RIC 2012

Session W10, Flooding: Lessons Learned and Near-Term Regulatory Actions

Cause Investigation of Tohoku Tsunami and Recipe for assessing Design Tsunami based on knowledge obtained

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6. Summary

1. Background and Purpose

(1) The Tohoku EQ. occurred off the Pacific coast on March 11, 2011, and caused a huge tsunami, which struck several NPP sites (Fukushima Daiichi and Daini, Onagawa, Tokai Daini) on the east coast of Japan.

(2) At Fukushima Daiichi, the reactor core was damaged and radioactive materials were released. While at Onagawa, Tokai and Fukushima Daini, no core damage occurred.

(3) NISA has been advancing a project for investigating cause of the Tsunami, preparing a recipe for assessing design tsunami height and reviewing design tsunamis.

(4) As a part of the above Project, JNES investigated the cause of the Tsunami and clarified major factors contributing to tsunami wave heights at Fukushimi Daiichi and Daini and also their difference.

(5) JNES is making the above recipe based on the investigation results and lessons and findings learnt from the Tsunami.

(6) The outline of the above items (3)-(5) are presented at this time.

2. Characteristics of Tohoku EQ. and Tsunami

2.1 The tsunami camed at Fukushima Daiichi NPP

- **While the reactors were shut down normally, they were attacked by tsunami about 46 minutes after the earthquake occurred.**
- **Various equipment of the water intake system and emergency diesel generators were flooded.**
- **External power supply was also lost due to damage by strong ground motions and tsunami.**
- **In this situation, station blackout (SBO) occurred took place.**
- **As a consequence, functions of reactor cooling system was lost, core damage (CD) occurred and radioactive materials were released to the off-site area.**

【福島第1原発 津波来襲状況 2011年3月11日 固体廃棄物貯蔵庫東側のり面(6号機の近傍(南側)から東側を撮影)＝東京電力提供

【福島第1原発への津波来襲状況 2011年3月11日 廃棄物処理建屋4階から北側を撮影】午後3時42分ごろ(2)＝東京電力提供

【福島第1原発 津波来襲状況 2011年3月11日 固体廃棄物貯蔵庫東側のり面(6号機の傍(南側)から東側を撮影)＝東京電力提供

Photos of the tsunami coming to Fukushima Daiichi (Provided by TEPCO)

2.2 Characteristics of the source, observed ground motions and tsunami waveforms, slippage distribution

(1) Massive earthquake size of Mw 9.0

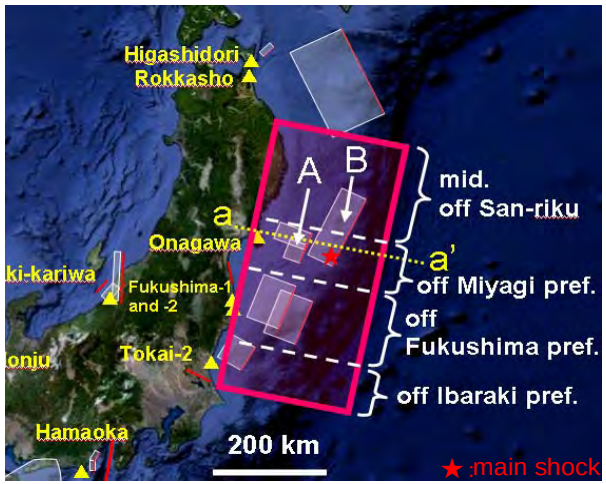
(2) Spatial conjunction among multiple source areas

(3) Tendency of time lags seen among observed seismic ground motions

(4) Overlapping of waves different in character as judged from observed tsunami waveforms

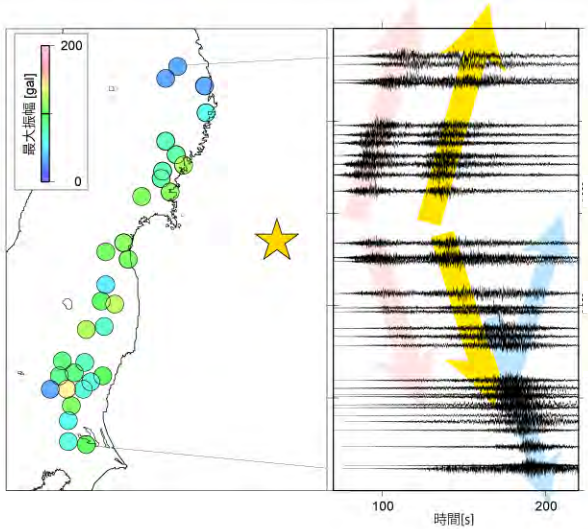
(5) Distribution of large slippages near the Japan Trench

(1),(2) Source area



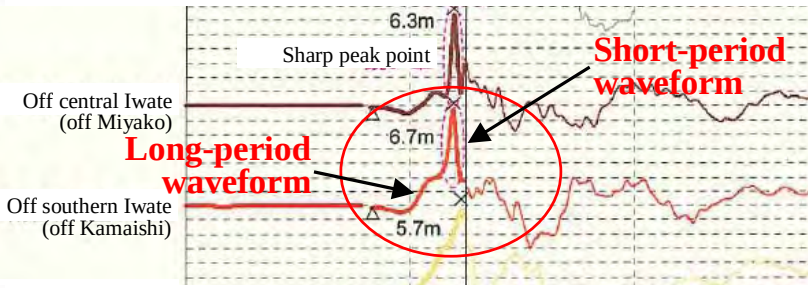
Google

(3) Observed ground motions



Quot. From NIED

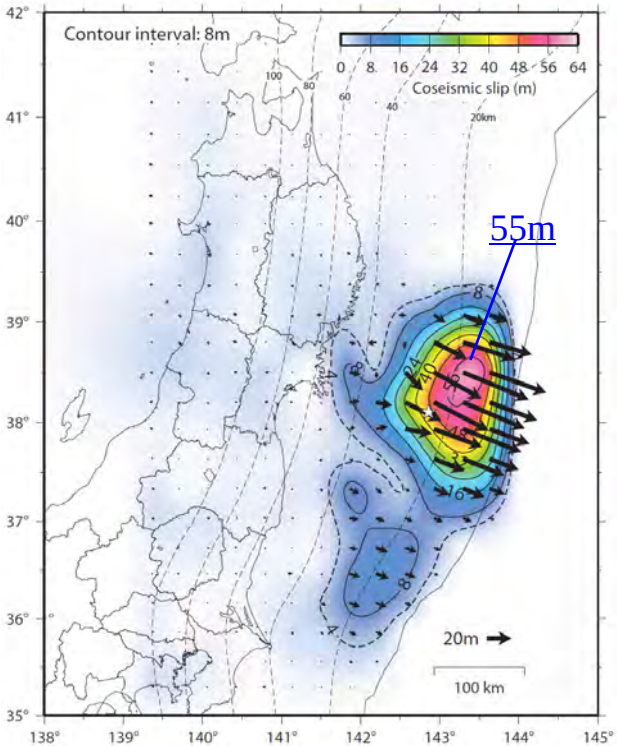
(4) Observed tsunami waveforms



Quot. From PARI

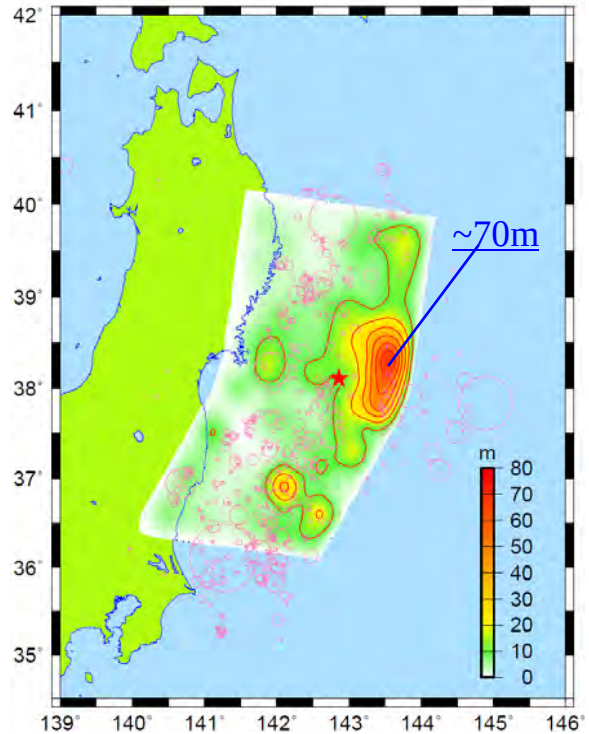
(5) Distribution of large slippages near the Japan Trench

Model-A based on geodetic data



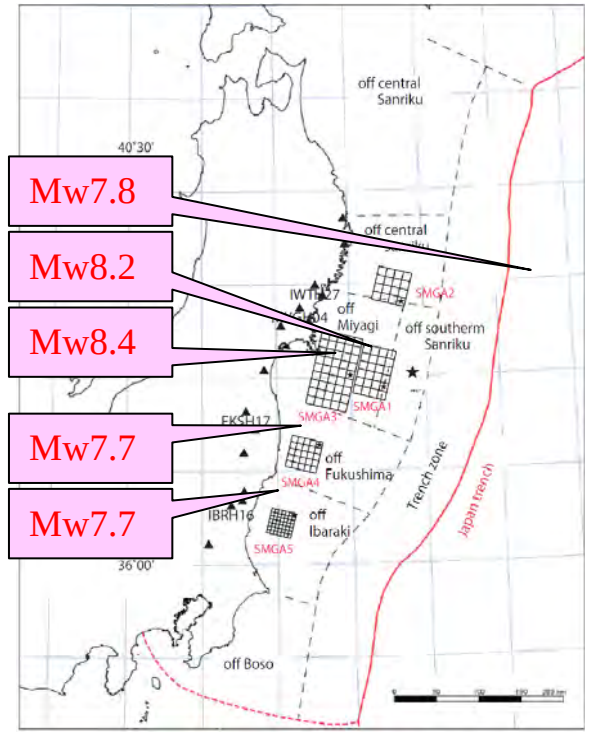
Modeled by the Geographical Survey Institute and the Japan Coast Guard

Model-B based on long-period seismic ground motion



Modeled by JNES

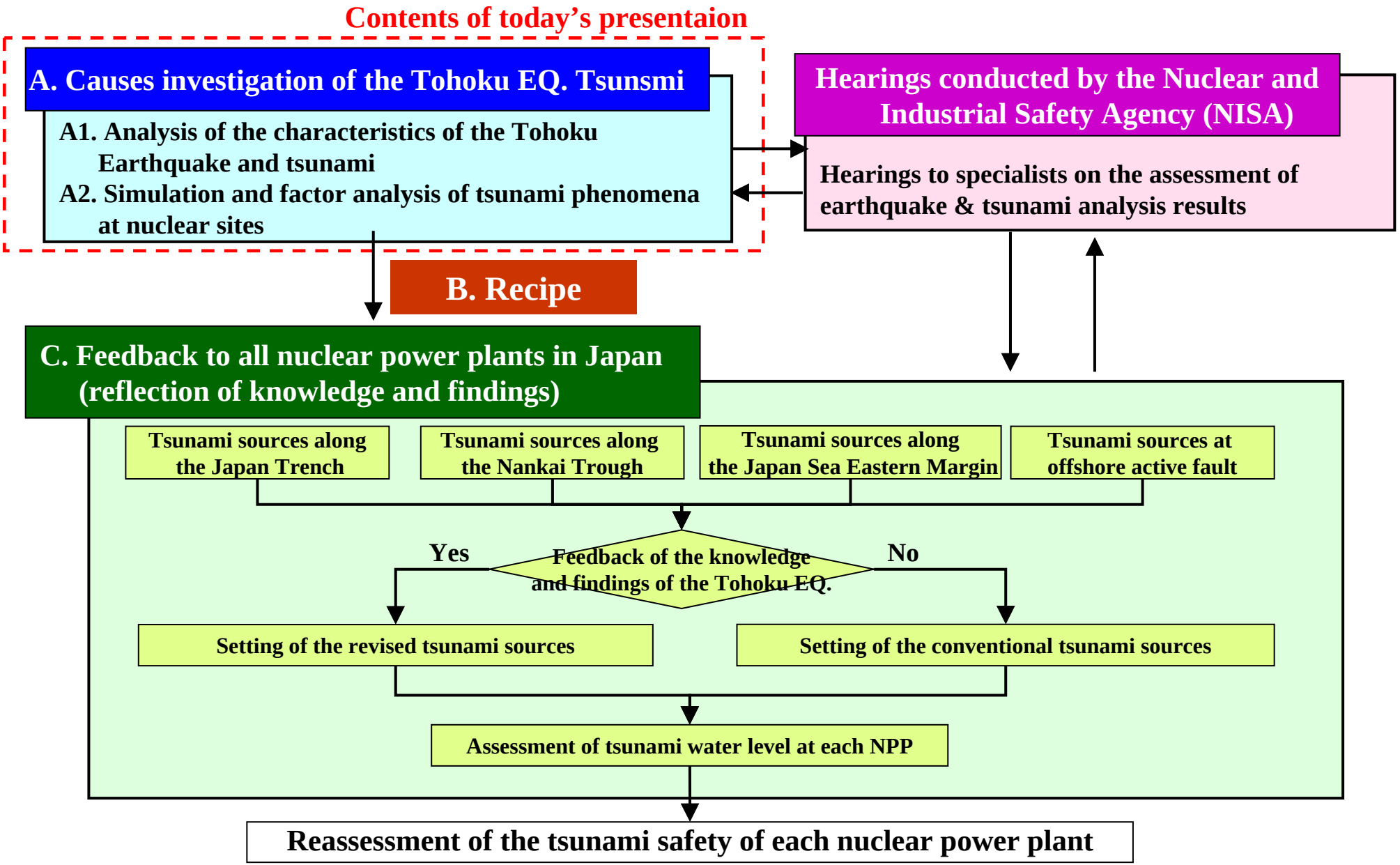
Model-C based on short-period seismic ground motion



