Ground Related Risk to Transportation Infrastructure

The value of infrastructure sensing

CSIC Cambridge Centre for Smart Infrastructure & Construction

Berkeley UNIVERSITY OF CALIFORNIA

Kenichi Soga
University of California-Berkeley

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

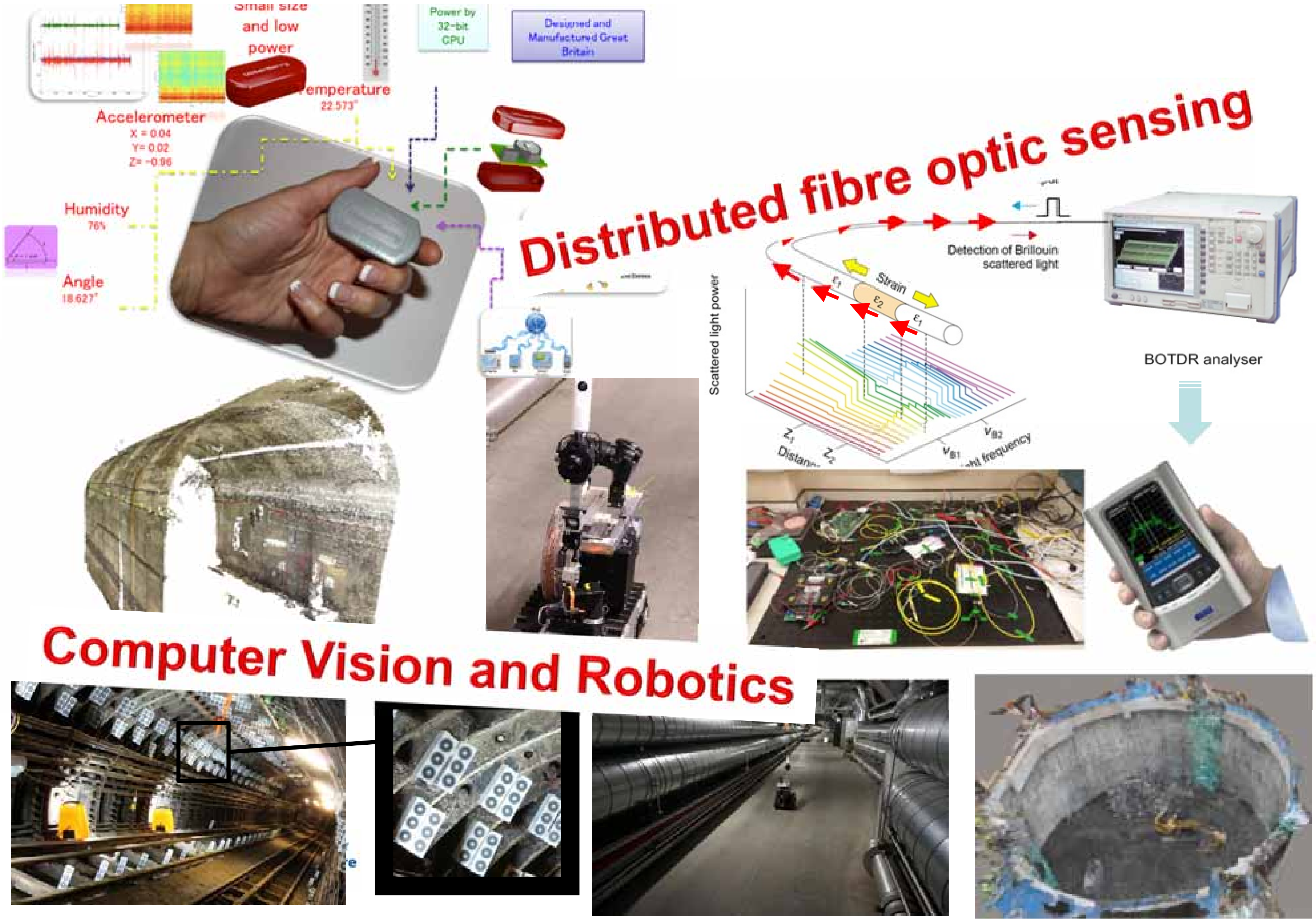
- **Motivation 2 – To extend asset life & reduce management costs**
  - **Performance monitoring** of actual operational geotechnical structures
  - Mainly field monitoring for long time (life-long)
  - For maintenance, future proofing against hazards (EQs, flooding), safety, etc.

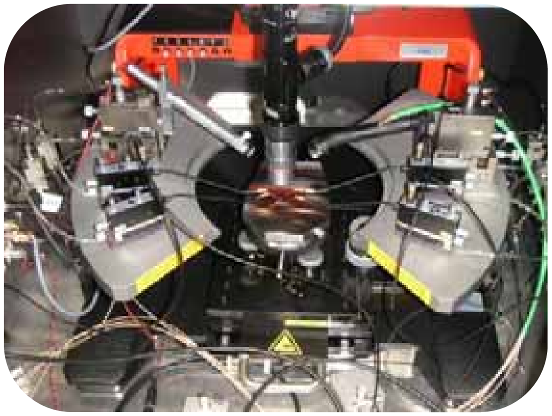
- Typically Motivation 1 dominates in geotechnical engineering. But there is increasing demand for Motivation 2 as part of the Internet of Things (IoT) revolution happening at the moment.

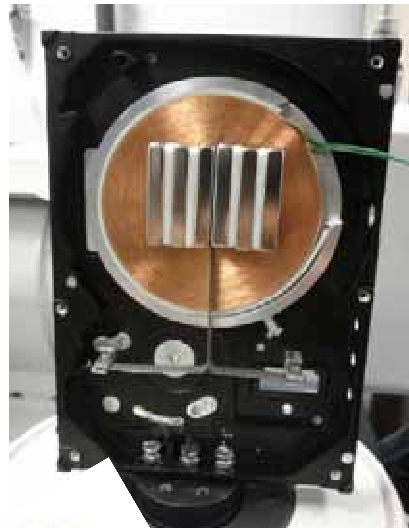
Type 2 sensors - **performance monitoring**

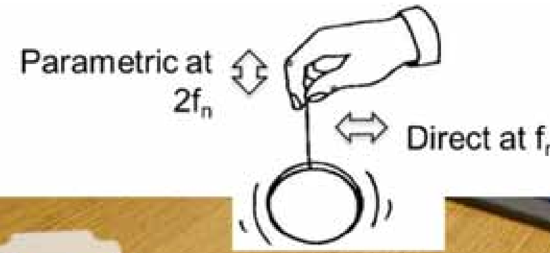
- Promotes the “Observational Method” from construction, maintenance and decommission
- Resilience monitoring, Post-hazard recovery monitoring
- Need to be robust and long life time
- Potentially wide adaption as part of routine geotechnical practice
- Quick installation process may be needed to avoid 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
  - ??

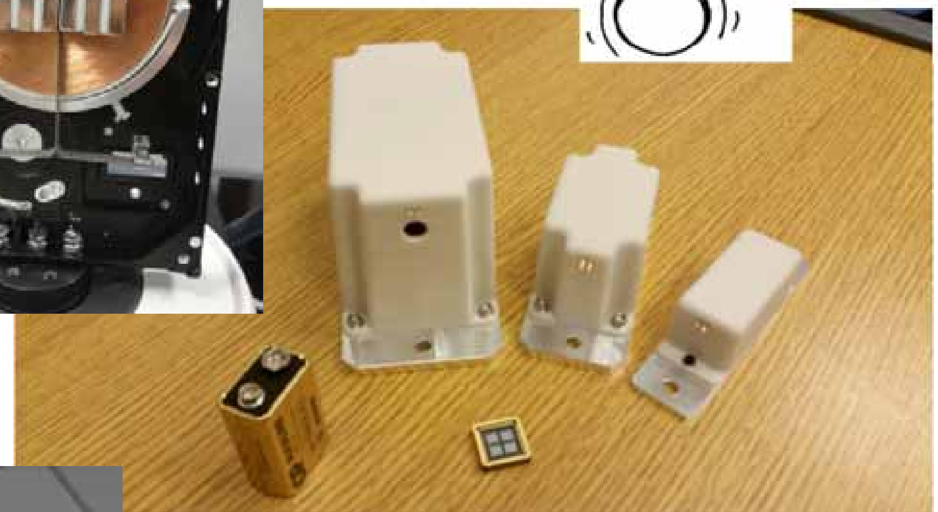
Ultra low power wireless sensor network

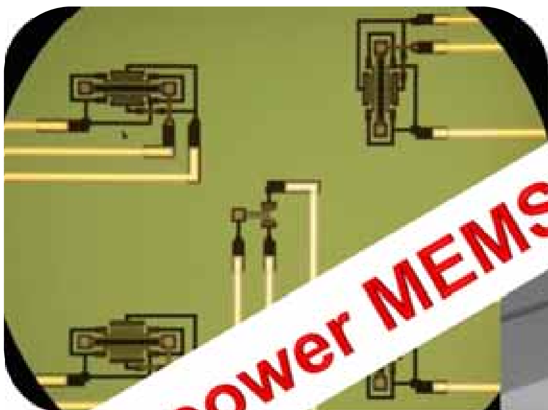


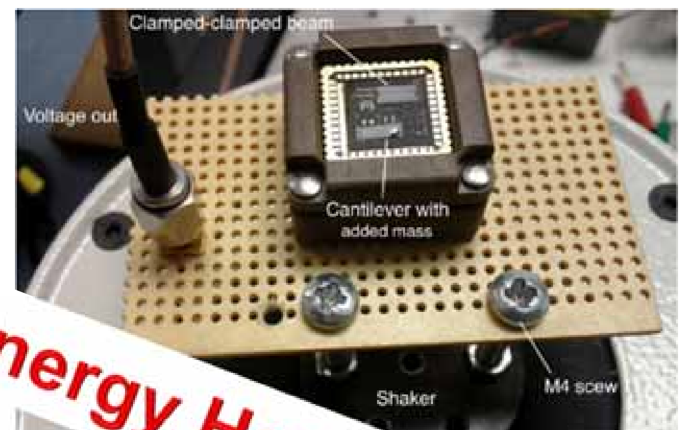












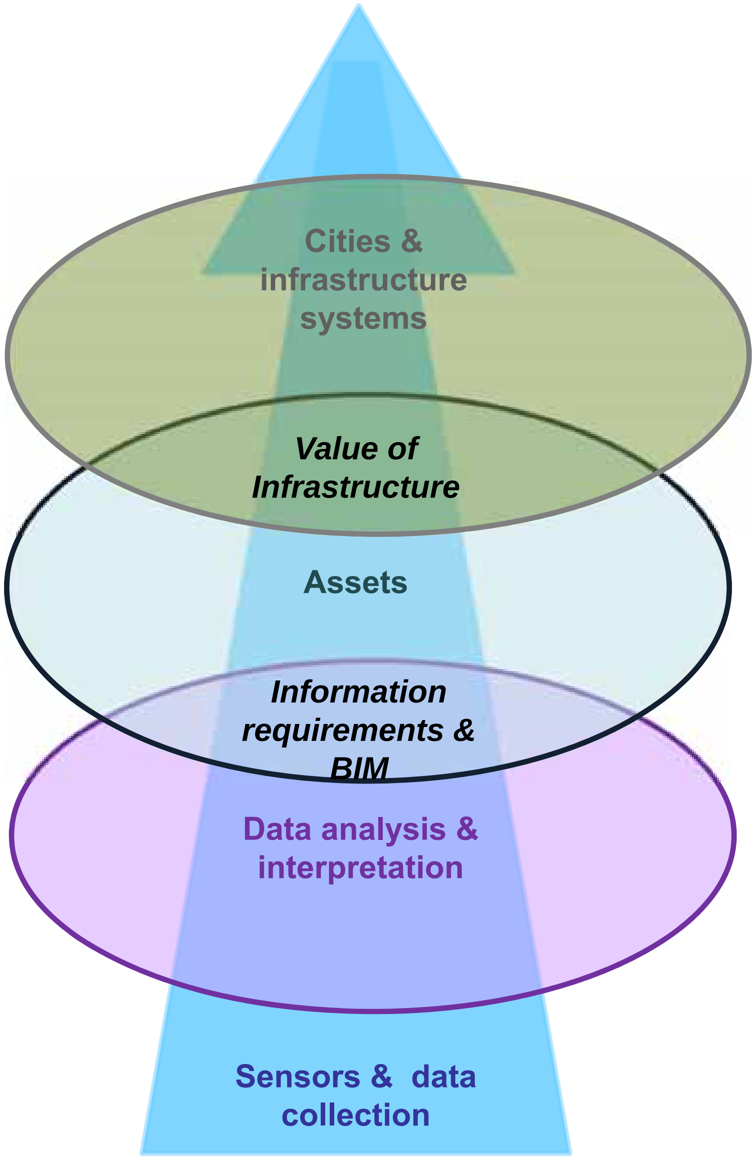
Low power MEMS sensors

Energy Harvesting

& Construction

Berkeley
UNIVERSITY OF CALIFORNIA

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?*

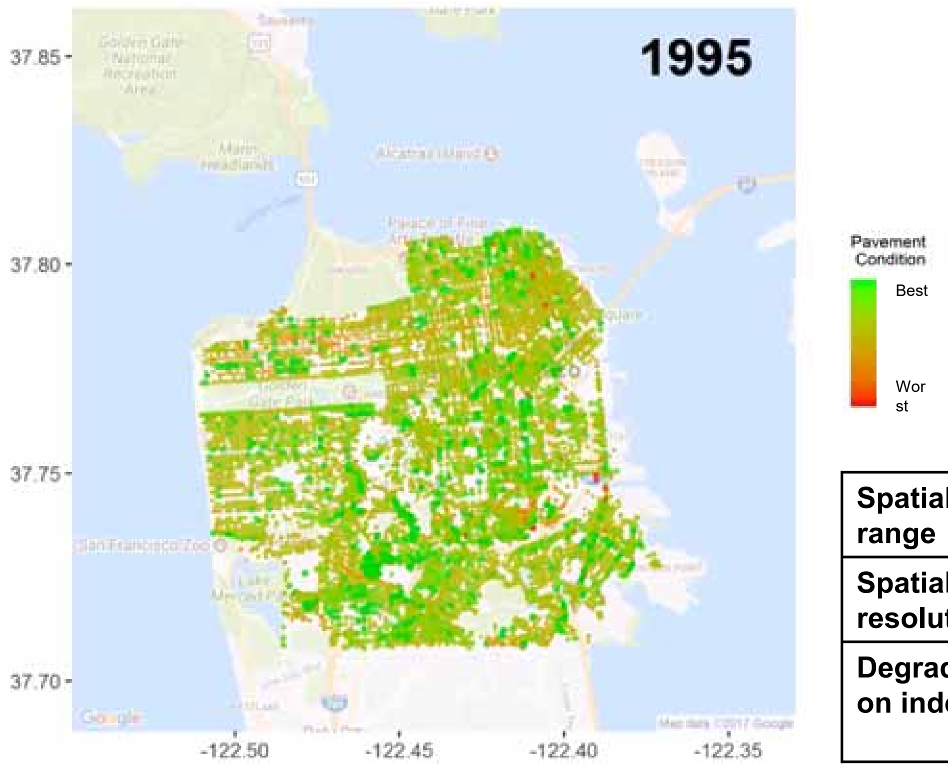
EFFICIENT ANALYSIS AND INTERPRETATION IN REAL TIME
- *How do we best design, construct & monitor our structures to deliver the performance we need?*
- *What data do we need to do this, & how do we interpret it?*

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

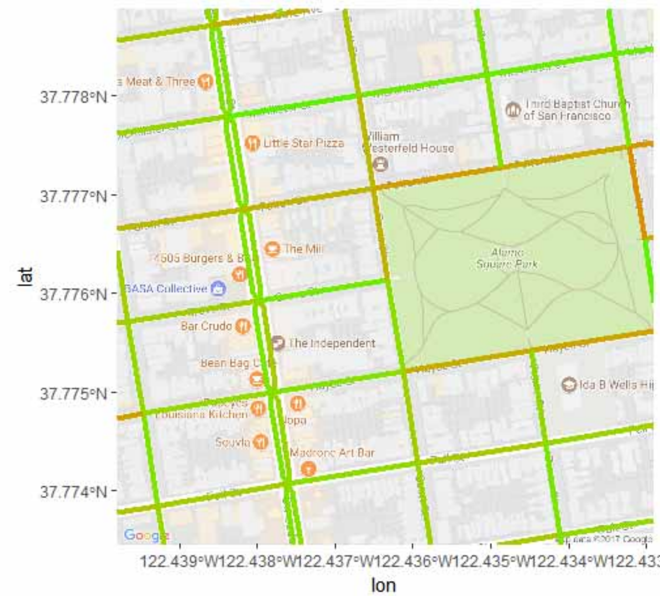
San Francisco, USA

Animation of pavement condition change in San Francisco

(Interpolated to annual data)



Zoom in to street level (Alamo Square)



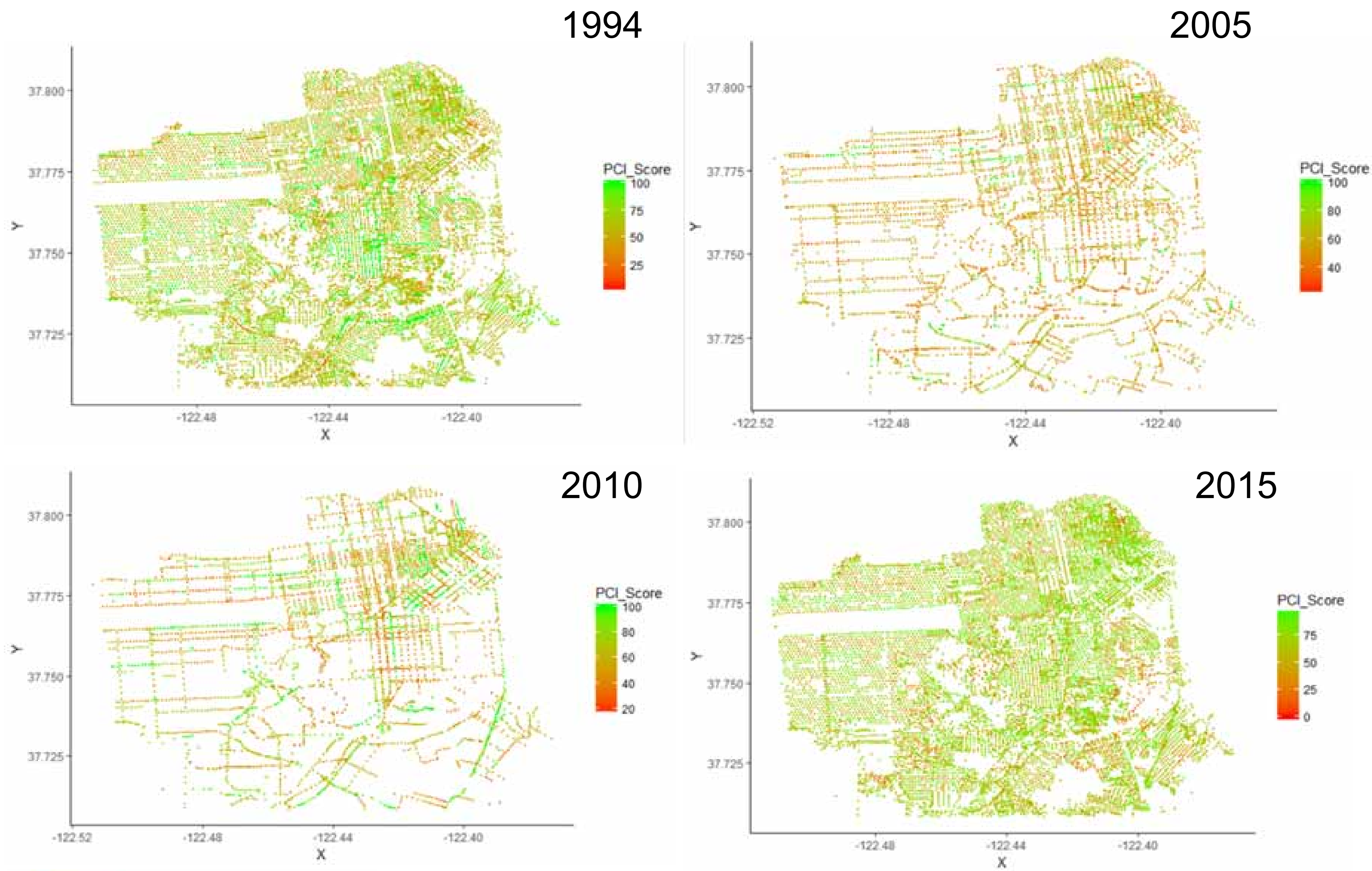
Spatial range	All streets in SF (2000 km)	**Temporal span**	Early 1990s - now
Spatial resolution	Streets (intersection to intersection)	**Temporal resolution**	Every 2-3 years
Degradation index	Pavement Condition Index (PCI)	**Total number of records**	120,000 Collected by human raters.

