Ground Related Risk to Transportation Infrastructure

The value of infrastructure sensing

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Motivations for Geosystem Sensing

- There are two general motivations why we want to measure things in geotechnical engineering.

- **Motivation 1 – To make step changes in geotechnical engineering practice**
  - Performance Testing of new geotechnical structures or processes
  - Laboratory testing, centrifuge testing, field testing
  - To prove new research or design hypothesis

- **Motivation 2 – To extend asset life & reduce management costs**
  - Performance monitoring of actual operational geotechnical structures
  - Mainly field monitoring for long time (life-long)
  - For maintenance, future proofing against hazards (EQs, flooding), safety, etc.

- Typically Motivation 1 dominates in geotechnical engineering. But there is increasing demand for Motivation 2 as part of the Internet of Things (IoT) revolution happening at the moment.
Type 2 sensors - performance monitoring

- Promotes the “Observational Method” from construction, maintenance and decommission
- Resilience monitoring, Post-hazard recovery monitoring
- Need to be robust and long life time
- Potentially wide adaption as part of routine geotechnical practice
- Quick installation process may be needed to avoid any disturbance to the actual construction process.
- Examples
  - Computer vision
  - Embedded sensors such as distributed fiber optics
  - Low power sensors
  - Wireless sensor network
  - Satellite monitoring
  - ??
Ultra low power wireless sensor network

Distributed fibre optic sensing

Computer Vision and Robotics
Low power MEMS sensors

Energy Harvesting
A Bigger Picture....
The Value of Sensing needs to be evaluated.

CITY-SCALE SYSTEM OF SYSTEMS
- What economic value does our infrastructure create?
- How does our infrastructure best serve our communities?
- What form should our infrastructure take?

LIFETIME VALUE OF INFRASTRUCTURE
- How do we operate, manage & maintain our assets to deliver best whole life value?
- How do we futureproof our assets against changing requirements & against shocks?
- What decisions? what information?

EFFICIENT ANALYSIS AND INTERPRETATION IN REAL TIME
- How do we best design, construct & monitor our structures to deliver the performance we need?
- What data do we need to do this, & how do we interpret it?

ROBUST SENSOR SYSTEMS
- What sensors do we need?
- How can we make them robust?
- Reliable, robust systems for data collection
- Standards to enable interoperability
San Francisco, USA

Animation of pavement condition change in San Francisco (Interpolated to annual data)

- **Spatial range**: All streets in SF (2000 km)
- **Temporal span**: Early 1990s - now
- **Spatial resolution**: Streets (intersection to intersection)
- **Temporal resolution**: Every 2-3 years
- **Degradation index**: Pavement Condition Index (PCI)
- **Total number of records**: 120,000 Collected by human raters.

San Francisco Public Works
San Francisco pavement condition

1994

2005

2010

2015

CSIC
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San Francisco PCI versus Age:
By Functional Classification & Surface Type
A Deterministic Pavement Performance Model

\[
PCI = 100 - \frac{CHI \times \rho}{\left[\ln\left(\frac{\alpha}{\text{AGE} - \text{SHIFT}}\right)\right]^\beta}
\]

- \( \alpha \): regression constant that controls the age to which the curve is asymptotic
- \( \beta \): regression constant that controls how sharply the curve bends
- \( \rho \): regression constant that controls the age at which the inflection point in the curve occurs
- CHI: PCI bending multiplicative adjustment factor
- SHIFT: age shifting additive adjustment
- AGE: the age in time since construction to the time at which PCI is to be calculated
- Source: Deshmukh, Maithilee Mukund. *Development of Equations to Determine the Increase in Pavement Condition Due to Treatment and the Rate of Decrease in Condition After Treatment for a Local Agency Pavement Network*. Diss. Texas A & M University, 2010.
San Francisco PCI ~ Age:
observed & model, simplified with CHI=1, SHIFT=0

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<th>AC/AC</th>
<th>AC/PCC</th>
<th>PCC</th>
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</table>
**London, UK**

Pavement condition in Greater London, 2014

**Spatial range**
TfL “Red Routes” in London (800~1600km)

**Temporal span**
2011-2014

**Spatial resolution**
10m

**Temporal resolution**
Annual data

**Degradation index**
Multiple: cracks, longitudinal and horizontal profiles ...

**Total number of records**
550,000
Collected by dedicated survey vehicles

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Road Condition Index (RCI)

<table>
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<th>0-40</th>
<th>40-100</th>
<th>&gt;100</th>
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SCANNER survey (Surface Condition Assessment for the National Network of Roads), Transport for London
Osaka, Japan (Prof Nagayama, University of Tokyo)

Zoom in to street level (Osaka Castle)

Spatial range: Osaka Area
Temporal span: 2016.7 - present
Spatial resolution: 10m
Temporal resolution: Real time
Degradation index: International Roughness Index (IRI)
Total number of records: 3000 per day*

* Assume each taxi ride is 5km. Based on 179 successful taxi uploads in May 2016.

iDRIMS system, Professor Tomonori Nagayama and Professor Masashi Toyoda at Tokyo University
Macro View

Gerard Casey  Krishna Kumar
Micro View
Crowd sourced data
Google Travel time distributions

Northbound

Southbound
Travel time distributions

Journey time distribution 7th-13th March, 2016

Northbound

Southbound
Travel time distributions

A208, Chiselhurst. Newshopper.co.uk, 2016
Context specific volume-delay functions
Speed-saturation functions
Agent Based Model – Scenario testing
Hourly movement of 1 million agents (about 10% of London Population)

Emerging behaviour, cascading behaviour, reactive & adaptive agents….
- Graph MapReduce
- In-memory cluster computing
- Decentralised data structures

- Graph size
  - ~250k nodes
  - ~800k edges

- ~1.5GB .gml to 43MB .json.gz
Iterative decision making models

Decision making Model

Data

+ disruptive event {sudden precipitation}

How should transit operators respond locally and globally?