Modeled by Prof. Irikura

- The source rupture processes (Model-A and B) were estimated on the basis of the geodetic data on the onshore and offshore areas as well as long-period seismic ground motions.
- The Both Models indicated a high possibility that large slippages concentrated in the vicinity of the Japan Trench, triggering massive tsunamis.

3. Framework of Project



4. Cause Investigation of the Tohoku EQ. Tsunami

4.1 Conditions of estimating tsunami source model

(1) The above characteristics (1)-(5) of the Tohoku EQ. Tsunami are taken into account.

(2) Tsunami waveforms and trace heights observed in areas other than nuclear sites as well as those observed in four nuclear sites are simulated by a common tsunami source model.

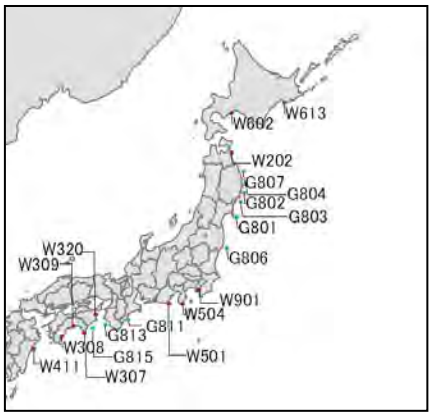
<u>Four nuclear sites:</u>
<u>Onagawa, Fukushima Daiichi, Fukushima daini, and Tokai Daini</u>

Merit of simulating through a common tsunami source model:

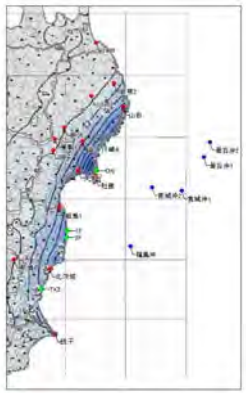
⇒Comparative analysis of different tsunami heights at nuclear sites are possible under common conditions.

4.2 Procedure of estimating tsunami source model

- Tsunami waveform data observed at 26 locations



- Crustal movement data observed at 23 locations



a Collection and arrangement of observation data

Setting of target observation data

b Setting of the geometry of the tsunami source model

c Calculation of Green function

Joint inversion analysis

Slippage distribution of the tsunami source model (provisional)

Numerical analysis of the tsunami

Has the situation of the four nuclear sites been simulated well?

No → Correction of slippages

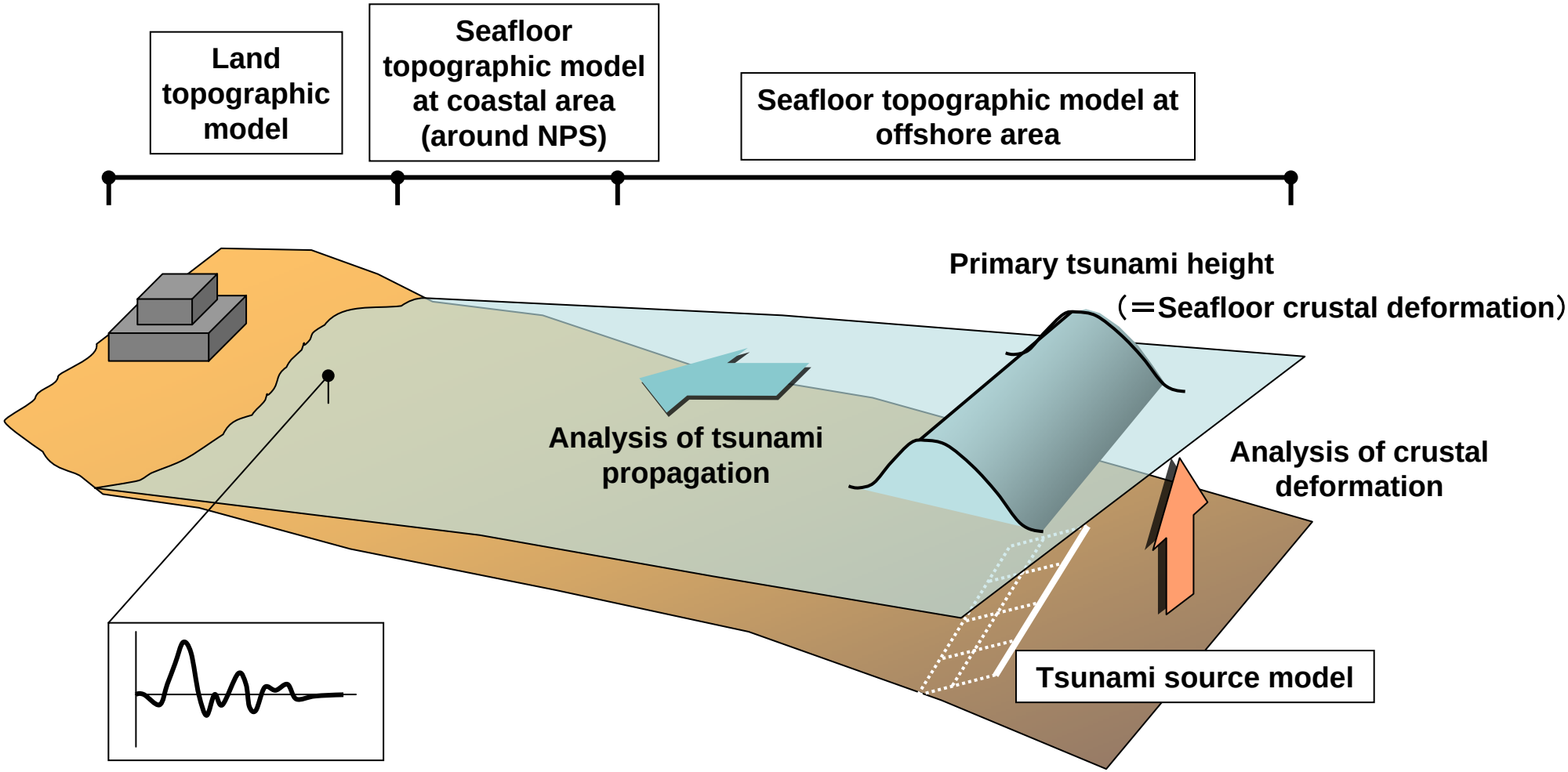
Yes

Consistency with the source rupture process related to earthquake and earthquake ground motions

d Slippage distribution of the tsunami source model (determined)

The factors analysis contributing to the difference of tsunami heights among the nuclear power plant sites

(1) Assessment flow of tsunami water level



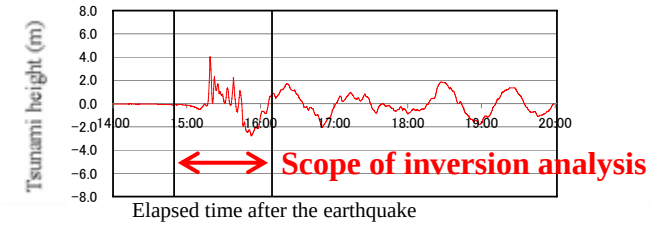
Water level changes due to Tsunami

= f（tsunami source model, seafloor topographic data（offshore area, coastal area））

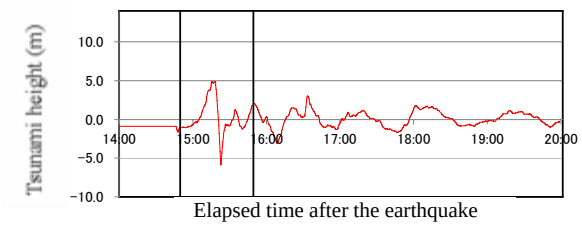
(2) Observed tsunami waveforms

■ Observed tsunami waveform at the GPS bouys (9 locations)

