4. Outline of Earthquake and Tsunami

A M_w 9.0 (M_w by JMA) earthquake occurred off the Pacific Coast of Tohoku at 14:46 JST (5:46 UTC) on March 11, 2011 and generated gigantic tsunami in the Tohoku and Kanto regions of the northeastern part of Japan. This was a thrust earthquake occurring at the boundary between the North American and Pacific plates. A M_w 7.5 foreshock preceded the mainshock on March 9 and many large aftershocks including two M_w 7-class aftershocks followed the mainshock.

4.1 Earthquake Mechanism

Many researchers are studying source process of the 2011 Tohoku earthquake using different kinds of data, such as seismic waves, aftershocks' locations, GPS, tsunami, etc. Here shows as an example the first result for the source process from regional strong motion data by Yoshida *et al.* (2011)[4-1]. The main features are as follows. (a) The main rupture is located to the east of the initial break point (the shallower side of the hypocenter), and maximum slip amounts were more than 25 m. (b) The size of the main fault was about 450 km in length and 200 km in width; the duration of rupture was more than 150 s; and M_w was 9.0. (c) The initial rupture gradually expanded near the hypocenter (0–40 s) and subsequently propagated both southward and northward.

Other analyses show more or less very similar results to this result shown in Fig. 4.1-1. A result by tsunami inversion is shown in the section 4.4.2.

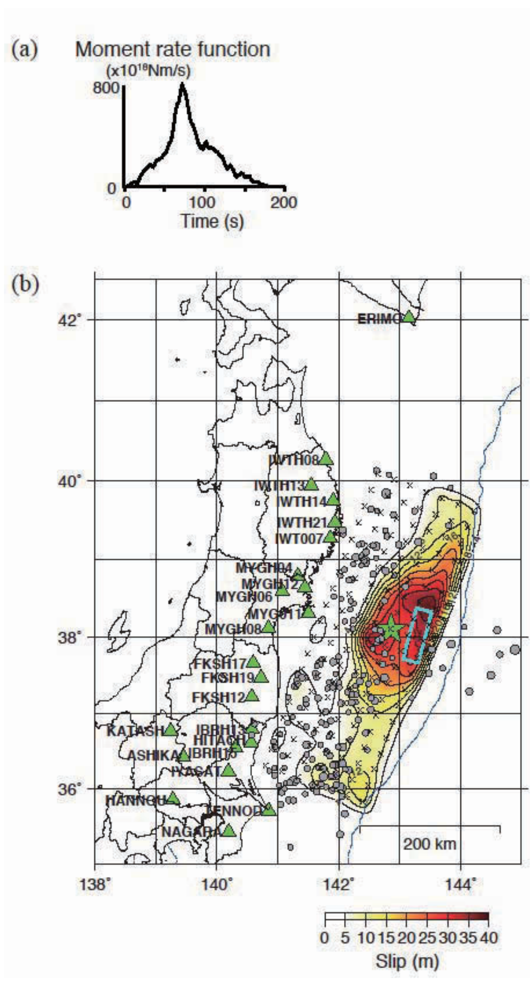

Fig. 4.1-1 Finite-source model from inversion of strong motion waves[4-1]: (a) Moment rate function. (b) Slip distribution on the fault. Large green star represents the epicenter of the mainshock, and gray circles represent aftershocks ($M \geq 5.0$) within 24 h of the mainshock. Triangles denote seismic stations used in this analysis. Contour interval in slip distribution is 4 m. The light blue rectangle shows the estimated peak of the highly uplifted area obtained from tsunami arrival times.

