement between the observed and the predicted waveforms at the coastal points near Miyako and Kamaishi. At the other coastal points, however, predicted tsunami amplitudes were halves of the observations. In the case of the IT array configuration, the forecasting results improved dramatically. At the time of 20 min after the event, the pressure variation due to the coseismic seafloor deformation appears on the records at two additional IT array stations. We consider that in this case four offshore OBPG data constrained the source strongly, which make tsunami forecasts accurate. Similar improvements were found in the results for the OT array case. The additional OBPG stations are located far from the source, but the most part of the first tsunami wave was observed there until 20 min after the event because the almost all path run much deep ocean. The present results indicate that when strong tsunami energy were observed at offshore stations, the forecasting accuracy would be improved greatly, even though offshore station was not located between a source region and a coastal point where tsunami should be forecasted.

Keywords: real-time tsunami forecasting, near-field tsunami, ocean bottom pressure gauge, GPS buoy, DART

Issues specific to offshore tsunami observation in near-field

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The March 11 Tohoku earthquake (M9.0) destroyed vast coastal zone of the northern Japan together with many coastal tide gauges. It also did offshore tsunami observation stations off Tohoku. A part of them, like GPS tsunami buoys, was already recovered but the others are not. In 2011, JMA and MEXT started their plans to construct new offshore tsunami observation networks off Tohoku. When these networks will be built up once, it is possible that the offshore data, which will be transmitted to the land on real-time base, may improve the reliability of the regional forecast for near-field tsunamis. However, there seem to be issues to be overcome for achieving precise near-field tsunami forecast. We would like to discuss two of them below.

First issue is pressure resolution in ocean-bottom pressure gauge (OBPG). When a large earthquake occurs, offshore ocean-bottom pressure gauges (OBPG) usually record tsunami and preceding pressure fluctuations with frequencies much shorter than the period of the tsunami. The pressure fluctuations are primarily attributed to seismic Rayleigh waves traveling through oceanic lithosphere from a distant earthquake (Fillioux, 1982). In some cases, such pressure fluctuation masks tsunami signals for nearby earthquakes (Okada, 1995; Tsushima et al., 2009). In the 2003 Tokachi-oki earthquake (Mw8.0), however, a pressure signal with an amplitude of a few hundreds of kPa (equivalent to several tens of meters H₂O) was observed with the near-field OBPGs, while tsunami amplitude was estimated only an order of a few kPa (equivalent to only a few tens of centimeters H₂O). The period of the main energy of the observed pressure signals was several seconds that are much shorter than tsunami period. In addition, the tsunami and pressure signals were completely overlapped. The large pressure signals observed is considered mostly low-frequency hydroacoustic waves reverberating between the sea surface and ocean bottom through water layer, which was theoretically predicted by Kajiura (1970), and these are closely related to ocean-bottom vertical motion due to an earthquake (Matsumoto and Mikada, 2005; Nosov et al., 2007) and remain mostly in the source region (Nosov, 2000). The near-field experience in 2003 suggests that to extract tsunami information precisely from OBPG records for coastal tsunami forecast, we will have to observe ocean-bottom pressure in much wider range of amplitude from an order of millimeters H₂O to an order of, at least, several tens of meters H₂O and in much broader frequency range from an order of 0.1 seconds to an hour. Pressure resolution of OBPGs attached on the existing Japanese cabled observatories is not so fine to satisfy the above conditions. In near-future, near-field OBPG measurement will require finer pressure resolution than the present.

Second issue is sudden temperature change on deep ocean floor. In the 2003 Tokachi-oki earthquake, we found that the temperature within OBPGs in the source region suddenly decreased by an order of 0.1 degree C per ten minutes, which was much rapid change in the deep ocean floor environment off Tokachi (Hirata et al., 2003). Such sudden change in temperature caused artificial pressure signal that distort tsunami waveforms owing to a transient thermal response of OBPGs (Takahasi, 1983; Hirata and Baba, 2006). The mechanism of such sudden temperature change remains unresolved so that we cannot decide whether this is local phenomena or not. Any near-field tsunami forecast based on records monitored with OBPGs, experienced a sudden temperature change, may include not small prediction error unless the transient thermal effect of OBPGs is properly corrected.