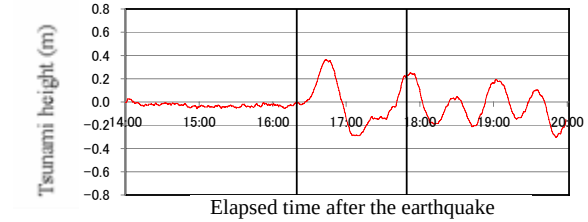
Off northern Iwate
G807



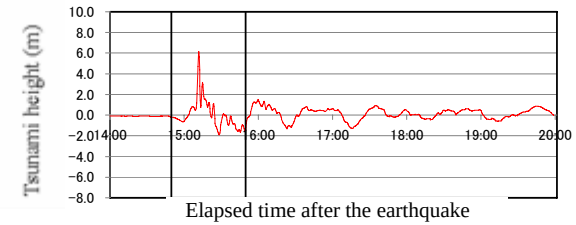
Off central Miyagi
G801



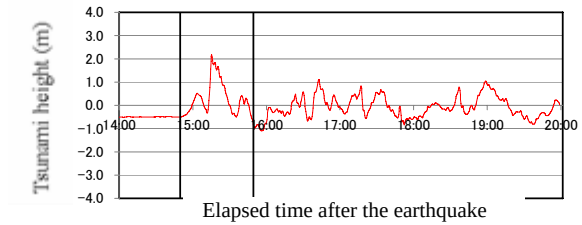
Off Kaiyo, Tokushima Pref.
G815



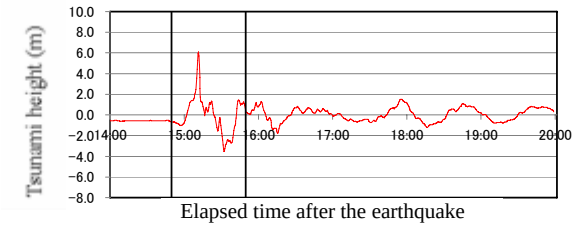
Off central Iwate
G804



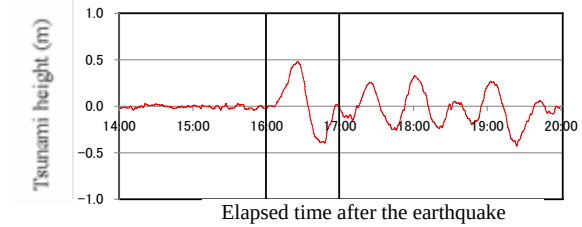
Off Fukushima Pref.
G806



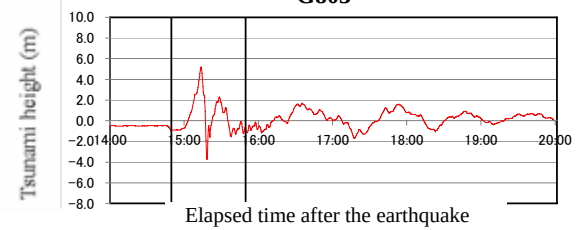
Off southern Iwate
G802



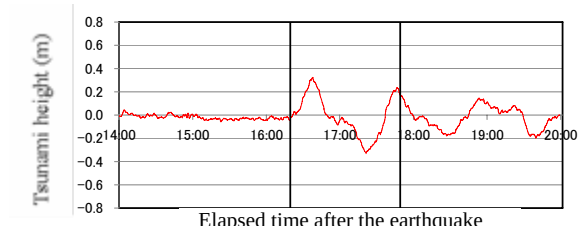
Off Owase, Mie Pref.
G811



Off northern Miyagi
G803



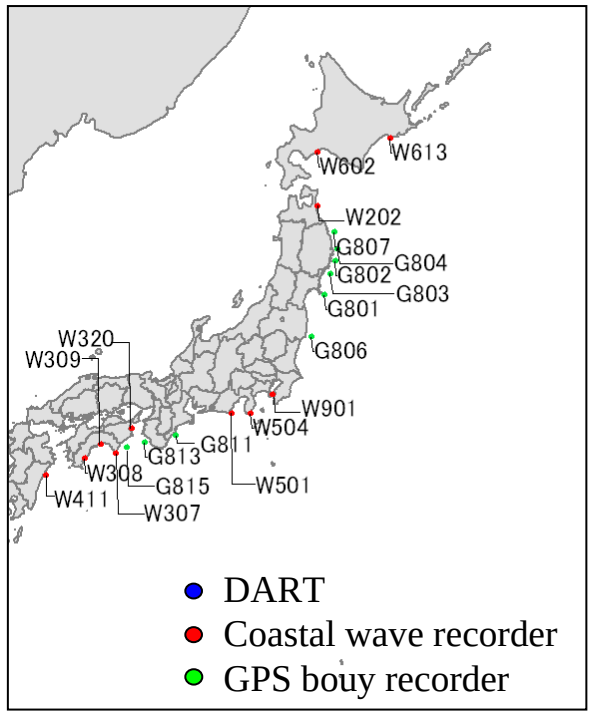
Off southwestern Wakayama
G813



Clock time on March 11

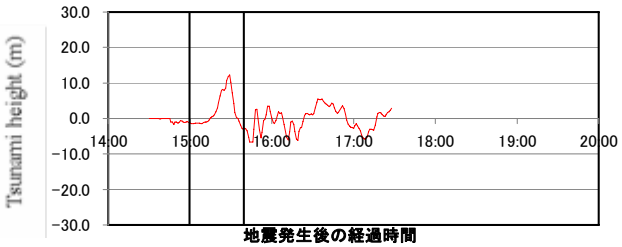
Clock time on March 11

Observation points



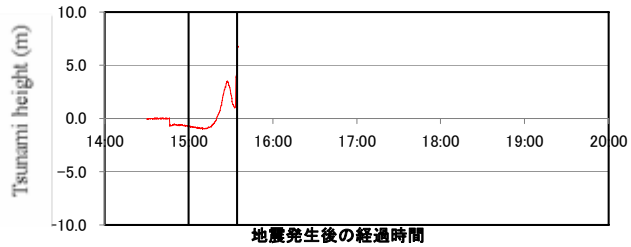
■ Observed tsunami waveform at nuclear sites (located at 3 points)

Onagawa
(Tohoku Electric Power Co.)



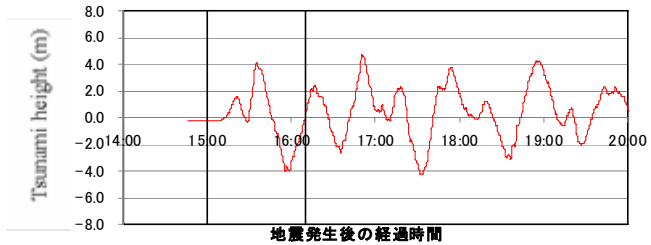
Clock time on March 11

Fukushima Daiichi
(Tokyo Electric Power Co.)

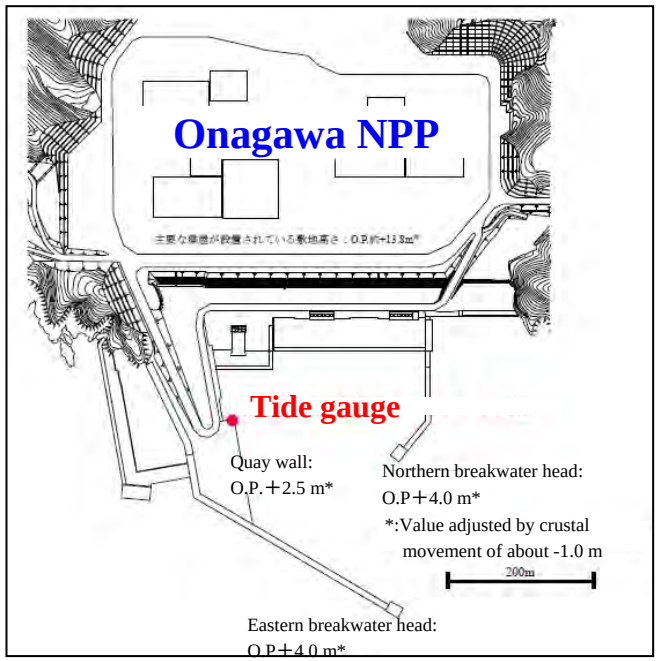


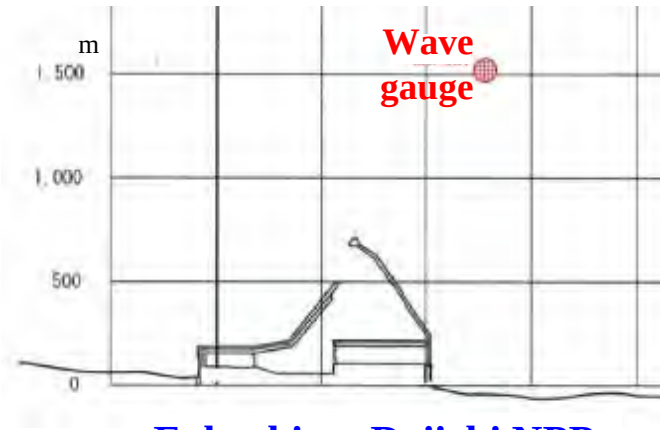
Clock time on March 11

Tokai Daini
(Japan Atomic Power Co.)



Clock time on March 11





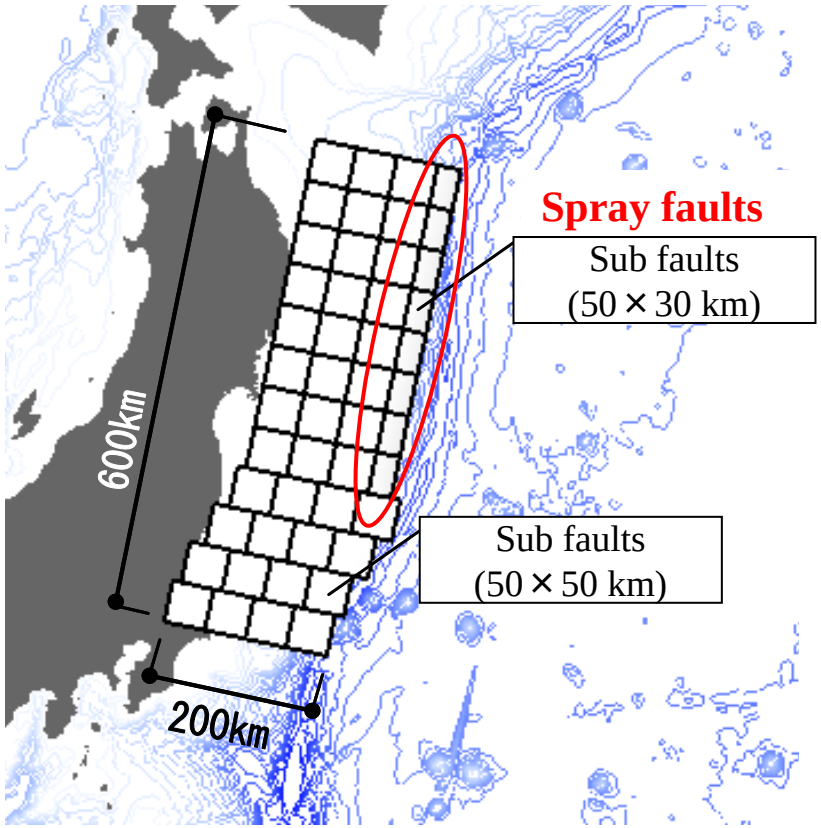
Fukushima Daiichi NPP

Tokai Daini NPP

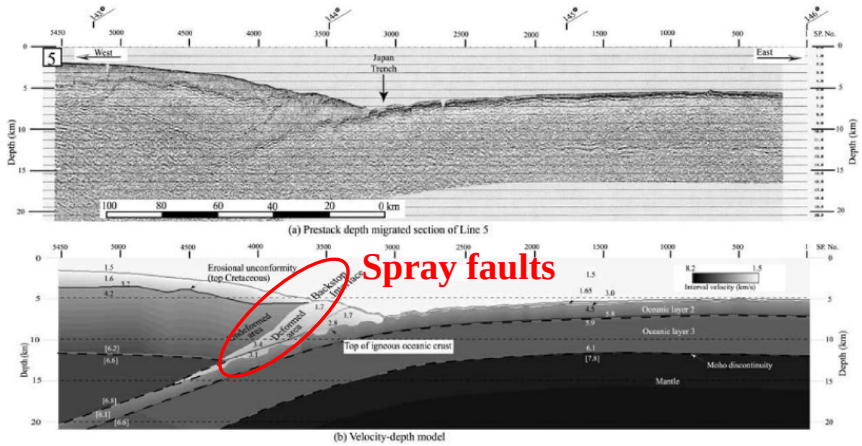
∗ Since tsunami waveform could not be measured at the Fukushima Daini Nuclear Power Station, its licensee could not submit related data.

(3)Setting of the geometry of the tsunami source model

- Entire area of the faults: Length, 600 km /Width, about 200 km
- The number of sub faults: 40（50x50 km）and 8（50x30 km）
- Referenced tsunami source models:
  The Model by Fujii and Satake (2011) and the one by Tohoku University (2011)
- The spray faults along the Japan Trench was taken into consideration.



