Investigation of mechanisms causing ground motion and tsunami due to the 2011 Tohoku Earthquake at Nuclear Power Plant sites

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SUMMARY:
The tsunami caused by the 2011 Tohoku earthquake resulted in a severe accident at the Fukushima Daiichi nuclear power plants (NPPs). In light of analysis of the generation mechanisms of the earthquake and tsunami, a tsunami source model is inferred and further verified by the seismic source model inferred from ground motions. Distribution of large slip in the area along the Japan trench is a common finding obtained from both models. Through simulation analysis of the observed tsunami at the NPP sites, it becomes clear that the large slip in the shallow area along the Japan Trench, the time difference of rupture propagation, and the time delay of tsunami propagation are the main factors that significantly affect the tsunami heights.

Keywords: The 2011 Tohoku earthquake, Tsunami, Nuclear site, rupture process

1. INTRODUCTION

The 2011 off the Pacific Coast of Tohoku Earthquake (the Tohoku EQ) occurred at 14:46 on March 11, 2011. The safety systems at the Fukushima Dai-ichi Nuclear Power Plant (NPP) detected seismic ground motions and inserted the control rods into the reactors to shut them down safely. The reactors at the Fukushima Dai-ni NPP, the Onagawa NPP, and the Tokai Dai-ni NPP were also shut down safely. Subsequently, however, these power plants were struck by tsunami. At the Fukushima Dai-ichi NPP, the seawater intake system and emergency power system for cooling reactors became flooded, and the external power supply facilities simultaneously became non-functional. These events led to the loss of the reactor cooling function, which in turn resulted in the release of radioactive materials outside the NPP facilities.

In April 2011, the Japan Nuclear Energy Safety Organization (JNES) started work on a project (JNES Project) with the aim of investigating the causes of the tsunami resulting from the Tohoku EQ (Tohoku EQ Tsunami) and also the aim of designing emergency measures. We participated in this JNES Project in order to help push it forward. As part of the project, we collected and analyzed information on Tohoku EQ Tsunami published by relevant agencies and organizations in order to compile the latest findings. First, we clarified the characteristics of Tohoku EQ Tsunami based on the knowledge we compiled. Then, we drafted a plan to investigate the causes of Tohoku EQ Tsunami. Subsequently, based on this plan, we devised a method for estimating a tsunami source model, established said model, and verified the results we obtained using the model against the seismic source model for seismic ground motions. In addition, we analyzed reproducibility for both nuclear sites and other locations and investigated the factors responsible for the difference in tsunami height among the nuclear sites. We are also applying these results to push forward with the JNES Model for establishing design tsunami based on probabilistic tsunami evaluation.

Regarding these efforts, the latest knowledge as of the end of May 2011 was compiled in the report submitted by the Japanese Government to a ministerial-level international conference of the International Atomic Energy Agency (IAEA) held on June 23, 2011. The latest knowledge as of the end of August 2011 and the results regarding the reproducibility of the observed tsunamis were compiled in the report submitted by the Japanese Government to IAEA international conference held on September 23, 2011. The results of the investigation into the causes of Tohoku EQ Tsunami were reported and used during a discussion for hearing opinions on the earthquake and tsunami which was held by the Nuclear and Industrial Safety Agency (NISA) of the Ministry of Economy, Trade and Industry (NISA Opinion Hearing) on October 31, 2011. The JNES Model mentioned above was reported in the interim report for a NISA Opinion Hearing held on March 28, 2012.

This report first outlines the characteristics of Tohoku EQ Tsunami and then describes a method for estimating a tsunami source model, the results obtained by said model, and details verifying said model. Subsequently, the report outlines the results of reproducibility for both nuclear sites and other locations. It also touches on the analysis of factors responsible for the difference in tsunami height among nuclear sites. Finally, the report summarizes our results and suggests how the investigation should be continued going forward.

2. CHARACTERISTICS OF THE 2011 TOHOKU EARTHQUAKE TSUNAMI

(1) Characteristics Related to Earthquake Size and Seismic Source Area
The Tohoku EQ occurred at the boundary between the North American Plate and the Pacific Plate along the Japan Trench on March 11, 2011. According to an announcement of the Japan Meteorological Agency (No. 16, 2011), the seismic source was located in an area about 130 km off the coast of Sanriku and 24 km in depth. The earthquake size in terms of moment magnitude (Mw) was 9.0.

