Retrieval of the Long Term Ground Settlement of Ocean Reclaimed Land in Shanghai with Multi Platform Time-series InSAR

Dr 3 project Id. 10644

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Ground settlement time evolution of ocean reclaimed lands in Shanghai:

- a joint analysis of PSI and SBAS

- a joint C/X-band SBAS-DInSAR analysis
Land reclamation

- A feasible measure for solving land scarcity
- In lowland countries and coastal cities

- 1600 km$^2$ of land was reclaimed from 2002 to 2011, in China
- 133.3 km$^2$ of land was reclaimed from 2002 to 2006, in Shanghai
- 1000 km$^2$ of new land in 20 years
Nanhui New City Study Area

- located in the southeastern Pudong District of Shanghai
- 300 km²
- 45% of the land was reclaimed from intertidal flats.
- The flats extend seaward over a maximum distance of 20 km and have a very low topographic gradient.
- Since the levels between the Yangtze River and the Hangzhou Bay are remarkable, the sediment transport is across the flats, with the high flats enclosed by dikes.

A Landsat image, collected on June 6, 2000, and the distribution of dikes built during different time periods.
Reclamation procedure

1\textsuperscript{st} phase (1994~1995): Southern area
2\textsuperscript{nd} phase (2002~2004): Central area
3\textsuperscript{rd} phase (2003~2006): Northeastern area
4\textsuperscript{th} phase (2003~2006): Northwestern area

Reclamation Methods

To promote siltation and land formation

- sand dams
- border dikes
- dredger fill
Bedrock geology and tectonics

The bedrock is buried at depths of 240 - 320 m.
Previous field observed ground deformation

- Ground subsidence in Nanhui New City has occurred since 1980.
- From 2001 to 2006, both the cumulative settlement and the rate of annual ground subsidence were greater in the northern sector of the city than in the southern sector.
- The maximum annual ground subsidence rate was approximately 15 mm/year.
Ground settlement in Land reclamation areas

- inherent problem
- ground failures and damage infrastructures
- primary consolidation: faster, 70%
- long-term compression
Joint Analysis of PS-IPTA and SBAS Results
51 SAR images from 2003 to 2010

PSI Analysis – SAR Distribution
• independently processed
• a common master image
• a common reference point
• outside the reclamation platforms
• almost stable
✓ AGS: 0.4 mm/year
✓ STD: 0.5 mm/year
### Dredger fill type and typical engineering parameter of reclamation in Nanhui New City

<table>
<thead>
<tr>
<th>Alluvial deposit</th>
<th>Spatial distribution</th>
<th>Summary description</th>
<th>Typical thickness (m)</th>
<th>Water content (%)</th>
<th>Bulk density (kN·cm⁻³)</th>
<th>Void ratio</th>
<th>The coefficient of permeability for vertical flow (cm a⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Type A</strong></td>
<td>Dishui Lake and area east of 1973 dike</td>
<td>Silty soil, saturated, slightly dense</td>
<td>&gt; 3</td>
<td>30.7</td>
<td>18.6</td>
<td>0.86</td>
<td>2.88</td>
</tr>
<tr>
<td><strong>Type B</strong></td>
<td>West Dishui Lake and area between 1973 and 1994 dikes</td>
<td>Clay soil, saturated, flow plastic</td>
<td>2 to 3</td>
<td>38.5</td>
<td>17.6</td>
<td>1.11</td>
<td>6.43</td>
</tr>
</tbody>
</table>

- **Type A**: remains in reclamation process from 2002 until today
- **Type B**: primary consolidation has not yet completed, remarkable residue settlement observed
• IPTA case

✓ a network of 20 K coherent PS
✓ 6 K located in reclaimed platforms
✓ a threshold of 1.1 rad for STD between the displacement time-series and a 2-D regression model
• SBAS case
  ✓ a network of 35 K DS targets identified by using a temporal coherence threshold of 0.7
Cross-comparison analysis between IPTA and SBAS DInSAR techniques over the investigated ocean-reclaimed lands

• First, it allows for isolation of a group of very stable DS and PS targets with high accuracy deformation measurements.

• Secondly, the proposed PS-SBAS cross-comparison analysis is profitable for assessing the retrieval accuracy of DInSAR-based deformation time-series.

• to isolate a group of very coherent and phase-preserving scatterers in the reclaimed areas.

• to investigate the validity of a geotechnical model derived from laboratory tests, to then predict the future evolution of displacement in reclaimed platforms.
Cross-comparison strategy

- focusing on the difference in the mean LOS velocities as estimated by the PS-IPTA and SBAS
- 1) coherent DS and PS targets should fall inside the same cell of the geocoded grid
- 2) For the given $p$-th PS point, we compared the IPTA displacement time-series to the (average) displacement time-series of the DS targets that are located in near proximity of the considered $p$-th PS target.
- More precisely, we concentrated on an area of about 200 x 200 m centred on the position of the $p$-th PS target.
- comparing the IPTA and the SBAS velocities
  - good agreement between two different DInSAR-based measurements
  - points located away from the line of equation $V_{PS}(t) = V_{SB}(t)$ correspond to critical areas where reclaiming procedures were still active from 2007 to 2010
  - most of which were located near the coastline
• the SBAS/IPTA velocity differences
  – the average displacement difference in common pixel
  – the investigated region: -1.5 mm/year
  – two Type A/Type B reclaimed regions: 0.9 mm/year
• the SBAS/IPTA time-series difference
  – the IPTA/SBAS standard deviation values for all of Nanhui New City: 6 mm
  – in the Type A/Type B regions: 5 mm
• 87% of PS targets retrieved using IPTA are characterized by a standard deviation difference less than 10 mm and a mean velocity difference less than 3 mm/year.