Section of Japan Trench

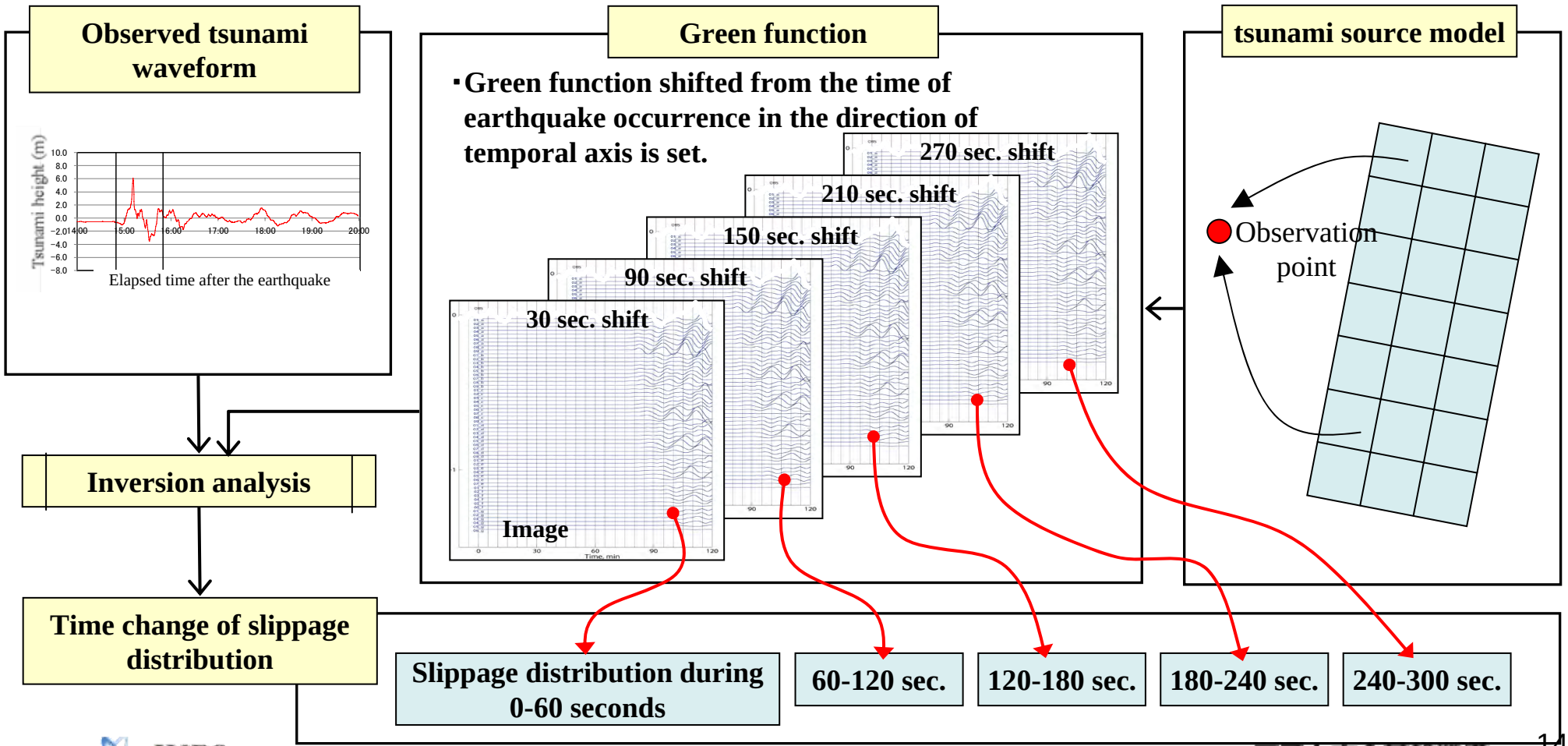


Tsuru et al. ;Along-arc structural variation of the plate boundary at the Japan Trench margin: Implication of interplate coupling , JOURNAL OF GEOPHYSICAL RESEARCH, vol. 107, 2002

(4) Spatial and temporal heterogeneity slippages distribution

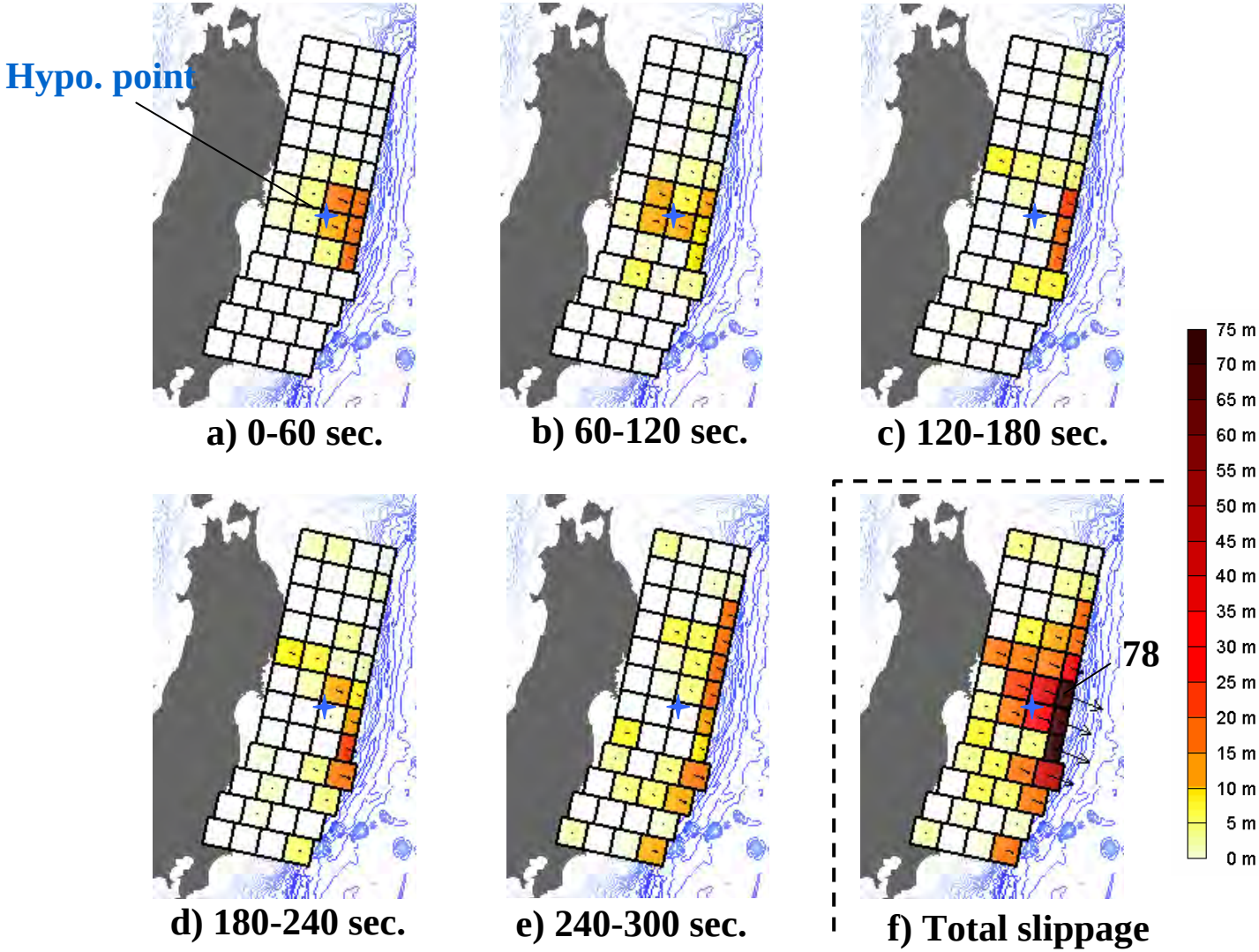
Actual phenomenon: Multiple source areas moved in conjunction and with time lag.

Modeling of sources: Initial break time (fracture initiation time) and duration is considered for each sub fault and the time change of its slippage distribution is described.



(5) Estimated tsunami source model

■ **Time change of the slippage distributions in the tsunami source model**

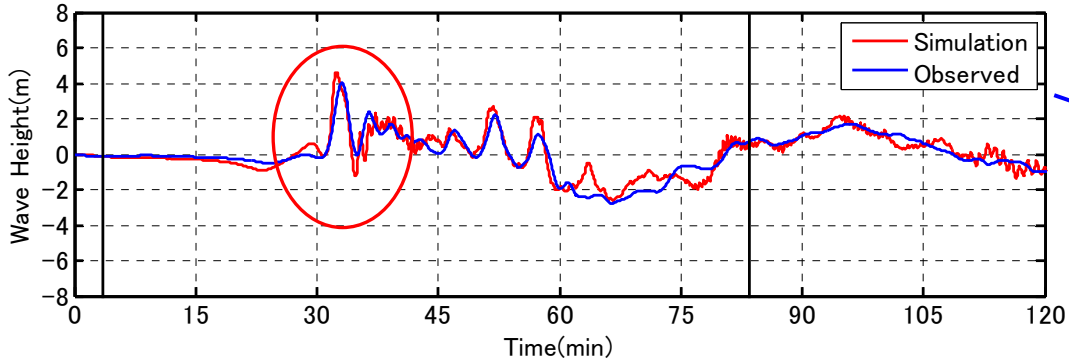


- **Slip (fault displacement) started to spread after the initial break point, and then spread to relatively deep areas, finally moving toward shallow areas along the Japan trench and continuing further.**
- **Maximum slippage: 78 m**
- **Mw: 9.1**
- **These results mostly agree with the results estimated on the basis of the source model of seismic ground motion.**

