Technical Workshop on the Accident of TEPCO's Fukushima Dai-ichi NPS

Tsunami Survey Results in the NPS and Reproduction Analysis Using Tsunami Inversion

July 24, 2012

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TEPCO 東京電力

TOKYO ELECTRIC POWER COMPANY

Agenda

1. Overview of the Great East Japan Earthquake (GEJE) and Tsunami

2. Tsunami survey for inundation height and run-up height in the NPS site

3. Tsunami inversion analysis and reproduced tsunami in the NPS site

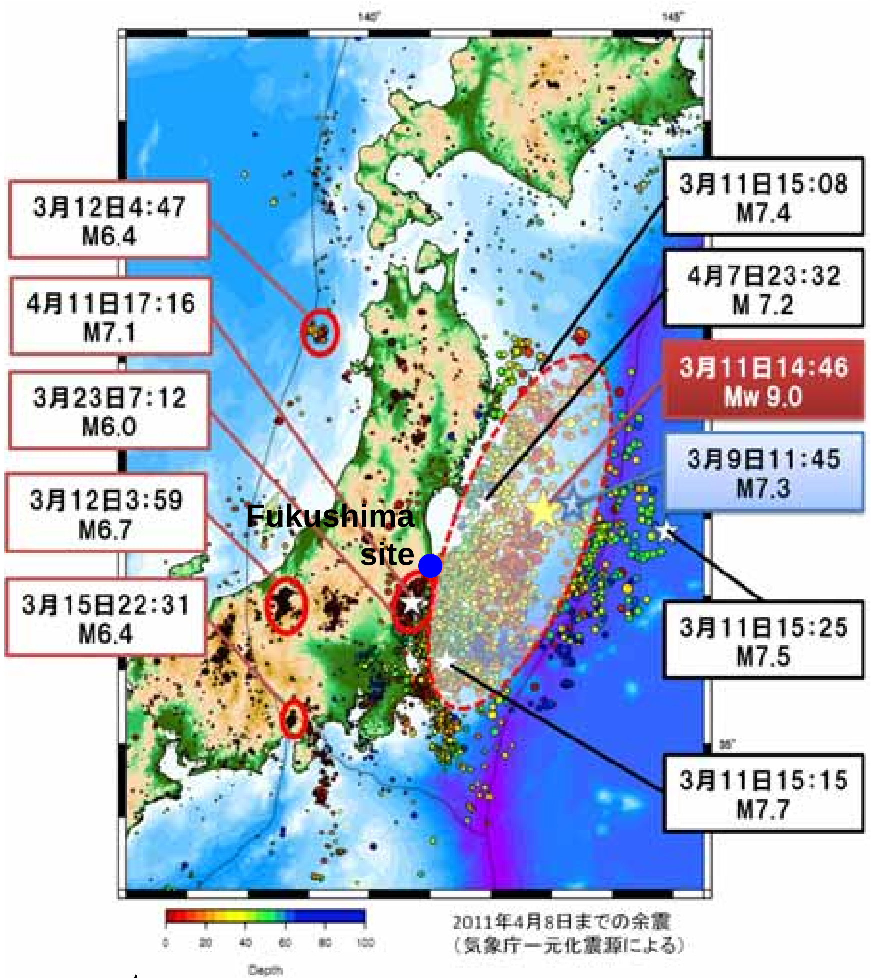
4. Comparison of the tsunamis that hit Fukushima Dai-ichi and Fukushima Dai-ni

5. Summary

1. Overview of the GEJE and Tsunami (1)

(1) General Information of the GEJE

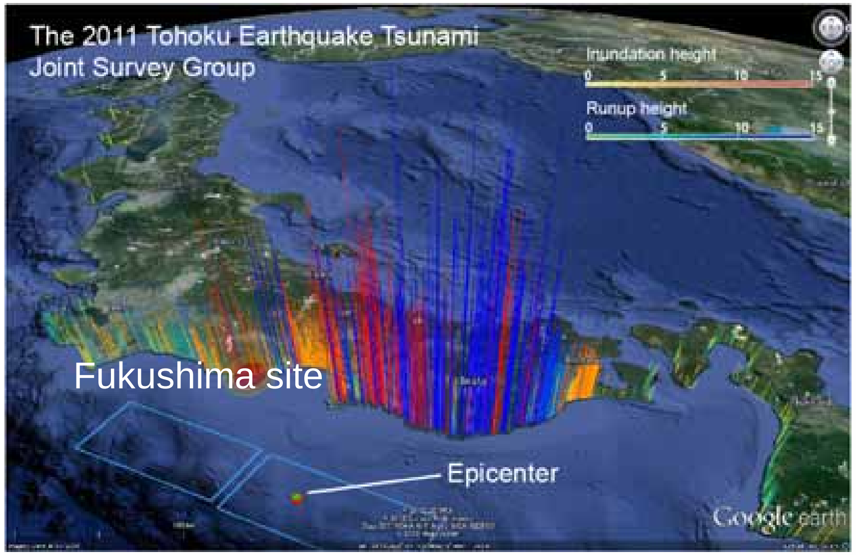
- Date & Time : March 11, 2011, 14:46
- Location : 38.297 ° N, 142.372 ° E
- Depth : Approx. 24km
- Rupture area : off the coast from Iwate to Ibaraki pref.
- Magnitude : 9.0 (in Moment Magnitude)
- Focal mechanism : Reverse fault, WNW-ESE



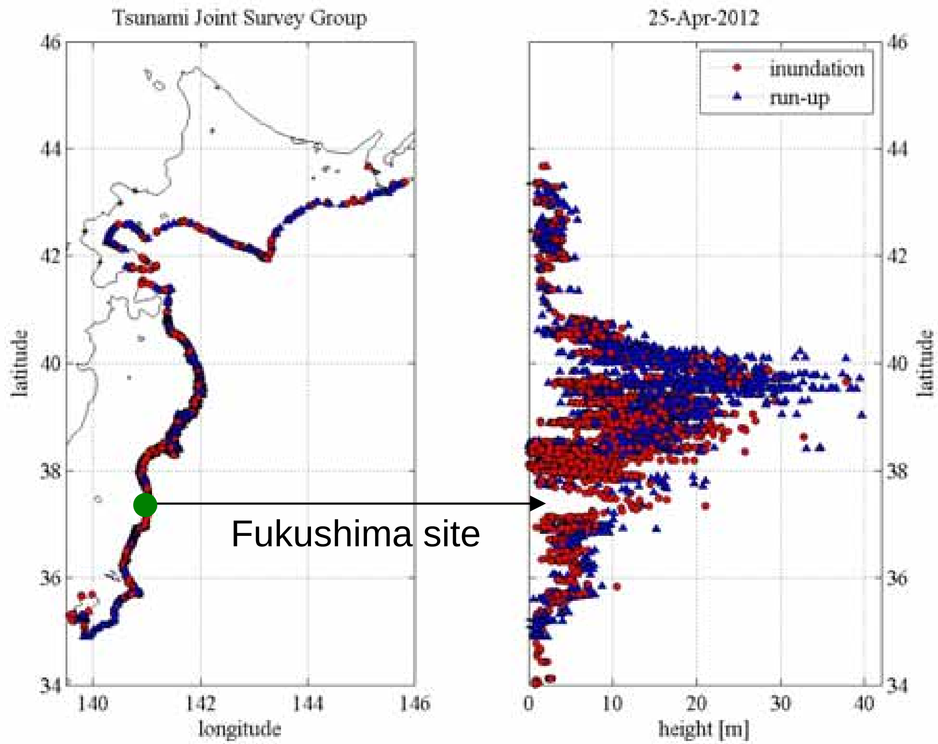
(Earthquake Research Institute, Tokyo University)

1. Overview of the GEJE and Tsunami (2)

(2) Flooding height and run-up height



Touch in the materials by the 2011TTJT (http://www.coastal.jp/ttjt/)



- The 2011 Tohoku Earthquake Tsunami Joint Survey Group reported flooding height and run-up height at 5,243 points.
- The affected area was several times larger than for the Meiji Sanriku Tsunami of 1896.
- Maximum run-up heights greater than 10 m are distributed along 530 km of coast and maximum run-up heights greater than 20 m are distributed along 200 km of coast.
- Maximum Inundation height in Fukushima was beyond 20m

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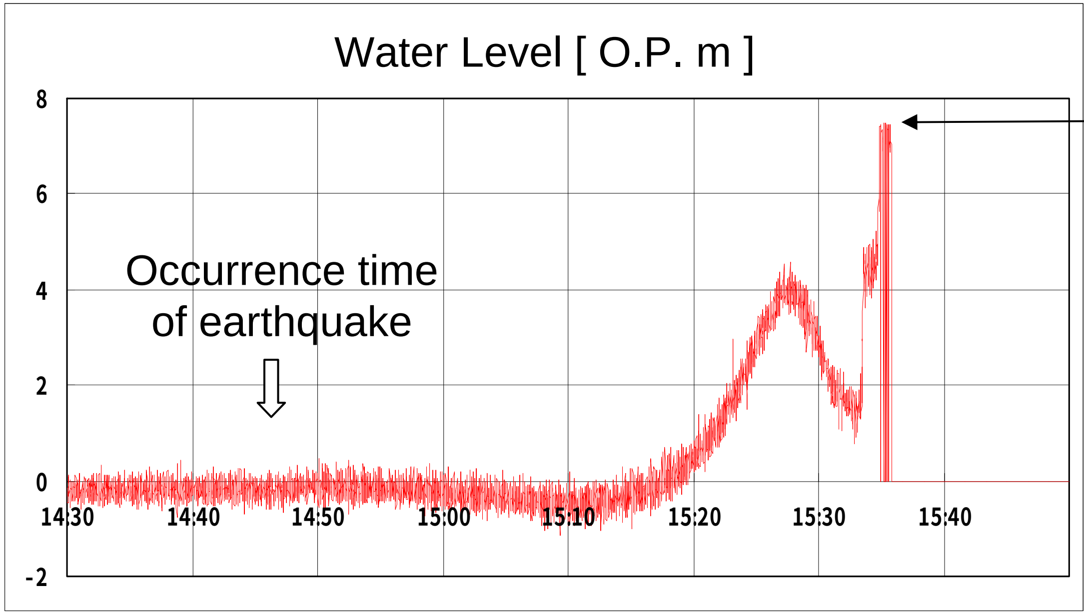
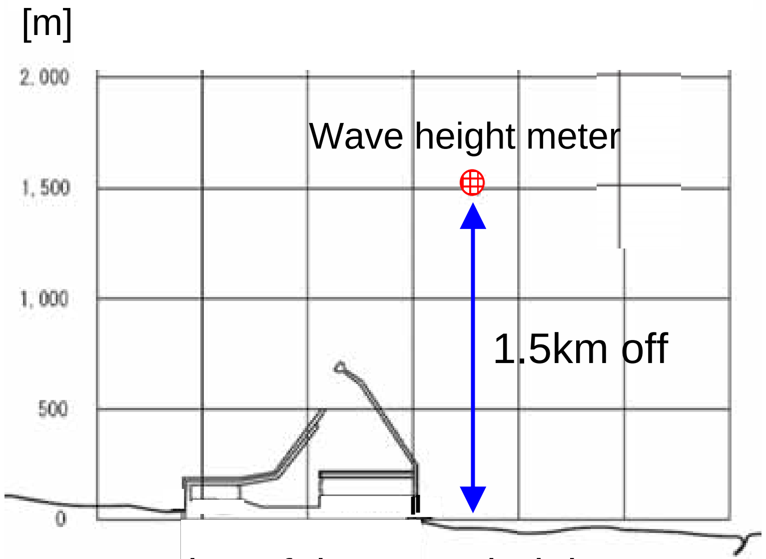
2. Tsunami survey for inundation height and run-up height in the NPS site
(1)-1 Fukushima Daiichi NPS : The wave height record



Upper limit of the measurement range : +7.5m

After that, no data was measured.

Wave height meter record off of Fukushima Daiichi NPS



Location of the wave height meter

[Specifications of the wave height gauge]

- Using ultrasonic wave
- Measurement Range : −7.5m - +7.5m
- Sampling Rate : every 0.5 second

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2. Tsunami survey for inundation height and run-up height in the NPS site
(1)-2 Fukushima Daiichi NPS : Pictures at the time when tsunami struck

① Tsunami inundation height approx. O.P.+15.5m

Height of the tank approx.5.5m (ground level O.P.+10m)

The tank is almost completely submerged

② Tsunami over O.P.+10m break water

Height of the tank approx.15m (ground level O.P.＋4m)

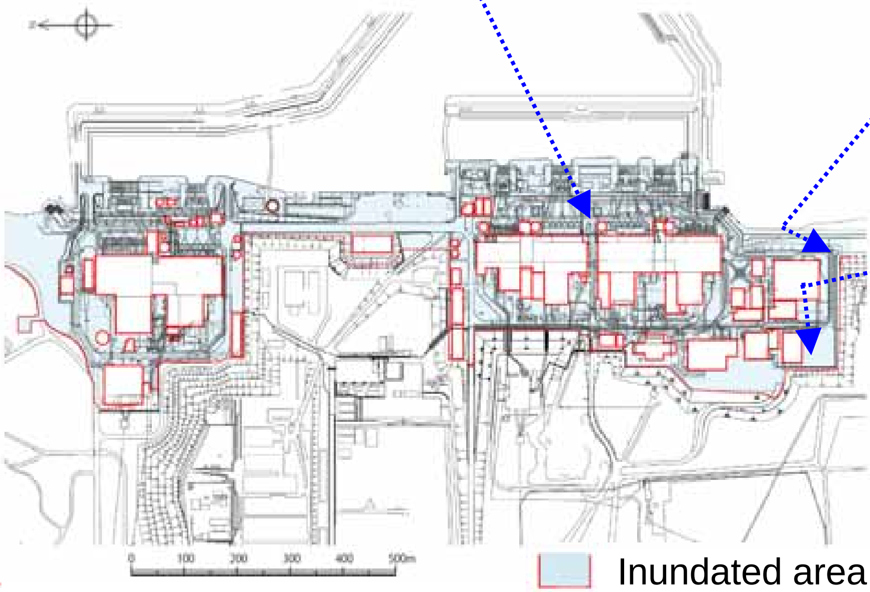
Two-thirds of the tank is submerged

Height of the break water O.P.+10m

2. Tsunami survey for inundation height and run-up height in the NPS site
(1)-3 Fukushima Daiichi NPS : Example of tsunami survey

