Clustering fluctuation patterns of groundwater levels in Tokyo caused by the Great East Japan Earthquake using self-organizing maps

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1 June, 2017
1. Background and Objective
2. Groundwater Monitoring Network in Tokyo and Data Used
3. Clustering Method using Self-Organizing Maps (SOM)
4. Identified Fluctuation Patterns and Discuss Their Causes
5. Conclusions
Location of Tokyo

Tokyo, Japan

12,000km

Cancun
Tokyo Metropolis

Third smallest prefecture (2188km²) out of 47  (1/23 of Quintana Roo)
The largest population (13.2 million)  (8.8 times larger than Quintana Roo)
The highest population density (6000/km²)
1/10 of whole National Budget
Whole Japanese Archipelago is in serious peril of severe earthquakes, because it is situated in the Circum-Pacific Seismic Zone.
Most of the megacities not only in Japan but also Southeast Asian countries are located on the alluvial plains where the ground is very soft and especially vulnerable for groundwater related disasters.

Since groundwater is a crucial water resource for most of the cities around the world, it is very important to understand and evaluate the impact of a huge earthquake on groundwater.

However, so far, almost no such studies have been carried out mainly because no densely distributed groundwater level observations were available at a short time interval when a large earthquake occurred.
The most powerful earthquake ever recorded in Japan with a magnitude of 9.0 (Mw) (4th strongest in the world), occurred at 14:46 JST on March 11, 2011.

More than 18,000 people were sacrificed or missing mostly by Tsunami.

In Tokyo, 5 upper intensity was observed, where more than 400km away from the epicenter.
Groundwater Monitoring Network in Tokyo

- Observation sites: 42 sites
- Confined wells: 89 wells
- Unconfined wells: 13 wells

The hourly groundwater levels have been observed since 1952.
Inside a Groundwater Observation House

- 42 observation sites in Tokyo.
- Most observation sites have several different depth observation wells.
Taking full advantage of the unique rare case data from the dense groundwater monitoring network in Tokyo, we identify the fluctuation patterns of groundwater levels caused by the Great East Japan Earthquake using SOM, which has never been investigated in Tokyo area.
One-month hourly time series data of 98 wells (85 confined and 13 unconfined wells) in March, 2011, excluding missing data wells.

The fluctuation patterns of the time series were analyzed and identified by SOM.
Groundwater level changes by the Earthquake

The effects of rain → None

Confined Wells

32-1: C-DR

26-1: C-N

20-1: C-DI

Scheduled blackouts

16-1: C-DC

Peculiar case

6-1: C-IC

©明
Groundwater level changes by the Earthquake

Unconfined Wells

14-4: U-I
Scheduled blackouts

5-1: U-I
SOM was developed by Kohonen, which is one of unsupervised training Neural Networks. SOM projects high-dimensional, complex data onto two-dimensional regularly-arranged nodes. SOM obtains useful and informative reference vectors of all nodes. In this study, SOM is used to cluster fluctuation of groundwater level changes.
## Input data for SOM

<table>
<thead>
<tr>
<th>Site No.</th>
<th>Well No.</th>
<th>Difference in water level</th>
<th>Strainer depth</th>
<th>Site name</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>(a)</td>
<td>(b)</td>
<td>(c)</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>-12.5</td>
<td>-11.2</td>
<td>4.8</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>-14.8</td>
<td>-7.8</td>
<td>3.9</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>-14.0</td>
<td>-15.0</td>
<td>-0.1</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>-27.3</td>
<td>-0.1</td>
<td>-0.4</td>
</tr>
<tr>
<td>42</td>
<td>2</td>
<td>-16.0</td>
<td>-2.4</td>
<td>15.3</td>
</tr>
<tr>
<td></td>
<td>③</td>
<td>0.5</td>
<td>4.3</td>
<td>6.8</td>
</tr>
</tbody>
</table>