San Francisco Public Works

CSIC Cambridge Centre for Smart Infrastructure & Construction

Berkeley UNIVERSITY OF CALIFORNIA

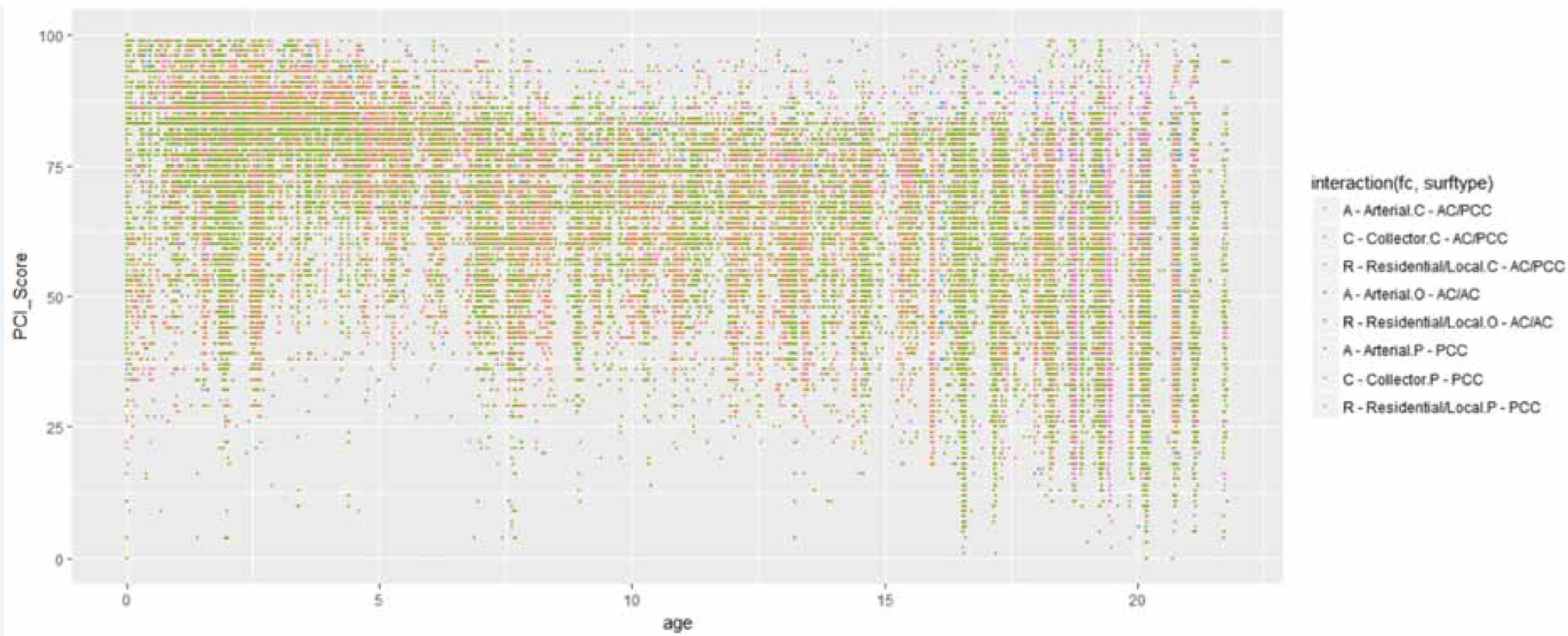
San Francisco pavement condition



CSIC Cambridge Centre for Smart Infrastructure & Construction

Berkeley UNIVERSITY OF CALIFORNIA

San Francisco PCI versus Age:
By Functional Classification & Surface Type



CSIC Cambridge Centre for Smart Infrastructure & Construction

Berkeley UNIVERSITY OF CALIFORNIA

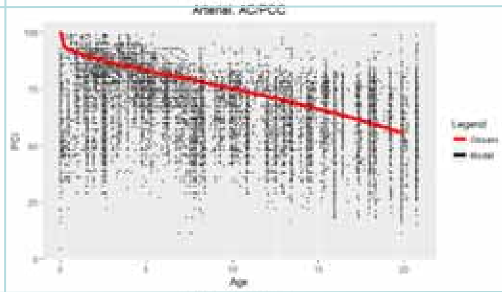
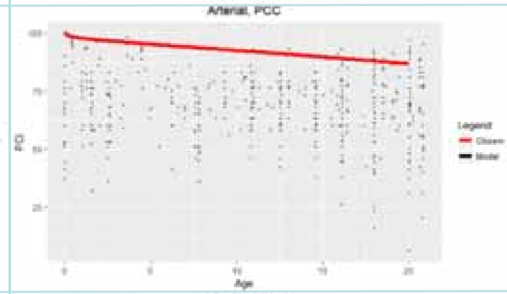
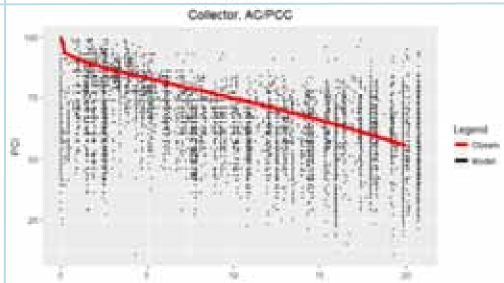
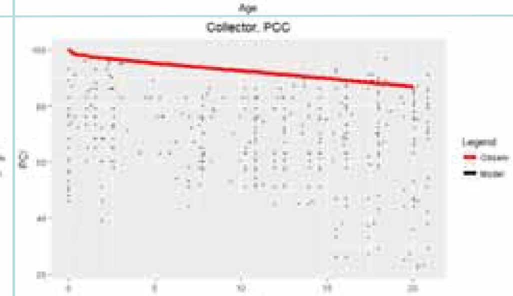
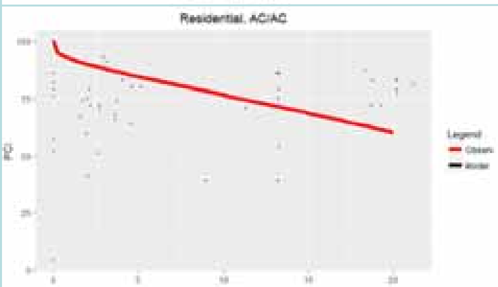
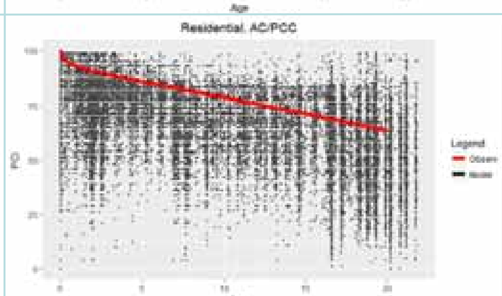
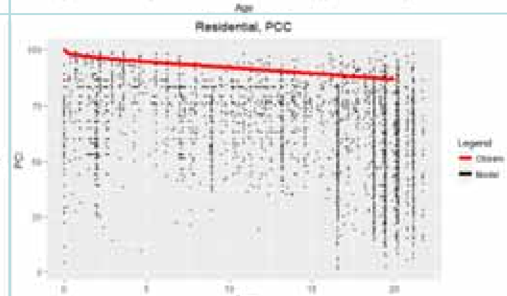
A Deterministic Pavement Performance Model

$$PCI = 100 - \frac{CHI \times \rho}{[\ln(\frac{\alpha}{AGE - SHIFT})]^{\frac{1}{\beta}}}$$

- α: regression constant that controls the age to which the curve is asymptotic
- β: regression constant that controls how sharply the curve bends
- ρ: 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:

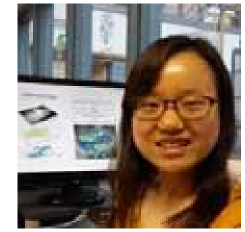
observed & model, simplified with CHI=1, SHIFT=0

	AC/AC	AC/PCC	PCC
Arterial	**No Data**		
Collector	**No Data**		
Residential			

CSIC Cambridge Centre for Smart Infrastructure & Construction

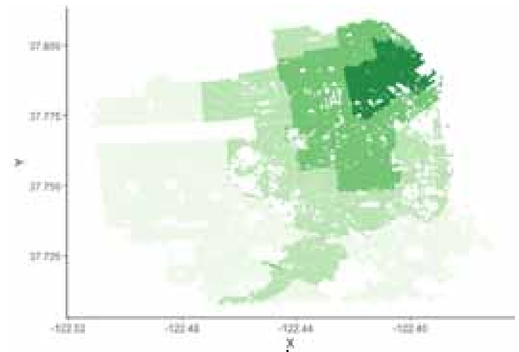
Berkeley UNIVERSITY OF CALIFORNIA

Bingyu Zhao
with Alan Turing Institute

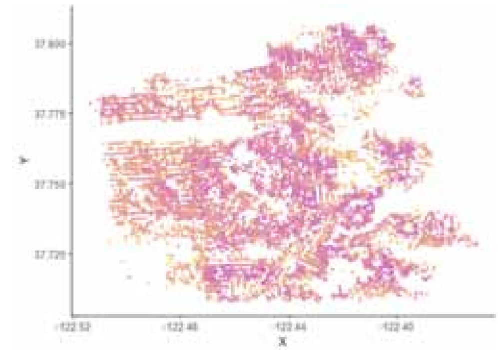


Truck Volume

Land Use



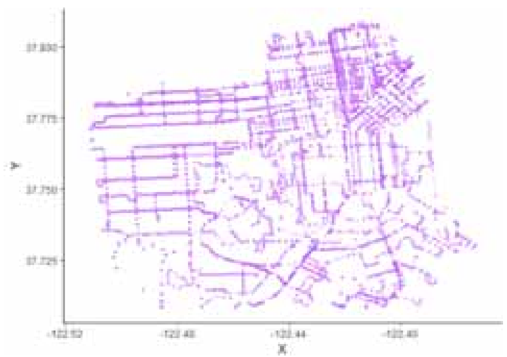
Slope



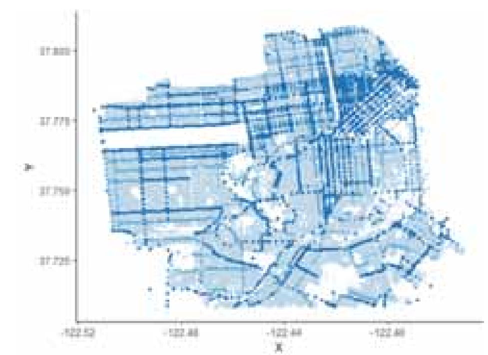
Spatial Modelling

Car Volume

Bus Volume

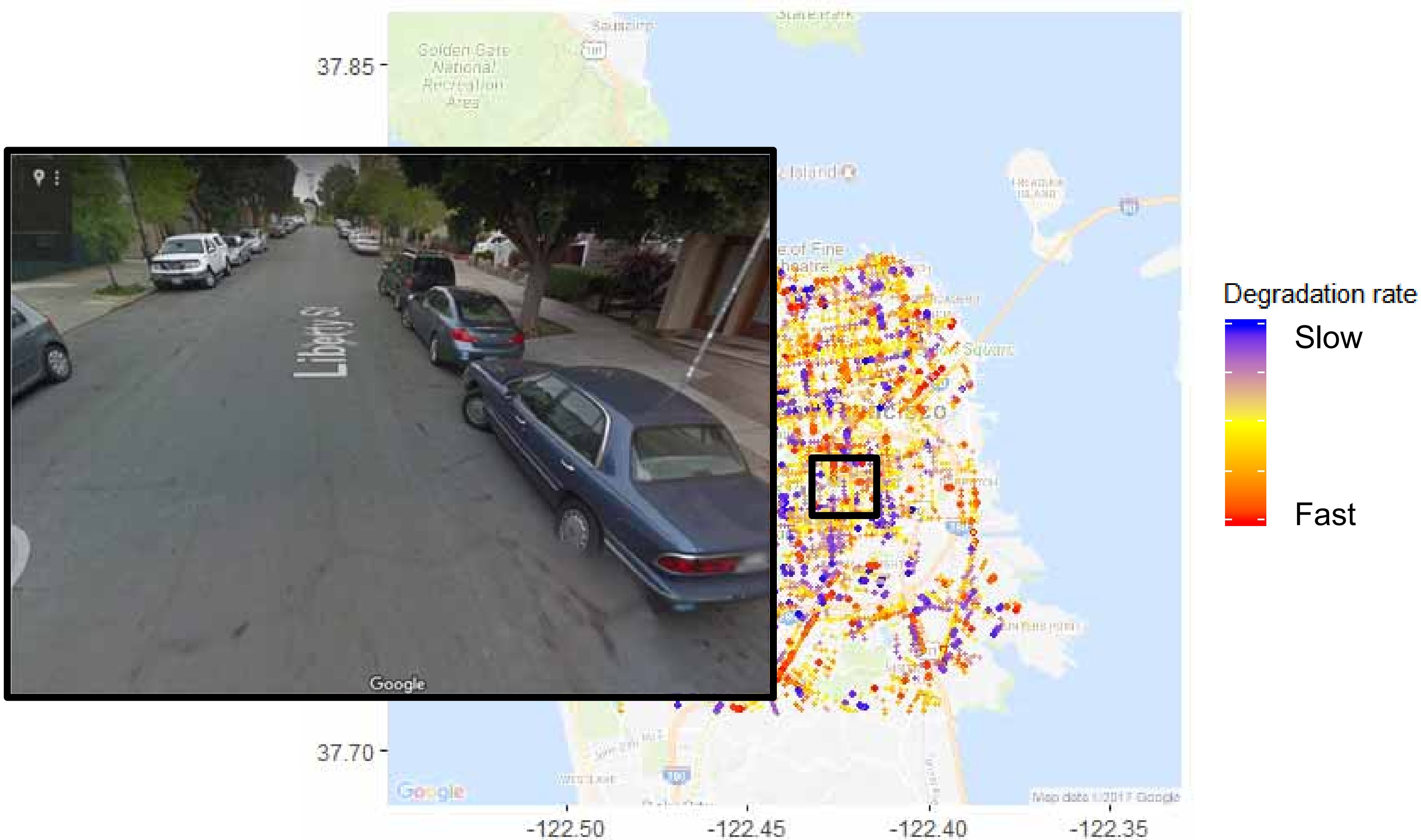


Road Class



CSIC Cambridge Centre for Smart Infrastructure & Construction

Berkeley UNIVERSITY OF CALIFORNIA



CSIC Cambridge Centre for Smart Infrastructure & Construction

Berkeley UNIVERSITY OF CALIFORNIA

London, UK

Pavement condition in Greater London, 2014

Road Condition Index (RCI)
0-40 40-100 >100

Zoom in to street level (London Bridge)

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

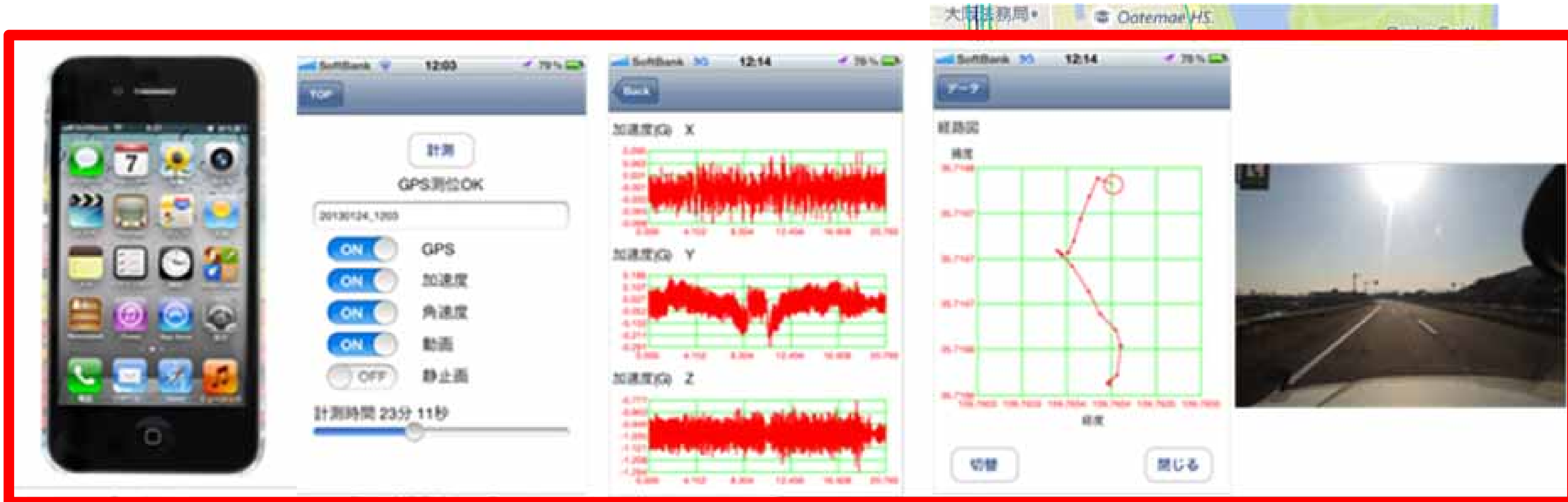
CSIC Cambridge Centre for Smart Infrastructure & Construction

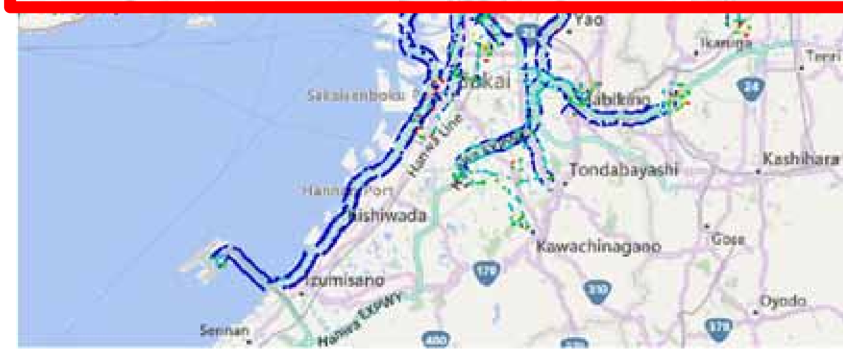
SCANNER survey (Surface Condition Assessment for the National Network of Roads), Transport for London

Berkeley UNIVERSITY OF CALIFORNIA

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* Collected by smart phone mounted to commercial vehicles

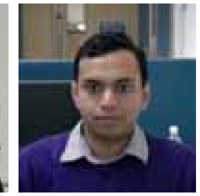
* Assume each taxi ride is 5km. Based on 179 successful taxi uploads in May 2016.

Cambridge Centre for Smart Infrastructure & Construction

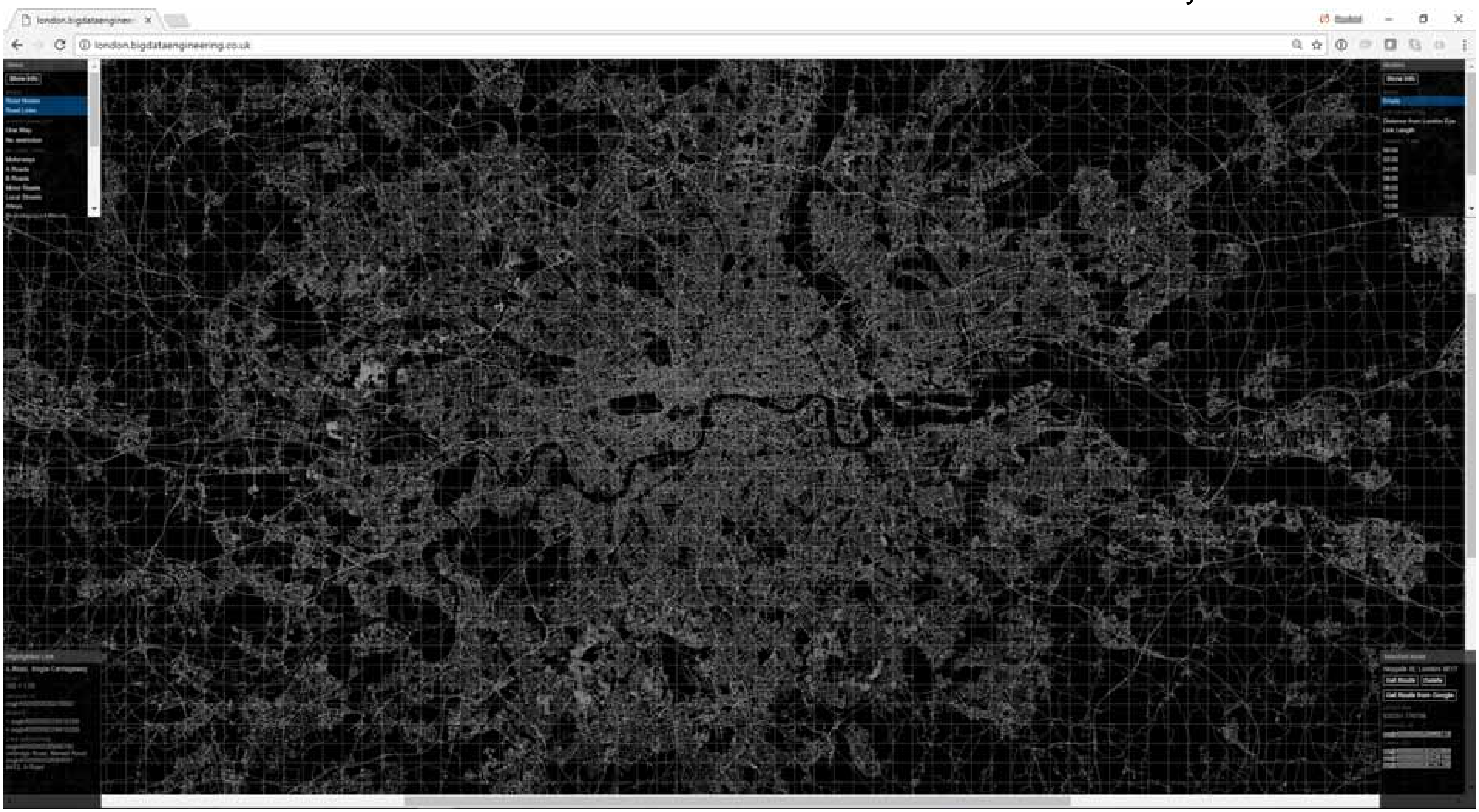
iDRIMS system, Professor Tomonori Nagayama and Professor Masashi Toyoda at Tokyo University

