Some features of strong ground motions and structural damage during the 2011 Mw 9.0 Off the Pacific Coast of Tohoku Earthquake

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Today’s Topics

1. Some features of structural damage during the 11 March 2011 Mw 9.0 Tohoku earthquake
2. Short-period source model estimated from strong motion data
3. Period-dependence of rupture processes
4. Recipe of predicting strong ground motions for subduction megathrust earthquakes
5. Estimation of strong ground motions at damaged sites during 2013 Tohoku earthquake for fragility curves of buildings
Outline of the 2011 Tohoku Earthquake

2011/03/11, 14:46. Depth=24km, Interplate

• Mw=9.0 (the largest earthquake recorded in Japan)
• JMA seismic intensity=7. Largest PGA approached 2933 gal (Tsukidate, Kurihara city of Miyagi Prefecture)
• Focal region was very large (450km X 200km)
• Damage area was wide (20 prefectures, Tokyo, Osaka)
• Over 1200 strong ground motion records were observed all over Japan.

Buildings damage data (FDMA, 2012)

Total collapse  Partial collapse  Partial damage

March 11, 2012

Geospatial Information Authority
Period characteristics of ground motions

Kobe Earthquake, 1995

Teq = 2πPGV/PGA

Relationship between Total-Collapse Ratio and Seismic Intensity

Dependence on construction year during 1995 Kobe earthquake

Red: before 1961
Blue: after 1981

After investigation in Nishinomiya during 1995 Kobe earthquake (CDMC, 2004)
2. Short-period source model estimated from strong motion data

- Five distinctive wavapackets were detected on strong motion seismograms at stations near the source fault.
- The arrival azimuths of those wavepackets were estimated using the semblance analysis in several small arrays.
- The locations of strong motion generation areas (SMGAs) are coincident with the origins of those wavepackets.

Re-estimation of Locations of SMGAs from Semblance Analysis of Wave-Packets seen in Short-Period Seismograms

After Irikura and Kurahashi (2011)
Simulation of Strong Ground Motions during the 2011 Tohoku Earthquake Using the Empirical Green’s Function Method

- Strong Motion Generation Areas are relocated using the semblance analysis of the wave-packets in small arrays.
- The observed data from medium-sized earthquakes occurring near each strong motion generation area are adopted as the empirical Green’s functions.
- Strong motion records of the 2005 Miyagi-Oki earthquake (Mw 7.2) are used as the empirical Green’s functions for SMGA1 (WP1) and SPGA3 (WP2).

Mini-arrays (A, B, C, D, E, F, and G) for estimating arrival azimuths of wave-packets
Semblance Analysis for Wave Packets using Local Arrays

\[ S_{\text{r}}(s) = \frac{1}{N} \sum_{i=1}^{M} \left[ \sum_{j=1}^{N} u(x_i, t_{j} + s \cdot x_i) \right]^2 \]

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 x 34</td>
<td>2.68E+20</td>
<td>16</td>
</tr>
<tr>
<td>SMGA2</td>
<td>23.1 x 23.1</td>
<td>1.41E+20</td>
<td>20</td>
</tr>
<tr>
<td>SMGA3</td>
<td>42.5 x 42.5</td>
<td>6.54E+20</td>
<td>20</td>
</tr>
<tr>
<td>SMGA4</td>
<td>25.5 x 25.5</td>
<td>1.24E+20</td>
<td>25.2</td>
</tr>
<tr>
<td>SMGA5</td>
<td>38.5 x 38.5</td>
<td>5.75E+20</td>
<td>25.2</td>
</tr>
</tbody>
</table>
Comparison of Observed and Synthesized (SMGA1,2,3のみ)

Miyagi

Onagawa site

Acceleration Records with remarkable distinctive pulses

Horizontal NS

Horizontal EW

Hypo_distance(km)

Time (sec)

0 50 100 150

0 50 100 150
Heterogeneity of stress parameters inside SMGA

Heterogeneous stress parameters inside SMGA

Matsushima and Kawase (2006)

Uniform slip velocity model

Distinctive pulse

Heterogeneous slip velocity model 1 (x2)

Heterogeneous slip velocity model 2 (x4)
Period range of ground motions generated from the SMGAs

- Longer-period motions from the Strong Motion Generation Areas (SMGAs) are estimated using numerical Green’s functions: the Discrete Wavenumber method (Bouchon, 1981) and the Reflection/Transmission coefficient matrix method (Kennet, 1983) using a stratified medium.

- Effective period range of ground motions generated from the SMGAs are confirmed by comparing simulated motions with observed motions.