The Headquarters for Earthquake Research Promotion has estimated that the seismic source area of the Tohoku EQ was longer than 400 km and as wide as 200 km, extending from a region off the coast of Iwate prefecture to a region off the coast of Ibaraki prefecture.

(2) Characteristics Seen in Observed Crustal Movement
According to the continuous GPS observation data provided by the Geospatial Information Authority of Japan (GSI), the crustal movement accompanying the Tohoku EQ occurred across a wide area of the Tohoku region. In particular, distinct crustal movement appeared in the coastal area extending from Miyagi prefecture to Fukushima prefecture. Oshika Observation Point in Miyagi prefecture recorded a horizontal deformation of about 5.3 m in the east-southeast direction and a vertical deformation of about 1.2 m (subsidence)(GSI, 2011).

(3) Characteristics Seen in Observed Seismic Ground Motions
National Research Institute for Earth Science and Disaster Prevention (NIED) compiled the waveform data (KiK-net) on the main shock that was recorded at observation points throughout the Pacific coastal area in the Tohoku region. NIED had demonstrated the possibility that multiple earthquakes occurred successively within a short period of time lead to this giant earthquake (NIED, 2011).

(4) Characteristics Seen in Observed Tsunami Waveform
Port and Airport Research Institute (PARI) published the tsunami waveform data observed by GPS buoy recorders. According to the tsunami waveform data observed off the coast of the southern region of Iwate prefecture (off the coast of Kamaishi), the water level gradually rose about 2 m in about 6 minutes after the tsunami struck and subsequently rose rapidly to a peak of 6.7 m in 4 minutes. The tsunami waveform is characterized by this two-step rise (PARI, 2011).

3. METHOD FOR ESTIMATING THE TSUNAMI SOURCE MODEL

3.1. Procedure for Estimating the Tsunami Source Model
In investigating the occurrence mechanism of Tohoku EQ Tsunami, we estimate a tsunami source

model capable of reproducing the tsunami waveforms observed at various points around Japan as well as the data (e.g., tsunami waveforms and inundation heights) observed at nuclear sites (i.e., Fukushima Dai-ichi NPP, Fukushima Dai-ni NPP, Onagawa NPP, and Tokai Dai-ni NPP) focusing on the characteristics described in chapter 2.

For this investigation, the tsunami source model is estimated with the joint inversion analysis method (Satake, 1989), which covers observed crustal deformations as well as observed tsunami waveforms. Fig. 1 illustrates the procedure for estimating the tsunami source model by this method. First, observation data are collected and organized as the target of the inversion analysis. Next, a tsunami source model is established by considering the entire tsunami source to be a cluster consisting of multiple sub faults. And, the tsunami waveform and crustal deformation corresponding to each observation point is estimated by determining the geometric forms of sub faults and assuming their unit slippages in the model. These results are known as Green's functions.

In addition, the slippage (provisional value) of each sub fault is determined so that the sum of the Green's functions matched the observed tsunami waveforms and observed crustal deformations at every target observation point. Tsunami propagation analysis using this tsunami source model is carried out for the above four nuclear sites to confirm that the calculated values matched the trace heights at the sites. If the calculated values do not reproduce the trace heights, tsunami propagation analysis is carried out again for the modified slippages. This process is repeated until the calculated values sufficiently reproduced the trace heights. Finally, the consistency between the established tsunami source model and the seismic source fault model (estimated from observed seismic ground motion) is confirmed, thereby verifying the slippages shown by the tsunami source model.