Inundated Height approx. O.P.+14 - 15m

Run-up Height approx. O.P.+15-16m

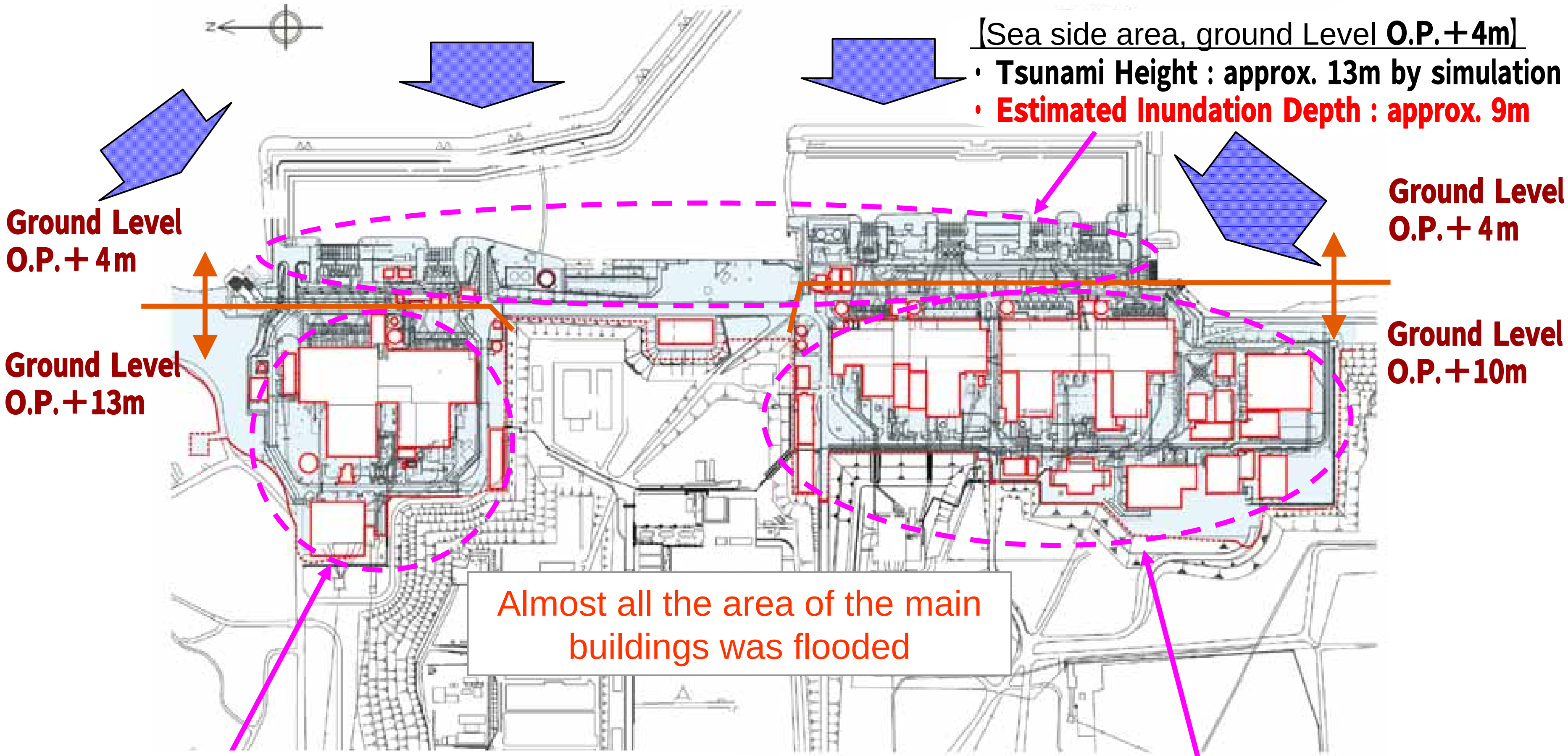


Run-up Height approx. O.P.+14-18m

2. Tsunami survey for inundation height and run-up height in the NPS site
(1)-4 Fukushima Daiichi NPS : Tsunami survey result

Inundated area

Run-up was confirmed from the sea-side area over the slope to the main building area.



【Unit 5 & 6, Ground Level O.P.＋13m】
- Inundation Height : approx. O.P.＋13 - 14.5m
- **Inundation Depth : approx. 1.5m or less**

【Unit 1 – 4, Ground Level O.P.＋10m】
- **Inundation height approx. O.P.＋11.5 - 15.5m**
- **Inundation Depth approx. 1.5 - 5.5m**

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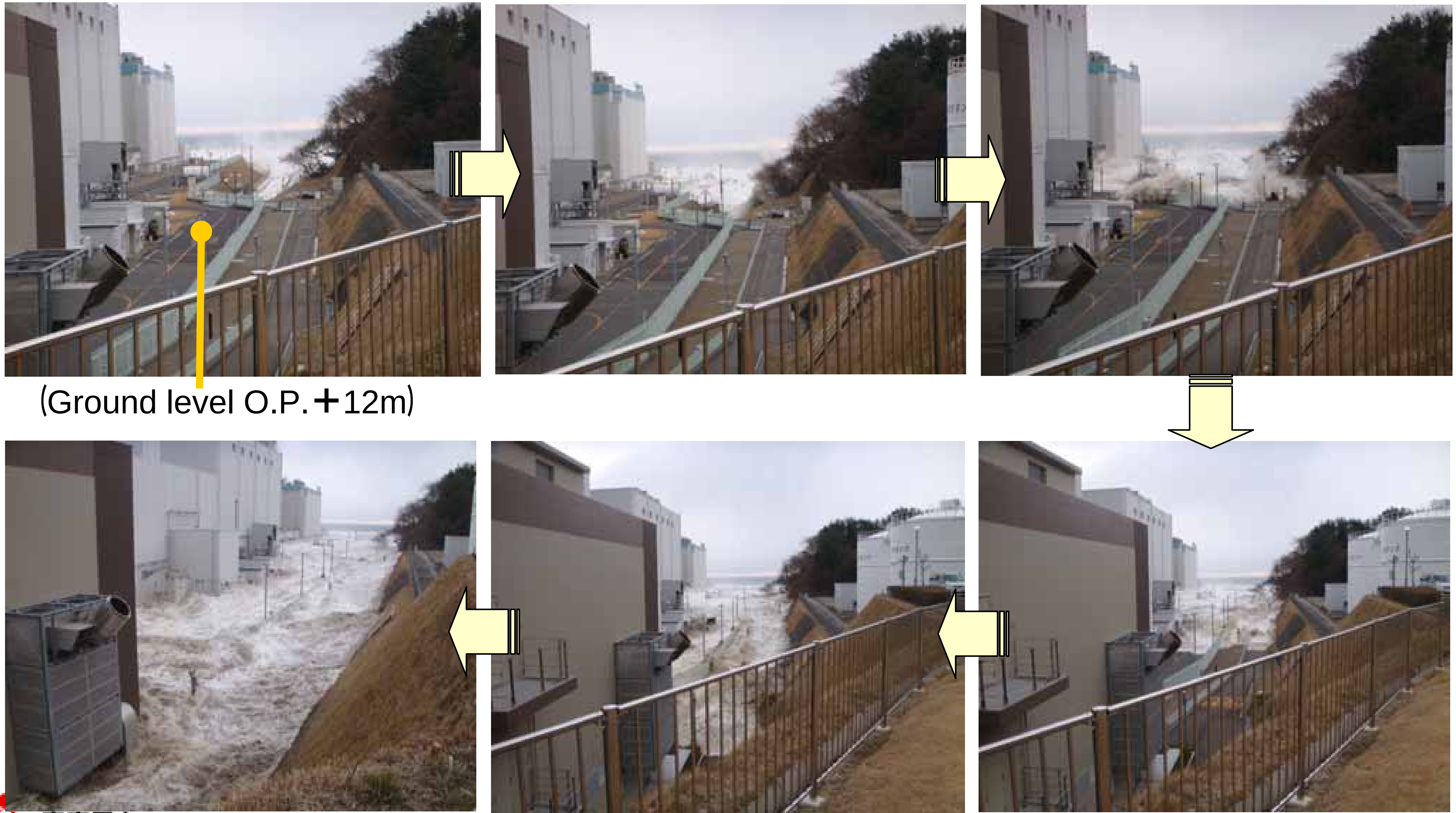
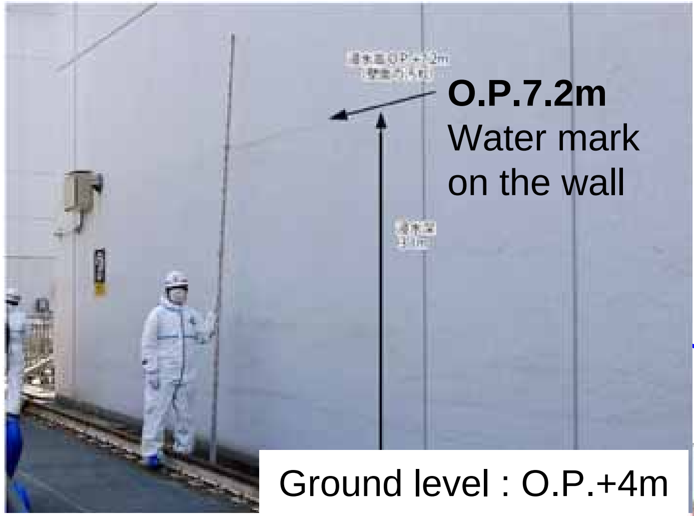
2. Tsunami survey for inundation height and run-up height in the NPS site
(2)-1 Fukushima Daini NPS : Pictures at the time when tsunami struck

○ Concentric tsunami run-up at the south side of Unit-1

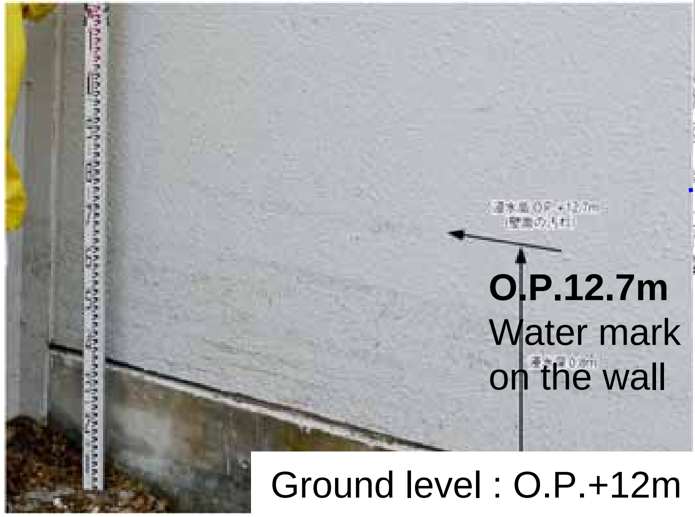


2. Tsunami survey for inundation height and run-up height in the NPS site
(2)-2 Fukushima Daini NPS : Example of tsunami survey

