Ocean bottom data

The observation record of the ocean bottom pressure gauge. At around 14:46, the ground motion of the earthquake (M9) reaches the pressure gauge and at TM1 (coast-side), the sea level is gradually rising from that point.

The sea level rose 2 m, and after 11 minutes, the level went drastically up to 3m, which makes 5m of elevation in total. At TM2: located 30km toward the land, a same elevation of sea level was recorded with 4 minutes delay from TM1.

釜石沖海底ケーブル式地震計システムで観測された海面変動

東京大学地震研究所

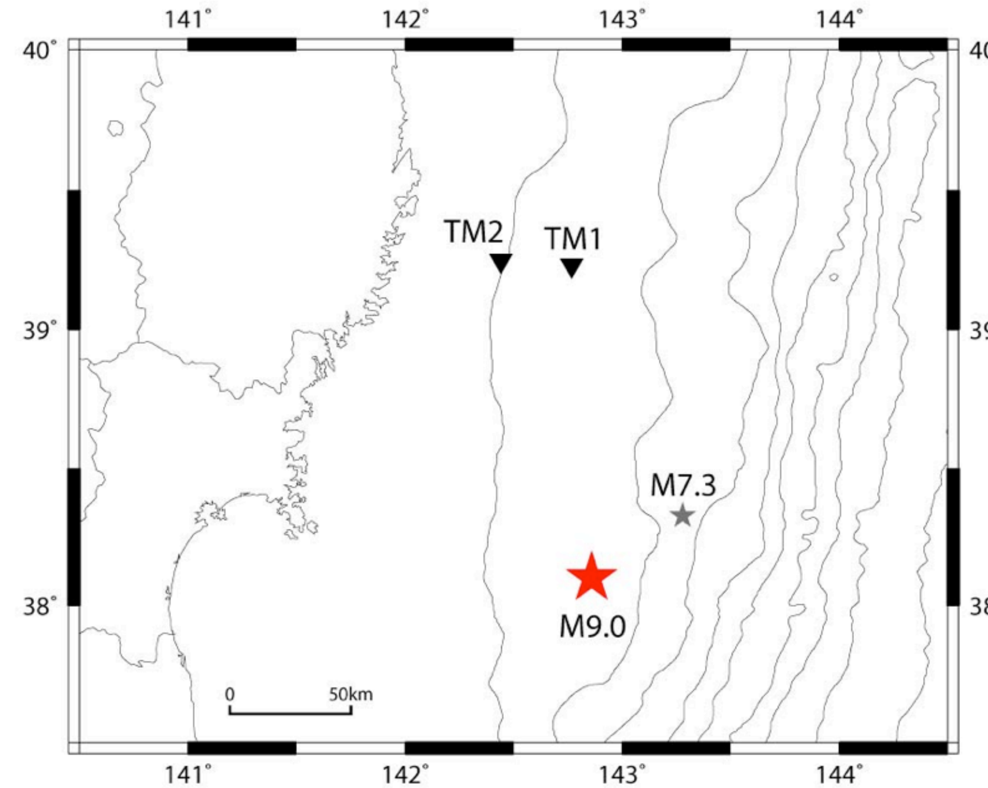


図１　釜石沖ケーブル式海底水圧計の位置

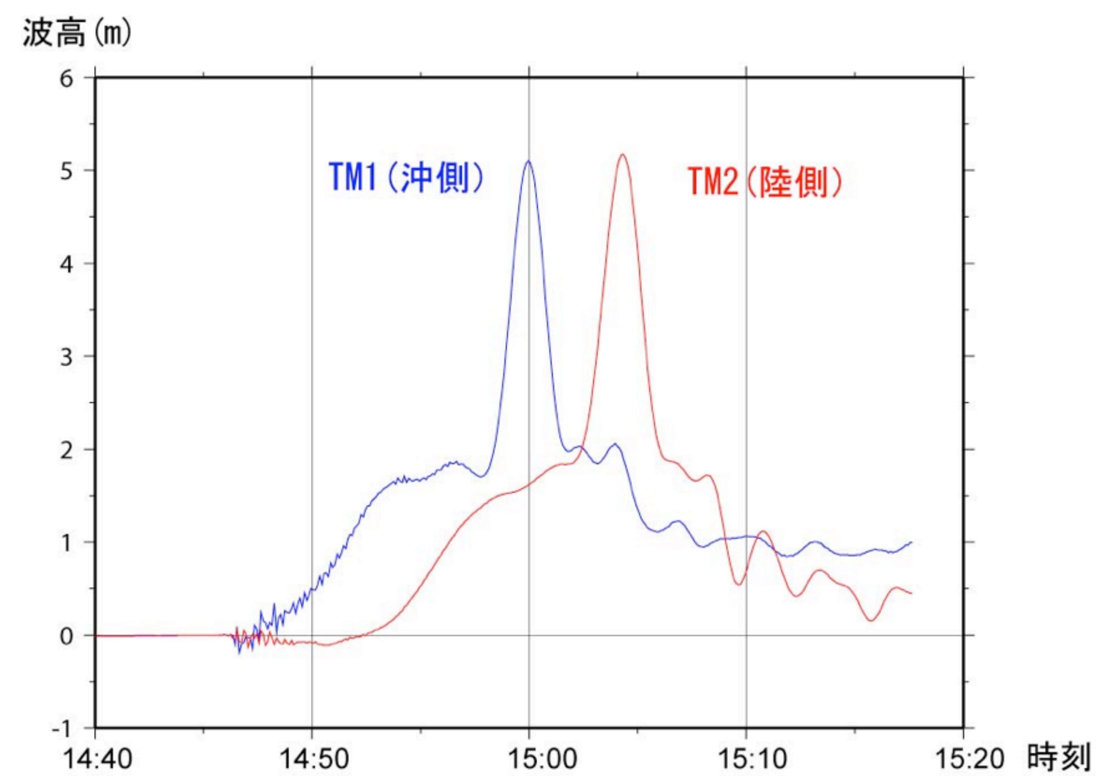
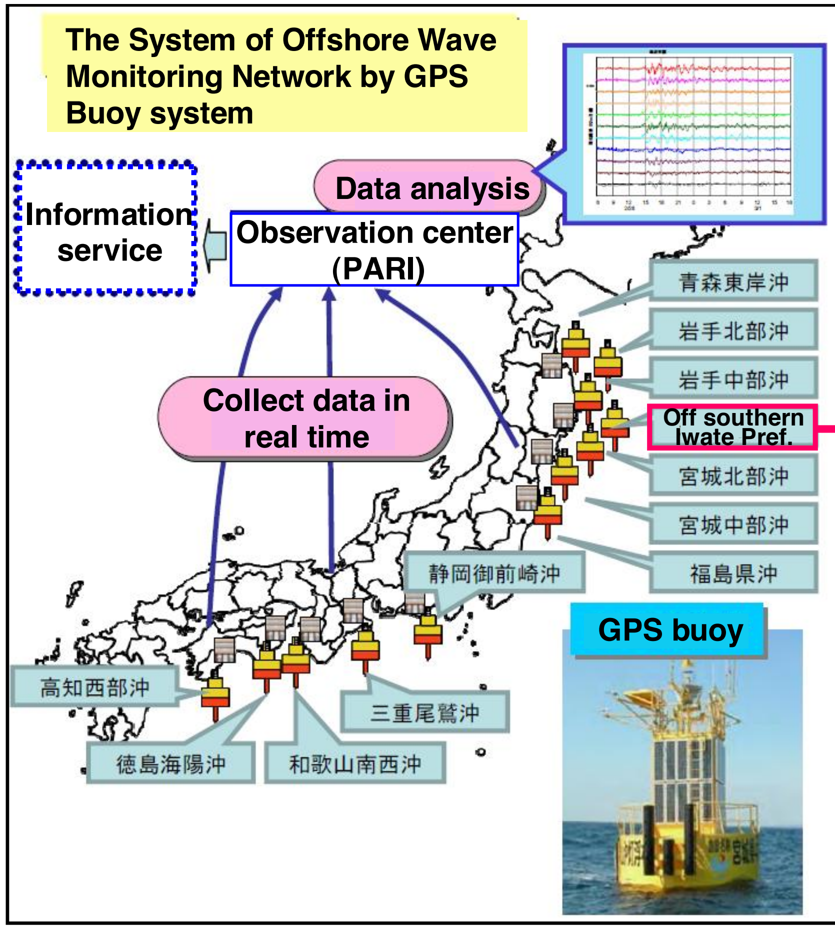
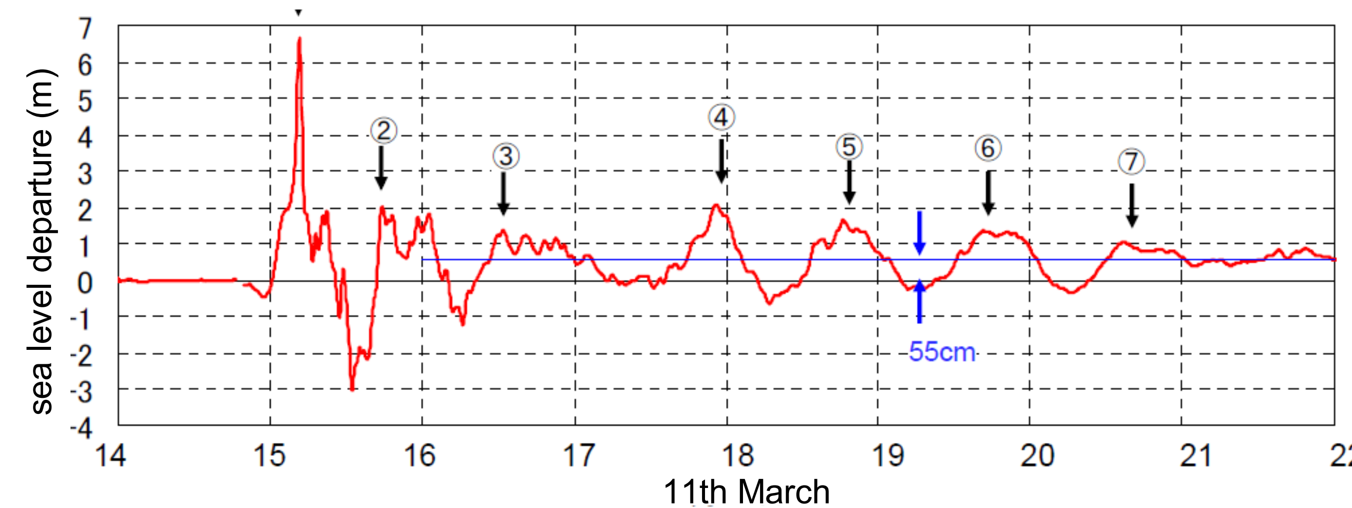


図２　海底水圧計の観測記録。14時46分頃、本震（M9.0）の振動が水圧計に伝わり、TM1（海寄り）では、その時から徐々に海面が上昇している。約２m上昇し、約11分後にはさらに約3m急激に上昇し、合計約5m海面が上昇した。約30km陸寄りに設置されているTM2では、TM1から約4分遅れて同様の海面上昇を記録した。

Tsunami wave characteristics

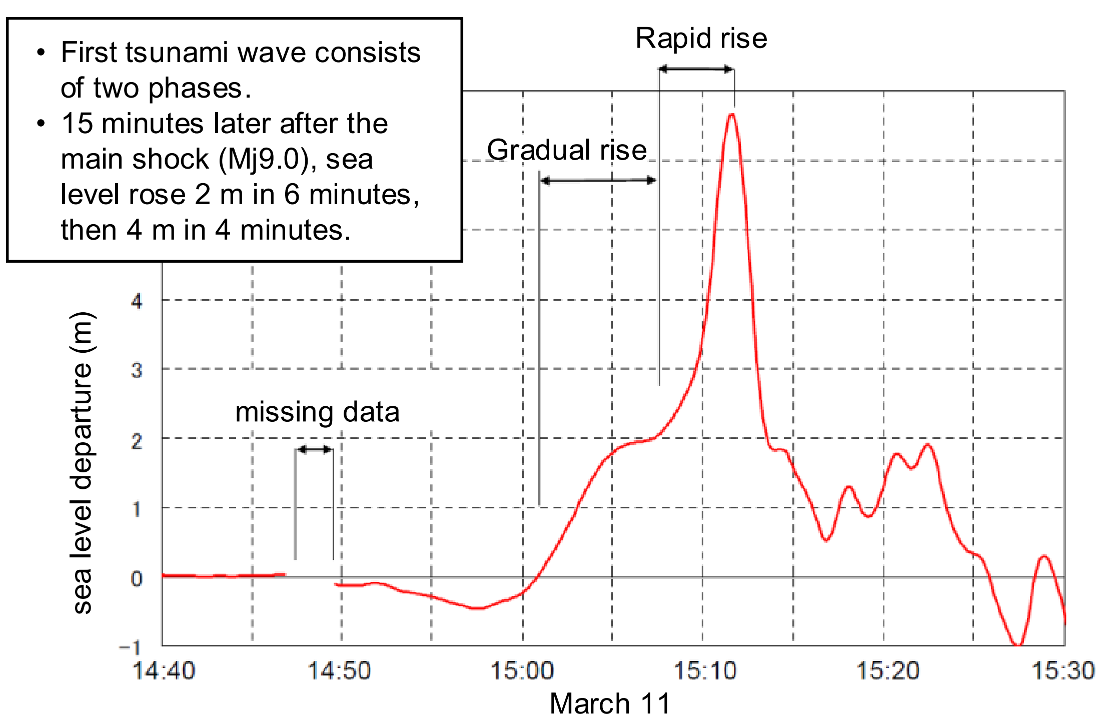


Tsunami waveform record from GPS buoy data off southern Iwate Pref. (204m off Kamaishi)

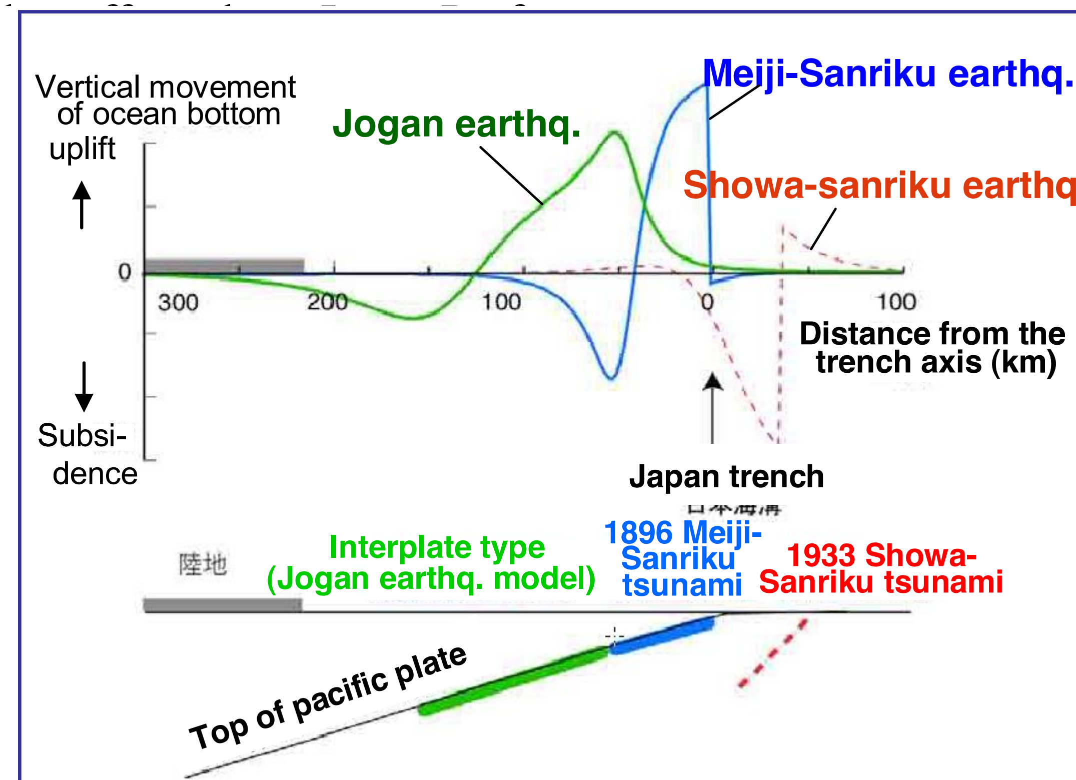


- The maximum wave height was 6.7 m (first wave) off southern Iwate Pref. at 15:12.
- First tsunami wave was extremely high.
- Wave period
  - First to third tsunami wave: irregular period
  - Fourth to seventh tsunami wave: about 50 minutes period
- Total amount of rose in average sea level were 55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