• It is evident that most of the points have a velocity difference less than 1 mm/year (green points).

• Spotted areas with differences of 2-3 mm/year are present over the southern sector of coastline.
we identified a set of very coherent points in both Type A and Type B dredger fill platforms, characterized by an IPTA/SBAS velocity difference of less than 1 mm/year and an IPTA/SBAS standard deviation difference less than 5 mm.
Our results demonstrate

- even in a critical region, such as the one represented by a reclaimed land, DInSAR accuracy is mostly preserved
- is in good agreement with that provided by previous studies

<table>
<thead>
<tr>
<th>Ground subsidence monitoring methods</th>
<th>Annual rate of subsidence (mm/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IPTA</td>
<td></td>
</tr>
<tr>
<td>Type A of dredger fill</td>
<td>Average value 22</td>
</tr>
<tr>
<td>Type B of dredger fill</td>
<td>Average value 9</td>
</tr>
<tr>
<td>Dredger fill</td>
<td>Average value 18</td>
</tr>
<tr>
<td>SBAS</td>
<td></td>
</tr>
<tr>
<td>Type A of dredger fill</td>
<td>Average value 24</td>
</tr>
<tr>
<td>Type B of dredger fill</td>
<td>Average value 8</td>
</tr>
<tr>
<td>Dredger fill</td>
<td>Average value 20</td>
</tr>
<tr>
<td>Centrifuge modelling test (^3) [55]</td>
<td>19</td>
</tr>
<tr>
<td>Step benchmarks of littoral area (^4) [59]</td>
<td>13</td>
</tr>
<tr>
<td>Levelling and GPS benchmarks of Shanghai (^4) [76,55]</td>
<td>12</td>
</tr>
<tr>
<td>Levelling benchmarks of reclamation area in Nanhui city [75]</td>
<td>Average value 16</td>
</tr>
</tbody>
</table>
Geotechnical analysis for settlement measurement

- Settlement due to reclamation will continue over the lifetime of the reclamation facility:
  - a primary consolidation phase
  - a secondary compression stage of the alluvial deposit creep of the reclamation fill.

The majority of settlement due to primary consolidation takes place immediately after the completion of the reclamation process, and may continue for dozens of years.

- Geotechnical models have been established with settlement monitoring data and geotechnical tests:
  - to generate a complete time-settlement curve for reclamation fill
  - to make long-term predictions of the magnitude of consolidation settlement.
- Centrifuge modeling has the ability to reproduce the same stress levels as the full-scale construction in a small-scale model.
- This centrifuge model test is a useful tool for the simulation and prediction of long-term subsidence.
- Of particular interest for the alluvial soil characteristics of Shanghai is the model settlement derived from laboratory centrifuge tests.
- This laboratory model permits us to analyze ground settlement caused by self-weight consolidation.
- In this model, the relationship between self-weight consolidation settlement and time is considered:

\[ s_{CMT} (t) = S_m \frac{(t)}{k + (t)} \]
A. Fitting of the geotechnical model with DInSAR-based deformation

- 450 points located in the Type A and Type B areas used
- very accurate PS/DS pixels located in the two reclaimed platforms, characterized by an IPTA/SBAS velocity difference of less than 1 mm/year and an IPTA/SBAS standard deviation difference less than 5 mm.
- for each coherent PS/DS target, by searching for the best-fit curve in the least-squares sense
- The quality of the non-linear curve fitting was checked by calculating the standard deviation of the difference between the DInSAR time-series and the best-fit model.
- On average, the obtained standard deviation is 1 mm, thus showing good agreement between the two datasets.
- Note also that the accuracy of DInSAR-based measurements in Type A/Type B regions is equal to 5 mm. Accordingly, the estimated model confidence is globally at about 6 mm.
• By analyzing the retrieved displacement models, we obtained some preliminarily predictions about the expected cumulative deformation (calculated with respect to the first SAR acquisition of February 26, 2007) in 2015, 2020, and 2025.

• As evident, the eastern areas (where reclamation procedures started more recently) are expected to be subject in the near future to larger and more long-lasting deformations than in the western sectors.
B. Consolidation time estimation

- We assumed that the ground settlement consolidation phase was completed when the (expected) residual deformation rate was less than 0.5 mm/year.

- Accordingly, we evaluated the model displacement rate by calculating the first derivative of the obtained time-varying model.