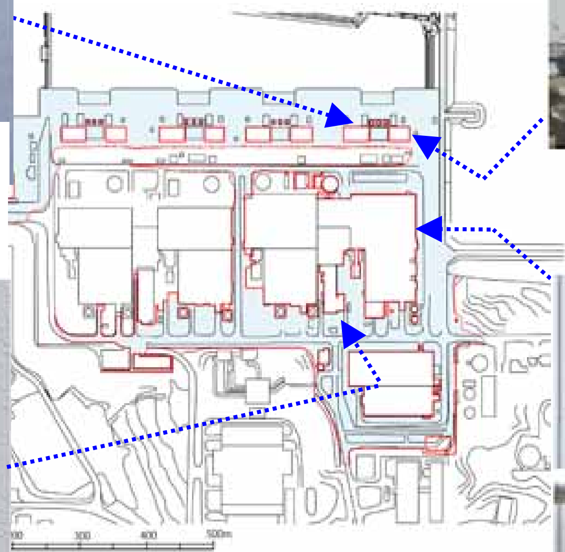


Inundation Height O.P.7.2m

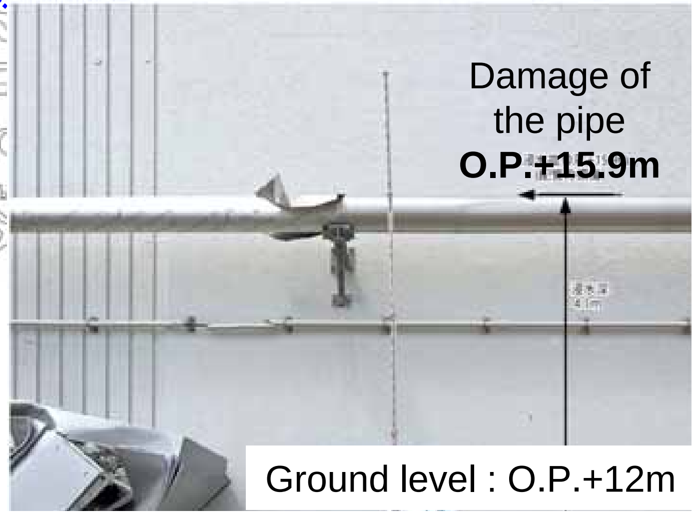
Inundation Height : O.P.+12.6m



Inundated Height O.P.+12.7m



Inundated area



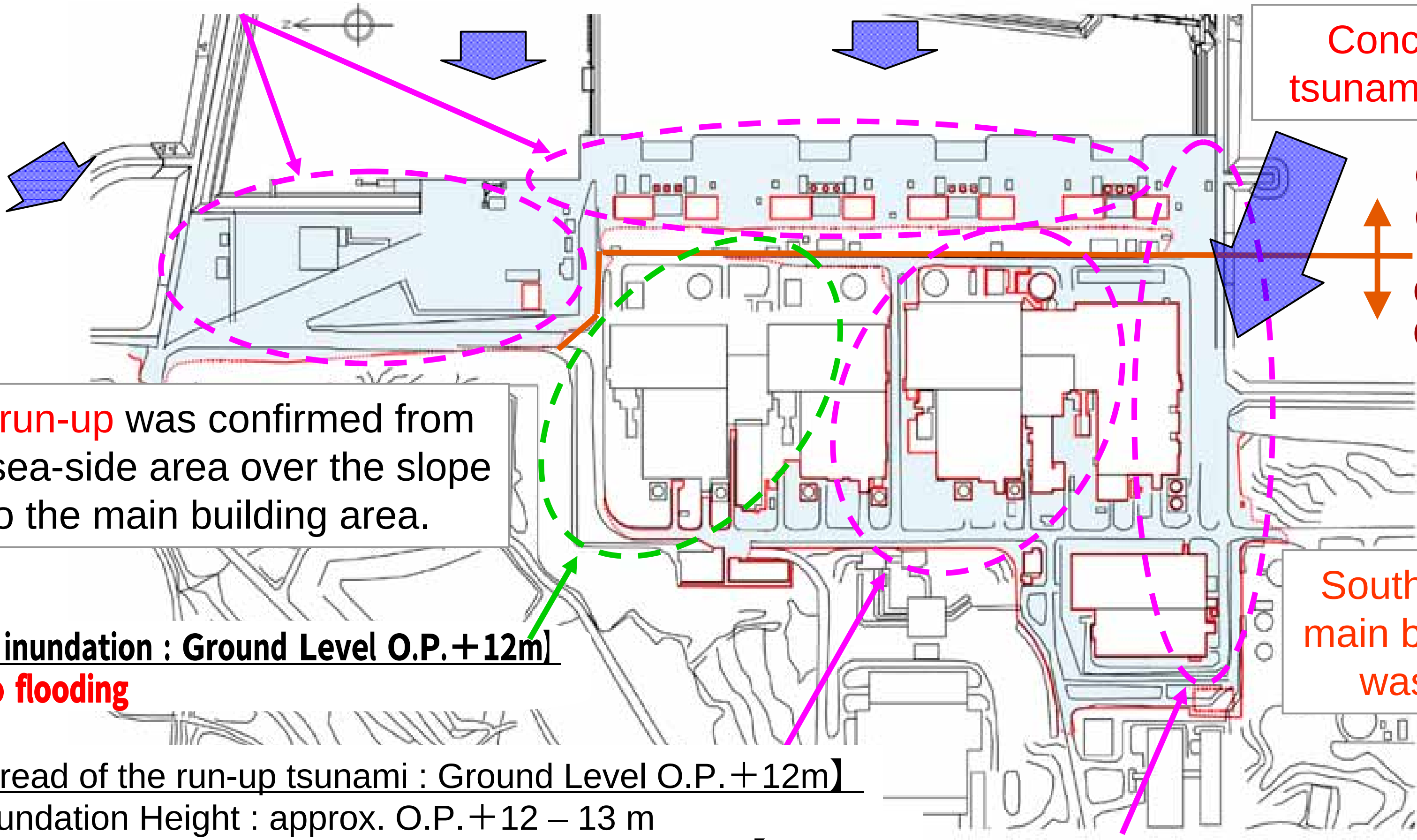
Inundation Height : O.P.+15.9m

2. Tsunami survey for inundation height and run-up height in the NPS site
(2)-3 Fukushima Daini NPS : Tsunami survey result

【Sea side area : Ground Level O.P.＋4m】
- Tsunami Height : approx. 7 – 8 m
- Inundation Depth : approx. 3 - 4 m

All the area of the sea side (Ground Level O.P.+ 4m) was flooded

Inundated area



【No inundation : Ground Level O.P.＋12m】
- No flooding

【Spread of the run-up tsunami : Ground Level O.P.＋12m】
- Inundation Height : approx. O.P.＋12 – 13 m
- Inundation Depth : approx. 1 m or less

【Concentric tsunami run-up : Ground Level O.P.＋12m】
- Inundation Height : approx. O.P.＋12 - 14.5 m
- Inundation Depth : approx. 2.5m or less

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2. Tsunami survey for inundation height and run-up height in the NPS site
(3) Comparison between Fukushima Daiichi and Daini

Fukushima Daiichi NPS		Fukushima Daini NPS
Approx. 13m	Tsunami Height ※	Approx. 9m
Widespread tsunami run-up westward from the pacific to the main building area	Run-up Route	Concentric tsunami run-up from the south-east part of the site
Almost all the area of the sea side area (O.P.+4m) and the main building area (O.P.+10m or 13m)	Inundation Area	All the sea side area (O.P.+4m) and South half of the main building area (O.P.+12m)
Approx. 5.5m around Unit 1-4 Approx. 1.5m around Unit 5&6	Inundation Depth	Approx. 2.5m around south of Unit.1 No inundation around Unit.4

※ Tsunami reproductive simulation by tsunami source model discussed below

The scale of the tsunami which struck NPSs

Fukushima Daiichi NPS > Fukushima Daini NPS

Carry out an analysis regarding the difference of the tsunami scale (Chapter 4)

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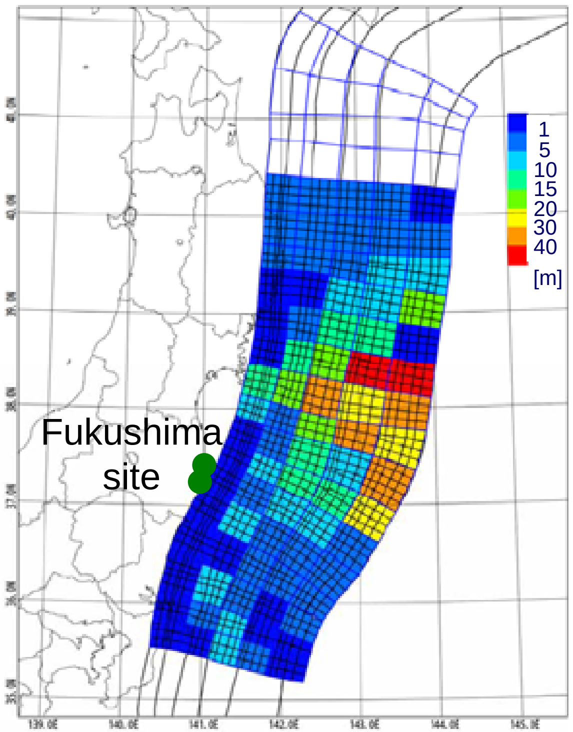
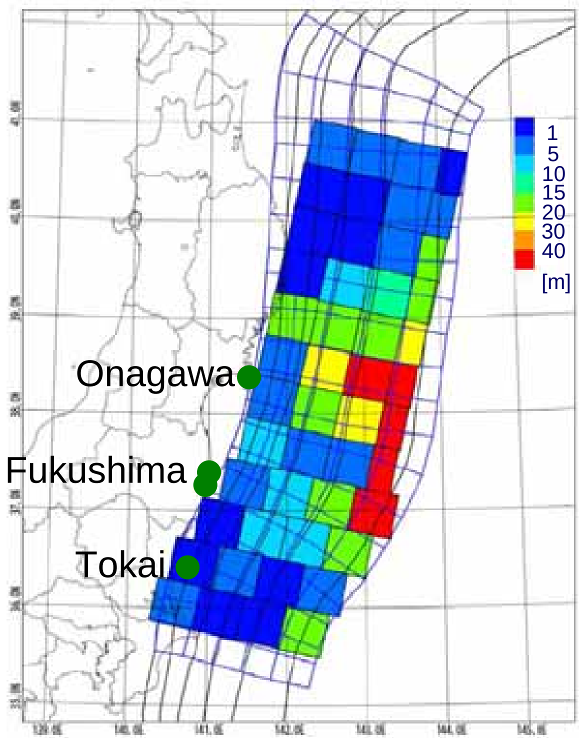
3. Tsunami inversion analysis and reproduced tsunami in the NPS site
(1) Assumption for the source of the GEJE : Tsunami inversion

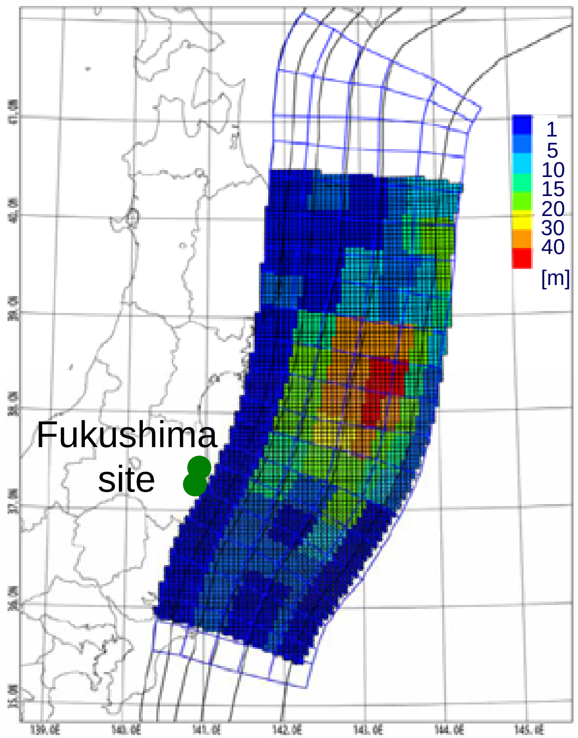
- In July 2011, TEPCO proposed the source model using tsunami inversion. (discussed below)
- After that, another source models using tsunami inversion were proposed.
- Each model has its own feature.
- Common Point in the results : Displacement off of Miyagi and Fukushima is large.



TEPCO (2011.7) : Lay weight on the balance of tsunami trace and tide record in broad area



JNES (2011.10) : Lay weight on the reproduction at 4 NPS



Cabinet Office (2012.3) : Lay weight on the tide record

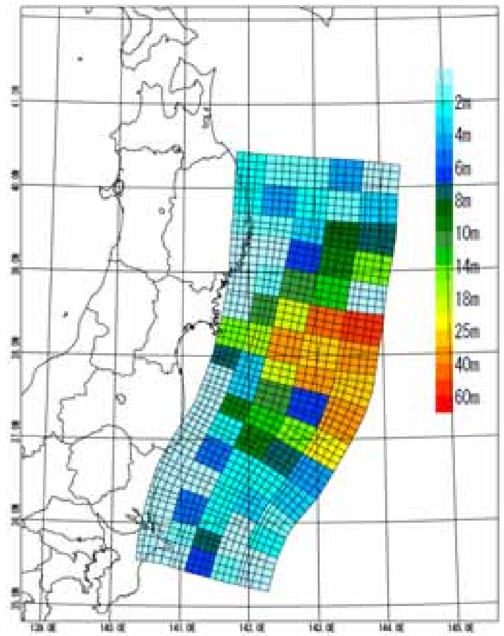
3. Tsunami inversion analysis and reproduced tsunami in the NPS site

(2) Objective of the tsunami inversion by TEPCO

- Tsunami source model : Some models have been proposed based on the tide record at that time.

- Plural target parameters
  → a) tide record, b) flooding height and run-up height, c) crustal movement and d) inundated area (Hokkaido – Chiba Pref.)

- Tsunami inversion analysis
  → Building a well-balanced tsunami source model.



(3) Outline of the inversion method

Annaka et al. (1999)

The tsunami inversion method using
a) Tide record
b) Flooding height and run-up height

EXTEND

Proposed method

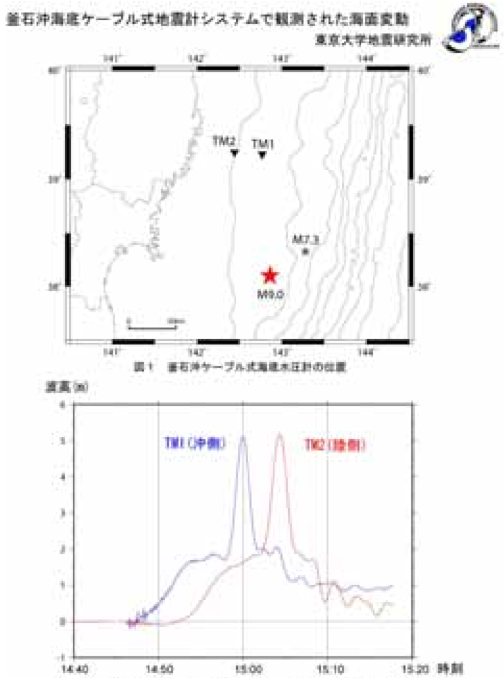
The tsunami inversion method using
a) Tide record
b) Flooding height and run-up height
c) Crustal movement
d) Inundated area

3. Tsunami inversion analysis and reproduced tsunami in the NPS site
(4)-1 Input data for the tsunami inversion

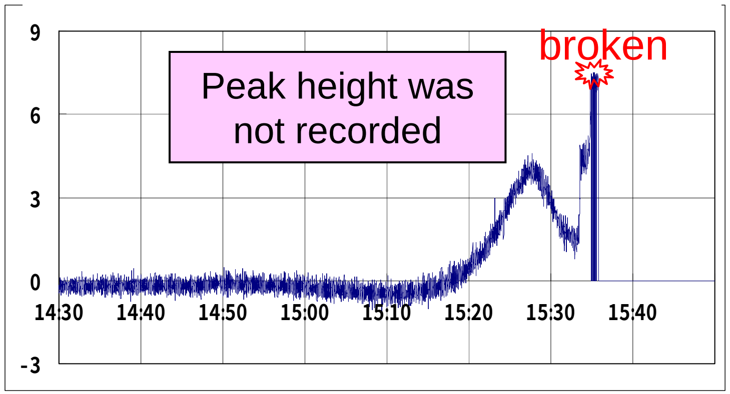
(a) Tide record

- Japan Meteorological Agency
- Ports and Harbors Bureau, Ministry of Land, Infrastructure, Transport and Tourism
- National Oceanic and Atmospheric Administration
- Earthquake Research Institute, University of Tokyo
- Electric Power suppliers

- 45 site from Hokkaido to Chiba Pref.
- The digital data with time intervals of 10 seconds was created for each point.



