III. Disaster Damage in Japan from the Tohoku District - Off the Pacific Ocean Earthquake and Resulting Tsunamis

1. Damage by the earthquake and tsunami in Japan

(1) Outline of the Tohoku District - Off the Pacific Ocean Earthquake

1) Tectonic setting and earthquake mechanism

The Japanese Archipelago is situated at the boundaries of four tectonic plates: the North American, Eurasian, Pacific and Philippine Sea plates, as shown in Figure III-1-1. The Japanese Archipelago receives strong compression from two directions caused by subductions of the Pacific and Philippine Sea plates.

The Tohoku District – Off the Pacific Ocean Earthquake (hereinafter referred to as this earthquake) occurred on the boundary of the North American plate along the Japan Trench and the Pacific plate as shown in Fig. III-1-1 at 14:46 on March 11, 2011. The Japan Meteorological Agency (JMA) estimated that the hypocenter was approximately 130 km off the coast of Sanriku, the depth was 24 km and the size was Moment Magnitude[1] M_w9.0 (The 16th report from JMA). And the Headquarters for Earthquake Research Promotion (hereinafter referred to as HERP) assumes that the source area of this earthquake covered from the offshore area of Iwate Prefecture to that of Ibaraki Prefecture, and its size was above 400km long, and approximately 200km wide. Mechanism solutions showed a reverse fault with a compressional axis in the west-northwest- east-southeast direction. ("Evaluation of Tohoku District - Off the Pacific Ocean Earthquake" released by the earthquake investigation committee, HERP on April 11).

The hypocenter of this earthquake was off the coast of Miyagi Prefecture as shown in Figure III-1-2 and the rupture was estimated to have propagated simultaneously from the hypocenter in the area off Miyagi Prefecture to the area off Iwate Prefecture in the north and the area off Fukushima Prefecture and Ibaraki Prefecture in the south according to documents released by the HERP and so on. The offshore area of Miyagi Prefecture, as a part of source area of this earthquake, consists of two source areas A and B as shown in

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1 Moment magnitude: A magnitude scale relating the size of an earthquake to the energy released. It can accurately measure the sizes of large earthquakes.

Fig. III-1-2. It is estimated that the rupture started at the hypocenter, which was located in B, propagated westwards to area A, and further spread to the area east to area B. As shown in a cross-section of a-a’ in Figure III-1-2, the estimated rupture started at the hypocenter (about 24 km deep), propagated to area A in the deep portion, and further spread to the shallow portion east to area B. It is estimated that the areas with large slip were the area near the southern trench off the Sanriku coast and a part of near-trench areas from the offshore area of North Sanriku to that of Boso, with the maximum slip of above 20 m.

2) Examples of analysis for crustal movement, seismic source process and tsunami source process

The Geospatial Information Authority of Japan (GSI) has released a report of crustal movements caused by the earthquake on the basis of GPS observation as shown in Fig.III-1-3. According to this figure, the significant crustal movement occurred in the area from the coast of Miyagi Prefecture to Fukushima Prefecture, and subsidence ranged from 0.5 m to 1.2 m (average subsidence is about 0.8 m). At Ojika observatory in Miyagi Prefecture, the horizontal displacement in a east-southeast direction was about 5.3 m and the vertical displacement was about 1.2 m.

The JMA analyzed source process[2] for this earthquake and has released slip distribution information as shown in Fig.III-1-4 with the use of observation records from K-NET and KiK-net operated by the National Research Institute for Earth Science and Disaster Prevention (NIED), together with waveform data from JMA accelerometers. JMA assumed the fault size as 450 km long and 150 km wide, and its analysis results was that a moment magnitude of 9.0 was obtained and the rupture duration time was 170 sec. In this analysis, slip gradually enlarged near the rupture start point (hypocenter: at 38.10 degrees north latitude, 142.86 degrees east longitude and 23.7 km deep) for about 0 to 60 seconds, and proceeded to the south and to the north separately. The area with large slip was east to northeast side of the rupturing start point (shallower than the hypocenter) and the maximum slip amount was about 30 m. The area with large slip is generally consistent with results from other Japanese or oversea research institutes.

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2 Source process: rupture propagation on the fault plane. Usually inferred from waveform inversion which minimizes the difference between the observed waveforms and theoretical ones synthesized from those of subfaults.

For example, Fujii and Satake carried out tsunami waveform inversion[3] by using tsunami observation records from JMA and other institutions and analyzed the process of tsunami wave source (Refer to Fig.III-1-5). In this, also, the areas with large slip amount is distributed in northeast side of the seismic source (black area in the Figure), which agrees with JMA results. Results of slip distribution analysis by the JMA and results of tsunami analysis by Fujii and Satake indicate that the large slip at the shallow plate boundary in the east side of the start point of rupturing is the factor that brought about the large tsunami.

3) Relation with HERP evaluation of long-term seismicity in Japan

The HERP has released evaluation results of earthquake occurrence probability within the next 10, 30 and 50 years, respectively, , as shown in Fig.III-1-6 for those trench-type earthquakes with a certain magnitude (earthquake occurrence probability within 30 years, based on January 1, 2011). Among these evaluation cases, the HERP has estimated a 99% occurrence probability within 30 years for the Miyagi-ken Oki (literately, off the coast of Miyagi Prefecture) earthquake (seen in Fig. III-1-6) with a magnitude of M7.5 and was alerting the public to this probability. The rupture start point (in the offshore area of Miyagi Prefecture), the assumption of consecutive ruptures of two seismic sources A and B within the same area and the timing of the occurrence were almost the same as evaluated. However, the committee admitted that the size of the source area, which covers the offshore areas of central Sanriku, Miiyagi Prefecture, Fukushima Prefecture, and Ibaraki Prefecture, the consecutive rupturing, and the magnitude M9 were beyond expectation (Earthquake Research Committee, HERP: The evaluation of the Tohoku District - Off the Pacific Ocean Earthquake released on March 11). Moreover, in contrast to the fact that the rupture spread from the hypocenter to the shallow area of the plate boundary, and slip amount was above 20m, it was assumed that the shallow plate boundary along the Japan trench in the offshore area of Miyagi Prefecture was not able to store a large amount of strain energy, because the area was assumed to be creeping. Some experts, however, commented that the area was strongly coupled, the strain energy has hence been stored for a long time, and the rupturing off the coast of Miyagi Prefecture became the trigger for this earthquake.

(2) Ground motion and tsunami height of the Tohoku District – Off the Pacific Ocean Earthquake

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[3] Tsunami wave inversion: Analysis method to estimate source process by using the time-series data.

1) Ground motion observation

Acceleration waveforms (two horizontal components and one vertical component) recorded at NIED K-NET and KiK-net observation stations in the vicinity of Onagawa NPS, Fukushima Dai-ichi NPS, Fukushima Dai-ni NPS and Tokai Dai-ni NPS are showed in Fig.III-1-7.

Large peaks were produced around 30 seconds and 80 seconds after the earthquake occurred at the observation station (MYG011: distance from the epicenter 127 km) around Onagawa NPS near the epicenter. Although a similar peak is observed in the acceleration records at the observation station near Fukushima Dai-ichi NPS (FKS011: distance from the epicenter 176 km), the second peak was larger than the first. These two peaks are assumed to be caused by rupturing in the vicinity of source area A and source area B.

Incidentally, only one peak was observed 120 seconds after in the acceleration waveform at the observation station near the Tokai Dai-ni Power Station (IBR007: distance from the epicenter 274 km). As for the reason for this, it is assumed that ground motion due to rupturing at seismic sources B and A within the offshore area of Miyagi Prefecture decayed and the effect of the rupture propagation from the offshore areas of Fukushima Prefecture to Miyagi Prefecture on the ground motions in the vicinity of Tokai Dai-ni NPS became larger. Factors effecting significantly on ground motion at a NPS site may include, of the wide source area, the rupture area close to the site, the rupture characteristics, and the consecutive rupturing pattern. Meanwhile, factors effecting significantly on tsunami water level might include the magnitude, the range of the source area, the slip amounts, and the consecutive rupture pattern. It is expected that the difference among those factors will be clarified hereafter in research institutes at home and abroad.

The seismic intensity distribution in East Japan is shown in Fig.III-1-8. The maximum intensity in Kurihara City in Miyagi Prefecture was 7. The area that was hit by a JMA intensity 5 or stronger covered a large area from the Tohoku district and Kanto regions. The intensity at the area near Onagawa NPS, Fukushima Di-ichi NPS, Fukushima Dai-ni NPS and Tokai Dai-ni NPS were 5 strong to 6 strong.

2) Tsunami observation

The observed tsunami waveform by the GPS wave meter at Kamaishi City in Iwate

Prefecture as measured by the Port and Airport Research Institute is shown in Fig. III-1-9. The observed maximum level of the tsunami was 6.7 m for the first wave that hit approximately 26 minutes after the earthquake struck at 14:46. The cycle of the tsunami was irregular and uncertain for the first to third waves, but the intervals between the fourth to the seventh waves were approximately 50 minutes. As for its features, the first wave had two steps and was 2 m at 6 minutes after the event and this increased to 6.7 m during the next 4 minutes.

The observed tsunami water level as measured by the JMA in the coastal area of East Japan is shown in Fig. III-1-10. The observed tsunami water level was 8.5 m or more in Miyako point, 8.6 m or more in Ayukawa point in Ishinomaki City and 9.3 m or more in Soma point. Tsunamis were also observed hitting the Pacific coast in Canada, the U.S. and Latin America etc., and a maximum height of 2 m was observed in Chile.