1) Well No. ○: Unconfined groundwater, 2) (a) ~ (d): cm, (e): m

(a) 16:00, 11 March – 14:00 of the same day
(b) 14:00, 12 March – 16:00, 11 March
(c) the mean value of 14 March – 14:00, 12 March
(d) the mean value of 31 March – that of 14 March
(e) The altitude value of the depth of the screen. (T.P.: standard mean sea level of Tokyo Bay)

Considering the **crustal deformation** in Tokyo after the Earthquake was **4 cm** at the most, ± less than **5 cm** fluctuation water level in (a) to (d) is shown as 0, and ±**5 cm** or any value greater is shown as +1 or -1.
Input data for SOM

(a) 16:00 11th — 14:00 11th
(b) 14:00 12th — 16:00 11th
(c) The mean value 14th — 14:00 12th
(d) the mean value of 31th — that of 14th

Scheduled Blackout

Rain fall, No.19-1, No.23-1, No.25-3, No.30-2

Underground-water level (T.P.+m)

Rain fall (mm/h)
SOM Implementation

Map size \( M = 5\sqrt{n} \)

- \( M \): Number of total node,
- \( n \): Number of Input data

\[ n = 98 \quad \rightarrow \quad M = 50 \text{ node} \]
Identified Values for 5 Variables by SOM

(a) Just after the quake
(b) Next day
(c) three days later
(d) End of month

Legend:
- Large
- Small
- Deep
- Shallow

(e) Strainer depth

Legend:
- Difference in underground water level (standardized)
- Depth of screen (standard mean sea level of Tokyo Bay)

Number of Wells belong to each node
The fluctuation patterns of groundwater level could be classified into eight clusters, which are summed up to three groups.
Cluster 3: Sharp drawdown just after the earthquake, and rised higher than the original level.

Cluster 5: Sharp drawdown just after the earthquake, and recovered to the original level.

Cluster 6: Abrupt rise just after the earthquake, and decreased. Shallow wells.
Cause of Sharp Drawdowns

Ground Movements in Tokyo

- Pressure release by crustal expansion

<table>
<thead>
<tr>
<th>Legend</th>
</tr>
</thead>
<tbody>
<tr>
<td>○ Nerima A Erectorical Triangulation Points</td>
</tr>
<tr>
<td>- 341 direction of horizontality fluctuation</td>
</tr>
<tr>
<td>- 081171 No. of Erectorical Triangulation Point</td>
</tr>
<tr>
<td>- 341 amount of fluctuation</td>
</tr>
</tbody>
</table>

Legend:
- ○ Nerima A Erectorical Triangulation Points
- 341 direction of horizontality fluctuation
- 081171 No. of Erectorical Triangulation Point
- expansion
- compression

Crustal Deformation for East Japan Area
Cause of Abrupt Rises

 Phenomenon of soil liquefaction

Legend
- Compaction
- Sandy Soil
- Silt
- Screen

Elevation T.P.+
No.5-1
-1.85m
No.14-4
3.21m
Cause of Rising Tendency after Drawdown

Monthly Amount of Groundwater Pumping Rate for 3 years from 2009 to 2011

- Decrease of Groundwater Pumping Rate
Conclusions

- The Great East Japan Earthquake triggered the fluctuations of groundwater level in Tokyo.
- By applying SOM, the fluctuation patterns of groundwater level were classified into eight clusters and three groups.
- Sharp drawdown just after the Earthquake was the typical phenomenon for confined wells, which is caused by the pressure release derived from crustal expansion.
- Abrupt rise just after the Earthquake, esp. for shallow wells will be caused by the soil liquefaction.
- The most common fluctuation pattern is the drawdown followed by the rising tendency, which is mainly caused by decreased groundwater pumping rate.
Thank you for your kind attention!
Just after the earthquake (14:00~16:00)

Confined groundwater 89 wells

▲: Water level Rising over 5cm
▼: Water level Drawdown over 5cm
ー: Water level NO change

▲: 3 wells (Lowland)  ▼: 79 wells (All zone)  ー: 7 wells (Terrace)
Unconfined groundwater 13 wells

Just after the earthquake (14:00~16:00)

- ▲: 2 wells (Lowland)
- ▼: 1 well (All zone)
- -: 10 wells (Terrace)