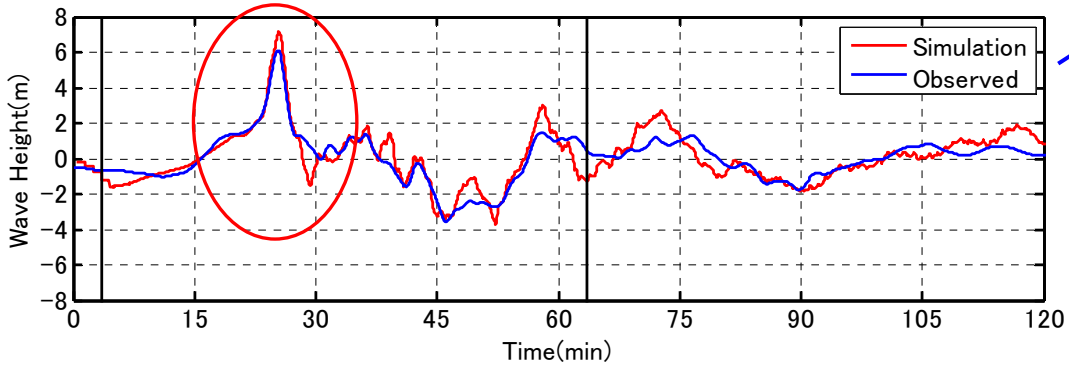
4.3 Simulated the tsunami phenomenon

(1) Tsunami waveforms at the GPS bouys

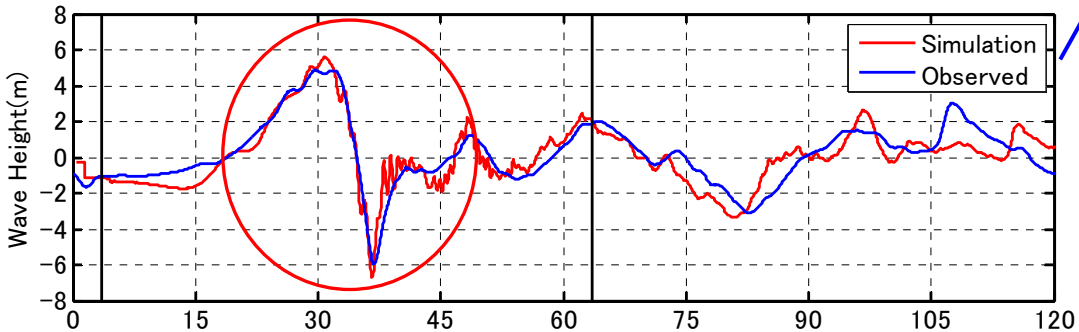
Off Northern Iwate
G807



Off southern Iwate
G802

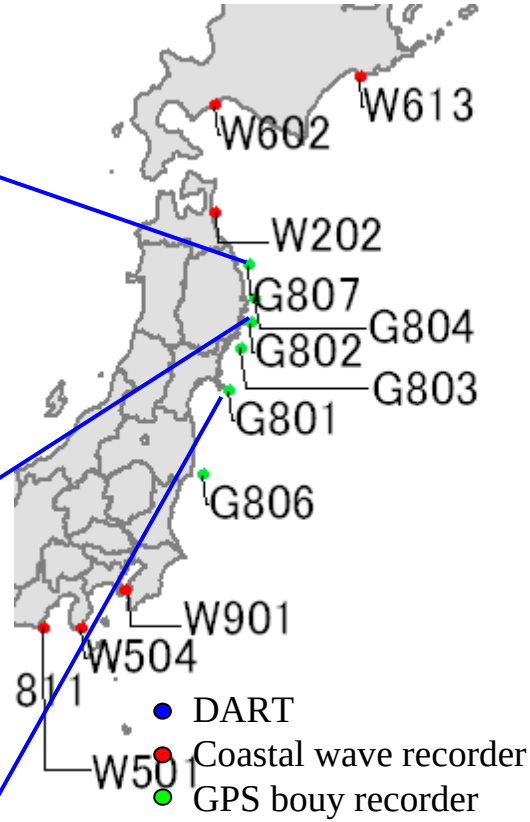


Off central Miyagi
G801



Elapsed time after the earthquake

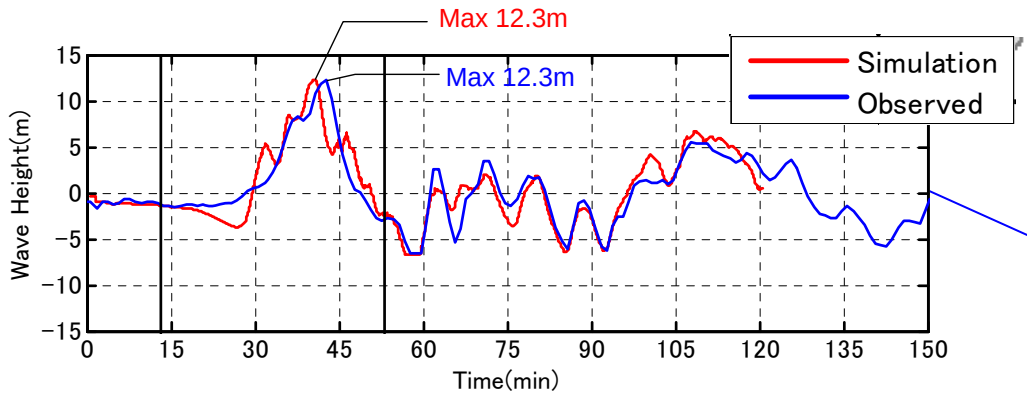
Observation points



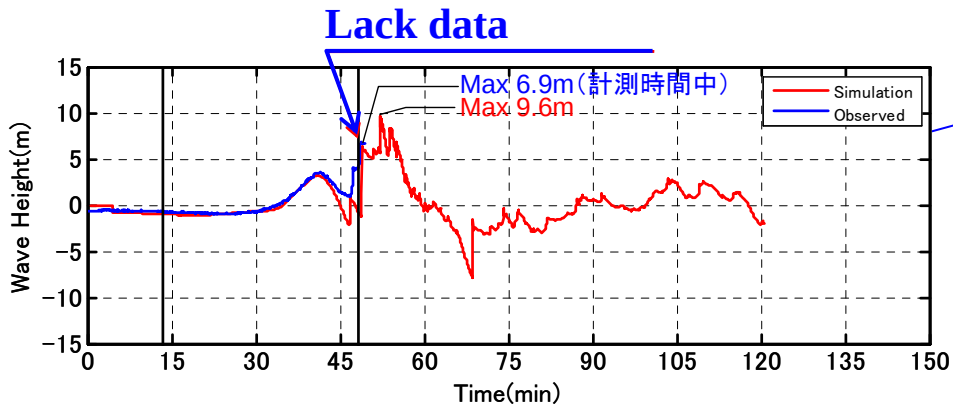
The simulation waveform well reproduced the observed waveform include the 1st wave.

(2) Tsunami waveforms at Nuclear Power Plant Sites

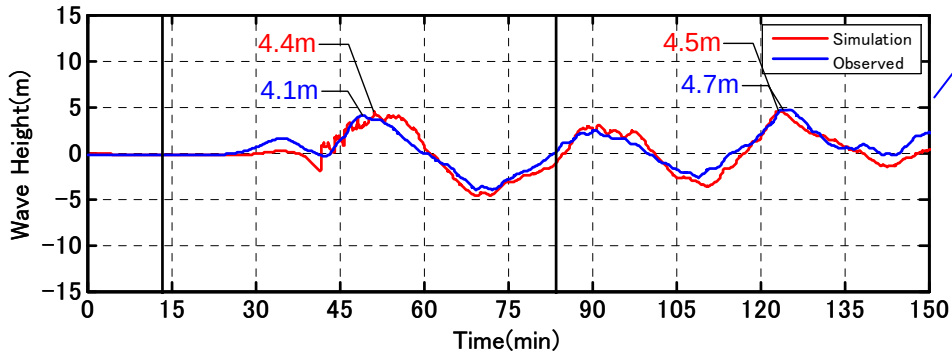
Onagawa NPP

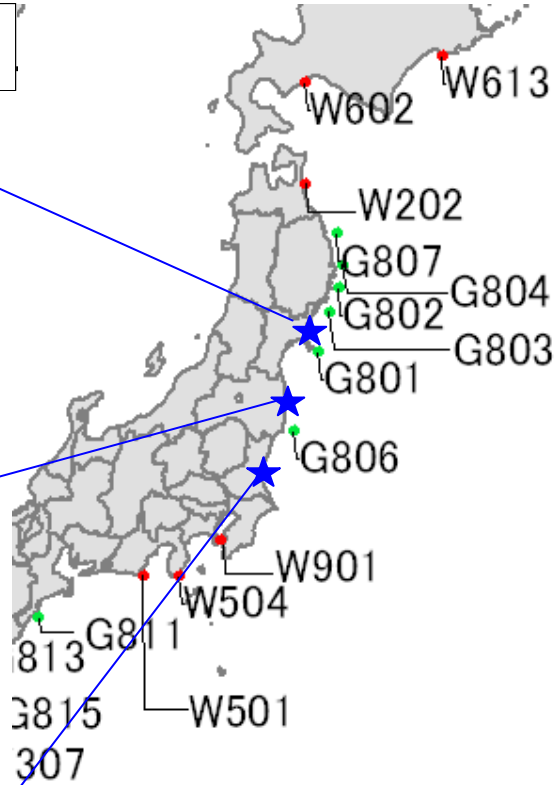


Fukushima Daiichi NPP



Tokai Daini NPP

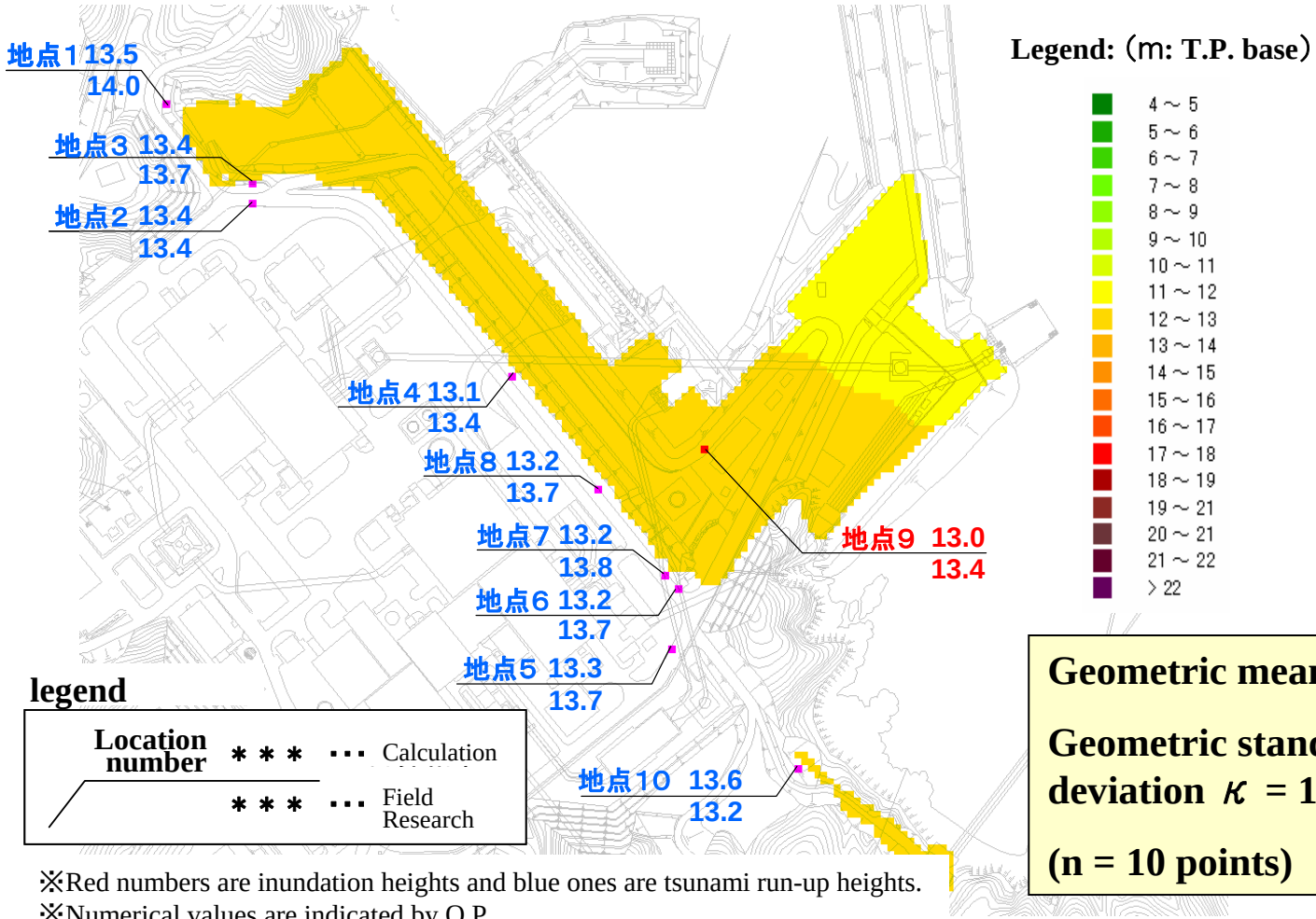




The simulation waveform well reproduced the observed whole waveform.

Elapsed time after the earthquake

(3) Inundation area and tsunami heights at Onagawa NPP



Geometric mean K = 1.03

Geometric standard deviation κ = 1.02

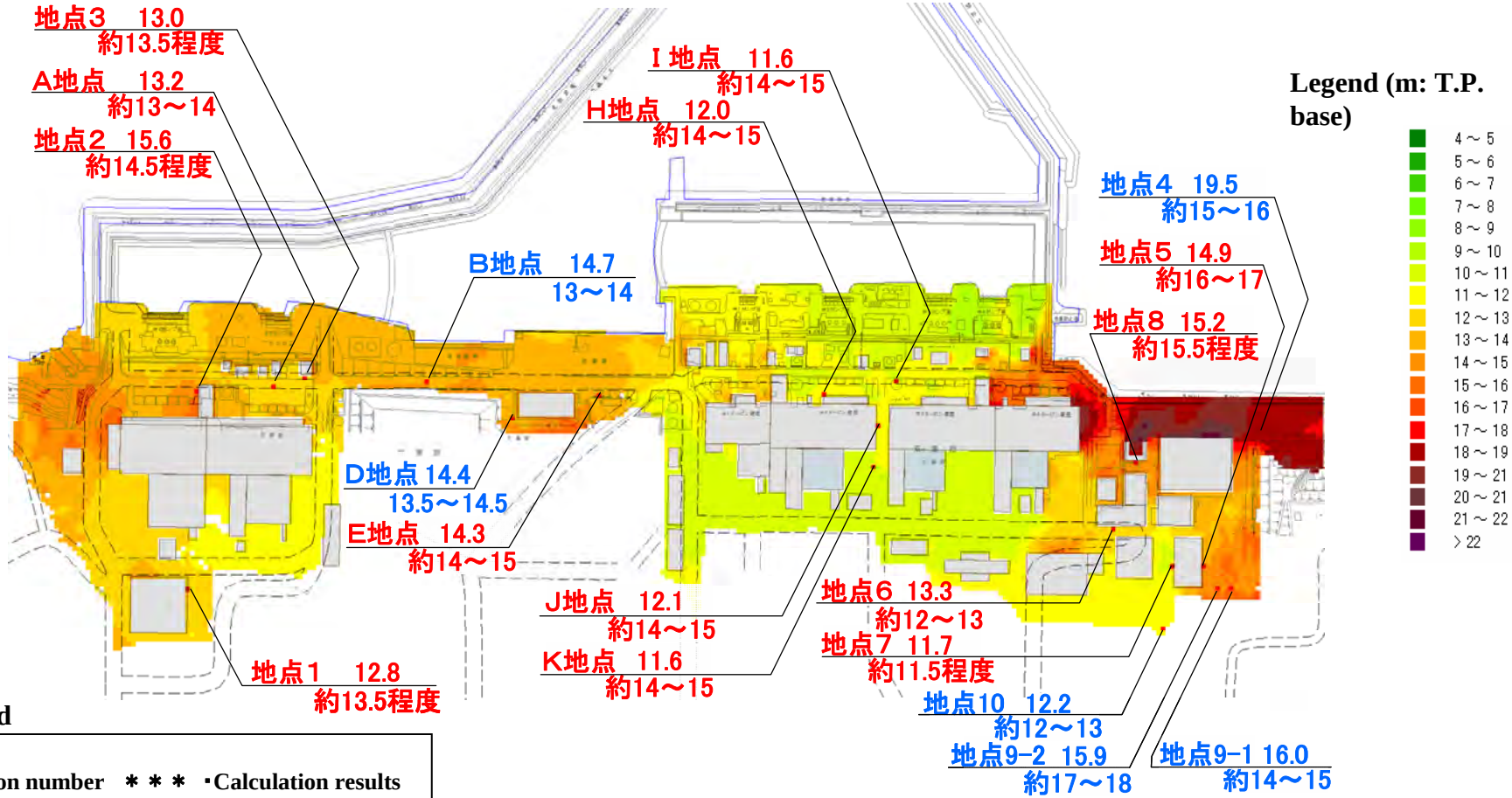
(n = 10 points)

※Red numbers are inundation heights and blue ones are tsunami run-up heights.
※Numerical values are indicated by O.P.