Reference: Independent Administrative Institute Port and Airport Research Institute

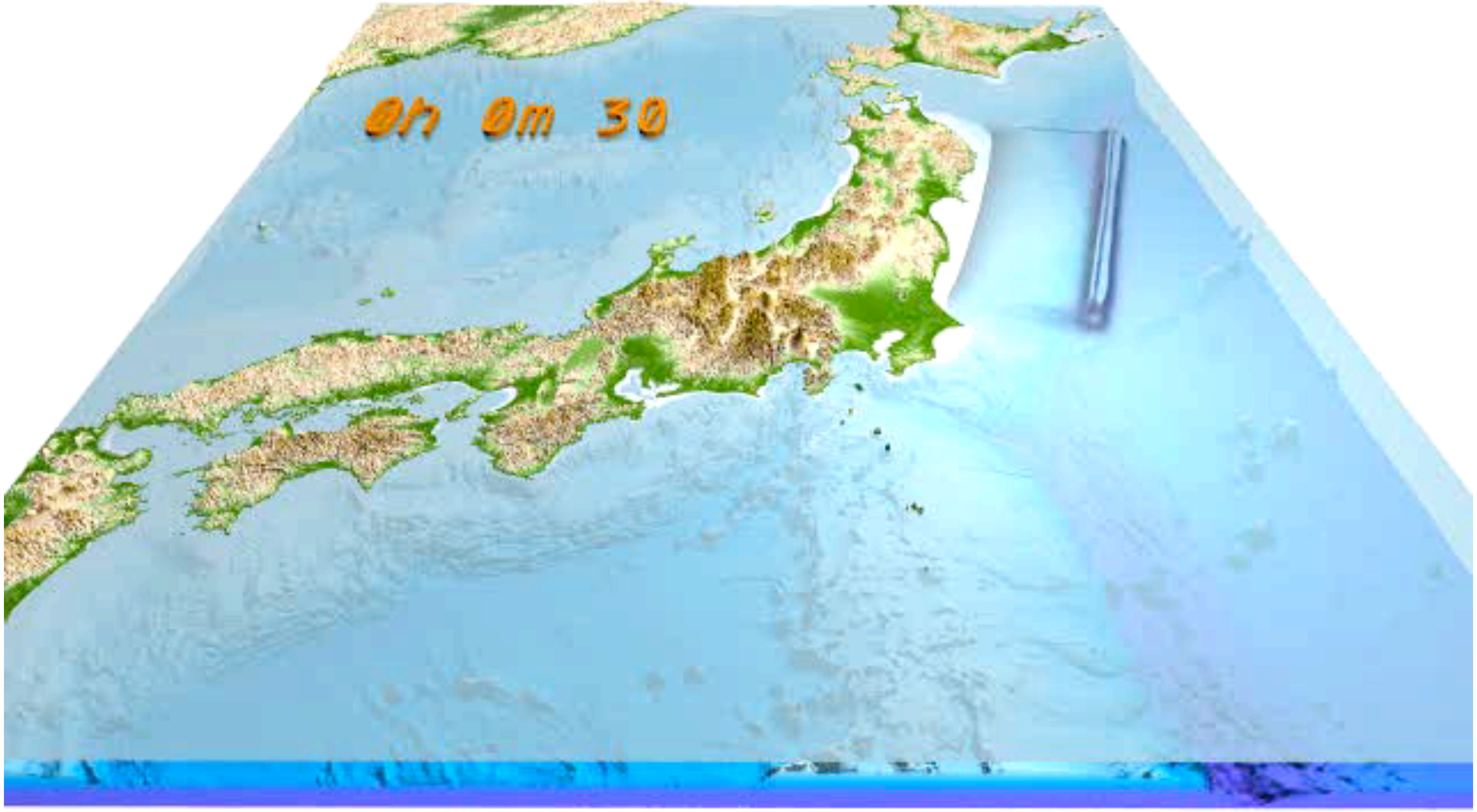


Reference: Independent Administrative Institute Port and Airport Research Institute



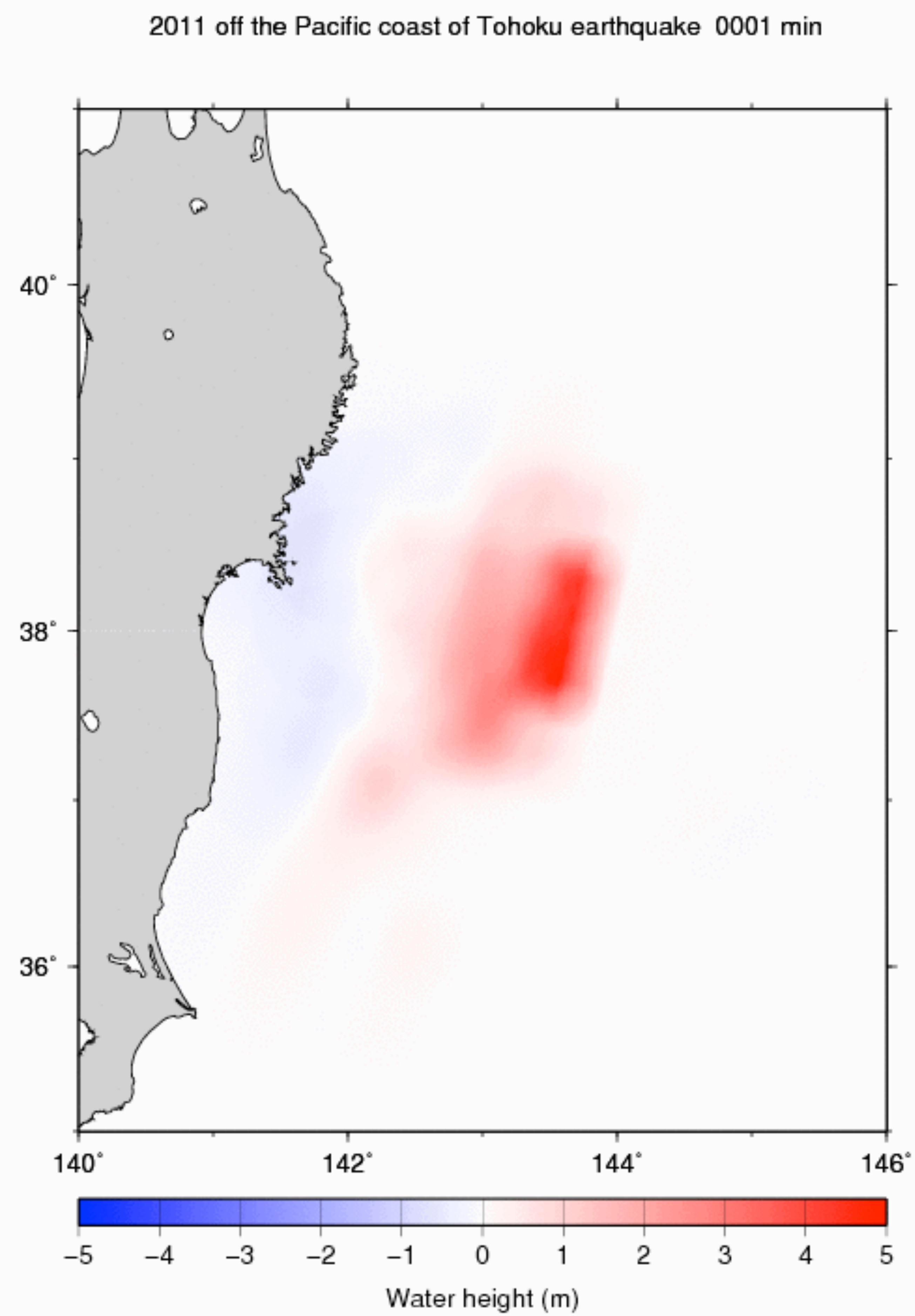
Reference : Satake (2011) Paper preparing for NIED meeting on Apr.17.

Tsunami animation: time scales...



"Earthquake Research Institute, University of Tokyo, Prof. Takashi Furumura and Project Researcher Takuto Maeda"

Tsunami data and simulations: source

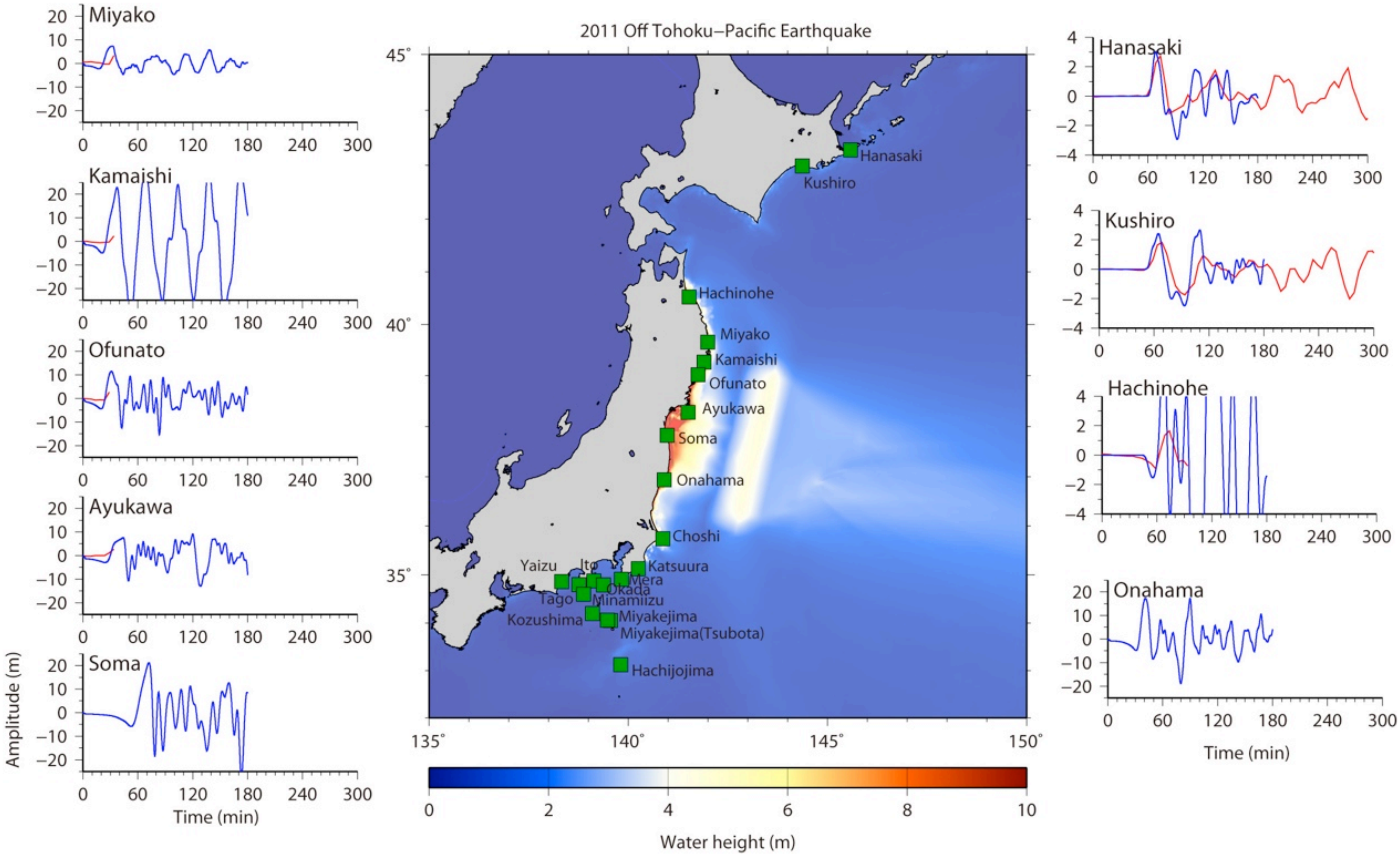


Tsunami Propagation

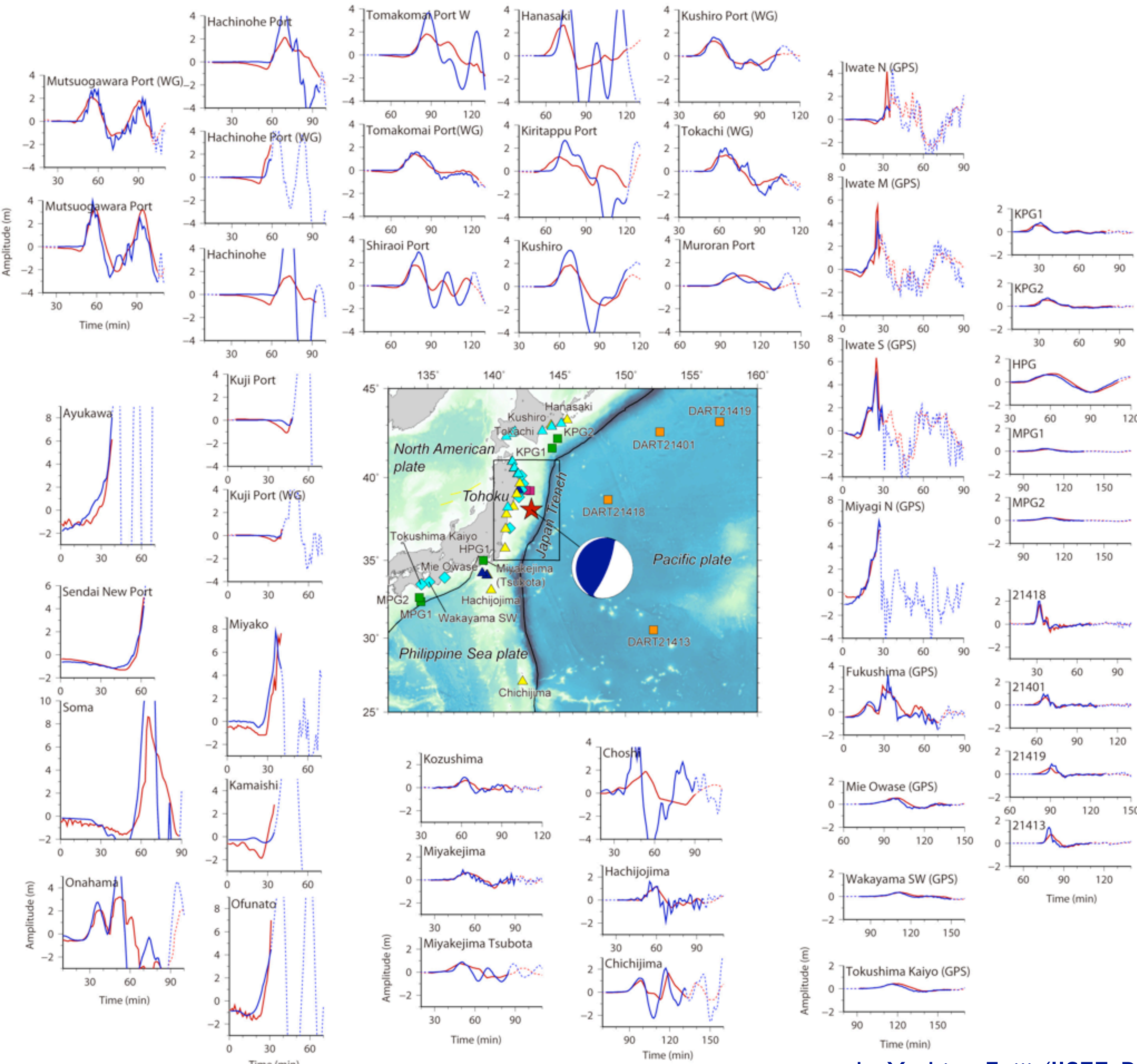
The red color means that the water surface is higher than normal sea level, while the blue means lower.

