Case Study of Japan: Crustal deformation monitoring with GNSS and InSAR

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Outline

• Introduction
  • Tectonic background in Japan.
• Two main techniques for monitoring crustal deformation: GNSS CORS and InSAR
• Monitoring consecutive deformation with GNSS CORS
• Semi-Dynamic geodetic reference frame of Japan
• Detecting coseismic displacement with InSAR
• An example: the 2016 Kumamoto Earthquakes
  • Detection of displacement, Source fault modeling
Tectonic background in Japan

- Japan is located on an area where four active plates are colliding.
- Subduction rates are 8.5 cm/yr for Pacific plate, 2.5 cm/yr for Philippine sea plate, and 0.9 cm/yr for Eurasian plate relative to North American plate.
- Such active plane tectonics makes the country continuously deforming and prone to earthquakes and volcanic activities.
- Crustal deformation monitoring is essential to maintain geodetic reference frame.

Martin et al. (2012)
Two techniques for monitoring

- GSI of Japan is monitoring crustal deformation of Japan with two techniques; GNSS CORS network (GEONET) and SAR interferometry (InSAR) of ALOS-2.

GNSS CORS network
- GEONET -

InSAR of ALOS-2

Analysis by GSI from ALOS-2 raw data of JAXA
GEONET

GNSS Earth Observation Network System

- GNSS continuously operating reference stations (CORS) covering Japanese archipelago for surveying and crustal deformation monitoring.
- 1318 stations (As of July 2017).
- Average spacing between stations about 20 km.
- Precise coordinate time series at each CORS station.
- Powerful tool for both monitoring secular crustal deformation and episodic coseismic displacement.
GEONET station

- Stainless steel pillar (5m tall)
- Chokering Antenna
- Clinometer and thermometer
- Dual frequency receiver (GPS, QZS, Galileo, Glonass)
- 24-hr observation
- 1-sec and 30-sec sampling
- 1-Hz real-time data transfer for crustal deformation monitoring and N-RTK services
- Both IP/VPN real-time and mobile phone communication
Secular deformation by plate tectonics

- Secular crustal deformations have been observed by GEONET.
- Length of a baseline between east and west coast regions is decreasing at the rate of about 10-20 mm/yr.
- The pattern of deformation is not simple because of complicated tectonics.

Diamond: Baseline length (mm)

Horizontal displacement vector map detected by GEONET coordinate time series

(A) Baseline length (mm)

(B) Naruko-Tobishima

(Heki, 2001)
Monitoring with GEONET

- GNSS CORS offers precise coordinate time series at each station.
- Dense GNSS CORS network provides precise displacement field.
- GEONET covers the whole area of Japan with 20km average spacing.
- Precise displacement field of Japan has been monitored with GEONET since 1994.

Horizontal absolute displacement vector map detected by GEONET coordinate time series from 1997 to 2017
How to model crustal deformation

1) Cumulative crustal deformation is calculated from coordinate time series at each CORS station (average spacing 20km)

2) Deformation is estimated for each 5km grid by interpolating the deformation at each CORS station.

3) Users can estimate crustal deformation anywhere in the country by interpolating the estimated deformation at the grids.

4) The cumulative crustal deformation is updated once a year.
Cumulative deformation from GEONET

Horizontal Displacement

From reference epoch to 2017/01/01

Vertical Displacement

From reference epoch to 2017/01/01

※Reference epoch: 1997/01/01 (Hokkaido and West Japan)
2011/05/24 (West Japan)
Semi-Dynamic datum of Japan

- GSI has developed cumulative crustal deformation model from GEONET and utilized it for maintenance of geodetic reference frame of Japan.
- Geodetic reference frame of Japan is Semi-Dynamic datum.
- All positions are described as positions at reference epoch.
- Reference epoch is 1997/01/01 (Hokkaido and West Japan) and 2011/05/24 (West Japan).
- Semi-Dynamic correction is a method to align epoch of surveying to reference epoch. (Correction values are updated once a year)

Flow of Semi-Dynamic correction

- Positions of CORS at reference epoch
  - Add correction value to positions of CORS
- Positions at CORS at this year
- GNSS positioning of new points
- Positions of new points at this year
  - Remove correction value from positions of new points
- Positions of new points at reference epoch

Position

Cumulative deformation = Correction value

Reference Epoch
(1997/01/10 or 2011/05/24)

This year
(2017)

Time
Detection of Coseismic displacements

List of large earthquakes in Japan caused large crustal displacements

<table>
<thead>
<tr>
<th>Date</th>
<th>Event Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1995.1.17</td>
<td>Kobe EQ (M7.2)</td>
</tr>
<tr>
<td>2000.10.6</td>
<td>Tottori EQ (M7.3)</td>
</tr>
<tr>
<td>2003.9.26</td>
<td>Off-Tokachi EQ (M8.0)</td>
</tr>
<tr>
<td>2004.10.12</td>
<td>Niigata-Chuetsu EQ (M6.8)</td>
</tr>
<tr>
<td>2007.3.25</td>
<td>Noto peninsula EQ (M6.8)</td>
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<tr>
<td>2007.7.16</td>
<td>Off-Chuetsu EQ (M6.8)</td>
</tr>
<tr>
<td>2008.6.14</td>
<td>Iwate-Miyagi EQ (M7.2)</td>
</tr>
<tr>
<td><strong>2011.3.11</strong></td>
<td><strong>Off-Tohoku EQ (M9.0)</strong></td>
</tr>
<tr>
<td>2014.11.22</td>
<td>Nagano EQ (M6.7)</td>
</tr>
<tr>
<td>2016.4.16</td>
<td>Kumamoto EQ (M7.3)</td>
</tr>
</tbody>
</table>