According to Satake, the wave height of the tsunami is assumed to have been made by the superposition of the long–period wave accompanied by the slip in rather deep areas, such as with the Jogan Earthquake (in 869) and short- period high waves by the slip in shallow areas such as the Meiji Sanriku-oki Earthquake (in 1896) (Refer to Fig.III-1-11). Therefore, it is assumed that after the short-period high tsunami arrived at the coast area and ran up subsequently, the long-period tsunami surged repeatedly over a large duration and hence enlarged the run-up area. The run-up height was 38.9 m in Aneyoshi, Miyako City, Iwate Prefecture, according to an investigation by the Japan Society of Civil Engineers. The run-up height in the Sanriku area exceeded that of the Meiji Sanrikuoki Earthquake (1896) and the Showa Sanrikuoki Earthquake (1933) (Refer to Fig. III-1-12).

3) Occurrence of aftershocks and induced earthquakes

Cumulated numbers of aftershocks of M5 or greater, M6 or greater, and M7 or greater were 444, 76 and 5, respectively, as of May 6. The most powerful aftershock occurred at 15:15 on March 11, and the magnitude of the earthquake was M7.7. As for other main aftershocks, they occurred at 15:25 on the same day far off the coast of Miyagi Prefecture (the depth was approximately 34 km and M7.5), and at 23:32 on April 7 off the coast of Miyagi Prefecture (depth was approximately 40 km and M7.0).The aftershock on April 7 occurred at approximately 40 km east from Ojika Peninsula, and large ground motion was observed in Onagawa NPS.

The occurrence of the triggered earthquakes is shown in Fig.III-1-13. Triggered earthquakes occurred all over Japan including Nagano Prefecture, Akita Prefecture, and Fujinomiya in Shizuoka Prefecture and Fukushima Prefecture. As for earthquakes near NPPs, a M6.7 earthquake occurred near the Tokamachi fault belt in the northern area of Nagano Prefecture approximately 50km southeast from Kashiwazaki NPS on March 12. And a M7.1 earthquake occurred near the Idozawa fault belt approximately 50 km southwest of Fukushima Dai-ichi NPS on April 11. This earthquake was a normal fault-type earthquake with a tension axis that ran along a west-southwest to east-northeast direction, and which occurred at the shallow depth within the plate. The Tohoku Region is a region with a distinctive distribution of active faults in reverse faults, and this is the first time a normal-fault-type inland earthquake was found.

Along with this, on April 28, the Nuclear Safety Commission (NSC) stated the following opinions written below and issued an investigation demand to NISA, which has been reviewing the seismic safety evaluation for existing nuclear reactor facilities etc. (hereinafter referred to as “seismic back-checks”) by reflecting the “Regulatory Guide for Reviewing Seismic Design of Nuclear Power Reactor Facilities“(decided by the NSC on September 19, 2006, hereinafter referred to as “new seismic guidelines”). NISA issued a similar direction to the utilities on April 28.

- If an earthquake occurrence was identified in the areas where earthquake activity was not active, or if an earthquake occurred near faults which were not the active faults that require seismic design consideration, the earthquake has to be evaluated.

- If there is a fault with the possibility to affect the sites after implementing evaluations mentioned above, it is necessary to evaluate the ground motion.

(3) Major damage status caused by the Tohoku District-Off the Pacific Ocean Earthquake

1) Emergency earthquake information (alert) by JMA and related measures taken by local governments

a. Announcement of emergency earthquake information (alert) and details of tsunami information

When a tsunami disaster is anticipated, the JMA announces a “tsunami alert” or “tsunami

advisory” approximately three minutes (targeted) after the earthquake occurs. The announcement procedure for providing information for earthquakes and tsunamis is shown in Fig.III-1-14, and details of the tsunami alert and tsunami advisory are shown in Table III-1-1.

b. The time and details of announcement of tsunami alert by JMA and comparison with those confirmed

The estimated arrival time, height, and confirmed results are compared in Table III-1-2 as for each announcement for a tsunami alert by the JMA for the Pacific coast of East Japan. JMA announced tsunami alerts or tsunami announcements three times at 14:49 (3 minutes after the earthquake struck), at 15:14 (28 minutes after the earthquake), and at 15:30 (44 minutes after the earthquake) after the earthquake at 14:46. The main contents are shown below.

- In the first announcement (14:49, 3 minutes after the earthquake), the JMA announced tsunamis of 6m and 3m would hit Miyagi and Fukushima Prefectures, respectively.

- In the second announcement (15:14, 28 minutes after the earthquake), the tsunami’s arrival had already been identified in Aomori, Iwate, Miyagi, and Fukushima Prefectures. At this point, the estimated tsunami height was corrected to 6 m, 10 m or more, and to 6m in Iwate Prefecture, Miyagi Prefecture, and in Fukushima Prefecture, respectively. However, a tsunami measuring 8m maximum arrived at Miyako, Kamaishi and Ofunato cities in Iwate Prefecture between 4 to 7 minutes after the announcement. Also in Ayukawa in Miyagi Prefecture, 8.6 m or more wave arrived 12 minutes after.

- In the third announcement(15:30, 44 minutes after the earthquake), arrival was confirmed in Aomori, Iwate, Miyagi, Fukushima and Chiba prefectures, and the arrival of a tsunami was also estimated for Ibaraki Prefecture. In these cases the estimated tsunami height was corrected to 10 m or more in all prefectures except for Aomori Prefecture. The highest waves had already arrived in Miyako City and Ofunato City in Iwate Prefecture, ,and Ayukawa in Miyagi Prefecture.

The estimated tsunami height in the third announcement (15:30, 44 minutes after the earthquake) by the JMA was 8 m and 10 m or more, but the highest waves had already arrived approximately 10 to 12 minutes before the announcement.

c. Evacuation status in the local governments who received Tsunami alert from JMA

A "tsunami alert (large tsunami)" announced by the JMA initially estimated the height as 3 m or so for Iwate and Fukushima Prefectures (from the beginning a 6 m height tsunami was predicted for Miyagi Prefecture). However, this was corrected to 6 m 30 minutes later, and corrected again to 10 m or higher 15 minutes later. The evacuation status in each local government responding to these tsunami alerts is shown in Table III-1-3 by taking examples of the responses from Yamada Town, Kamaishi City, Ofunato City and Rikuzen Takada City in Iwate Prefecture, and Mminamisanriku Town, and Kesennuma City in Miyagi Prefecture based on the homepage of the Asahi Shimbun.

The details of the announcements over the community wireless systems in cities, towns and villages were different from government to government. Some cities, towns and villages were not able to receive the follow-up reports due to electric outages, and continued to announce waves of heights of "3 meters or so" in line with the initial report. Therefore there were some local communities where many people suffered causalities because they considered it sufficiently safe to shelter only to the second floors of buildings, for example rather than evacuating to higher ground. The announced height of three m may well have played a role in preventing appropriate evacuation in some cases. Announcements ordering people to evacuate instead of just announcing the estimated tsunami height were effective for some local governments.

d Improvement measures for tsunami alerts by JMA

The JMA did the best to announce information for this earthquake and tsunami in light of current technologies. However, it is realized that a complete back-check and extensive preparations for future situations is essential to provide best-case information that enables a safe and effective response to future M9-class mega earthquakes. Therefore the JMA announced on May 19, 2011 to progress with the improvement of tsunami information steadily by learning lessons from the experience of this earthquake and tsunami.

Specific details are as follows. (1) Verification of details and timing of issued tsunami alerts, (2) Verification of technical issues points (the initially announced magnitude was M7.9; the magnitude was re-evaluated, and was revised higher as time went by.

Therefore it is essential to develop technology to estimate the correct magnitude as quickly as possible). (3) To identify what kinds of issues are remained for the future.

The JMA announced that it would conduct study sessions whose members are experts from universities, research institutes, etc., and related organizations, etc. for disaster preparedness, toward the improvement of tsunami alerts, and that the first session would be held on June 8. The JMA also announced that it would summarize their direction of its tsunami alert improvement after gathering and sorting out opinions from experts, by around the autumn of this year.

Adding to that, the JMA mentioned that it would substantiate its information issuance such that the public will be able to use it in practice. In this, the JMA is moving forward not only by itself, but in collaboration with various organizations including related administrative agencies and local governments. The JMA also mentioned that, in the case of tsunami, the point of view of education is important and it would try to make the public better informed and conduct educational outreach.

2) Overall damage situation

In terms of the area inundated by the tsunami, according to the GSI, Miyagi Prefecture had an area of 327 km^2 inundated, Fukushima Prefecture an area of 112 km^2 and Iwate Prefecture had an area 58 km^2 inundated. The total inundated area was up to 561 km^2 (GSI No.5 Report on approximate inundated area). The total number of residential buildings damaged was approximately 475,000 including fully-destroyed, half-destroyed, partially-destroyed and inundated structures. The number of cases of damage to public buildings and cultural and educational facilities was as many as 18,000.

In terms of the extent of damage to infrastructural lifelines, there were approximate 4,000 spots of road damage identified and approximately 7,280 spots of damage to railways (including approximately 1,680 spots caused by the tsunamis). In addition, approximately 460,000 households suffered from gas supply stoppages, approximately 4,000,000 households were cut off from electricity, and 800,000 phone lines were knocked out. (Sources: Emergency Disaster Response Headquarters as of 16:00 on May 30; East Japan Railway Company as of April 17; Japan Gas Association, as of March 12; Ministry of Economy, Trade and Industry as of April 12; Emergency Disaster Response Headquarters, peak damage estimate calculated from 12:00 on March 12).

There were over 120 sites of damage from landslides including mudslides, slope failures, and ground deformation (NIED release as of May 19). Dams burst, and several people went missing in Fukushima Prefecture. Large-scale ground liquefaction occurred in the coastal areas such as Urayasu City, Makuhari City etc. and on the Kujukuri plain etc. in Chiba Prefecture (Environment Research Center in Chiba Prefecture (Second Report) posted on April 15).

24,769 people have been reported as dead or missing (Emergency Disaster Response Headquarters, as of 17:00 on May 30.)

3) Damage to seawalls and the like around harbor installations

Based on the research results of damage to seawalls and ancillary facilties, the effect of scouring[4] and wave power is shown as follows.