Berkeley UNIVERSITY OF CALIFORNIA

Macro View

Gerard Casey Krishna Kumar



Cambridge Centre for Smart Infrastructure & Construction

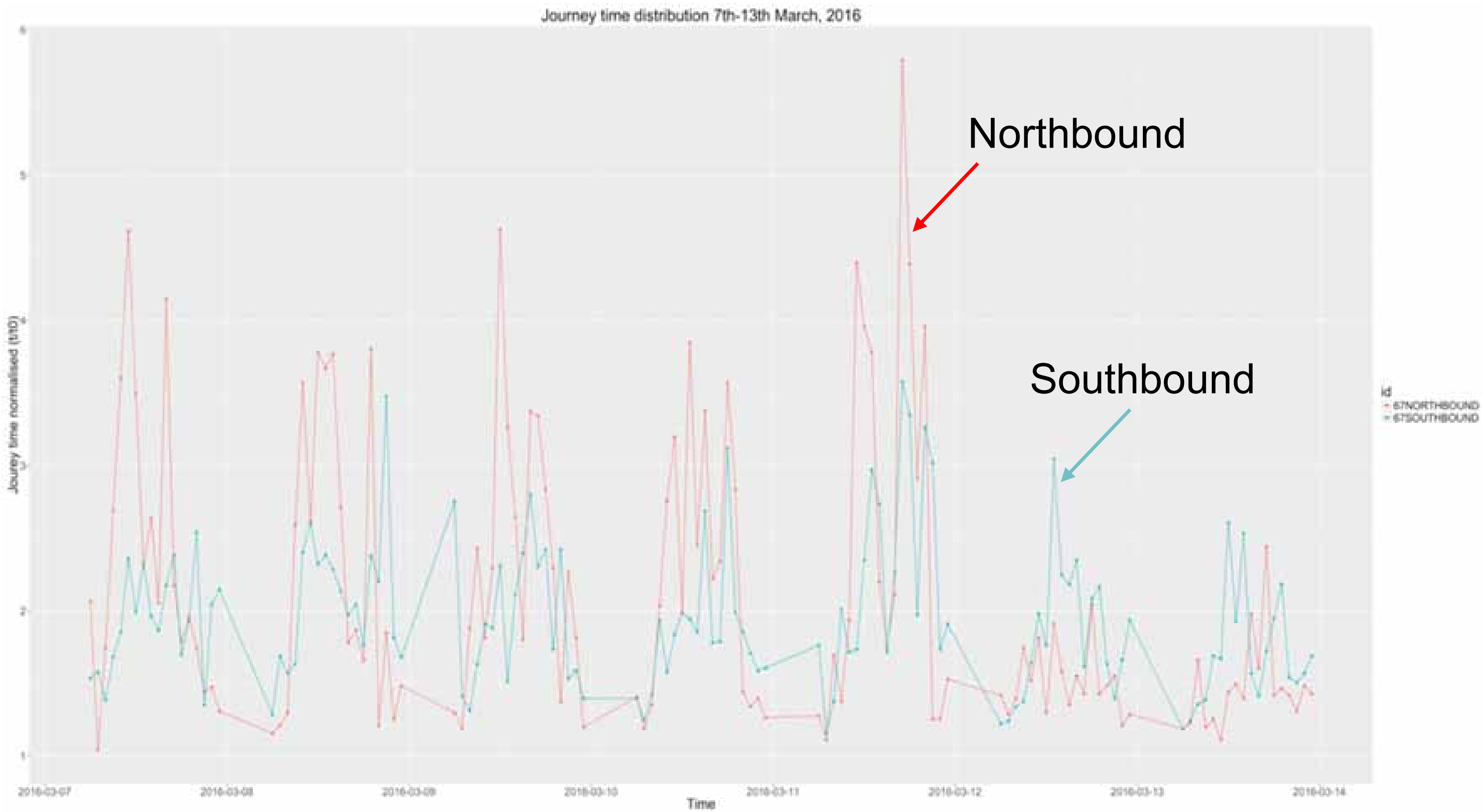
Berkeley UNIVERSITY OF CALIFORNIA

Micro View

Cambridge Centre for Smart Infrastructure & Construction

Berkeley UNIVERSITY OF CALIFORNIA

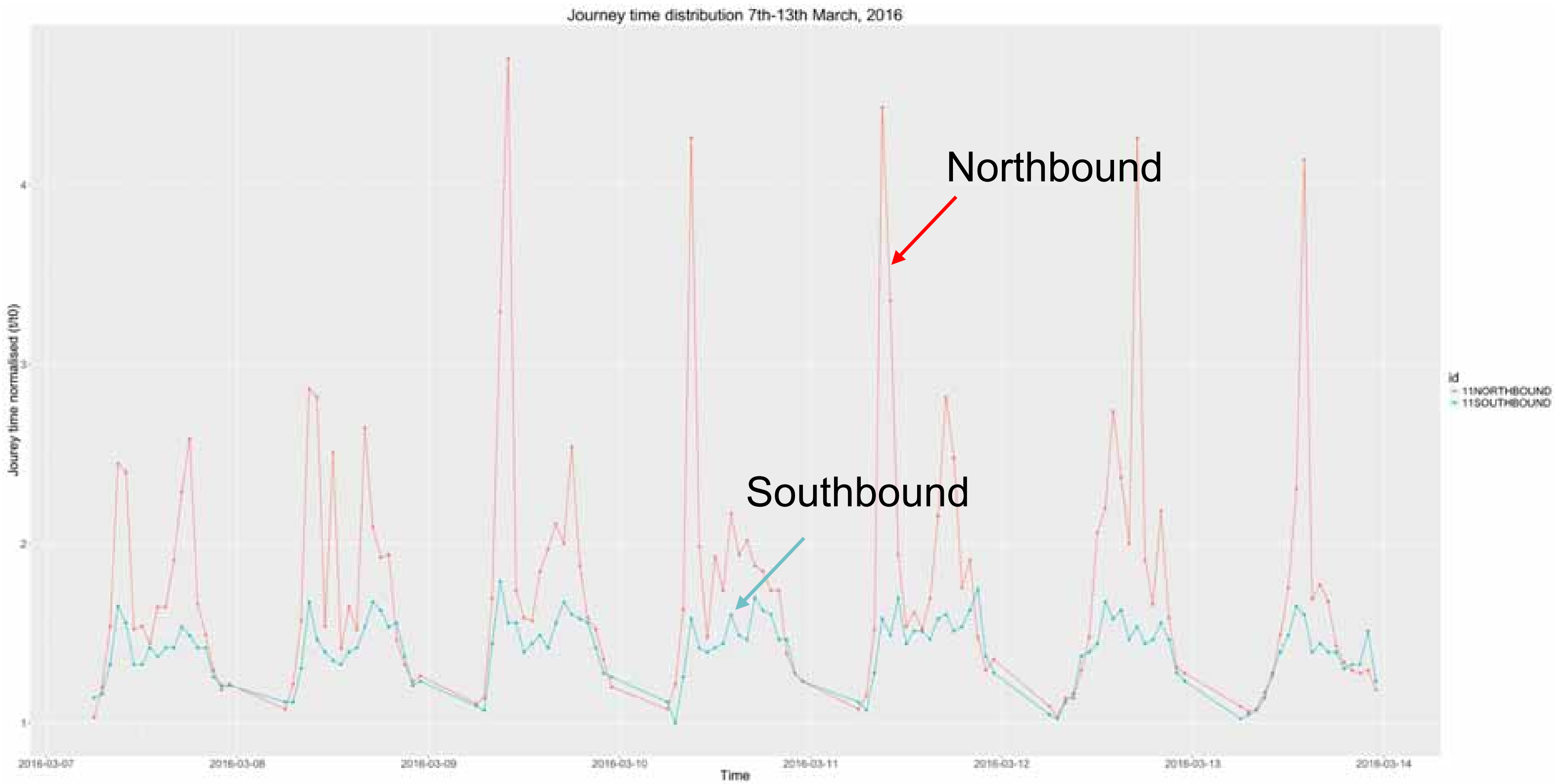
Crowd sourced data
Google Travel time distributions



Cambridge Centre for
Smart Infrastructure & Construction

Berkeley
UNIVERSITY OF CALIFORNIA

Travel time distributions



Cambridge Centre for
Smart Infrastructure
& Construction

Berkeley
UNIVERSITY OF CALIFORNIA

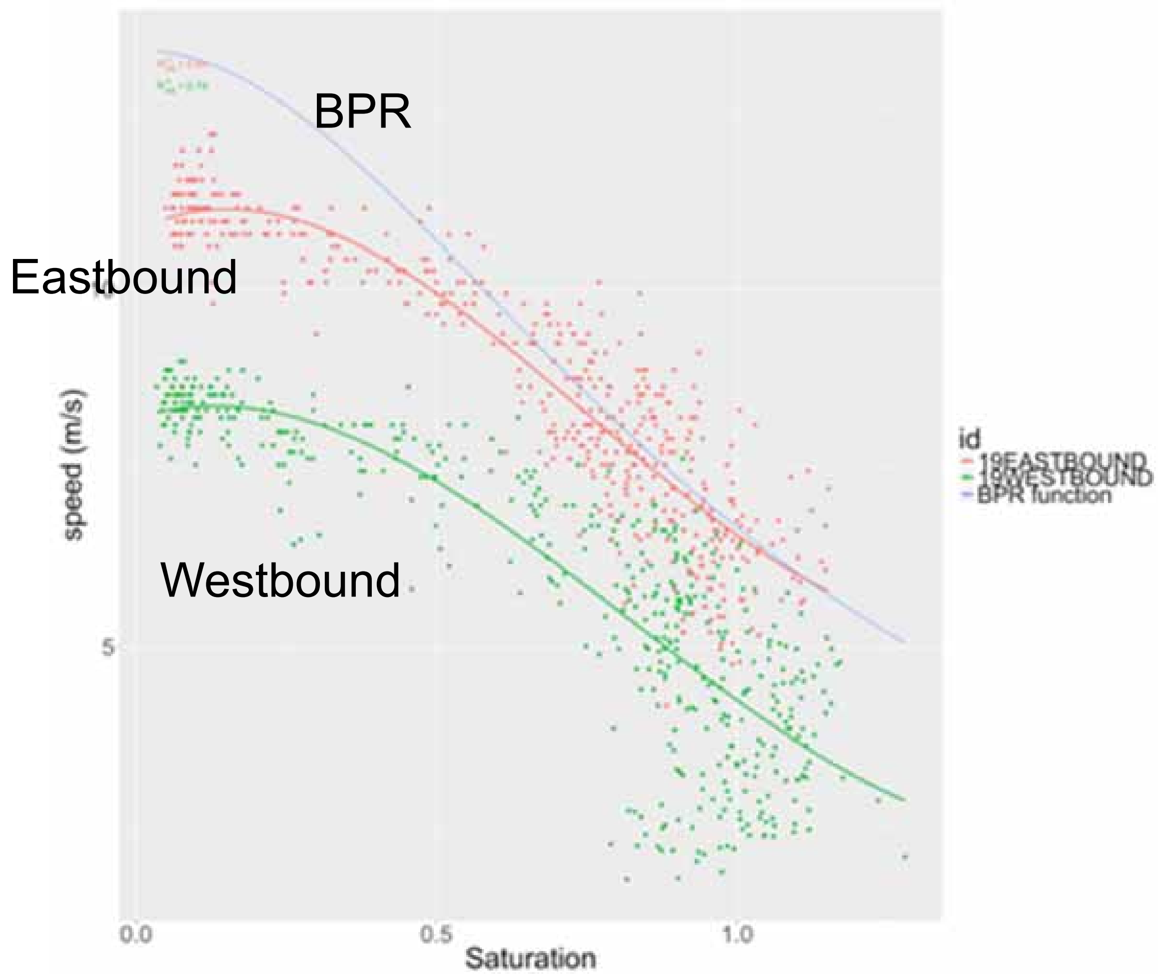
Travel time distributions

A208, Chiselhurst. Newshopper.co.uk, 2016

Cambridge Centre for Smart Infrastructure & Construction

Berkeley UNIVERSITY OF CALIFORNIA

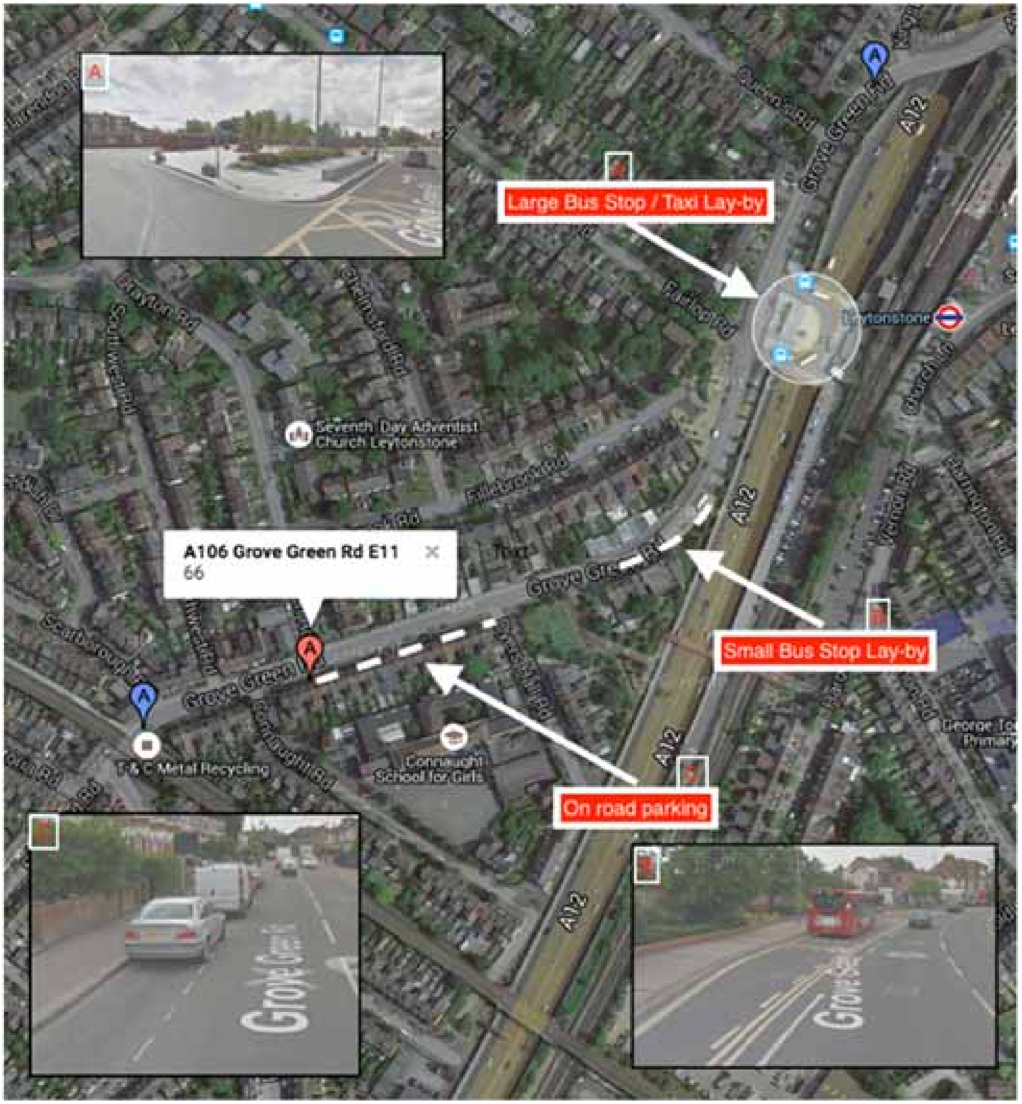
Context specific volume-delay functions



CSIC Cambridge Centre for Smart Infrastructure & Construction

Berkeley UNIVERSITY OF CALIFORNIA

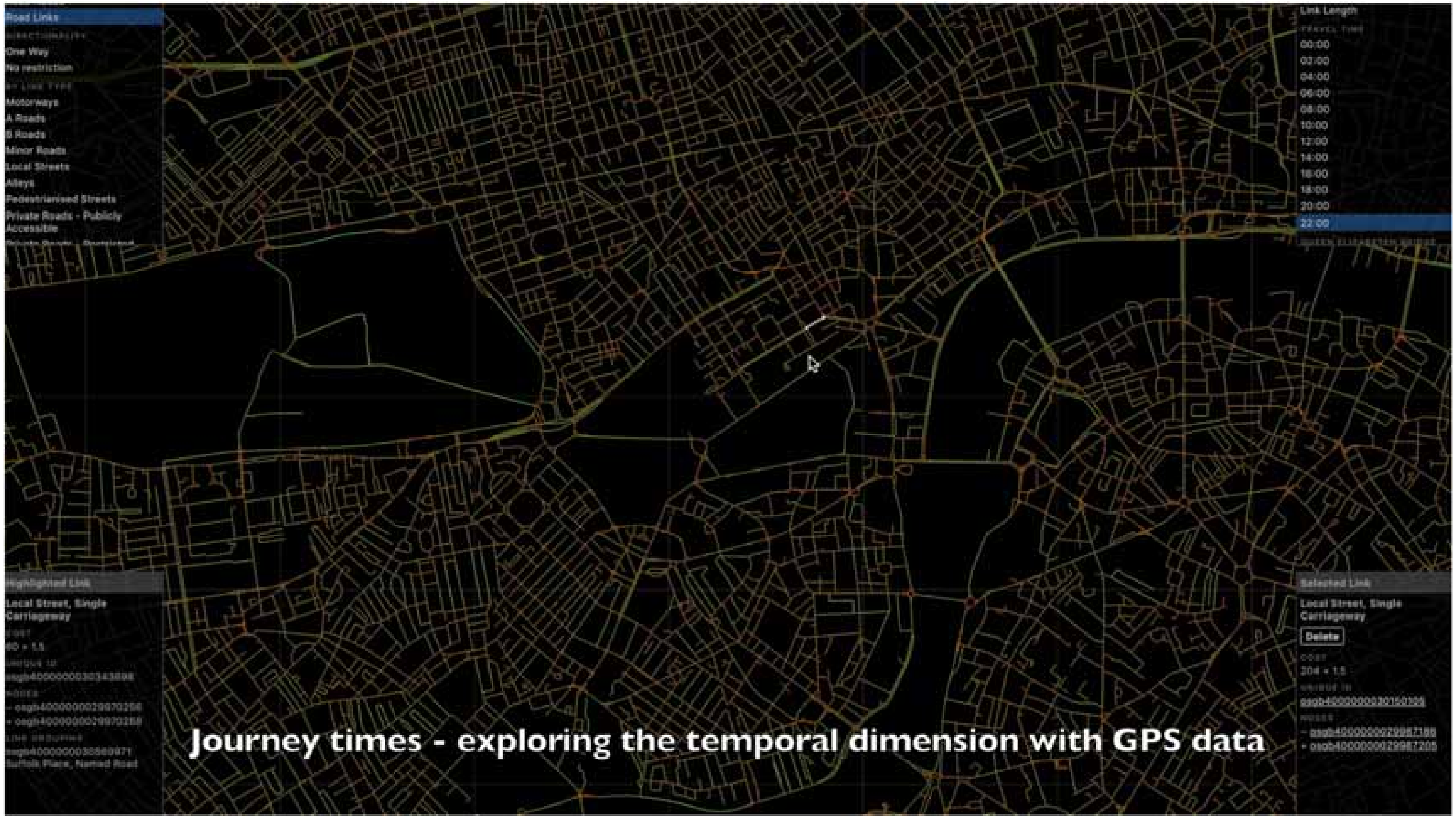
Speed-saturation functions



CSIC Cambridge Centre for Smart Infrastructure & Construction

Berkeley UNIVERSITY OF CALIFORNIA

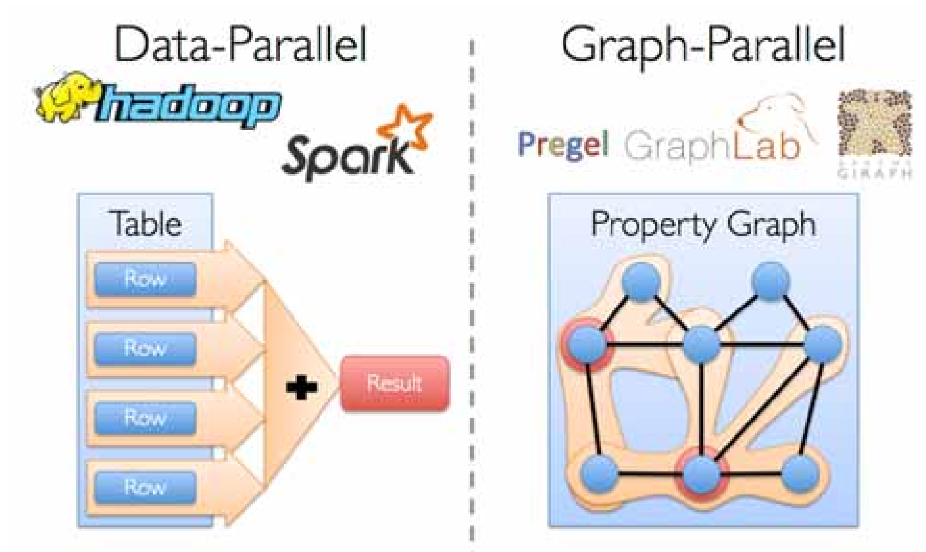
Agent Based Model – Scenario testing
Hourly movement of 1 million agents (about 10% of London Population)

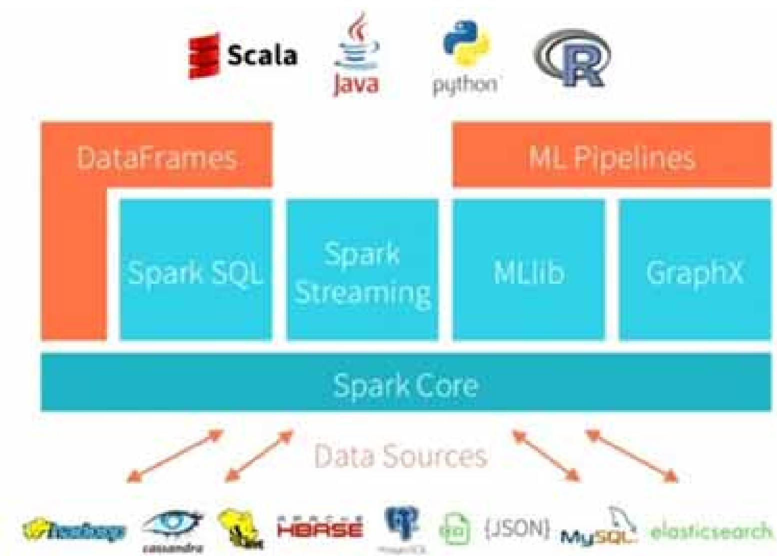


Emerging behaviour, cascading behaviour, reactive & adaptive agents….