by Yushiro Fujii (IISEE, BRI) and Kenji Satake (ERI, Univ. of Tokyo)
http://iisee.kenken.go.jp/staff/fujii/OffTohokuPacific2011/tsunami_inv.html

Tsunami data and simulations



Tsunami data and simulations: source

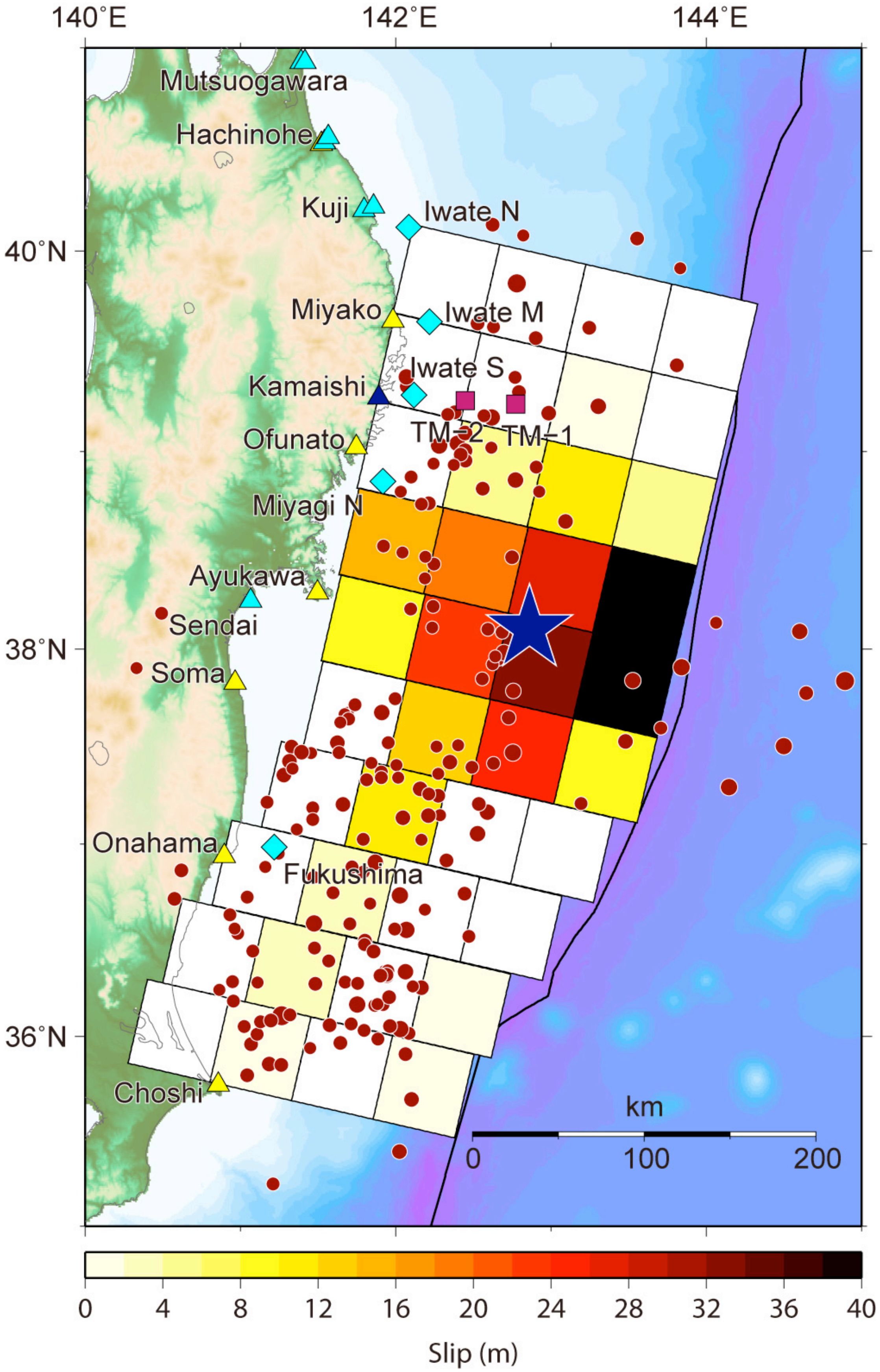


Simulated Tsunami around Japanese coasts

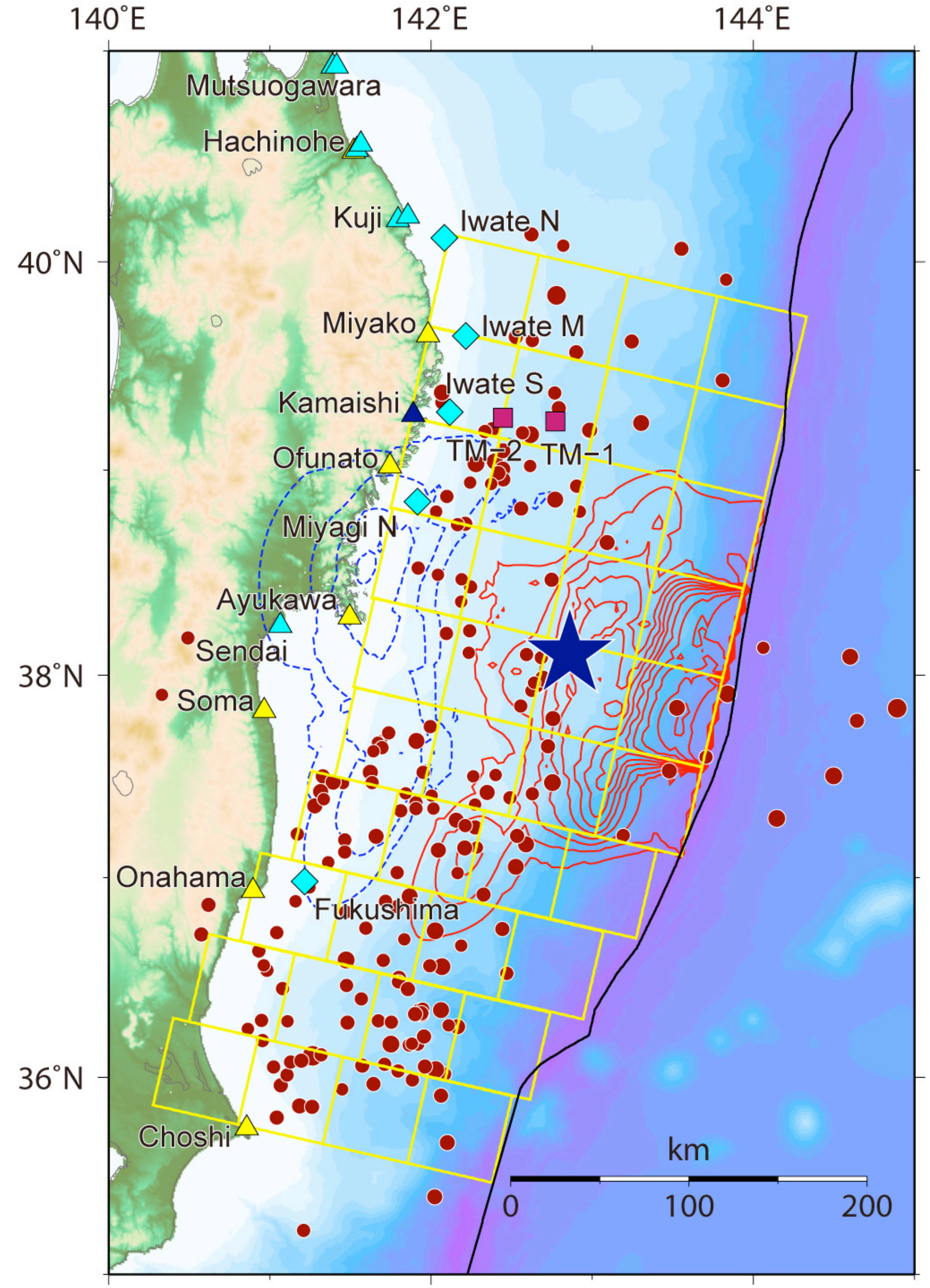
Red and blue lines indicate the observed tsunami waveforms at Japanese tide gauges and ocean bottom tsunami sensors and synthetic ones, respectively. Solid lines show the time windows used for inversion.

by Yushiro Fujii (IISEE, BRI) and Kenji Satake (ERI, Univ. of Tokyo)
http://iisee.kenken.go.jp/staff/fujii/OffTohokuPacific2011/tsunami_inv.html

Tsunami data and simulations: source



Slip distribution on the fault mode



Calculated seafloor deformation due to the fault model

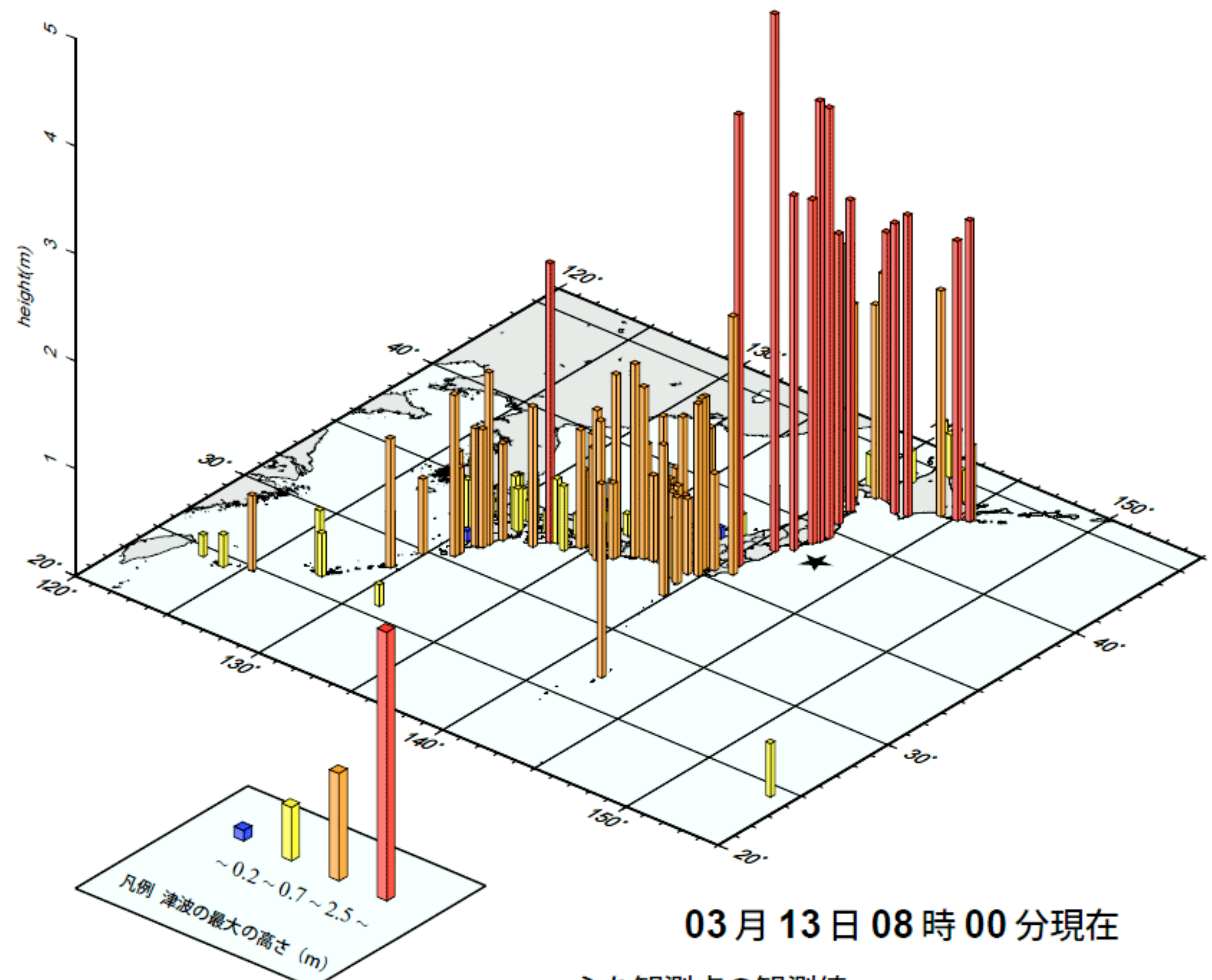
by Yushiro Fujii (IISEE, BRI) and Kenji Satake (ERI, Univ. of Tokyo)
http://iisee.kenken.go.jp/staff/fujii/OffTohokuPacific2011/tsunami_inv.html

Distribution of tsunami heights

Figure from the Headquarters for Earthquake Research Promotion (at March 13)