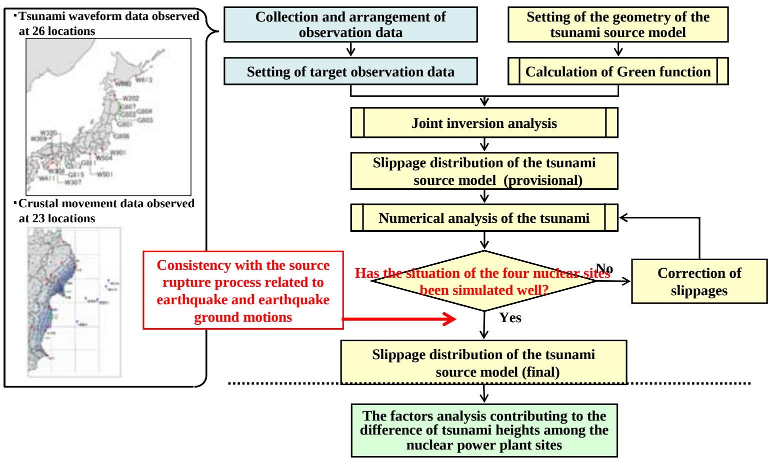


Figure 1. Procedure for estimating the tsunami source model

3.2. Target Observation Data

Joint inversion analysis was carried out for tsunami waveforms observed by the following: the GPS buoy recorders (at nine observation points) of the PARI; the tide gauges (at 11 observation points) of the Ports and Harbors Bureau of the Ministry of Land, Infrastructure, Transport and Tourism; the tsunami recorders (at three observation points) of the U.S. National Oceanic and Atmospheric Administration (NOAA); and the tide gauges (at three observation points) at the Fukushima Dai-ichi NPP, the Onagawa NPP, and the Tokai Dai-ni NPP. In addition to this data, the joint inversion analysis also covered the vertical crustal movement data (at 18 onshore observation points and 5 submarine observation points) observed by the Geospatial Information Authority of Japan and the Japan Coast Guard as well as that observed at each nuclear site.

3.3. Characteristics on Tsunami source modelling

3.3.1. Geometric Form of the Tsunami Source Model

To consider the characteristic of earthquake size (Mw 9.0), we referred to the tsunami source model by Fujii et al. (2011) as well as by Imamura et al. (2012) in order to establish a wide-range tsunami source model covering an area about 600 km long and 200 km wide as shown in Fig. 2. This model consists of 48 sub faults (40 sub faults 50 km square and 8 sub faults 50 km long and 30 km wide).

To consider the characteristics of the spatial conjunction of earthquakes with time lag , we used the difference in rupture starting time (i.e., the amount of delay from the starting time of the initial rupture) and rupture duration as parameters for our tsunami source model. Before the Tohoku EQ occurred, these parameters had been considered to be of negligible influence on tsunami water levels in coastal areas. Since the tsunami source area of the Tohoku EQ was extensive, however, the difference in rupture starting time and rupture duration between multiple sub faults may have significantly influenced tsunami water levels in the coastal areas. Accordingly, we used these values as parameters in our tsunami source model. Subsection 3.3.2., which follows, describes how we dealt with the characteristic, the time lag of the earthquakes.

On the other hand, the spray faults branching off from the plate boundary lie in the shallow area near the Japan Trench (Tsuru et al., 2002). Those spray faults have steeper slants than the plate boundary, and thus they may have caused short-period waveforms to occur. Accordingly, for the present investigation, we modeled the geometric form of the spray faults and incorporated this into our tsunami source model. Our spray fault model is can be seen in the northern half of the eastern column of the tsunami source model in Fig. 2.

3.3.2. Spatial and Temporal Heterogeneity of Slippages in the Tsunami Source Model

As described in Chapter 2, the Tohoku EQ resulted from the spatial conjunction of earthquakes that occurred in multiple seismic source areas with time lag. Accordingly, we incorporated parameters to represent this phenomenon into our tsunami source model. Specifically, we used the rupture starting time and rupture duration of each sub fault as parameters, thereby representing the temporal variations in slippage distributions. Fig. 2 shows the concept behind these steps for incorporating the parameters into the model.

First, Green's functions were established on the assumption that all sub faults started to rupture at the time the Tohoku EQ occurred. Subsequently, these Green's functions were shifted in the direction of the temporal axis by 30, 90, 150, 210, and 270 seconds to yield five types of Green's functions. Finally, appropriate Green's functions were extracted from these shifted functions by inversion analysis to ensure that superposition of the extracted Green's functions multiplied by a corresponding appropriate factor (i.e., the corresponding slippage) matched the observed waveform. For example, the 30-sec.-shifted Green's function corresponds to the slippage indicating the sum of slippages occurring from 0 to 60 seconds after the Tohoku EQ occurred.

