Recipe of strong motion prediction for future earthquakes

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Basic Ideas for Predicting Strong Ground Motion

1. Characterized Source Model based on Waveform Inversion Results (Somerville et al., 1999; Miyakoshi et al., 2002)

2. Scaling Relations for the Outer Fault Parameters and Inner Fault Parameters (Somerville et al., 1999; Irikura and Miyake, 2001)

3. Estimation of the Parameters based on the Dynamic Asperity Source Model (Das and Kostrov, 1986; Boatwright, 1988)

Source Characterization for Simulating Strong Ground Motion

Wald et al. (1991)

1989 Loma Prieta earthquake ($M_w 6.9$)

Tangential Ground Velocities

effective source dimension

($L_{eff}, W_{eff}$ are derived by auto-correlation of slip distribution)

Somerville et al. (1999)

Mai and Beroza (2000)
Identification for Rupture and Asperity Area
(Somerville et al., 1999)

**Rupture area**
- More than 0.3 times the average slip of the whole fault.

**Asperity area**
- More than 1.5 times the average slip of the whole fault.

** Removed area**

![Slip Distribution Table]

Slip [m]
Characterized Source Model

**Kagoshima (3/26)**

- **Slip [m]**
  - (Forward) AKU ← 0.18 0.51 (Backward) → MIY

- **Strike; N280E**
  - Dip; 79°
  - Asperity area
  - Off-Asperity area

**Displacement (B.P.F.: 2~10 sec)**

- **AZU** (0.92)
- **IZU** (2.35)
- **OHK** (0.96)
- **MIN** (2.24)
- **AKU** (2.35)
- **MIY** (7.93)
- **YOK** (2.25)
- **SEN** (1.80)
- **KUS** (1.60)
- **KMO** (1.30)

- **NS**
- **20s**
- **20km**
- **( ) ; cm**
Asperity Area vs. Off-Asperity Area

Observation

Characterized Source Model

Inversion

Characterized Source Model

(A)

(B)

Forward site

5s

3.16

3.19

2.81

1.37

2.02

Backward site

5s

7.86

5.09

5.30

5.33

2.15

(A)

(B)

5s

3.16

3.19

2.81

1.37

2.02

(A)

(B)
What is characterized source model? (1)
- simulation of broadband ground motion for the 1997 Kagoshima-ken Hokuseibu earthquake -

Miyake et al. (2000)
The 1999 Kocaeli Earthquake (Turkey)
1999 Taiwan Chi-Chi Earthquake

Total Slip:
Horizontal
Strong motion generation area is coincident with the area of asperities characterized by the waveform inversion.

Somerville et al. (1999) and Miyakoshi et al. (2001)

Kamae and Irikura (1998, 2000), Kamae et al. (1999), and Miyake et al. (2001)
Relation between Rupture Area and $M_0$

→ Outer Fault Parameters

Relation between Combined Area of Asperities and $M_0$

→ Inner Fault Parameters

Somerville et al. (1999) and Miyakoshi et al. (2001)
Asperity Source Model for Simulating Strong Ground Motion

Boatwright (1988)

Stress drop distribution characterized

Slip distribution given from kinematic inversion

Ground motion simulation

Source characterization
**Asperity Source Model** *(Das and Kostrov, 1986)*

**Basic Equations**

### Seismic Moment
*(Boatwright, 1986)*

\[
M_0 = \frac{16}{7} \Delta \sigma_a r^2 R
\]

\[
M_0 = \frac{16}{7\pi^{3/2}} \Delta \sigma_a S_a S^{1/2}
\]

### Stress Drop
*(Boatwright, 1988)*

\[
\Delta \sigma_a = \frac{7}{16} \frac{M_o}{r^2 R}
\]

\[
\Delta \sigma_a = \frac{7\pi^{3/2}}{16} \frac{M_o}{S_a S^{1/2}}
\]