The height of tide (T.P. -0.32 m) during the tsunami attack was taken into account to derive the analysis result (T.P.±0m).

Simulation tsunami heights have reproduced the trace heights well.

(4) Inundation area and tsunami heights at Fukushima Daiichi NPP



Legend

Location number　＊＊＊ ・Calculation results

＊＊＊ ・Field research

The height of tide (T.P. -0.32 m) during the tsunami attack was taken into account when deriving the analysis result (T.P.±0m).

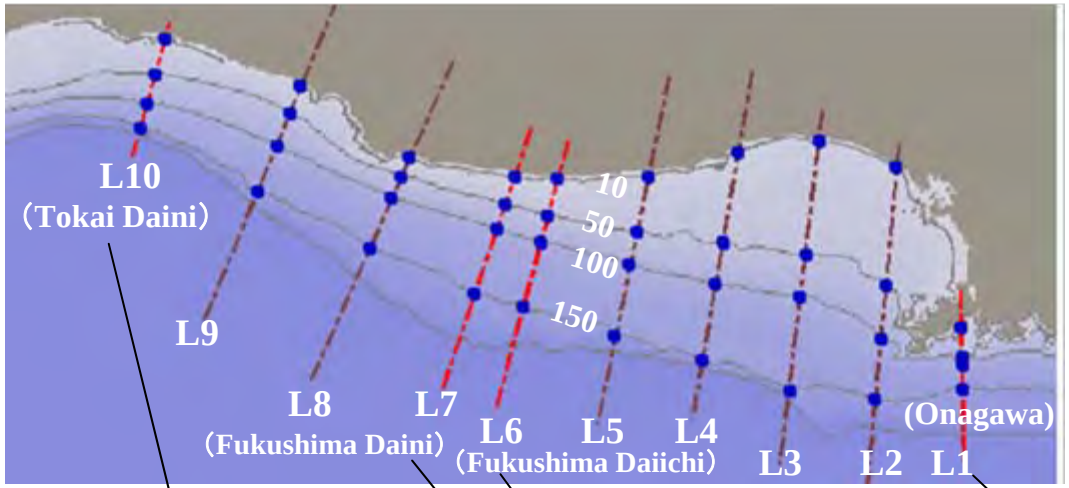
※Red numbers are inundation heights and blue ones are tsunami run-up heights.
※Numerical values are indicated by O.P.

Geometric mean K = 1.03 and geometric standard deviation κ = 1.13 (n = 19 points)

Simulation tsunami heights have reproduced the trace heights well.

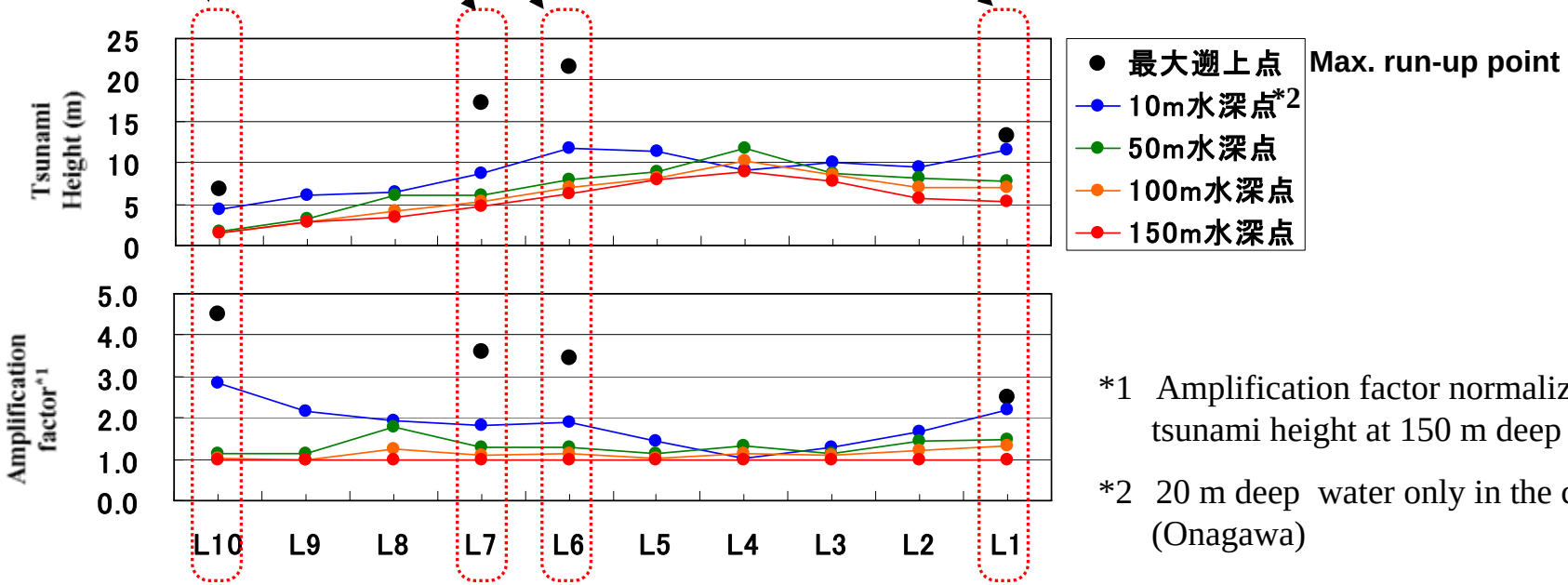
4.4 Comparative analysis of different tsunami heights at nuclear sites

(1) Tsunami height amplification characteristics in accordance with water depth



- **Tsunami heights at 150 m deep water peaked at the Sendai Plain offshore (L4) and then decreased in a north-south direction.**
- **The difference in tsunami height between the Fukushima Daiichi (L6) and the Fukushima Daini (L7) increased as the water depth decreased. However, amplification factors were almost the same.**

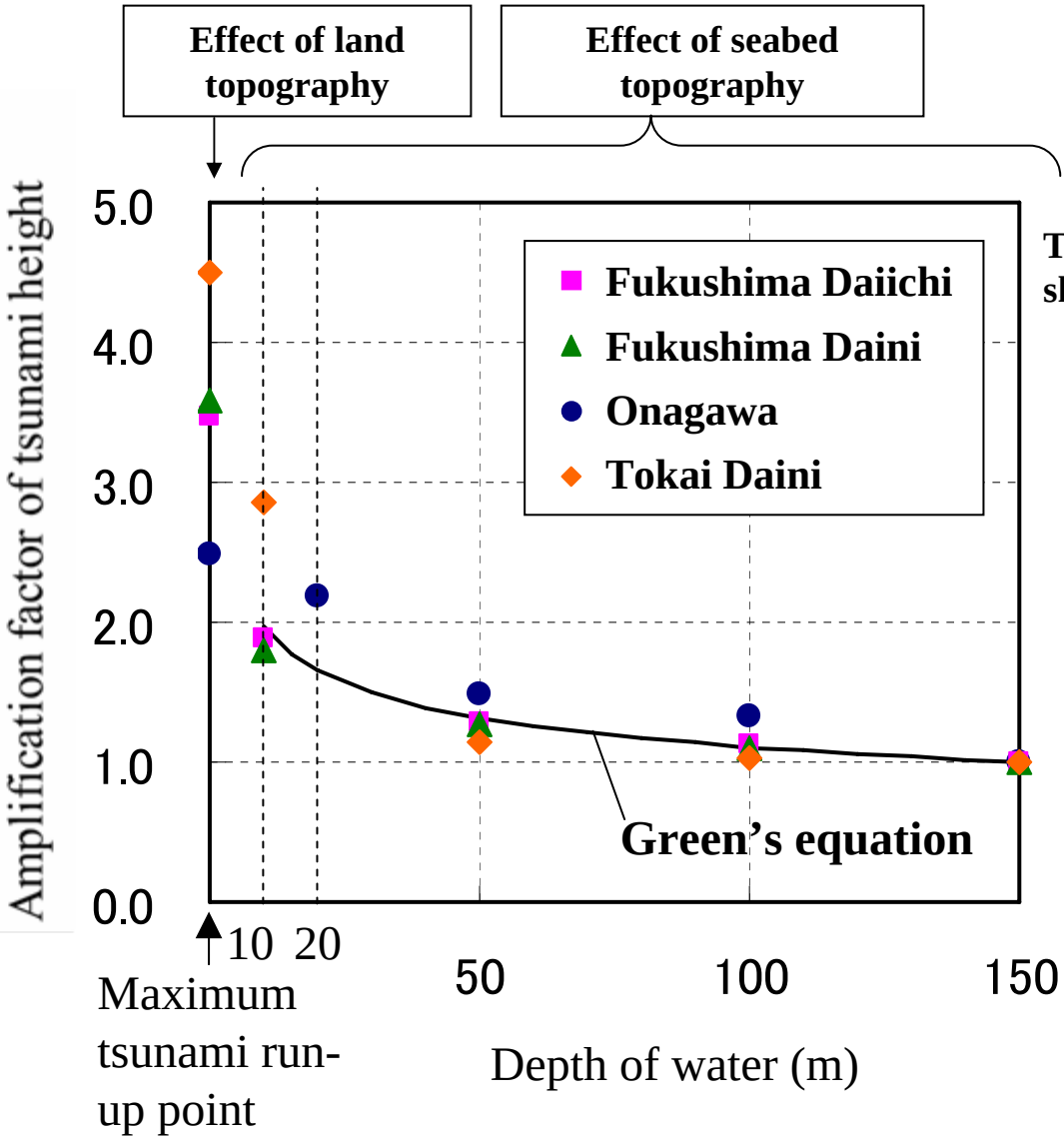
  ⇒ Effect of the local topography nearby both sites was small.
- **Was the tsunami-height amplification factor at the Onagawa (L1) smaller than those of other sites?**



*1 Amplification factor normalized by the tsunami height at 150 m deep water

*2 20 m deep water only in the case of L1 (Onagawa)

(2) Effect of submarine topography on wave-height amplification characteristics



Green's equation*1

$$Hh^{1/4} = const.$$ ***H***: wave height, ***h***: water depth

This equation is based on the premise that reflection at the shore is ignored and a wave ray spacing does not change.

⇒ This provides ideal (not unique) slope-like wave-height amplification.

- Tsunami-height amplification at the entire offshore area of the Fukushima Daiichi and Daini generally conforms to the Green's equation.

  ⇒Submarine topography of this area is not unique.

- Tsunami-height amplification at the Tokai Daini greatly deviates from the Green's equation at 10m water depth.

  ⇒The effect of reflected waves at the shore was the likely cause.