http://www.jishin.go.jp/main/index-e.html

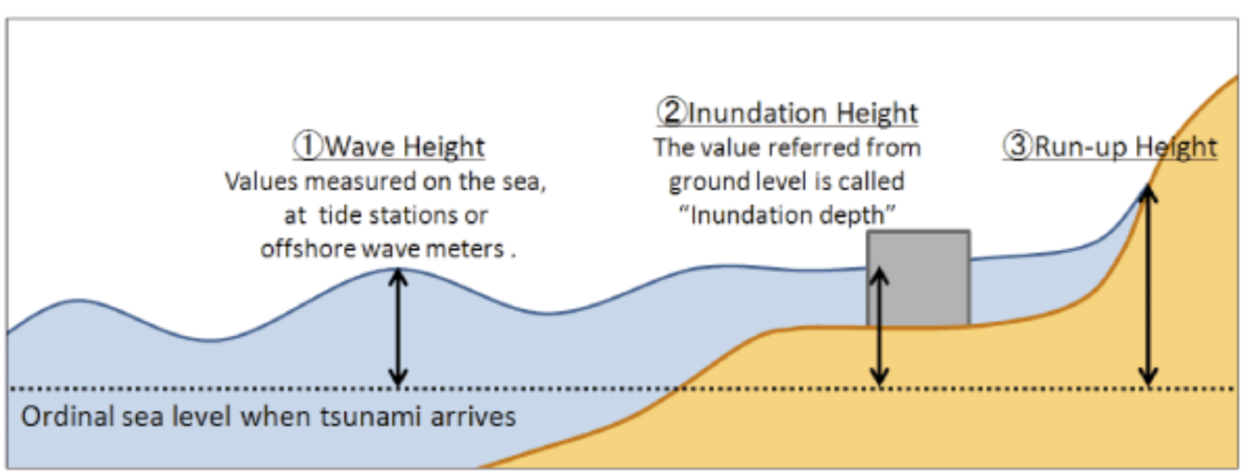
津波観測状況



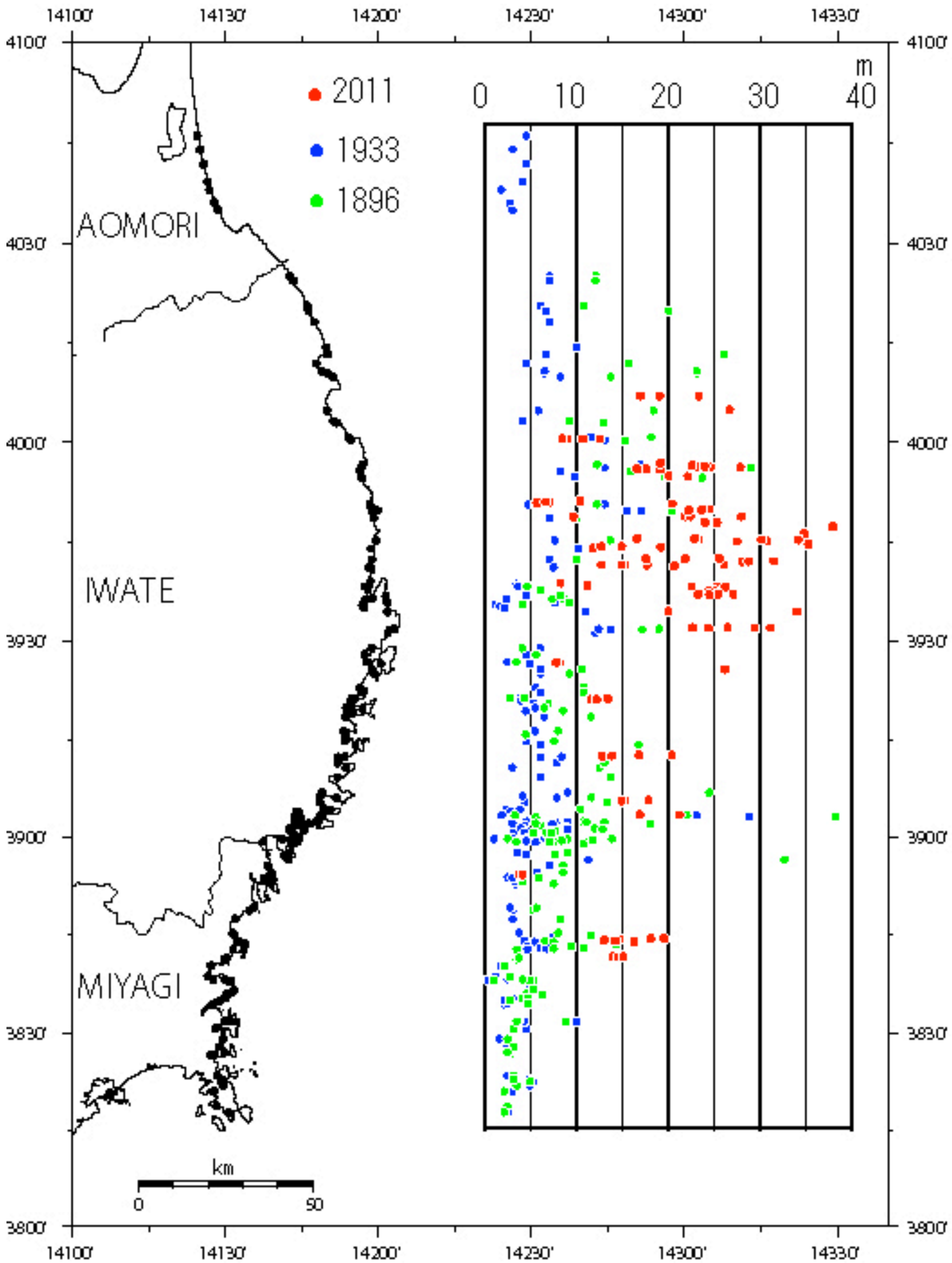
主な観測点の観測値

	第一波			最大波	
相馬	11日 14時 55分	押し	0.3m	11日 15時 50分	7.3m以上
大洗	11日 15時 15分	押し	1.8m	11日 16時 52分	4.2m
釜石	11日 14時 45分	引き	0.1m	11日 15時 21分	4.1m以上
宮古	11日 14時 48分	押し	0.2m	11日 15時 21分	4.0m以上
石巻市鮎川	11日 14時 46分	押し	0.1m	11日 15時 20分	3.3m以上
大船渡	11日 14時 46分	引き	0.2m	11日 15時 15分	3.2m以上
むつ市関根浜	11日 15時 20分	引き	0.1m	11日 18時 16分	2.9m
根室市花咲	11日 15時 34分	引き	微弱	11日 15時 57分	2.8m
十勝港	11日 15時 26分	引き	0.2m	11日 15時 57分	2.8m以上
浦河	11日 15時 19分	引き	0.2m	11日 16時 42分	2.7m

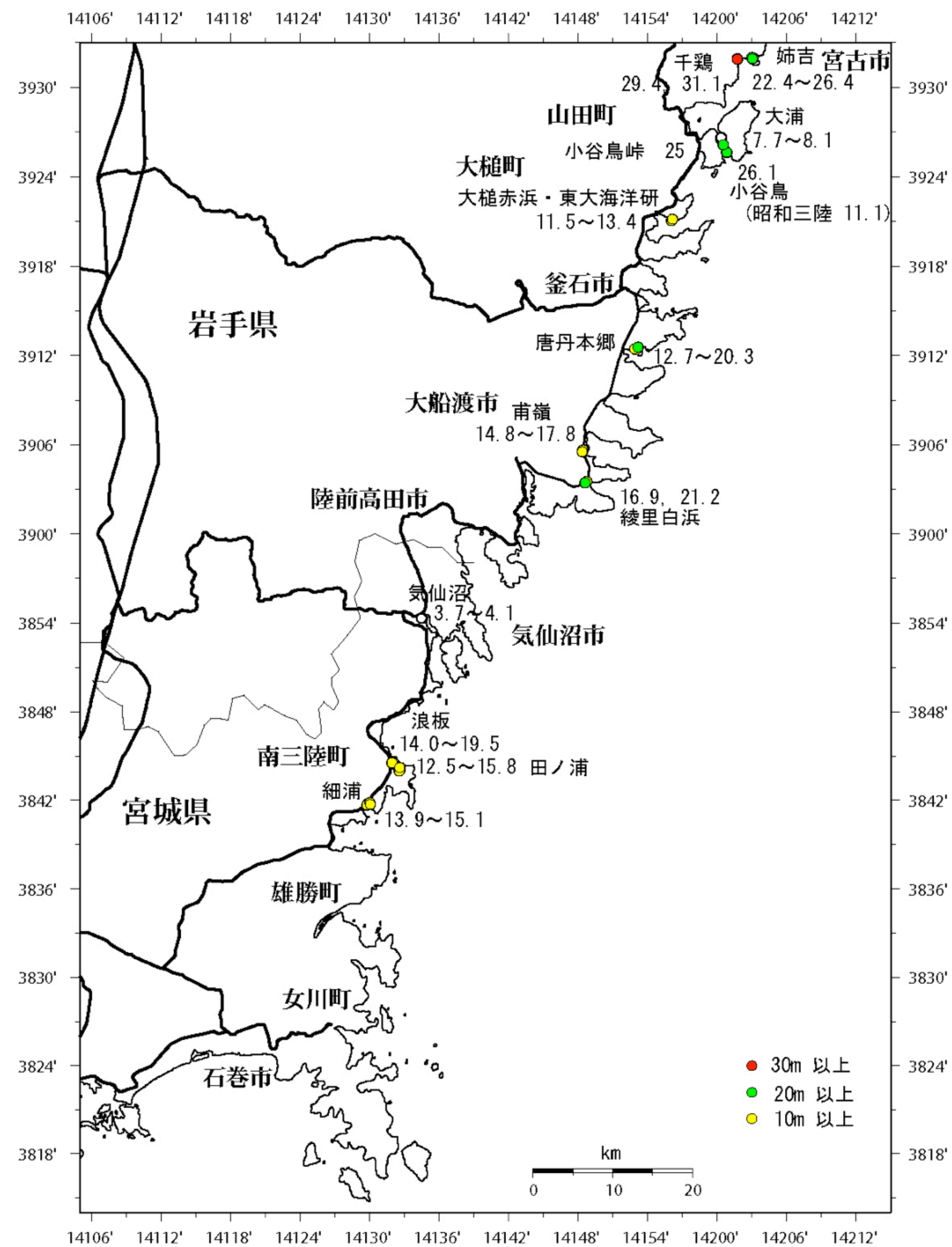
気象庁作成



Distribution of tsunami heights



Northern sanriku – comparison with the tsunami in Meiji period and Showa period



Southern Sanriku

By: Dr.Tsuji, Dr.Satake, Project Researcher: Ishibe, Project Researcher: Nishiyama

Distribution of tsunami heights (upd)

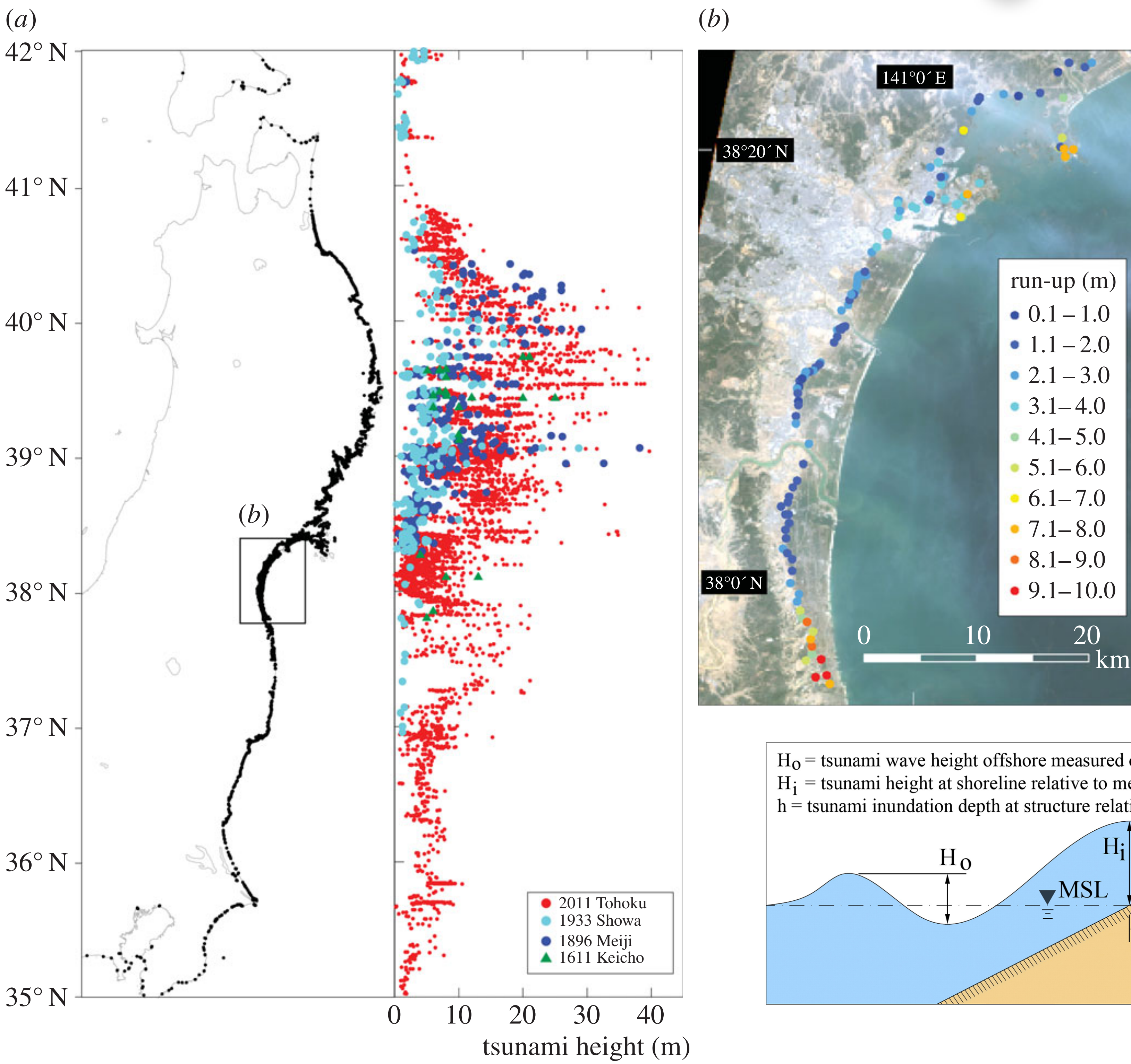
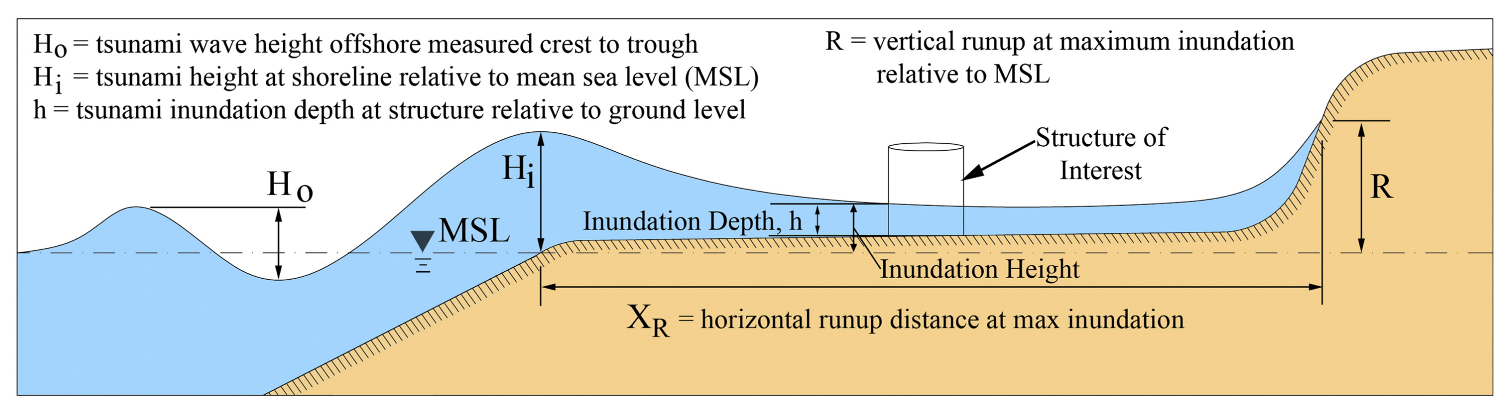


Figure 2. (*a*) The measured heights of the 2011 Tohoku tsunami [22] and historical Sanriku earthquake tsunamis (1611, 1896 and 1933 events). The historical tsunami data were provided by Japan Tsunami Trace Database [24] maintained by Tohoku University and the Japan Nuclear Energy Safety Organization (JNES). Black dots on the coastline indicate the points of the 2011 tsunami height measurement. The tsunami run-up height reached up to 40 m in Iwate prefecture. (*b*) The extent of the tsunami inundation zone with the measurement of the run-up heights at tsunami inundation limit in Sendai Coast [23].



Koshimura S, Shuto N. 2015 Response to the 2011 Great East Japan Earthquake and Tsunami disaster. Phil. Trans. R. Soc. A 373: 20140373.

A tale of two NPPs

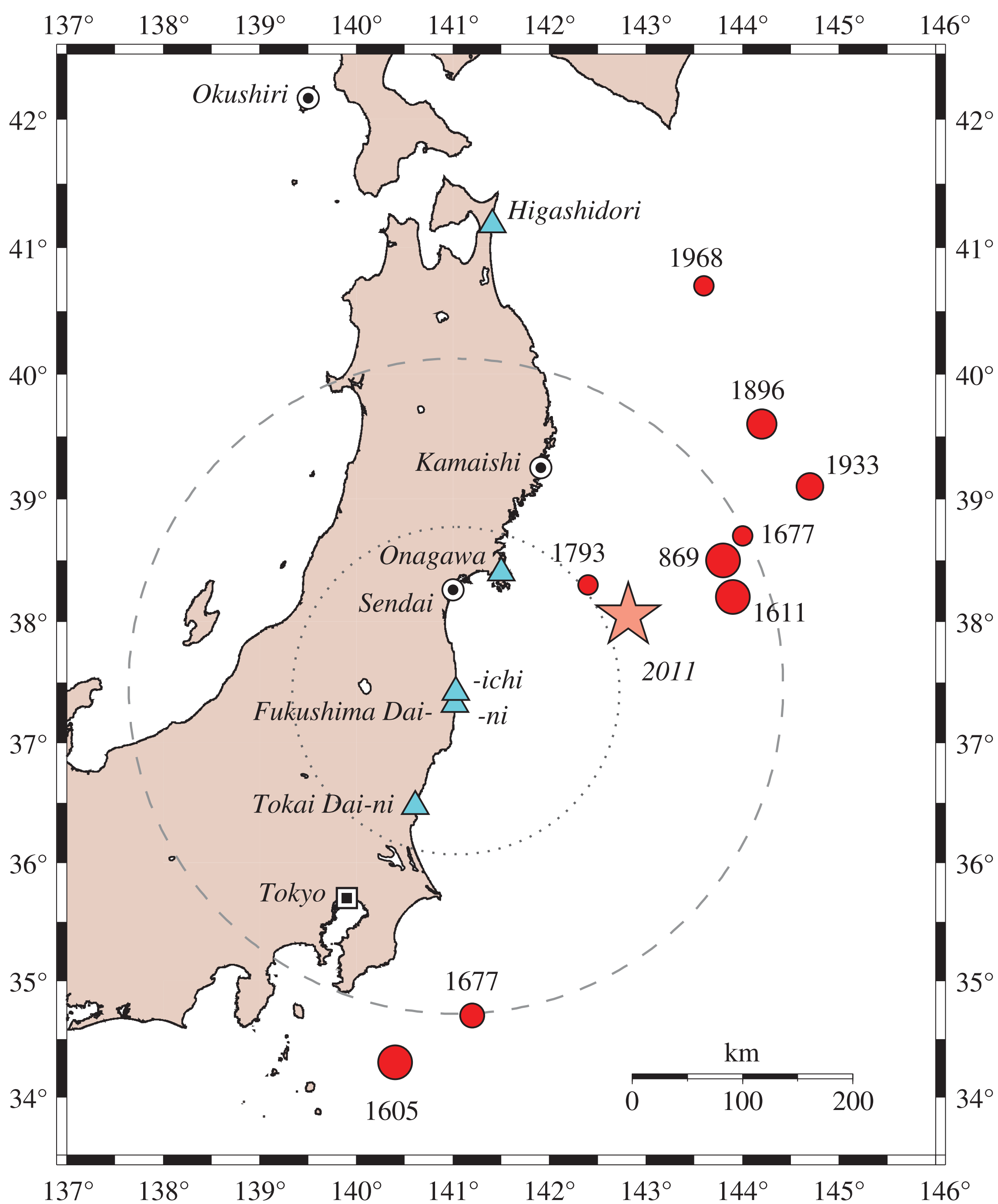


Figure 1. Locations of NPPs (triangles) affected by the 11 March 2011 earthquake (star) and tsunami, and relevant historical earthquakes in North East Japan listed in the 1974 catalogue of Soloviev & Go [14]. Events are shown with red dots, whose radius is adjusted to the Soloviev tsunami intensity scale; 150 and 300 km radius circles from Fukushima Dai-ichi are shown with dotted and dashed lines, respectively, depicting the region over which international standards require consideration of hazard sources.

