Health Assessment of Levees Using Remote Sensing and Field Monitoring

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International Workshop on Remote Sensing for Disaster Response
September 15-16, 2011
Four-Year Project: Development of a Multiscale Monitoring and Health Assessment Framework for Effective Management of Levees and Flood-Control Infrastructure Systems - TIP supported

Joint Venture

Rensselaer Polytechnic Institute (M. Zeghal, T. Abdoun, B. Yazici)

Geocomp (A. Marr)
Overview

• Introduction
• Vision and project overview
• Remote sensing (InSAR)
• Field Monitoring
• Multi-scale identification and health assessment
• Concluding remarks
Introduction

• Integrity and reliability of flood-control infrastructure (levees, earthen dams, etc.) essential components of homeland safety

• Aging and deteriorating flood-control infrastructure:
  – ASCE's 2009 Report Card: a grade of D to dams and a grade of D- to levees
Motivation
Health Assessment: Current State-of-the-Practice

• Levee health assessed based on visual inspection
  – Primarily periodic site visits (monthly to annually and more)
  – Surface information (incomplete and mostly qualitative)
  – Focus on components

• Provides
  – Limited damage or weakness detection capability
  – Inconclusive health assessment
  – Limited predictability of overall system performance
Vision

Sensor-Aided Model-Based Approach:

• Monitoring:
  – Global: Remote sensing (InSAR)
  – Local: Shape-Acceleration-Pore Pressure Array
  – Bridging: GPS

• Health Assessment
  – Multi-scale (global, intermediate and local) model-based framework
Remote Sensing

Objectives:

• Monitor large areas of levee system (10s of sq. kms)
  – Obtain few meters/pixel resolution for observed area

• Estimate deformation in levee structures with millimeter accuracy
  – Interferometric Synthetic Aperture Radar (InSAR)

• Estimate near surface moisture content
  – Polarimetric Synthetic Aperture Radar (PolSAR)
SAR: Synthetic Aperture Radar

- Large **Synthetic** antenna obtained using history of radar echoes generated during spacecraft forward motion

Image courtesy of Power et al. (2006)
Differential InSAR: DInSAR

Generates (using 2 or more SAR Interference images):

- digital elevation maps
- surface deformation

Image courtesy of H. Zebker

Image courtesy of Fugro
Radar Satellites


ERS1 & ERS2

ENVISAT

RADARSAT-1

RADARSAT-2

ALOS-PALSAR

TerraSAR-X

Tandem-X

RCM Constellation

Sentinel 1

Sentinel 2

SAOCOM

CosmoSky-Med Constellation
SAR Imaging Modes

• **Strip map**
  – “Average” coverage area

• **Scan SAR**
  – **Increased** swath width
  – **Reduced** resolution and signal-to-noise ratio

• **Spotlight**
  – **Reduced** swath width
  – **Increased** resolution
TerraSAR-X (9.67 GHz)

• **SpotLight:**
  1.8m x 3.4m resolution
  scene size 10 km (width) x 5 km (length)

• **StripMap:**
  3.5m x 8.0m resolution
  scene size 30 km (width) x 50 km (length)

• **ScanSAR:**
  18m x 18m resolution
  scene size 100 km (width) x 150 km (length)

“Sampling rate” every 11 days
PSInSAR to address Challenges in DInSAR

PSInSAR (persistent scatter) used to address lack of coherence due to:

- **Geometric decorrelation** – Satellite must be as close as possible to the same orbital position when images are acquired over time

- **Temporal decorrelation** – Movement of scatterers or temporal change in the dielectric properties
  - Vegetation growth
  - Change in soil moisture, snow cover, etc.