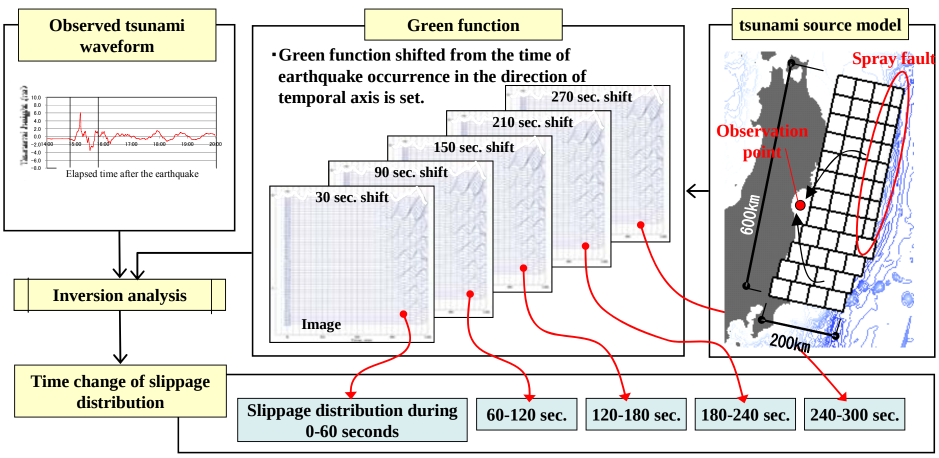
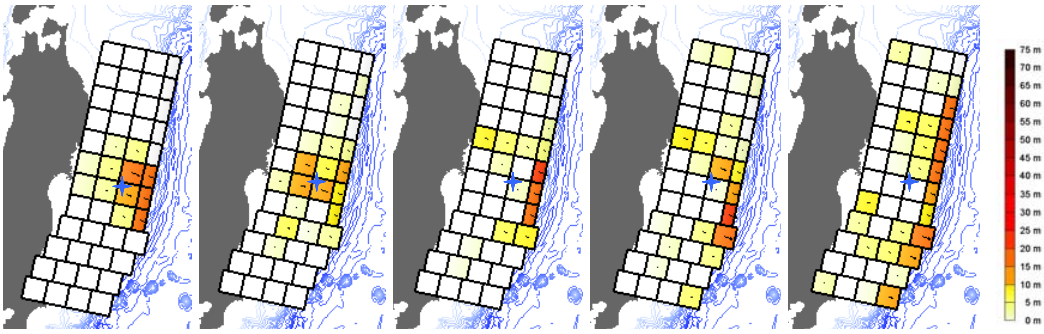


Figure 2. Procedure for setting the time change of slippage distribution in the tsunami source model

4. ESTIMATED TSUNMI SOURCE MODEL AND VERIFICATIOIN USING SEISMIC SOURCE MODEL

4.1. Slippage Distributions Estimated in the Tsunami Source Model

Figs. 3 (a) through (e) show the estimated result. These results indicate the minute-by-minute temporal variations in the slippage distribution after the occurrence of the Tohoku EQ. According to Figs. 3 (a) through (e), the plate slippage extended continuously as follows: the slippage expanded near the rupture starting point; next, it propagated to the slightly deeper area west of the rupture starting point; and then it moved on, mainly to the shallow area along the Japan Trench. Large slippages occurred intensively in the shallow area along the Japan Trench; the moment magnitude reached Mw 9.1 (calculated by the expression μDS, where μ is the modulus of rigidity ($4.63 \times 1{,}010$ N/m^2), D is the slippage, and S is the fault area). Sugino et al. (2012) described the fault parameters for each sub fault in detail.

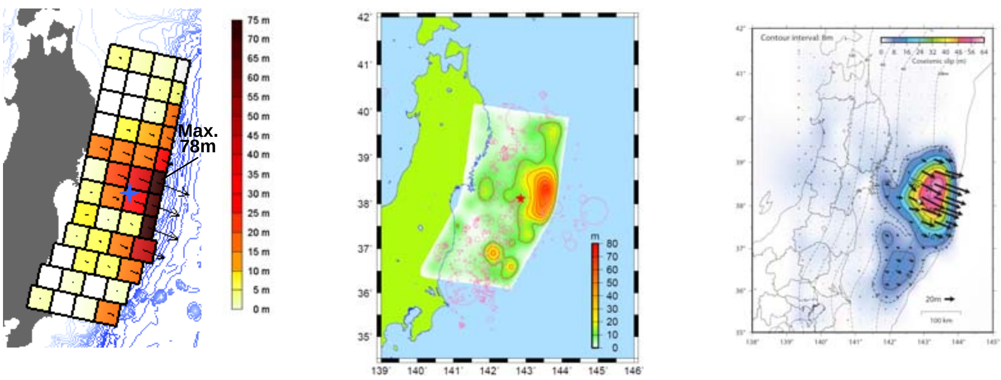


(a) 0-60 sec. (b) 60-120 sec. (c) 120-180 sec. (d) 180-240 sec. (e) 240-300 sec.

