

THE 2011 OFF THE PACIFIC COAST OF TOHOKU-OKI EARTHQUAKE AND TSUNAMI: INFLUENCE OF THE SOURCE CHARACTERISTICS ON THE MAXIMUM TSUNAMI HEIGHTS

Ergin ULUTAS¹

¹ Department of Geophysical Engineering, Engineering Faculty, Kocaeli University, Kocaeli, Turkey, ergin@kocaeli.edu.tr

ABSTRACT: This study was undertaken with reference to the Japan earthquake of 11 March 2011. The aim of the study is to simulate the wave propagation of the tsunami of this earthquake, by comparing with the available deep ocean pressure sensors (DART) and tide gauge records. Nonlinear shallow water equations are solved with a finite difference scheme, using a computational grid with different cell sizes over GEBCO30 bathymetry data. Co-seismic source models proposed by different organizations and researchers were carried out to explain the tsunami propagation. The source models were used to model the deformation on sea bottom which is translated directly to the water surface. The approach is based on the dislocation algorithm for a finite rectangular fault and empirical scaling laws for earthquake sources. Based on the various source models, arrival times and maximum wave heights are presented here followed by the analysis of the results. The assumption of the average uniform slip models may be a good approach for the tsunami simulations offshore and far from the source area. However, the heterogeneities of the slip distribution within the fault plane are significant for the wave amplitude in the near field. For this purpose, a finite fault model was chosen as the finite fault solution giving us the slip distribution along the fault. The chosen finite fault model was used as an input for the simulation of the tsunami propagation in the region. The rupture process of the large finite fault, including multiple fault segments, can profoundly influence the amplitudes, periods and arrival times of the tsunami waves. Thus, the tsunami at an observation point might be obtained by summing the contributions over all multiple fault segments.

The modeled waves compared with the recorded waves at DART and tide gauge stations in respect to travel times and maximum amplitudes. The source parameters established from the slip distribution is efficient to fit the observations, confirming that the tsunami is much more sensitive to the seismic moment and slip of the source. The results, compared to the observations on DART and tide gauge records based on the proposed source models, enable the identification of the regions of highest tsunami waves in the same region.

Key Words: Great East Japan earthquake, tsunami, shallow water theory, tsunami simulation, fault model

INTRODUCTION

The March 3, 2011 Tohoku-Oki earthquake generated a tsunami that was observed all over the Pacific region and caused enormous demolition in coastal Japan. This is the fourth largest earthquake in the world and the largest in Japan since instrumental recordings began in 1900. The tsunami is also most deadly and destructive event caused by an earthquake after the 2004 Sumatra earthquake. This devastating tsunami mostly affected coastal districts of Iwate, Miyagi, Fukushima, Ibaraki and Chiba Prefectures with maximum heights greater than 10 m. The official death toll from the earthquake was confirmed as 15216 and injured as 5719 (JRCS, 2011). Epicentral parameters from USGS (United States Geological Survey) are 38.297°N, 142.372°E, origin time 05:46:24 UTC (14:46:24 JST). The moment magnitude determined by JMA (Japan Meteorological Agency) and USGS was 9.0 with a depth of 23.7 and 30 km respectively. There had been hundreds of aftershocks, many greater than magnitude 6 (Fig.1). The largest of the aftershocks was M_w : 7.7. The main shock is much larger than the expected earthquakes on the asperities of the Off-Miyagi Prefecture (Yamanaka and Kikuchi 2004). Although few events greater than magnitude 8.0 have occurred in the last several hundred years in the region, none of them triggered enormous high wave tsunami heights as this earthquake. This situation is an indication of the re-evaluation of tsunami simulations to understand the rupture processing and mechanism of tsunamis considering the future earthquakes in the same area. Furthermore, it is much more important than past, as a result of increasing population due to the economic development of the coastal provinces of Japan.

