Outline

• Intro to Land Deformation Monitoring in Urban Context
• Intro to INSAR
• Monitoring Solution Overview
• Case#1: Seattle SR99 Bored Tunnel
• Case#2: Canadian Cases
Sinking or soaring?
by The China Watch on March 7, 2012

This hole appeared near Shanghai Railway Station to have been caused by subsidence because of movement of underground water table. Photo: Cai Xianmin/GT

The collapse differs in each of the six structures and buildings that make up the T-2, variations airport authorities compensated by ramps, baseboards and gravel.
Winnipeg, New Residential Development

Extreme subsidence in a Winnipeg residential area, consistent with slumping of the riverbank.

Source: GoogleEarth Streetview

Linear rate
Infrastructures and Urban Land Deformation
Urban Infrastructure

Construction related subsidence

‘Big Bertha’ TBM Repair

Structural failures

I-35W Minneapolis Bridge Collapse

Natural hazards

Karst sinkhole, Florida, USA

Resource management

Mexico City subsidence
## Infrastructure Types

<table>
<thead>
<tr>
<th>Type</th>
<th>Characteristics</th>
</tr>
</thead>
</table>
| Buildings | • Vertical surfaces -> layover, cast radar shadows  
• Thermally active (vertical elongation of tall buildings, horizontal spreading of metal roofed industrial buildings) |
| Bridges   | • Multiple deformation sources (thermal expansion, vehicle loading, wind)  
• Complex radar return (e.g. double bounce off water) |
| Roads     | • Low radar backscatter from asphalt -> increases measurement noise -> requires filtering  
• May be cluttered by traffic parked cars, trees |
| Tunnels   | • Not directly observable  
• Overburden relaxation, groundwater removal may result in deformation of surface infrastructure within zone of influence |
| Others    | • Rail, dikes, airports, port facilities, ... |
## Deformation Drivers

<table>
<thead>
<tr>
<th>Deformation driver</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dewatering (aquifer depletion)</td>
<td>Mexico City, California</td>
</tr>
<tr>
<td>Dewatering (construction related)</td>
<td>Vancouver water filtration tunnel, Seattle SR99 tunnel</td>
</tr>
<tr>
<td>Sinkhole formation</td>
<td>Limestone karst region of Pennsylvania, USA</td>
</tr>
<tr>
<td>Excavation</td>
<td>Cut-and-cover sections of Vancouver ‘Canada Line’ project</td>
</tr>
<tr>
<td>Construction induced loading</td>
<td>New construction in alluvial areas</td>
</tr>
<tr>
<td>Unstable slopes</td>
<td>Urbanized hillsides – e.g. La Paz Bolivia</td>
</tr>
<tr>
<td>Structural failure</td>
<td>Aging infrastructure</td>
</tr>
</tbody>
</table>
Introduction to InSAR
Information From Satellites

Passive Sensor
- Optical (Electro-optical)
  - WorldView-2
  - Pléiades 1A/B
  - Landsat8

Active Sensor
- Synthetic Aperture Radar (SAR)
  - RADARSAT-2
  - RISAT
  - TerraSAR-X
  - COSMO-SkyMed
  - Sentinel-1
What does a SAR Sensor See?

- SAR is a side-looking sensor, receiving backscatterer and movement (LOS) information.

SAR Geometry

- Dark
- Medium
- Bright
InSAR concept
Using Satellite SAR to Measure Surface Movement

First Satellite Pass

Second Satellite Pass

Reflected Signal

Reflected Signal

Phase Shift

Ground Uplift

InSAR Surface Deformation Map

Products © MDA Geospatial Services Inc. (2011)
Line-of-sight measurements

- Actual deformation is a 3D vector quantity
- InSAR measures projection of deformation along sensor line-of-sight → a 1D quantity
- 2 (or more) view geometries can be combined to measure other dimensions
Estimating 2D deformation with InSAR

1. Simple example of dewatering deformation

2. Line-of-sight InSAR measurements (apparent east/west shift)

3. Vector decomposition

- East/West
- North/South
- Up/down

Normalized deformation

+ 1.0

- 1.0
InSAR Methods

Linear deformation rate maps of Vancouver’s YVR airport (RADARSAT-2, Ultra-Fine, 40 scenes)
## InSAR Methods

<table>
<thead>
<tr>
<th>Method for Reducing Noise</th>
<th>Characteristics</th>
<th>Weakness</th>
</tr>
</thead>
</table>
| **DSI** (Distributed Scatterer InSAR) | Averaging over rectangular grid to reduce noise. | • Resolution loss  
• Contaminate good points |
| **PSI** (Persistent Scatterer InSAR) | Identify low noise points and form sparse grid. | • Throw out most data  
• Poor spatial coverage  
• N_scenes > 15 |
| **HDS** (Homogeneous Distributed Scatterer) | Adaptive spatial filtering based on temporal intensity distributions*  
Optimizes SNR/resolution tradeoff | • N_scenes > 15 |

Vancouver airport (YVR)

Adaptive multi-looking recovers tarmac signal while preserving spatial resolution over terminal buildings
Case Study: Seattle Tunneling Project
SR99 Tunnel Project

- 3.2 km bored tunnel under downtown Seattle, U.S.A.
- 17.5 m diameter tunnel boring machine → ‘Big Bertha’
- TBM failed after 10% completion of tunnel
- Repair involves 24 m wide x 37 m deep rescue shaft with significant dewatering required → potential for surface displacement
SR99 Tunnel Project Timeline

Preparations for boring.