CSIC Cambridge Centre for Smart Infrastructure & Construction

Berkeley UNIVERSITY OF CALIFORNIA





- Graph MapReduce
- In-memory cluster computing
- Decentralised data structures

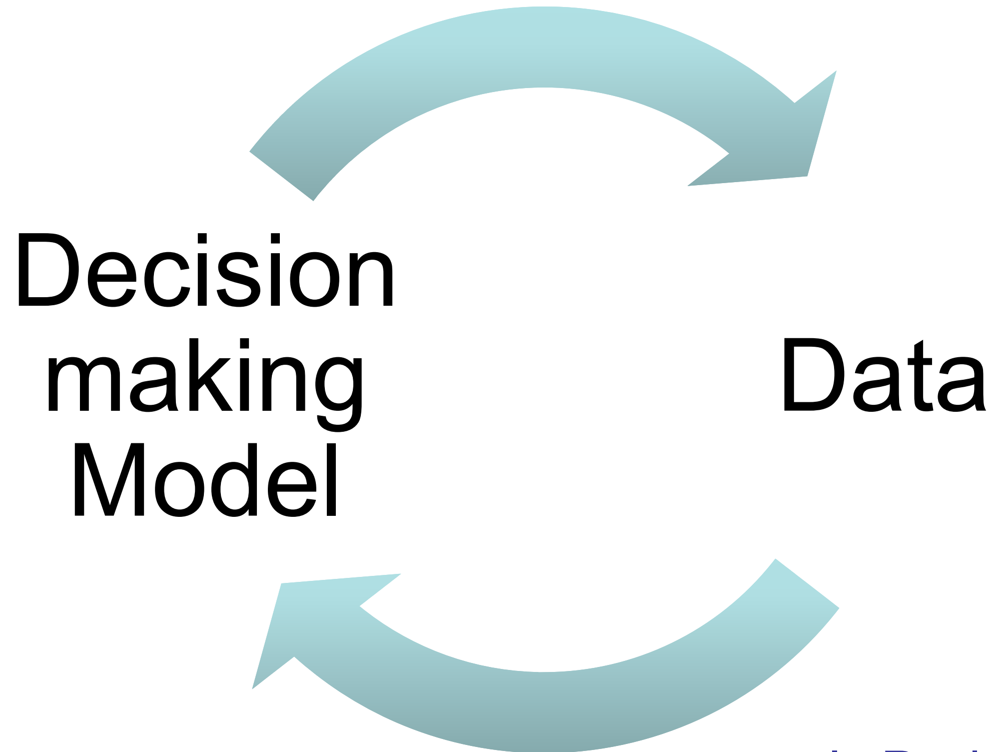
- Graph size
    - ~250k nodes
    - ~800k edges

- ~1.5GB .gml to 43MB .json.gz

CSIC Cambridge Centre for Smart Infrastructure & Construction

Berkeley UNIVERSITY OF CALIFORNIA

Iterative decision making models

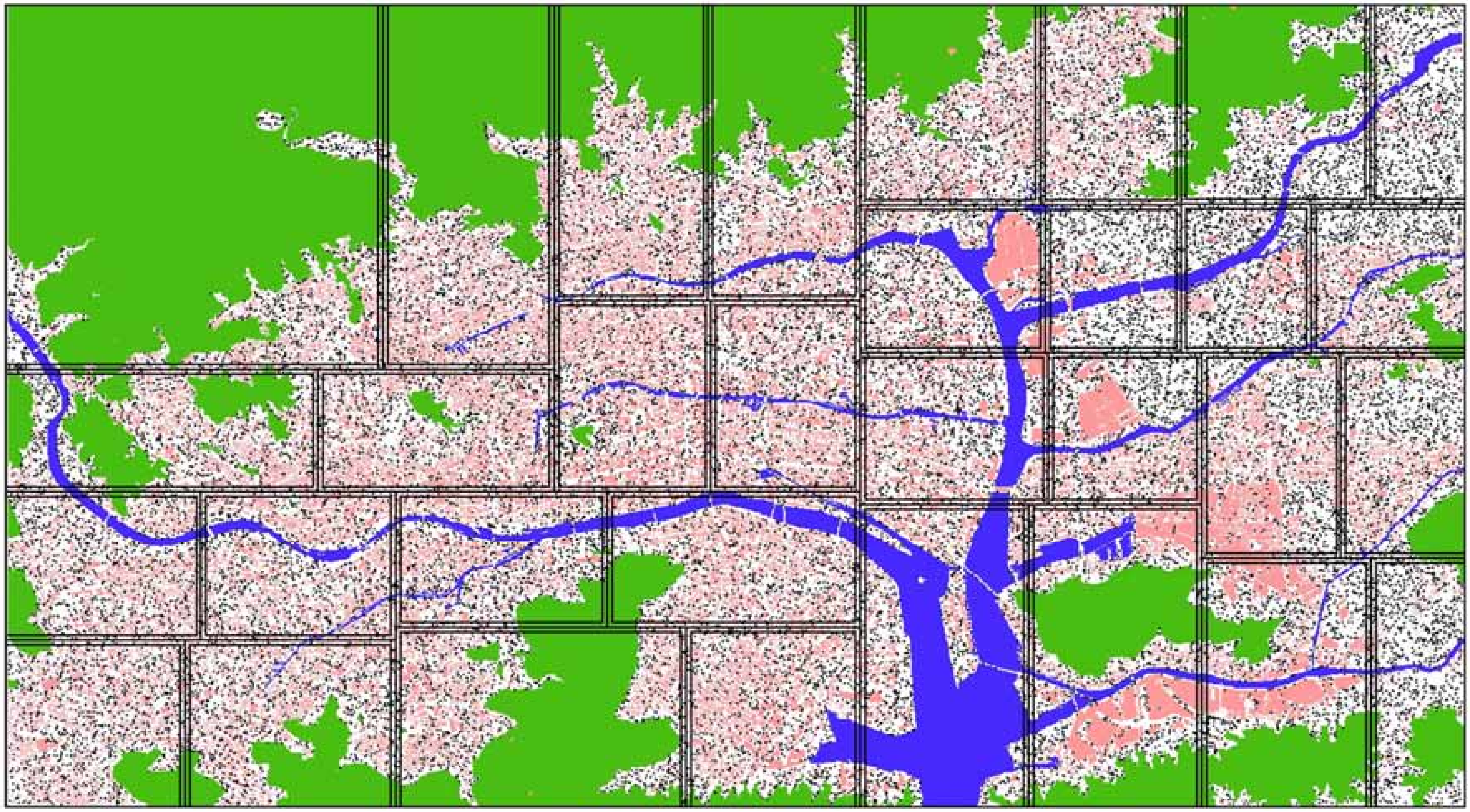


+ disruptive event
{sudden precipitation}

In Real-time

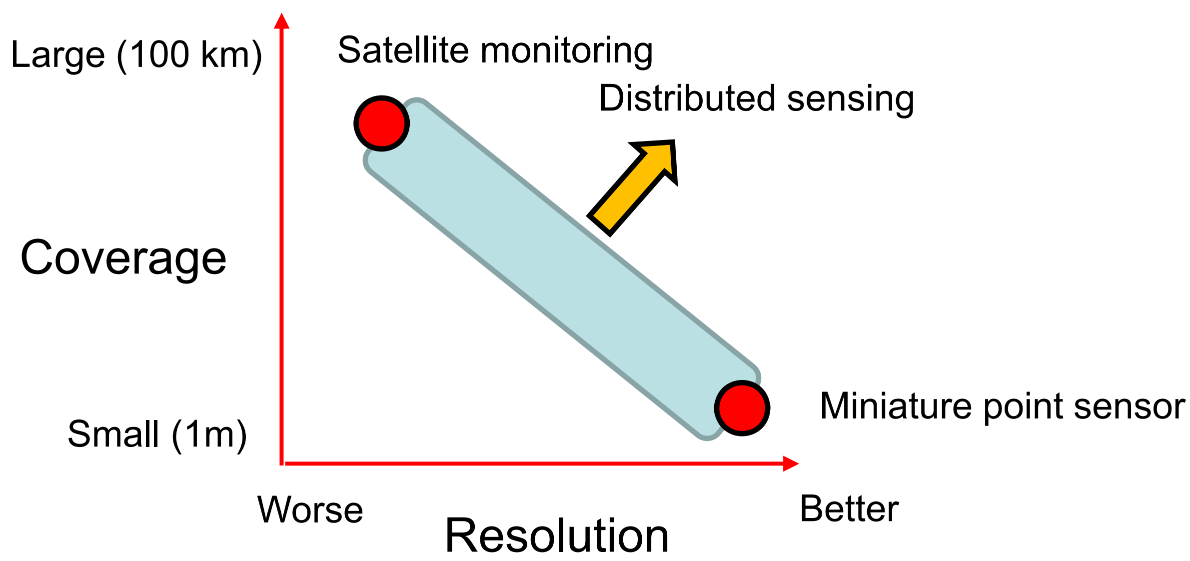
- How should transit operators respond locally and globally?
- How should traffic lights respond?

Muneo Hori, University of Tokyo

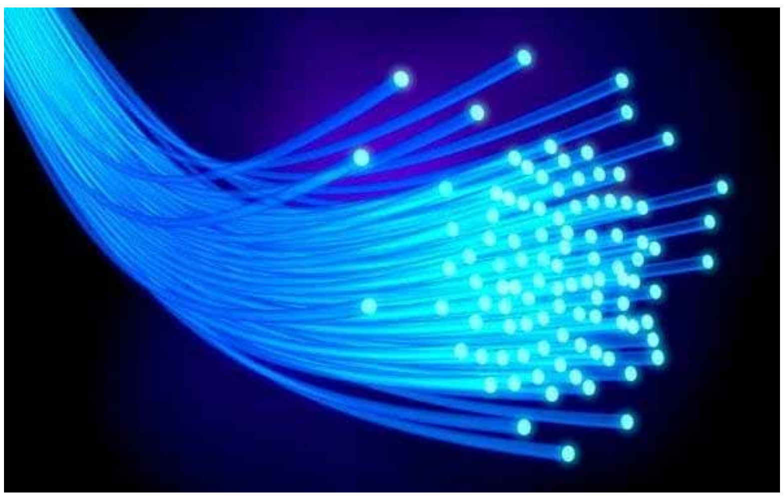


Sensor development - Trend

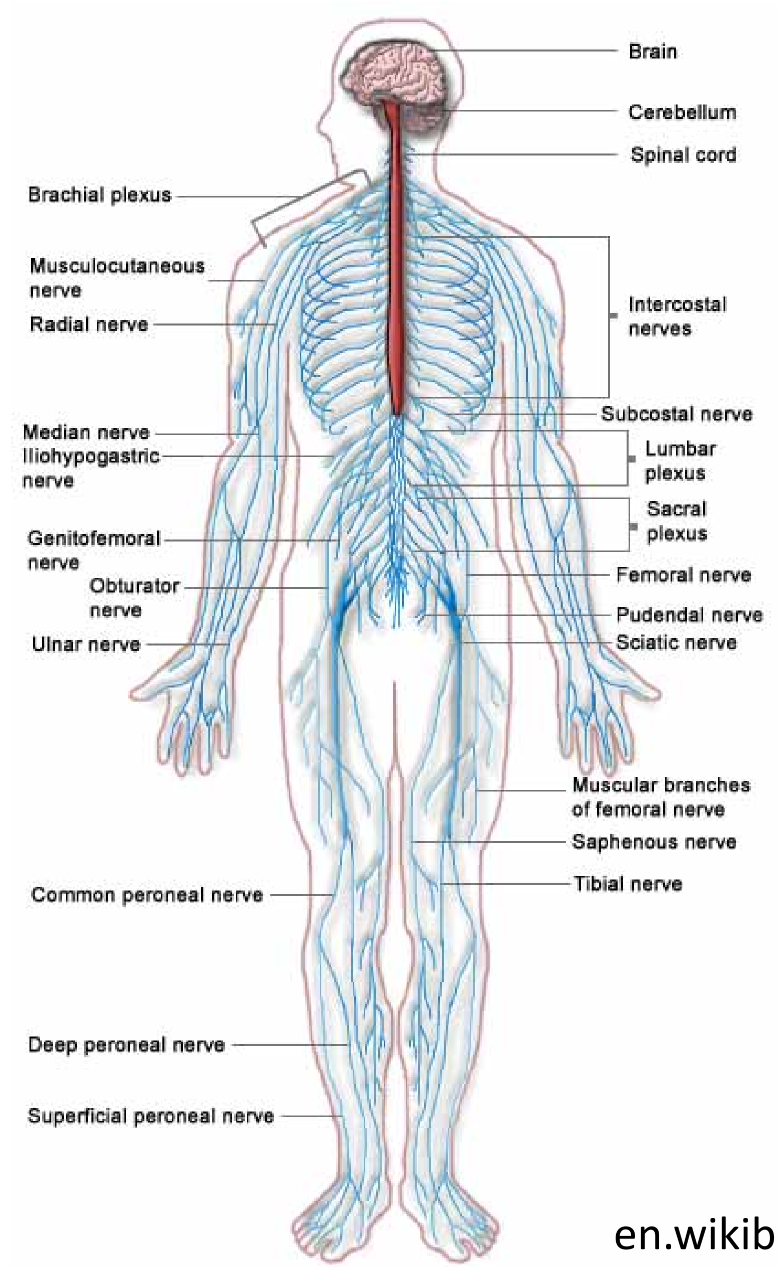
- Better accuracy, resolution and precision
- “Point” sensors to “Distributed” sensors
- Wider coverage
- Smaller and low power
- More dynamic (faster data acquisition)
- More robust
- Better communication (wireless)
- **Long performance**



Distributed Fibre Optics Sensing



Telegraph.co.uk

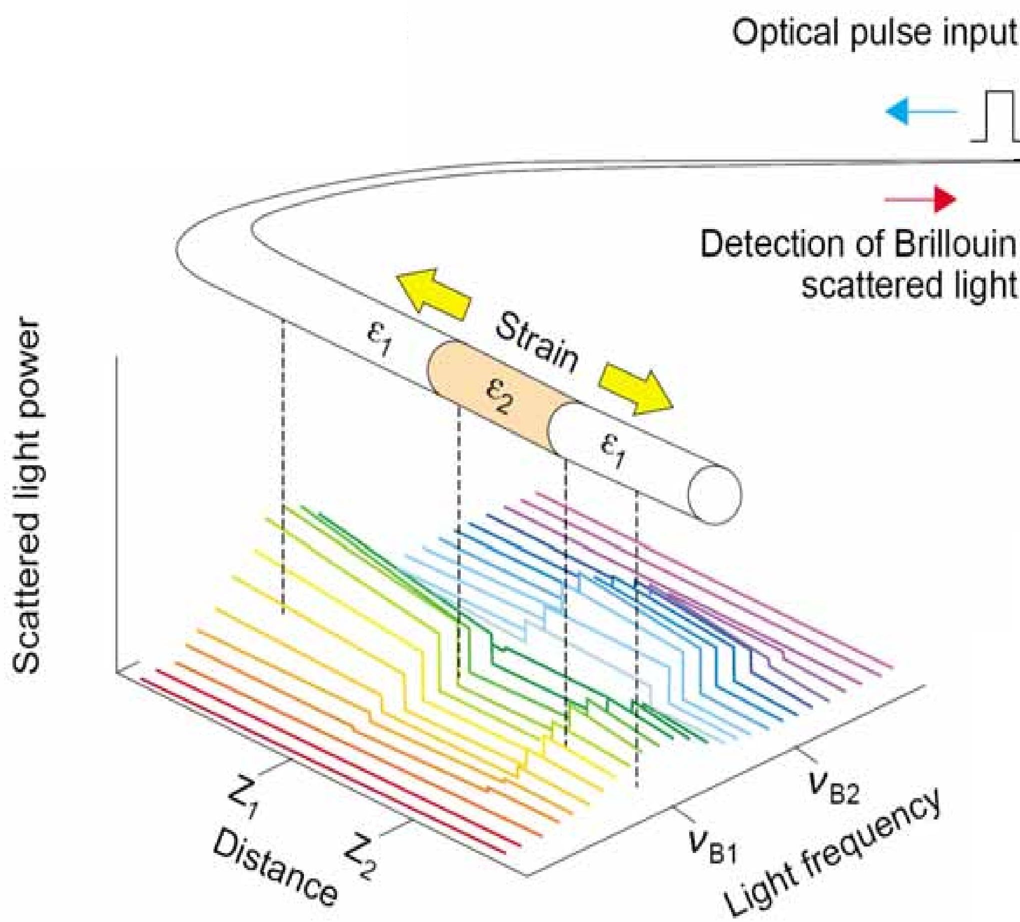


en.wikibooks.org

CSIC Cambridge Centre for Smart Infrastructure & Construction

Berkeley UNIVERSITY OF CALIFORNIA

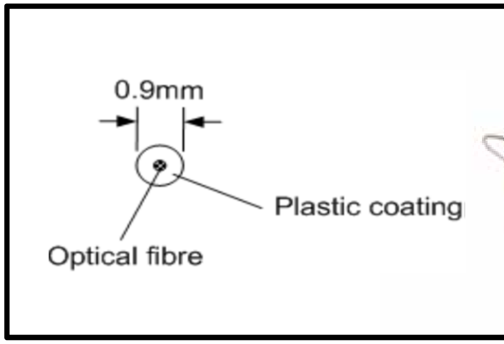
Distributed Sensing providing "Continuous Strain/temperature/vibration Profile" along the fibre optic cable

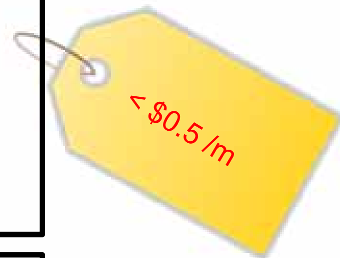


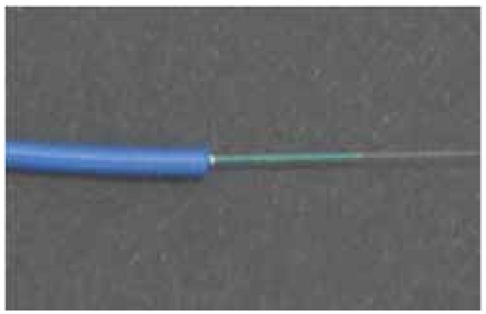
The frequency shift of the Brillouin scattered light is proportional to the strain.

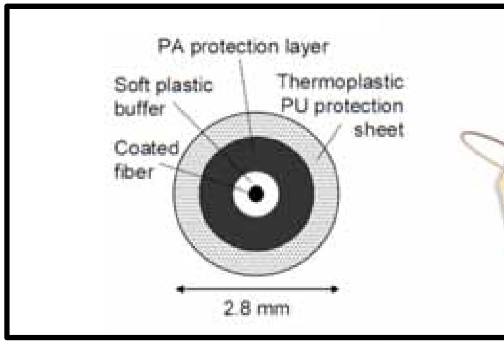
- Distance range ≈10-30km
- Readout resolution = 0.05m
- Gauge length resolution = 0.2-1m
- Strain Resolution = 10-30με

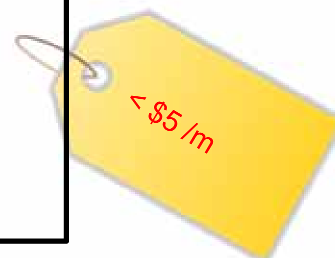
Strain sensing cables (tight buffer)

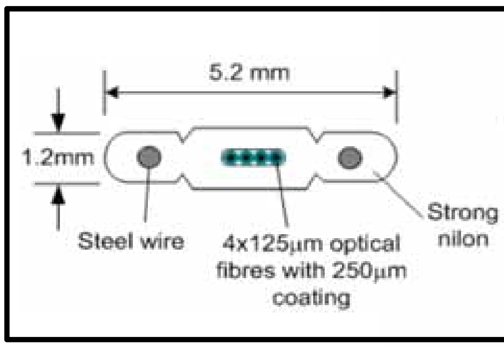


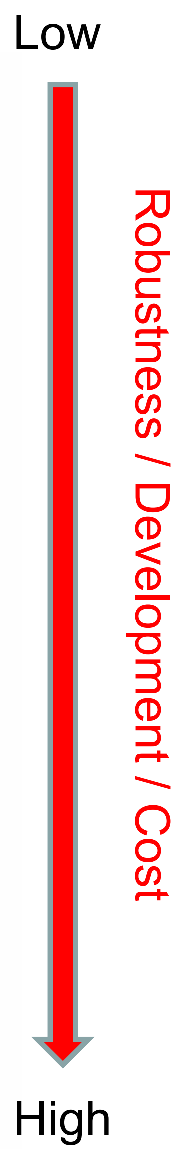










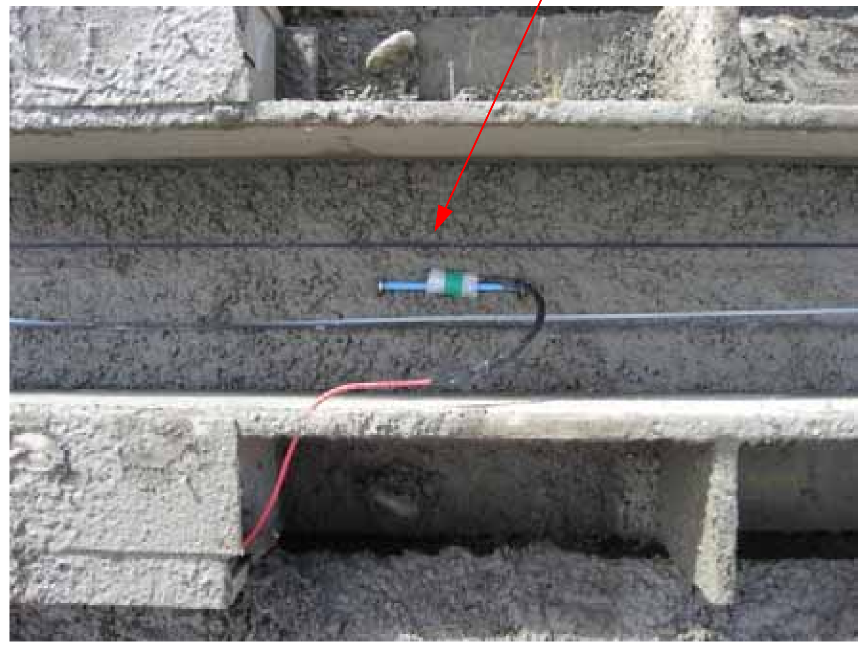


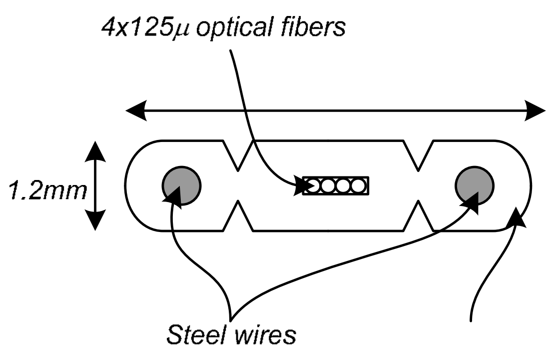
CSIC Cambridge Centre for Smart Infrastructure & Construction

