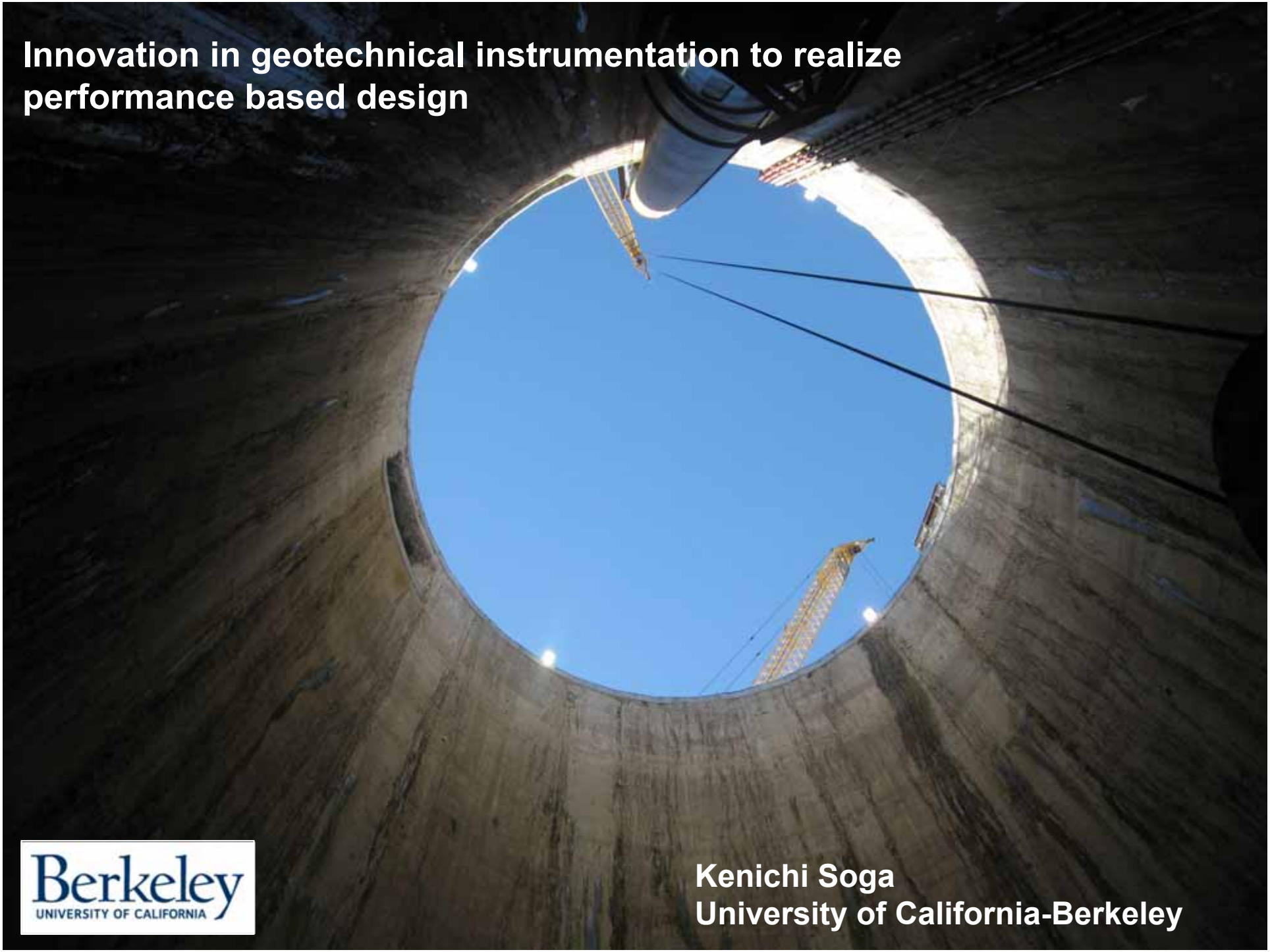
Innovation in geotechnical instrumentation to realize performance based design