- It is worth remarking that neither the end time of consolidation phase nor the shapes of the best-fit models depend on the exact knowledge of reclamation completion time, but only on the consolidation time duration itself.

\[ T_e : s'_{CMT}(T_e) = 0 \]
• “rough” estimates of the x-percentage total consolidation time duration was obtained as follows

\[ T_e^{(x)} : s_{CMT} \left( T_e^{(x)} \right) = \frac{x}{100} \cdot s_{CMT} \left( T_e \right) \cdot s_{CMT} (0) \]
• Best-fit models, as well as end times of consolidation phases for the four point targets labeled as (a)-(d), located in Type A/Type B regions, have been evaluated.

• We also estimated the values of the standard deviation between the model and the DInSAR-based measurements for the four pixels.
<table>
<thead>
<tr>
<th>Consolidation degree</th>
<th>70%</th>
<th>80%</th>
<th>90%</th>
</tr>
</thead>
<tbody>
<tr>
<td>x-percentage total consolidation time (year)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Type A area</td>
<td>9.8</td>
<td>13.8</td>
<td>20.4</td>
</tr>
<tr>
<td>Type B area</td>
<td>5</td>
<td>6.7</td>
<td>9.2</td>
</tr>
<tr>
<td>Western (WS) Type A area</td>
<td>7.8</td>
<td>10.9</td>
<td>15.7</td>
</tr>
<tr>
<td>Eastern (ES) Type A area</td>
<td>13.4</td>
<td>19.3</td>
<td>29.2</td>
</tr>
</tbody>
</table>

**Type B area**
- Our results indicate that 70% of the consolidation settlement was completed 5 years after the completion of construction, corresponding to 2010.
- 90% of the settlement is thought to have occurred after about 9 years.
- This is in agreement with what was expected in a previous study.

**Type A area** was reclaimed after Type B area.
- Type A takes longer x-percentage total consolidation time than does Type B.
- The average values in the WS are less dispersed and range from about 8 to 15 years.
- The average values for the ES sector have greater fluctuation and range from 13 to 29 years. This is due to the fact that the reclamation of the ES sector was not completely finished in 2010.
A DInSAR Investigation of the Ground Settlement Time Evolution of Ocean-Reclaimed Lands in Shanghai

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DOI: 10.1109/JSTARS.2015.2402168
A joint C/X-band SBAS-DInSAR analysis
Available Interferometric SAR datasets

- **35 ENVISAT images** (2007-2010)
- **40 CSK images** (2013-2010)
- **12 TSX images** (2009-2010)
Joint C/X-band DInSAR analysis

Our final goal is the generation of unique displacement time series, namely $d \equiv [d_0, d_1, \ldots, d_{N1+N2+N3-3}]$, spanning the overall time interval $t = t^{ENV} U t^{CSK} U t^{TSX}$.

Note that the time gap between CSK and ENVISAT/TSX SAR data makes it unreliable the use of the Singular Value Decomposition (SVD) method to link different data subsets, as done in the conventional SBAS-DInSAR approach.
ENVISAT SBAS-DInSAR results (2007-2010)
CSK SBAS-DInSAR results (2013-2015)
TSX SBAS-DInSAR results (2009-2010)
SBAS-DInSAR results: comparison between C- and X-band

35 ENVISAT images (2007-2010)

40 CSK images (2010-2013)

12 TSX images (2009-2010)
SBAS-DInSAR results: joint C/X-band analysis

Mean Deformation Velocity [cm/year]
Joint ENV/TSX SBAS-DInSAR analysis

• The unique ENV/TSX deformation time series can be achieved by taking into account the mainly vertical expected deformation in ocean-reclaimed platforms to link the different time series, by applying an efficient combination of the generated ENVISAT and TSX SBAS-DInSAR interferograms as belonging to different subsets.

• This is based on a minimum-norm criterion of the velocity deformation, easily obtained in our case via the application of the SVD method.
SBAS-DInSAR results: joint ENV/TSX analysis
• The integration of CSK data, which cover a larger time period with respect to TSX are available and investigated.

• To do this, the availability of time-dependent models for the ongoing deformation will be strategic to properly link CSK measurements with joint ENV/TSX time series, thus overcoming the existing temporal gap between 2011 and 2013.
Joint analysis of SBAS-DInSAR results and geotechnical models

The obtained deformation velocity map and the corresponding time series relevant to two pixels located in the maximum deformation ocean-reclaimed area of Shanghai are shown here. The black, red and green triangles represent the ENVISAT, TSX and CSK SAR data, respectively; moreover, the continuous black line portrays the deformation signal, as retrieved by the model fitting operation.
Due to alluvial soil characteristics of Shanghai, we select the time-dependent centrifuge model derived by centrifuge modeling test, which permits to analyze expected (vertical) ground deformation caused by self-weight consolidation:

\[ y(t) = S_m \frac{t}{k} + C(t) + t \]

We perform our data modeling analysis by considering parameters \( S_m, K, \lambda \) and \( C \) and by searching for the best-fit curve in the least-square sense between the SBAS deformation measurements and the considered model. The optimization of the non-linear problem is then efficiently solved, and the standard deviation of the difference between model and data is calculated as a quality factor.
Thank you!

For any question concerning the project, please contact:

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