4.2 Relocation of Earthquakes

Foreshocks, mainshock, and aftershocks of the 2011 Tohoku earthquake (M_w 9.1 by global CMT) were relocated using the modified joint hypocenter determination (MJHD) method[4-2)] in order to obtain their precise hypocenters and to identify fault planes of larger earthquakes. *P*-wave arrival times at stations worldwide reported by the U. S. Geological Survey (USGS) were used. It was confirmed by relocated hypocenters that the mainshock and aftershocks had occurred along the plate boundary between the North American and Pacific plates (Fig. 4.2-1). It was also confirmed that the M_w 7.5 foreshock, which occurred two days before the mainshock, and the largest aftershock (M_w 7.9), which occurred half an hour after the mainshock, were thrust earthquakes along the plate boundary. The second largest aftershock (M_w 7.6), which was a normal-faulting earthquake and was a bending-stress intra-plate event caused by the strain reduction on the subduction thrust, occurred at the outer rise of the Japan Trench and was well relocated with its aftershocks. It was found that its fault plane dipped westward and it bounded the aftershock distribution on the seaward side. This implies that the western side of the fault plane had subsided, corresponding with the westward plate subduction. The size of the one-day aftershock area was ~450 km x ~150 km if the outer rise area is excluded. If the outer rise area is included, the size was ~450 km in the northerly direction and ~400 km in the easterly direction. The details of these analyses are given by Hurukawa (2011)[4-3)].

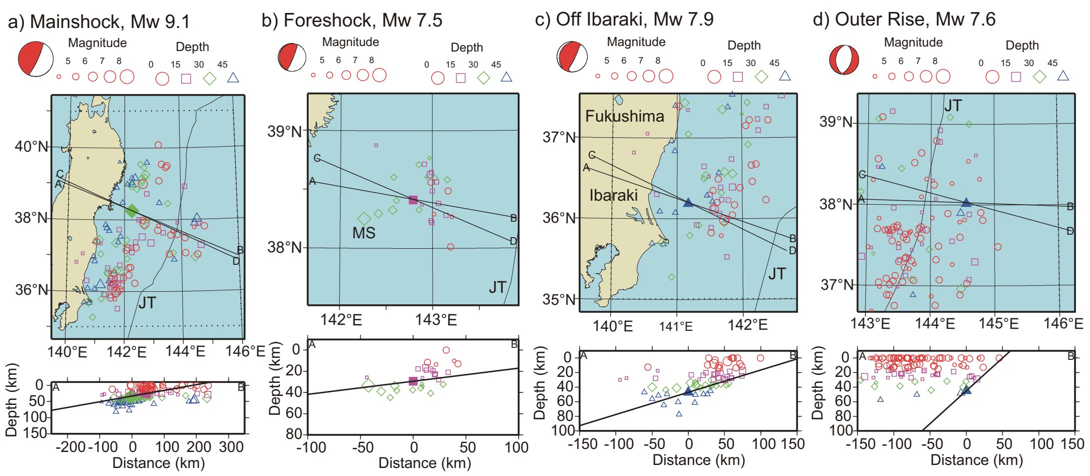

Fig. 4.2-1 Relocated hypocenters by the MJHD method[4-3)]: Epicentral distribution and a vertical cross section along A-B line, which is perpendicular to strike of the nodal plane of the global CMT solution, are shown. This nodal plane corresponds with the fault plane. a) The mainshock (2011/03/11 5:46 UTC) and immediate aftershocks within 24 hours. b) The largest foreshock (2011/03/09 2:45 UTC) and its aftershocks. MS indicate the mainshock. c) The largest M_w 7.9 aftershock off Ibaraki (2011/03/11 6:15 UTC) and aftershocks within 24 hours after the mainshock. d) The M_w 7.6 aftershock at the outer rise (2011/03/11 6:25 UTC) and aftershocks. JT: Japan Trench.

4.3 High Frequency Energy Radiation Duration and its Corresponding Magnitude

Durations of high frequency energy radiation (HFER) measured from tele-seismic P waves well correlate with source times, and can be used as their guesses. HFER durations of the 2011 Tohoku earthquake were measured using broadband waveforms recorded at the Global Seismograph Network stations; we retrieved data from the data management center of the IRIS (Incorporated Research Institutions for Seismology). Figure 4.3-1 shows the measured HFER durations as a function of station azimuths. Their mean was 170.5 s. This suggests that the source time of this event was around 3 minutes. The azimuthal dependence shown in Fig. 4.3-1 suggests that the rupture which generated strong HFERs propagated in the southwest direction.