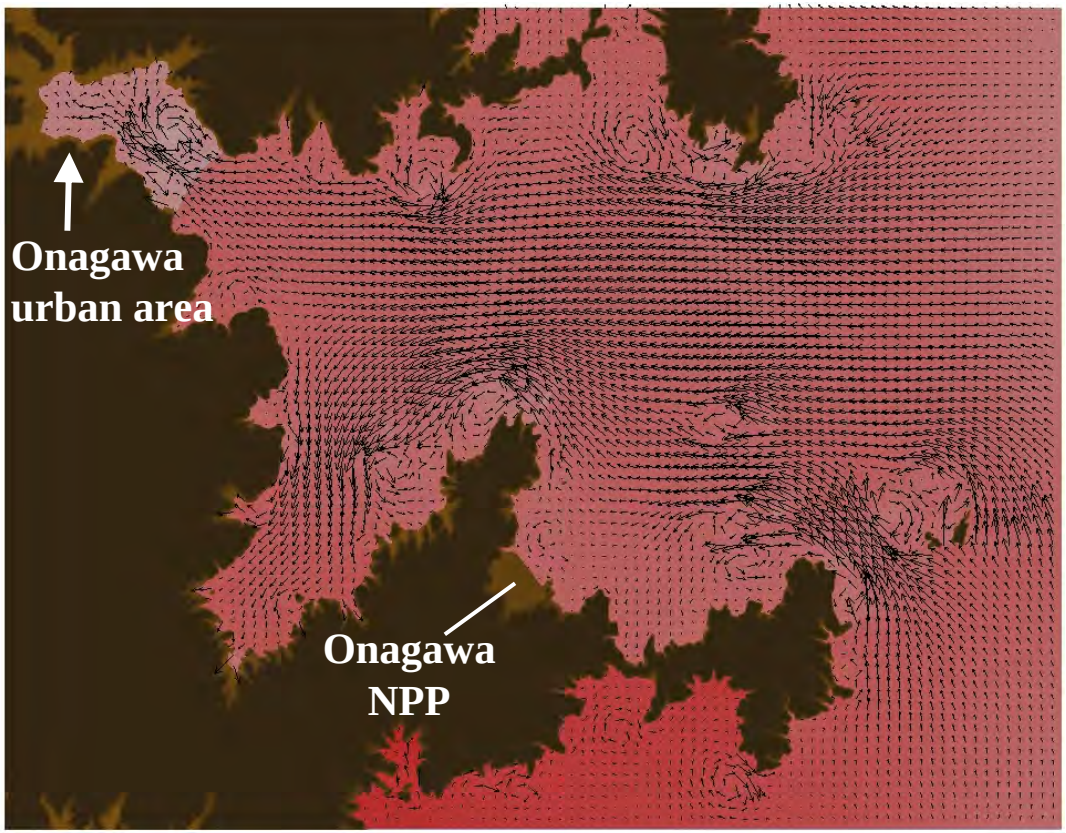
- Tsunami-height amplification at Onagawa deviates from the Green's equation and was small at onshore tsunami run-up area.

  ⇒This suggests site-specific topographic effect.

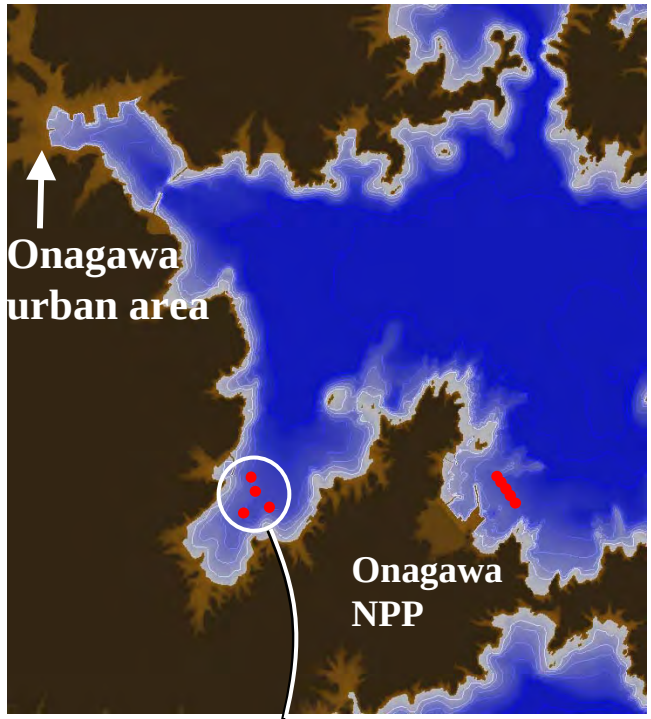
Reference*1 "Tsunami Encyclopedia" by Shuto et al. (Asakura Shoten)

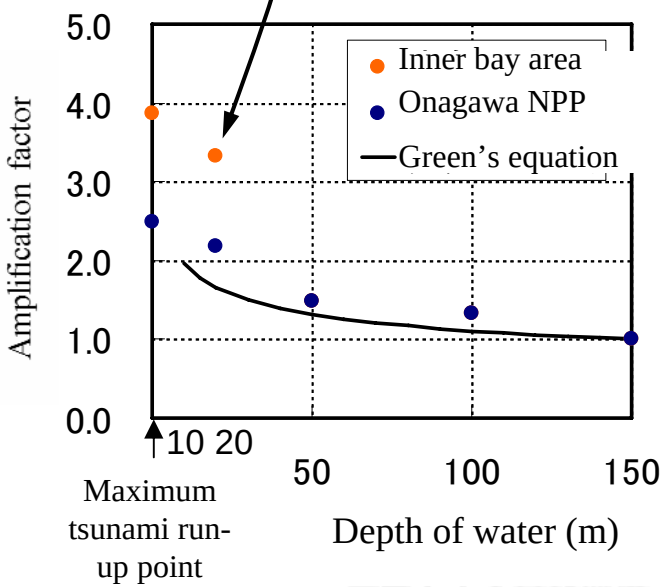
(3) Local topographic effect at the Onagawa NPP

■ **Flow condition of tsunami immediately before the maximum wave height occurred (flow velocity vector)**



37 min and 30 sec after the earthquake occurred



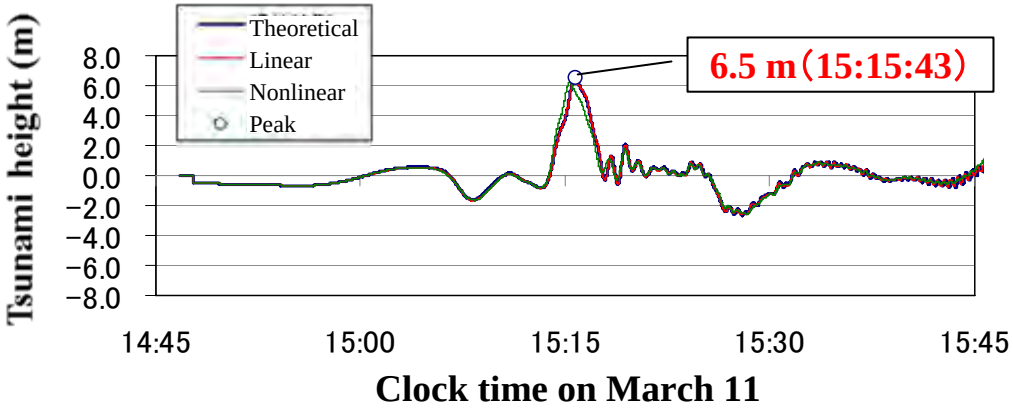


- **Tsunami momentum headed toward the inner part of Onagawa Bay.**
- **Onagawa NPP is located near the bay entrance, where the momentum of the tsunami deviated.**

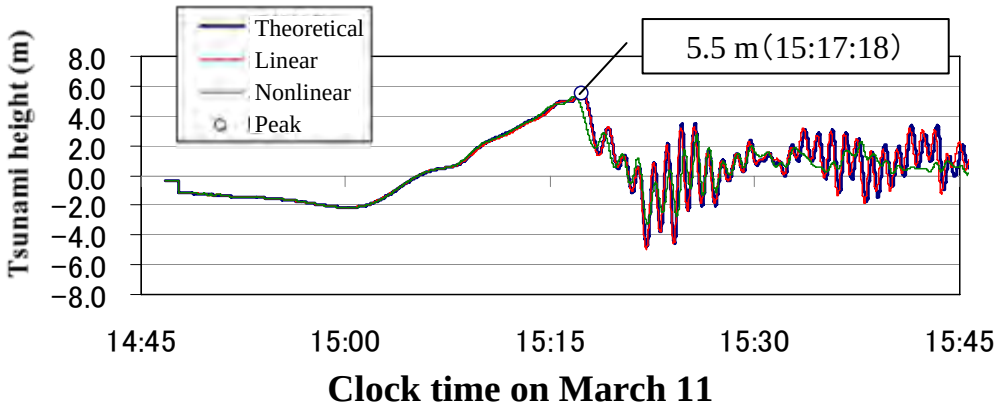
⇒The local topographic effect of the Onagawa NPP suppressed the tsunami-height amplification.

(4) Contribution of each sub fault to the tsunami height at 150 m deep (1/3)

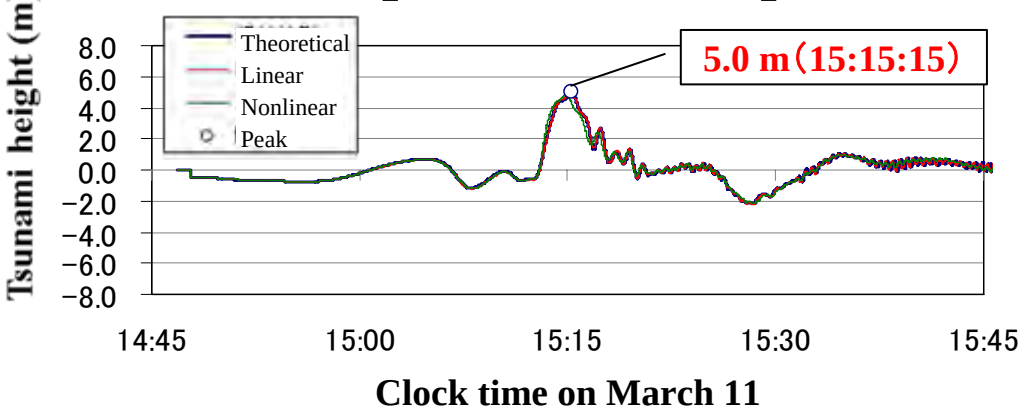
【Fukushima Daiichi】



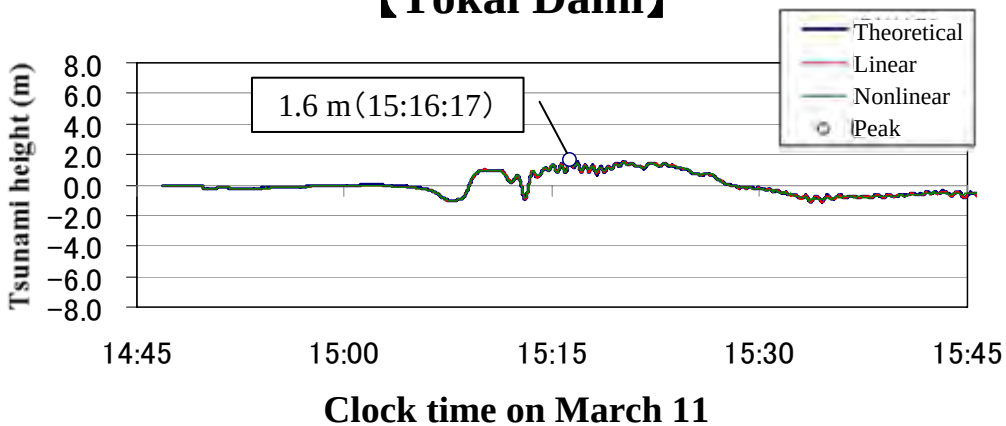
【Onagawa】



【Fukushima Daini】



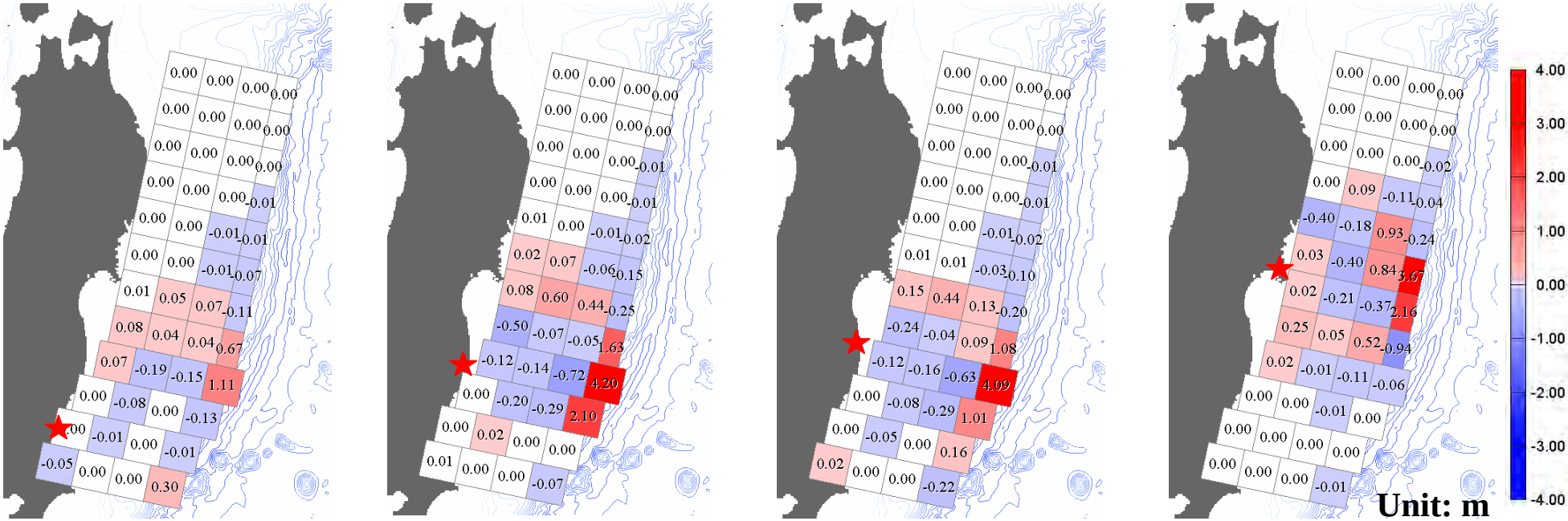
【Tokai Daini】



- **Which sub fault affected each nuclear site ?**
- **What caused the difference of 1.5 m between the Fukushima Daiichi and Fukushima Daini ?**