Tsunamis are very large ocean or sea wave triggered by various large scale disturbances of the ocean floor such as submarine earthquakes, volcanic activities or landslides (Yosal et al., 2007). The lengths of tsunami waves may be up to a two hundred kilometers from one wave crest to another. The length and period of tsunami waves are a function of the sudden vertical changes in the sea floor. The sudden vertical changes cause a large volume of the water to be displaced from its equilibrium position to new position. The displacement of large bodies of water due to seismic disturbances results in a change in the body of water rise called tsunami. Although they have relatively small heights off shore, they may become enormous as they approach shallow coastal areas.

Tectonically active regions like the Japan are adversely and repeatedly hit by tsunamis. The Pacific coast of Japan has experienced tsunamis from the earthquakes around the Pacific Ocean several times in this century (Watanabe, 1985; Tanioka et al., 1997). The subduction of Pacific Plate along the Japanese Trench is responsible for many large underthrusting earthquakes and giant tsunamis in that region. The 2011 off the Pacific coast of Tohoku-Oki Earthquake occurred off the Pacific coast of the northeastern part of Honshu. The occurrence of this earthquake and gigantic tsunami will quantify to examine the different aspects of researchers for the evaluation and assessment of earthquakes and tsunamis in the region. Hence, it was aimed to concentrate on tsunami simulation of the 2011 off the Pacific coast of Tohoku-Oki Earthquake by using different orientations of the tsunami sources and to compare the numerical results with the available data observations.

TSUNAMI SOURCE MODELS

The accurate prediction of maximum heights and tsunami arrival times rely mainly on the estimation of earthquake parameters and fault plane models. The impulsive fault plane models assume that the seafloor deforms instantaneously and the entire fault line ruptures simultaneously (Wang and Liu, 2006). The initial condition for the expected tsunami in the region may be taken to coincide with the vertical coseismic displacement of the sea floor induced by the earthquake. To determine the propagation time and the final amplitude of tsunamis at a site due to submarine earthquakes, it is necessary to identify the magnitude, location of epicentre and source parameters of tsunamigenic earthquakes. The source parameters for tsunami simulations are faulting geometry (source depth, strike, dip, rake angles), seismic moment, fault surface, fault area, amount of slip, location (distance from shore) and beach geometry (water depth and beach slope) (Yosal, et al., 2007). The vertical co-seismic displacement of the sea floor, assumed to be responsible for the initial water surface

deformation giving rise to the tsunami, was computed using the dislocation algorithm provided by Okada (1985) in this study. For this purpose, it was collected the earthquake parameters and source characterizations issued by different researchers and organizations that would be an input for the tsunami simulations of the earthquake (Table 1).

The size of the source area for this event was given by different researches. The width and length of the fault plane (LFP) was suggested from the 150 km to 240 wide km and from 450 to 640 km long. The aftershock sequence included 3 aftershocks with magnitudes of 7.0 or larger, nearly 40 with magnitudes between 6.0 and 7.0, and over 350 events in the magnitude range from 5.0 to 6.0 in the 200 km wide, 500 km long aftershock region (Ammon et al., 2011). The aftershocks occurred at an edge of the relatively large slip area of the mainshock (Yoshida et al., 2011). The 200 km wide, 500 km long aftershock region was assumed for the fault area except for the rupture area constructed through inversion of teleseismic studies referenced in Table 1. The width of the fault plane (WFP) for this event was estimated as in the following equations due to the measured width yielded by aftershock distribution:

$$WFP = \frac{MS}{\cos(\delta)} \quad (1)$$

where WFP is width of fault plane, MS is measured width, and δ is dip angle. The top of the fault was calculated as follows:

$$TOF = h - ((\sin \delta)d) \quad (2)$$

where TOF is top of the fault in km, h is the depth of earthquake (hypocenter), δ is dip angle and d is the half of fault WFP. It was adopted the hypocentral depth estimates for the initiation of the earthquake is 24 km (JMA, 2011) and 30 km (Ammon et al., 2011) respectively. The hypocenter was assumed at the center of the fault. It should be note that a centroid location, which is a release point of seismic energy mainly, is not always the same as the hypocenter. Therefore, the hypocentral depths were used instead of centroid depths to define the size of rupture area. Then, the remained parameters as it was pointed out before were examined and compiled to provide inputs for the Okada (1985) vertical dislocation model. In order to make numerical simulations, the different source and rupture parameters employed. Numerical simulations were performed in 7 stages by considering the different source parameters as CS (Candidate Sources) (Table 1): 1) the manually determined rCMT (research CMT) solution 23 minutes after origin time (Polet and Tihio, 2011), (2) the gCMT solution of a CMTs using long period surface waves issued by National Earthquake Information Center (NEIC) of the United States Geological Survey (USGS, 2011), (3) Moment tensor inversion of 123 W-phase recordings (Ammon et al., 2011), (4) the rupture process of the earthquake using teleseismic body waves located in the 480×150 km² fault area (Koketsu et al., 2011; Yagi, 2011), (5) Multiple double couples (MDC) analysis conducted using 1-hour long period seismic waves (Shao et al., 2011), (6) USGS finite fault model (Hayes, 2011), (7) the fault parameters adapted to match the reasonable tsunami simulation waveforms.

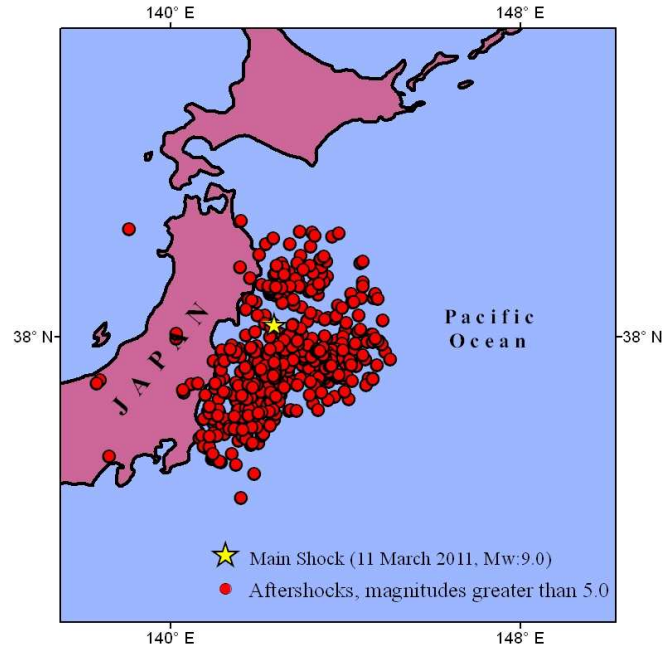


Fig. 1. Locations of main and aftershocks of Tohoku-Oki Earthquake (Data from NEIC, 2011)

The candidate source (CS) models except CS6 specify the focal geometry and the scalar moment, but not the slip distribution along the fault; consequently an average uniform slip over the entire fault area was assumed. If it is assumed an earthquake with magnitude M_w , the amount of slip motions can be computed using the following equations:

$$M_0 = \mu DLW \quad (3)$$

$$M_w = \frac{2}{3} \log_{10} M_0 - 10.7 \quad (4)$$

where μ is the rigidity of earth mantle, D is the amount of average slip motion (slip) and L is the length of the fault plane and W is the width of the fault plane, M_0 is the scalar moment of an earthquake and M_w is the moment magnitude of an earthquake (Aki, 1966; Hanks and Kanamori, 1979). The earthquake source parameters, their units, calculated average slip and vertical dislocations were given in Table 1. The displacements of sea floor calculated for every candidate sources were given in Fig. 2. On the other hand, the calculation of average slip via equation (3) has limitations due to the correct estimation of fault width and fault length for up-dip fault motions. However, joint source inversion results show that the rupture behavior of the earthquake resulted in >50 m slips and the rupture occurred on a large triangular shaped slip zone with the average slip over the entire fault model was about 15-20 m (Lay et al., 2011; Lee et al., 2011). Thus, it was also used 20 m uniform average slip for the comparisons of the simulations with the DART (Deep-Ocean Assessment and Reporting of Tsunamis) and tide gauge records..