Figure 3. The time change of slippage distribution in the tsunami source model

4.2. Verification of the Tsunami Source Model by Using the Seismic Source Model

Wu et al. (2012) had estimated seismic source models based on observed seismic ground motions. These seismic source models were estimated for long periods (exceeding 10 seconds) and short periods (about 0.1 second) separately by focusing on the period strip of the observed seismic ground motion. In particular, as observed long-period seismic ground motions are considered to correspond to the overall motion of ruptures at the seismic source, they can be expected to be closely related to the submarine crustal deformations that cause tsunami. Therefore, we verified the validity of our tsunami source model with the slippage distributions of the seismic source model, which was estimated on the basis of observed long-period seismic ground motions.



(a) Tsunami source model

(b) Seismic source model based on long-period waves (<0.1Hz)

(c) Source model based on geodetic data (GSI and JCG, 2011)

Figure 4. Comparison of the slippage distribution

Fig. 4(a) shows the total slippage distribution of the tsunami source model. This slippage was obtained by summing the slippages for each sub fault estimated in Section 4.1. Fig. 4(b) shows the slippage distribution of the seismic source model estimated for observed seismic ground motions with long periods between 10 and 125 seconds. The tsunami source model and the seismic source model were estimated separately based on different sets of observation data. However, the results obtained from both models are consistent with one another in that both models' slippage distributions exhibit intensive large slippages in the shallow area along the Japan Trench, with maximum slippages ranging between about 70 and 80 m.

In addition, these results nearly agree with the slippage distribution based on geodetic data shown in Fig. 4(c). Therefore, we concluded that the slippage distribution of this tsunami source model is valid. This investigation has caused us to realize once again that in order to investigate earthquakes and tsunami, from the viewpoint of comprehensively understanding such phenomena, it is essential to combine approaches from both fields and apply them to the investigation.

5. REPRODUCTION OF THE 2011 TOHOKU EARTHQUAKE TSUNAMI

5.1. Reproduction of Observed Tsunami Waveforms

Fig. 5 indicates the characteristics of the observed tsunami waveforms and analyzed waveforms. Fig. 5(a) shows the tsunami waveforms observed with GPS buoy recorders (blue lines) and analyzed waveforms (red lines) for the locations other than nuclear sites. In Fig. 5(a), the analyzed waveforms closely match the observed tsunami waveforms, indicating that sufficient reproducibility has been achieved. In particular, the short-period waveform of the first wave observed off the coast of southern Iwate prefecture (G802) is sufficiently reproduced by the corresponding analyzed waveform; the Tohoku EQ Tsunami is characterized by this observed short-period waveform of the first wave. High reproducibility of waveforms is also confirmed for the other observation points. Fig. 5(b) shows the observed tsunami waveforms and analyzed waveforms for nuclear sites. The analyzed waveforms closely match the observed tsunami waveforms, indicating that sufficient reproducibility has been achieved for the nuclear sites as well. However, at the Fukushima Dai-ni NPP, no observation results were recorded because of the impossibility of measurement.