Table 2. Summary of NPPs design conditions and damage to power supplies.

NPPs	pre-2011 estimated tsunami heights (m) [16,32]	2011 tsunami heights/ NPP elevations (m) [32]	off-site power lines damaged/total [33]	EDGs damaged/ total [33]
Onagawa[a]	13.6[c]	13/14.8[f]	4/5	2/8
Fukushima Dai-ichi[a]	6.1[d]	13/10-13	6/6	12/13
Fukushima Dai-ni[a]	5.0[e]	9/12	3/4	9/12
Tokai Dai-ni[b]	5.7[e]	5/8	3/3	1/3

[a] Elevations are relative to Onahama Peil (O.P.), which is 0.74 m below standard mean sea level of Tokyo Bay. This reference water level was used for Onagawa and Fukushima NPPs.
[b] Mean sea level at Hitachi Point (H.P.) was used as reference level at Tokai Dai-ni.
[c] Determined based on Sanriku earthquakes.
[d] Determined based on Shioyazaki-oki earthquake [34].
[e] Determined based on the tsunami source model set by Ibaraki Prefecture.
[f] This was the original plant height. There was 1 m subsidence at the site due to earthquake.

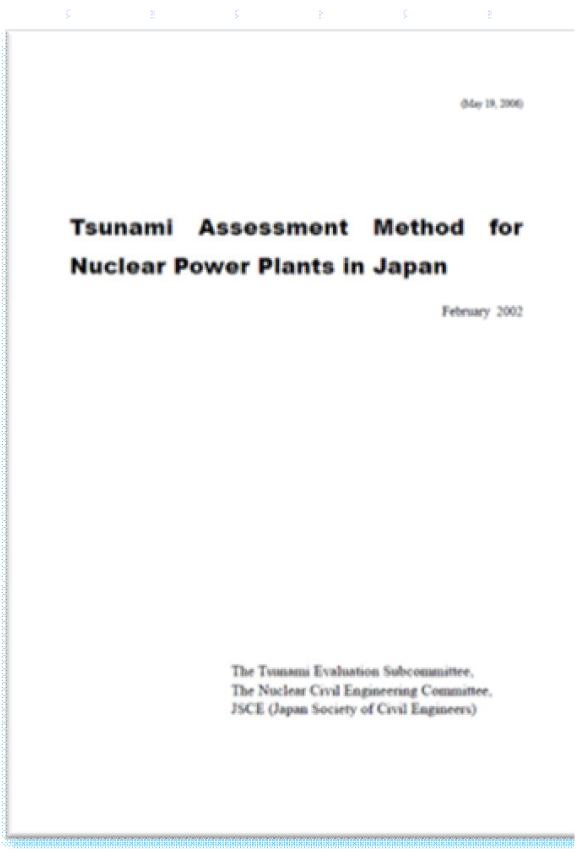
Tsunami Assessment method for NPP in JSCE, Japan

The TSUNAMI EVALUATION SUBCOMMITTEE,
Nuclear Civil Engineering Committee, JSCE

Masafumi Matsuyama (CRIEPI)

History of TES

- Phase I 1999-2000
  The maximum and minimum water levels by deterministic method
  → "Tsunami assessment method for NPP in Japan」 (2002)"
- Phase II 2003-2005
  Probabilistic Tsunami Hazard Analysis for the max. and min. water levels
  Numerical simulation of nonlinear dispersion wave theory with soliton fission and split wave-breaking
  Tsunami wave force on breakwater
- Phase III 2006-2008
  Topography change due to tsunami
  Development of probabilistic Tsunami Hazard Analysis
- Now → Phase IV 2009-2011
  Revising of 「Tsunami assessment method for NPP in Japan」


(May 19, 2006)

Tsunami Assessment Method for Nuclear Power Plants in Japan

February 2002

The Tsunami Evaluation Subcommittee,
The Nuclear Civil Engineering Committee,
JSCE (Japan Society of Civil Engineers)

Niigata meeting, November 2010
http://www.jnes.go.jp/seismic-symposium10/presentationdata/3_sessionB.html

Tsunami Assessment method for NPP in JSCE, Japan

The TSUNAMI EVALUATION SUBCOMMITTEE,
Nuclear Civil Engineering Committee, JSCE

Masafumi Matsuyama (CRIEPI)

Deterministic method (2002)
Main flow chart

Sub flow 1

Verification of fault model(s) and numerical calculation system on the basis of historical tsunami(s)

↓

Sub flow 2

Estimation of the design water levels on the basis of **parametric study** in terms of basis tsunamis

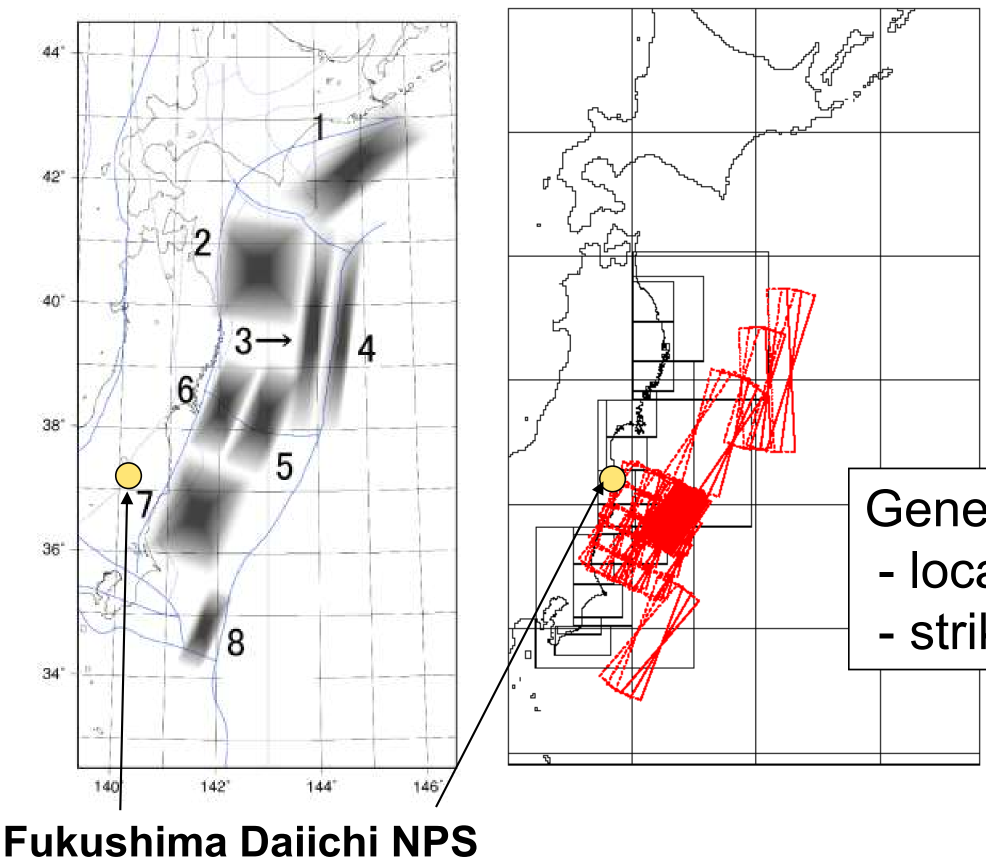
↓

tide → Design high water level / Design low water level

↓

End

General parametric study in the near field

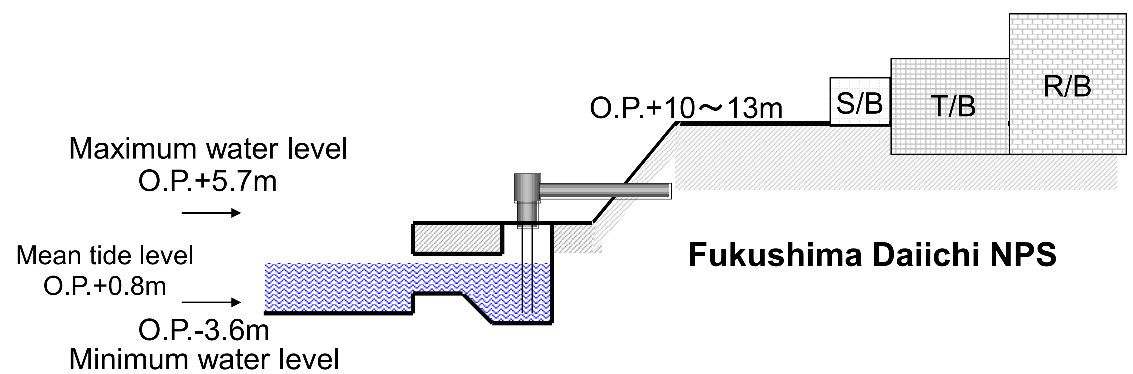


General parametric study
- location
- strike

東京電力 7

Summary of Evaluation

Maximum water level = 4.4m + O.P.＋1.3m = O.P.+5.7m
Minimum water level = -3.6m – O.P.±0.0m = O.P.-3.6m



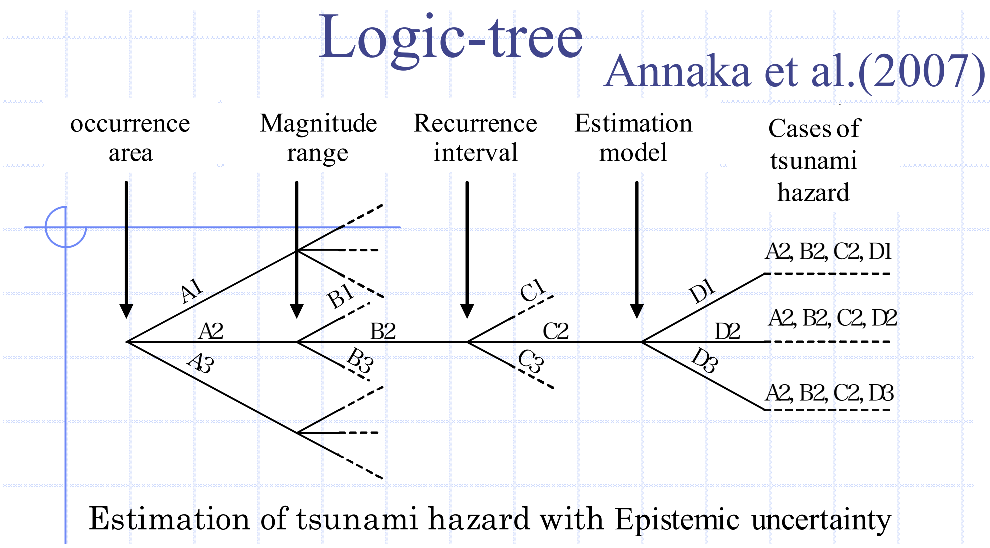
We assessed and confirmed the safety of the nuclear plants based on the JSCE method which was published in 2002.

Niigata meeting, November 2010
http://www.jnes.go.jp/seismic-symposium10/presentationdata/3_sessionB.html

Tsunami Assessment method for NPP in JSCE, Japan

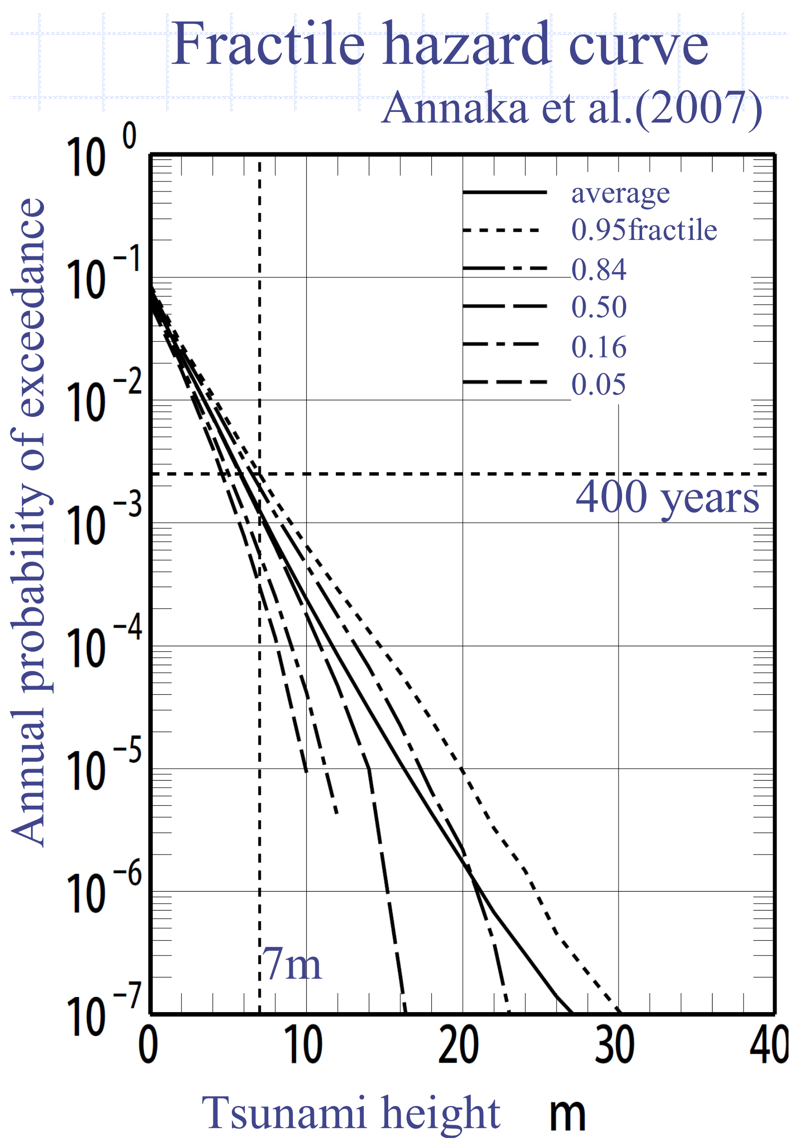
The TSUNAMI EVALUATION SUBCOMMITTEE,
Nuclear Civil Engineering Committee, JSCE