Earthquake Research Institute, University of Tokyo



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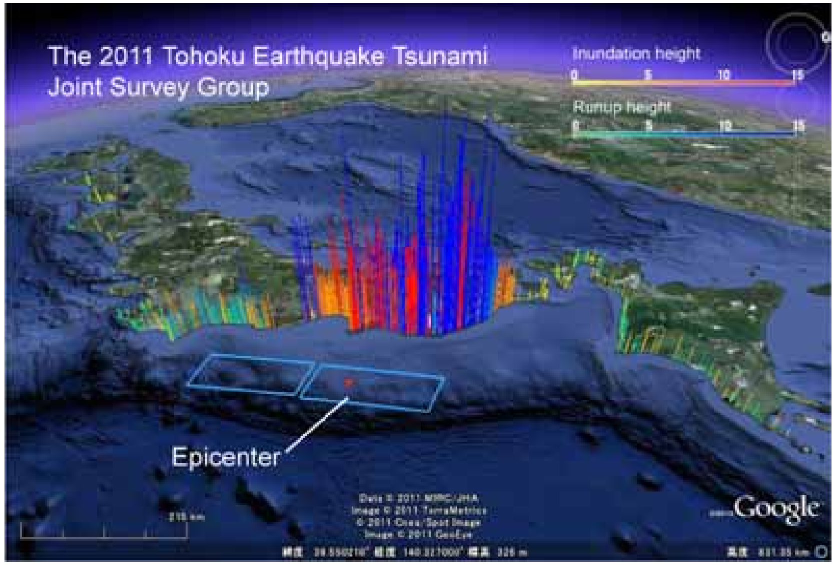
3. Tsunami inversion analysis and reproduced tsunami in the NPS site
(4)-2 Input data for the tsunami inversion

(b) Flooding height and run-up height

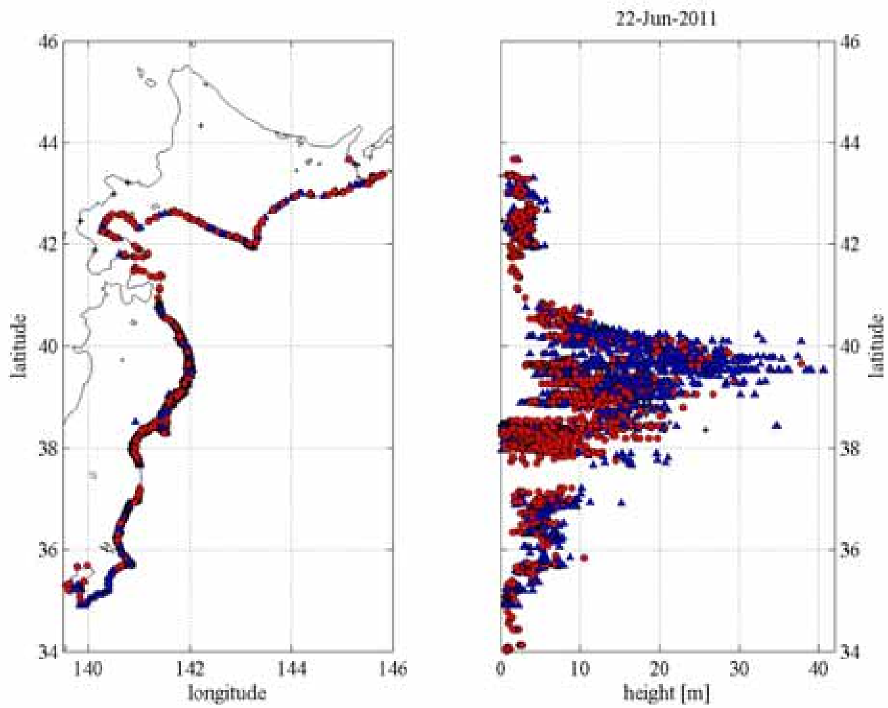
- The prerelease version by the 2011 Tohoku Earthquake Tsunami Joint Survey Group

  - Among all 3,256 data, some data were excluded and we used a total of 2,820 points –

- Survey result by TEPCO in Fukushima site : Daiichi 19 points, Daini 71 points.



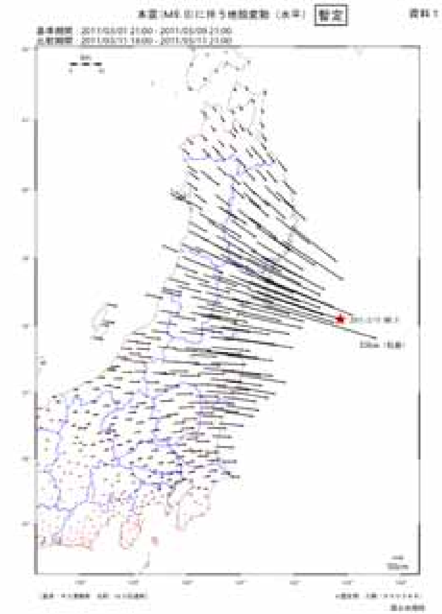
（http://www.coastal.jp/ttjt/ , version June 22, 2011）



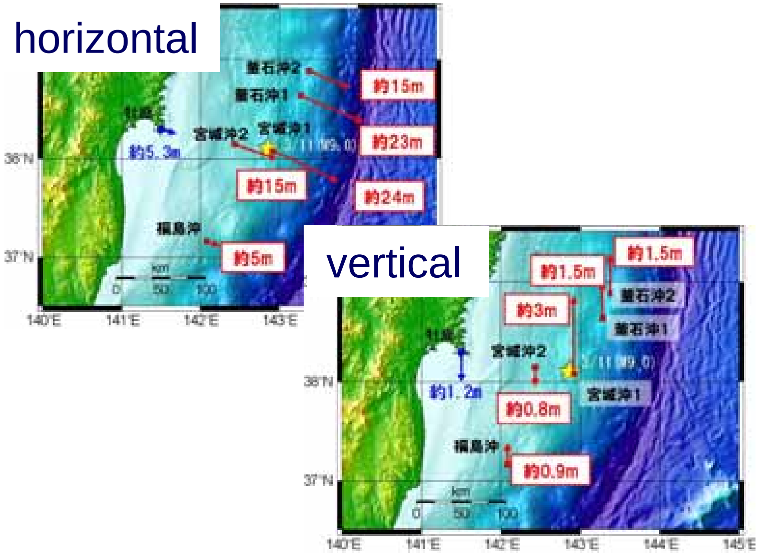
3. Tsunami inversion analysis and reproduced tsunami in the NPS site
(4)-3 Input data for the tsunami inversion

(c) Crustal movement : Approx. 1200 points

- Land areas : Geospatial Information Authority of Japan
- Marine areas : Japan Coast Guard



(http://www.gsi.go.jp/chibankansi/chikakukansi40005.html)



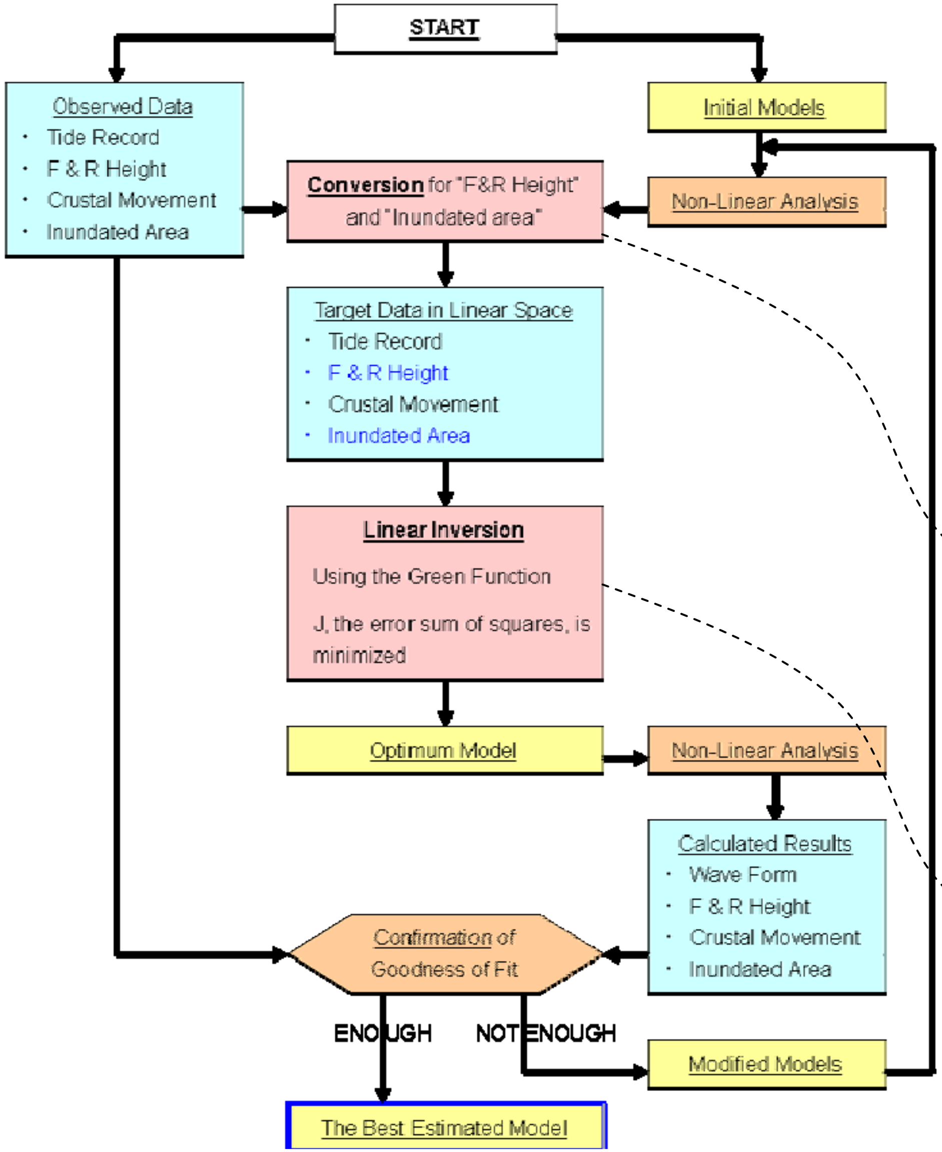
(http://www1.kaiho.mlit.go.jp/GIJUTSUKOKUSAI/jishin/11tohoku/index.html#movement)

The Geospatial Information Authority of Japan

(d) Inundated area : 73 regions

- From Aomori to Chiba Pref. : The Geospatial Information Authority of Japan
- Survey result by TEPCO in Fukushima Pref.

3. Tsunami inversion analysis and reproduced tsunami in the NPS site
(5) Process of the inversion : Flowchart



LINEAR INVERSION

◆ The nonlinear inversion is desirable.
◆ The vast computational time is required.

⇩

We carried out the linear inversion using the Green function

CONVERSION

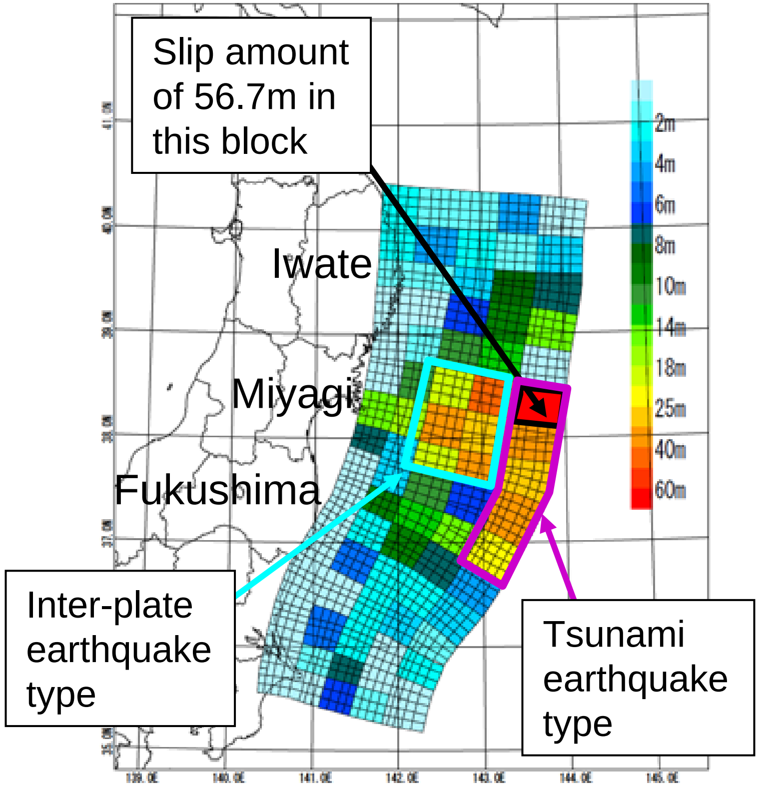
◆We need the conversion between the nonlinear and the linear tsunami analysis.
◆Flooding height and run-up height
 → Tsunami height in linear space
◆Inundated area
 → Tsunami height in linear space

The error sum of squares

◆Calculate the error sum of squares for each data in the linear inversion,
◆Weighted for calculated error
◆Minimize the sum of weighed error

3. Tsunami inversion analysis and reproduced tsunami in the NPS site
(6) Displacement distribution of the best estimated tsunami source model

- The proposed source model with a magnitude (Mw) of 9.1.
- The model consists of 1,255 small fault elements and arranged them into 80 blocks.
- Each block has a different fault slip amount.
- Non-linear analysis with min. 5m grid was carried out for the proposed model



3. Tsunami inversion analysis and reproduced tsunami in the NPS site
(7)-1 Reproducibility of Numerical Simulation : Tsunami height

Comparison of the flooding height and run-up height

- Reproducibility : K=1.04 and κ=1.40 in comparison with the 2,820 data points.
- These values satisfy the criteria established by the Japan Society of Civil Engineers, that is 0.95<K<1.05 and κ<1.45.