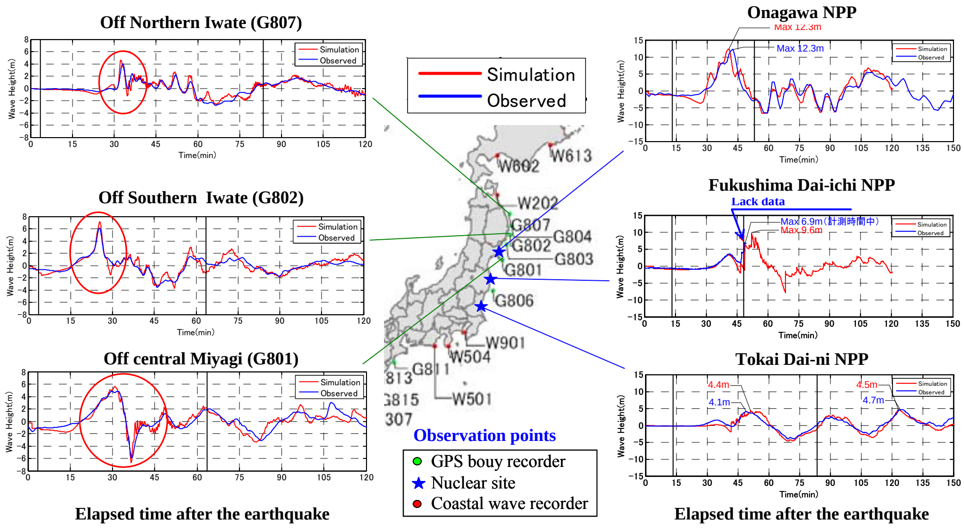


Figure 5. Simulation results on tsunami waveforms

As described above, the tsunami source model demonstrated preferable reproducibility for both nuclear sites and other locations. This may be because we incorporated the difference in rupture starting time and slippage duration for each sub fault as parameters into this tsunami source model in order to consider temporal variations in slippage distribution. For tsunami with wide tsunami source areas, such as Tohoku EQ Tsunami, it is crucial to consider temporal variations in slippage distribution per sub fault. This approach will play an essential role in research related to tsunami caused by inter-plate earthquakes, such as those expected to occur in locations such as the Nankai Trough.

5.2. Reproduction of Trace Heights at Nuclear Sites

We also confirmed the reproducibility of trace heights (i.e., run-up heights and inundation heights) for the four nuclear sites. Fig. 6 shows the trace heights obtained by a field survey at Fukushima Dai-ichi NPP and the corresponding calculation results. Fig. 6 indicates that the trace heights (e.g., the run-up heights) obtained by the reproduction calculations closely match the results obtained via the field survey. This good reproducibility is also supported by the fact that the corresponding Aida's indexes (Aida, 1977) are K = 1.03 and κ = 1.13 (19 observation points), thereby satisfying the above-mentioned conditions for preferable reproducibility. The Aida's indexes corresponding to the other nuclear sites are as follows: K = 0.98 and κ = 1.12 (71 observation points) for Fukushima Dai-ni NPP; K = 1.03 and κ = 1.02 (10 observation points) for Onagawa NPP; and K = 1.03 and κ = 1.05 (13 observation points) for Tokai Dai-ni NPP. Good reproducibility has been demonstrated for these nuclear sites as well.

Thus, good reproducibility of data (e.g., trace heights) has been achieved for the four nuclear sites using one tsunami source model. This is advantageous in that a one tsunami source model can be used to render possible quantitative comparison and analysis of data (e.g., differences in tsunami height among nuclear sites) under identical conditions.

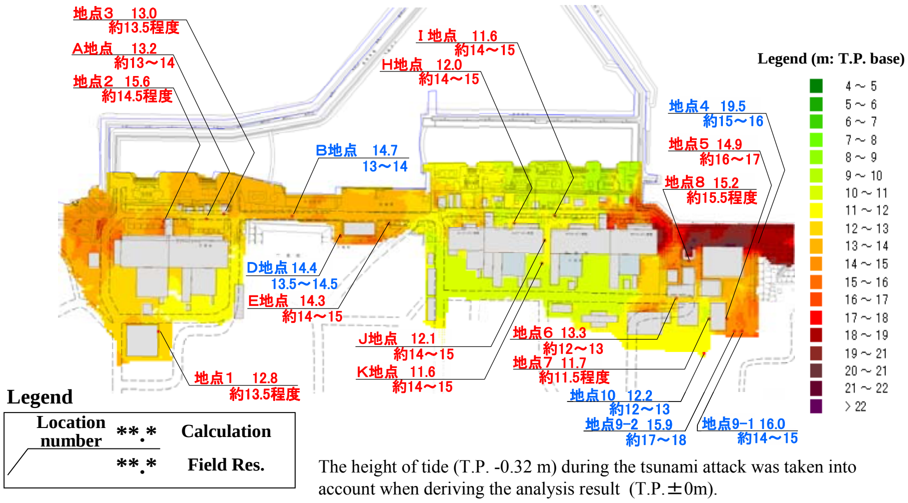


Figure 6. Simulation results on inundation area and tsunami heights at Fukushima Dai-ichi NPP