▲: Water level Rising over 5cm
▼: Water level Drawdown over 5cm
-: Water level No Change
## Categorization of the Fluctuation Patterns

### 89 Confined Wells

<table>
<thead>
<tr>
<th>Confined</th>
<th>Groudwater level fluctuations</th>
<th>wells</th>
</tr>
</thead>
<tbody>
<tr>
<td>C-D I</td>
<td>Confined groundwater - Decrease then Increase</td>
<td>45</td>
</tr>
<tr>
<td>C-D C</td>
<td>Confined groundwater - Decrease Continuing until end of March</td>
<td>21</td>
</tr>
<tr>
<td>C-D R</td>
<td>Confined groundwater - Decrease then Recover to the level before the earthquake</td>
<td>13</td>
</tr>
<tr>
<td>C-I I</td>
<td>Confined groundwater - Increase, temporary decrease, Increase again</td>
<td>1</td>
</tr>
<tr>
<td>C-I C</td>
<td>Confined groundwater - Increase, Continuing until end of March</td>
<td>1</td>
</tr>
<tr>
<td>C-I D</td>
<td>Confined groundwater - Increase then Decrease</td>
<td>1</td>
</tr>
<tr>
<td>C-N</td>
<td>Confined groundwater - No significant changes</td>
<td>7</td>
</tr>
</tbody>
</table>
# Grouping of Fluctuation Patterns

## Unconfined Wells

<table>
<thead>
<tr>
<th>Confined</th>
<th>Groudwater level fluctuations</th>
<th>wells</th>
</tr>
</thead>
<tbody>
<tr>
<td>U–D</td>
<td>Unconfined groundwater – Decrease</td>
<td>1</td>
</tr>
<tr>
<td>U–I</td>
<td>Unconfined groundwater – Increase</td>
<td>2</td>
</tr>
<tr>
<td>U–N</td>
<td>Unconfined groundwater – No significant changes</td>
<td>10</td>
</tr>
</tbody>
</table>

Confined Groundwater level fluctuations wells

U–D Unconfined groundwater - Decrease
U–I Unconfined groundwater - Increase
U–N Unconfined groundwater - No significant changes
Consideration of Confined wells

Factor of no significant changes

- Diminution of pressure was little because of not minute geological formations.
Types of Observation Wells

- **Float-gage Type**: 96 wells
- **Stylus Type**: 8 wells

**Double Pipe System**: 30 wells

**Single Pipe System**: 74 wells
Groundwater level changes by the Earthquake

Confined Wells

<table>
<thead>
<tr>
<th>Water level</th>
<th>Max</th>
<th>site No.</th>
<th>Min</th>
<th>site No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>lowering</td>
<td>-83.3cm</td>
<td>8-2</td>
<td>-0.4cm</td>
<td>3-1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Water level</th>
<th>Max</th>
<th>site No.</th>
<th>Min</th>
<th>site No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>rising</td>
<td>+14.8cm</td>
<td>8-1</td>
<td>+0.9cm</td>
<td>33-1</td>
</tr>
</tbody>
</table>
クラスター別の水位変動パターン特性

Cluster 1

Cluster 2

Cluster 3

Cluster 4

Cluster 5

Cluster 6

Cluster 7

Cluster 8

(a) 地震直後  (b) 翌日  (c) 3日後  (d) 月末  (e) 深度

― ― ～ 第1四分位
― ― ～ 中央値
― ― ～ 第3四分位
3-3 Group-1の分布特性

- Cluster-1, Cluster-3, Cluster-8
- Group-1:
  地震直後に大きく水位低下、翌日までに回復
  14日までに上昇・31日まで継続、深度は中間的
3-3 Group-2の分布特性

・Cluster-2, Cluster-5, Cluster-7

・Group-2:
直後に比較的大きな水位低下・翌日まで継続,
14日までに戻り傾向・31日まで継続, 深度は深め
3-3 Group-3の分布特性

- Cluster-4, Cluster-6

Group-3: 直後に若干の水位上昇, または大きな変動なし
その後も大きな変動なし, 深度はかなり浅い