The ground around the bases of tidal embankments and seawalls were scoured by runups and rundowns and many of the bases were observed to have suffered collapses as shown in Fig. III-1-15. And the lining of embankments and seawalls (concrete portions that cover rocks and ground inside embankments) suffered boring from the lower edge of bases, and failed to play a role of lining. Given this situation, there is the possibility that sand embankments would collapse through by scouring due to runups and rundowns and breakwater walls would be scoured or collapse if tsunamis breach the sand embankments when these are used as coastal defenses. Therefore technical guidelines should be prepared and organized for several kinds of countermeasures.

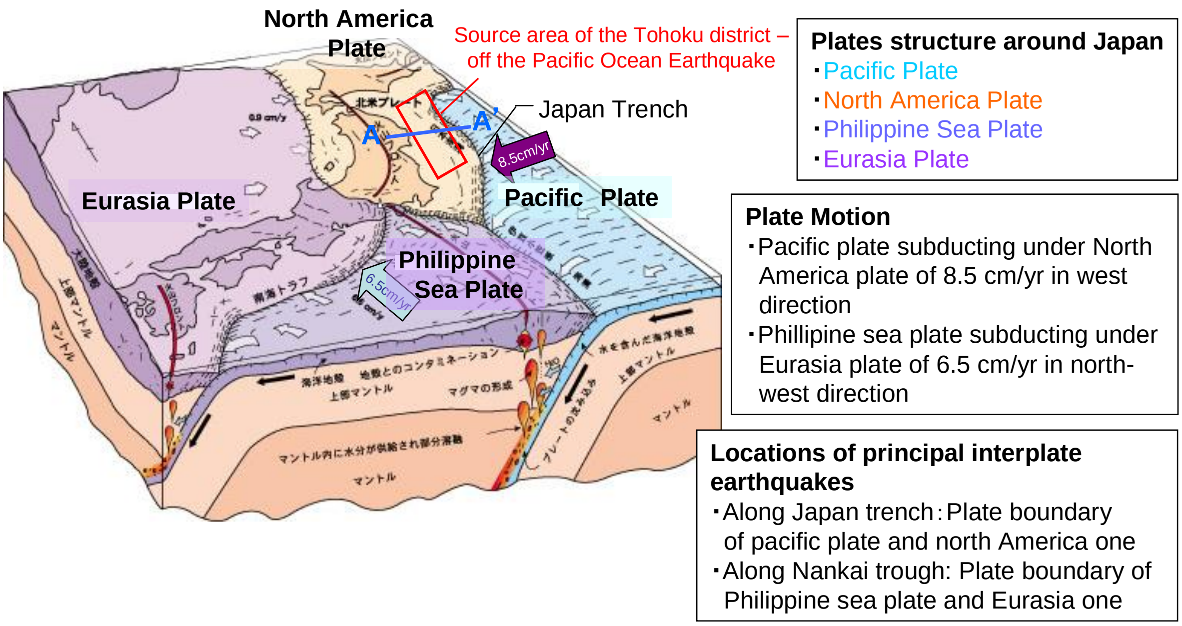
Ancillary facilities for embankments were run down by strong wave pressure of tsunami as shown in Fig. III-1-15. As for treatment of wave pressure, the Tsunami Evaluation Subcommittee in the Japan Society of Civil Engineers pointed out in 2002 that it was necessary to improve the treatment of wave pressure distribution characteristics etc. of soliton breakup waves, in the wave pressure calculation formula. Therefore the calculation formula in the tsunami assessment method (2007) in this committee was improved by using the data obtained from water tank testing. Further upgrading of assessment technologies is important along with the application of this formula to damage by this

[4] Scouring: Phenomenon in which seashores and earth and sand at the sea bottom are shove off mechanically by Tsunami. Grounds around the bases of embankments were rushed away due to runups and rundowns in this tsunami, and bases lost their bearing capacity, and embankments collapsed.

tsunami and for verification.

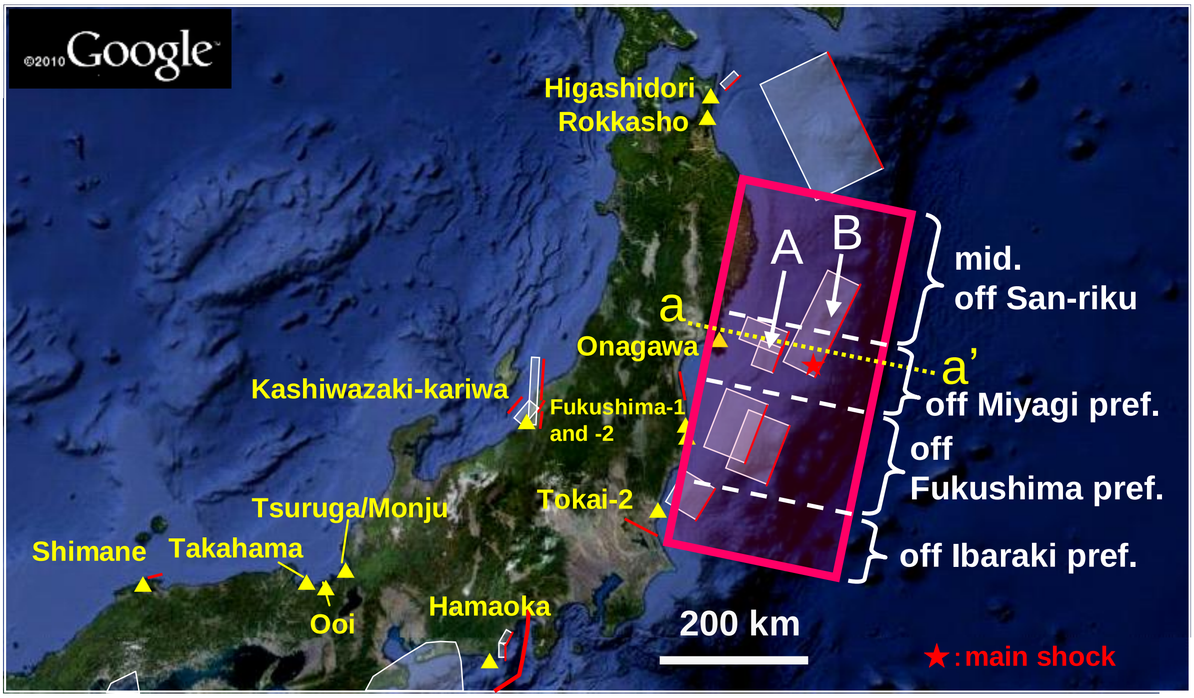
The tidal embankment in the Taro area of Miyako City in Iwate Prefecture is referred to locally as the "Great Wall of China" as it towers 10 meters high. However, even this collapsed when hit by a tsunami that was 15m high, or possibly higher, and significant damage occurred within the embankment as shown in Fig. III-1-16 (left photo) (Asahi Shimbun posted on March 20). Incidentally, the 15.5 m embankment as shown in Fig. in III-1-16 (right photo) was installed in the Ootabu area, Fudai village in Iwate Prefecture following a strong desire of the village chief learning from previous experiences with tsunami. This embankment was able to resist the 15m tsunami and prevented the damage within the embankment zone (Yomiuri Shimbun, posted on April 3). These areas are rias type coastlines that have, historically, suffered significantly from giant tsunamis in the 15m range such as the Meiji Sanriku Tsunami (1896) and the Showa Sanriku Tsunami (1933), the lesson of preparation against a 15m-class tsunami has been instructed. (Yomiuri Shimbun, posted on March 30). Against these tsunamis, there was a sharp contrast between the Ootabe area, which heeded the lessons of the past, and the Taro area.

In the Aneyoshi area, Miyako City in Iwate Prefecture, there is a stone monument with the warning not to build houses in the area lower than that point as shown in Fig. III-1-17 (left picture) at the entrance (height 60 m) of the village, showing lessons learned from runups of the two historical tsunamis mentioned above. By observing this lesson, the area was able to avoid casualties this time even though the tsunami ran up (the actual runup height was 38.9 m) near the village as shown in the figure (right picture).

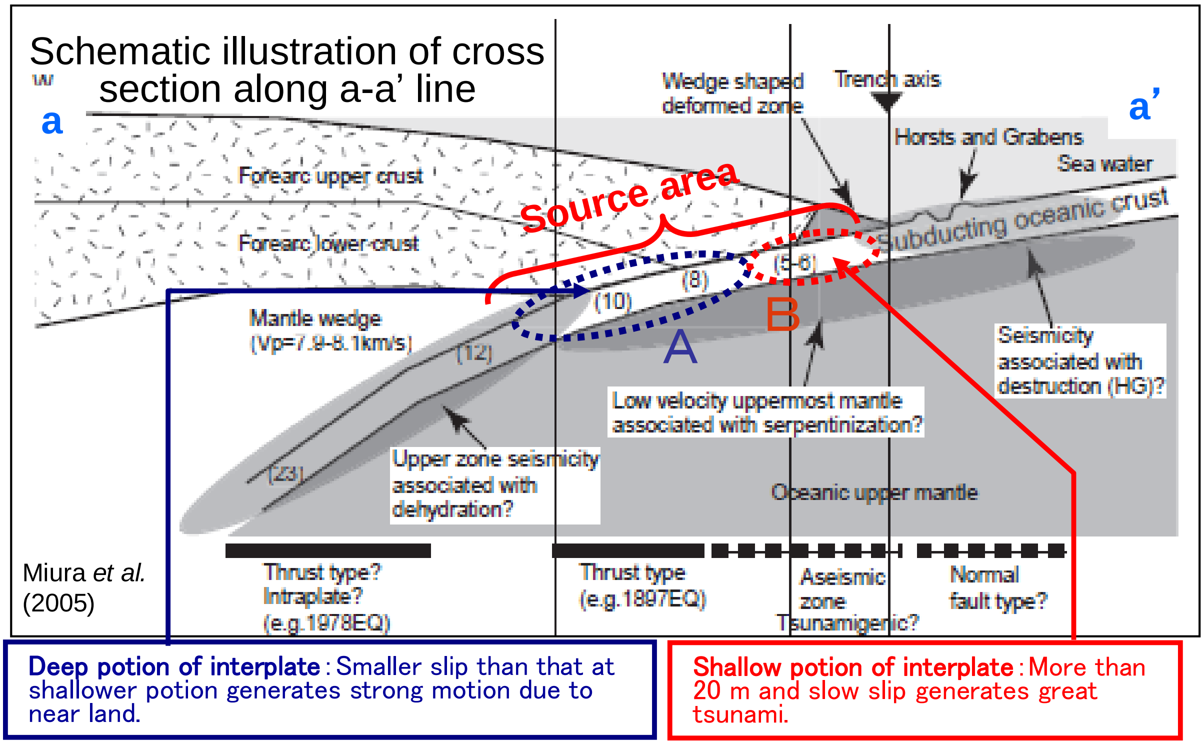


Reference: JGCA HP [Online]. http://www.zenchiren.or.jp/tikei/index.htm
Partially modified by JNES.