- **Atmospheric effects** – dispersion
  - Change in temperature, pressure, water vapor

- **Sparsity of temporal data**
Coherence

DInSAR

PSInSAR

Coherence map: TSX data

Average value

0.5~0.6

0.2 0.9

Average value

0.85~0.9

0.7 1
Elevation and Displacement Rate

Elevation (m)

Rate of subsidence (mm/year)
height (m): 7.636
deformation rate (mm/y): -5.674
deformation rate uncertainty (mm/y): 0.681
Settlement Rate

Deformation Rate

-8.2 (Point A)
-7.6
-5.0 ~ -6.2
-3.5 ~ -4.9

mm/year

TerraSAR-X Stripmap
2009 March 13 - 2010 October 28
19 images
Improving Accuracy and Space Resolution

Reflectors: improves signal intensity

PSInSAR

SqueeSAR™ (TRE)
Field Instrumentation

- Shape acceleration pore pressure (SAP) array
  - Higher resolution
  - Higher sampling rate (seconds to minutes)
- GPS array
  - Higher sampling rate (daily to few hours)
  - Cost effective (~ $1500)
Adaptive multi-scale:

- **Global**
  - InSAR data (strip mode)
  - InSAR data (spotlight mode)

- **Intermediate**
  - InSAR data (spotlight mode)
  - GPS data

- **Local**
  - Shape-acceleration-Pore Pressure data
  - GPS data
Health Assessment Rationale

- Calibrated baseline levee model
  - a priori information
- Updated levee models
  - baseline model
  - new measurements
- Evaluation of health status and identification of damage (if any)
  - discrepancies between baseline and updated models
  - other information
Coarse global analysis:

• Stripmap InSAR measurements
• 2D shear beam

\[
\frac{\partial \tau}{\partial s} - q^{\text{ext}} = 0
\]

\[\tau = \tau(\tau_1, \tau_2)\]

\[q^{\text{ext}}: \text{All external loads}\]
Intermediate-Scale Health Assessment

**Fine** global analysis:
- Spotlight InSAR measurements
- Neural network and 3D simple models

- Location of displacement estimated using InSAR
- GPS sensor location
Intermediate-Scale Health Assessment

**Intermediate Analysis:**
- Spotlight mode InSAR measurements
- GPS measurements (higher sampling rate)
- 2D refined model of critical section

![Diagram of geological layers with points indicating InSAR displacement and GPS sensor locations.]

- Weak soil
- Location of InSAR displacement
- GPS sensor location
Intermediate-Scale Health Assessment

- **Localization**
  - Neural networks

- **Parameter Identification**
  - Localization used to constrain geometry of possible weak zones.
  - Optimization algorithms used to identify “geometry” of weak zones and to quantify associated stiffness properties.

- **Health assessment**
  - Based on internal (strain) energy of weak zone(s)
Intermediate-Scale Health Assessment

Localization

Neural networks trained to identify possible locations of weak zones given surface displacements/deformation.
Intermediate-Scale Health Assessment

Localization Results (Example)

- **LD** – Left Deep
- **LS** – Left Shallow
- **RI** – Right Intermediate
### Localization Results

<table>
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<tr>
<th>Identified Category</th>
<th>Actual Category</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
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<td>0.5 mm uncertainty in displacement readings</td>
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<td>94</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>94.9% 5.1%</td>
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<tr>
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<td>8</td>
<td>109</td>
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<td>0</td>
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<td>76.8% 23.2%</td>
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<td>89.2% 10.8%</td>
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<td>113</td>
<td>96.6% 3.4%</td>
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</tr>
</tbody>
</table>

Correct classifications for Independent Test:
86%
correct classifications for displacements > 2 mm:
93.5%
Intermediate-Scale Health Assessment

Identification of stiffness parameters
Intermediate-Scale Health Assessment

Identification Algorithm

Initial Model

Model after weakening

\[ p_{\text{optm}} \rightarrow \min_{p} \| \Delta d \| \]

Parameter Identification

Weakening scenario:
Energy-based Safety Assessment
Health Assessment: Quantification

Quantification based on progression of:

• Degradation of stiffness and strength parameters
• Weakened zones and associated energy
Local-Scale Health Assessment

**CMP**-Control Motion Approach: prescribed motion at all sensor “node” locations (Elmekati and Zeghal)

**CMP**-Finite Element formulation
Concluding Remarks

Health assessment framework:

• Sensing tools
  – Remote sensing
  – SAP
  – GPS

• Local-Intermediate-Global health assessment
  – Provides an evaluation of levee condition
  – Provides ample time to implement required repairs before major events (hurricanes, floods, ...)
  – Enables resilient of flood control levee systems (lower risk of having a catastrophic failure)

• Provides an automated monitoring and data collection program that could be used to organize and implement a rehabilitation program.
Questions?