Berkeley UNIVERSITY OF CALIFORNIA

Robustness

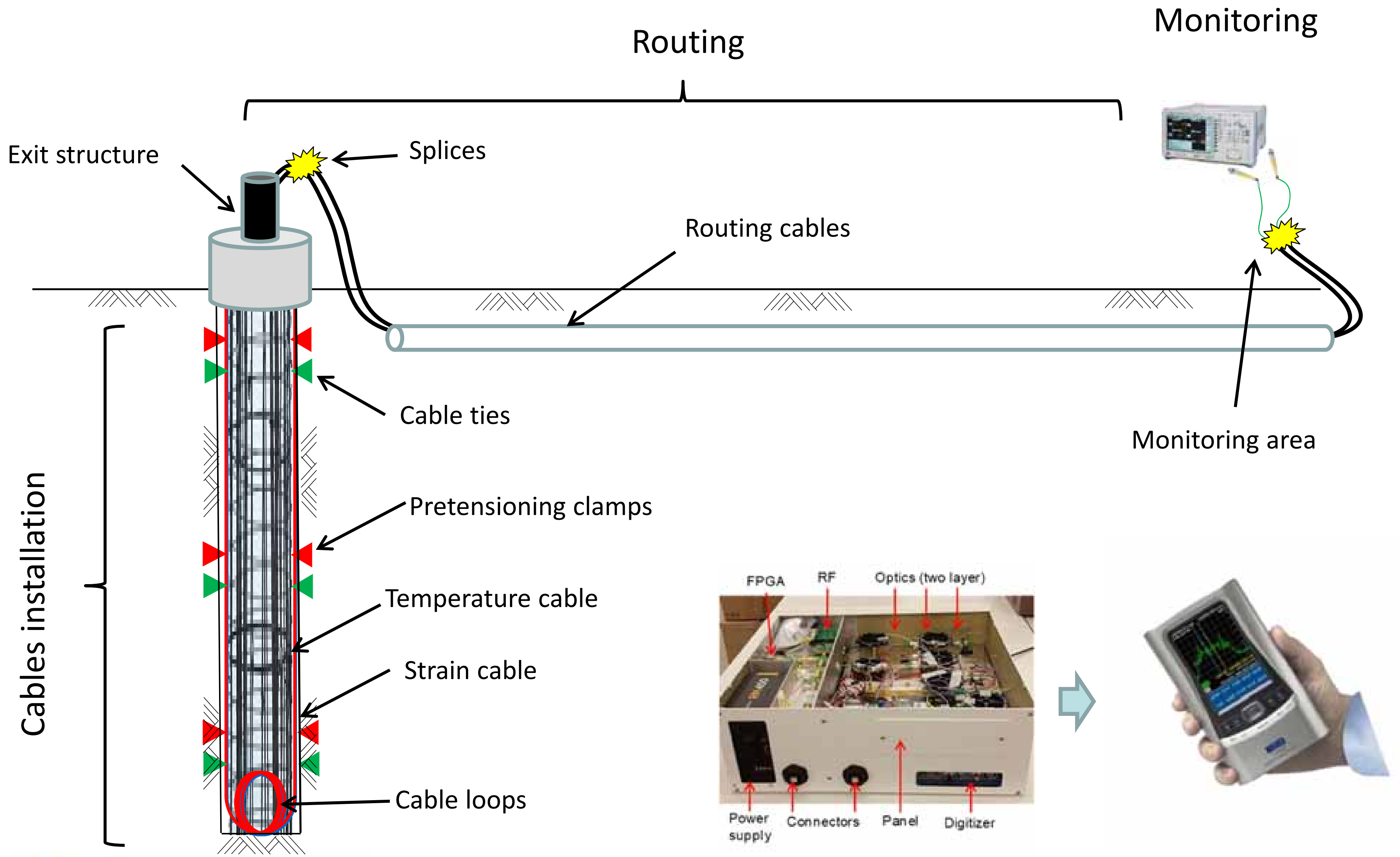
Fujikura Reinforced Fibre Optic Cable





FUJIKURA SM 4 Reinforced

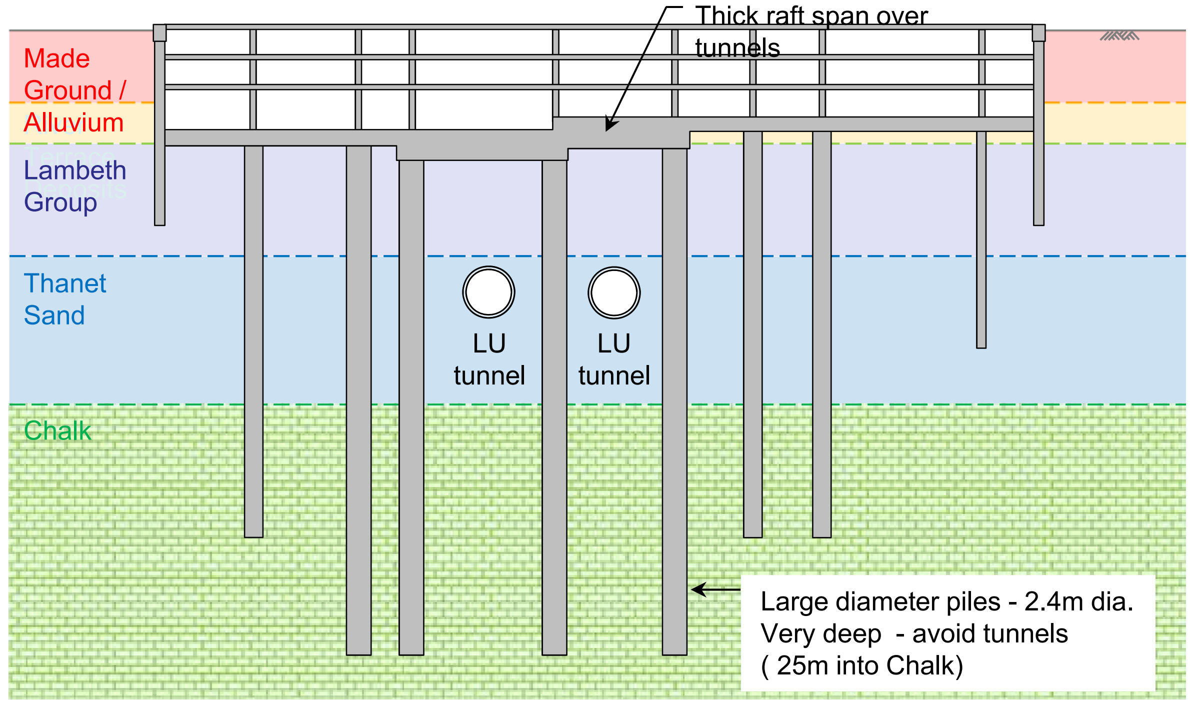
System components



CSIC Cambridge Centre for Smart Infrastructure & Construction

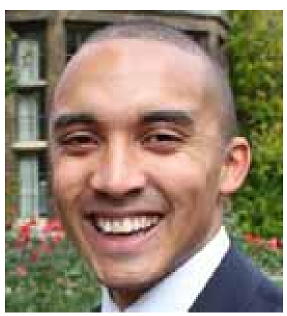
Berkeley UNIVERSITY OF CALIFORNIA

A building construction at the Isle of Dog, London



ARUP

Echo Ouyang



Musa Chunge

Cedric Kechavarzi

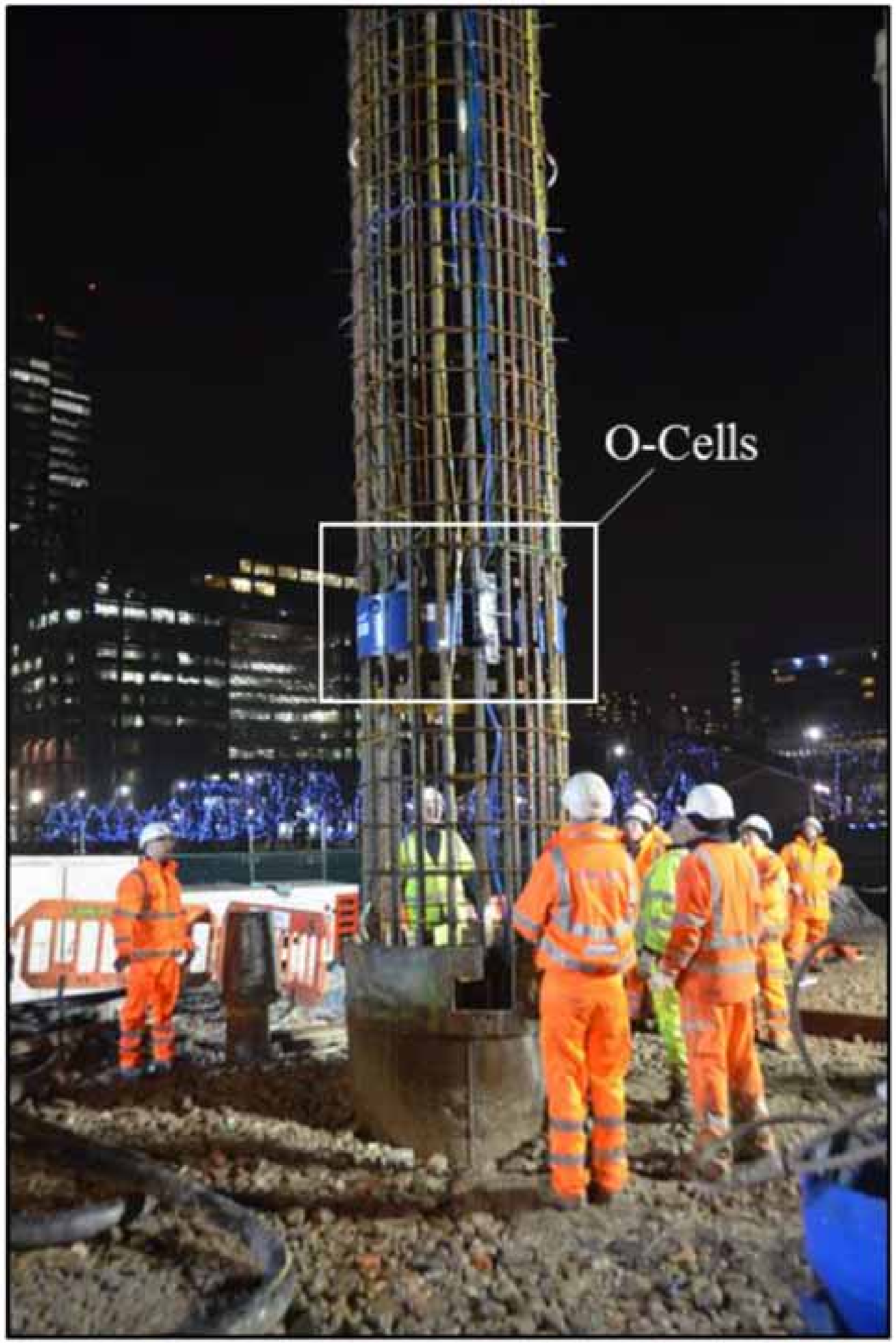
Loizos Pelecanos

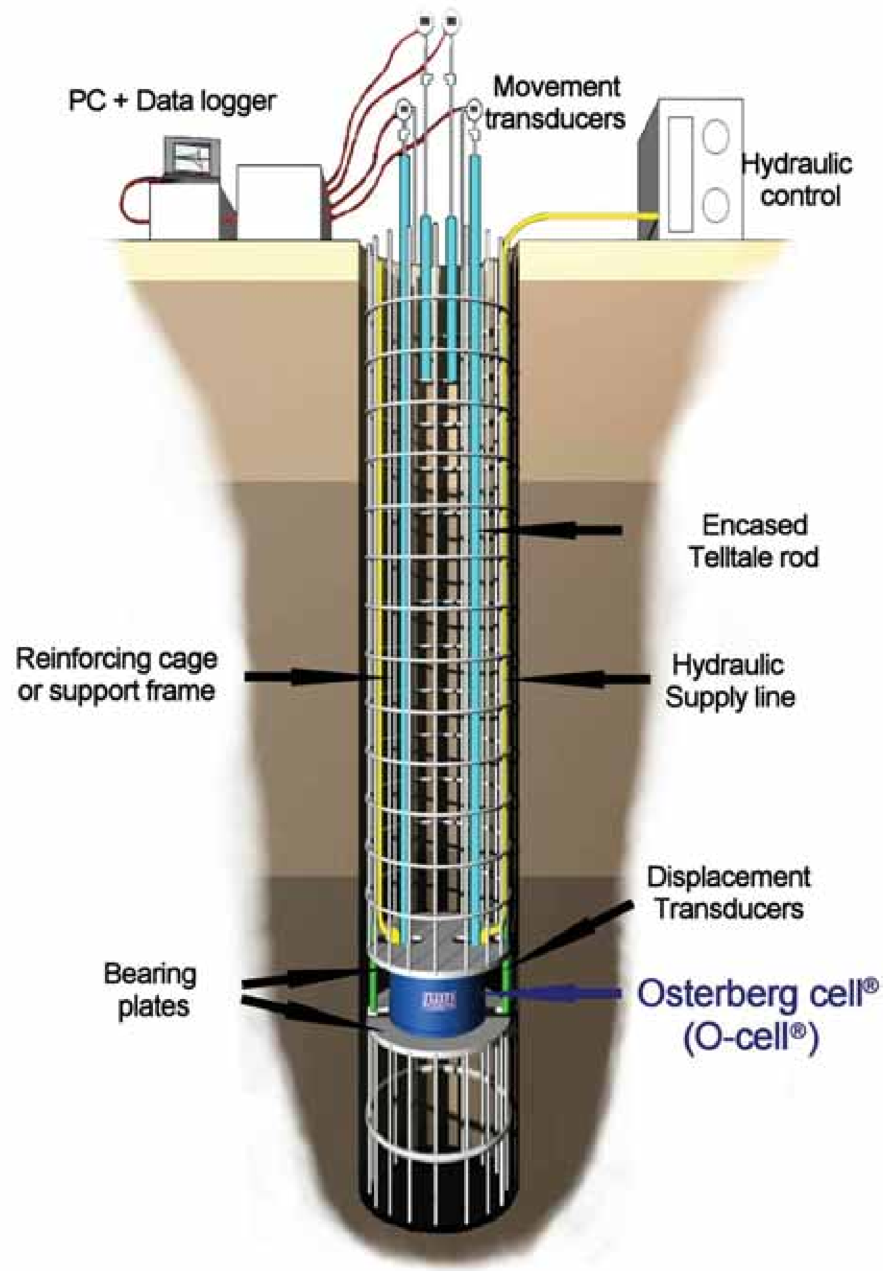
Vivien Kwan

Duncan Nicholson

CSIC Cambridge Centre for Smart Infrastructure & Construction

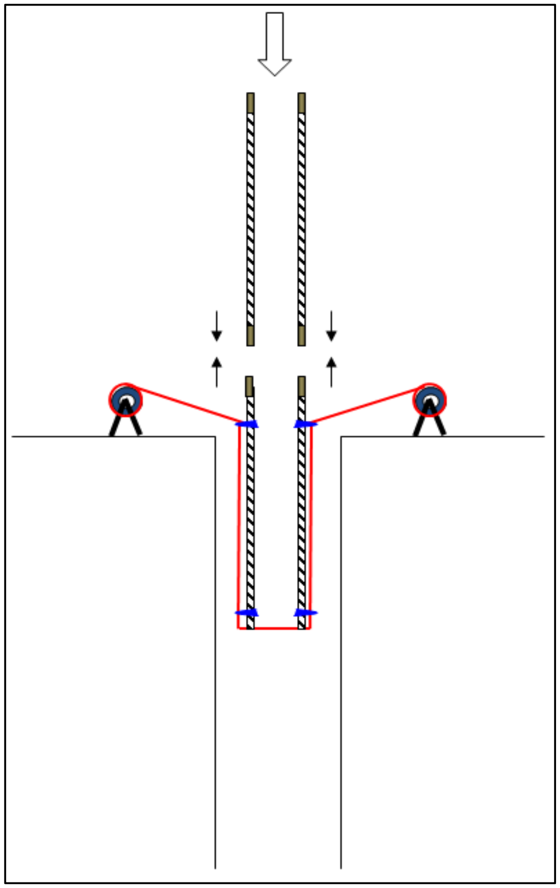
Berkeley UNIVERSITY OF CALIFORNIA

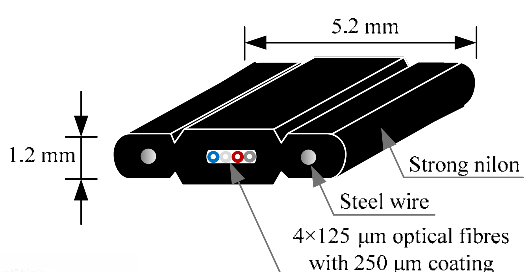


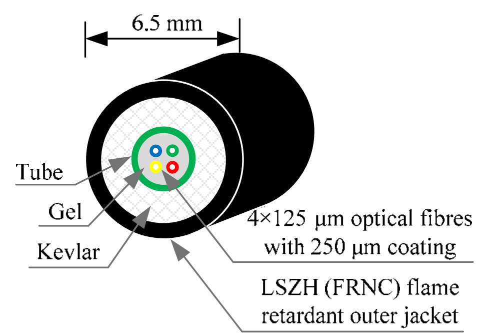


www.loadtest.com

No disturbance to actual construction operations







CSIC Cambridge Centre for Smart Infrastructure & Construction

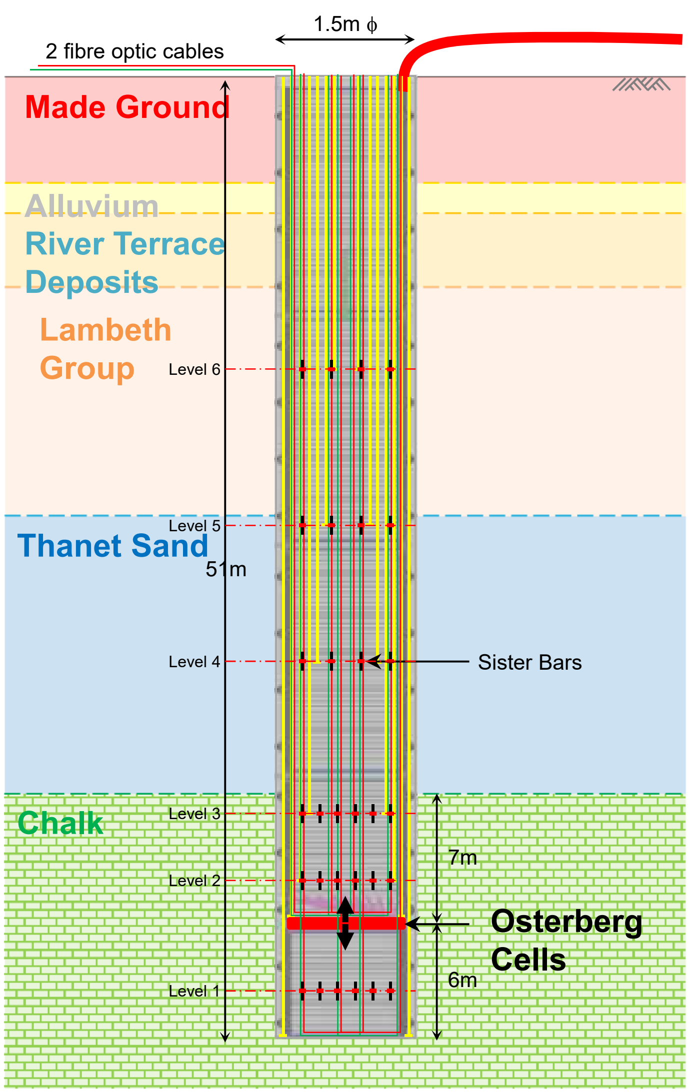
Berkeley UNIVERSITY OF CALIFORNIA

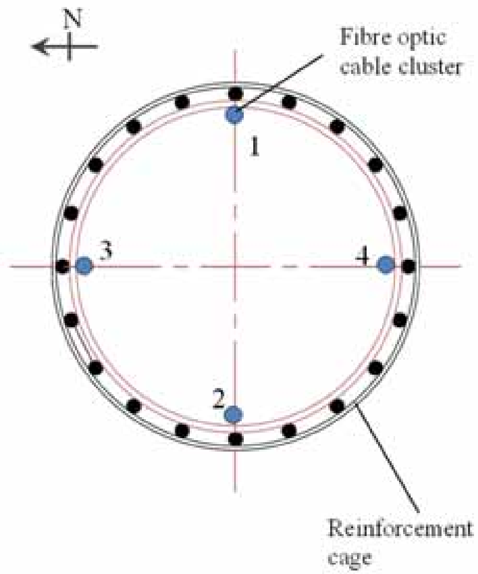
Conventional Strain Gauge System

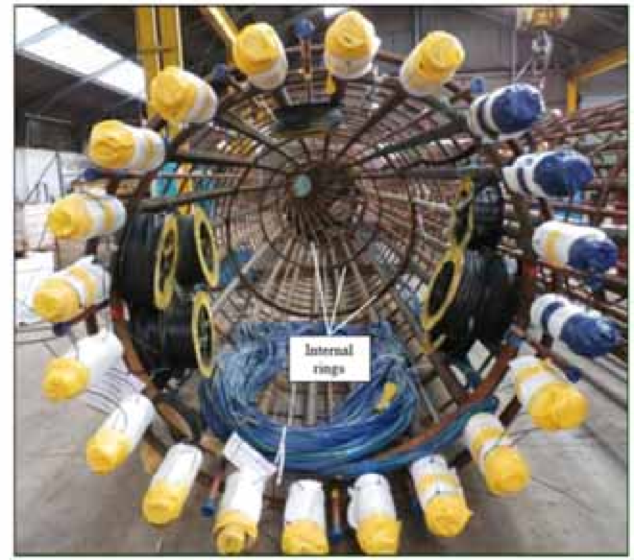
Distributed FO system

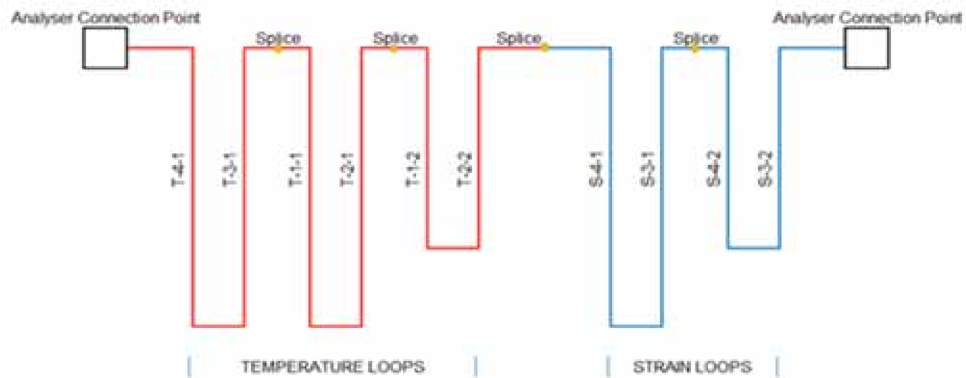
CSIC Cambridge Centre for Smart Infrastructure & Construction