The magnitude of this event was calculated using the following formula of Hara (2007) [4-4]:

$$M = 0.79\log A + 0.83\log\Delta + 0.69\log t + 6.47 \qquad \text{(Eq.4.3-1)}$$

where M is an earthquake magnitude, A is the maximum displacement (m) during the estimated duration of HFER from the arrival time of a P-wave, Δ is the epicentral distance (km), t is the estimated duration (s) of HFER. The mean of the calculated magnitudes for all the stations was 8.96. Figure 4.3-2 shows the contribution of the first and second terms (i.e., maximum displacement with distance correction) and that of the third term (i.e., HFER duration) for this event and other large ($M_w \geqq 8$) shallow earthquakes that occurred since 1994. Compared to the December 26, 2004 Sumatra earthquake (M_w 9.0-9.3), the HFER duration of this event was shorter, while the maximum displacement was larger. The details of these analyses are given by Hara (2011)[4-5].

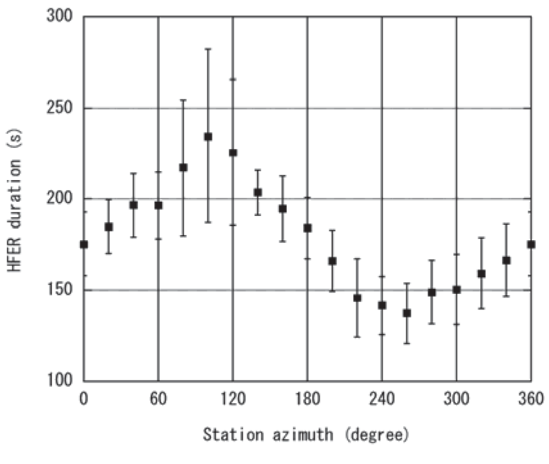

Fig. 4.3-1 The measured HFER durations as a function of station azimuths. The moving window (±30 degree) averages are shown.

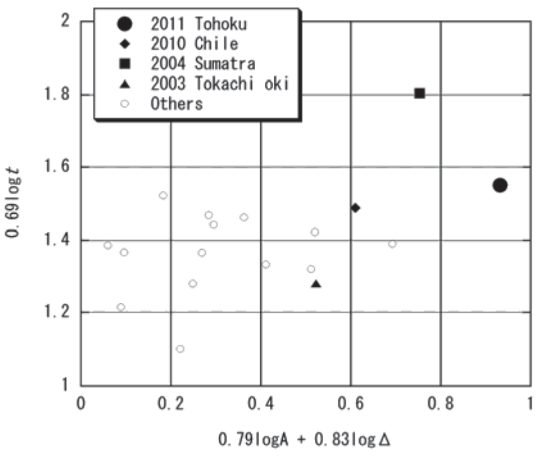

Fig. 4.3-2 Contributions to magnitudes from maximum displacement amplitudes and epicentral distances (the horizontal axis) and those from HFER durations (the vertical axis)

4.4 Tsunami

4.4.1 Observed tsunami heights

The 2011 Tohoku tsunami was recorded instrumentally at four types of gauges. They are ocean bottom tsunami sensor (OBTS), GPS gauge, wave gauge (WG) and tide gauge (TG), which are installed in deep to shallow sea. Japan Meteorological Agency (JMA) reported the tsunami heights observed at coastal tide gauges (Fig. 4.4-1). According to JMA (2011) [4-6], the tsunami heights were less than 3 m along the coasts of Hokkaido to Aomori prefectures, and more than 4 m along the coasts of Iwate, Miyagi and Fukushima prefectures. Many coastal tide gauges on the Pacific coast of the Tohoku region stopped recording after the first tsunami arrival, because of power failure or the stations were damaged by the tsunami. Later JMA retrieved the tide gauge records on site and announced that the observed tsunami heights were more than 8.5 m at Miyako, more than 8.0 m at Ofunato, more than 7.6 m at Ayukawa (Ishinomaki), and more than 9.3 m at Soma.

