Rapidly accelerating subsidence in Maceió (Brazil) detected by multi-temporal DInSAR analysis

Magdalena Vassileva$^{1,2}$
Djamil Al-Halbouni$^1$, Mahdi Motagh$^{1,2}$, Torsten Dahm$^1$, Thomas Walter$^1$, Hans-Ulrich Wetzel$^1$

$^1$German Research Centre for Geosciences, Potsdam Germany
$^2$Leibniz University Hannover, Institute of Photogrammetry and Geoinformation, Hannover, Germany
Overview

Motivations of the study:
- Maceió municipality is suffering **severe geological instability** related to mining activities near the cost of the Mundaú Lagoon;
- **Fractures on both buildings and roads** have intensified mainly in Pinheiro neighborhood since the beginning of 2018, especially after **strong rainfall event** on 15th of February 2018 and a **seismic shock** of local magnitude 2,4mR on 3rd of March 2018;
- **Geodetic ground measurement are not available**;
- **Historic and updated geodetic InSAR measurements have not been provided yet**.

Our goals:
- Detect the **onset** of the instability;
- Track the **temporal and spatial evolution** of the instability;
- Estimate the **cumulative subsidence** rate;
- Estimate possible **horizontal deformations**;
- Have an overview understanding of the evolution of the **source of the subsidence**.

Methods:
- **Multi-temporal DInSAR analysis** (SBAS technique) using multi-sensor SAR data from 10.2003 up to 03.2020;
- **Geophysical modelling** (Mogi and Okada) to model the evolution of the source;
- **2D geomechanical modelling** to simulate 2 real salt-cavities, their stages of instability and the possible future development evolution of the surface displacement.
Maceió is the capital of Alagoas (Brazil)
Tot. population ~ 1 million inh.
Pinheiro pop. ~ 10,500 inh.
Mutange pop. ~ 1,500 inh.
<table>
<thead>
<tr>
<th>mission</th>
<th>orbit path</th>
<th>band</th>
<th>alos (°)</th>
<th>ILOS (°)</th>
<th>N.° of images</th>
<th>period</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASAR ENVISAT</td>
<td>DESC</td>
<td>C (5.331 GHz)</td>
<td>23.8</td>
<td>-77.7</td>
<td>8</td>
<td>23/03/2005 - 28/03/2007</td>
</tr>
<tr>
<td>ALOS-1 POLSAR</td>
<td>ASC</td>
<td>L (1.2 GHz)</td>
<td>37.1</td>
<td>78.8</td>
<td>16</td>
<td>17/01/2007 - 28/01/2011</td>
</tr>
<tr>
<td>ALOS-2 POLSAR</td>
<td>DESC</td>
<td>L (1.2 GHz)</td>
<td>35</td>
<td>-78.2</td>
<td>6</td>
<td>13/04/2015 - 22/05/2017</td>
</tr>
<tr>
<td>ALOS-2 POLSAR</td>
<td>ASC</td>
<td>L (1.2 GHz)</td>
<td>35.4</td>
<td>77.3</td>
<td>13</td>
<td>10/10/2015 - 07/09/2019</td>
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<tr>
<td>SENTINEL-1A</td>
<td>DESC</td>
<td>C (5.331 GHz)</td>
<td>35</td>
<td>77.9</td>
<td>107</td>
<td>07/10/2016 - 08/03/2020</td>
</tr>
</tbody>
</table>

**Dataset**
[07.2004 - 03.2020]

**Data gap**
[01.2011 - 02.2015]
Already in 2004-2005 a 4 cm/year of subsidence appears. The subsidence intensify during the years. It reach its maximum value of velocity of 24 cm/year in 2018.
Since the end of 2016 the horizontal velocity is around 4 cm/year westward. It intensify since 2017 to 9 cm/year.
LOS Time-Series

Strong rainfall event
2.4mR seismic shock

LOS Disp. Sentinel-1 10.2016-03.2020
We have many active cavities which contribute to the subsidence, however in this study we assumed a unique source model. Salt mines are located in a depth between 700 and 1000 m and are all close to the Mundaú Lagoon.