Masafumi Matsuyama (CRIEPI)



Probabilistic Tsunami Hazard Analysis (PTHA)

- Probabilistic estimation of tsunami risk
  - Estimation of the <u>deterministic</u> design tsunamis
- Considering uncertainties in estimation
  - Errors in fault parameters
  - Errors in the numerical calculation system (numerical simulation, topography data)
  - Incomplete knowledge and data about the earthquake process



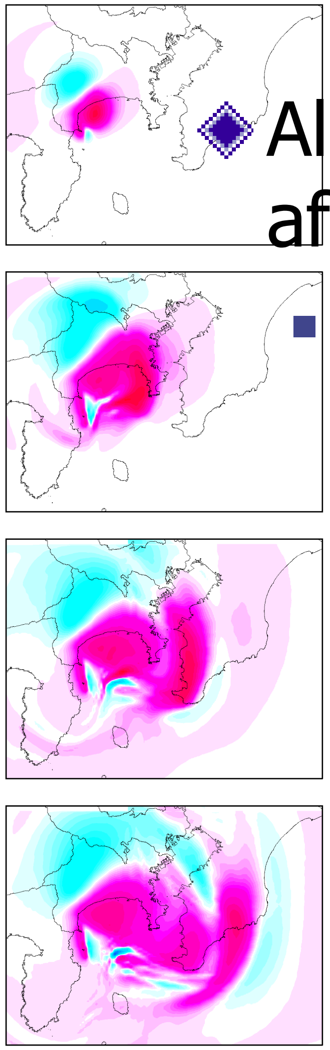
Niigata meeting, November 2010
http://www.jnes.go.jp/seismic-symposium10/presentationdata/3_sessionB.html

Tsunami Assessment method for NPP in JSCE, Japan

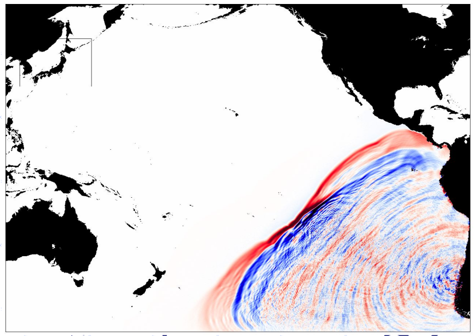
The TSUNAMI EVALUATION SUBCOMMITTEE,
Nuclear Civil Engineering Committee, JSCE

Masafumi Matsuyama (CRIEPI)

A brief review of recent activities



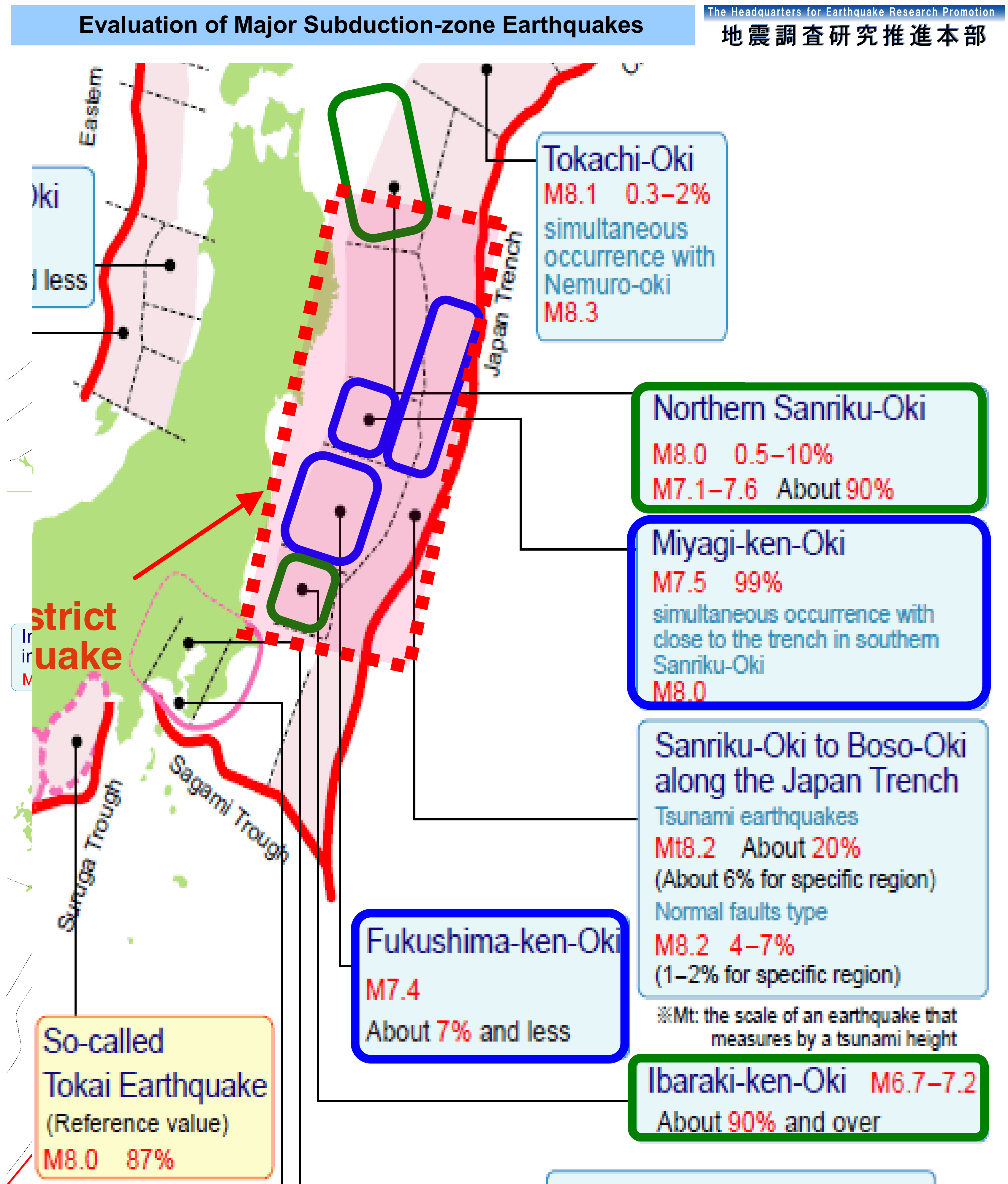
- Almost ten years have passed after tsunami manual released.
  - Recent advances and new knowledge
    - Tsunami source model (fault model)
      - Re-evaluation of historical tsunami faults
      - Spatial inhomogeneity in terms of slip
    - Numerical simulation
      - New simulation method of crustal motion (GMS, Grand Motion Simulator by NIED*)
      - New simulation method of far field tsunami
        - Nonlinear dispersion theory



*National Research Institute for Earth Science and Disaster Prevention, Japan

Niigata meeting, November 2010
http://www.jnes.go.jp/seismic-symposium10/presentationdata/3_sessionB.html

Expectations...

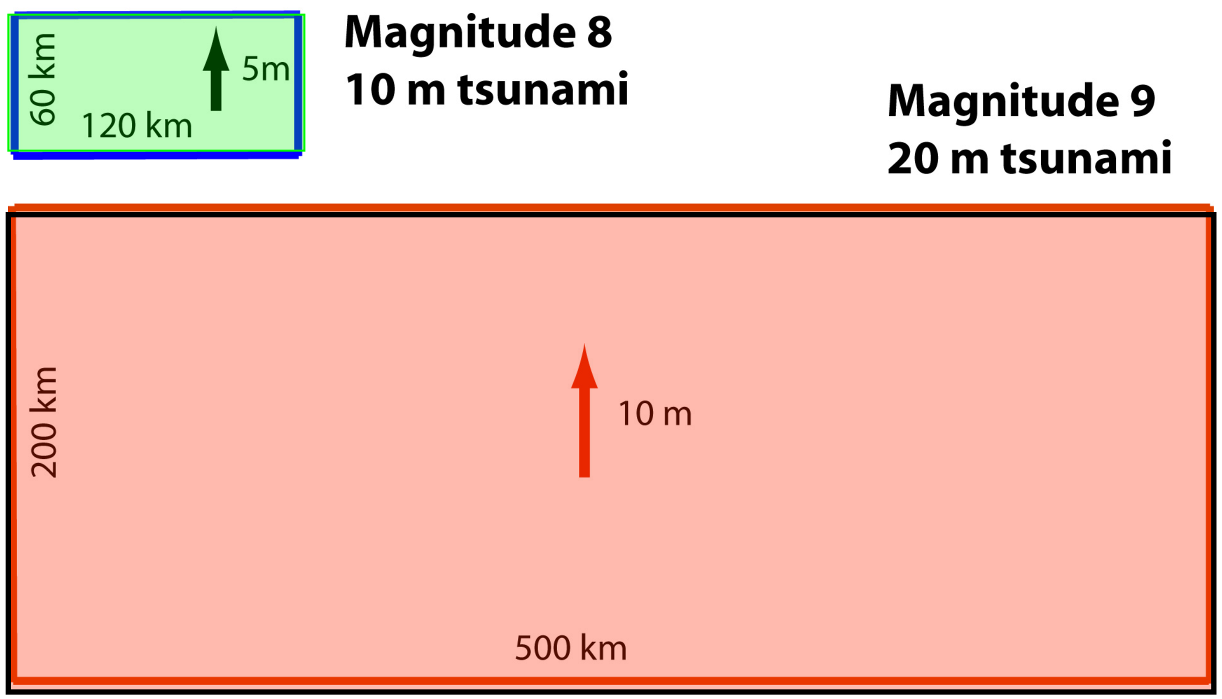


"Estimated magnitude and long-term possibilities within 30 years of earthquakes on regions of offshore based on Jan. 1, 2011."

"Estimated magnitude and long-term possibilities within 30 years of earthquakes on regions of offshore based on Jan. 1, 2008."

Reality...

Planning assumed maximum magnitude 8 Seawalls 5-10 m high



Tsunami runup approximately twice fault slip

M9 generates much larger tsunami

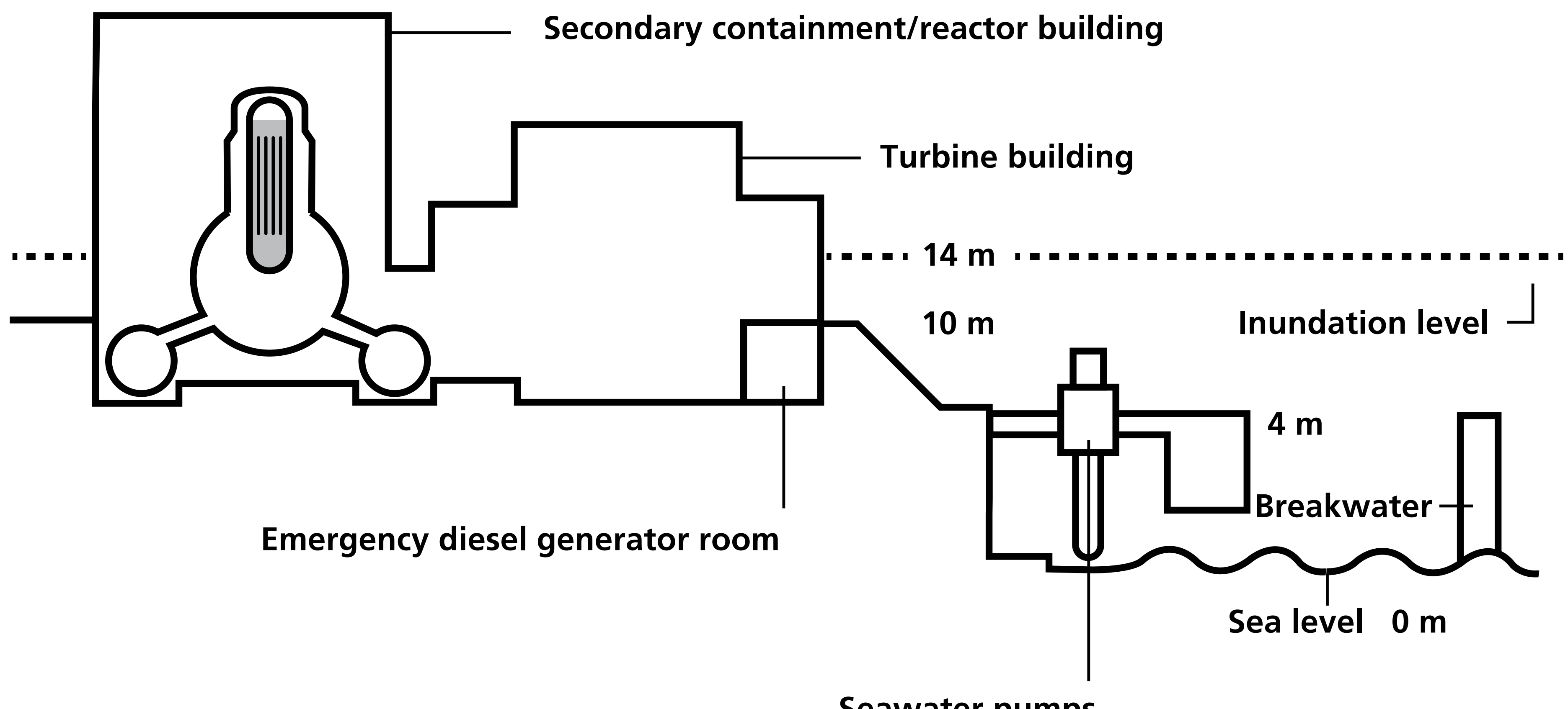
Stein, S. and E. Okal, The size of the 2011 Tohoku earthquake needn't have been a surprise, EOS, 92, 227-228, 2011.

Reality...

Fukushima Daiichi's design-basis tsunami was estimated to have a maximum height of 3.1 meters above mean sea level. TEPCO decided to locate the seawater intake buildings at 4 meters above sea level and the main plant buildings at the top of a slope 10 meters about sea level.

In 2002, on the basis of a new methodology for assessing tsunami safety developed by the Japan Society of Civil Engineers, TEPCO voluntarily reevaluated the tsunami hazard and adopted a revised design-basis tsunami height of 5.7 meters.

NISA neither updated the licensing documents to reflect this change nor reviewed TEPCO's analysis.



Simplified cross-section through one of the reactors at Fukushima Daiichi showing the approximate location of critical components damaged by the tsunami. Not drawn to scale.