- Verification of the fault parameters are made, mainly inner fault parameters of Strong Motion Generation Areas (SMGAs) estimated using the empirical Green’s function method

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Velocity Structure Models (Vs)

1-D velocity structures from stations to source are modeled comparing synthetic motions with observed ones from small events.
Comparison between Observed and Synthetic Motions in Miyagi Prefecture

Frequency Range 0.05 – 1.0 Hz

Comparison between Observed and Synthetic Motions in Kanto Region

Frequency Range 0.05 - 1Hz

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Comparison between Observed and Synthetic Motions in Miyagi Prefecture

Frequency Range
0.01 - 0.1Hz

Comparison between Observed and Synthetic Motions in Miyagi Prefecture

Frequency Range
0.01-1Hz
3. Period-dependence of rupture processes
   – Comparison of short-period source model and long-period source models inverted long-period strong motion data, tsunami waveforms, geodetic data -

- Short-period source models using backprojection of teleseismic short-period P-waves (e.g. Ishii, 2011; Honda et al., 2011)

- Long-period source models inverted from tsunami data (Fujii et al., 2012), geodetic data (Iinuma et al., 2012) and joint data (Yokota et al.)

Comparison between slip distribution using long-period motions (Suzuki et al., 2011) and SMGAs in this study
Comparison of Short-Period Source Model in This Study with Short-Period Released Energy by the back-projection method

US Array Data by Ishii (2011)

Kanto Array Data by Hoda et al, (2011)

Slip Distribution of the 2011 Tohoku Earthquake
DPS data including inland and off-shore observation

Tsunami Waveform Data

Geographical Institute (2011)
Fujii and Satake (2011)
4. Recipe of predicting strong ground motions for subduction-zone megathrust earthquakes

- Rupture process of subduction-zone megathrust earthquakes show period-dependence.

- New source image for period-dependent source process is expressed as multi-step heterogeneous-source-model.

- Strong ground motions of engineering interest in the period-range from 0.1 to 10 sec are estimated using the basic characteristic source model with outer-fault parameters and inner fault parameters, that is, just one step heterogeneity source model.

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**Multi-Step Heterogeneous Source Model - 1**

**First step: Heterogeneity model for short periods 0.1 – 20 s**

**Second step: Heterogeneity model for very short-periods 0.05 – 0.2 s**

Heterogeneous stress parameters inside SMGA

Matsushima and Kawase (2006)
Comparison between SMGAs in this study and source locations of past earthquakes off the Pacific coast of Tohoku

Heterogeneous Model for Broad-band Motions from 0.1 to 10 s

The SMGAs are located along outer edge of the large-slip zone delineated based on the seismicity rate (Kato and Igarashi, 2012)

Brue solid line is the outer edge of the large-slip zone of the mainshock, ~35 km.

Stress parameter ($\sigma_a$) on strong motion generation areas is given as ~26 MPa from the empirical relations for mega-thrust earthquakes.
5. Estimation of strong ground motions at damaged sites during 2013 Tohoku earthquake

- Velocity structures beneath strong motion stations are identified by use of earthquake H/V spectral ratios (Kawase et al., 2011).

- Empirical Green’s functions at bedrock beneath the strong motion station are calculated with observed ground motions on the surface from small events and transfer functions between surface and bedrock.

- The transfer functions at damaged sites are calculated from velocity structures beneath the sites using microtremor H/V (Arai and Tokimatsu, 2000; Sanchez-Sesma, et al., 2011).

- Ground motions at damaged sites during the mainshock are calculated the transfer functions, the empirical Green’s functions and the short-period source model of the mainshock.

3.1 Methodology of estimating ground motions at damaged sites during the mainshock

\[
O_{GK}(\omega) = F(\omega) = E(\omega) \\
B_K(\omega) = O_{GK}(\omega)/TF_K(\omega) \\
E_{GD}(\omega) = B_D(\omega) \times TF_D(\omega)
\]
Microtremor measurement

Microtremor H/V in Osaki and Kurihara, Miyagi

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4.3 Fragility curves in subdistricts

**CR:** Collapse ratio

- **Peak Ground Acceleration**
  - $R^2=0.0001$
  - $R^2=0.332$

- **Peak Ground Velocity**
  - $R^2=0.462$
  - $R^2=0.446$

- **JMA Seismic Intensity**

- **Spectral Intensity**
Summary

1. The 2011 Tohoku earthquake (Mw 9.0) produced devastating tsunami waves, causing 16,500 fatalities (including missing) and serious damage to nearby Fukushima nuclear power plants. Extremely strong and long-duration ground motions were also generated, but damage due to strong ground motions were relatively less.

2. Short-period source model of the 2011 Tohoku earthquake (Mw 9.0) have five distinctive strong–motion-generation areas (SMGAs) fitting observed acceleration and velocity records to synthetic motions. The SMGAs are located west of the hypocenter and along the down-dip edge of the source fault. Synthetic motions from the SMGAs match well with observed motions in the period-range from 0.1 to 10 sec.

3. Period-dependence of rupture process was found, that is large slips in shallow zones of the source fault near the trench west of the hypocenter and short-period generation in deeper zones west of the hypocenter.

4. Strong ground motions of engineering interest in the period-range from 0.1 to 10 sec are estimated using the characteristic source model with outer-fault parameters and inner fault parameters as the recipe of predicting strong ground motions for subduction earthquakes.

Basic Characterized Source Model

Step 1: Heterogeneous Model for Broad-band Motions from 0.1 to 10 sec
Comparison between observed and synthetic waveforms in the region near the source fault (Miyagi and Onagawa)

Comparison of Seismic Intensity between Observed and Synthetics