### Acceleration Source-spectrum
*(Madariaga, 1977)*

\[
A_0^a = 4\pi \beta v_R \Delta \sigma_a r
\]

\[
A_0^a = 4\pi^{1/2} \beta v_R \Delta \sigma_a S_a^{1/2}
\]

\[
r \ll R
\]

\[
\Delta \sigma_a \neq 0, \quad \Delta \sigma_b = 0
\]

\[
S = \pi R^2, \quad S_a = \pi r^2
\]
Relation between Combined Asperity Size \((Sa)\) and Total Rupture Area \((S)\)

- \(Sa\): Combined Asperity Area
- \(S\): Total Fault Area
- \(Sa/S = 0.22\)
- \(Da\): Average Slip on Asperities
- \(D\): Average Slip on Total Fault
- \(Da/D = 2.0\)

(Somerville et al., 1999)

\[\Delta\sigma_c: \text{Average stress drop} \]
\[\Delta\sigma_a: \text{Stress drop on asperity} \]

\[\Delta\sigma_a = \Delta\sigma_c \cdot \frac{S}{S_a}\]
(a) Single-Asperity Model

\[ \Delta \sigma_{\text{asperity}} = \frac{7}{16} \frac{M_0}{R r^2} \]

(b) Single-Crack Model

\[ \Delta \sigma_{\text{crack}} = \frac{7}{16} \frac{M_0}{R^3} \]

\[ D(x) = ? \]

\[ D(x) = \frac{24}{7\pi} \frac{\Delta \sigma_{\text{crack}}}{\mu} \sqrt{R^2 - x^2} \]
Dynamic rupture simulation for circular asperity models

- A simple slip weakening model
- Staggered grid finite difference method
- Calculate time histories of slip-velocity, slip, and stress for a single and multiple circular asperity model
- Compare the results between spontaneous and fixed rupture models
- Our code ability is checked compared the results for the circular asperity model solved by Fukuyama and Madariaga (1998) using BIEM.
Parameters of asperity source model

S  : Entire rupture area (= 400 km²)
Sa  : Combined asperity area (= 0.22 S)
Sb  : Background area (= S - Sa)
Δσₐ : Stress drop on asperities
Δσₐ : Stress drop on background area (-0.2Δσₐ to +0.2Δσₐ)
Dc  : Critical slip (= 0.4 m)
Se  : Strength excess for background area
    (=0.3Δσₐ for spontaneous rupture model, = 0 for fixed rupture velocity model)
Δx : Grid size for finite difference method
Time-slip velocity at the position assigned from 1 to 8 in the right figure obtained from dynamic simulations for stress-drop ratio $\Delta\sigma_b/\Delta\sigma_a = 0.0$. 
Slip Distribution for Single and Double Asperity

Dasp: Average slip on asperity
D: Average on total fault
Empirical Relation for Controlling Inner Fault Parameters
- Acceleration Source Spectra (Ao) versus Seismic Moment (Mo) -

\[ Ao \propto Mo^{1/3} \]

\[ A_0^a = 4\sqrt{\pi \beta v_r} \cdot \sigma_a \cdot \sqrt{S_a} \]
\[ Sa = \left(\frac{7\pi}{4} \cdot \beta v\right)^2 \cdot \frac{M_o^2}{S \cdot (A_0^a)^2} \]

Dan et al. (2001)
What parameters do we need to have for predicting strong ground motions from future earthquakes

1. Where is the source area of future earthquake?
   - Entire rupture area → Total seismic moment
     → Outer fault parameters

2. Slip heterogeneity (Roughness) of faulting
   - Strong motion generation area
     → Asperities and stress drop on the asperities
     → Inner fault parameters

3. Extra important parameters
   - Rupture starting point,
   - Rupture propagation pattern, Rupture velocity
**Source Modeling based on the Recipe**