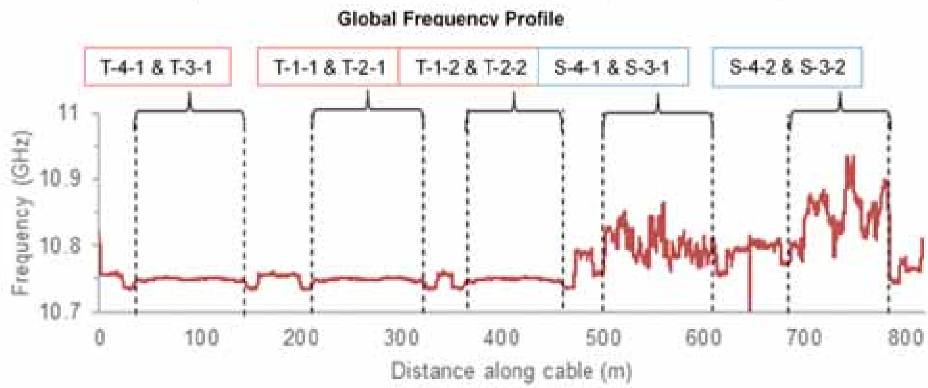
Berkeley UNIVERSITY OF CALIFORNIA



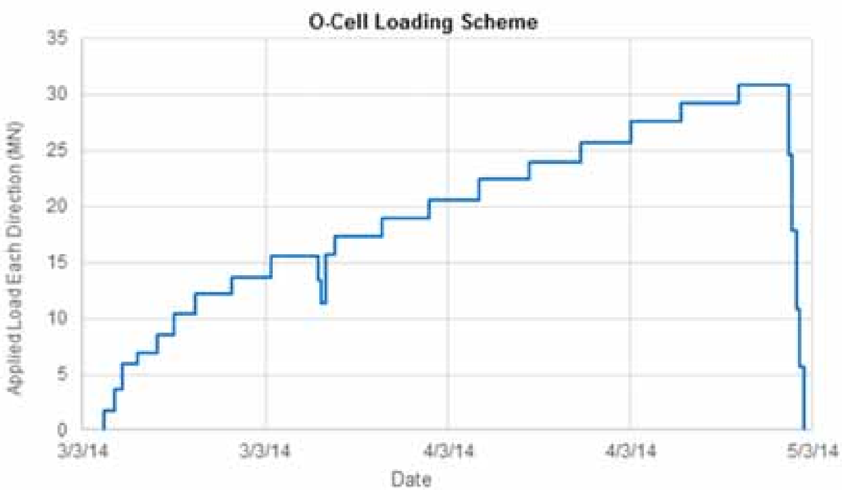


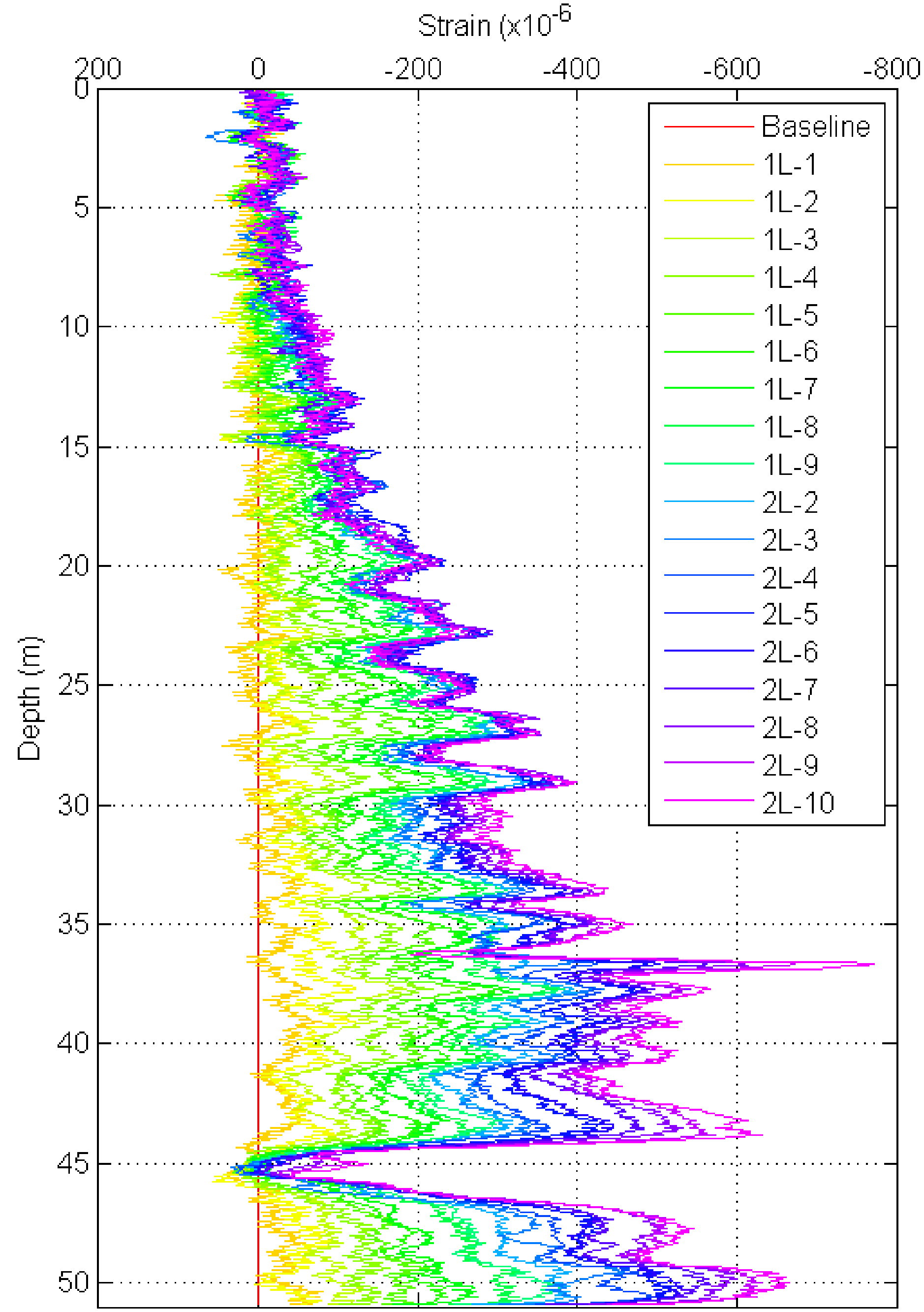






- Diameter = 1.5m
- Length = 51m
- Osterberg-cell
- Load up to 31MN





CSIC Cambridge Centre for Smart Infrastructure & Construction

UNIVERSITY OF CALIFORNIA

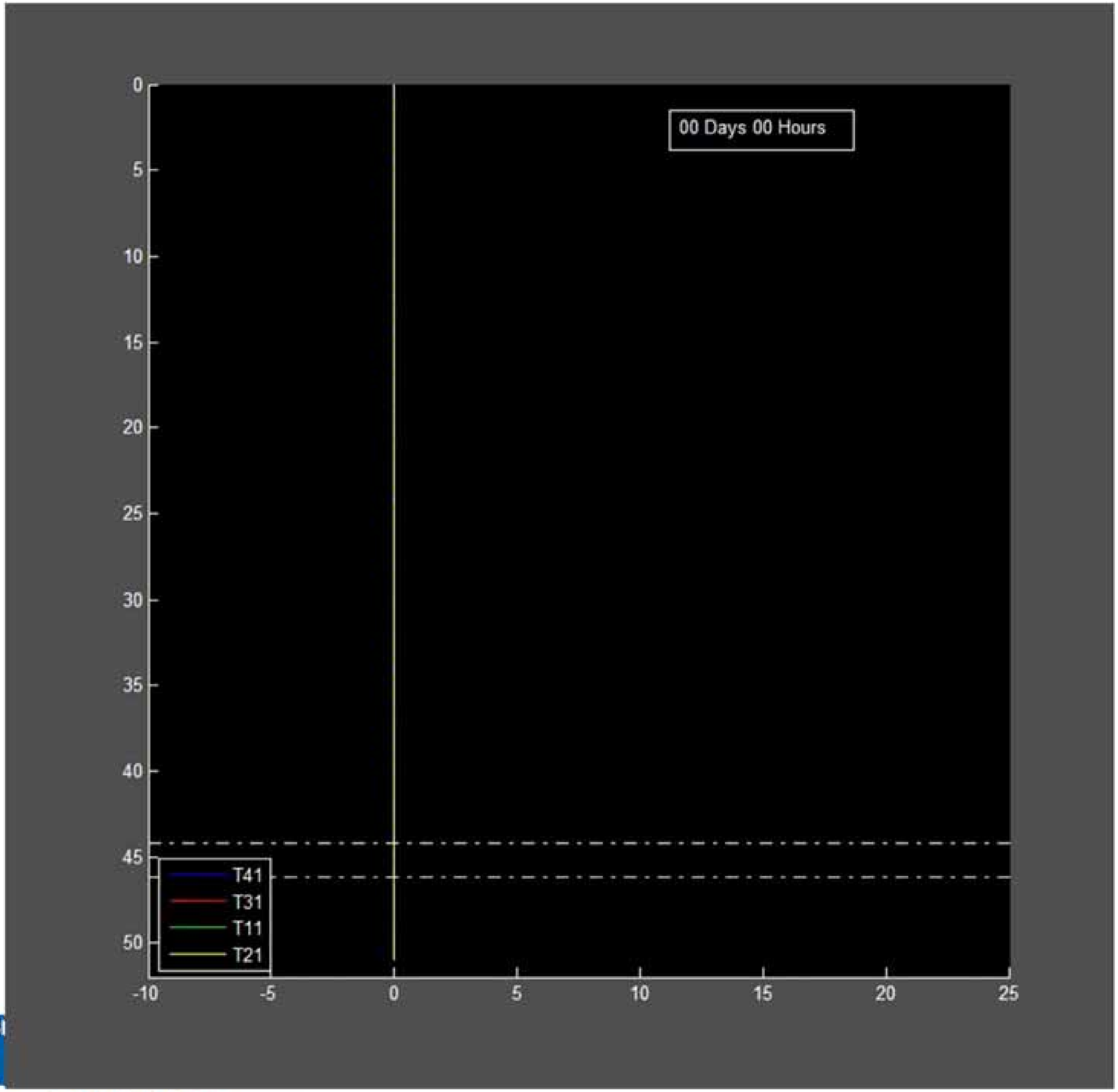
PROBLEMS WITH PILE CONSTRUCTION

- ✓ 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.

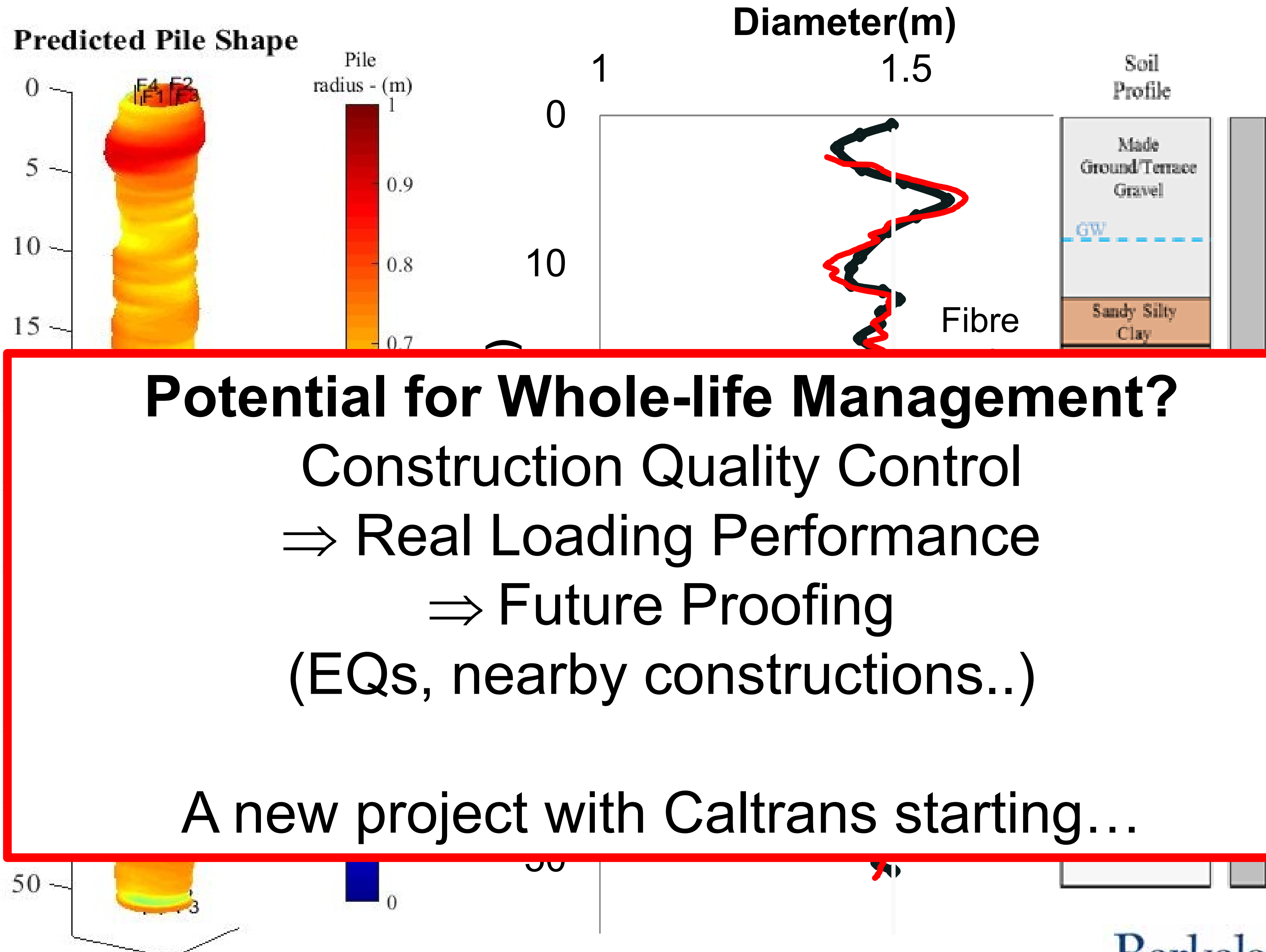
Cambridge Centre for Smart Infrastructure & Construction (CSIC)

Berkeley UNIVERSITY OF CALIFORNIA



CSI

Berkeley
UNIVERSITY OF CALIFORNIA



Potential for Whole-life Management?

Construction Quality Control

⇒ Real Loading Performance

⇒ Future Proofing

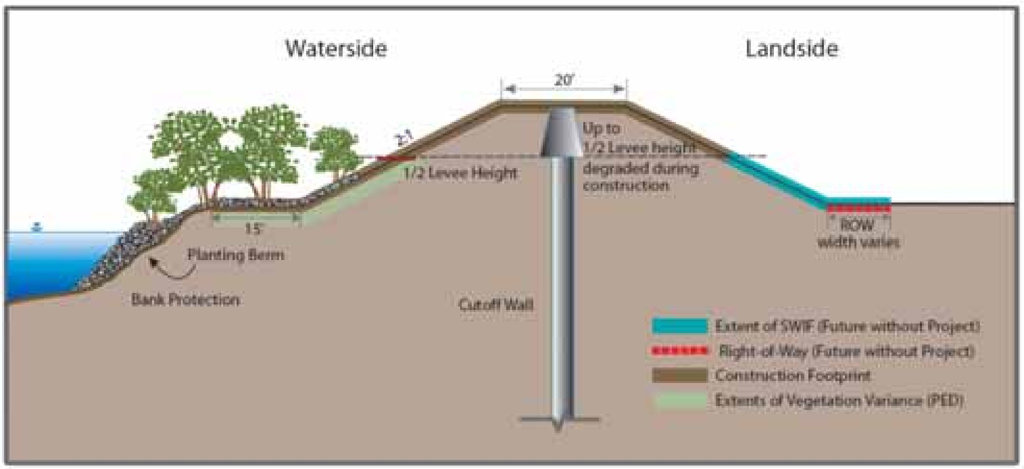
(EQs, nearby constructions..)

A new project with Caltrans starting…

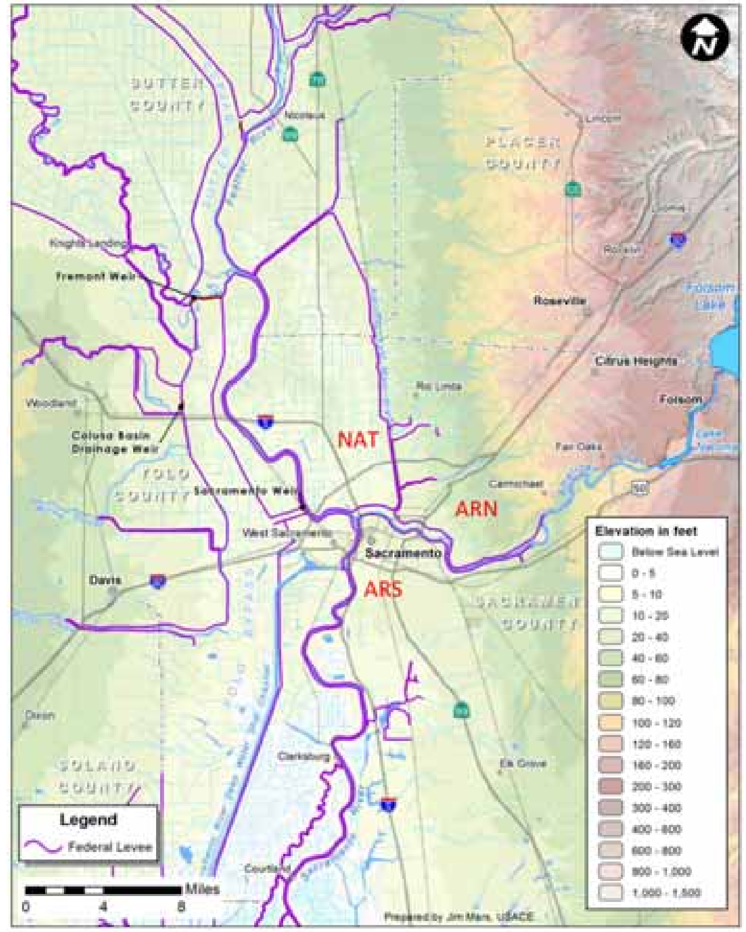
Berkeley
UNIVERSITY OF CALIFORNIA

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.



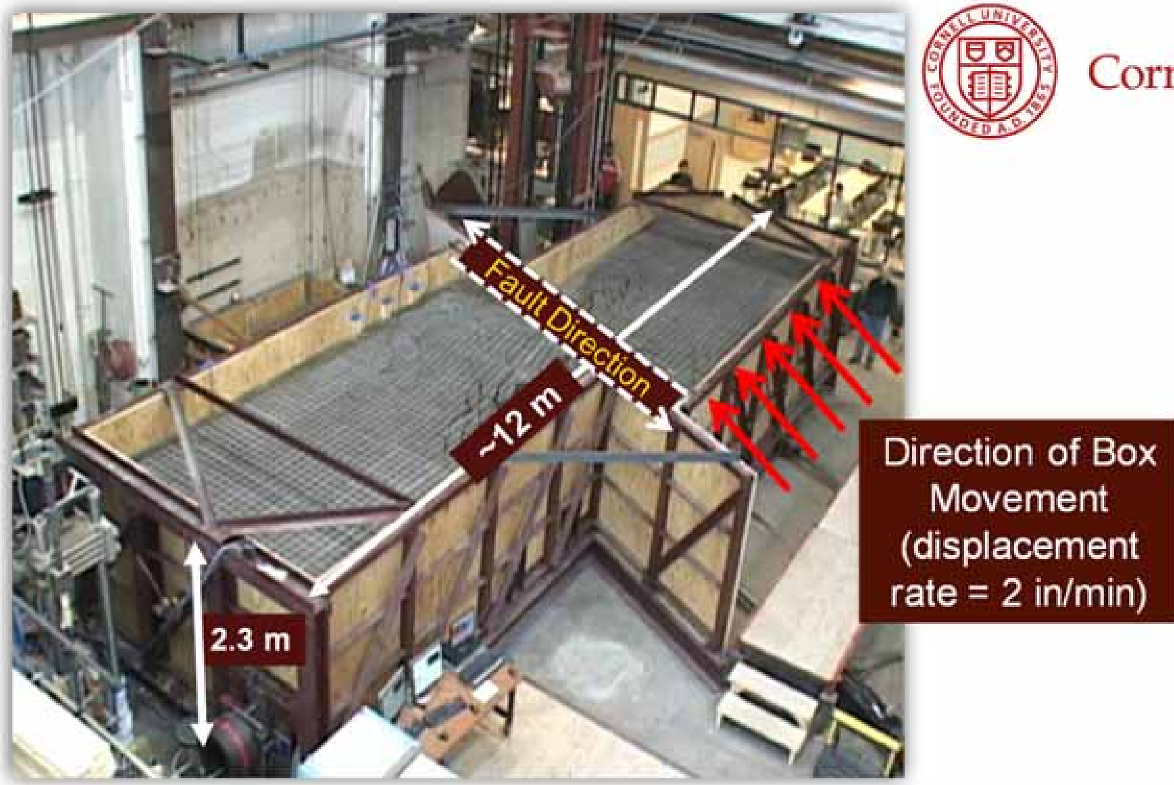
US Army Corps of Engineers

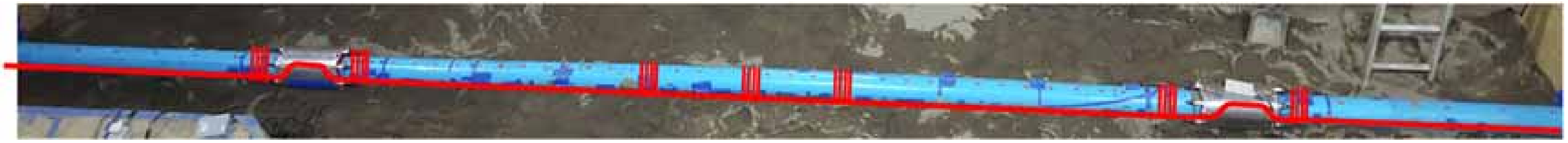
Cambridge Centre for Smart Infrastructure & Construction