Reproduction index by Aida (1978)

$$K_i = R_i / H_i$$

$$\log K = \frac{1}{n}\sum_{i=1}^{n} \log K_i \quad , \quad \log \kappa = \left[\frac{1}{n}\left\{\sum_{i=1}^{n}(\log K_i)^2 - n(\log K)^2\right\}\right]^{1/2}$$

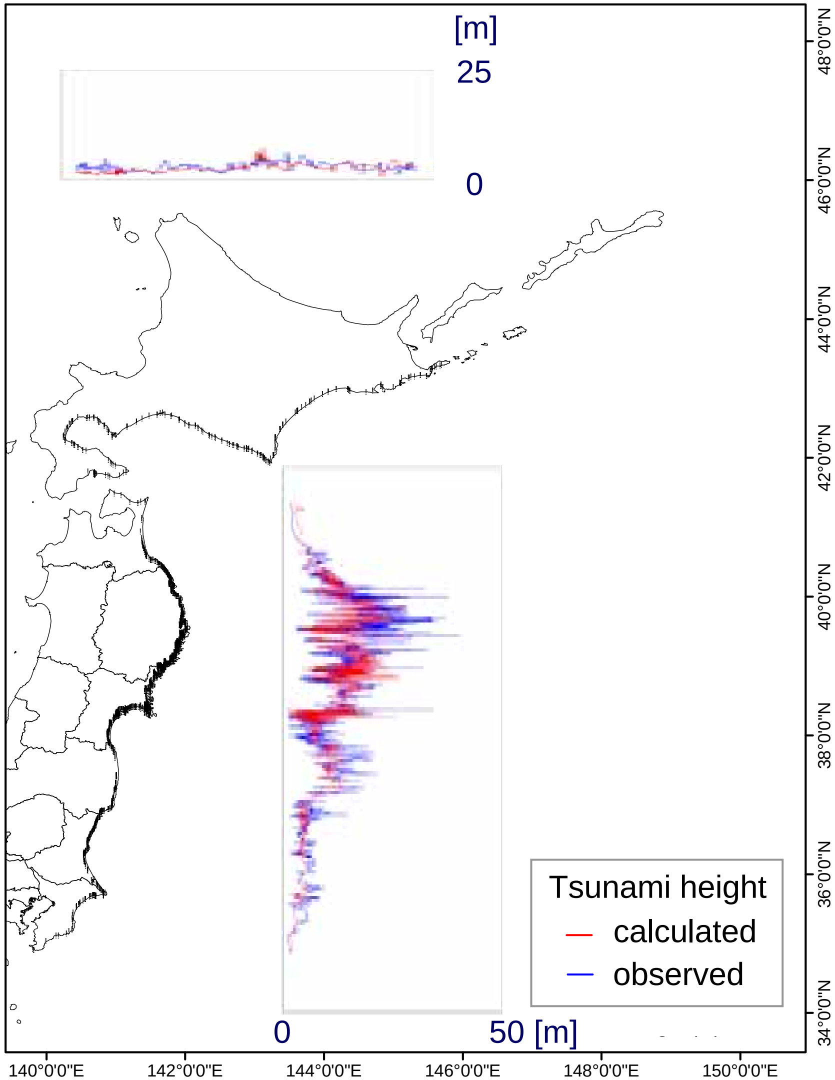
n : Number of the locations

R_i : Observed tsunami height at location i

H_i : Calculated tsunami height at location i

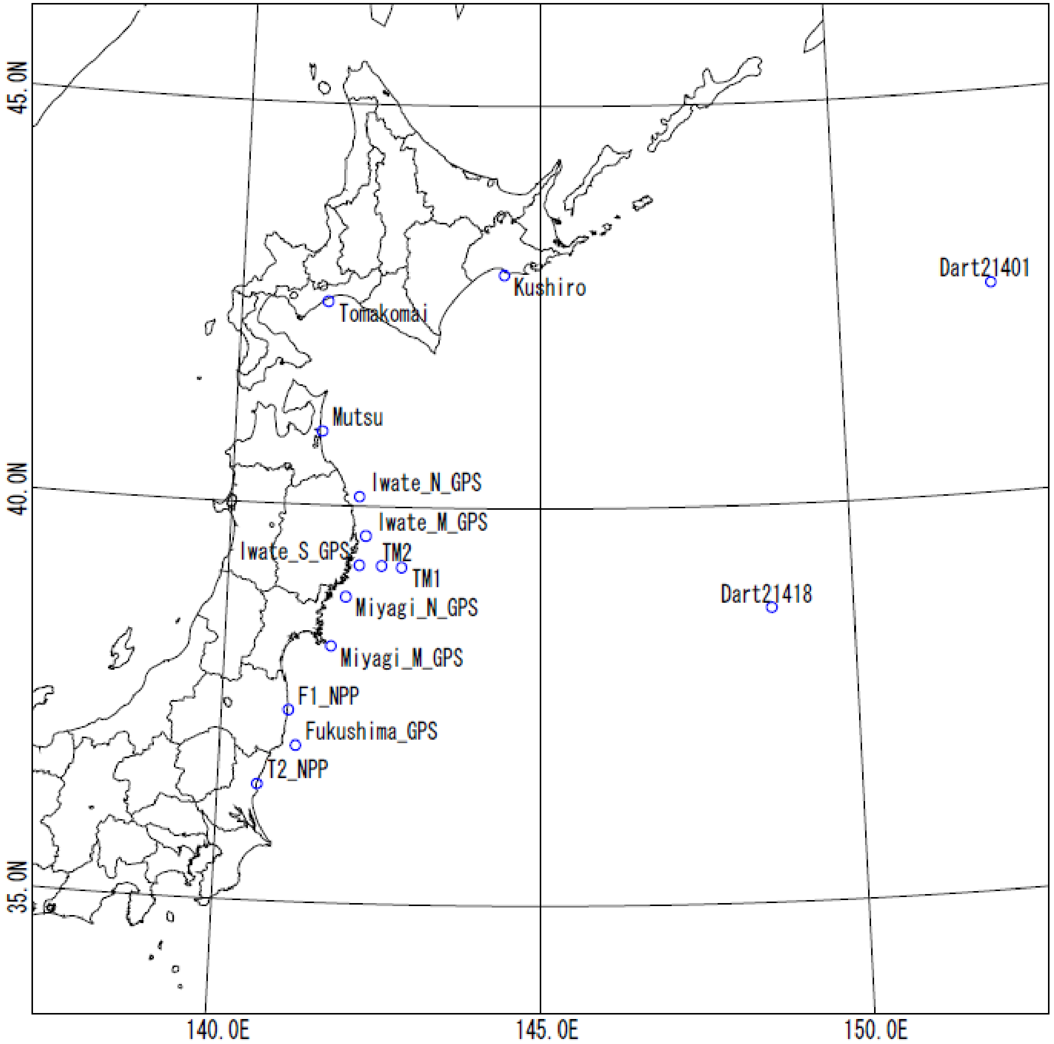
The criteria established by JSCE (2002)

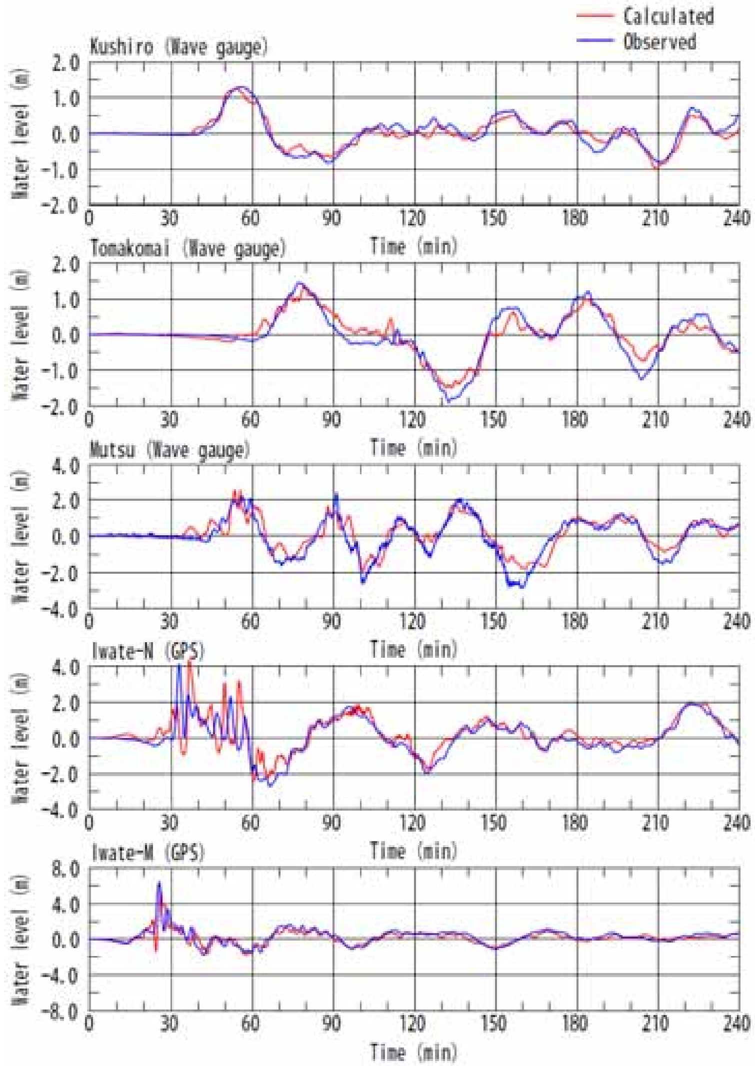
0.95<K<1.05 and κ<1.45



3. Tsunami inversion analysis and reproduced tsunami in the NPS site
(7)-2 Reproducibility of Numerical Simulation : Tide record

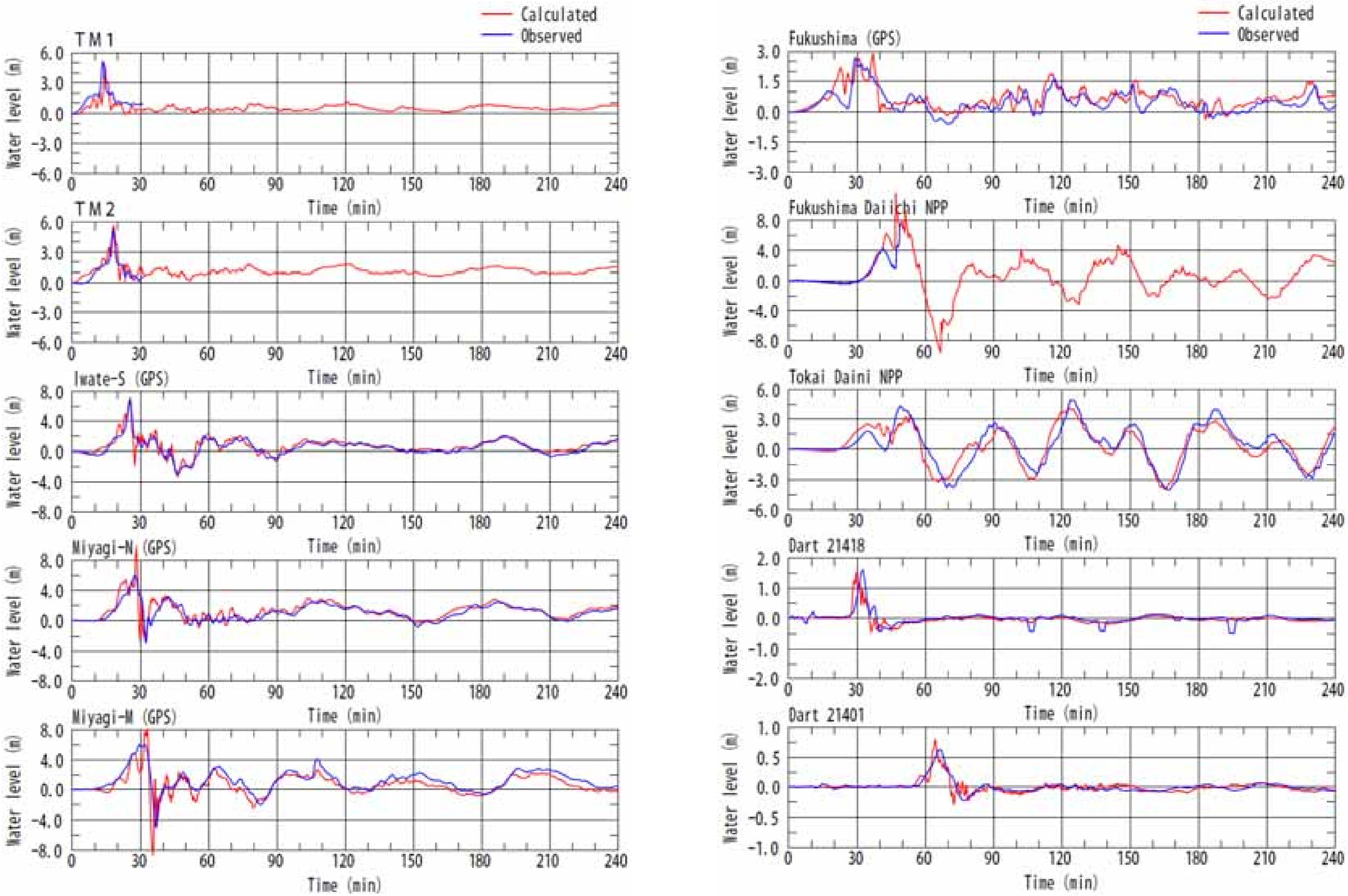
Comparison of the tide record





3. Tsunami inversion analysis and reproduced tsunami in the NPS site
(7)-2 Reproducibility of Numerical Simulation : Tide record

