Quickly Imaging Global Large Earthquakes Using Seismic Waveforms

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A balance between quickness and accuracy

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In collaborative with

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2011 Mw 9.1
Tohoku Earthquake

The tsunami, seen crashing into homes in Natori, Miyagi prefecture. AP

Fukushima nuclear crisis: March 11th earthquake caused >0.5 g ground acceleration and 15 m tsunami run-ups, the latter topped the plant's 5.7 m seawall
1278 broadband seismic stations available in IRIS DMC after the 2011 Tohoku earthquake
PROCESSING: Rapid Global Earthquake Finite-Fault Inversion

INITIAL INPUT (Automatic)
- Hypo & CMT
- Waveforms
- Geodetics

REVIEWED INPUT (Interactive)
- Data Review
- Adjust Constraints

INVERSION
- Finite Fault Inversion
- Constraints

PRODUCTS
- Slip Model
  - Predicted Peak Ground Motions
  - Computed Stress Change
- ShakeMap
  - Overall Impact
  - Damage & Losses
- Fault Model Database
  - Hazard Change
  - Modified Probabilities
  - Triggering

Independent Fault Info
- Aftershocks, Fault Offset & Geometry

Courtesy of D. Wald
How to improve a geophysical inversion?

• Increasing the amount of observations.
• Reducing the number of unknowns
• Improving the criteria for the minimization.
• Avoiding the local minima

\[ \vec{M} \text{ is the vector of unknowns; } \]
\[ \vec{D} \text{ is the vector of observations } \]
\[ \vec{D}_{predicted} = G(\vec{M}) \]

An inversion is searching for:

\[ \vec{M}_{target} : \min(\vec{D}_{predicted} - \vec{D}_{observed}); \]
Finite Fault Approximation (Ji et al., 2002, 2003)

\[ Y_{jk}(t, t', \bar{x}) = \sum_p G^i_{jk}(\bar{x}'_p, \bar{x}, t) \ast \delta(t - \Delta t_{jk}^p - t') \]

\[ u(t, \bar{x}) = \int_\infty_{-\infty} \int \int [u_i(\xi, \tau)] c_{ijpq} \partial G_{np}(\bar{x}, t - \tau; \xi, 0) / \partial \xi_q d \sum \]

\[ u(t, \bar{x}) \approx \sum_{j=1}^{n} \sum_{k=1}^{m} D_{jk} [\cos(\lambda_{jk}) Y^1_{jk}(t, t', \bar{x}) + \sin(\lambda_{jk}) Y^2_{jk}(t, t', x)] \ast \dot{S}_{jk}(t) \]

- **D_{jk}**: Slip amplitude
- **\lambda_{jk}**: Rake angle
- **\dot{S}_{jk}(t)**: Slip rate function
- **t'**: Rupture initiation time
- **Y^i_{jk}(t, t', \bar{x})**: Subfault Green’s functions

\[ S(t) = \begin{cases} 
\frac{1}{t_s + t_e} (1 - \cos(\pi t)) & 0 < t < t_s \\
\frac{1}{t_s + t_e} (1 - \sin(\pi(t - t_s)/t_e)) & t_s < t < t_s + t_e 
\end{cases} \]

- **t_s**: Starting - phase time
- **t_e**: End - phase time

Slip rate function S(t)
Data Included

Seismic Data

Geodetic Data

Geological Data

Seismogram

GPS Site at Yellowstone

A 4-m waterfall created by Chi-Chi earthquake
Teleseismic Body Wave & Surface waves

- **Original system** used only (1-150 s) broadband body waves, similar to peer studies.
- **Current system** further includes long period (166s-250s) seismic waves.

Records of 2004 Mw 9.15 Sumatra Earthquake, Courtesy of J. Park
Conducting Quick finite fault inversion:
A balance between quickness and accuracy

Quickness
- Reducing the time for data to become available
- Reducing the time to setup the inversion
- Reducing the time of finite fault inversion

Accuracy
- Improving the quality of ‘a priori’ information, such as hypocenter location, fault geometry, velocity structure, and source representation
- Increasing the amount of independent measurements

Easy to learn

Dr. Gavin Hayes, USGS
How quick to obtain a solution after data becomes available?

Five minutes: data process, point source inversion, and calculating Green's functions.

Five minutes: inversion for a source with 200 subfaults, using a PC with a 4-core 2.66GHz Intel CPU (test done in 2010).
However,

- Even without considering the latency of network, it takes 12-25 minutes to have P & SH waves, and 1 hour to have long period surface waves.

- System can be operated automatically. But during the current practices, users inspect the preliminary waveform comparisons and inverted slip models. They often make some empirical corrections using the provided tools and might conduct multiple inversions before the result is released online.
Why long period seismic waves?

2006 Nov 15, Mw 8.3
Kurile island Earthquake

Legend:
Red contour:
2 m iso-slip contour
Red dots
aftershocks
White dots
seismicity
Why long period seismic waves?