6. ANALYSIS OF FACTORS ASSOCIATED WITH DIFFERENCES IN TSUNAMI HEIGHT AMONG NUCLEAR SITES

The Tohoku EQ tsunami assaulted four nuclear sites: the Fukushima Dai-ichi NPP, Fukushima Dai-ni NPP, Onagawa NPP, and Tokai Dai-ni NPP. We applied the tsunami source model estimated in Section 4.1 to these tsunamis to analyze the relevant factors (e.g., difference in tsunami height among the nuclear sites).

6.1. Tsunami-height Amplification Factor and Topographic Effect at Nuclear sites

Fig. 7 shows the relationship between water depth and the tsunami-height amplification factor at the four nuclear sites as well as the relationship given by the following Green's equation (Shuto el al. 2008).

$$Hh^{1/4} = const. \tag{5.1}$$

In this equation, H is the tsunami height and h is the water depth. This Green's equation can be applied if one assumes that reflection on the coastline is negligible and that refraction will not change the wave ray spacing. This is based on the premise that submarine topography is not unique to the location concerned. In other words, if tsunami height and water depth do not satisfy the relationship given by this equation, site-specific topographic effects are acting.

Fig. 7 shows that the amplification factors at Fukushima Dai-ichi NPP and Fukushima Dai-ni NPP nearly satisfy this Green's equation. Accordingly, the submarine topography near these power plants is not unique to those sites. At Tokai Dai-ni NPP, however, the deviation of the amplification factors from the values given by Green's equation increases as the points becomes closer to the site. This may be because the tsunami that assaulted Tokai Dai-ni NPP was not as high as those that assaulted the other nuclear sites, so a condition of near-total reflection may have been established at the shore.

On the other hand, the amplification factors at Onagawa NPP exhibit a tendency distinctly different from those of the other nuclear sites. These amplification factors start to deviate slightly from the values given by Green's equation at the point at depth 100 m, taking relatively small values in the onshore tsunami run-up area. This may be because Onagawa NPP is located near the entrance of Onagawa Bay, the topography of which allowed the momentum of the tsunami to pass by the site toward the inner part of the bay. The other nuclear sites lie along nearly straight coastlines, and such topography caused those sites to confront the momentum of the tsunami directly. This is supported by the flow condition of the tsunami at Onagawa NPP immediately before the tsunami reached its maximum height. We confirmed that the stream of the tsunami tended to proceed toward the inner part of Onagawa Bay, and we confirmed that the amplification factor of the tsunami height in the area of the inner part of the bay was larger than that of the factor for Onagawa NPP.

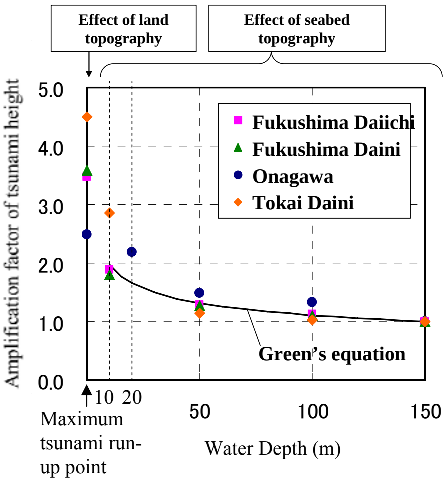
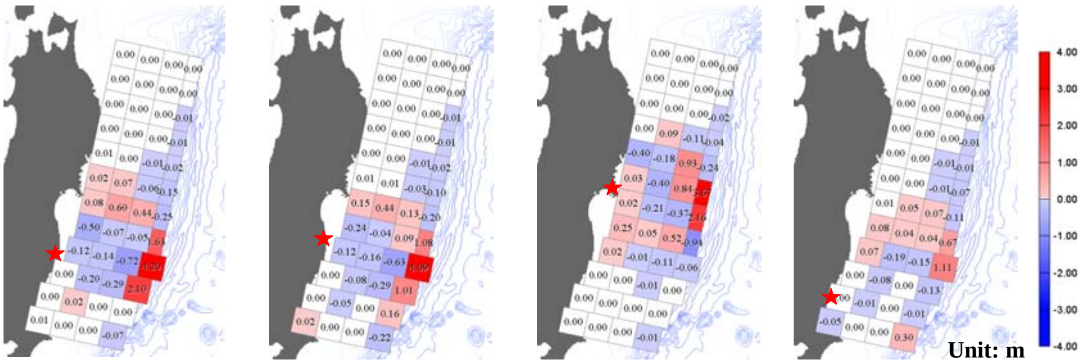


