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

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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

(Fukushima site

(Earthquake Research Institute, Tokyo University)
1. Overview of the GEJE and Tsunami (2)

(2) Flooding height and run-up height

- 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 20 m
Agenda

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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

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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

Wave height meter record off of Fukushima Daiichi NPS

[Specifications of the wave height gauge]
- Using ultrasonic wave
- Measurement Range: -7.5m - +7.5m
- Sampling Rate: every 0.5 second

Upper limit of the measurement range: +7.5m
After that, no data was measured.
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

- **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

- **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

Removal of vegetation on the slope
O.P.+15-16m

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

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

Ground level : O.P.+10m

Water mark on the wall
O.P.+14-15m

Water mark on the slope
O.P.+15-16m

Ground level : O.P.+10m

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

- 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

- Almost all the area of the main buildings was flooded.

**Sea side area, ground Level**
- Run-up was confirmed from the sea-side area over the main building area.
- Inundation Height : approx. O.P. + 13 - 14.7m
- Inundation Depth : approx. 1.5m or less
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

(Ground level O.P. + 12m)
2. Tsunami survey for inundation height and run-up height in the NPS site
(2)-2 Fukushima Daini NPS : Example of tsunami survey

- Inundated area
  - O.P. 7.2m (Ground level: O.P. +4m)
  - Inundation Height: O.P. +12.7m
  - Water mark on the wall

- Inundated Height: O.P. +12.6m (Deformation of the ladder O.P. +12.6m)

- Ground level: O.P. +4m

- Damage of the pipe O.P. +15.9m

- Inundation Height: O.P. +15.9m

- O.P. 12.7m (Ground level: O.P. +12m)
  - Water mark on the wall

- Inundated Height O.P. +12.7m
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

Concentric tsunami run-up
- Inundation Height: approx. O.P. + 12 – 13 m
- Inundation Depth: approx. 1 m or less

South half of the main building area was flooded

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

No run-up was confirmed from the sea-side area over the slope to the main building area.

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

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

- Tsunami reproductive simulation by tsunami source model discussed below

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The scale of the tsunami which struck NPSs

**Fukushima Daiichi NPS > Fukushima Daini NPS**

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

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5. Summary
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.

![Tsunami Inversion Analysis](image)

- 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
  - 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

- 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

Peak height was not recorded

Fukushima Daiichi, TEPCO
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.
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

(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

**Flowchart**

1. **START**
2. **Observed Data**
   - Tide Record
   - F & R Height
   - Crustal Movement
   - Inundated Area
3. **Conversion** for "F & R Height" and "Inundated area"
4. **Target Data in Linear Space**
   - Tide Record
   - F & R Height
   - Crustal Movement
   - Inundated Area
5. **Linear Inversion**
   - Using the Green Function
   - J, the error sum of squares, is minimized
6. **Optimum Model**
7. **Confirmation of Goodness of Fit**
8. **ENOUGH**
9. **The Best Estimated Model**
10. **Non-Linear Analysis**
11. **Calculated Results**
    - Wave Form
    - F & R Height
    - Crustal Movement
    - Inundated Area
12. **Modified Models**
13. **Non-Linear Analysis**
14. **Initial Models**
15. **START**
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
(6) Displacement distribution of the best estimated tsunami source 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 $\Delta=1.40$ 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 $\Delta<1.45$.

Reproduction index by Aida (1978)

$$K_i = \frac{R_i}{H_i}$$

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

$n$: 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 $\Delta<1.45$
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

Comparison of the tide record

![Graphs showing tide record comparisons](image-url)
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 -

Calculated

Observed

0.5m
1.0m
1.5m

0.5m
1.0m
1.5m

0.5m
0.5m
1.0m
1.5m
1.5m
1.0m
0.5m

Oshika
1.2m

0.5m

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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 - in the marine area -

- 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

![Graph showing the comparison of observed and calculated inundated areas across different regions.]
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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

The tsunami height amplifies twice from the offing to the shore.
The amplification ratio is similar at Daiiichi and Daini.

Effect of the amplification is similar at Daiiichi and Daini.
The difference of the tsunami between Daiiichi and Daini was already formed in the offing – deep 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 -

Daiichi offing 6.1m
Daini offing 4.7m
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

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

Displacement distribution of the
“inversion model”

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

Inter-plate earthquake type

Tsunami earthquake type

Fukushima Daiichi
6.13m in total

Fukushima Daini
4.74m in total

Unit [m]
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

- A strong degree of overlap of the peak phase at the offshore of the Fukushima Daiichi NPS.
- 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.
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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 (from 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.
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.