Keywords: tsunami, offshore, observation, tsunami forecast

Early warning system with GPS-TEC observation

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Traveling ionospheric disturbances generated by an epicentral ground/sea surface motion, ionospheric disturbances associated with Rayleigh-waves as well as post-seismic 4-minute monophasic atmospheric resonances and other-period atmospheric oscillations have been observed in large earthquakes. In addition, a giant tsunami after the subduction earthquake produces an ionospheric hole which is widely a sudden depletion of ionospheric total electron content (TEC) in the hundred kilometer scale and lasts for a few tens of minutes. The tsunamigenic ionospheric hole detected by the TEC measurement with Global Position System (GPS) was found only in huge subduction earthquakes. This occurs because plasma is descending at the lower thermosphere where the recombination of ions and electrons is high through the meter-scale downwelling of sea surface at the tsunami source area, and is highly depleted due to the chemical processes. The results imply that magnitude of the tsunamigenic ionospheric hole is related to that of the tsunami. It means that we can directly observe the tsunami several minutes after the subduction earthquake occurs.

Keywords: Early warning system, Tsunamigenic ionospheric disturbance, GPS

Quantitative Analysis of Magnetic Signals induced by the 2011 Tohoku Tsunami Flow around Chichijima Island(Part 2).

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¹JMA, ²IFREE JAMSTEC

Magnetic field generated by the 2011 off the Pacific Coast of Tohoku Earthquake Tsunami (March 11) was observed at the Chichijima geomagnetic observation station. Significantly at first, the onset of the geomagnetic perturbation precedes the tsunami observation at Chichijima tide gauge (Futami observation station) by 20 minutes. In order to interpret this phenomena, we constructed a numerical model has 10*10 grids spacing 100km around Chichijima island, and estimates the sea water flow and height at each grid. These tsunami data were also estimated the influence to the geomagnetism according to Hamano model (Hamano et al., 2011).

Comparing the results to the geomagnetic observation, the preceding geomagnetic perturbation is considered that it was induced by the earliest arrival tsunami waves at north-west offshore area of the island. And it is also shown that the geomagnetic observation can detect tsunami waves in wide area comparing to the tsunami observation by tide gauge. But we could say that the simulation results were not sufficient, because 10*10 grids might not be enough for induced magnetic field by tsunami waves.

At this lecture, we will show the enough results using 100*100 grids spacing 2km. Moreover, we will show the simulated induced magnetic field by the fictitious geomagnetic observatory at the coast of Iwate and Miyagi prefectures where damaged by the 2011 Tsunamis. These results could have the meaning to the disaster prevention. Although the magnetic observation at coast has disadvantage for tsunami detection, because of shallow water depth around the station does not have A strong excitation magnetic field. However, this method or equipment does not need to soak in the sea water, the observation method using generated magnetic field can observe tsunami waves even from hill on land. Therefore, it may be able to continue observation when tide gauge stations will be destroyed by huge tsunamis. It will be shown the simulated results in this case.

Keywords: tsunami, geomagnetic field, motional induction, Chichijima, Kakioka, Faraday's Law

Tsunami source estimation of the 2011 Tohoku-oki earthquake (M9.0) and its foreshock (M7.3) using ocean bottom magnetic

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The electromagnetic induction theory predicts that motion of conductive seawater in the geomagnetic field induces variation of electromagnetic fields as known as dynamo effect. Thus electromagnetic observation is expected to be a novel tsunami meter that can detect propagated direction of tsunamis in addition to the sea level change (e.g. Toh et al., 2011). When the 2011 Tohoku-oki earthquake (M9.0, March 11) occurred, an ocean bottom electromagnetometer (here after OBEM) settled near the Japan Trench (39.0N latitude, 144.8E longitude, 5830m deep) clearly recorded tsunami induced magnetic signals.

The variations in the magnetic field after the main shock show a unipolar impulsive wave for a short duration (about 4 min) in all three components. The vertical magnetic field indicates the tsunami travel time to the OBEM station (4 minutes from the initial rupture). Amplitude of the vertical impulse (15 nT) corresponds to 2.3 m of sea level change. In addition, the horizontal magnetic field components indicate propagated direction of tsunami to the OBEM station (WNW). Based on this information, the tsunami source of the main shock was determined along the Japan Trench but at about 100 km north from main rupture zone of the main shock (around 39.0-39.5N latitude, 144.8E longitude). Joint analysis of OBEM data and offshore sea-level gage data (GPS gages and deep pressure gages) supports this location and constrained the tsunami source to a narrow east-west area (<30 km in width). On the other hand, the tsunami induced vertical magnetic signal associated with the foreshock was detected after 10 minutes from the rupture initiation. Based on the back propagation curves of the arrival time of tsunami to the OBEM station and the offshore sea-level stations, the tsunami source of the fore shock was determined around 38.4N latitude and about 80km west from the Japan trench, almost same location of the epicenter. Thus the estimated tsunami sources of the fore and main shocks are quite different although the epicenters of main and fore shocks are determined in the almost same location. In addition, elastic fault models are hard to explain observed tsunami waveforms by the main shock including OBEM data although it can explain observed tsunami waveforms by the fore shock. They imply different source mechanism of these tsunamis and thus detailed study of the tsunami source model is required especially for the main shock.