Fig. III-1-1 Plate tectonics around Japan.

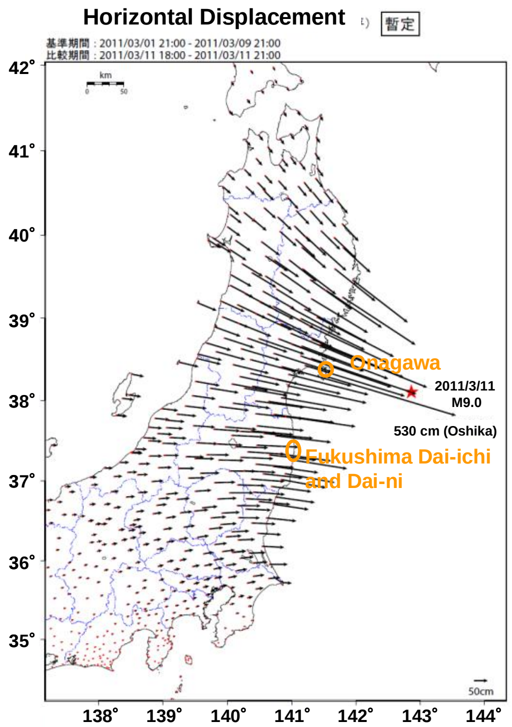


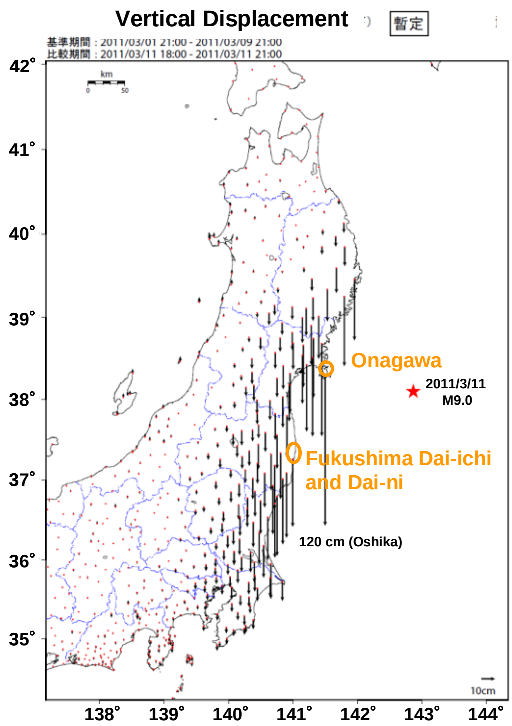
JNES modified a part of the Google map.



Reference: Miura et al. (2005: Tectonophysics, Vol.407)
Partially modified by JNES.

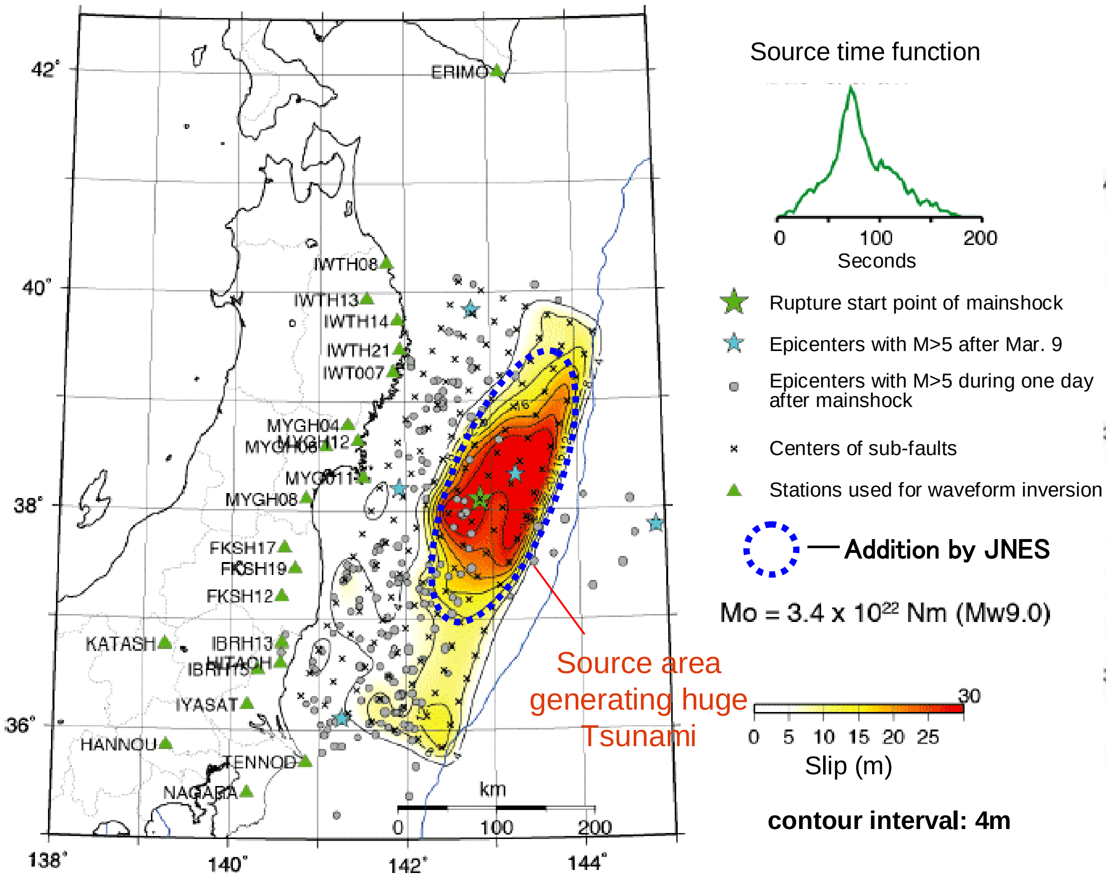
Fig. III-1-2 The source area of the earthquake on Mar. 11 consisting of multi-segment rupture.





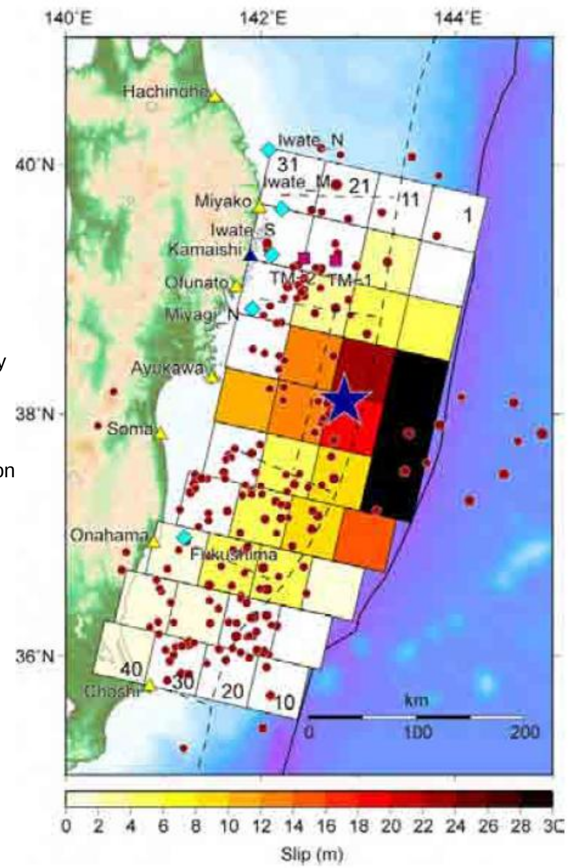
Reference: GSI Release (GSI preliminary values at 11. Mar. 2011)
[Online]. http://www.gsi.go.jp/
Partially modified by JNES.

Fig. III-1-3 Coseismic crustal deformation associated with the main shock. Horizontal deformation (Left) and vertical deformation (Right).