**Outer fault parameter**

**Step 1:** Fault Length (L) and Fault Width (W) from geological and geomorphological survey → Fault Area (S)

**Step 2:** Average Stress Drop ($\Delta \sigma$) from empirical relations (e.g., about 3.0 MPa for subduction earthquakes)

**Step 3:** Estimate Total Seismic Moment ($M_o$) from $S$ and $\Delta \sigma_c$ assuming a circular crack model → M8.1 & M8.4

$$
M_0 = \frac{16}{7\pi^{1.5}} \Delta \sigma_c \cdot S^{1.5}
$$
$W_{\text{max}}$ for subduction earthquakes

South-West Japan

Cascadia (half scale)

Hyndman et al.
(1997)
**Table 4.1. Earthquake scaling relations**

<table>
<thead>
<tr>
<th>Size regime</th>
<th>Slip scaling</th>
<th>Moment scaling</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. ( L &lt; W^* )</td>
<td>( \Delta u \propto L )</td>
<td>( M_0 \propto L^3 )</td>
</tr>
<tr>
<td>2. ( W^* &lt; L &lt; 10W^* )</td>
<td>( \Delta u \propto L )</td>
<td>( M_0 \propto L^2W^* )</td>
</tr>
<tr>
<td>3. ( L \geq 10W^* )</td>
<td>( \Delta u \propto W^* )</td>
<td>( M_0 \propto LW^*^2 )</td>
</tr>
</tbody>
</table>

*Shaw and Scholz (2001)*

*Scaling proposed by Scholz (2002)*
Rupture area vs. $M_0$ (inland crustal earthquakes)

- **This study**
- Scholz (1982) strike slip
- Wells and Coppersmith (1994) ($M_0 > 7.5 \times 10^{18} \text{ Nm}; M_w > 6.52$)
- Somerville et al. (1999)
- S.D. ($\sigma$)
- Factor of 2 and 0.5
- Low angle dip-slip fault

**Legend:**
- $L = 10W_{\text{max}}$
- $L = W_{\text{max}}$
- $2.3 \text{ MPa}$

**Axes:**
- X-axis: $M_0 (Nm = 10^7 \text{ dyne-cm})$
- Y-axis: Rupture area ($\text{km}^2$)
Rupture area vs. $M_0$ (subduction earthquakes)
Source Modeling based on the Recipe

**Inner fault parameter (1)**

- **Step 4:** Estimate Combined Asperity Area from empirical relation $S_a - S$
  - Assume Case 1: $S_a/S = 0.3$ and Case 2: $S_a/S = 0.15$

- **Step 5:** Estimate Stress Drop $\Delta \sigma a$ on Asperities from multi-asperity model
  - (e.g., Case 1: $\Delta \sigma a = 10.1 \text{ MPa}$ for $S/S_a=0.30$ and Case 2 : $\Delta \sigma a = 20.1 \text{ MPa}$ for $S/S_a=0.15$)

- **Step 6:** Estimate number of asperities

- **Step 7:** Estimate Slip on each asperity

$$D^i_a = C \cdot \frac{\Delta \sigma_a}{\mu} \cdot r_i$$
Rupture area vs. combined area of asperities

Crustal earthquakes

\[ S_a = 0.215 \, S \]

Subduction earthquakes

\[ S_a = 0.25 \, S \]
**Source Modeling based on the Recipe**

**Inner fault parameter (2)**

**From empirical relationship between Ao and Mo**

- **New Step 4:** Acceleration source spectral-level Aoa from asperity area and Aob from background area area given by Madariaga (1977)

\[
A_0^a = 4\sqrt{\pi} \beta \nu_r \cdot \sigma_a \cdot \sqrt{S_a} \\
A_0^b = 4\sqrt{\pi} \beta \nu_r \cdot \sigma_b \cdot \sqrt{S_b}
\]