Keywords: tsunami electromagnetism, OBEM, 2011 Tohoku-oki earthquake

3-D simulations of tsunami generation using an unstructured mesh FEM: investigation of the 2011 Tohoku-Oki Earthquake

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For a detailed investigation of tsunami generation processes caused by fault motion in a large earthquake, a three-dimensional tsunami generation and propagation simulation approach using an unstructured mesh finite element method is proposed. The present method is applied to the 2011 off the Pacific coast of Tohoku Earthquake (M9.0) and the validity of the method is tested.

In simulations of tsunamis resulting from earthquakes, the sea bottom deformation is calculated from faulting parameters, using for example the equations of Okada (1985), and the free surface deformation is often assumed to equal this. However, this assumption is not always true. When the timescales for the bottom deformation are large, when the horizontal spatial scales of the deformation are small, or when the water depth is large, the free surface deformation tends to be smaller than the bottom deformation. For example, Saito and Furumura (2009) quantitatively evaluated this 'filtering' effect. One of their conclusions was that the filtering effect is important when the horizontal scale of the deformation is smaller than ten times the water depth, in the case of a short deformation timescale.

In the 2011 Tohoku Earthquake, it is indicated that a large slip in a shallow part of the crust caused short wavelength tsunami waves (e.g. Fujii et al., 2011; Maeda et al., 2011). To properly deal with this kind of short wavelength initial water height distribution, it is necessary to take account of the difference between the bottom and free surface deformations induced by the filtering effect.

An analytical solution based upon an approximation is sometimes used to calculate the free surface deformation from the bottom deformation to take into account the filtering effect (e.g. Takahashi, 1942; Kajiura, 1963). The effect can be modeled realistically by solving the full 3-D equations without any approximation (e.g. Takahashi and Furumura, 2009). However, the computational cost of solving the 3-D equations in a wide source region like the 2011 Tohoku earthquake is very large. Therefore, in this study, the 3-D incompressible Navier-Stokes equations are solved using an unstructured mesh finite element method, which can efficiently refine the mesh and hence position computational degrees of freedom at points to maximize accuracy and minimize computational expense. The unstructured mesh also enables accurate reproduction of the complex bathymetry near the trench. In the simulations, the bottom deformation is imposed as an inflow boundary condition for velocity, which is caused by the movement of the sea water just above the sea bottom (Saito and Furumura, 2009). In the vertical direction, the nodes should be placed so that the sea bottom boundary layer and the vertical velocity and pressure profiles are efficiently resolved.

In this presentation, a comparison between analytical solutions from linear potential theory and the simulation results, an application of the present method to the 2011 Tohoku earthquake generated tsunami, and the computational performance including the parallel efficiency will be reported.

Keywords: unstructured mesh, finite element method, tsunami, simulation, the 2011 off the Pacific coast of Tohoku Earthquake

Tsunami prediction of Japanese Island based on numerical simulations

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¹NIED

We have investigated tsunamis generating along the coast of Japanese Island by a numerical simulation. Tsunami simulations are based on a linear shallow-water wave equation. We assumed 200 sources around Japanese Island and evaluated tsunamis at stations located every about 20 km along the coastlines. The initial tsunami height is assumed ellipsoid-shape. We calculated initial travel times of tsunami and travel times of maximum tsunami height on the stations from every source, and then we made tsunami information maps. We compared the results and observations in order to examine the validity of the simulations. Based on a distribution of initial tsunami height shown by Saito et al. (2011), our results well explain observations of the 2011 Tohoku giant tsunami.

Acknowledgements: We used the tsunami observation data reported by Japan Metrological Agency.

Keywords: tsunami, numerical simulation, travel time, initial tsunami height, maximum tsunami height