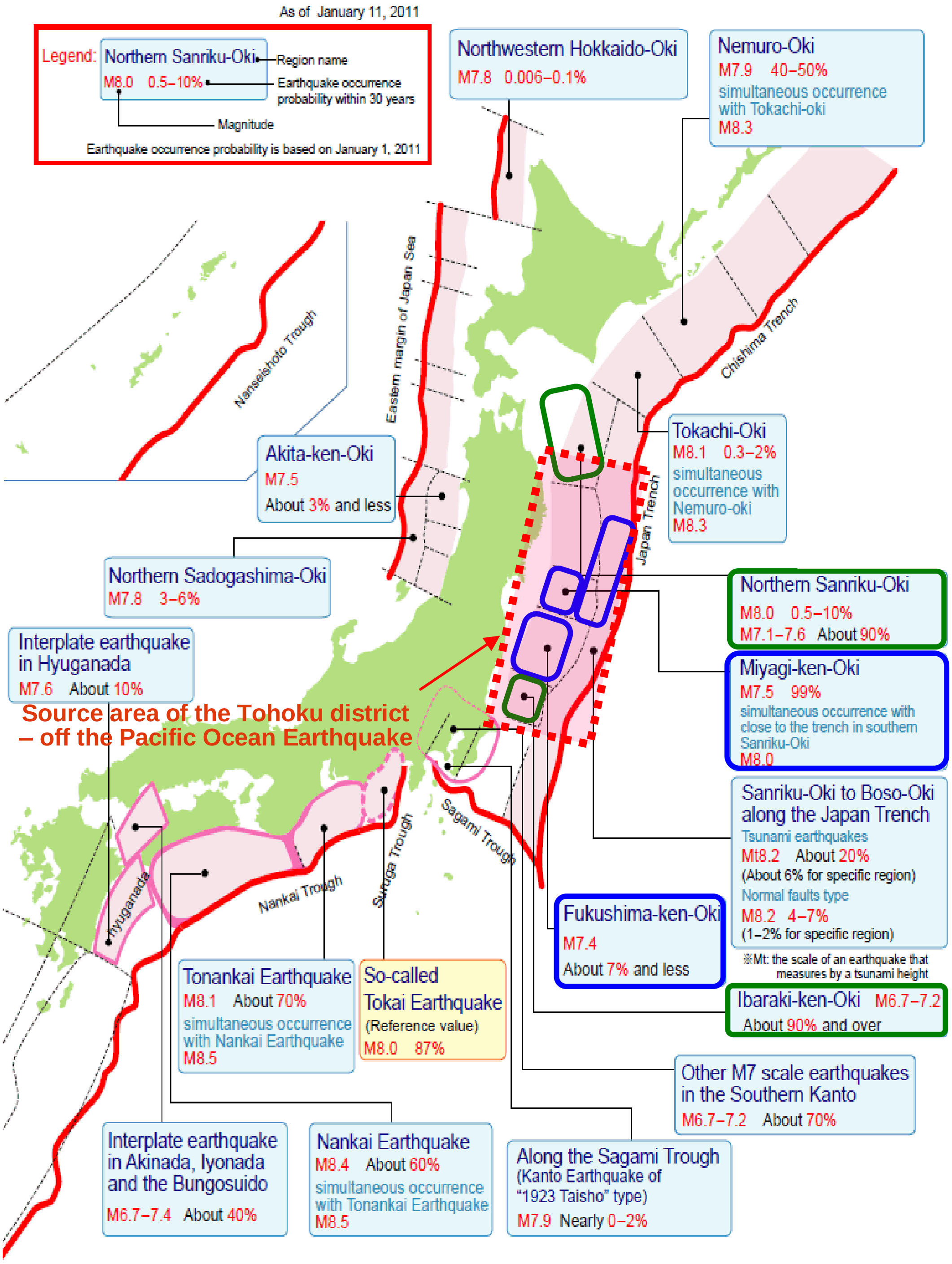
Reference: JMA Release
[Online]. http://www.mri-jma.go.jp/Dep/sv/2011tohokutaiheiyo/source-process2.pdf
Partially modified by JNES.

Fig. III-1-4 Source model based on seismic waveform inversion (JMA).



Reference: Fujii and Satake (Tsunami source model
(Ver. 4.0) [Online]. http://iisee.kenken.go.jp/staff/fujii/
OffTohokuPacific2011/tsunami_ja.html
Partially modified by JNES.

Fig. III-1-5 Source model from tsunami inversion.



Reference: Earthquake Research Comit., HERP Release
[Online]. http://www.jishin.go.jp/main/index-e.html
Partially modified by JNES.

Fig. III-1-6 Comparison of the source areas of the main shock and scenario earthquakes evaluated by Long-Term Evaluation Subcommittee, Earthquake Research Committee, Headquarters for Earthquake Research Promotion (HERP).

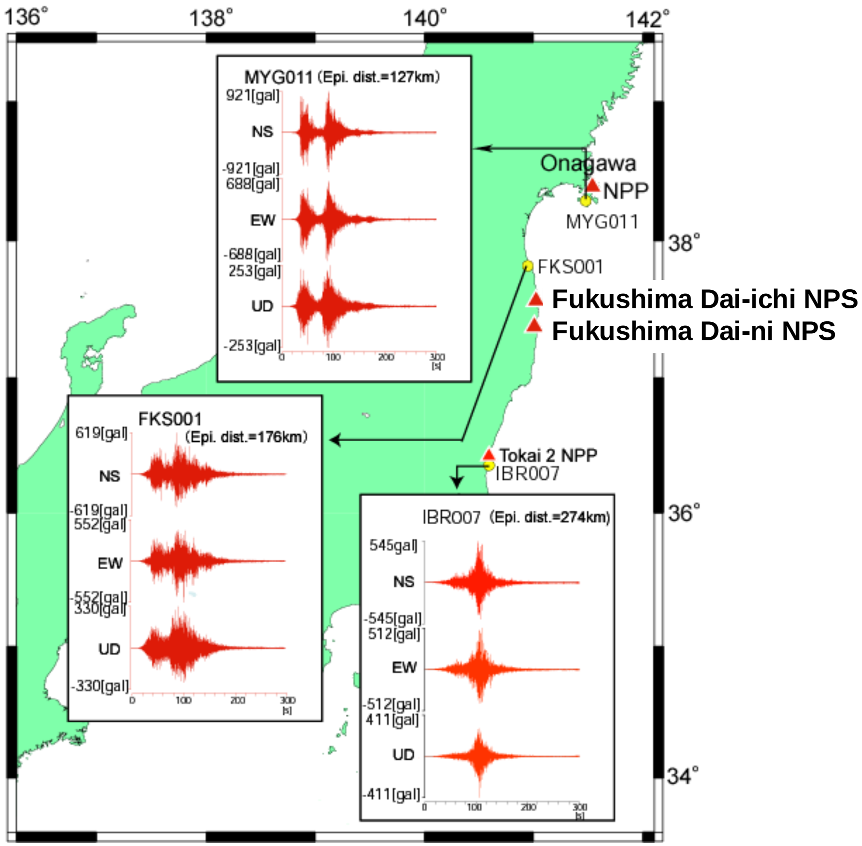
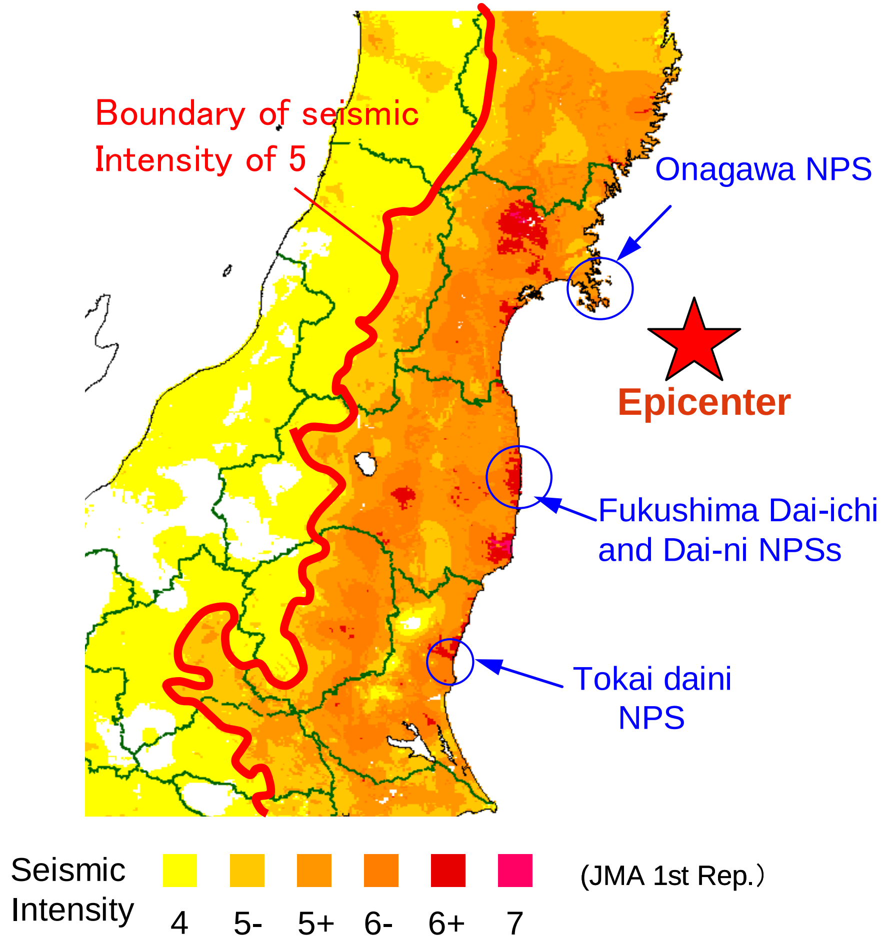
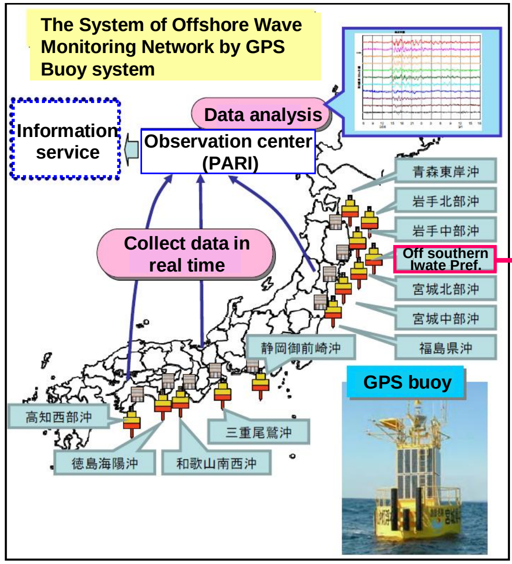


Fig. III-1-7 Acceleration seismograms recorded at around NPSs.