Kenichi Soga
University of California-Berkeley

Acknowledgement

- GeoVirgina Organizing Committee and Qamar Kazmi
- University of California, Berkeley – PhD students and post-docs
- University of Cambridge, Cambridge Centre for Smart Infrastructure and Construction – PhD students and Researchers

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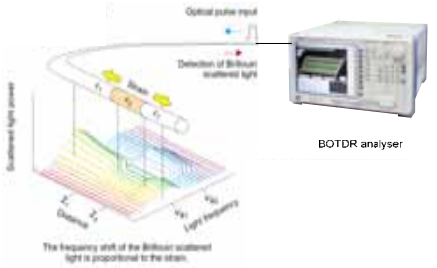
Examples of distributed strain/displacement sensors

Distributed fiber optics - Embedded sensor for life-long monitoring

- Fibre optics – 30-100με
- Fibre optics – 0.03-0.1 mm resolution (for 1 m gauge length)



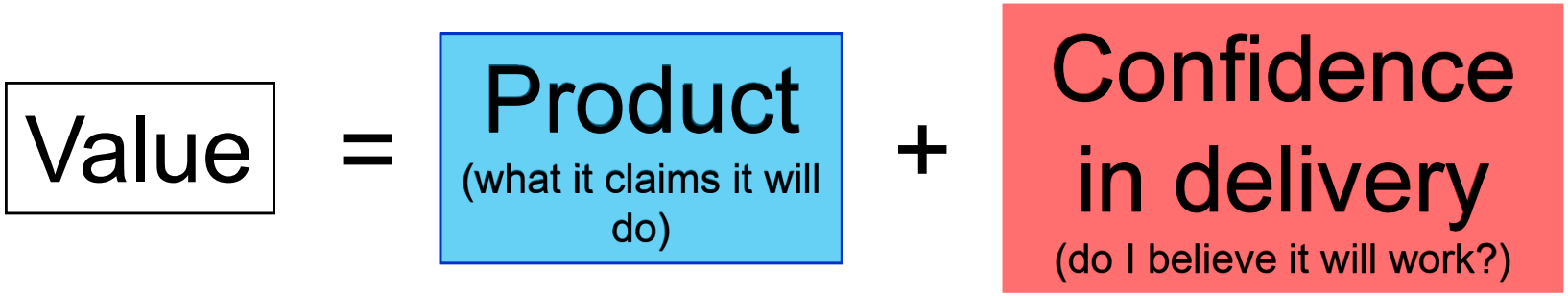
Computer Vision and LIDAR

- Fixed system – 0.1 mm resolution
- Not Fixed system – 3-5 mm resolution

WSN – Continuous monitoring at difficult-to-access sites

- Wisen
- Utterberry – sub millimeter resolution

“Value” as a tool

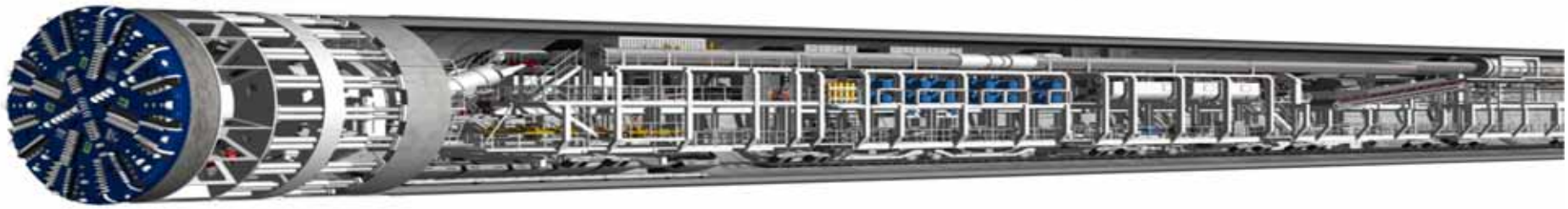


“Innovations have more chance of adoption if their benefits are mapped”

Dr Keith Bowers, London Underground Limited

Crossrail – New London Underground Line in London

- 118 km from east to west
- 37 stations
- 9 new stations (8 sub-surface)
- Increase London's rail-network capacity by 10%