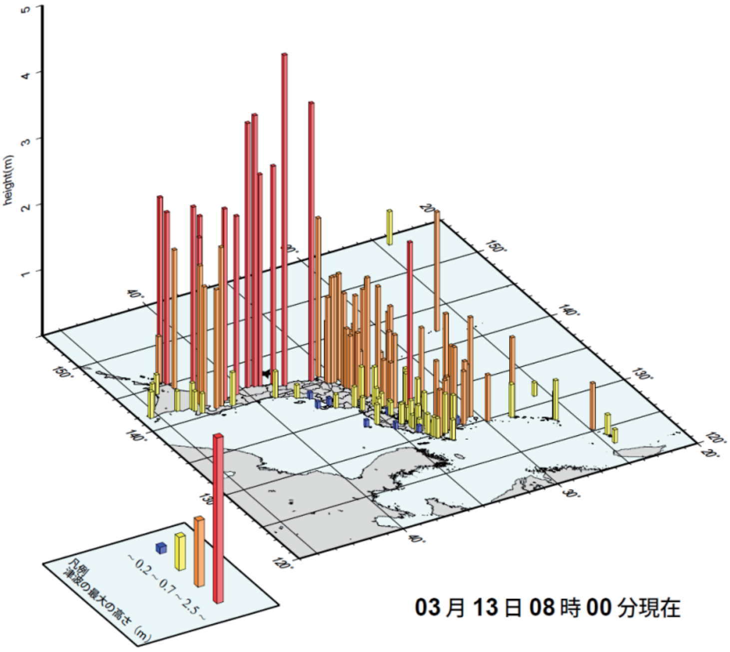

Fig. 4.4-1 Observed tsunami heights at tide gauge stations as of March 13th 8 AM[4-6]

Tsunami heights in the coastal areas of Japan were measured and reported by the 2011 Tohoku Earthquake Tsunami Joint Survey Group which consists of coastal engineers, seismologists, tsunami researchers from universities or research institutes, and other tsunami-related officials. The field surveys were mainly conducted along the Pacific coasts from Hokkaido to Okinawa. The survey results all end up on the internet site and are being updated appropriately[4-7]. According to the preliminary survey results, inundation or runup heights were about 5 m in the Pacific coasts of Hokkaido, up to 10 m in Aomori and Chiba prefectures, more than 30 m in some locations along the Sanriku coasts of Iwate, up to 20 m in Miyagi prefecture (Fig. 4.4-2, as of 5 July 2011).

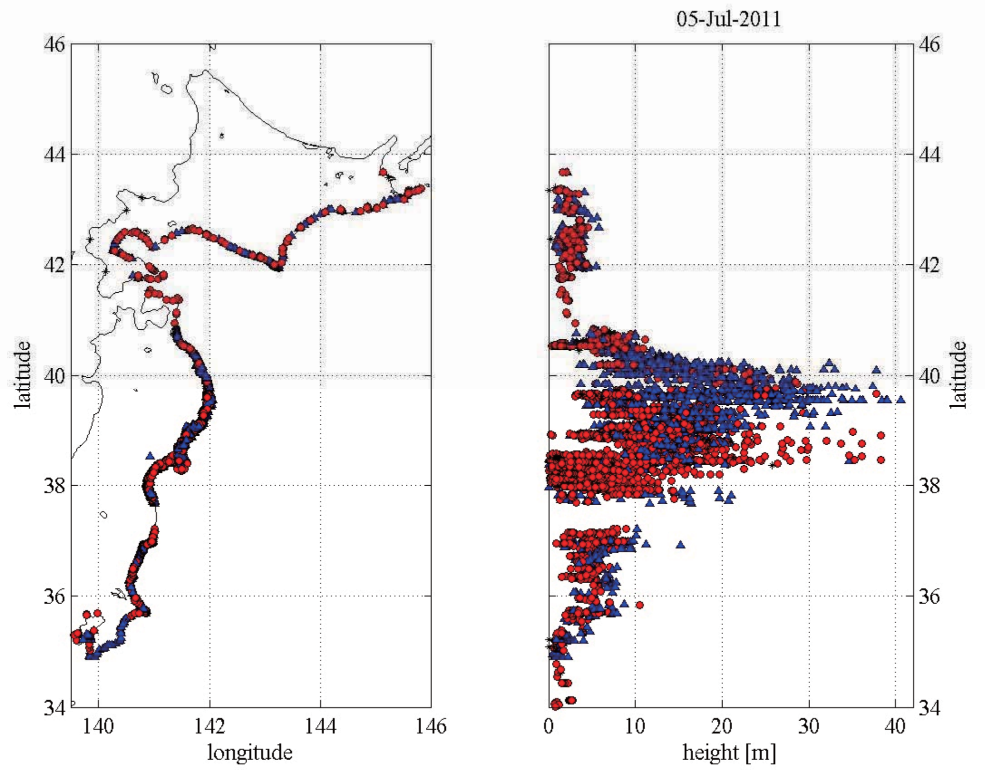

Fig. 4.4-2 Distribution of measured tsunami heights by the field surveys[4-7]: Red circles and blue triangles indicate inundation heights and runup heights, respectively.

