Seafloor Geodesy

A New Challenge for Approaching Great Earthquakes around Japan

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18th International Workshop on Laser Ranging
Fujiyoshida, Japan
11 November 2013
The Great East Japan Earthquake (M9.0)
The Great East Japan Earthquake (M9.0)

14:46
11 March 2011

Property damages (doors)
- Total Collapse: 126,583
- Half Collapse: 272,315
- Partially Damaged: 742,867

Personnel damages (persons)
- Killed: 15,883
- Missing: 2,652
- Injured: 6,149

Tectonic Overview around Japan

North American Plate

Eurasian Plate

Philippine Sea plate

Pacific Plate

Rupture area

Nankai Trough

Japan Trench

triggered tsunami

Earthquake!

Earthquake!
Seafloor Geodesy has found huge offshore displacements!!

Sato et al. (2011) reported in Science Magazine
Seafloor Geodesy

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JCG operating SLR at Simosato

- Operated more than 30 years since 1982
- Core site of the Marine Geodetic Control project in Japan

Poster Presentation
Po35: “Satellite Laser Ranging at Shimosato Hydrographic Observatory”
Role of Space Geodesy

for earthquake research
Early VLBI results by Heki et al. (1987)
Role of Space Geodesy for earthquake research

• Verifying and understanding plate tectonics
  – Measurement of present-day long-range movement
    ~ Success in SLR & VLBI

• Monitoring crustal deformation
  – Real-time measurement
  – Contribution to modeling
    ~ Development of high-density GPS network
Dense GPS network in Japan

- 1200 reference points
- Real time operation

Intraplate movement for interseismic period

(Modification to the figure produced by the Geodetic Society of Japan)
Role of Space Geodesy for earthquake research

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Seafloor Geodesy ~ Open a new window in this field
How it works?

In the coseismic case for the 2011 event (M9.0)
Coseismic movement (onland+seafloor) associated with the 2011 event

- **Horizontal**
  - on land (by GSI)
  - on seafloor (by JHOD)

- **Vertical**
  - on land (by GSI)
  - on seafloor (by JHOD)

M9.0

5m 100 km

50cm 100 km
Slip distribution model with and without seafloor data

Without Seafloor data

Maximum 27m

With seafloor data

Maximum 56m

from GSI web page
Mechanism of Tsunami Excitation

Continental Plate

Oceanic Plate
Slip distribution model with and without seafloor data

Without Seafloor data

Maximum 27m

With seafloor data

Maximum 56m

from GSI web page
How & what to measure?

General aspects
How to measure?

GPS/Acoustic combination technique
What is a target?

Interseismic movement
at centimeters level!!

Coseismic movement
could be at meters level
What is a target?

Seafloor movement at centimeters level

coupled area (asperity)
where landward plate is dragged down together
Seafloor Geodesy

Observation by JCG
GPS/A Observation system with S/V

(Hull-mounted system)

GPS antenna

Motion sensor

Seafloor stations (Mirror-type transponders)

Acoustic transducer

Seafloor

XBT

XCTD

CTD

Photo by JAMSTEC
Onsite operation

The vessel runs at a speed of 5-8 knots.

1300 shots (5 hours) × 4 times

Ranging data of about 5200 shots
Flow of data analysis

(1) Acoustic wave analysis

Acoustic Wave Data

Round-trip travel time b/w vessel and transponder

(2) Kinematic GPS analysis

GPS Data

Antenna position

Correction

Attitude Data

Transducer position

(3) Underwater positioning

Seafloor station position

Correction

Sound Speed Data

Seafloor Reference Point
(1) Acoustic wave analysis

Transmitted (M-sequence signal)  Received

Original M-seq signal

Cross-correlation method

$1 \lambda = 100 \mu \text{sec} \sim 15\text{cm}$
Flow of data analysis

(1) Acoustic wave analysis

- Acoustic Wave Data
- Round-trip travel time between vessel and transponder

(2) Kinematic GPS analysis

- GPS Data
- Antenna position
- Transducer position
- Correction
- Attitude Data

(3) Underwater positioning

- Sound Speed Data
- Seafloor station position
- Seafloor Reference Point
(3) Underwater positioning

Acoustic Ranging

Sound speed error

Ranging error

Seafloor station

Linear Inversion
- Station position
- Sound speed

\[
\begin{pmatrix}
\Delta t_{1E} \\
\Delta t_{2E} \\
\vdots \\
\Delta t_{nE}
\end{pmatrix} = G_E \cdot \begin{pmatrix}
\Delta x_E \\
\Delta y_E \\
\Delta z_E
\end{pmatrix}
\]
Major error source

- Errors included in the sound speed

- Sound speed in water $\sim 1.5\text{km/s}$
- Temporal & Spatial variation
- $0.1\% \sim 15\text{cm/s}$
- $D=2000\text{m} \sim 20\text{cm difference}$

Error reduction through estimation of sound speed
Sound speed estimation

Estimation condition
- horizontally layered
- 2\textsuperscript{nd} polynomial approximation in time

(Fujita et al., 2006)
Precision of seafloor positioning

~Example of time series at TOKW~

**East-West**

RMS = 1.7 cm

\[ -4.3 \pm 0.5 \text{ cm/year} \]

**North-South**

RMS = 1.3 cm

\[ 2.0 \pm 0.3 \text{ cm/year} \]
Seafloor Geodesy

Major Results

for the interseismic period
Distribution of Seafloor Reference Points
(before the 2011 Great East Japan Earthquake)