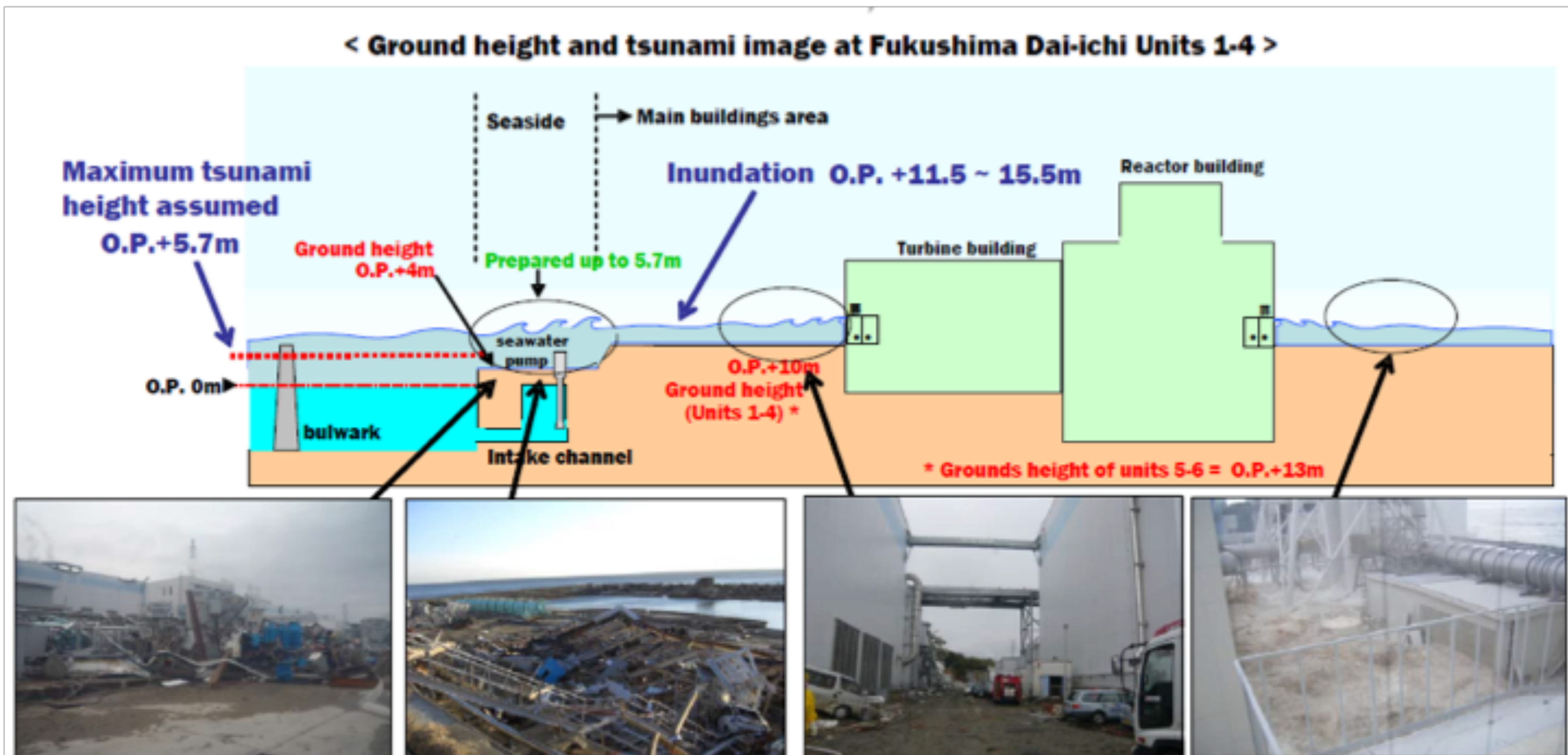
From "WHY FUKUSHIMA WAS PREVENTABLE", James M. Acton and Mark Hibbs, 2012.

Reality...

Extremely Confidential

The tsunami swallowed not only the seaside, but the whole area of Dai-ichi, including the mountain side. Both the reactor and turbine buildings were completely inundated. => The safety allowance against tsunami is obviously underestimated.

Maximum tsunami height (estimation) = + 5.7m ➔ **Actual inundation height = + 11.5 ~ 15.5m**



- A heap of rubble in the area of 4m altitude. Hardly transport vehicles, personnel, or supplies.
- Even at an elevation of 10m, cars had drifted. Even on the mountain side of the building, a 5.5m-height tank has been swallowed up, just like a swimming pool.

Reality...

Damage by the earthquake such as the liquefaction and break of infrastructure was larger at Fukushima Dai-ichi (Intensity: upper 6*) than at Dai-ni (lower 6*). One of the major factors which had retarded the accident management at both plants afterwards.

*: Maximum acceleration at Dai-ichi was 550gal (east to west) and 350gal at Dai-ni (up to down). Both observed at the lowest floors of the reactor buildings.

Damage at Fukushima Dai-ichi

- Road is completely cracked and fissured
- Major bend in guardrail
- Many cracks along the side of the road
- People and vehicles can hardly pass

- Road has caved in for several meters
- Drum can has rolled into the middle of the street
- No cars can pass. People can hardly walk

- Several meters of chasm even at elevated ground

- Ground has caved in

- Gap between building and ground (a depression in ground?)

Damage at Fukushima Dai-ni

Cascade...

- The plant site was at approximately 30 m O.P. , on a natural berm that ran alongshore. According to documents filed in 1967 with Japanese authorities, TEPCO graded the 30 m O.P. berm to 10 m.

- A major regulatory failure was in the specification of the design earthquake. The TEPCO analysis appears to have relied exclusively on a variation of source characteristics for an M ~ 7.5 event.

- Analysis appears not to have included any run-up and flooding estimates for the NPP at its base elevation. Long wave run-up up a vertical seawall can exceed twice the value of the incident wave height.

Sea gate in Hachinohe

http://minkara.carview.co.jp/userid/405365/car/375387/1923923/photo.aspx

Sea gate (9.3 m high)

http://ja2xt.mu-sashi.com/Numazu5.htm

Sea walls

Sea wall with stairway evacuation route used to protect a coastal town against tsunami inundation in Japan.

Photo courtesy of River Bureau, Ministry of Land, Infrastructure and Transport, Japan.

Elevated platform used for tsunami evacuation that also serves as a high-elevation scenic vista point for tourist.
Okushiri Island, Japan. Photo courtesy of ITIC

Deepest breakwater in Kamaishi (Iwate)

Tsunami walls...

The 2.4 km long tsunami wall in Miyako, Iwate Prefecture, was destroyed. The 6 m, 2 km long, wall in Kamaishi, Iwate Prefecture, was overwhelmed but delayed the tsunami inundation by 5 minutes.

The 15.5 m tsunami wall in Fudai, Iwate Prefecture, provided the best protection, but it is good to know that the original design was only 10 m. The village mayor fought to make it higher from information in the village historical records.

The biggest problem is that tsunami walls may give a false sense of security and other preparedness measures may NOT be undertaken.

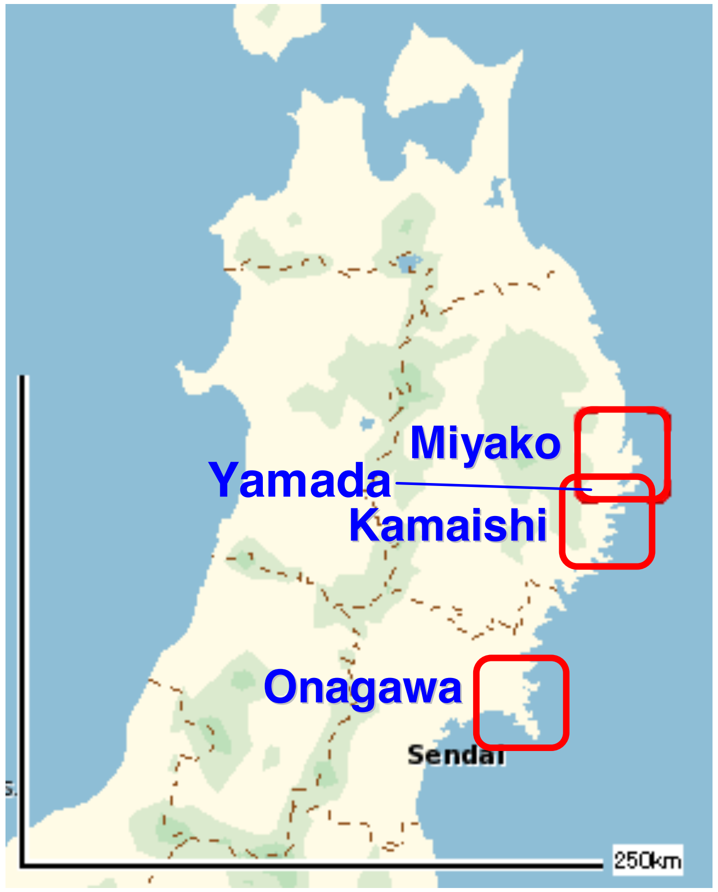
Woody Epstein, 2011

Sea wall at Fudai

49 foot sea wall:
completed in 1967; floodgates were added in 1984.

Following the 1896 Meiji tsunami, village mayor Kotoku Wamura pressed for a seawall at least 15 meters high, often repeating the tales handed down to him growing up: that the devastating tsunami was 15 meters.

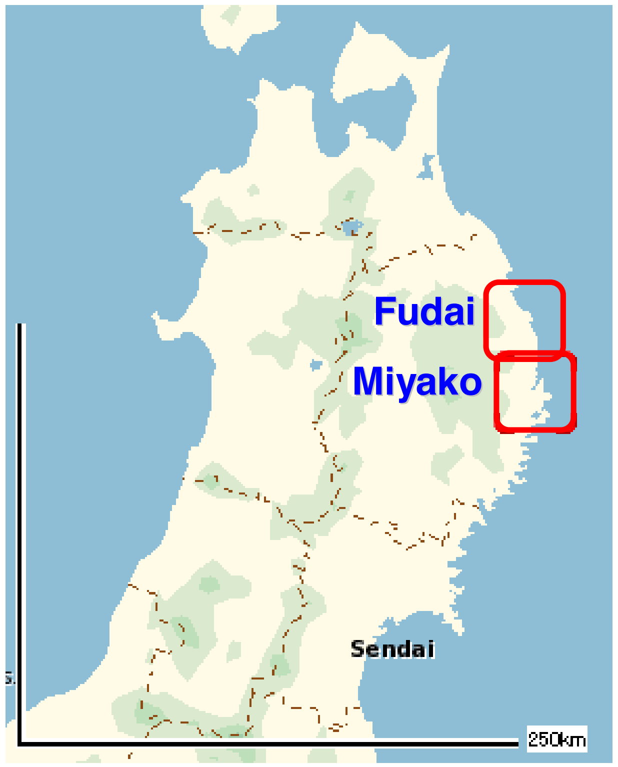
Reality...



Destruction by tsunami scouring

Destruction by wave pressure

Miyako and Fudai...



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.

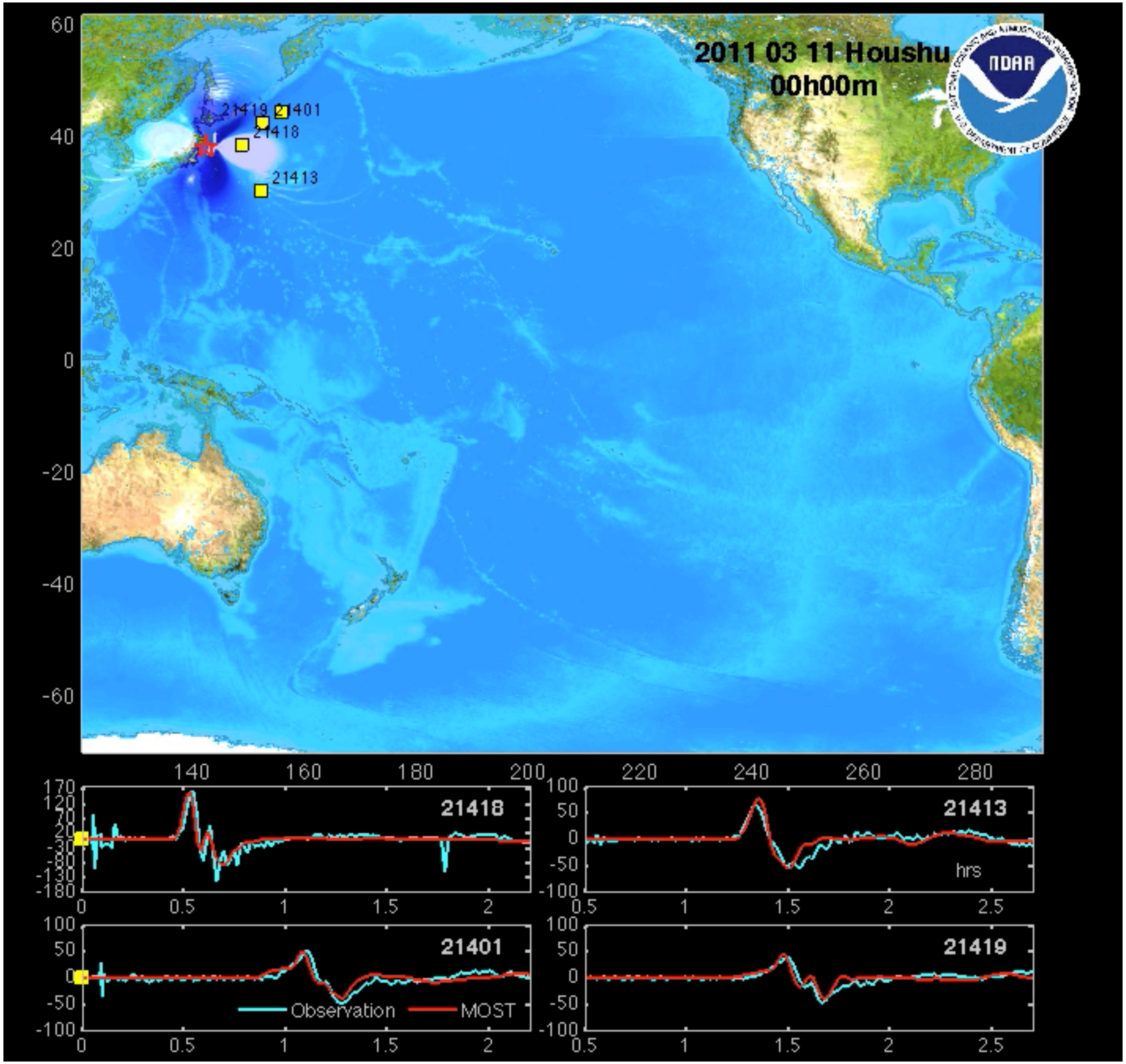
Fig. III-1-16 Difference of seawall heights resulting in different consequence.

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

Tsunami stones (Tsunami-seki)

Tsunami animation - NOAA

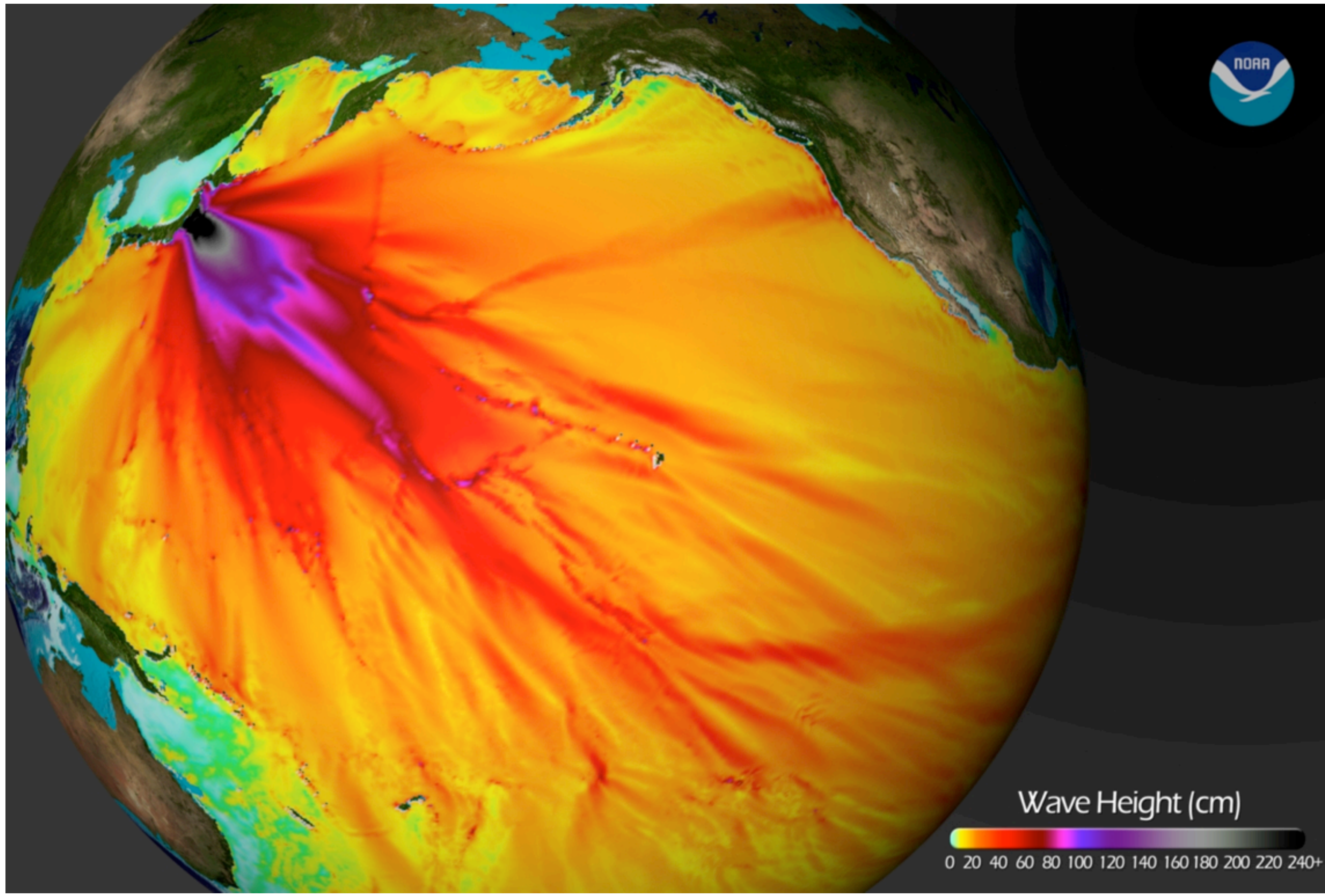


https://www.ngdc.noaa.gov/hazard/11mar2011.html

Propagation forecast

A tsunami propagation forecast model contours the forecasted maximum wave amplitudes (in cm) from the tsunami detailing the tsunami energy propagation.