4.4.2 Tsunami source model and simulated maximum tsunami heights

A tsunami waveform inversion was performed to estimate the tsunami source of the 2011 Tohoku earthquake[4-8]. The tsunami waveforms were recorded at various types of sensors such as OBTSs of Deep-ocean Assessment and Reporting of Tsunamis (DART) by National Oceanic and Atmospheric Administration (NOAA), cabled OBTSs by Japan Agency for Marine-Earth Science and Technology (JAMSTEC) and Earthquake Research Institute (ERI), The University of Tokyo, GPS wave gauges, tide and wave gauges by Japan's Nationwide Ocean Wave information network for Ports and Harbours (NOWPHAS) and tide gauges of JMA and Japan Coast Guard (JCG). The stations used for the tsunami waveform inversion are shown in Fig. 4.4-3.

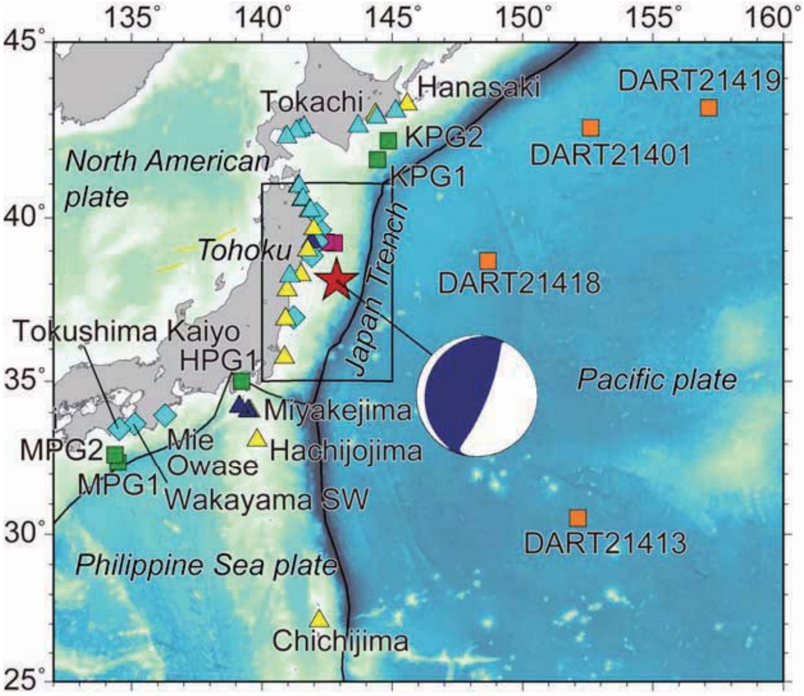

Fig. 4.4-3 Epicenter of the 2011 Tohoku earthquake (red star), W phase MT solution by USGS, and stations that recorded the tsunami[4-8]. Triangles, diamonds and squares indicate the locations of coastal (tide or wave) gauges, offshore GPS wave gauges and OBTSs or DART systems, respectively. Colors indicate operating agencies (yellow: JMA, blue: JCG, green: JAMSTEC, orange: NOAA, light blue: NOWPHAS, and purple: ERI). Square indicates the region shown in Fig.4.4-4.

Forty subfaults are located within the aftershock area (see Fig. 4.4-4). The length and width are 50 km × 50 km for each subfault. The focal mechanisms of the all subfaults are strike: 193º, dip:14º and slip:81º from the USGS's W-phase moment tensor solution. The top depths of the subfaults were assumed to 0 km, 12.1 km, 24.2 km and 36.3 km for near-trench, shallow, middle and deep subfaults, respectively. An instantaneous rupture was assumed on the fault.