Table 1. Source parameters used in this study

Source parameters	CS-1	CS-2	CS-3	CS-4	CS-5	CS-6	CS-7 (This study)
Mw	8.9	9.1	9.0	9.0	9	9.0	9.0
Seismic Moment		5.31	3.9	5.6	3.4	4.90	
Depth (km)	24	30	30	23	26	30	24
LFP(km)	500	500	500	500	480	550	500
WFP (km)	205	203	205	200	150	260	200
Strike, Dip, Rake	186/12/76	203/10/88	202/13/92	199/10/92	200/12/83		199/10/92
TOF (km)	2.74	12.36	7.09	5	8.4	7.75	7.5
Average Slip (m)	6.1	13.08	9.47	14.0	11.81	8.57	20
Max-Min	2.62	5.35	4.16	5.82	5.00	8.76	8.27
Vert.dislocation (m)	-0.97	-2.38	-1.42	-2.37	-2.37	-1.95	-3.33

WFP and Average slip was calculated from Eq .(1) and Equation 3 except for the CS-5 and CS-6
Seismic moment scale: 10^{22} Nm

TSUNAMI MODELLING, BATHYMETY DATA, ANALYSIS AND COMPARISONS

Shallow water wave equations that are applicable to cases where the horizontal scale of the flow is much bigger than the depth of the fluid are used in tsunami modeling (Liu et al., 2009). Numerical simulations of tsunami propagation for 7 candidate sources were performed using a model called TUNAMI-N2 (Imamura et al., 2006). The model was originally authored by Professor Fumihiko Imamura in Disaster Control Research Center in Tohoku University (Japan) through the Tsunami Inundation Modeling Exchange (TIME) program (Goto et al., 1997). TUNAMI-N2 is one of the key tools for developing studies for propagation and coastal amplification of tsunamis in relation to different initial conditions. GEBCO (General Bathymetric Chart of the Ocean) with a 30 arc-second global bathymetry data were used in simulations. It was used two levels of computation grids for proper amplification. The grids consist of a 4' grid describing the open ocean (Computation area A) and 1' grid (Computation area B) describing the Coasts of Honshu. The maps of maximum tsunami heights are shown in Fig. 3. Four deep ocean pressure sensors named DART and tide gauge stations were used as the comparison points of tsunamis. The locations of DART and tide gauge stations were shown in Figure 3h. 4' grid was chosen to compare the simulated and observed results in the open ocean. 1' grid was chosen for the comparison of tide gauges and DART 21418 which is the nearest DART to Japan. The total calculation time was set to three hours for the computation area of A, and the total calculation time was set to one hour for the computation area B. Tsunami Analysis Tool (TAT) developed by Annunziato (2007) were used to visualize tsunami travel time, tsunami propagation, maximum heights and comparison of the results with DART and tide gauge records. For each of the tsunami sources defined in Table 1, time series of sea level were extracted from the model outputs at the closest grid point to the several observation locations. These time series and simulated tsunami heights were shown in Fig. 4. The figures consist of arbitrary chosen observation locations showing the observed and simulated tsunami heights.