Berkeley UNIVERSITY OF CALIFORNIA

Prof Tom O'Rourke
Dr Brad Wham

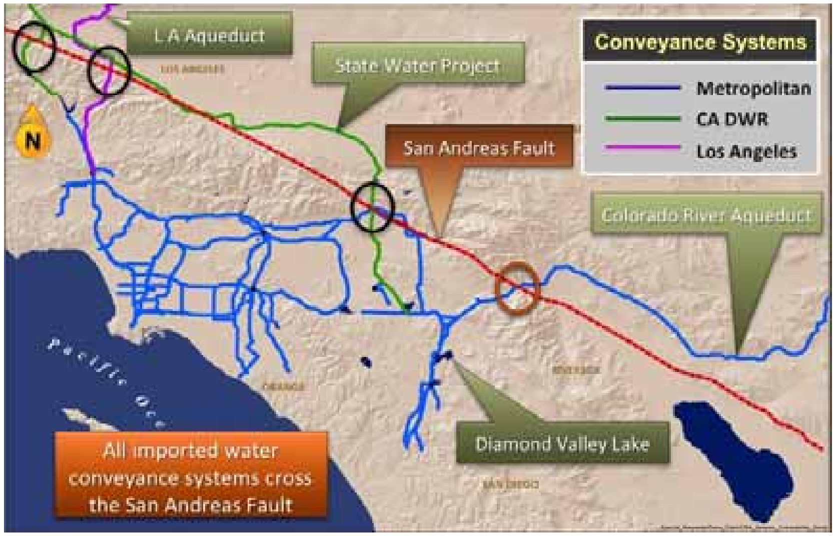
Cornell University





Cambridge Centre for Smart Infrastructure & Construction

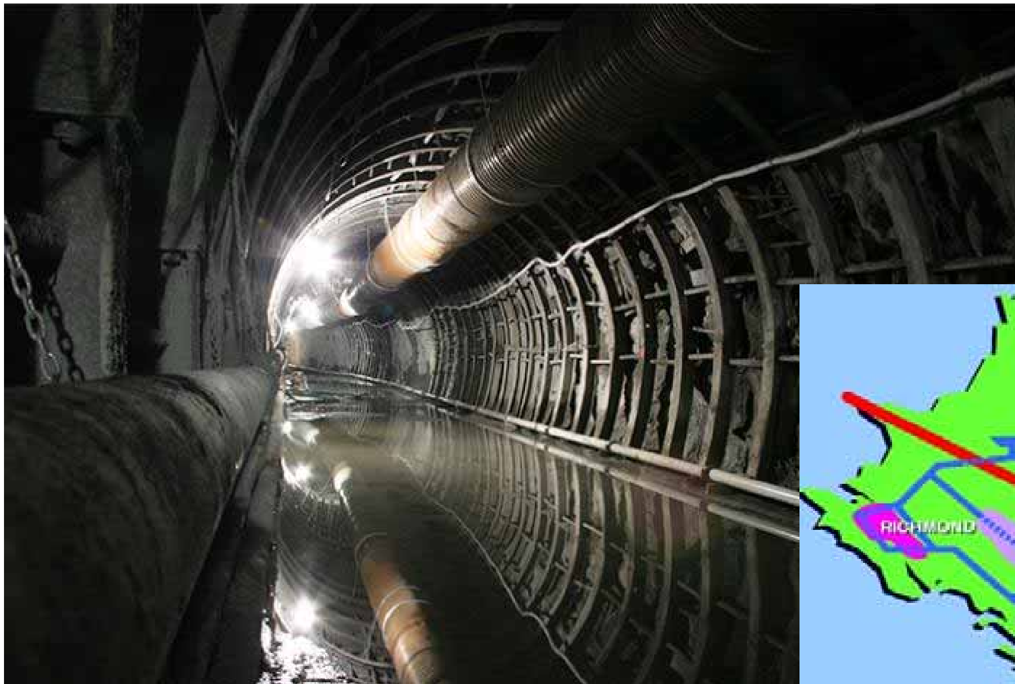
Berkeley
UNIVERSITY OF CALIFORNIA

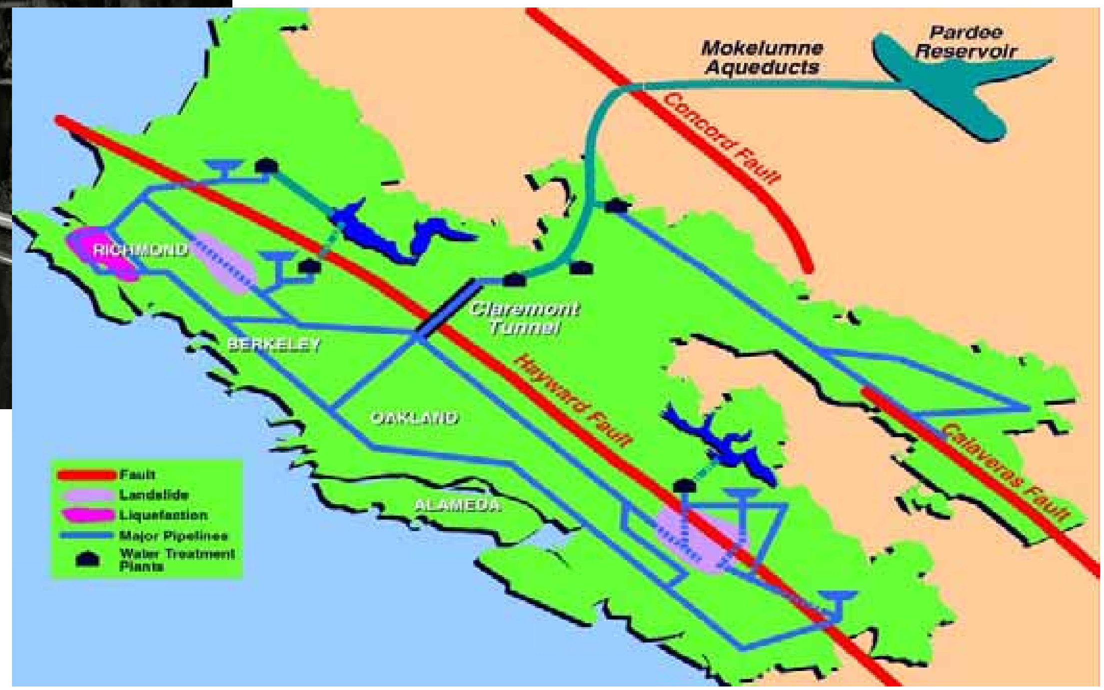


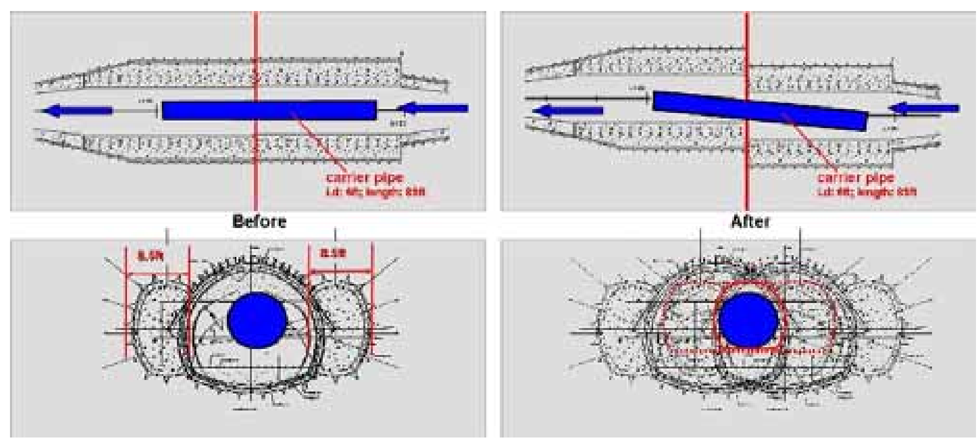
Elizabeth tunnel
Los Angeles Department of
Water and Power

Cambridge Centre for Smart Infrastructure & Construction

Berkeley UNIVERSITY OF CALIFORNIA







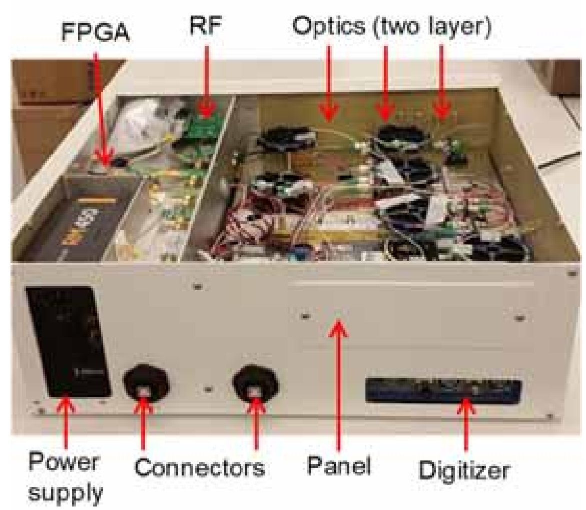
Claremont tunnel, East Bay Municipality Board

CSIC Cambridge Centre for Smart Infrastructure & Construction

Distributed Acoustic System

silixa.com

Distributed Dynamic Strain System



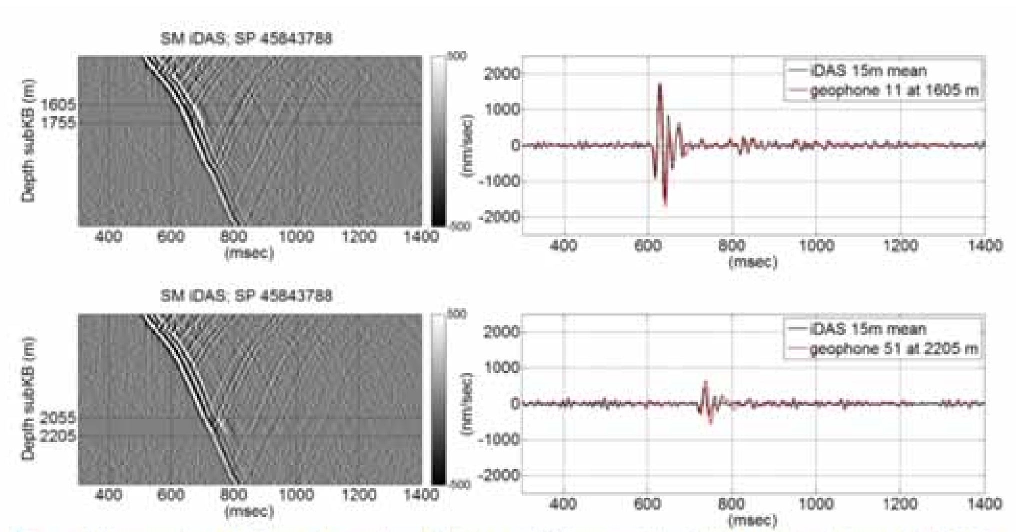
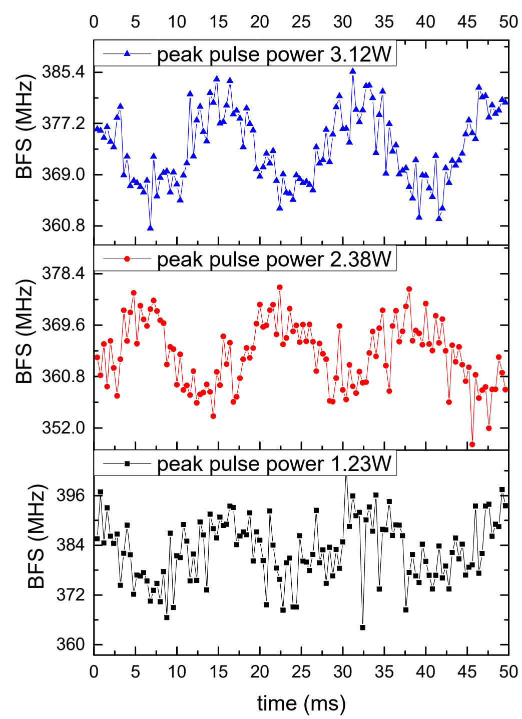


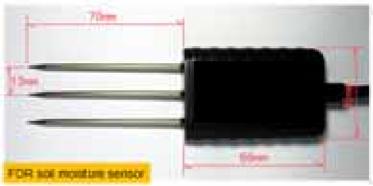
Figure 4 Comparison of DAS and geophone data for multi-trace gather (left) and single trace (right) for two depth zones.

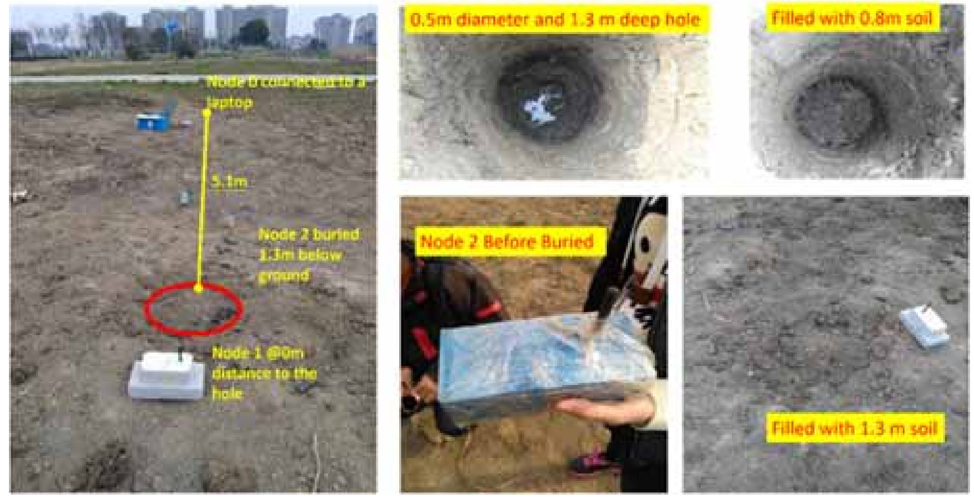
Miller et al. (2016)

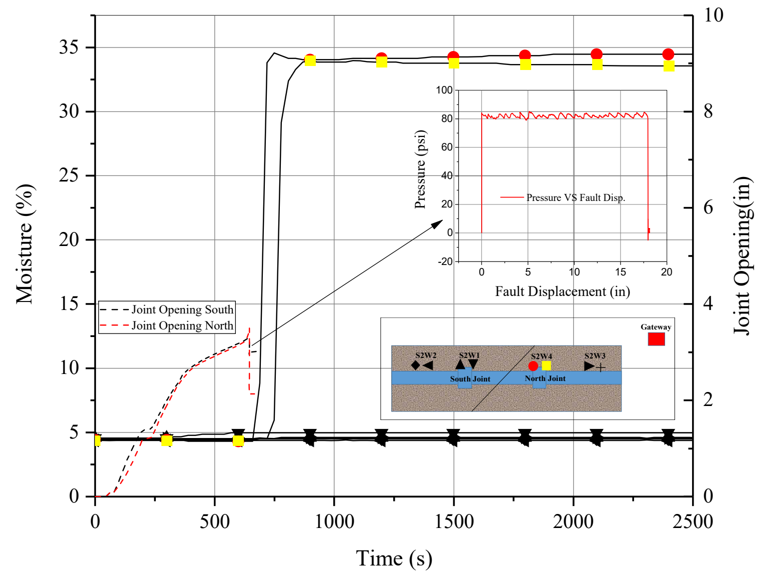
Dynamic strains measured by 60 Hz vibration input with different laser power inputs

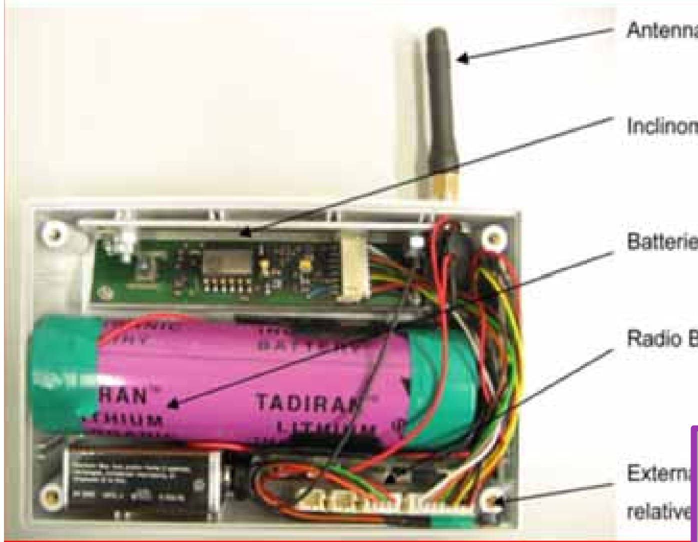


Underground wireless sensor network









2009

2012

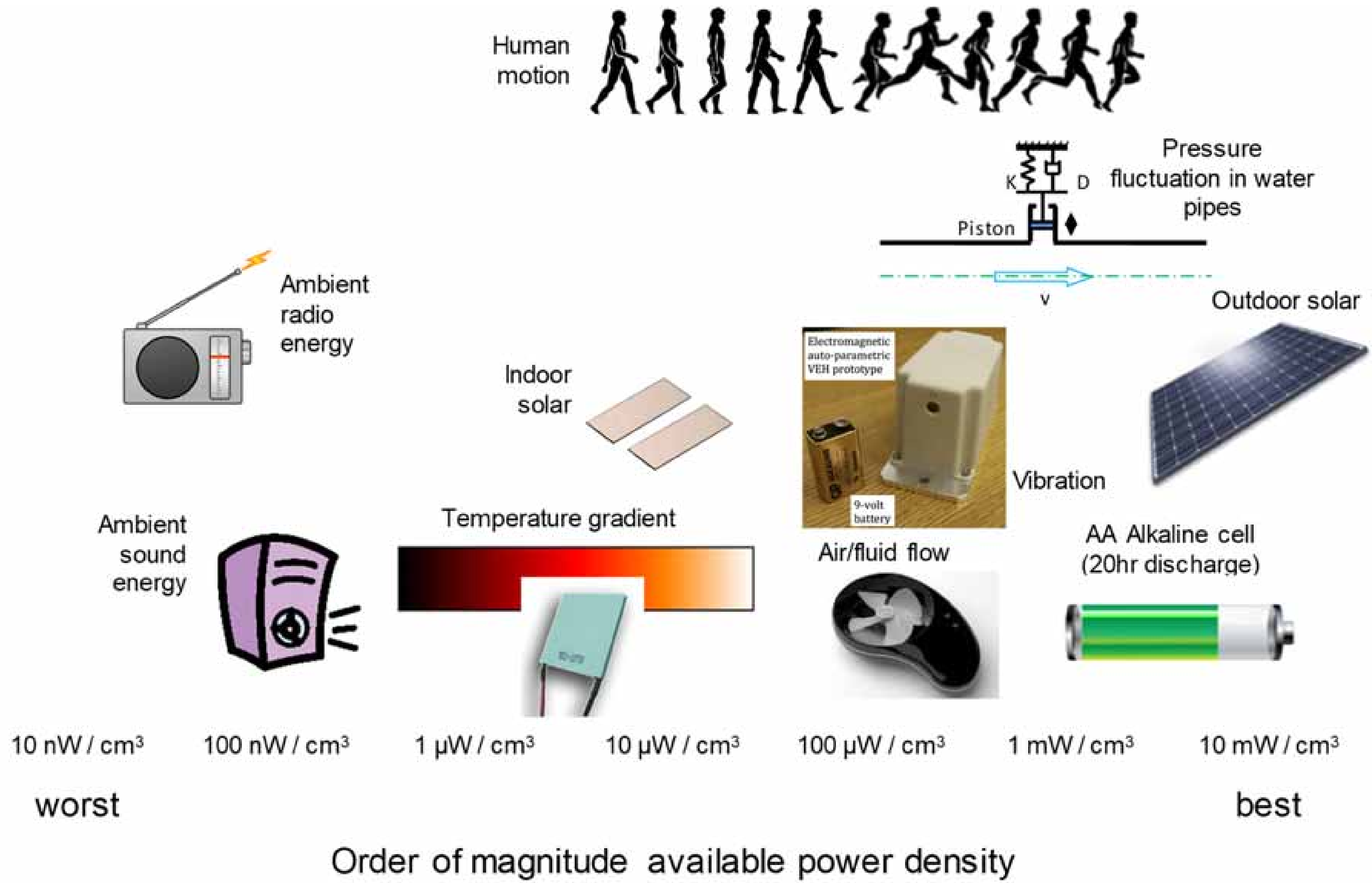
wisen innovation

2015

UTTERBERRY

Berkeley
UNIVERSITY OF CALIFORNIA

CSIC Cambridge Centre for
Smart Infrastructure
& Construction

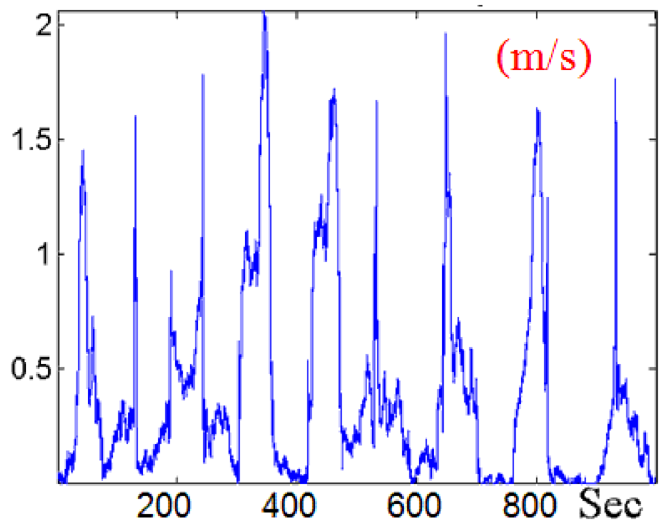


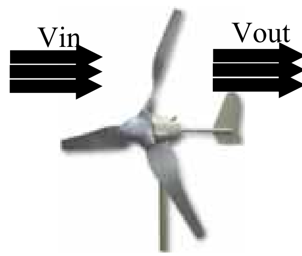
CSIC Cambridge Centre for Smart Infrastructure & Construction

Berkeley UNIVERSITY OF CALIFORNIA

Data from London Underground monitoring

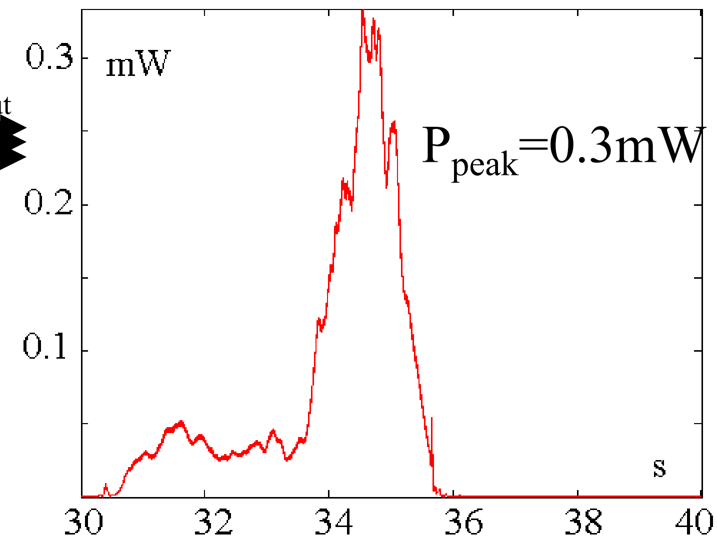
Air flow velocity in tunnel



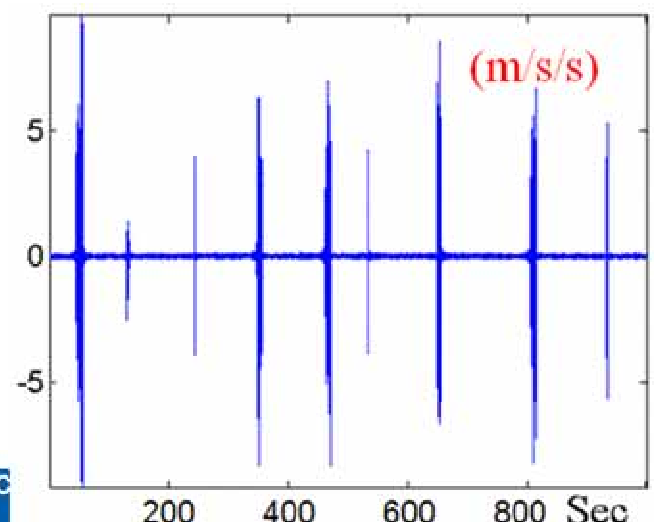


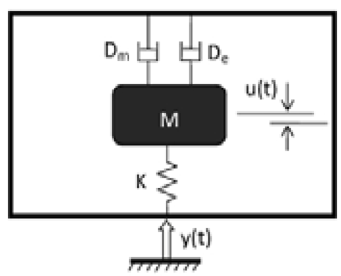
$$P = \frac{1}{2}\rho A V^3 C_P$$

Power

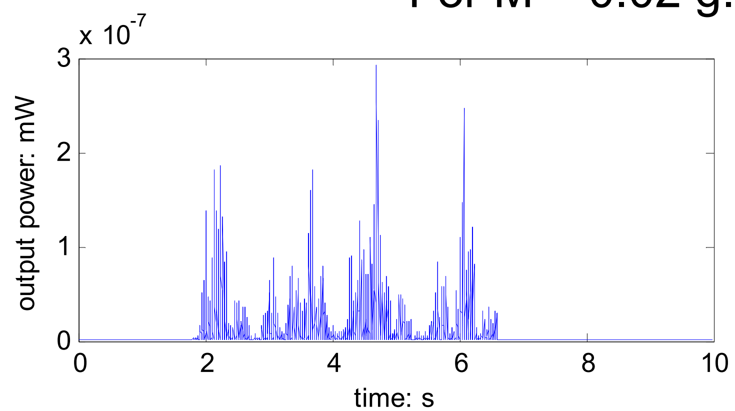


Tunnel acceleration





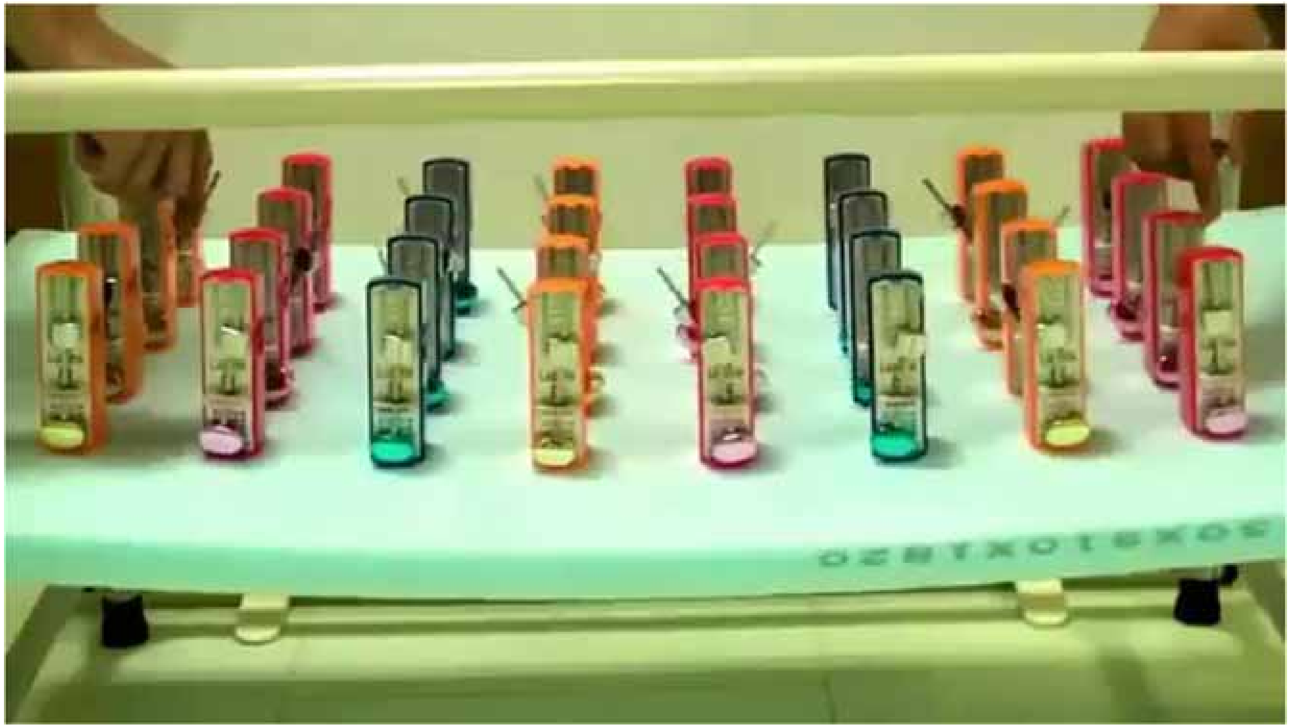
For M = 0.02 g.