In order to calculate the Green's functions from source to stations, static deformations of the seafloor, the initial conditions for tsunami, were calculated for a rectangular fault model[4-9] for each subfault. The used bathymetry data are 30 arc-second grid from JTOPO30 for tide gauges in Japan and 2 arc-minute grid for off shore (Pacific Ocean), resampled from GEBCO_08 30 arc-second grid data. To calculate tsunami propagation, the linear shallow-water, or long-wave, equations were numerically solved by using a finite-difference method[4-10].

The inversion result (Fig. 4.4-4) shows a tsunami source length (with more than 2 m slip) of about 350 km, extending from over southern Sanriku-oki, Miyagi-oki, Fukushima-oki as well as near the trench axis. The largest slips with more than 40 m are estimated along the Japan trench axis off southern Sanriku. Around the epicenter, in southern Sanriku region, the estimated slip was about 28 – 34 m. On the deeper subfault in Miyagi-oki region, the slip was 9 – 23 m. To the north of the epicenter, 5 – 11 m slip was estimated in a part of central Sanriku region. To the south, the slip was about 10 m in Fukushima-oki region, and less than 3 m in Ibaraki-oki region. The total seismic moment was calculated from these slip distributions as 3.8×10^{21} Nm (M_w 9.0) which is consistent with other studies based on seismic data analyses. The comparison of tsunami waveforms are shown in Fig. 4.4-5.