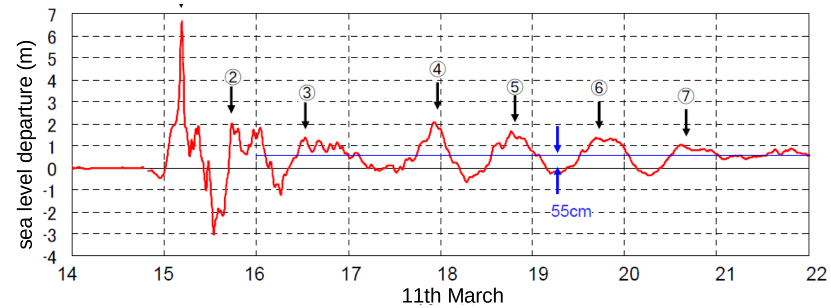


Reference: JMA Release [Online]. http://www.jma.go.jp/jma/index.html
Partially modified by JNES.

Fig. III-1-8 Map of JMA seismic intensities observed during the main shock.



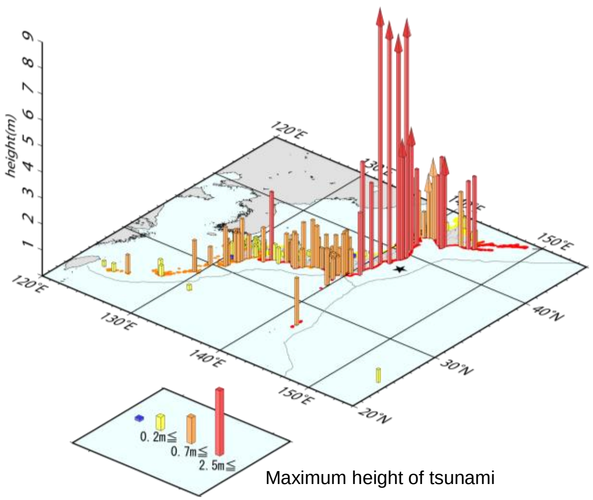
Tsunami waveform record from GPS buoy data off southern Iwate Pref. (204m off Kamaishi)



- The maximum wave height was 6.7 m (first wave) off southern Iwate Pref. at 15:12.
- First tsunami wave was extremely high.
- Wave period
  - First to third tsunami wave: irregular period
  - Fourth to seventh tsunami wave: about 50 minutes period
- Total amount of rose in average sea level were 55 cm after the earthquake.

Reference: Independent Administrative Institute Port and Airport Research Institute

Fig. III-1- 9 A tsunami wave observed at off southern Iwate Pref..

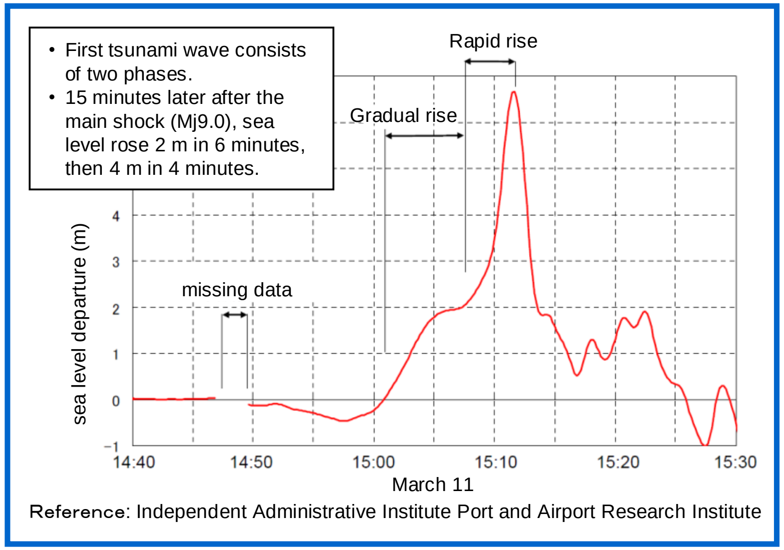


Observed Tsunami (time and height)

Station name	First tsunami	Maximum height of tsunami
Soma (Fukushima)*	March 11, 14:55 JST +0.3m	March 11, 15:51 JST +9.3m<=
Miyako (Iwate)*	March 11, 14:48 JST +0.2m	March 11, 15:26 JST +8.5m<=
Ofunato (Iwate)*	March 11, 14:46 JST -0.2m	March 11, 15:18 JST +8.0m<=
Ishinomaki (Miyagi)*	March 11, 14:46 JST +0.1m	March 11, 15:26 JST +8.6m<=
Oarai (Ibaraki)	March 11, 15:15 JST +1.8m	March 11, 16:52 JST +4.2m
Kamaishi (Iwate)*	March 11, 14:45 JST -0.1m	March 11, 15:21 JST +4.1m<=
Mutsu (Aomori)	March 11, 15:20 JST -0.1m	March 11, 18:16 JST +2.9m
Nemuro (Hokkaido)	March 11, 15:34 JST slight	March 11, 15:57 JST +2.8m
Tokachi (Hokkaido)*	March 11, 15:26 JST -0.2m	March 11, 15:57 JST +2.8m<=
Urakawa (Hokkaido)	March 11, 15:19 JST -0.2m	March 11, 16:42 JST +2.7m

*Maximum height of tsunami cannot be retrieved so far to the troubles.
Actual maximum height might be higher.

Fig. III-1-10 Map showing observed tsunami height (quoted from the paper preparing for the 1st meeting “Learn from Tohoku district – off the Pacific Ocean Earthquake” of expert examination committee, Central Disaster Prevention Council).



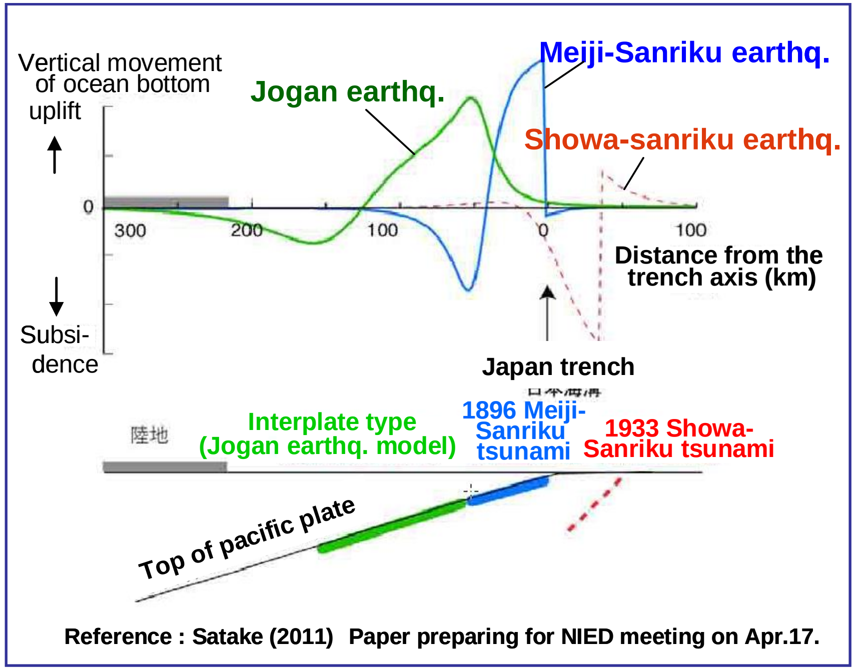
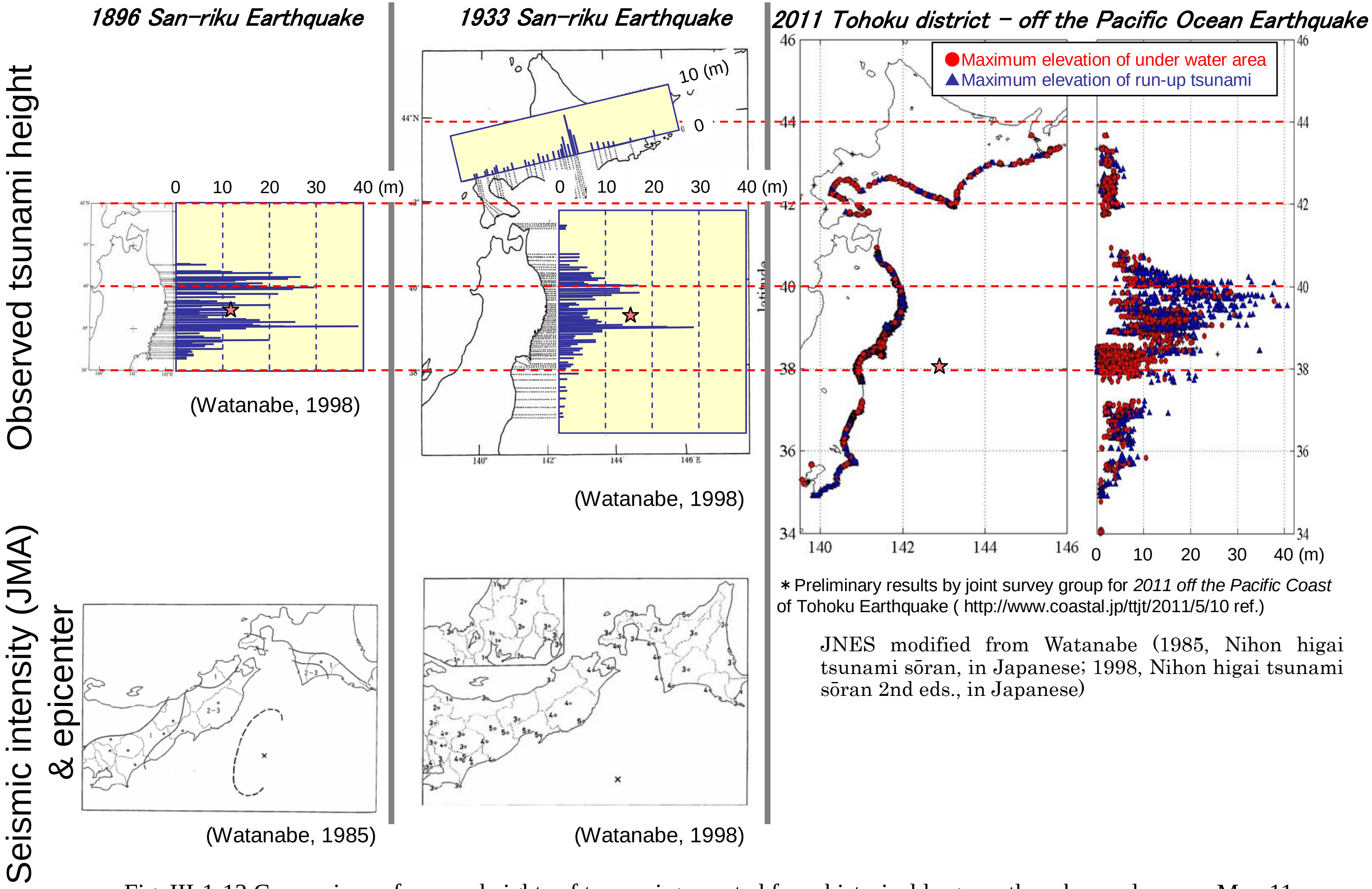


Fig. III-1-11 Characteristics of tsunami wave observed at off southern Iwate pref. for the main shock.