How should traffic lights respond?

In Real-time
Sensor development - Trend

- Better accuracy, resolution and precision
- “Point” sensors to “Distributed” sensors
- Wider coverage
- Smaller and low power
- More dynamic (faster data acquisition)
- More robust
- Better communication (wireless)
- Long performance

![Diagram showing coverage vs. resolution trends with points for miniature point sensor and satellite monitoring, indicating move towards distributed sensing.]
Distributed Fibre Optics Sensing
Distributed Sensing providing “Continuous Strain/temperature/vibration Profile” along the fibre optic cable

- Distance range ≈10-30km
- Readout resolution = 0.05m
- Gauge length resolution = 0.2-1m
- Strain Resolution = 10-30με
Strain sensing cables (tight buffer)

- Low cost (<$0.5/m)
- Low development cost (<$5/m)
- Low robustness (<$20/m)
Robustness

Fujikura Reinforced Fibre Optic Cable

4x125\(\mu\) optical fibers

1.2mm

Steel wires

FUJIKURA SM 4
Reinforced

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A building construction at the Isle of Dog, London

Made Ground / Alluvium
Lambeth Group
Thanet Sand
Chalk

Large diameter piles - 2.4m dia.
Very deep - avoid tunnels (25m into Chalk)

Thick raft span over tunnels

Echo Ouyang  Musa Chunge  Cedric Kechavarzi  Loizos Pelecanos  Vivien Kwan  Duncan Nicholson
No disturbance to actual construction operations
Conventional Strain Gauge System

Distributed FO system
- Diameter = 1.5m
- Length = 51m
- Osterberg-cell
- Load up to 31MN
Construction can be challenging
  - alignment
  - concrete quality and placement
  - soil collapse

Visible inspection not possible

Repair and rework is very difficult

Not all anomalies are defects/detrimental

FHWA-NHI-10-0161.
Potential for Whole-life Management?

Construction Quality Control

⇒ Real Loading Performance

⇒ Future Proofing

(EQs, nearby constructions..)

A new project with Caltrans starting…
American River Levee Upgrade Project

- Sacramento Metropolitan area remains one of the most at risk areas for flooding in the United States.

- Levees constructed in the previous flood control project (1850-1950), Sacramento River Flood Control Project, were constructed of poor materials.

- Flows in either the American or Sacramento Rivers will probably stress the network of levees to the point of failure.

FO Monitoring of cement bentonite cut-off wall, currently upgraded.

US Army Corps of Engineers

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Direction of Box Movement
(displacement rate = 2 in/min)
Elizabeth tunnel
Los Angeles Department of Water and Power
Claremont tunnel, East Bay Municipality Board
Distributed Acoustic System

Distributed Dynamic Strain System

Dynamic strains measured by 60 Hz vibration input with different laser power inputs

Figure 4 Comparison of DAS and geophone data for multi-trace gather (left) and single trace (right) for two depth zones.

Miller et al. (2016)
Underground wireless sensor network
Order of magnitude available power density

- Ambient radio energy
- Indoor solar
- Ambient sound energy
- Temperature gradient
- Vibration
- Pressure fluctuation in water pipes
- Piston
- Outdoor solar

Levels:
- Worst: 10 nW/cm³, 100 nW/cm³
- Best: 1 µW/cm³, 10 µW/cm³, 100 µW/cm³, 1 mW/cm³, 10 mW/cm³
Data from London Underground monitoring

Air flow velocity in tunnel

Power

\[ P = \frac{1}{2} \rho A V^3 C_p \]

For \( M = 0.02 \text{ g} \).

1 uW per kg.
Parametric resonance

Direct excitation

Fundamental mode of resonance: $\omega = \omega_0$

$$\ddot{x} + \frac{2c_1}{m} \dot{x} + \frac{c_2}{m} \dot{x} |\dot{x}| + \frac{\mu}{m} x^3 + \omega_0^2 x = \omega^2 A \cos(\omega t)$$

Parametric excitation

Principal (1st order) parametric resonance: $\omega = 2\omega_0$

$$\ddot{x} + \frac{2c_1}{m} \dot{x} + \frac{c_2}{m} \dot{x} |\dot{x}| + \frac{\mu}{m} x^3 + \left(\omega_0^2 - \frac{\omega^2 A}{l}\right) \cos(\omega t) \dot{x} = 0$$
Vibration power harvester

Output power, mW

Drive acceleration, RMS / g at EH centre frequency

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Strain (0.5-2μW)
Accelerometer
Inclinometer
Noise sensor
Gas sensor
etc.

Energy harvesting
Vibration
Temperature
Pressure fluctuation
Air-flow

Power management

Self-Powering Sensors and Communication
Best Practice Guides for Monitoring Civil Infrastructure

Distributed Fibre Optics Sensing for Monitoring Civil Infrastructure
A practical guide
Cedric Kechawari, Kenichi Soga, Nicholas de Battista, Lozaz Pelecanos, Mohammed Eshafie and Robert J Mair

Wireless Sensor Networks for Civil Infrastructure Monitoring
A best practice guide
David Rodenas-Herráiz, Kenichi Soga, Paul Fidler and Nicholas de Battista
Value of Infrastructure Sensing

• Distributed sensors are becoming available for field deployment
  – Some can be used for long-term monitoring
    • Fiber optics, power harvesting, computer vision…..

• But the business case may not be clear.
  – “How” many for “What” Value
  – ££($$) or Recovery time

• Move from Structure-level fragility to Corridor-level fragility
  – City-scale modelling using high performance computing technologies is becoming possible to assess the value of sensing
Thank you