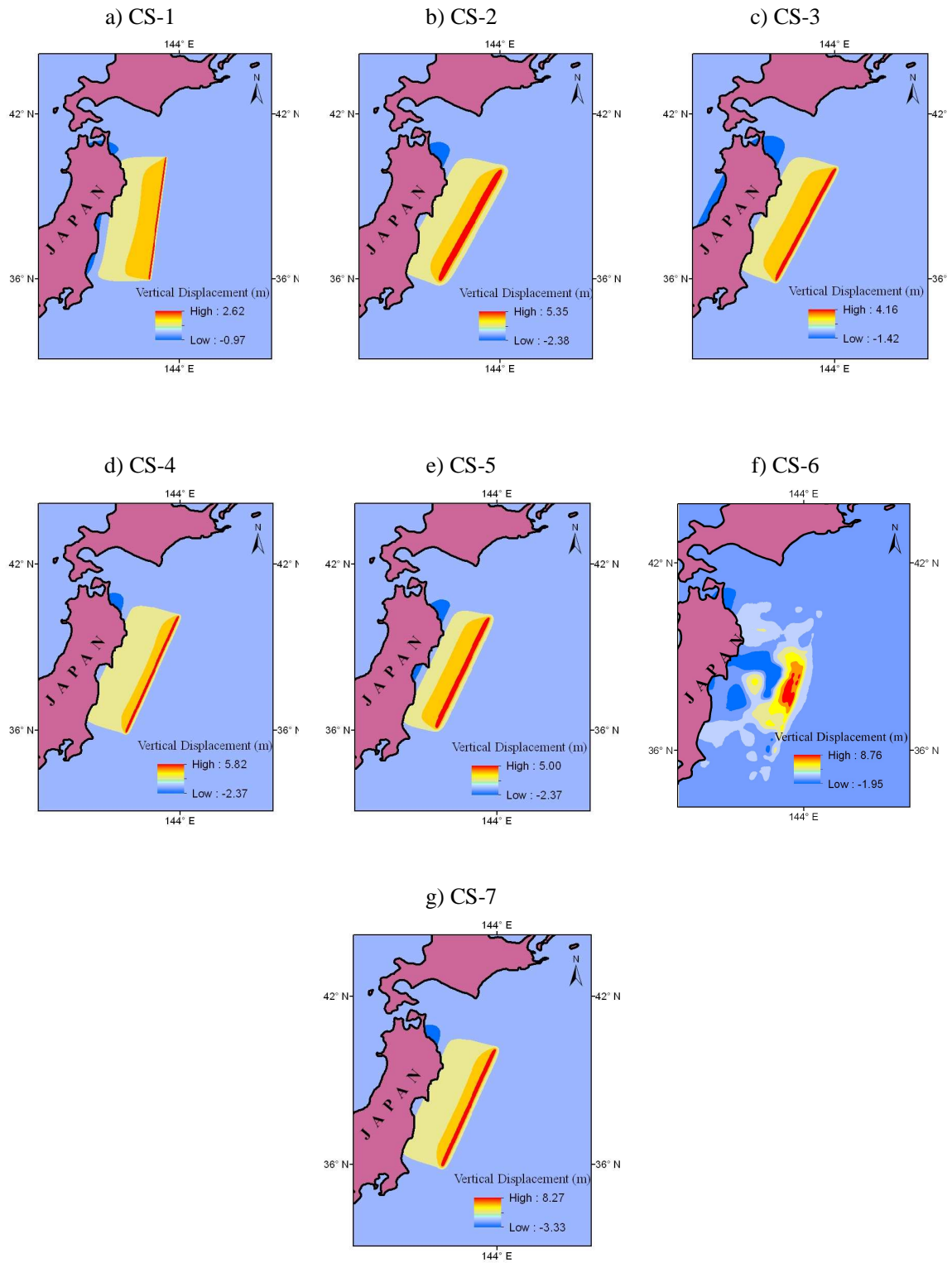


Fig. 2. Vertical dislocation of the sea floor due to different source models.