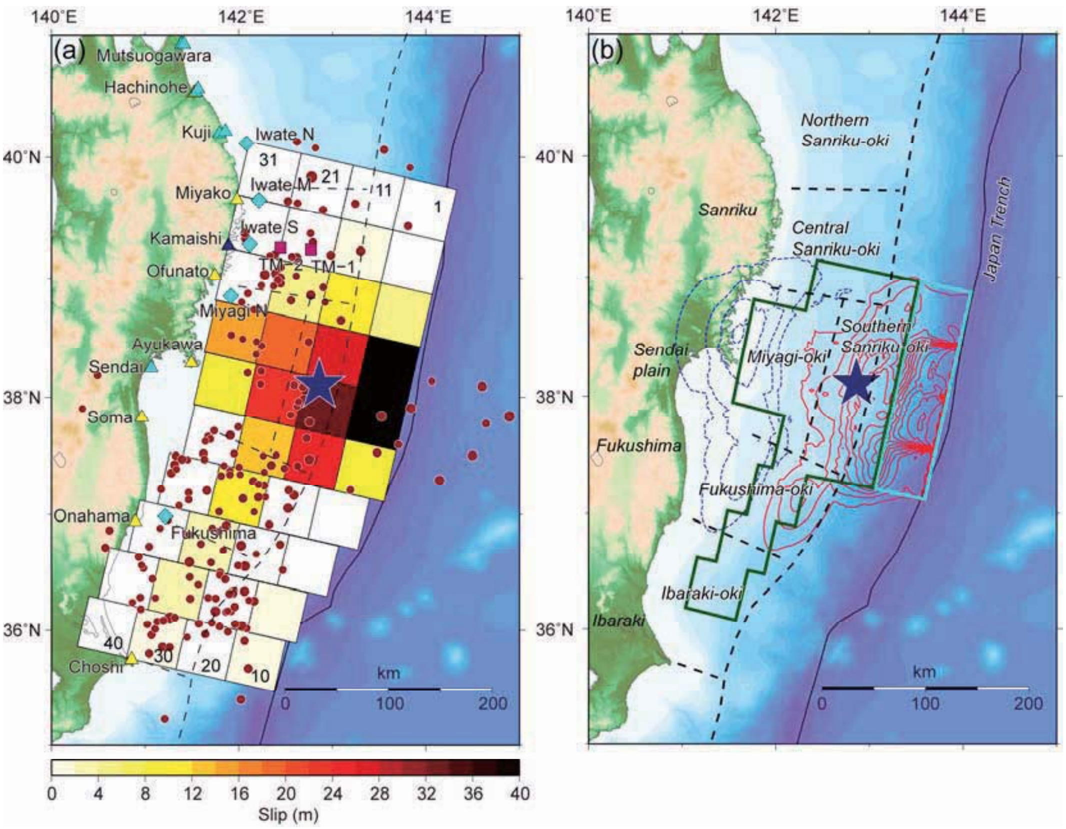

Fig. 4.4-4 (a) Slip distribution estimated by tsunami waveform inversion[4-8]. The subfault numbers are shown in the northernmost and southernmost subfaults. Star shows the mainshock epicenter. Circles indicate aftershocks within one day after the mainshock (JMA data). Dashed lines indicate regions where the probabilities and size of future subduction-zone earthquakes were estimated by Earthquake Research Committee (2009) [4-11]. Coastal and offshore stations (the same symbol as Fig. 4.4-3) are also shown. (b) Seafloor deformation computed from the estimated slip distribution. The red solid contours indicate uplift with the contour interval of 1.0 m, whereas the blue dashed contours indicate subsidence, with the contour interval of 0.5 m. The light blue and dark green frames show the subfaults with more than 2 m slips located near the trench axis and in deep interplate, respectively.