- **New Step 5:** Ao~Aoa is assumed from the following relations

\[
\frac{A_0^b}{A_0^a} = \frac{S_b}{S_a} \cdot \frac{\sigma_b}{\sigma_a} \ll 1 \quad \therefore \quad \frac{A_0^a}{A_0} = \frac{1}{\sqrt{1 + \left(\frac{A_0^b}{A_0^a}\right)^2}} < 1
\]

0.8~0.95 from the empirical relation for inland earthquakes

- **New Step 6:** Asperity area is estimated from Aoa, Mo and S

\[
S_a = \left(\frac{7\pi^2}{4} \beta \nu_r \right)^2 \cdot \frac{(M_o)^2}{S \cdot (A_0^a)^2}
\]

- **New Step 7:** Stress drop at asperity is estimated from the multi-asperity model

\[
\Delta \sigma_a = \overline{\Delta \sigma_c} \cdot \frac{S}{S_a}
\]
Hybrid Method

Division of each asperity to subfaults
(size of subfault: 1 km × 1 km)

Long period motion (> 1 sec)
3-D F.D.M. simulation for each subfault

Short period motion (< 1 sec)
Boore (1983) and Irikura (1986)

Estimation of amplification characteristics due to surface layers

Addition of both long and short period motions in time domain
Are asperities repetitious?

Some proofs:

1. Repetition of asperities from source inversion results the 1968 Tokachi-oki Earthquake and 1994 Sanriku-oki Earthquake
2. Coincidence of surface slip variation and locations of asperities the 1994 Landers earthquake and the 1999 Chi-chi earthquake

How to find the asperities?

1. Surface slip distribution along active faults
2. Seismic activity: less active inside asperities and relatively more active surrounding the asperities
3. Reflected (scattered) waves: strong : less reflection (scattering) coefficients inside asperities and relatively high outside asperities.
Repetition of Asperities
Spatial Distribution of Moment Releases during 1968 Tokachi-oki Earthquake and 1994 Sanriku-oki Earthquake

(Nagai et al., 2001)
Correlation between surface offsets measured along fault traced and asperities on fault segments during the 1992 Landers earthquake (Wald and Heaton, 1994)
98 active faults subject to fundamental survey in Japan

Earthquake Research Committee (1998)
Fault Segmentation for Itoigawa Shizuoka Tectonic Line (1)

Northern part and central part seem to be active simultaneously.

Earthquake Research Committee (2001)
Fault Segmentation for Itoigawa Shizuoka Tectonic Line

Northern part 1 → 26 km
Northern part 2 → 35 km
Central part 1 → 17 km
Central part 2 → 34 km

Total rupture length is set to 112 km.

Earthquake Research Committee (1998)
How to Evaluate Fault Width?

Seismic activity and structure survey provide us upper/lower limit of seismogenic zone.

Earthquake Research Committee (2001)
Simulated Acceleration Waveform

Earthquake Research Committee (2001)
Attenuation curve for PGA and PGV

*PGA*

*PGV*

Earthquake Research Committee (2001)
Prediction of Strong Ground Motion for Itoigawa-Shizuoka Tectonic-Line Fault Earthquake

PGV Attenuation-Distance Relation

Ground Motion Simulation by the Hybrid Method

Earthquake Research Committee (2002)
Source Modeling of the Miyagi-ken-oki earthquake - Based on the Recipe of Strong Motion Prediction -

Source Model for 1978 Miyagi-ken-oki earthquake

Comparison between observed and simulated velocity records at DKHB
Pseudo Velocity Response Spectrum for the Hypothetical A1 Event (the 1978 Miyagi-ken Oki earthquakes)
Seismic Intensity Map Calculated for Hypothetical Miyagi-ken Oki Earthquake

Solid Circle: Questionnaire seismic intensity for the 1978 Miyagi-ken Oki earthquake
PGV-Distance Relation for the Hypothetical A1 Event
(equivalent to the 1978 Miyagi-ken Oki earthquake)

Empirical relation by Shi and Midorikawa (1999)
Solid line: average.
Broken line: 1σ