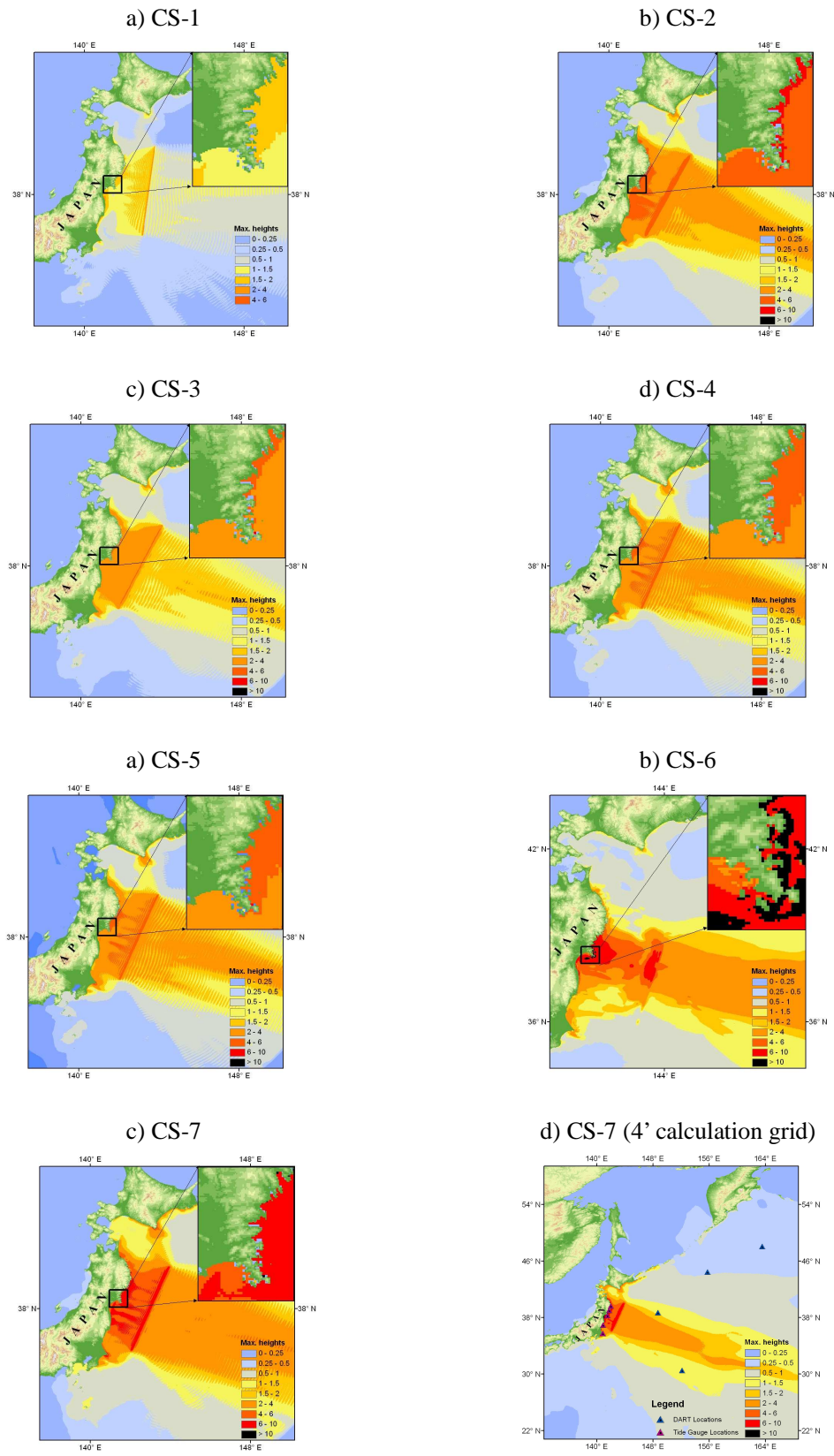


Fig. 3. Maximum computed heights for computation area A and B (CS-7, 4' calculation grid).

