Strong Ground Motions during the 2011 Pacific Coast Off Tohoku, Japan Earthquake

Kojiro Irikura\(^{(1)}\) and Susumu Kurahashi\(^{(2)}\)

\(^{(1)}\) Aichi Institute of Technology/Kyoto University
\(^{(2)}\) Aichi Institute of Technology
Today’s Topics

1. Outline of National Hazard Map in Japan before the 11 March 2011 Mw 9.0 earthquake off the Pacific coast of Tohoku

2. Features of strong ground motions from the 2011 Pacific Coast Off Tohoku, Japan Earthquake
   - PGV and PGA attenuation-distance relation
   - Why were so large acceleration motions produced?

3. Source model for generating strong ground motions

4. Summary
   Improvement of the recipe of predicting strong ground motions for mega-thrust earthquakes
Outline of National Hazard Map in Japan before the 2011 Pacific coast off Tohoku, Japan earthquake

- Revision of long-term evaluation of earthquake occurrence in region from off-Sanriku to off-Boso by the Earthquake Research Research Committee (November, 2011)
Programs defining the Seismic Hazard in Japan

1. Headquarters for Earthquake Research Promotion

Long-term Evaluation:
Evaluate probabilities of the next occurrence of large earthquakes for major active faults and subduction-zones along troughs.

Strong Ground Motion Evaluation
Construct seismic hazard maps, probabilistic and deterministic.

Probabilistic hazard map: predicted likelihood of ground motion level occurring in a given area within a set period of time.

Shaking map for scenario earthquakes: strong ground motion from hypothetical source models for specified active faults

2. Central Disaster Management Council

Conduct damage assessments from specific disastrous earthquakes estimating the extents and sizes of the disasters and their impact on individuals and public facilities
Probability of Earthquake Occurrence in 30 years

Inland Crustal-Earthquakes

Subduction Earthquakes

Headquarter of Earthquake Research Promotion (2010)
Long-term evaluation of seismic activity for the region from the off Sanriku to the off Boso

M9.0 earthquake

Tsunami earthquake region
Long-term evaluation of seismic activity for the region from the off Sanriku to the off Boso

<table>
<thead>
<tr>
<th>Earthquake</th>
<th>Magnitude</th>
<th>Occur. prob. within 30 years</th>
</tr>
</thead>
<tbody>
<tr>
<td>Characteristic earthquake in ①</td>
<td>Approx. M8.0</td>
<td>0.2%～10%</td>
</tr>
<tr>
<td>Interplate earthquakes other than characteristic earthquake in ①</td>
<td>M7.1～M7.6</td>
<td>About 90%</td>
</tr>
<tr>
<td>Earthquakes in ②</td>
<td>Unknown</td>
<td>Unknown</td>
</tr>
<tr>
<td>Miyagi-oki earthquake in ③</td>
<td>Approx. M7.5</td>
<td>99%</td>
</tr>
<tr>
<td>Sanriku-nanbu earthquake in ④</td>
<td>Approx. M7.7</td>
<td>80%～90%</td>
</tr>
<tr>
<td>Interplate earthquakes in ⑤</td>
<td>Approx. M7.4</td>
<td>About 7% or less</td>
</tr>
<tr>
<td>(Successive occurrence of multiple earthquakes)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Interplate earthquakes in ⑥</td>
<td>M6.7～M7.2</td>
<td>About 90% or more</td>
</tr>
<tr>
<td>Earthquakes in ⑦</td>
<td>Unknown</td>
<td>Unknown</td>
</tr>
<tr>
<td>Tsunami bearthquake in ⑧</td>
<td>Approx. Mt8.2</td>
<td>About 20%</td>
</tr>
<tr>
<td>Intraplate earthquakes (normal fault type) in ⑧</td>
<td>Approx. M8.2</td>
<td>4%～7%</td>
</tr>
</tbody>
</table>

Rupture of Mw 9.0 started from this region.

Large Tsunami was generated.

Earthquake Research Committee (2002)
Examples of Probabilistic Seismic Hazard Map

- Probability of exceedance for more than seismic intensity 6- in 30 years
- Seismic intensity map for 3% probability of exceedence in 30 years
Revision of Probability of Earthquake Occurrence in the Region from the off Sanriku to the off Boso

<table>
<thead>
<tr>
<th>Name of past earthquakes and seismic magnitude</th>
<th>Probability of earthquake occurrence</th>
<th>Cumulative Probability*</th>
<th>Passage rate</th>
<th>Upper: Average return period</th>
<th>Lower: Latest occurrence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Off Pacific Coast of Tohoku earthquake</td>
<td>9.0</td>
<td>4 – 6 %</td>
<td>10 – 20 %</td>
<td>20 – 30 %</td>
<td>30- 60 %</td>
</tr>
</tbody>
</table>

※Cumulative probability is defined as probability by that time.