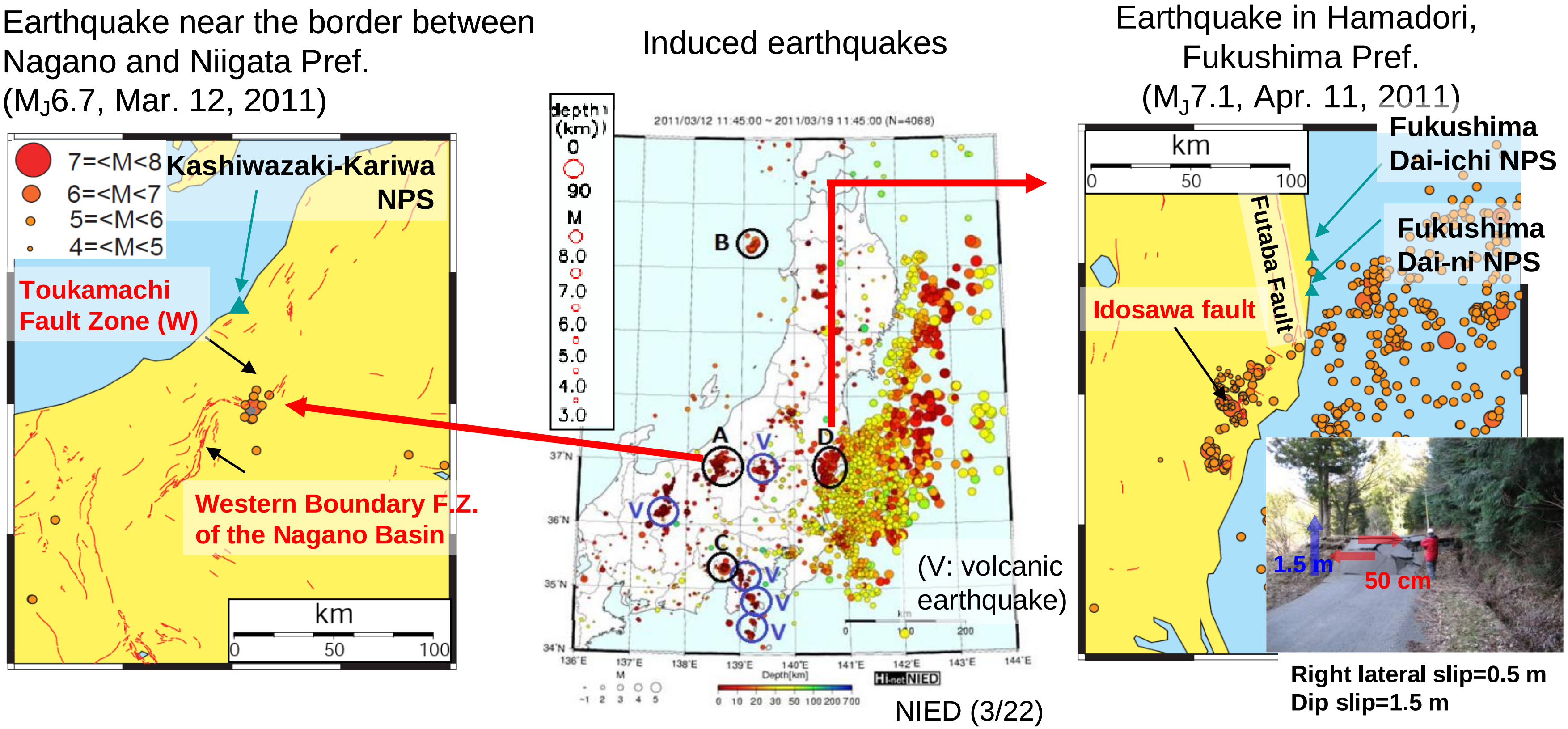
Comparison the height of 3.11/2011 Tsunami with historical San-riku Tsunami



＊Preliminary results by joint survey group for *2011 off the Pacific Coast of Tohoku Earthquake* (http://www.coastal.jp/ttjt/2011/5/10 ref.)

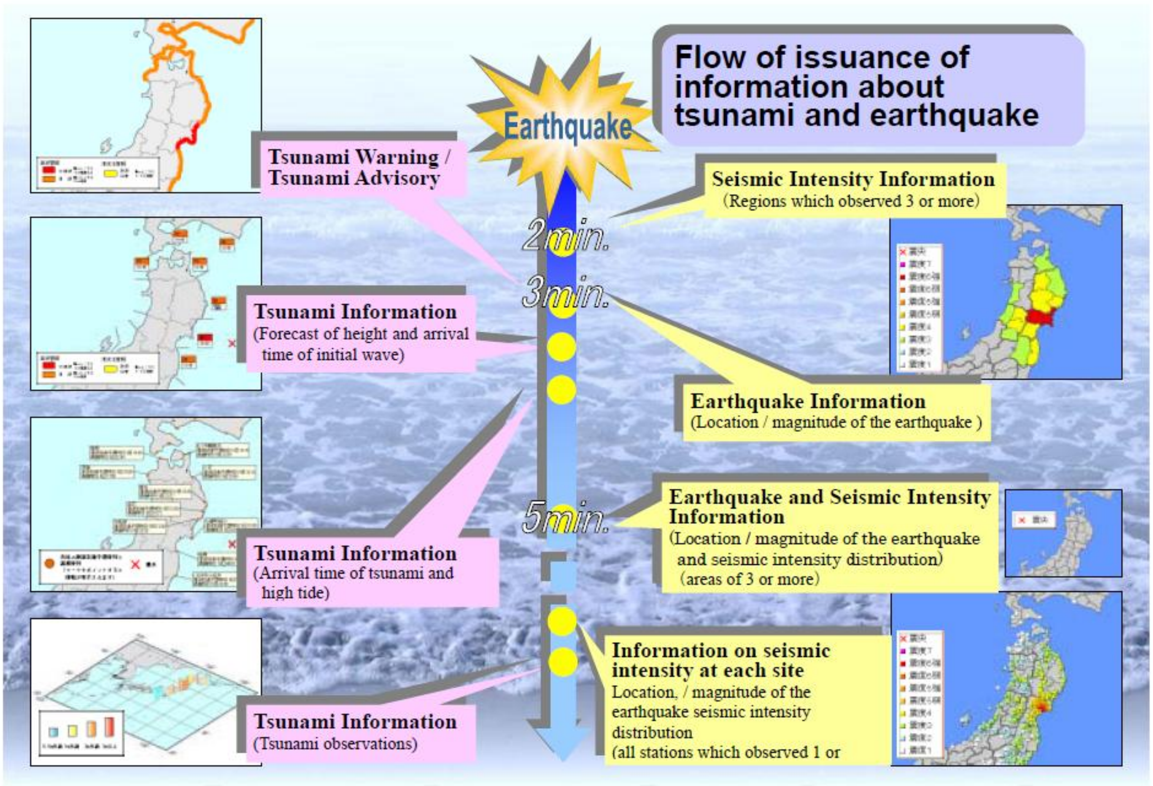
JNES modified from Watanabe (1985, Nihon higai tsunami sōran, in Japanese; 1998, Nihon higai tsunami sōran 2nd eds., in Japanese)

Fig. III-1-12 Comparison of run-up heights of tsunami generated from historical large earthquakes and one on Mar. 11.



Basemap from NIED
[Online]. http://www.bosai.go.jp/news/oshirase/20110323_01.pdf

Fig. III-1-13 Induced earthquakes by the mainshock.



Reference: JMA Release [Online]. http://www.seisvol.kishou.go.jp/eq/eng/fig/info.html

Fig. III-1-14 Flow of issuance of information about tsunami and earthquake by JMA.

Table III-1-1 Explanation of tsunami information and tsunami warning/advisory issued by JMA.

Tsunami Warning / Advisory

Category		Indication	Forecast tsunami height
Tsunami Warning	Major tsunami	Tsunami height is expected to be 3 meters or more.	Forecast heights are specifically indicated for every region; namely 3m, 4m, 6m, 8m and 10m or more.
	Tsunami	Tsunami height is expected to be up to 2 meters.	Same as above, but 1m or 2m.
Tsunami Advisory		Tsunami height is expected to be about 0.5 meters.	0.5m

Tsunami Warning / Advisory and Tsunami Information

Messages about tsunami	Indication
Tsunami Warning / Advisory	When the earthquake with the possibility that the tsunami is generated occurs, JMA provide the tsunami warning or tsunami advisory according to expected tsunami height. Tsunami warning (Major tsunami, tsunami) or tsunami advisory is provided within about three minutes after the occurrence of earthquake.
Tsunami information (forecast of height and arrival time of initial wave)	Forecast of height and arrival times of initial wave are provided for each forecast region.
Tsunami Information (arrival time of tsunami and high tide)	Information on high tide and forecast arrival time of tsunami at several points are provided.
Tsunami Information (tsunami observations)	Arrival time and observed tsunami height at tsunami observation stations are provided.