A. Body & surface waves. Smoothing rupture front constraint
C. Body waves only, Smoothing rupture front constraint

2006 Kuril island Eq
Good news:

A upgrade of GSN stations has just been accomplished. The dynamic range of most broadband sensors becomes 8 times larger. For the future giant earthquakes we can count on long period broadband waveforms at stations within 30° away from the source. These data can be available within half hour.
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Comparison of Body waves

[Shao et al., 2011]
Comparison of Long period seismic waves

[Shao et al., 2011]
Comparison of inverted slip models

(a) Slip model constrained by teleseismic data.
2013 Mw 6.6 Lushan earthquake

The earthquake has resulted in 196 people dead, 24 missing, at least 11,826 injured.

http://www.sc.xinhuanet.com/content/2013-04/26/c_115562255.htm
Comparison of Slip Models

1. Using P waves in velocity.
2. Correcting 3D effects of the surface waves.

[Hao. 2013, GRL, submitted]
Check-board Test

(a) Target

(b) Teleseismic

(c) Strong motion

(d) Joint
Unsuccessful case: 2012 Mw 8.6 Indian ocean earthquake

inaccurate “a priori” fault geometry

[Shao et al., 2012]
MDC Analysis of 2012 Indian Ocean earthquake [Ji et al., 2012]

Five-DCs is the preferred solution.

3-10 mHz seismic data.
Multiple double couple (MDC) inversions: A global survey of recent Mw>=8 earthquakes

Using the 2-6 mHz waveforms at vertical and transverse components

For five of 20 Mw>=8 earthquakes analyzed, using multiple point sources leads to significant improvement in waveform fits.

[Li et al., 2010]
SPICE BlindTest I (Mai et al., 2007)

- Data
  1: Seismic waveforms at 35 station (velocity, 0-2 Hz)

- “A priori” information
  1: Fault geometry
     (strike, dip, rake: 150°, 90°, 0°)
  2: Hypocentral location
  3: Velocity structure

- Parameter Boundaries
  Subfault size: 1km by 1km
  Slip amplitude: 0 - 8 m
  Rupture velocity: 1.3 – 4.0 km/s
  Rise time function
  starting time: 0.1 s -0.8 s
  ending time: 0.1 s -0.8 s
Hypothetic Test: Peak Slip

Model III: Peak slip = 2.5 m

Target_SC

Shao & Ji, GJI 2012
"Coherence" Function

High frequency signals are sensitive to the details of the slip models.

\[
e(f) = \frac{1}{N} \sum_{i} \frac{2 \text{REAL}[d_i(f)s_i^*(f)]}{d_i(f)d_i^*(f) + s_i(f)s_i^*(f)}
\]

![Model I](image1)

![Model III](image2)

Shao & Ji, GJI 2012
Average amplitude spectrum of the data used during the study of 2010 Tohoku Eq.
Coherence between Data and Synthetics

\[ e(f) = \frac{1}{N} \sum_{i=1}^{N} \frac{2 \text{REAL}[d_i(f)s_i^*(f)]}{d_i(f)d_i^*(f) + s_i(f)s_i^*(f)} \]

[Shao & Ji, 2012]
Suppose the excited ground motion at the $i$-th station can be represented as

$$s_i(t) = \sum_{j=1}^{N} M^j(t) * W^j_i(t)$$

For the $j$-th subevent, we can define simple back-propagation function (SBP) and network response function (NRF) as

$$sbp_j(t) = \sum_{i=1}^{L} s_i(t) * W^j_i(-t)$$

$$nrf_j(t) = \sum_{i=1}^{L} W^j_i(t) * W^j_i(-t)$$

It is straightforward to prove

$$mbf_j(t) = sbf_j(t) *^{-1} nrf_j(t)$$

Modified back-projection function (MBF)

$$mbf_j(t) = \dot{M}^j_0(t) + \sum_{k \neq j}^{N} \dot{M}^k_0(t) * \left[ \sum_{i=1}^{L} W^k_i(t) * W^j_i(-t) \right] *^{-1} nrf_j(t)$$

Target

Imaging error caused by the slip on the rest of fault plane

[Yano et al., in preparation]
As the high frequency radiation is mainly caused by the initial rupture, we assume the target subevent has a 0.8 s triangular slip rate function.

[Tinti et al., 2005]
Comparison of Back-projection (BP) Functions And Network Response Function (NRF)

[Yano, 2012]
Multiple point Sources

(a) SBP

(b) CBP

Contrast

[Yano, 2012]
Test of Back-projection:  
3. Coarse Line source

[Yano et al., 2012]
Back-Projection Test

4. dense Line source

[Contrast]

0.0 0.2 0.4 0.6 0.8 1.0

[150 point sources at 1 km grids]

[Yano et al., 2012]
Comparison of Moment Rate Functions

15 km interval target sources

1 km interval target sources

[Yano, 2012]
Single Variation in Moment Rate

While the back projection can determine the location of the single point that varies, the amplitude is proportional only to the height above the constant moment rate. Compare beginning and ending points with the point in the middle.

[Yano et al., in preparation]
Variation in Moment Rate

Moment rate function of Target Model

[Yano et al., in preparation]
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Conclusions

- Finite fault inversion (QFFI) systems are developed to quickly image the large earthquakes using local and distant seismic waveforms. When “a priori” information about fault geometry and hypocenter is reliable, the general characteristics of source could be well constrained with body and surface waves. A multiple double couple (MDC) algorithm was developed to handle the case that source might have irregular fault geometry.

- A good variance reduction to the broadband signals does not imply an equally well match to the seismic data in all frequency bands or within all individual time windows. Frequency dependent objective function need be constructed.

- Back-projection analysis is good to resolve the high frequency radiation from isolated sources. But for continuous rupture, high frequency radiation captured by the back-projection analyses generally DOES NOT have a one to one relationship with the true high frequency radiation from an individual slip patch.

- The fact that rupture front of large earthquakes could be imaged by back-projection analysis (e.g., Ishii et al., 2005) implies that the migration of rupture front is heterogeneous.