Earthquake Research Committee (November, 2011)
Strong ground motions from the 2011 Pacific Coast Off Tohoku, Japan Earthquake

- Strong ground motions observed along the coast line near the source fault have several distinctive pulses.

- Attenuation-distance relations of PGA and PGV.

- Very little damage caused by ground motions, although accelerations at some sites near the source area were very high.
Record Section of Short-Period Motions

After Irikura and Kurahashi (2011)
Comparison of Observed Data and Attenuation Relationships of PGA and PGV

**PGA**

**PGV**
Features of Ground Motions Records with Extremely High Acceleration

- Two Causes of Extremely High Acceleration

1) Ground Motions Records with more than 1000 gals remarkably deviated from attenuation-distance curves.
   Extremely high acceleration motions amplified by local surface geology, non-linear site effects.

2) Ground Motion Records with relatively high acceleration almost following attenuation-distance curves.
   Distinctive high acceleration pulses seem to propagate from station to station, attenuating with distance from fault distance.
Stations where more than 1000 gals were recorded.

Some PGAs observed at sites near the source fault seem to be remarkably deviated from attenuation-distance curves.
Surface Geology near Sites where more than 1000 gals were recorded.

Accelerations more than 1000 gals were recorded at relatively soft soil sites.
Closeup of acceleration waveforms for ground motion records with more than 1000 gals
H/V spectral ratio of ground motions at Tsukidate (K-NET) between mainshock and small earthquakes
Tsukidate (PGA=2933gal, DR=21.4%)
Stations where relatively high accelerations were recorded

Relatively high accelerations at stations near the source fault almost following attenuation-distance curves.

2011/03/11 14:46  Mw9.0
Str: 201 Dip:9   23.7km

Stations where relatively high accelerations were recorded
Acceleration Records with remarkable distinctive pulses

Horizontal NS

Horizontal EW
Source Model for Generating Strong Ground Motions during the 2011 Pacific Coast off Tohoku, Japan Earthquake

The short-period source model proposed by Kurahashi and Irikura (EPS, 2011) is revised based on re-estimation of locations of strong motion generation areas (SMGAs) using semblance analysis for estimating azimuths of seismic waves from the SMGAs.
Slip Distribution of the 2011 Tohoku Earthquake

DPS data including inland and off-shore observation

Tsunami Waveform Data

Source Model of the 11 March 2011 off Tohoku, Japan Earthquake

Slip Distributions by the separate inversions of (a) strong motion, (b) teleseismic, (c) geodetic, (d) tsunami datasets.

Yokota et al. (GRL 2011)
Record Section of Short-Period Motions

After Irikura and Kurahashi (2011)
Starting Points of SMGAs Estimated by Back-propagation Method

Location of each SMGA is estimated using a back-propagation method for previous model (Kurahashi and Irikura, 2011).
Strong Motion Generation Areas by Kurahashi and Irikura (2011) by Forward Modeling of Strong Motion Waveforms
Comparison of Observed and Synthetic Seismograms
Kurahashi and Irikura (2011)

Acceleration

Velocity
Comparison of Source Models for Generating Short-Period Motions

Reconsideration of locations of strong motion generation areas of the 2011 Pacific Coast off Tohoku, Japan Earthquake

Estimation of locations of SMGA from azimuths of seismic waves from each SMGA using small arrays.
Re-estimation of Locations of SMGAs from Semblance Analysis of Wave-Packets seen in Short-Period Seismograms

After Irikura and Kurahashi (2011)
Semblance Analysis for Wave Packets using Local Arrays

\[ S_e(s) = \frac{1}{N} \left( \frac{\sum_{k=1}^{M} \left[ \sum_{i=1}^{N} u(x_i, t_k + s \cdot x_i) \right]^2}{\sum_{k=1}^{M} \sum_{i=1}^{N} u(x_i, t_k)^2} \right) \]
センブランス解析は、平面波入射を仮定しているため、観測点をグループ分けして、仮想点震源（1メッシュ）におけるセンブランスを計算した。（上図）

各グループにおけるセンブランスを足して、最も大きな仮想点震源（1メッシュ）の部分が破壊域内となる

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Result of semblance analysis for WP1

Result of semblance analysis for WP 2
Result of semblance analysis for WP 3
Estimation of locations of SMGA1 and SMGA3 from semblance analysis

Location of SMGA1 from WP1

Location of SMGA3 from WP2
Selection of Empirical Green’s Functions (EGFs) for Simulating Short-Period Motions from SMGAs

Strong motion records of the 2005 Miyagi-oki earthquake

The records have clearly two wave-groups from SMGAs. Waveforms of the second wave-group are used as the EGFs for simulating ground motions from SMGA3 (WP 2).
Fourier Spectra of the EGFs