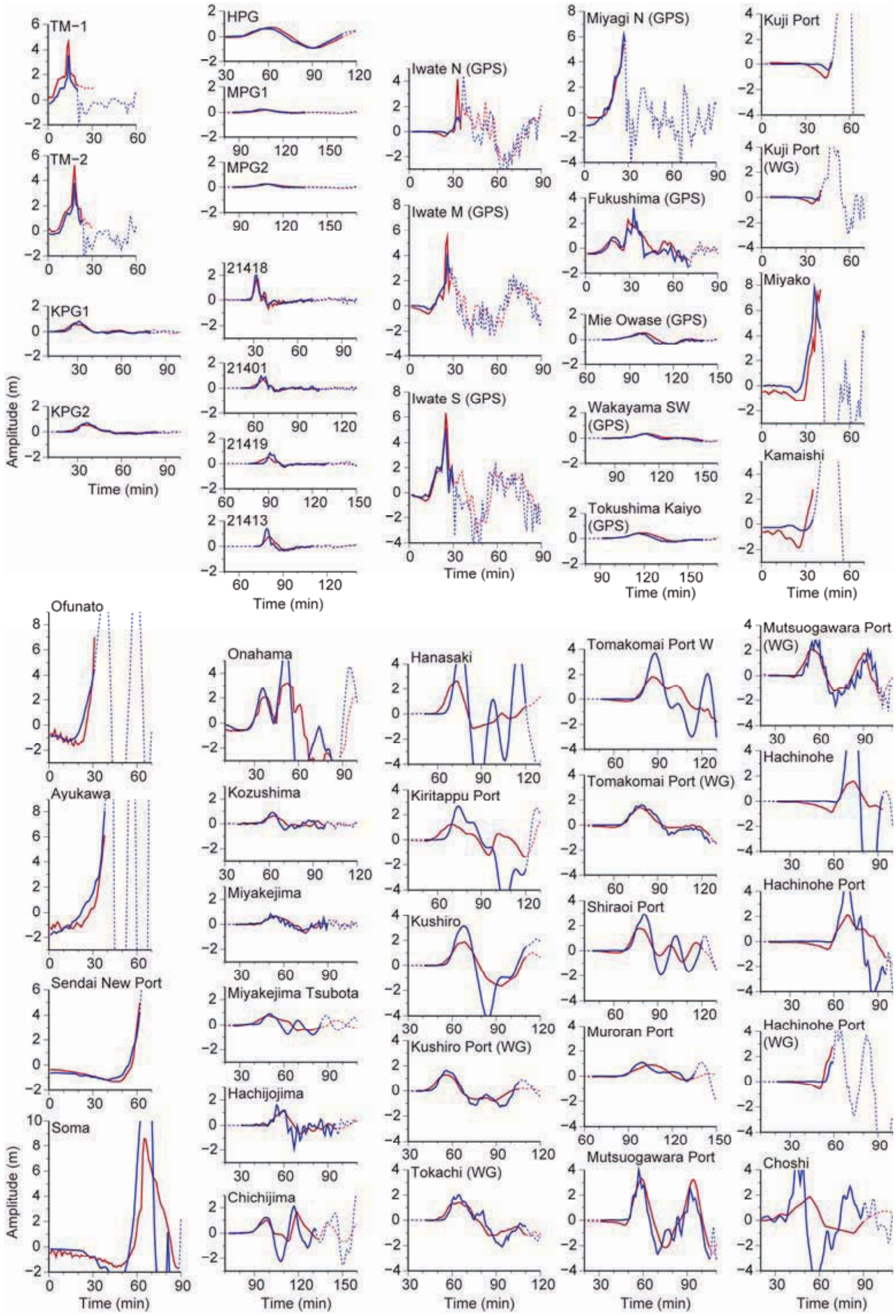

Fig. 4.4-5 Comparisons of the observed (red curves) and synthetic (blue curves) tsunami waveforms computed from the estimated slip distribution[4-8]. Time ranges shown by solid curves are used for the inversions; the dashed parts are not used for the inversions, but shown for comparison. Note the same vertical scales for bottom pressure gauges (the upper left two columns), GPS wave gauges (upper central two columns) and coastal tide and wave gauges (upper right one column and bottom columns). See Figs.4.4-3 and 4.4-4(a) for the station locations.

The tsunami heights were simulated along the Japanese coasts adopting the tsunami source model described above. The non-linear shallow-water equations were numerically solved by using a finite-difference method[4-10]. The used bathymetry grid is the 30 arc-second uniform grid from JTOPO30 data. The reproduced tsunami heights were about 5 – 10 m along the coasts from southern part of Iwate to Fukushima and more than 10 m in some locations such as a tip of peninsula or a back of bay (Fig. 4.4-6).

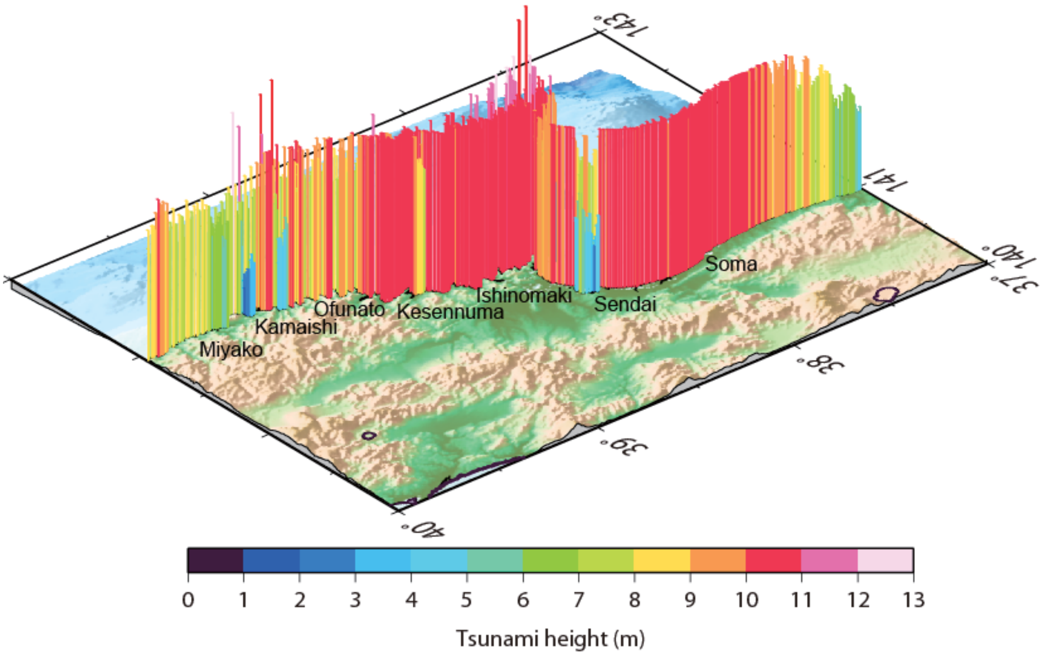

Fig. 4.4-6 Simulated tsunami heights along the coasts from southern part of Iwate to Fukushima prefectures. The used tsunami source model is based on Fujii *et al*. (2011) [4-8].

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