### point pressure source

<table>
<thead>
<tr>
<th>interval</th>
<th>vol (m³)</th>
<th>Depth (m)</th>
<th>East (m)</th>
<th>North (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>03.2015-03.2016</td>
<td>-3.87E+05</td>
<td>774</td>
<td>198124</td>
<td>8933762</td>
</tr>
<tr>
<td>03.2016-03.2017</td>
<td>-3.64E+05</td>
<td>730</td>
<td>198198</td>
<td>8933687</td>
</tr>
<tr>
<td>10.2016-10.2017</td>
<td>-5.25E+05</td>
<td>777</td>
<td>198108</td>
<td>8933746</td>
</tr>
<tr>
<td>10.2017-09.2018</td>
<td>-5.80E+05</td>
<td>697</td>
<td>198127</td>
<td>8933793</td>
</tr>
<tr>
<td>09.2018-09.2019</td>
<td>-5.35E+05</td>
<td>653</td>
<td>198179</td>
<td>8933841</td>
</tr>
</tbody>
</table>

### rectangular source-opening 600x150m

- We fixed the location with that from Mogi model;
- We considered horizontal plane (dip=0°);
- We fixed the plane size to 600x150m.

<table>
<thead>
<tr>
<th>interval</th>
<th>Openin g (m)</th>
<th>vol (m³)</th>
<th>Strike (°)</th>
<th>depth (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>03.2015-03.2016</td>
<td>-3.4</td>
<td>-3.0E+05</td>
<td>176</td>
<td>953</td>
</tr>
<tr>
<td>03.2016-03.2017</td>
<td>-3.0</td>
<td>-2.7E+05</td>
<td>171</td>
<td>873</td>
</tr>
<tr>
<td>10.2016-10.2017</td>
<td>-4.6</td>
<td>-4.2E+05</td>
<td>155</td>
<td>962</td>
</tr>
<tr>
<td>10.2017-09.2018</td>
<td>-5.2</td>
<td>-4.6E+05</td>
<td>165</td>
<td>857</td>
</tr>
<tr>
<td>09.2018-09.2019</td>
<td>-4.9</td>
<td>-4.4E+05</td>
<td>164</td>
<td>807</td>
</tr>
</tbody>
</table>
2D distinct element method (DEM) was used to simulate the evolution of two real size cavity models. Four different geomechanical stages were simulated:
1) initially stable pressurized cavity, with injection pressure of 1.5 MPa;
2) over fracturing and subsidence;
3) total collapse
4) final translation of the deformation to the surface.
Conclusions

Regarding the subsidence phenomena:

- Already in 2004/2005 subsidence started to appear;
- It has intensified up to 23/24 cm/year since 2018;
- A cumulative max. subsidence of 1.8 m was estimated from March 2015 to March 2020;
- A east-west horizontal motion is estimated up to 8/9 cm since 2018;
- Geophysical models show horizontally stable source, upward fracture propagation since 2016/17 and a clear volume change increment since 2016/17;
- Geomechanical models shows good agreement of the simulated subsidence with the DInSAR measurements and they also show upward fracture propagation;
- Based on the geomechanical modelling, in case of a total collapse of the two cavities, an approximate further 1m of subsidence is expected to occur, though no sinkholes.

General conclusions:

- InSAR is a powerful tool to detect and monitor in time geological instabilities especially in urban areas due to the higher coherence;
- The availability of archives of historical SAR data allows to obtain backdated geodetic measurements and to contribute to understand the onset of geological instabilities;
- The very high temporal resolution and not commercial Sentinel-1 data provides very good temporal displacement trend detection;
- The availability of both ascending and descending acquisitions allows also horizontal component estimation, which cannot be neglected in urban areas;
- Geomechanical and geophysical modelling (this last based on DInSAR data) provide good overview understanding of the source time and space evolution.