<table>
<thead>
<tr>
<th></th>
<th>Name</th>
<th>M</th>
<th>DX,DW</th>
<th>Stress Drop</th>
<th>Mo</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005/08/16 11:46</td>
<td>EGF1</td>
<td>7.2</td>
<td>8.5 km</td>
<td>20MPa</td>
<td>5.23E+18 **</td>
</tr>
<tr>
<td>2007/11/26 22:51</td>
<td>EGF2</td>
<td>6.0</td>
<td>7.7 km</td>
<td>4.2MPa</td>
<td>7.66E+17</td>
</tr>
</tbody>
</table>

** Suzuki and Iwata (2007) only Asp2
Revised Model

<table>
<thead>
<tr>
<th></th>
<th>L,W</th>
<th>Mo</th>
<th>Stress drop</th>
</tr>
</thead>
<tbody>
<tr>
<td>SMGA1</td>
<td>34 × 34</td>
<td>2.68E+20</td>
<td>16</td>
</tr>
<tr>
<td>SMGA2</td>
<td>23.1 × 23.1</td>
<td>1.41E+20</td>
<td>20</td>
</tr>
<tr>
<td>SMGA3</td>
<td>42.5 × 42.5</td>
<td>6.54E+20</td>
<td>20</td>
</tr>
<tr>
<td>SMGA4</td>
<td>25.5 × 25.5</td>
<td>1.24E+20</td>
<td>25.2</td>
</tr>
<tr>
<td>SMGA5</td>
<td>38.5 × 38.5</td>
<td>5.75E+20</td>
<td>25.2</td>
</tr>
</tbody>
</table>
Comparison between Observed and Synthetic Motions

MIYAGI Prefecture

Observed
Synthetic
Comparison between Observed and Synthetic Motions

- **FUKUSHIMA Prefecture**
  - FKSH17 Acc. Obs. 60gal
  - FKSH17 Acc. Syn. 72gal
  - FKSH17 Vel. Obs. 5cm/s
  - FKSH17 Vel. Syn. 13cm/s

- **IBARAGI Prefecture**
  - IBRH13 Acc. Obs. 37gal
  - IBRH13 Acc. Syn. 56gal
  - IBRH16 Acc. Obs. 102gal
  - IBRH16 Acc. Syn. 43gal
  - IBRH16 Vel. Obs. 7cm/s
  - IBRH16 Vel. Syn. 2cm/s
  - IBRH19 Acc. Obs. 68gal
  - IBRH19 Acc. Syn. 24gal
  - IBRH19 Vel. Obs. 4cm/s
  - IBRH19 Vel. Syn. 2cm/s
Distinctive High Acceleration Pulses

ONG1281103111446

MYGH0411031111446
Distinctive High Acceleration Pulses

Borehole station OP -128m at Onagawa NPP

Acc.(cm/s/s)

Time(sec)

-400
-200
0
200
400

0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150

-400
-200
0
200
400

45 46 47 48 49 50

95 96 97 98 99 100

-400
-200
0
200
400

Borehole station OP -128m at Onagawa NPP
Source Model of Simulating Distinctive Pulses

Heterogeneous stress parameters inside SMGA

Matsushima and Kawase (2006)
Uniform slip velocity model

Heterogeneous slip velocity model 1 (x2)

Heterogeneous slip velocity model 2 (x4)

Distinctive pulse
This study: Asano and Iwata (2011)

Satoh (2012)
Comparison between SMGAs in this study and source locations of past earthquakes off the Pacific coast of Tohoku
Strong Motion Generation Area versus Seismic Moment for Subduction Earthquakes

- 2005年宮城県沖地震 (Kamae, 2006; Satoh, 2006; Suzuki and Iwata, 2007)
- 1994年三陸はるか沖地震 (宮原・笹谷, 2004)
- 1978年宮城県沖地震 (Kamae, 2006)

After Satoh (2012)

2011 Tohoku Earthquake
- Asano and Iwata (2011)
- Kamae and Kawabe (2011)
- Irikura and Kurahashi (2012)
- Satoh (2012)
Acceleration Spectral-Level versus Seismic Moment for Subduction Earthquakes

After Satoh (2012)
Summary

Based on the results of our analysis in this study, we improve the recipe of predicting strong ground motions to be able to apply it to mega-thrust earthquake.

Outer source parameters

1. Source area and seismic moment of a target earthquake: Source area is set from the tectonic background in the objective regions.

2. Average stress drop over the entire source area: Average stress drop is estimated from the empirical scaling relation of source area versus seismic moment.
Summary 2

Inner fault parameters

3. Segmentation:
The segments of the source area are divided from seismic activities and geo-morphological setting in the target region.

4. Strong motion generation areas (SMGAs):
SMGA is arranged to assign one per a segment.

5. Average stress parameter for SMGA:
About 25 MPa from empirical relation

6. Heterogeneity of stress parameters inside SMGA (Matsushima and Kawase, 2006)