<u>Comparison of the tide record</u>



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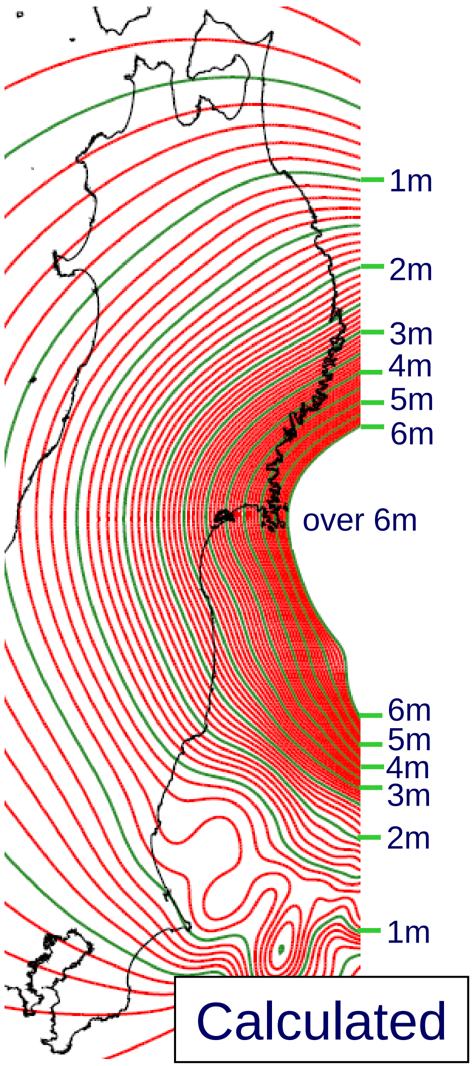
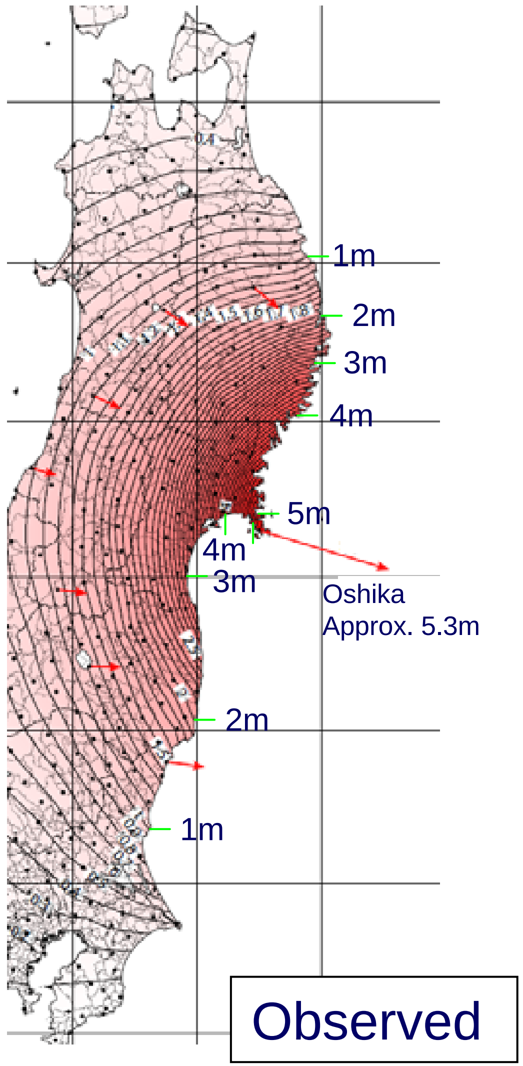
3. Tsunami inversion analysis and reproduced tsunami in the NPS site
(7)-3 Reproducibility of Numerical Simulation : Crustal movement

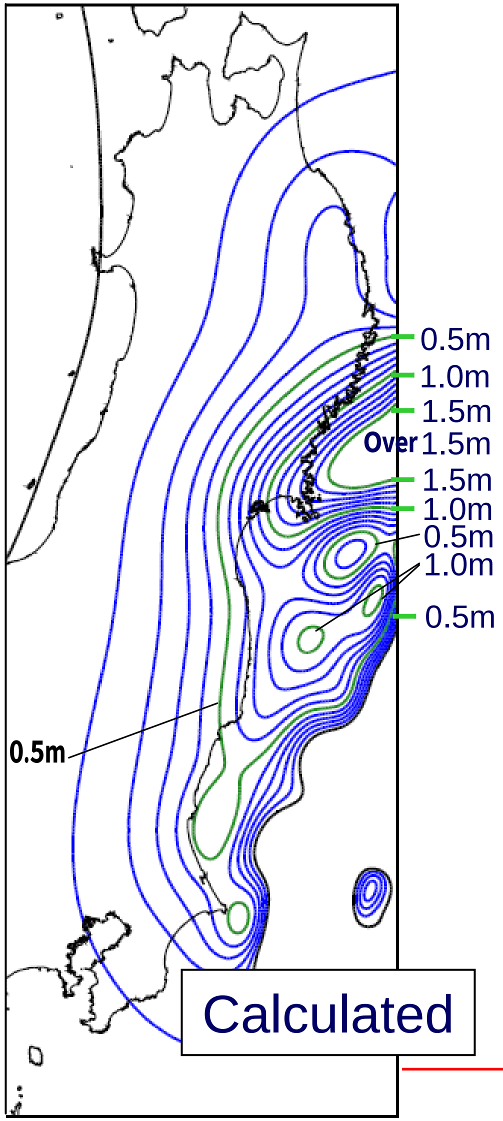
Comparison of the crustal movement – horizontal in the land area -

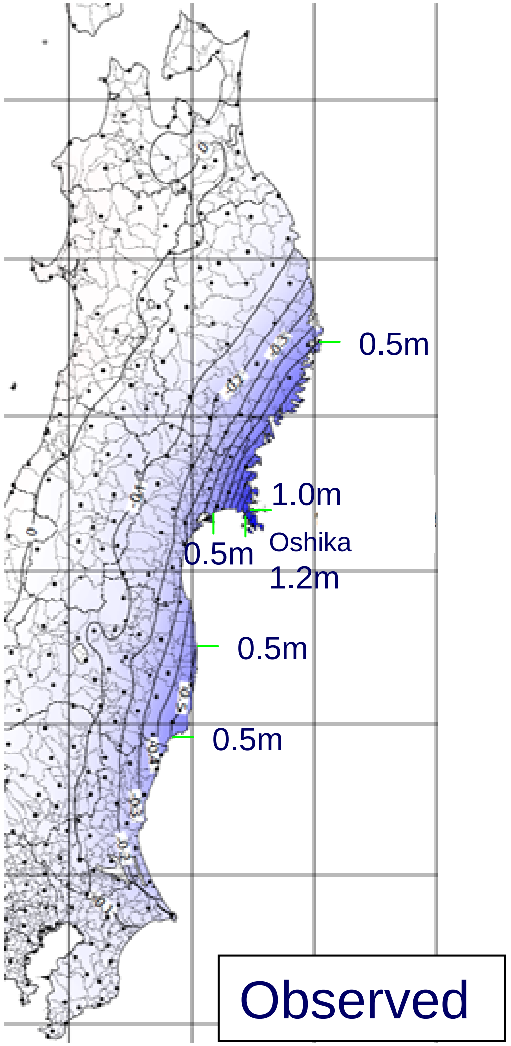




3. Tsunami inversion analysis and reproduced tsunami in the NPS site
(7)-3 Reproducibility of Numerical Simulation : Crustal movement

Comparison of the crustal movement – subsidence in the land area -

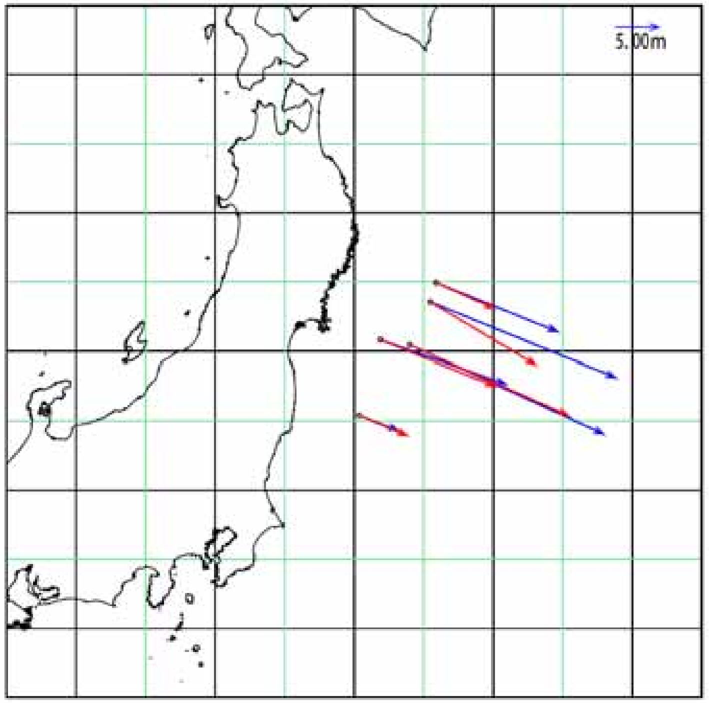




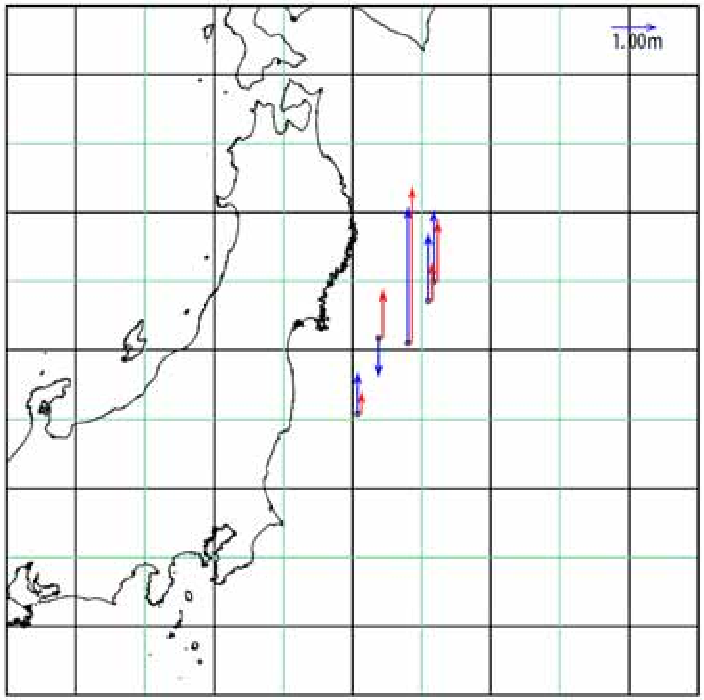
3. Tsunami inversion analysis and reproduced tsunami in the NPS site
(7)-3 Reproducibility of Numerical Simulation : Crustal movement

<u>Comparison of the crustal movement - in the marine area -</u>

Calculated
Observed



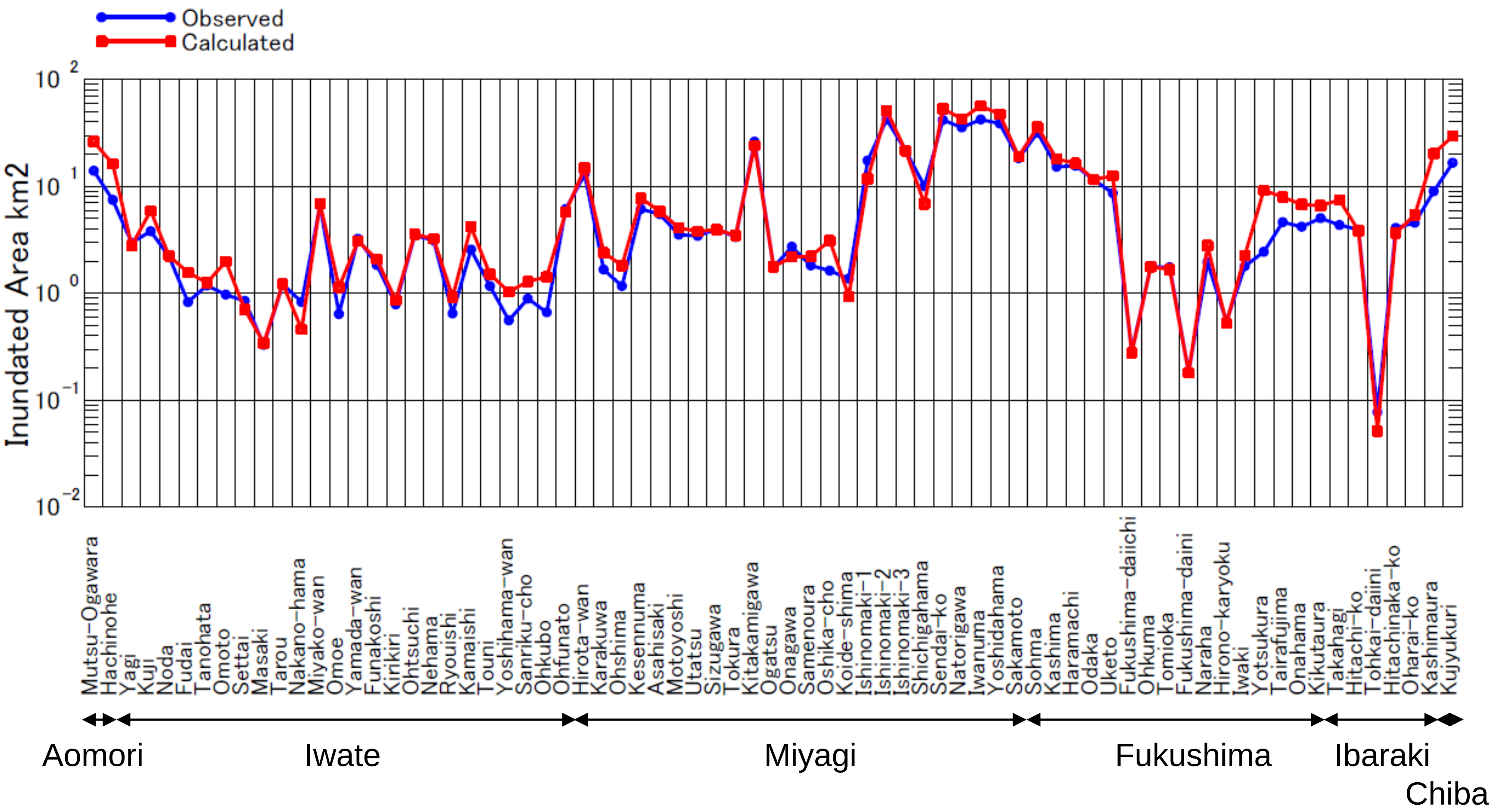
Horizontal



Vertical

3. Tsunami inversion analysis and reproduced tsunami in the NPS site
(7)-4 Reproducibility of Numerical Simulation : Inundated area