Tsunami heights of the North Sanriku-Oki earthquake of August 23rd, 1856

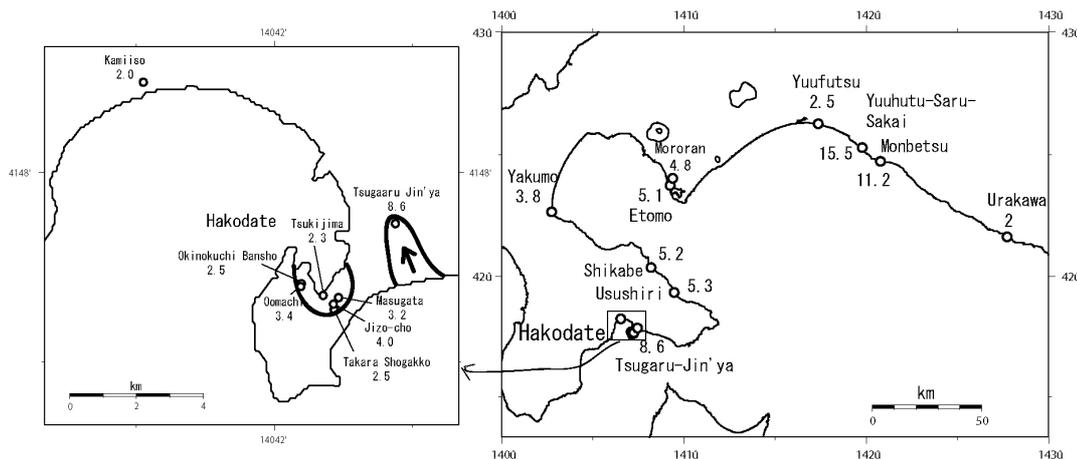
TSUJI, Yoshinobu^{1*}, IMAI, Kentaro², Horie, Takehito³, NONOYAMA, Kosuke³, IWABUCHU, Yoko⁴, IMAMURA, Fumihiko², Yoshino, Masahumi³

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A large earthquake (M7.5) occurred off the north Sanriku coast on August 23rd, 1856. A remarkable tsunami accompanied with the earthquake hit the Pacific coasts of north part of the Japanese Islands. The epicentral area is estimated nearly the same as that of the 1968 Tokachi Oki Earthquake. In the present study we conducted field surveys along the coast of Hokkaido, including Hakodate and Muroran cities. Hakodate was one of the two open ports to foreign countries at that time, and the consulate office of Russia had been founded. From three days before the main shock, foreshocks were felt twice or three times a day at Hakodate. The main shock occurred at 13 o'clock and the tsunami hit the port of Hakodate at around 15 o'clock. Sea level rose up about three meters and invaded into streets up to the streets about 300 meters from the west coast. Sea water invaded into the mansion of Tsugaru clum from the east coast up to the height of 8.6 meters above the sea level.

The total distribution of the tsunami height is shown in the figure.

Keywords: the 1856 North Sanriku Earthquake, historical tsunami, historical earthquake, tsunami in Hokkaido, tsunami at Hakodate



Atmospheric boundary waves excited by the tsunami generation - the great Sumatra-Andaman Islands Earthquake in 2004 -

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The sudden and strong vertical displacements of ocean surface are known to be the source of the long-period acoustic-gravity waves including the boundary waves in the atmosphere. Arai et al. (2011) observed atmospheric pressure changes caused by the tsunami generation of the 2011 Off the Pacific Coast of Tohoku earthquake, and identified them as "atmospheric boundary waves" on the basis of the waveform characteristics. The sudden and strong vertical displacements of ocean surface caused by the Sumatra-Andaman earthquake in 2004 also had produced long-period acoustic-gravity waves (Mikumo et al. 2008).

We re-explore barograph data observed around the source region of the Sumatra earthquake in 2004. Atmospheric pressure changes caused by the ocean uplift and subsidence were detected at 4 IMS (International Monitoring System for CTBT verification regime) stations. IMS stations provide two kinds of data, one is the band pass filtered (0.02-4Hz) output and the other is the absolute pressure output. Band pass filtered data are archived and used for CTBT's monitoring purpose. Absolute pressure data are not archived at all IMS stations. If the absolute data is not available, the band pass filtered data have been corrected by deconvolving the filter response and original records have been restored.

Long-period atmospheric pressure disturbance signals which were excited by uplift and subsidence related to the tsunami generation were observed at IS52 (Diego Garcia), IS33 (Madagascar), IS32 (Kenya) and IS35 (Namibia). The pressure signals were identified as atmospheric boundary waves based on their characteristics.

Earth orbiter "Jason-1" measures ocean surface topography. When the tsunami caused by the earthquake had been propagating through the Indian Ocean, Jason-1 flew over the propagating area. Jason-1 detected the two propagating tsunami wave fronts as the elevated ocean surface topography which indicates two isolated peaks. Detected atmospheric boundary waves also have the same characteristics. Atmospheric boundary waves retain the initial shape of the tsunami, because they are little dispersive. Observed signals suggest the Sumatra-Andaman earthquake had two isolated tsunami source regions.

Keywords: Atmospheric boundary wave, Tsunami source, International Monitoring System