Reference: JMA Release [Online]. http://www.seisvol.kishou.go.jp/eq/eng/fig/tsunamiinfo.html

Table III-1-2 Comparison of issuing times, arrival times and heights for estimated tsunami and observed one.

Tsunami Forecast Region	Estimated Tsunami Arrival Time and Height						Observed Tsunami Arrival Time and Height of Initial and Maximum Tsunami			
	Issued at 14:49* JST 11 Mar (3 minutes after the earthquake)		Updated at 15:14 JST 11 Mar (28 minutes after the earthquake)		Updated at 15:30* JST 11 Mar (44 minutes after the earthquake)		Initial Tsunami		Maximum Height Tsunami	
	Estimated Tsunami Arrival Time	Estimated Tsunami Height	Estimated Tsunami Arrival Time	Estimated Tsunami Height	Estimated Tsunami Arrival Time	Estimated Tsunami Height	Observed Time	Observed Tsunami Height	Observed Time	Observed Tsunami Height
PACIFIC COAST OF AOMORI PREF.	15：30	1m	Arrival of tsunami confirmed	3m	Arrival of tsunami confirmed	8m	Hachinohe 15：22	(-) 0.8m	Hachinohe 16：57	4.2m or higher
IWATE PREF.	Arrival of tsunami inferred	3m	Arrival of tsunami confirmed	6m	Arrival of tsunami confirmed	10m or higher	Kamaishi 14：45 Miyako 14：48 Ofunato 14：46	(-) 0.1m (+) 0.2m (-) 0.2m	Kamaishi 15：21 Miyako 15：26 Ofunato 15：18	4.1m or higher 8.5m or higher 8.0m or higher
MIYAGI PREF.	15：00	6m	Arrival of tsunami confirmed	10m or higher	Arrival of tsunami confirmed	10m or higher	Ayukawa 14：46	(+) 0.1m	Ayukawa 15：26	8.6m or higher
FUKUSHIMA PREF.	15：10	3m	Arrival of tsunami confirmed	6m	Arrival of tsunami confirmed	10m or higher	Soma 14：55	(+) 0.3m	Soma 15：51	9.3m or higher
IBARAKI PREF.	15：30	2m	15：30	4m	Arrival of tsunami inferred	10m or higher	Oarai 15：15	(+) 1.8m	Oarai 16：52	4.2m
KUJUKURI AND SOTOBO AREA, CHIBA PREF.	15：20	2m	15：20	3m	Arrival of tsunami confirmed	10m or higher	Choshi 15：13	(+) 0.5m	Choshi 17：22	2.4m

Reference: JMA (Tsunami Information: Estimated Tsunami arrival time and Height (Issued at 14:50* JST, 11 March 2011)) [Online]. http://www.jma.go.jp/jp/tsunami/info_04_20110311145026.html

JMA (Tsunami Information: Estimated Tsunami arrival time and Height (Updated at 15:14 JST, 11 March 2011)) [Online]. http://www.jma.go.jp/jp/tsunami/info_04_20110311151439.html

JMA (Tsunami Information: Estimated Tsunami arrival time and Height (Updated at 15:31* JST, 11 March 2011)) [Online]. http://www.jma.go.jp/jp/tsunami/info_04_20110311153109.html

JMA (The 2011 off the Pacific coast of Tohoku Earthquake ~14th report~) [Online]. http://www.jma.go.jp/jma/press/1103/13a/kaisetsu201103130900.pdf

JMA (Observed values of Tsunami records at Miyako and Ofunato) [Online]. http://www.jma.go.jp/jma/press/1103/23b/stn03231400.pdf

JMA (Observed values of Tsunami records at Ayukawa, Ishinomaki City) [Online]. http://www.jma.go.jp/jma/press/1103/29c/201103291900.pdf

JMA (Observed values of Tsunami records at Soma) [Online]. http://www.jma.go.jp/jma/press/1104/13a/201104131600.pdf

JMA (Observed values of Tsunami records at Hachinohe) [Online]. http://www.jma.go.jp/jma/press/1105/27b/kaisetsu201105271730.pdf

JMA (Observed values of Tsunami records at Ayukawa, Ishinomaki City (revised)) [Online]. http://http://www.jma.go.jp/jma/press/1106/03b/tsunami_ayukawa2.pdf

*Note） Announced time of tsunami warning presented on this table is slightly different from that on prompt reports on JMA web site.

Table III-1-3 Tsunami information in municipal disaster management radio communication network each local government.

■ Broadcasting from Municipal Disaster Management Radio Communication Network on Iwate Prefecture

	State of the broadcasting	Article related to Observed Tsunami	Evacuation in Responding to the Broadcast
Yamada Town	They said "more than 3 meters" of tsunami height. After that, they prepared the broadcast after they confirmed through the information of television that the expected tsunami heights reassessed at 6 meters. However they could not make the broadcast due to evacuating themselves to the rooftop because they could see the tsunami from the fire station building.	No description in articles.	Mr. Taro says that "Many people evacuated to the second floor of their house because they imagined tsunami of about 3 meters height. I evacuated in panic when I saw the tsunami getting over the sea wall."
Kamaishi City	They said through the loudspeakers at 96 points within the City that "It can be expected tsunami heights of about three meters at the most. We order the inhabitants who staying near coastlines the to immediate evacuation toward high ground level areas or tsunami shelters", based on the expectation issued by the Japan Meteorological Agency (JMA) at 2:50pm. The JMA reassessed the expectation of tsunami heights at 6 meters at 3:14pm, also reassessed it at more than 10 meters at 3:31pm. However the city hall has become to not receive the prefectural office's emails of information issued by the JMA. Meanwhile they repeated the instruction broadcasting 6 times.	Actually, it was assumed that the tsunami of about 9 meters height attacked the Port of Kamaishi.	In the citizens of Kamaishi City, there were many people who imagined "the tsunami of 3 meters high" and decided the safety by evacuation to the second floor. From 150 to 200 people in neighboring area of Unosumai District run in the disaster mitigation centre containing second floor located in the district, however the survivor was about 30 people because from the first to second floor of the centre was devastated by Tsunami. Mr. Furukawa who is refugee says "I would escaped from the event to hills if I could recognize the tsunami having higher than my understanding." Mr. Sakamoto who is fisherman says that we thought to not need to evacuate against the tsunami of 3 meters height because we have the complete sea walls for protection from a tsunami. Death and missing people was over 1300 in Kamaishi City.
Ofunato City	They did not say concerning tsunami heights from the beginning, however, they called out the issued warning against major tsunami and evacuation to high ground area.	The tsunami height which attacked the Port of Ofunato was assumed at about 9.5 meters.	Death and missing people was over about 500 in Ofunato City.
Rikuzentakada City and Ohtsuchi Town	They could not recognize the broadcast situation on that time because the recording documents about them were washed away.	No description in articles.	No description in articles.

■ Broadcasting from Municipal Disaster Management Radio Communication Network on Miyagi Prefecture

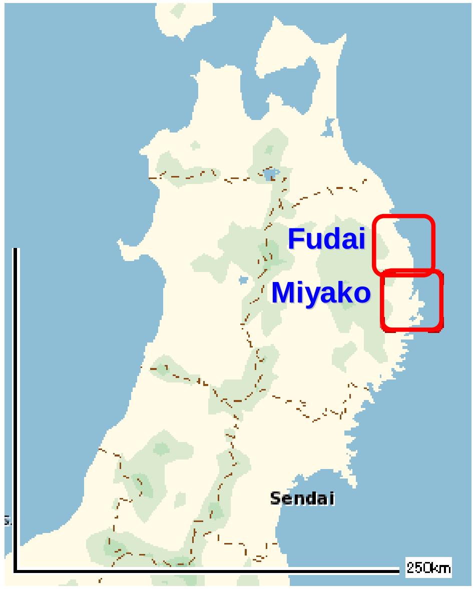
	State of the broadcasting	Article related to Observed Tsunami	Evacuation in Responding to the Broadcast
Minami Sanriku Town	They called out through the Municipal Disaster Management Radio Communication Network just after the earthquake immediately that "6 meters height of tsunamis are coming" because the JMA issued the warning against major tsunami of 6 meters height from the beginning.	The actual tsunami height exceeded 15 meters.	There were many people who evacuated to high ground areas in accordance with the radio broadcasting. Many officers were dead because the entire the three-story building of the town's Crisis Management Department was submerged by the tsunami.
Kesennuma City	According to the head office of countermeasures on Kesennuma City, they called out the evacuation through the Municipal Disaster Management Radio Communication Network when the JMA issued the warning against major tsunami on the day. Although they did not have records whether they could give a lot of care by indicated specific tsunami heights, they say that "we thoroughly called out the evacuation to high ground areas in any case".	No description in articles.	No description in articles.

Reference: The Asahi Shimbun Company Release [Online]. http://www.asahi.com/national/update/0420/TKY201104200249.html

Destruction by tsunami scouring

Destruction by wave pressure

Fig. III-1-15 Damages of seawall and harbor installation due to the tsunami.



The 10m-high seawall was destroyed in Taro district, Miyako city, Iwate Pref.

The 15.5m-high seawall was undestroyed in Otabe district, Fudai village, Iwate Pref.

Fig. III-1-16 Difference of seawall heights resulting in different consequence.

A photo from the village's point of view (i.e. facing the coast)

A photo from a viewpoint of facing the village taken at the spot slightly below the stone monument

Fig. III-1-17 Photos of a stone monument and tsunami invading area below the stone monument.