Comparison of the inundated area



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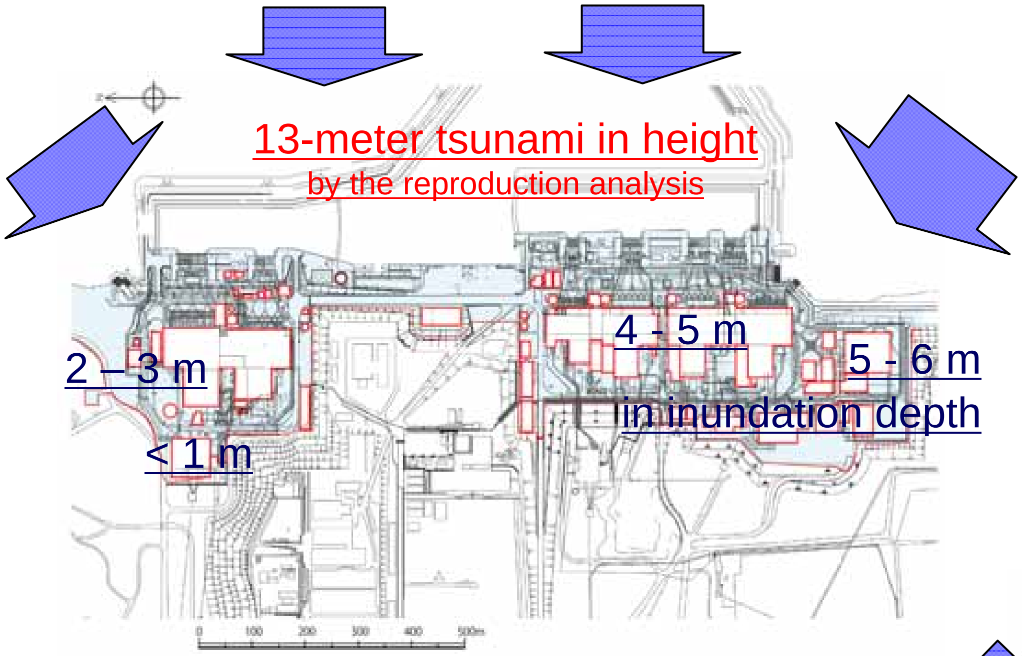
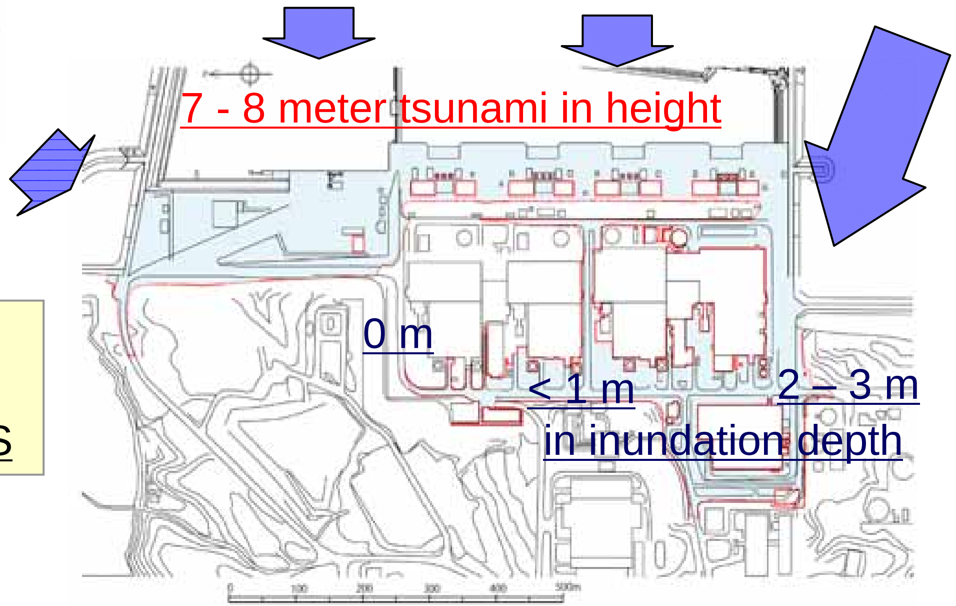
5. Summary

4. Comparison of the tsunamis that hit Fukushima Dai-ichi and Fukushima Dai-ni
(1) Summary of the survey result



Inundation depth in Daiichi was larger than that in Daini : 5-6m > 2-3m

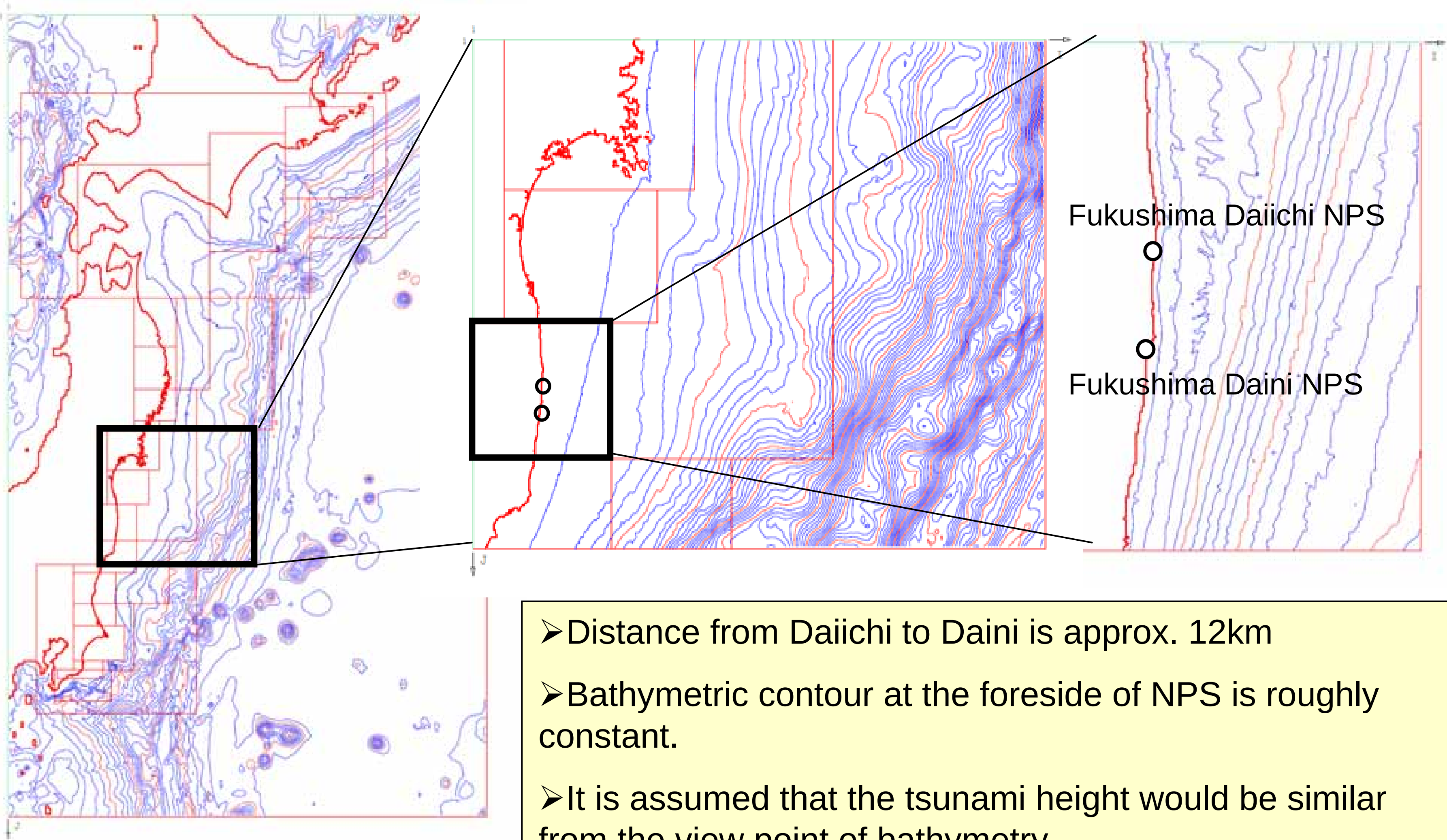
- Tsunami height in Daiichi was larger than that in Daini : 13m > 7 - 8m



The scale of the tsunami

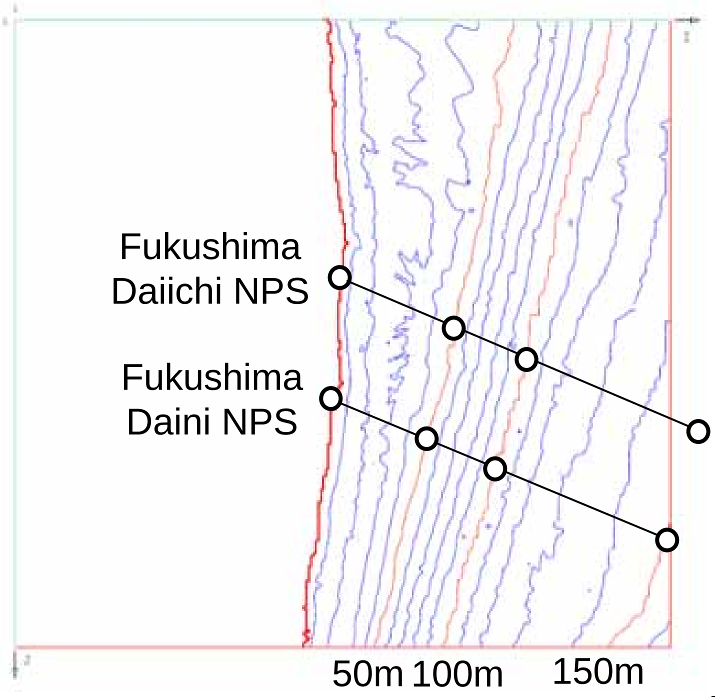
Fukushima Daiichi NPS > Fukushima Daini NPS

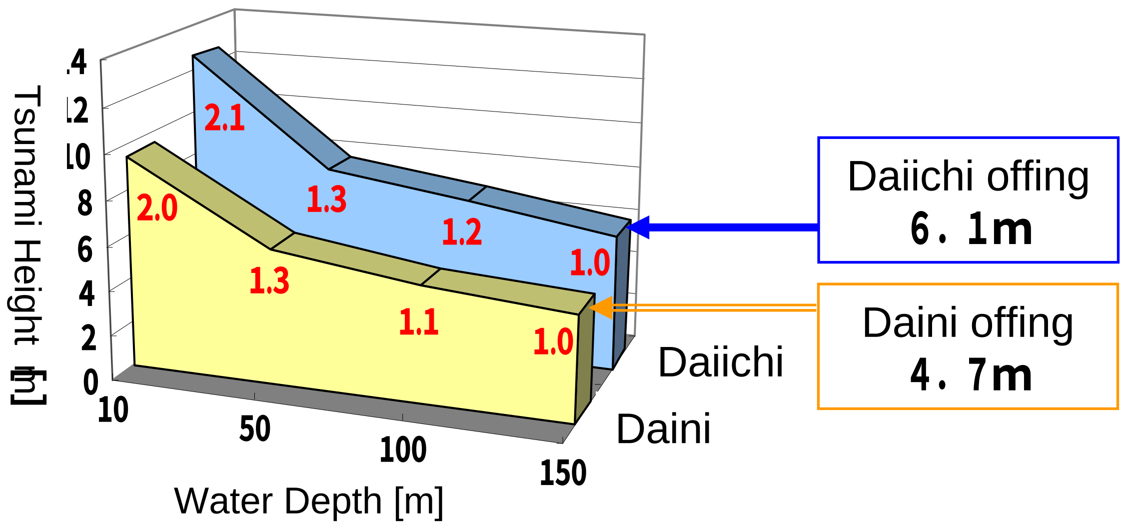
4. Comparison of the tsunamis that hit Fukushima Dai-ichi and Fukushima Dai-ni
(2) Effect of the Submarine Topography



- ➢Distance from Daiichi to Daini is approx. 12km
- ➢Bathymetric contour at the foreside of NPS is roughly constant.
- ➢It is assumed that the tsunami height would be similar from the view point of bathymetry.

4. Comparison of the tsunamis that hit Fukushima Dai-ichi and Fukushima Dai-ni
(3) Effect of the amplification in the shallow sea area





Change of the tsunami height from offing to shore

- Non linear analysis via the "inversion model"-

- The red letters mean an amplification ratio against at 150m -

➢The tsunami height amplifies twice from the offing to the shore.