Figure 7. Relationship between water depth and amplification factor of tsunami height at nuclear sites

6.2. Sub-fault Arrangement Contributing to Maximum Tsunami Heights at Nuclear Sites

We examined the factors responsible for the difference in tsunami height at points with depth 150 m. Since the nonlinear effect of waves was small at such points, the analyzed waveforms at the points can be represented by superposing the Green's functions for sub faults of the estimated tsunami source model. We made use of this characteristic to detect sub faults that contributed to tsunami reaching their maximum heights at the points with depth 150 m. To this end, we separated the maximum tsunami height off each of the nuclear sites into component tsunami heights, each of which was in turn a contribution from each corresponding sub fault. Fig. 8 shows the separated component tsunami heights. According to Fig. 8, although the tsunami source area was wide, only a part of the source significantly impacted each nuclear site. Different regions in the tsunami source area contributed to the impacts on different nuclear sites, but all were tsunami-earthquake generating regions located near the Japan Trench. Therefore, it is crucial for these nuclear sites to give special consideration to tsunami-earthquakes occurring near the Japan Trench.



(a) Fukushima Dai-ichi (b) Fukushima Dai-ni (c) Onagawa (d) Tokai Dai-ni

Figure 8. Contribution of each sub fault to the maximum tsunami height at 150 m water depth

7. SUMMARY

We compiled various observation records and analysis results presented by other research institutions and clarified the characteristics of this earthquake tsunami. On the basis of this understanding, we have estimated a tsunami source model to reproduce the tsunami that assaulted the nuclear sites as well as to analyze the differences in tsunami heights among the nuclear sites as part of our investigation into the tsunami occurrence mechanism. Through the present investigation, we obtained the following results.

(1) We estimated a tsunami source model by joint inversion analysis based on observation records (tsunami waveforms and crustal deformations) both in the wide area and at nuclear sites. This model sufficiently reproduced the observation records. In particular, by establishing this tsunami source model by incorporating temporal variations in slippage distributions as parameters, we were able to reproduce the characteristic waveform superposition seen in the tsunami waveforms observed during the Tohoku EQ Tsunami.

(2) The tsunami source and seismic source were estimated separately from different observation records. However, we confirmed that large slippages occurred intensively in the same shallow region near the Japan Trench both with the estimated tsunami source and with the estimated seismic source. Therefore, the crustal movement causing tsunami is closely associated with seismic ground motions with long periods exceeding 10 seconds.

(3) The tsunami source area of the Tohoku EQ Tsunami was vast. Accordingly, different regions in the tsunami source area had significant influence on the tsunami heights at different nuclear sites (Fukushima Dai-ichi and Dai-ni NPPs, Onagawa NPP, and Tokai Dai-ni NPP). However, we clarified that these regions were all located within a relatively narrow portion of the tsunami source area, the so-called “tsunami-earthquake occurrence area” near the Japan Trench.

The tsunami water level resulting from the Tohoku EQ exceeded the design tsunami water level substantially, resulting in the accident at Fukushima Dai-ichi NPP. This accident has revealed the presence of tsunami risk. To strengthen the safety of nuclear power plants against external events, including tsunami, a new standard based on risk quantification must be introduced. We will be going to design JNES Model for establishing the design basis tsunami based on probabilistic tsunami evaluation reflected the lessons learnt from our investigation into the occurrence mechanism of the Tohoku EQ Tsunami.

AKCNOWLEDGEMENT

Prof. F. Imamura from the Tohoku University, Prof. K. Satake from the University of Tokyo, Prof. T. Takahashi from the Kansai University give insightful comments and suggestions for our investigation. Emeritus Prof. at Kyoto University / Technical counsellor of JNES, H. Kameda gives valuable suggestions for the framework of this project. I would like to express my gratitude to them.

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