This led to a Pacific wide tsunami warning being issued.



Tsunami warning - NOAA

severe **Widespread Warning, Watch, or Advisory in Effect**

Click here to read the latest tsunami message.

All Regions	Pacific Ocean	Hawai'i	Indian Ocean	Caribbean Sea

Message pacific.2011.03.11.103059

Tsunami Information

Message Time:	11 Mar 2011 10:30 UTC
Message Num:	6
Message Text:	click to read
Message Type:	a Widespread Tsunami Warning is in Effect
Warning:	Japan, Russia, Marcus Is., N. Marianas, Guam, Wake Is., Taiwan, Yap, Philippines, Marshall Is., Belau, Midway Is., Pohnpei, Chuuk, Kosrae, Indonesia, Papua New Guinea, Nauru, Johnston Is., Solomon Is., Kiribati, Howland-baker, Hawaii, Tuvalu, Palmyra Is., Vanuatu, Tokelau, Jarvis Is., Wallis-futuna, Samoa, American Samoa, Cook Islands, Niue, Fiji, New Caledonia, Tonga, Mexico, Kermadec is, Fr. Polynesia, Pitcairn, Guatemala, El Salvador, Costa Rica, Nicaragua, Antarctica, Panama, Honduras, Chile, Ecuador, Colombia, Peru
Watch:	
ETAs / Obs:	measurements

Earthquake Information

	Preliminary (PTWC)	Official (USGS)
Origin Time:	11 Mar 2011 05:46 UTC	11 Mar 2011 05:46 UTC
Magnitude:	8.9 Mwp (reviewed by PTWC)	7.9
Latitude:	38.3° N	38.3° N
Longitude:	142.4° E	142.4° E
Depth:	24 km (14.9 mi)	24.4 km (15.2 mi)

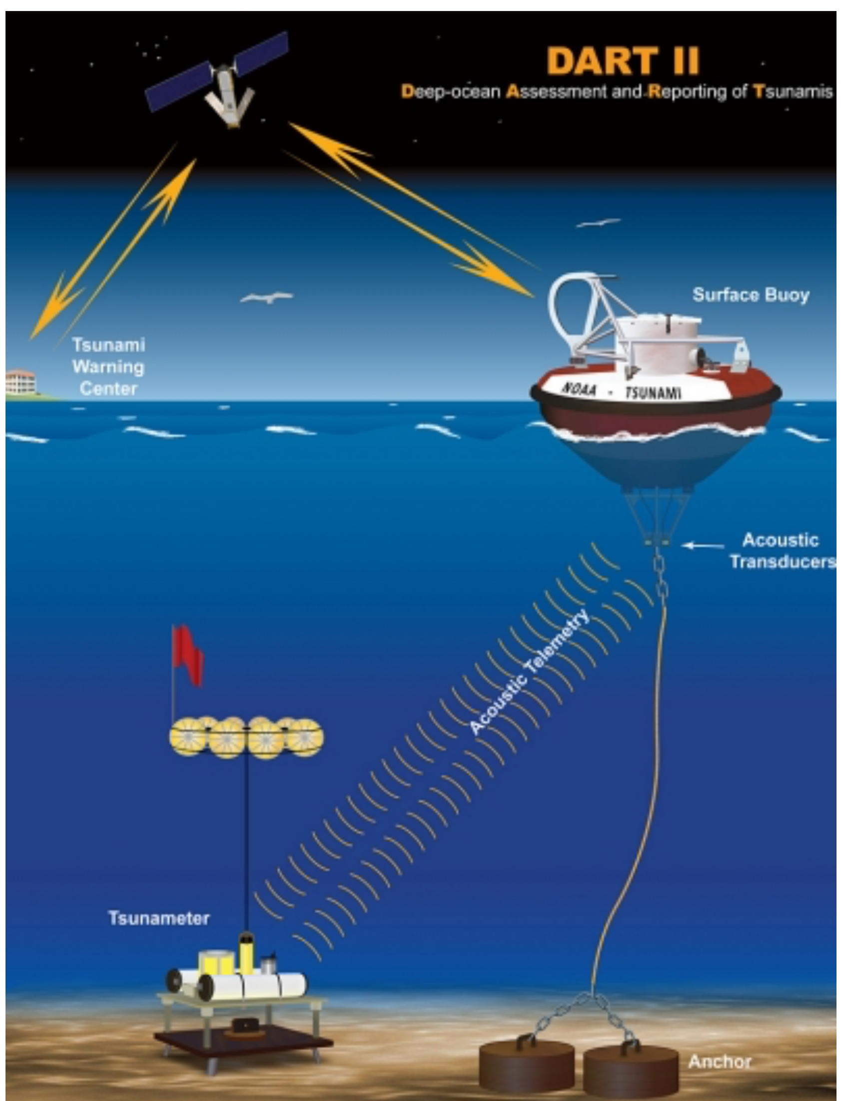
Location: Near East Coast of Honshu Japan

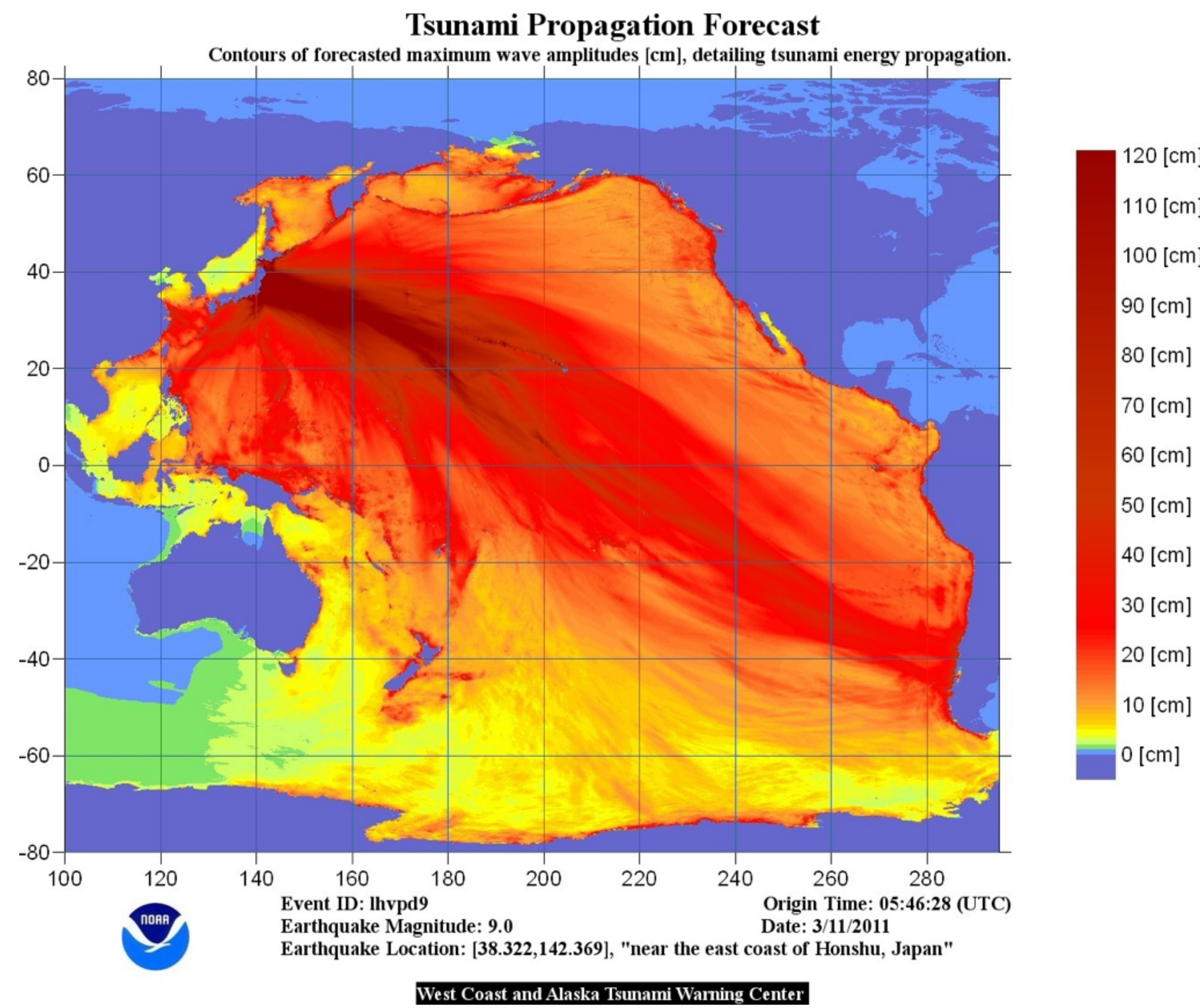
More Info.: updated earthquake information from the USGS NEIC

TEW

Table 1. Evolution of tsunami warning systems AFTER major tsunamis.

tsunami	resulting tsunami warning system
1896 Japan	Japan-1941
1946 Alaska, USA	USA-1949
1952 Kamchatka, Russia	Russia-1954
1960 Chile	International Pacific Basin-1965
1964 Alaska, USA	French Polynesia-1965
2004 Sumatra, Indonesia	Global- 2007





TEW - Japan

At night on 12 July 1993, an earthquake off the west coast of Hokkaido generated a huge tsunami. The southernmost area of Okushiri Island was completely devastated by the 11m tsunami, even though the area was protected by 4.5m seawalls.

In 1997, the Japan central government council, which consists of seven ministries, issued a guideline for comprehensive tsunami countermeasures that should be taken as part of regional tsunami disaster prevention.
In those guidelines, three basic concepts of tsunami countermeasures were recommended:

(i) building seawalls, breakwaters and flood gates to protect lives and properties;

(ii) urban planning to create a tsunami-resilient community through effective land-use management and arrangement of redundant facilities to increase the safe area, such as vertical evacuation buildings;

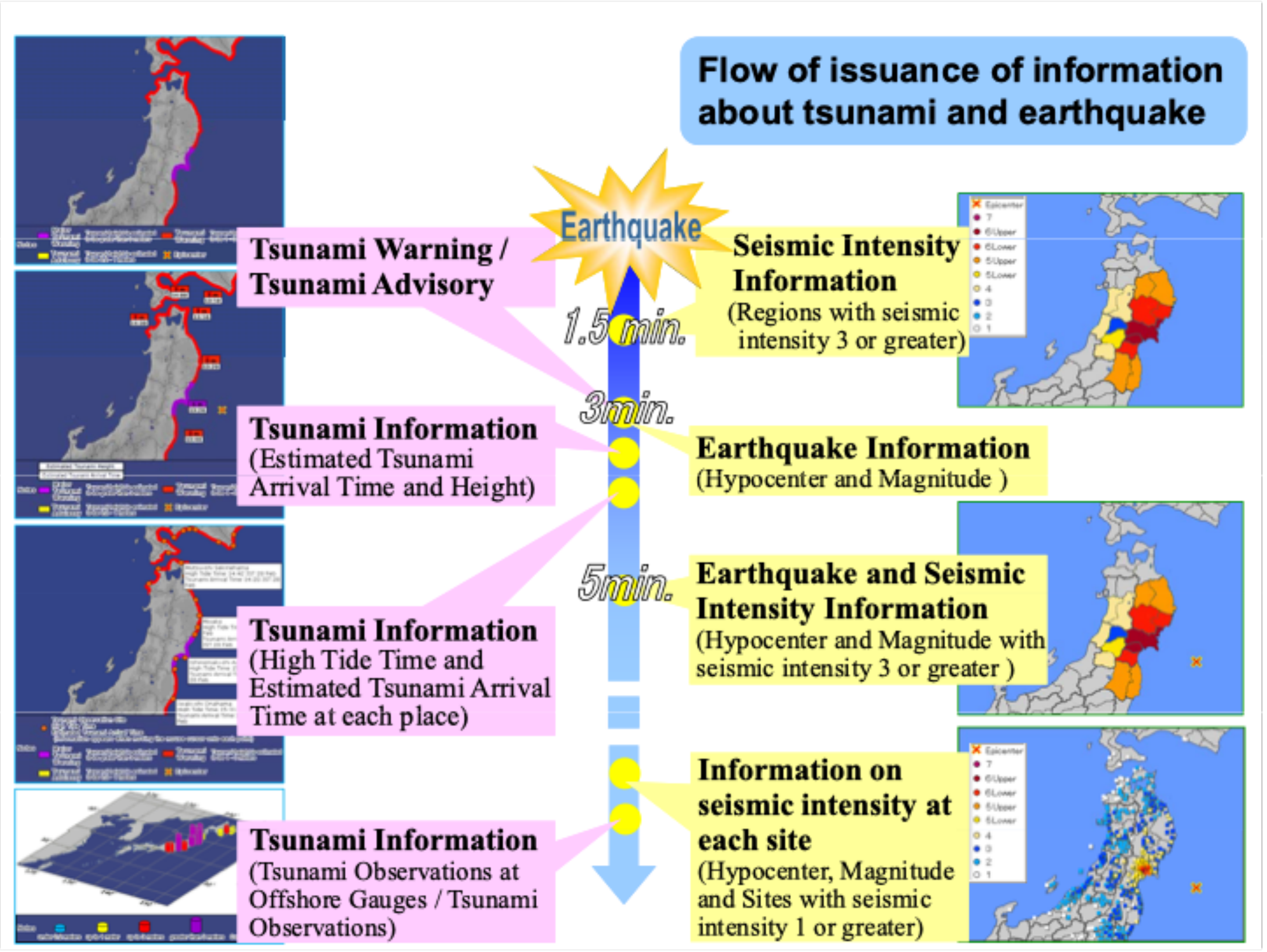
(iii) disaster information dissemination, evacuation planning and public education.

Koshimura S, Shuto N. 2015 Response to the 2011 Great East Japan Earthquake and Tsunami disaster. Phil. Trans. R. Soc. A 373: 20140373.

TEW - Japan

JMA prepared a pre-conducted tsunami propagation simulation database for over 100 000 earthquake scenarios around Japan.

The contents of the warning were classified into three categories, according to the estimation of tsunami height: 'Major tsunami' (estimated more than 3 m), 'Tsunami' (estimated 1 or 2 m) and 'Advisory' (0.5 m or less).



TEW - Japan (Tohoku-oki March 11)

When the 2011 event occurred at 14.46 JST on 11 March, JMA's initial estimate of the magnitude was 7.9. Based on the promptly estimated magnitude 7.9, 3 min after the quake (14.49 JST), JMA issued a Major tsunami warning to the coasts of Iwate, Miyagi and Fukushima prefectures with estimates of 3 m, 6 m and 3 m, respectively.

After the tsunami was observed at offshore tsunami buoys, JMA revised the contents of the warning with estimates of 3 m, 6 m, over 10 m, 6 m, 4 m and 4 m to the coasts of Aomori, Iwate, Miyagi, Fukushima, Ibaraki and Chiba prefectures.

Receiving the tsunami warning from JMA, some residents claimed that they thought they were safe based on the 3m estimation: they did not feel that they had to evacuate, as they felt safe behind a 10 m seawall. Even worse, in several communities, the radio or speaker system did not work because of the blackout caused by the earthquake.