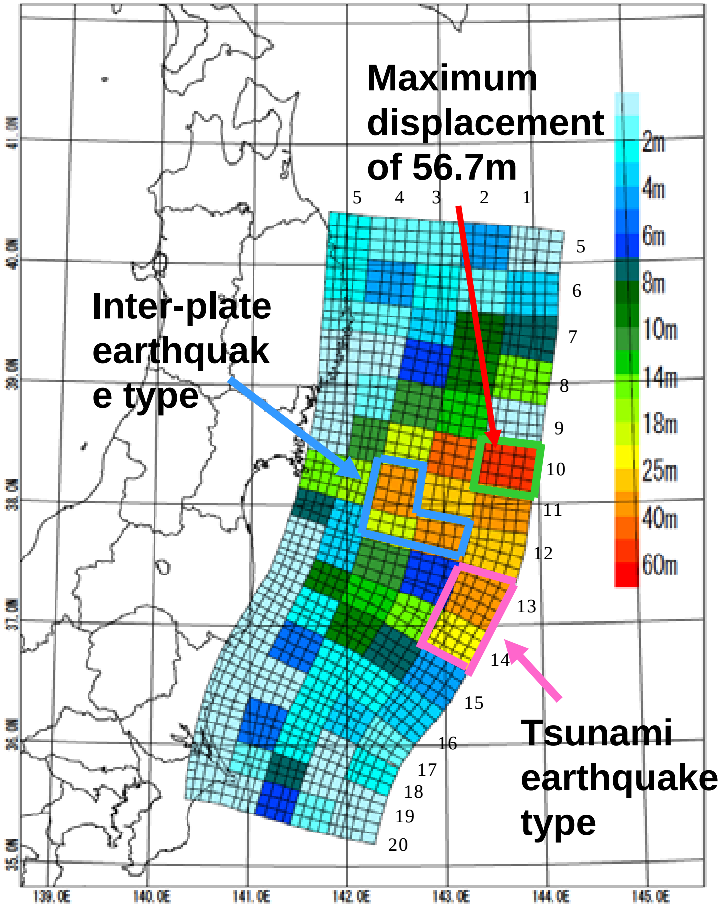
➢The amplification ratio is similar at Daiichi and Daini.

➢Effect of the amplification is similar at Daiichi and Daini.

➢The difference of the tsunami between Daiichi and Daini was already formed in the offing – deep sea area -.

4. Comparison of the tsunamis that hit Fukushima Dai-ichi and Fukushima Dai-ni
(4)-1 Effects of the Wave Source and Deep Sea Area

- Calculated results in the linear calculation per the “inversion model”
- Extract major factors (blocks) for the maximum tsunami height at each NPS offing



Displacement distribution of the “inversion model”

※ Nonlinearity can be largely ignored at a water depth of 150m

Unit [m]

Fukushima Daiichi

5	4	3	2	1	
0.00	0.00	0.00	0.00	0.00	5
0.00	0.00	0.00	0.00	0.00	6
0.00	0.00	0.00	0.00	0.00	7
0.00	0.00	0.00	0.00	0.00	8
0.00	0.00	0.01	0.00	0.00	9
0.00	0.06	0.04	-0.02	-0.03	10
0.20	0.51	0.75	-0.08	-0.05	11
-0.02	-0.04	0.66	1.01	-0.30	12
-0.01	-0.09	-0.40	0.16	1.73	13
-0.04	0.05	-0.01	-0.31	1.87	14
-0.11	0.06	0.06	0.02	0.16	15
-0.02	-0.11	-0.01	-0.07	0.19	16
0.00	-0.01	-0.06	-0.01	0.08	17
0.00	0.18	0.10	0.00	-0.02	18
0.00	0.01	0.02	0.00	0.00	19
0.00	0.00	0.00	0.00	0.00	20

Fukushima Daiichi
6.13m in total

Fukushima Daini

5	4	3	2	1	
0.00	0.00	0.00	0.00	0.00	5
0.00	0.00	0.00	0.00	0.00	6
0.00	0.00	0.00	0.00	0.00	7
0.00	0.00	0.00	0.00	0.00	8
0.00	0.00	0.00	0.00	0.00	9
0.00	0.03	0.02	-0.01	-0.02	10
0.15	0.26	0.24	-0.02	-0.03	11
0.07	0.08	0.77	0.22	-0.12	12
-0.01	-0.11	-0.25	0.21	1.59	13
-0.03	-0.06	-0.12	-0.10	1.73	14
-0.12	0.07	0.09	-0.17	0.11	15
-0.03	-0.01	0.00	-0.04	0.11	16
0.00	-0.02	-0.06	-0.12	0.09	17
0.00	0.17	0.07	0.00	-0.01	18
0.00	0.01	0.06	0.00	0.00	19
0.00	0.00	0.01	0.00	0.00	20

Fukushima Daini
4.74m in total

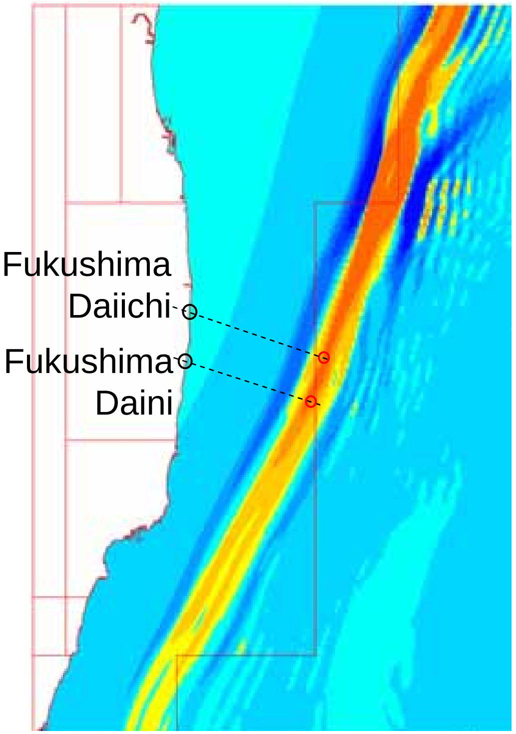
The contribution of the structural components for peak formation at offshore of each NPS with a water depth of 150m

4. Comparison of the tsunamis that hit Fukushima Dai-ichi and Fukushima Dai-ni
(4)-2 Effects of the Wave Source and Deep Sea Area

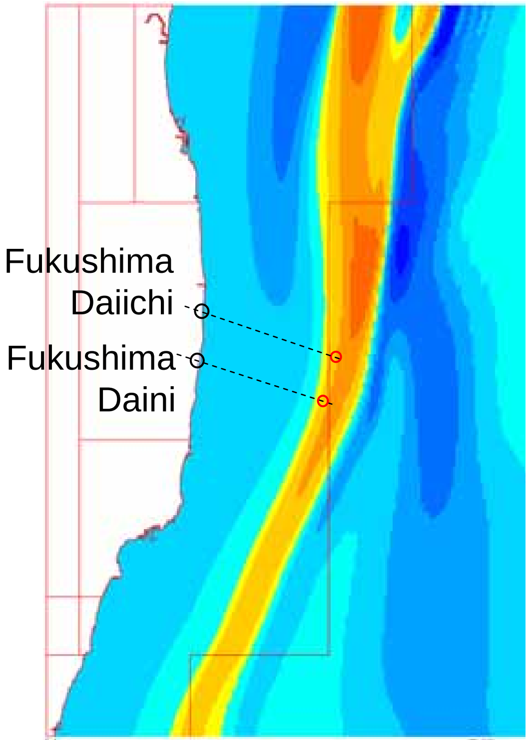
Major reason regarding the difference of the tsunami scale in Daiichi and Daini

We confirmed that the peak around site was formed by the overlap of the waves, which are the wave from the tsunami earthquake type off Fukushima and the wave from the inter-plate earthquake type off Miyagi.

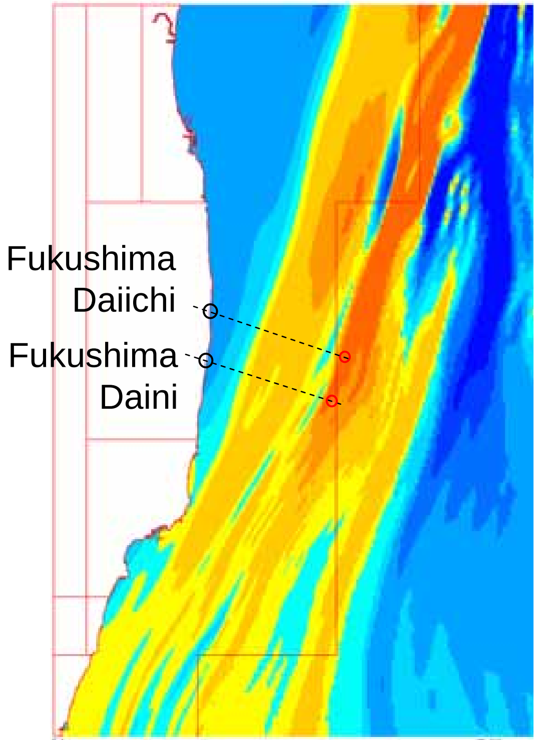
Time : About 15:13



The wave propagation from the tsunami earthquake type off Fukushima

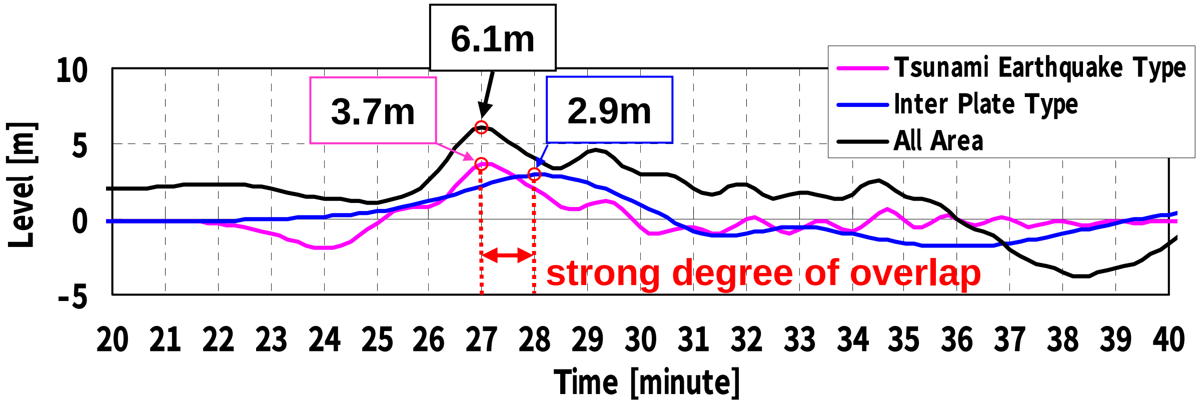


The wave propagation from the inter-plate earthquake type off Miyagi



The wave propagation from all the 80 blocks

4. Comparison of the tsunamis that hit Fukushima Dai-ichi and Fukushima Dai-ni
(4)-3 Effects of the Wave Source and Deep Sea Area : Major reason



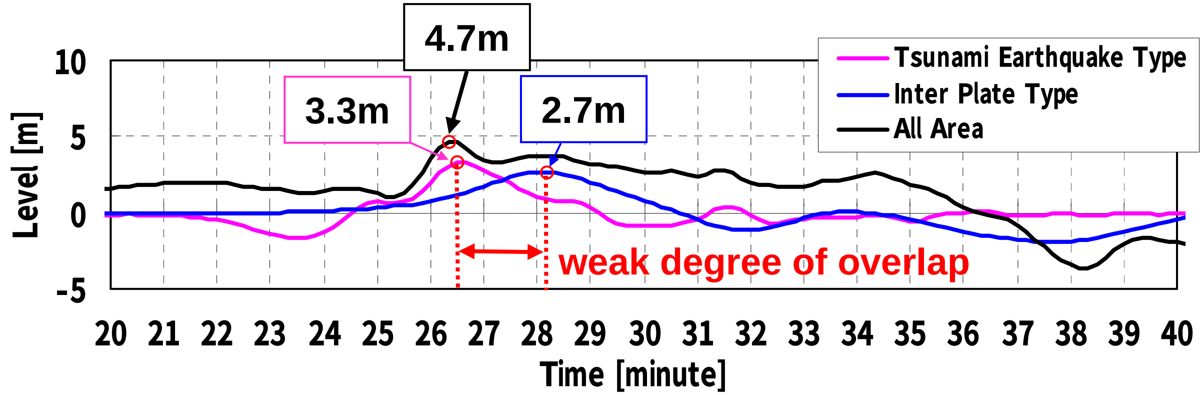
Approx. 30km off of Fukushima Daiichi NPS

➢A strong degree of overlap of the peak phase at the offshore of the Fukushima Daiichi NPS.

Major reason regarding the difference of the tsunami scale in Daiichi and Daini is estimated as the difference of the degree of overlap of the peak phase

➢A weak degree of overlap of the peak phase at offshore of the Fukushima Daini NPS.

➢The wave from the tsunami earthquake region arrives first and arrival of the wave from the inter-plate earthquake region is delayed at both NPS.



Approx. 30km off of Fukushima Daini NPS

Agenda

1. Overview of the Great East Japan Earthquake (GEJE) and Tsunami
2. Tsunami survey for inundation height and run-up height in the NPS site
3. Tsunami inversion analysis and reproduced tsunami in the NPS site
4. Comparison of the tsunamis that hit Fukushima Dai-ichi and Fukushima Dai-ni
5. Summary

5. Summary (1)

1. We carried out site surveys at Fukushima Daiichi and Fukushima Daini NPS.

   We found that the scale of the tsunami which struck Fukushima Daiichi NPS was greater than the one that struck Fukushima Daini NPS's

2. We carried out a tsunami inversion analysis for the GEJE.

   We focused attention on the a) tide record, b) flooding height and run-up height, c) crustal movement and d) inundated area over a wide area (form Hokkaido to Chiba).

   The proposed source model with a magnitude (Mw) of 9.1 consists of mutually independent 80 blocks, and the maximum fault slip amount is 56.7m.

   The observed tsunami data are reproduced quite accurately via the model in a well balanced manner.

3. We investigated the main reasons for the tsunami difference at Fukushima Daiichi NPS and Fukushima Daini NPS.

   We found that there are two major tsunami components, one is the Tsunami Earthquake type from off Fukushima and the other is the Inter-Plate Earthquake type from off Miyagi.

   The major reason for the tsunami difference is a degree of overlap of the peak phase, which is strong in Fukushima Daiichi NPS and is weak in Fukushima Daini NPS.

5. Summary (2)

4. As for future tasks for inversion model, asynchronism of the rupture start time of each region and the duration time were not considered in this model.

These two parameters could be effective in improving the tsunami source model.

In addition, the splay fault and landslide induced by the earthquake could also be effective in improving the model.