(4) Contribution of each sub fault to the tsunami height at 150 m deep (2/3)

【Tokai Daini】 【Fukushima Daiichi】 【Fukushima Daini】 【Onagawa】

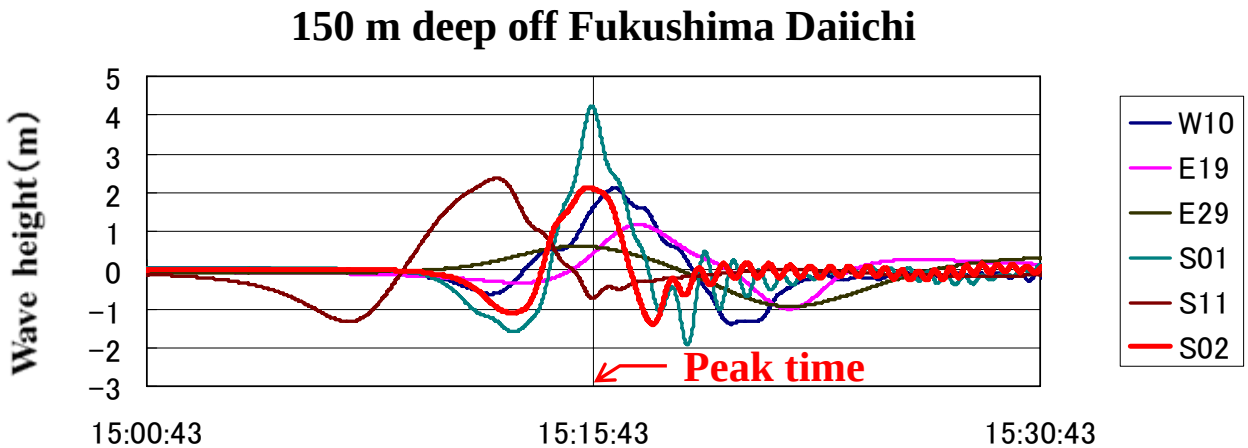


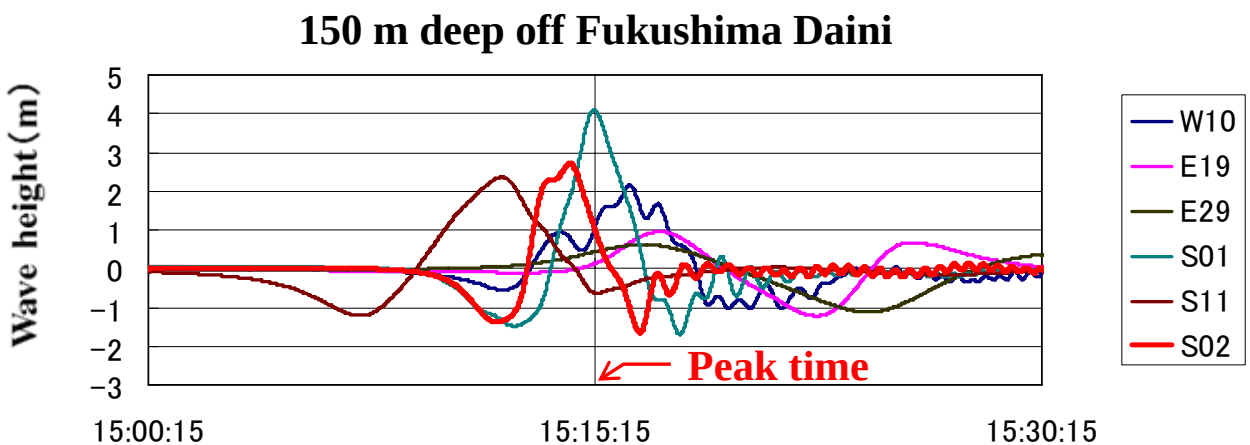
- At Fukushima Daiichi and Daini, sub faults at the shallow area near the Japan Trench off Fukushima Pref. significantly contributed to wave height elevation as a common phenomenon.
- At Onagawa, sub faults at the shallow area near the Japan Trench off northern Miyagi Pref. significantly contributed to wave height elevation.
- At Tokai Daini, sub faults at the shallow area near the Japan Trench off Fukushima Pref. significantly contributed to wave height elevation.

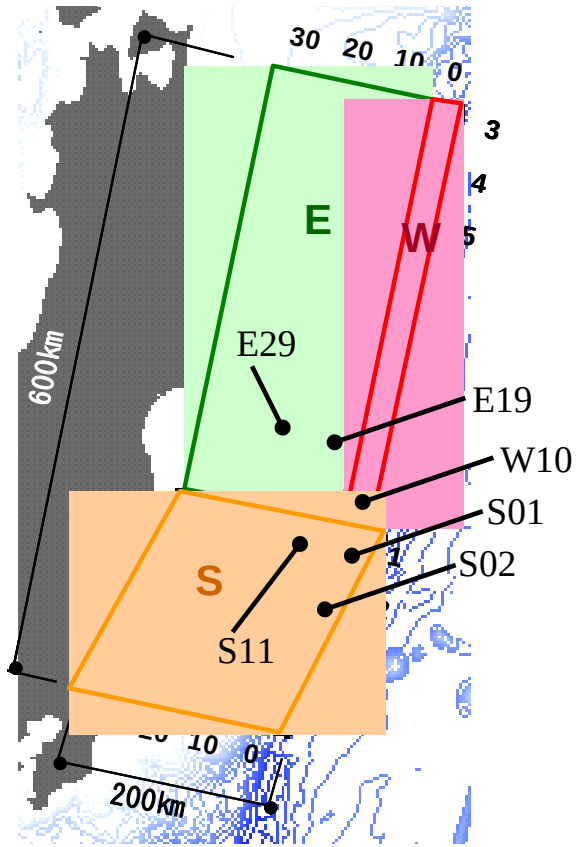
⇒The location of sub faults that significantly affected each site varies.

(4) Contribution of each sub fault to the tsunami height at 150 m deep (3/3)

■Waveforms of the six sub faults affecting the tsunami height at 150 m deep







- Maximum wave heights at 150 m deep water off Fukushima Daiichi and Fukushima Daini overlap with the peak at sub fault S01.
- The difference of 1.5 m in maximum wave height between the two sites was mainly caused by the timing of wave forms S01 and S02 overlapping each other.

5. Concept of Recipe for Assessing Design Tsunami

Basic Policy for Making Tsunami Recipe

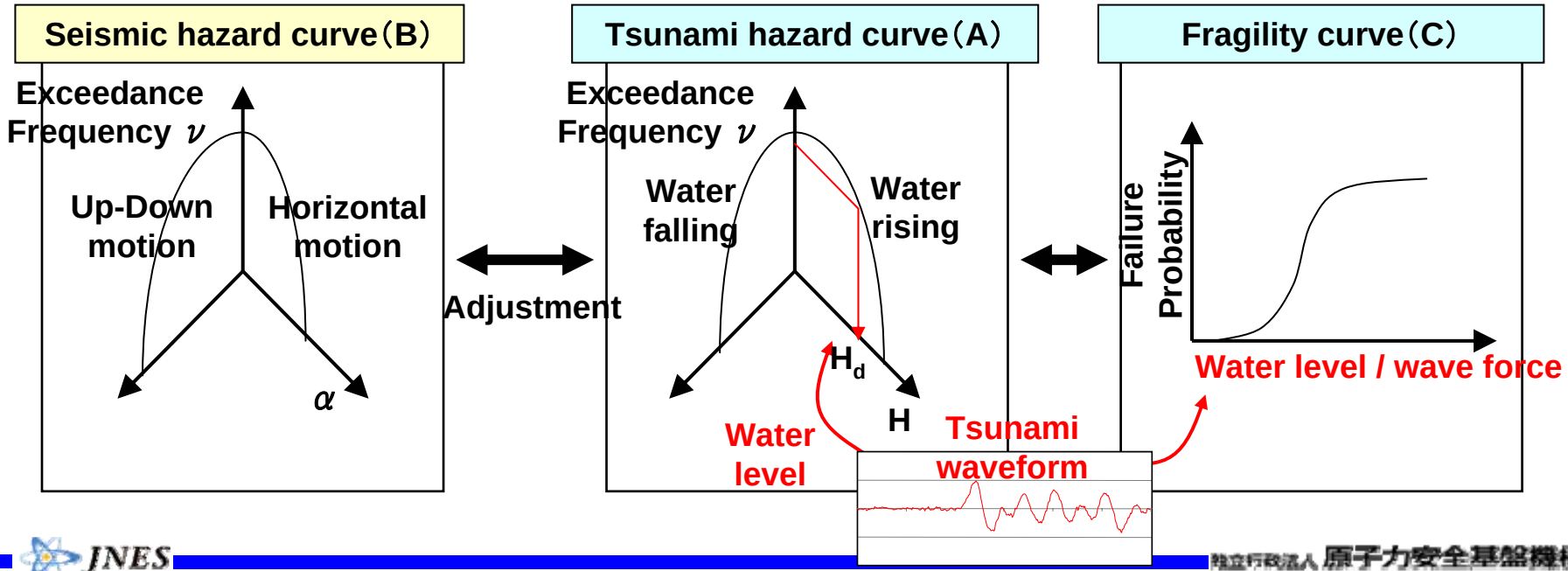
Investigation results on the Tohoku Earthquake by JNES and insights obtained by other organizations are reflected in the course of making the tsunami recipe.

a. **Design-basis tsunami wave form and height are determined based on the probabilistic tsunami hazard analysis (Figure A) taking uncertainties into consideration by the logic tree method.**

b. **Tsunami source model in tsunami hazard analysis is to be consistent with seismic source model in seismic hazard analysis (Figure B).**

c. **Tsunami wave form and height in tsunami hazard are representative measures of tsunami intensity. Measures of tsunami intensity are determined by fragility evaluations of components and structures (e.g. wave force, wave form).**

d. **Earthquakes accompanying tsunamis are classified into inter-plate earthquakes and intra-plate earthquakes. Tsunamis caused by inter-plate earthquakes are objects to be considered in this recipe.**



6. Summary

(1) JNES investigated the cause of the Tsunami and clarified the factors of the tsunami wave height at Fukushima Daiichi and Daini and their difference.

(2) JNES is making a recipe for assessing design tsunami in order to review design tsunami heights of NPPs in our country, based on the cause investigation results and findings obtained from the Tsunami. It is aimed to make early accomplishment.

(3) JNES is planned to support NISA in reviewing design tsunamis using the above recipe.

(4) JNES will make contributions to the world by opening actively information relevant to cause investigation results and the recipe to NRC, IAEA, etc.

(5) JNES will also work for further refinement of tsunami technology in cooperation with (with support from) international organizations such as NRC and IAEA. The production will be opened.