- Japan has experienced a number of large earthquakes.
- Some of the earthquakes caused large coseismic and postseismic displacements up to several meters.
- Positions of control points need to be revised as prompt as possible in order to support rehabilitation and reconstruction.
- GSI detected the displacement with GEONET and InSAR and revised positions of control points as soon as possible.
Example: Coseismic displacement

The 2016 Kumamoto EQ (M7.3)

- The sequence of strike-slip earthquakes occurred in Kumamoto prefecture on 14-16 April 2016.
- GSI promptly calculated coseismic displacement from GEONET.
- In addition, GSI conducted InSAR analysis of SAR satellite of Japan, ALOS-2.

Horizontal displacement detected by GEONET

Displacement detected by ALOS-2 InSAR
Monitoring by InSAR

- GNSS CORS are powerful tool to detect precise displacement at stations.
- InSAR is also powerful tool to detect detailed special distribution of displacement even in the area without CORS.
- GSI is monitoring ground surface with InSAR images of ALOS routinely (4~6 a year).
- GSI also conducts emergency InSAR analysis of ALOS-2 once events occur.

Analysis by GSI from ALOS-2 raw data of JAXA

Routine analysis covering the whole country

Kaikoura Earthquake (New Zealand)

Emergency analysis for catastrophic events
Coseismic displacement by InSAR

- ALOS-2 has left and right looking observation capability and can observe ground surface from multi directions.
- 3-D displacement field can be retrieved by combining observation from multi directions.
- For Kumamoto EQs, 3-D coseismic displacement filed was retrieved from SAR pixel offset analysis of three independent SAR images.
3-D displacement detected by SAR

- 3-D coseismic displacement field is retrieved from SAR pixel offset analysis of ALOS-2.
- The field reveals detailed spatial distribution of coseismic displacement.
- Although maximum displacement detected by GEONET is 75cm, the maximum revealed by ALOS-2 is over 2m in horizontal and over 1m in vertical.
- An area of revision was identified from the 3-D displacement field.

3-D coseismic displacement field retrieved by ALOS-2 analysis

Analysis by GSI from ALOS-2 raw data of JAXA

- Epicenters of the two foreshocks and mainshock
- Estimated active faults (HERP, 2013)
3-D displacement detected by SAR

- 2m uplift
- Subsidence

Kumamoto JR Station

Mt. Aso

3-D displacement detected by SAR

Analysis by GSI from ALOS-2 raw data of JAXA.
Source fault model

- GSI developed earthquake source fault model from coseismic displacement field constructed from GEONET and SAR analysis.
- Three source faults were estimated and consistently explain observed displacement.

### 3D View

<table>
<thead>
<tr>
<th>Fault</th>
<th>longitude [°]</th>
<th>latitude [°]</th>
<th>upper depth [km]</th>
<th>length [km]</th>
<th>width [km]</th>
<th>strike [°]</th>
<th>dip [°]</th>
<th>slip angle [°]</th>
<th>slip amount [m]</th>
<th>Mw</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fault A1</td>
<td>130.996</td>
<td>32.878</td>
<td>0.6</td>
<td>20.0</td>
<td>12.5</td>
<td>235</td>
<td>60</td>
<td>209</td>
<td>4.1</td>
<td>6.96</td>
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<tr>
<td>Fault A2</td>
<td>130.975</td>
<td>32.883</td>
<td>0.2</td>
<td>5.1</td>
<td>6.6</td>
<td>56</td>
<td>62</td>
<td>178</td>
<td>3.8</td>
<td>6.36</td>
</tr>
<tr>
<td>Fault B</td>
<td>130.807</td>
<td>32.770</td>
<td>0.8</td>
<td>10.2</td>
<td>13.0</td>
<td>205</td>
<td>72</td>
<td>176</td>
<td>2.7</td>
<td>6.65</td>
</tr>
</tbody>
</table>
3-D displacement retrieved from InSAR

- Volcanic activity caused displacement at Sakurajima volcano in 2015.
- GSI retrieve 3-D displacement from four InSAR images from different observation directions.

InSAR images from four observation directions

3-D displacement field retrieved from InSAR and comparison between InSAR and GNSS

Estimation of 3-D deformation at each pixel from four independent SAR images observed from different observing directions.
Summary

• GSI is monitoring crustal deformation in Japan by utilizing GNSS CORS network (GEONET) and InSAR.

• Secular deformation mainly caused by plate motions is monitored and deformation model is developed from GEONET coordinate time series.

• Displacements caused by earthquakes are also detected by GEONET and InSAR and source fault models are developed from detected displacement.

• Crustal deformation field is utilized for maintenance of geodetic reference frame.

• Secular deformation model is utilized for Semi-Dynamic Correction of geodetic coordinates.

• Coseismic displacement is utilized for revision of geodetic coordinates of control points.