Boring

Inspection dewatering (1500 L/min.)

Cutter head failure

Access shaft dewatering (3000 L/min.)

RADARSAT-2 dataset: 79 Spotlight mode images (Ascending and Descending)

Ongoing RADARSAT-2 acquisitions

2012 2013 2014 2015
## RADARSAT-2 data

<table>
<thead>
<tr>
<th>Stack</th>
<th>Start Day</th>
<th>End Day</th>
<th>Number of Scenes</th>
<th>Incidence angle (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SLA9 Ascending</td>
<td>2012/06/06</td>
<td>2015/02/15</td>
<td>41</td>
<td>37.0</td>
</tr>
<tr>
<td>SLA23 Descending</td>
<td>2012/06/06</td>
<td>2015/02/15</td>
<td>38</td>
<td>46.7</td>
</tr>
</tbody>
</table>

**Study Area**

- **SLA9_Asc**
- **SLA23_Des**

**Planned**

- Rescue shaft

**Completed**
Line-of-sight deformation

Cumulative (2012/06/06 – 2015/02/15)

Ascending

Descending

Same east/west pattern shift from example...

Normalized deformation

+ 1.0

- 1.0
**2D deformation**

**Cumulative (2012/06/06 – 2015/02/15)**

Same general patterns from example...

Normalized deformation

- 1.0

+ 1.0

1.5 cm/yr eastward

1.5 cm/yr westward

Vertical

East/West

+3.5 cm

-3.5 cm

1.5 cm/yr

N
Dewatering correlated deformation

2012/06/06 – 2014/11/01 : no deformation
2014/11/01 – 2015/02/15 : linear deformation

Dewatering correlated deformation is spatially consistent with localized dewatering induced deformation (both in vertical and east/west directions).

Pattern centered ~200 m south-east of rescue shaft.
Pre-dewatering linear deformation

(2012/06/06 – 2014/09/24)

Significant areas of long term (since June 2012) subsidence in area corresponding with infill of historic waterfront.
Pre-dewatering linear deformation

(2012/06/06 – 2014/09/24)

Westward deforming building shows external signs of damage and reinforcement.
Case Study: Canadian Cases
Seasonal Displacement

• Indicate areas with strong frost heave which will require more frequent maintenance

• Separate out seasonal effects from long-term trends
  – Seasonal/temperature-dependent effects often included in engineering design
  – Subtle long-term trends could indicate current/future problems
    • Displacement will eventually exceed tolerances
Regina Seasonal Displacement

Seasonal displacement

+0.3 mm/°C

-0.3 mm/°C

airport

overpass
Regina, Temperature-Correlated Displacement

Linear Rate

Temperature-correlated displacement

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Regina, Temperature-Correlated Displacement

Linear Rate

Temperature -correlated displacement

+1 cm/yr

-1 cm/yr

+0.3 mm/°C

-0.3 mm/°C

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Victoria Bridge, Montreal

Source: GoogleEarth Streetview

Victoria Bridge as viewed from Montreal Technoparc (on Nuns’ Island. South of bridge)
Victoria Bridge, Montreal

Minimal linear rate on majority of bridge. Some (Westward?) movement towards radar LOS on East side of bridge.

Fixed joints on right-hand side allow expansion to the West only.

Fixed joints on left-hand side allow expansion to the East only.
Summary
Monitoring solution Summary

**Monitoring Goal:**
- Infrastructure
  - Excavation
  - Boring
  - Dewatering
  - Loading

+ Construction
  - Excavation
  - Boring
  - Dewatering
  - Loading

**Requirements:**
- High Spatial Resolution
  - Resolve fine structures
  - Delineate margins
  - Estimate strain

- Decompose vertical & horizontal deformation

- Separate long term from construction related deformation

**Solution:**
- HDS - InSAR
  - Adaptively optimizes spatial resolution
  - Resolve infrastructure, roads, open areas

- 2D view geometry
  - Data from opposing look directions
  - Decompose to get vertical + east/west

- Temporal component modeling
  - Fits multiple deformation ‘templates’
Benefits of INSAR-based Monitoring

• Interferometry is a proven technique which can measure mm of surface movement in an urban environment
• Surface movement measurements from InSAR can be readily integrated into any other measurement program used such as GPS, or TotalStation survey methodologies
• Satellites provide wide area coverage allowing for routine monitoring
• Regular monitoring can be used as an alert for growing subsidence problems, and targeting engineering resources
Thank You!

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