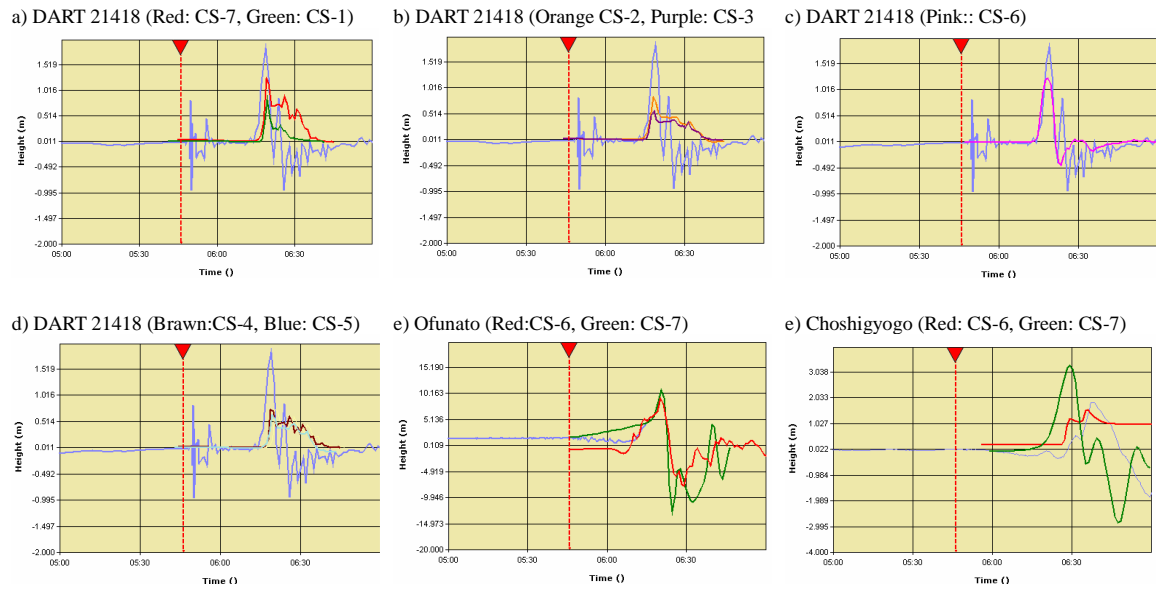


Fig. 4. Comparison of the observed (blue) and simulated tsunami heights in several location

CONCLUSIONS AND DISCUSSIONS

Numerical tsunami simulations were conducted with the proposed fault models and assumptions of the fault parameters of March 11, 2011 M_w :9.0 Tohoku-Oki earthquake. Variations in the tsunami wave field are examined in relation to uniform and non-uniform slip models that are characterized by fault parameters of the earthquake. The six different candidate sources assuming the uniform slip were compared with the slip distribution model issued by USGS. After employing the different source models and assumed fault parameters, the maximum vertical displacements of the sea floor were calculated 2.62, 5.35, 4.16, 5.82, 5.00, 8.76 and 8.27 for CS-1, CS-2, CS-3, CS-4, CS-5, CS-6 and CS-7 candidate sources respectively. The results show that an assumption of uniform slip underestimates the maximum height of tsunami amplitude by using the Eq. (3) in this earthquake due to the various predicted seismic moments. Thus, it should be noted that it is often difficult to validate the average slip due to the predicted length and width of the fault plane. Tests of assuming different average slip values indicate that the lower values of average slip calculated from Eq. (3) due to the fault area may not qualify the correct tsunami predictions in comparison to non-uniform slip distributions. It is still a challenge to use non-uniform slip distributions so-called finite fault models immediately after the earthquake in tsunami predictions. Because the calculation techniques are based on static and seismic data inversion selected based upon data quality and azimuthal distribution. Thus, the finite fault models may not be performed in a reasonable time that provides us multiple fault segments of variable local slip, rake angle, depth, rupture time and several other parameters.

The results also show that the most critical parameter affecting the tsunami heights is the prediction of seismic moment, dip of the fault, average slip and determination of the depth of top of the fault. The results show that the depth of top of the fault affects the tsunami heights due to the large width and large length of the fault. Hence, it should be note that the estimation of the hypocenter is important especially large mega thrust earthquakes. Near real time determination of seismic moments were issued lower immediately after the earthquake. Thus, the tsunami wave heights were simulated lower due to the rapid prediction of seismic moments issued by seismological organizations than those of post-event analysis. In summary, the findings of this study could be use to understand the effect of different source parameters on tsunami simulations. The goal of the study was not based on modeling the inundation area. However, the findings may be used by decision-makers that address the maximum heights of waves for the Honshu Island coasts.

ACKNOWLEDGMENTS

I would like to thank A. Annunziato for sharing Tsunami Analysis Tool (TAT) program visualizing tsunami simulations and comparing the simulations with DART and tide gauge records. I am also grateful to Japan Meteorology Agency for providing tide gauge data.

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