- Landward slope of the Major trench
  - Japan Coast Guard: 18
    about 100km interval
  - Tohoku Univ.: 6
    mainly off Miyagi Pref.
  - Nagoya Univ.: 8
    Suruga bay, Kumano basin

- Water depth mostly
  1500 - 2500m (JCG)
Tohoku region

where the huge earthquake has just occurred
Time series of the estimated positions before the 2011 earthquake (2002-2011.2, vs EU)

MYGW

Eastward
-5.5 +/- 0.2 cm/year RMS=0.7 cm

Northward
0.5 +/- 0.4 cm/year RMS=1.5 cm

8/16/2005 (M7.2)
3/11/2011 (M9.0)

MYGI

Eastward
-6.7 +/- 0.7 cm/year RMS=2.4 cm

Northward
3.6 +/- 0.6 cm/year RMS=2.3 cm

8/16/2005 (M7.2)
3/11/2011 (M9.0)

FUKU

Eastward
-1.9 +/- 0.4 cm/year RMS=3.2 cm

Northward
-0.1 +/- 0.4 cm/year RMS=3.4 cm

3/11/2011 (M9.0)
Interseismic crustal velocities
(before the 2011 earthquake)

- Miyagi: 5.5 cm/y
- Fukushima: 1.9 cm/y
- Tokyo: 8 cm/y
- Pacific Plate: 8 cm/y

Map showing interseismic crustal velocities with vectors indicating movement. The map also shows an illustration of strain accumulation and subduction processes.

Example of time series at FUKU

2011 event
Expansion of Seafloor Network

By Tohoku University

- 20 more sites in 2012
  - 1000～2000m ••• 1
  - 2000～3000m ••• 4
  - 3000～4000m ••• 2
  - 4000～5000m ••• 7
  - 5000m以深 ••• 6

1-D to 2-D
Nankai region

where huge earthquakes were repeated and are expected in the future
Nankai Megathrust earthquakes

- M8.4 (1946)
- M8.1 (1944)
- Mt. Fuji
- Tokyo
- Triggered tsunami
- Earthquake!
Nankai Megathrust earthquakes

- Repeated every 100-150 yrs

Hoei Eruption of Mt. Fuji (1707) 49 days after the earthquake

Modified from Seno (2012)
Hoei eruption (1707) of Mt. Fuji

Report by the Committee under the Cabinet Office

Spread of Volcanic Ash

View from SE of Mt. Fuji

Aerial photo (Hoei Crater)

※Photos are taken from Wikipedia
Seafloor reference points along the Nankai Trough
(before the 2011 Tohoku earthquake)
Time series of the estimated positions along the Nankai Trough

<table>
<thead>
<tr>
<th>Location</th>
<th>Eastward</th>
<th>Northward</th>
</tr>
</thead>
<tbody>
<tr>
<td>TOKE</td>
<td>4.4 years</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-3.8 ± 0.4 cm/year RMS = 1.8 cm</td>
<td>15 ± 0.2 cm/year RMS = 0.9 cm</td>
</tr>
<tr>
<td>TOKW</td>
<td>3.4 years</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-4.3 ± 0.5 cm/year RMS = 1.7 cm</td>
<td>20 ± 0.3 cm/year RMS = 1.3 cm</td>
</tr>
<tr>
<td>KUMA</td>
<td>3.4 years</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-1.9 ± 0.7 cm/year RMS = 1.9 cm</td>
<td>1.0 ± 0.5 cm/year RMS = 1.6 cm</td>
</tr>
<tr>
<td>SIOE</td>
<td>4.6 years</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-2.5 ± 0.4 cm/year RMS = 1.7 cm</td>
<td>1.9 ± 0.5 cm/year RMS = 2.0 cm</td>
</tr>
<tr>
<td>SIOW</td>
<td>3.4 years</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-3.8 ± 0.9 cm/year RMS = 2.7 cm</td>
<td>2.3 ± 0.6 cm/year RMS = 1.8 cm</td>
</tr>
<tr>
<td>MURO</td>
<td>4.3 years</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-2.6 ± 0.4 cm/year RMS = 1.6 cm</td>
<td>0.7 ± 0.4 cm/year RMS = 1.7 cm</td>
</tr>
</tbody>
</table>

Position reference: EU plate

March 11, 2011
Tohoku-oki earthquake (M9.0)

 Philippine Sea Plate
4~5 cm/year

Eastward
Northward
Velocity vectors on the seafloor along the Nankai Trough (~2011)
Back slip estimation with and without seafloor data

Preliminary results by Yokota et al. (2013)
Expansion of Seafloor Reference Points along the Nankai Trough (2011 ~)

6 pts to 15 pts  ➔  1-D to 2-D
Expanded Seafloor Geodetic Network in Japan

- Japan Coast Guard (2011-)
- Nagoya University (2013-)
- Tohoku University (2012-)

Legend:
- Japan Coast Guard
- Nagoya University
- Tohoku University

Scale:
- 0 km 100 km 200 km

Map of Japan with marked locations for each institution.
Another Seafloor Network in Nankai region
DONET* by JAMSTEC

- Seafloor cable network
  - DONET1: 20 pts, completed in Aug. 2011
  - DONET2: 30 pts, started in 2010
- Seismometer, Water-pressure gauge, Hydrophone ...

* DONET = Dense Oceanfloor Network system for Earthquakes and Tsunamis
Thank you for your attention!