1 uW per kg.

Foster+Partners

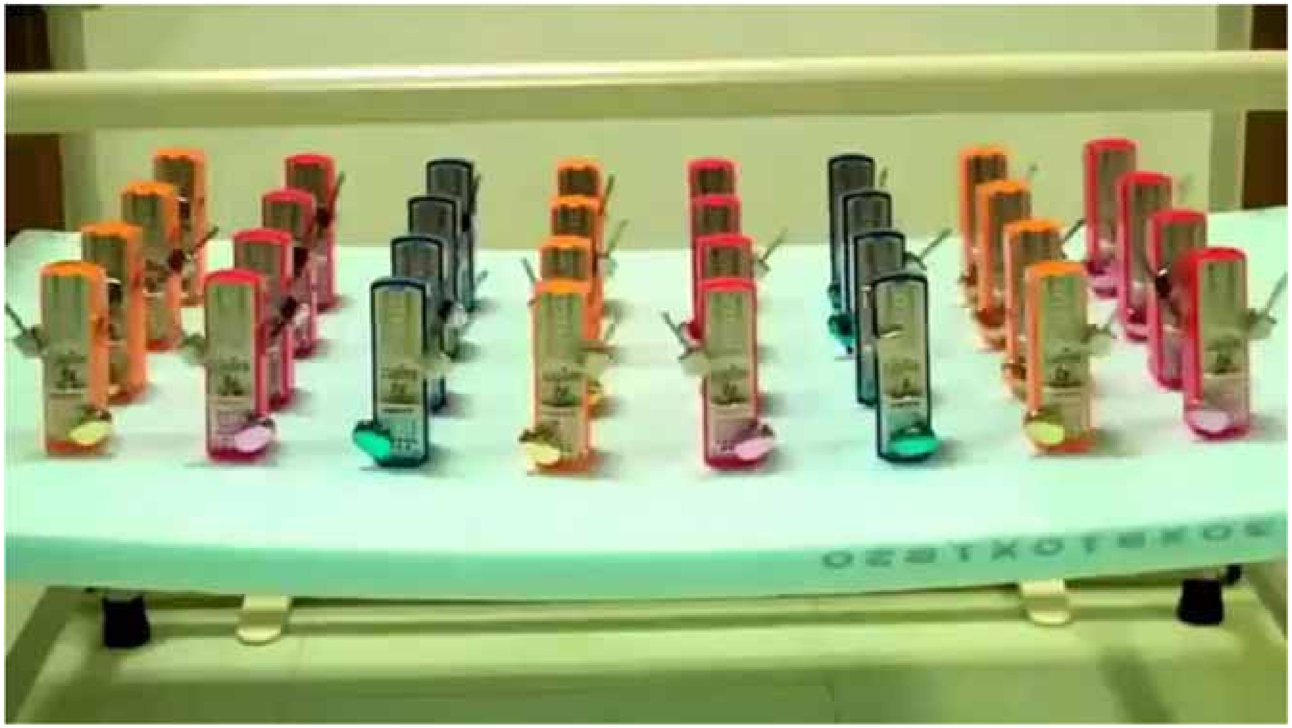
Berkeley
UNIVERSITY OF CALIFORNIA



Ikeguchi, Samtama Unversity

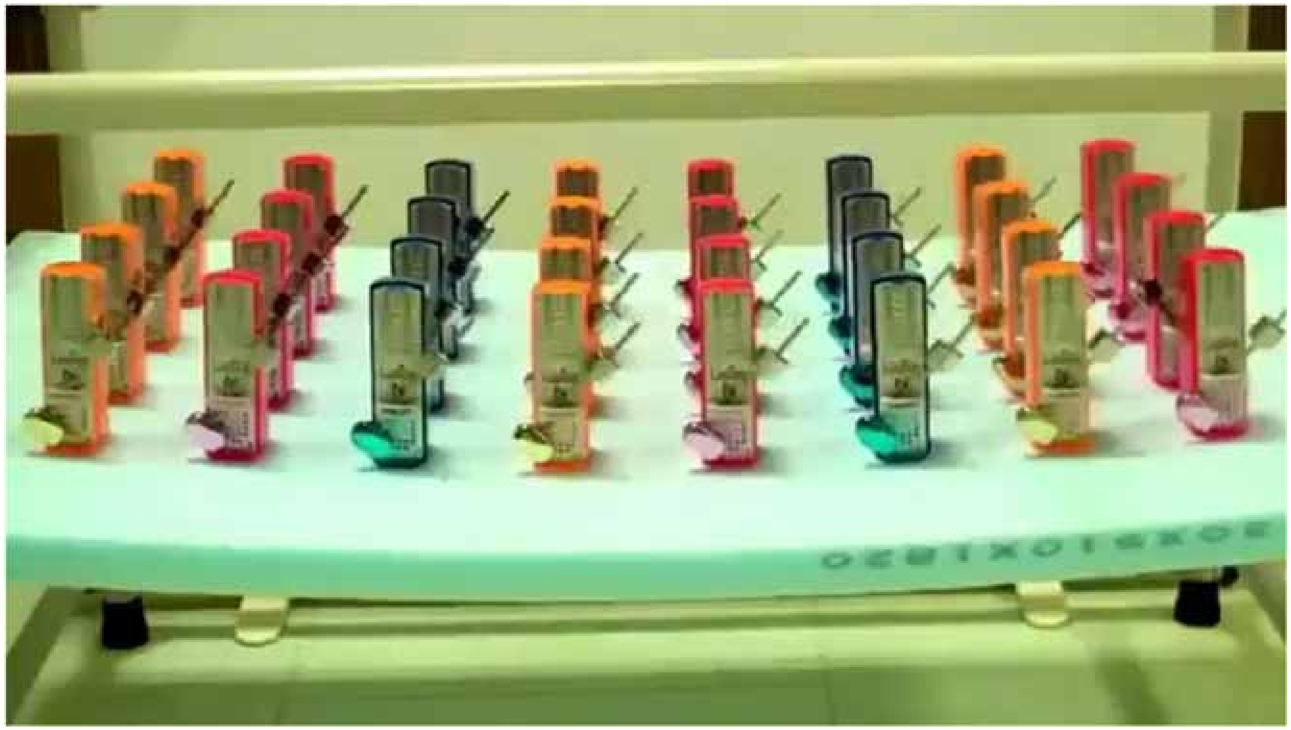
Cambridge Centre for Smart Infrastructure & Construction

Berkeley UNIVERSITY OF CALIFORNIA



CSIC Cambridge Centre for Smart Infrastructure & Construction

Berkeley UNIVERSITY OF CALIFORNIA



Cambridge Centre for Smart Infrastructure & Construction

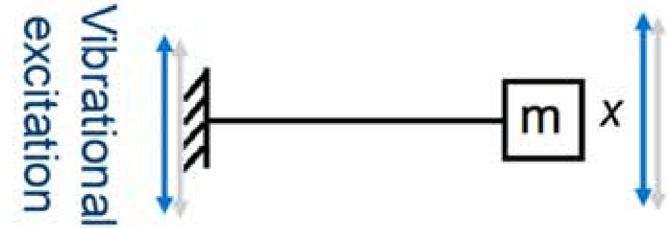
Parametric resonance



Direct excitation

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

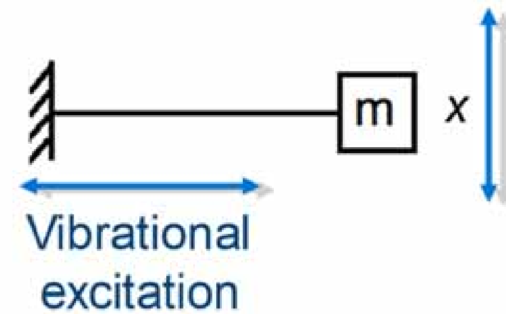
$$\ddot{x} + \frac{2c_1}{m}\dot{x} + \frac{c_2}{m}\dot{x}|\dot{x}| + \frac{\mu}{m}x^3 + \omega_0^2 x = \omega^2 A \cos(\omega t)$$

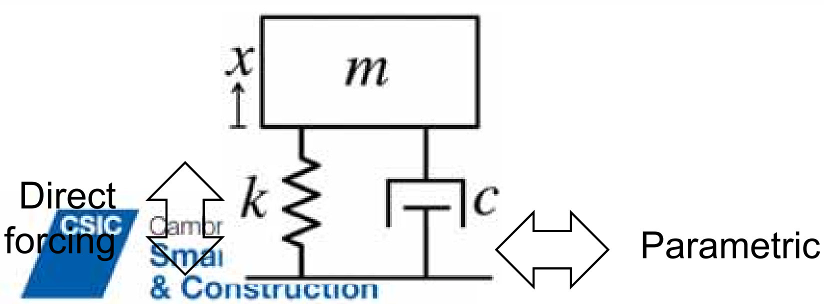


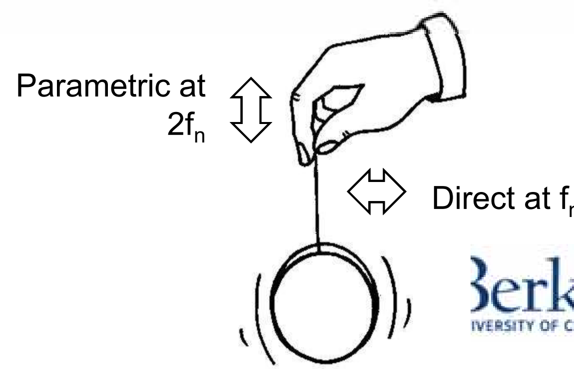
Parametric excitation

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

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







CSIC Cambr Smal & Construction

Berkeley
UNIVERSITY OF CALIFORNIA

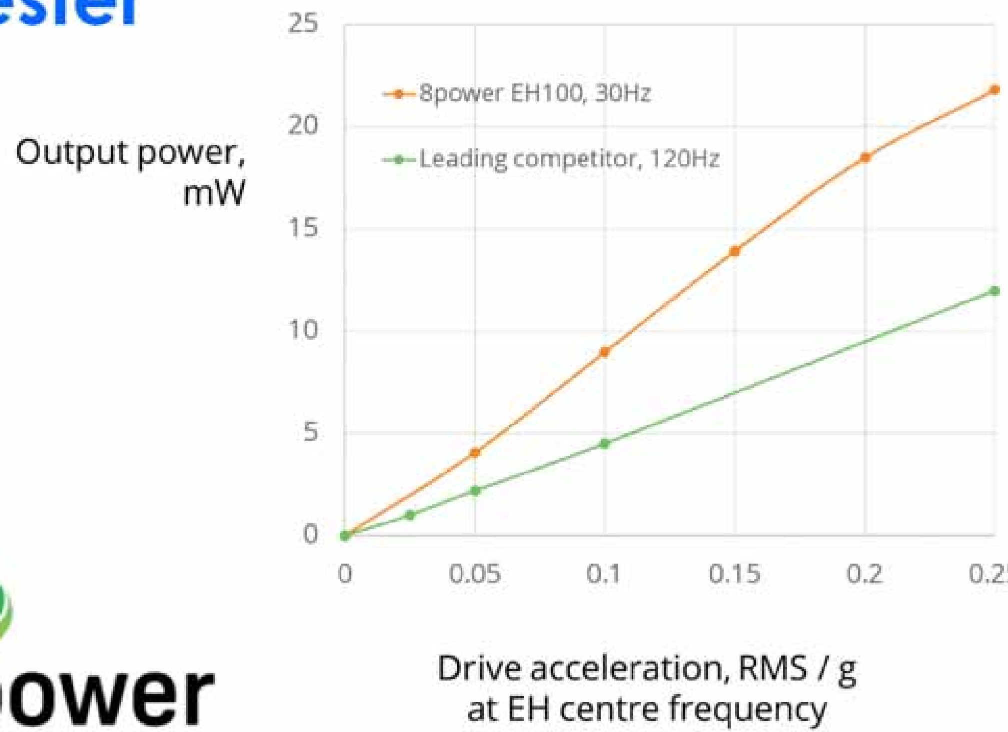
UNIVERSITY OF CAMBRIDGE

CSIC Cambridge Centre for Smart Infrastructure and Construction

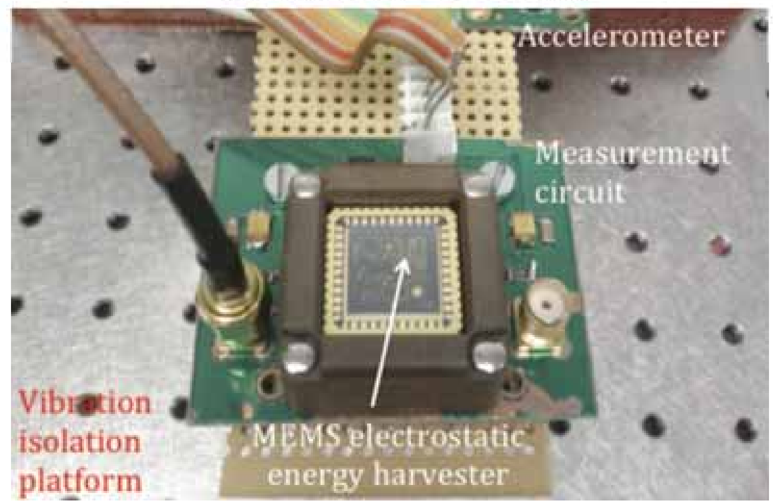
CSIC Cambridge Centre for Smart Infrastructure & Construction

Berkeley UNIVERSITY OF CALIFORNIA

Vibration power harvester

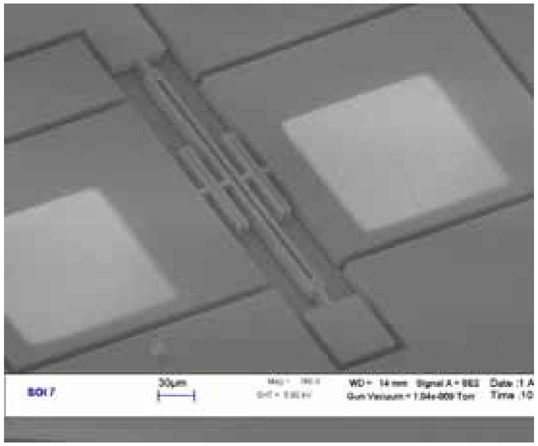


8power

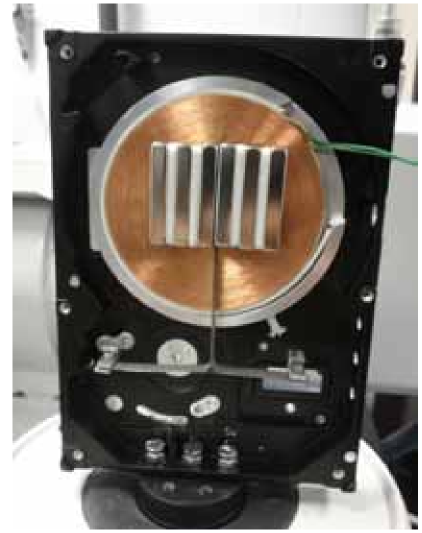


CSIC Cambridge Centre for Smart Infrastructure & Construction

Berkeley UNIVERSITY OF CALIFORNIA

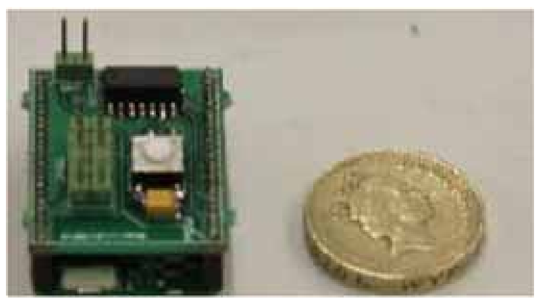


Strain (0.5- 2μW)
Accelerometer
Inclinometer
Noise sensor
Gas sensor
etc.



Energy harvesting
Vibration
Temperature
Pressure fluctuation
Air-flow

Power management

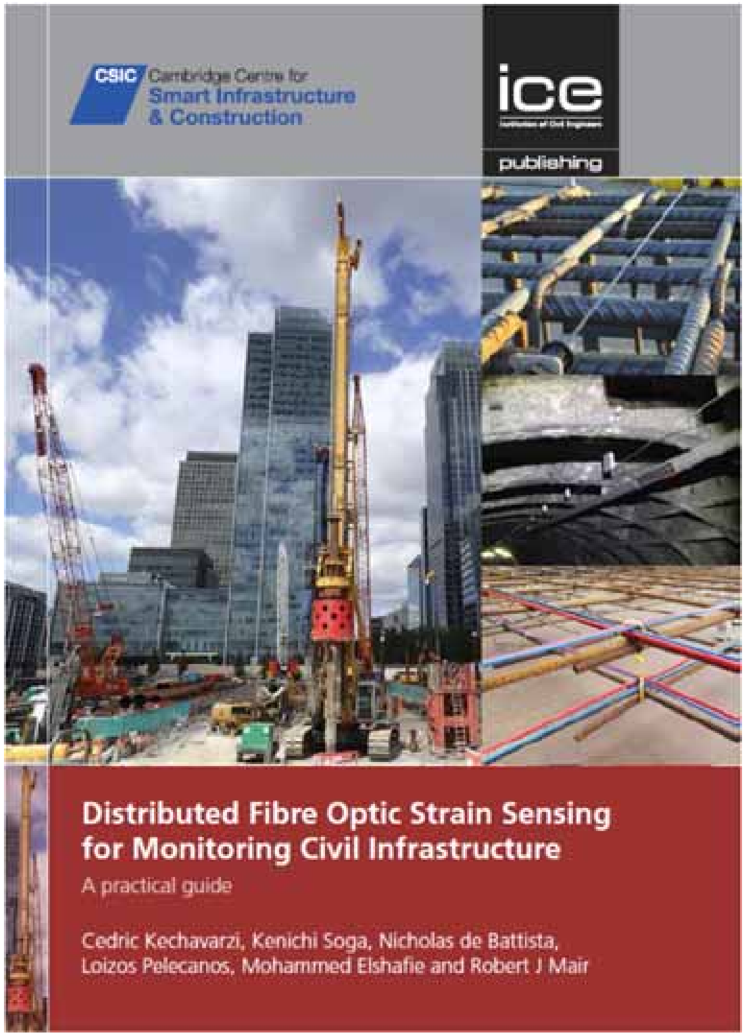


Self-Powering Sensors and Communication

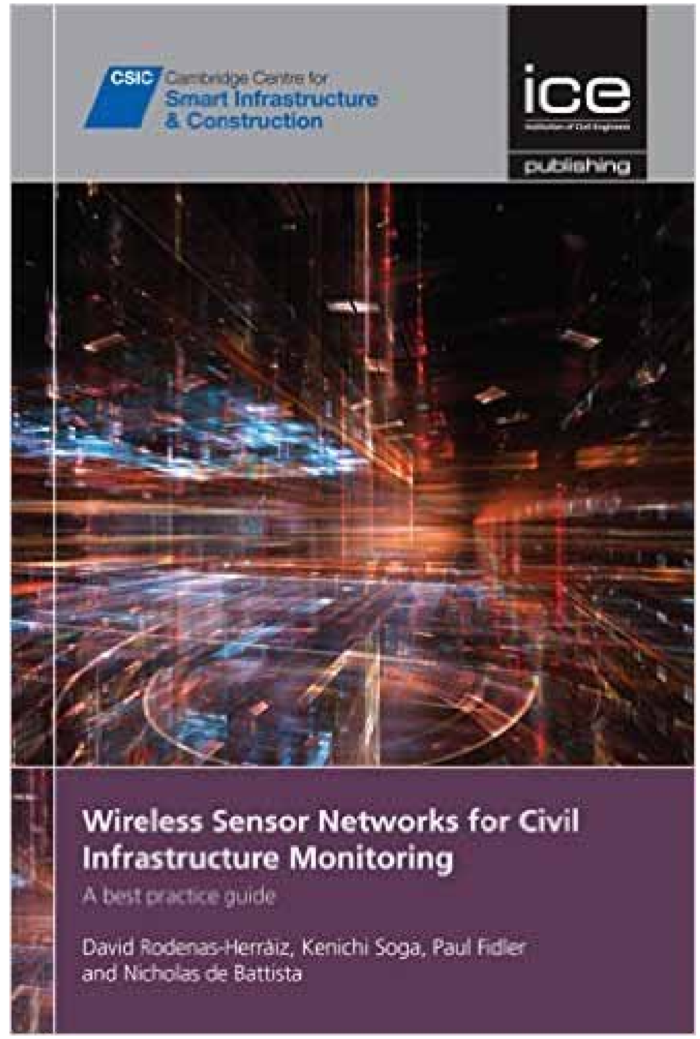
CSIC Cambridge Centre for Smart Infrastructure & Construction

Berkeley UNIVERSITY OF CALIFORNIA

Best Practice Guides for Monitoring Civil Infrastructure



Distributed Fibre Optics Sensing



Wireless Sensor Networks

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