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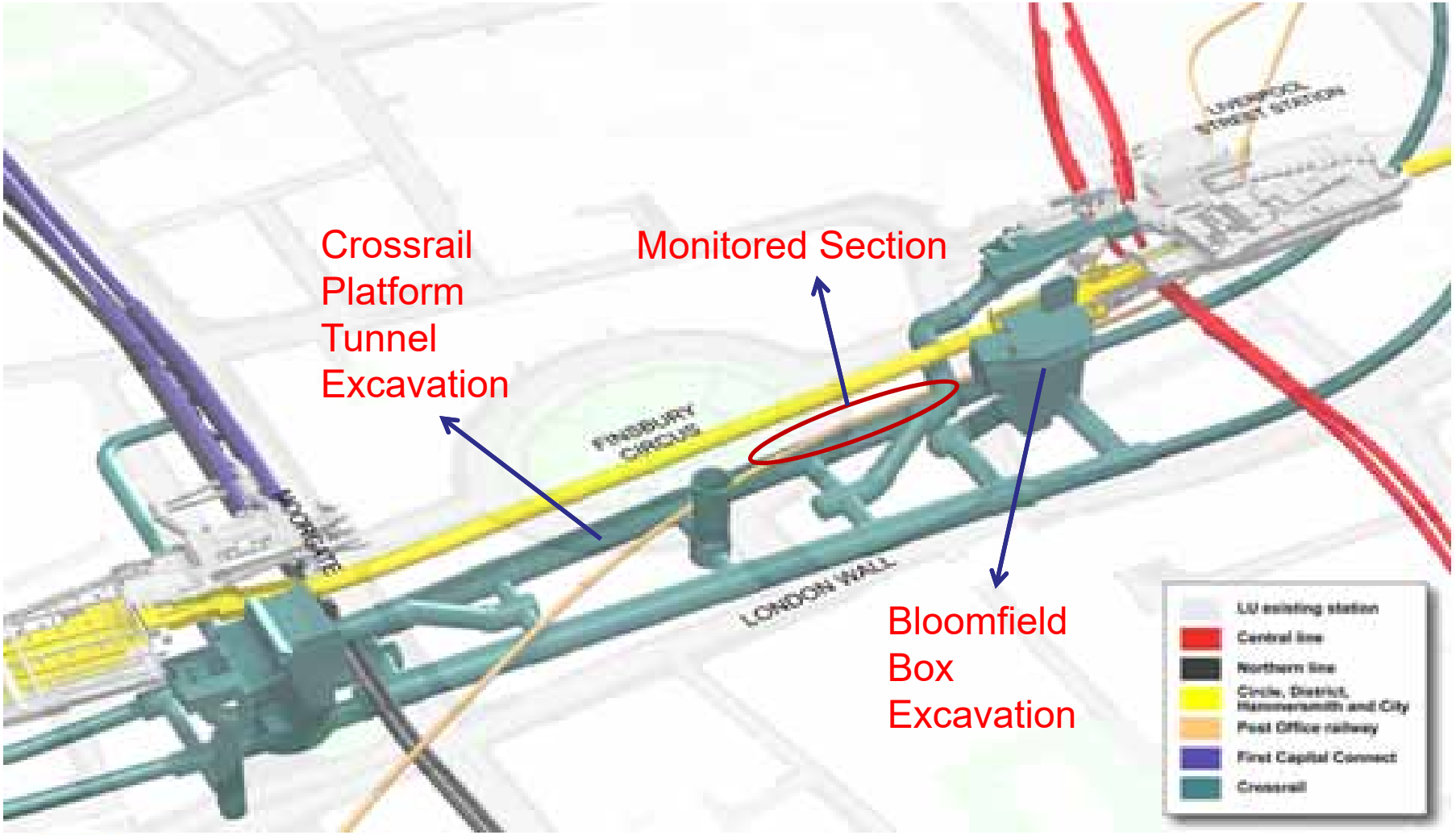
Monitored Section of the Royal Mail Tunnel
Crossrail – Liverpool Street Station – C510



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After Crossrail

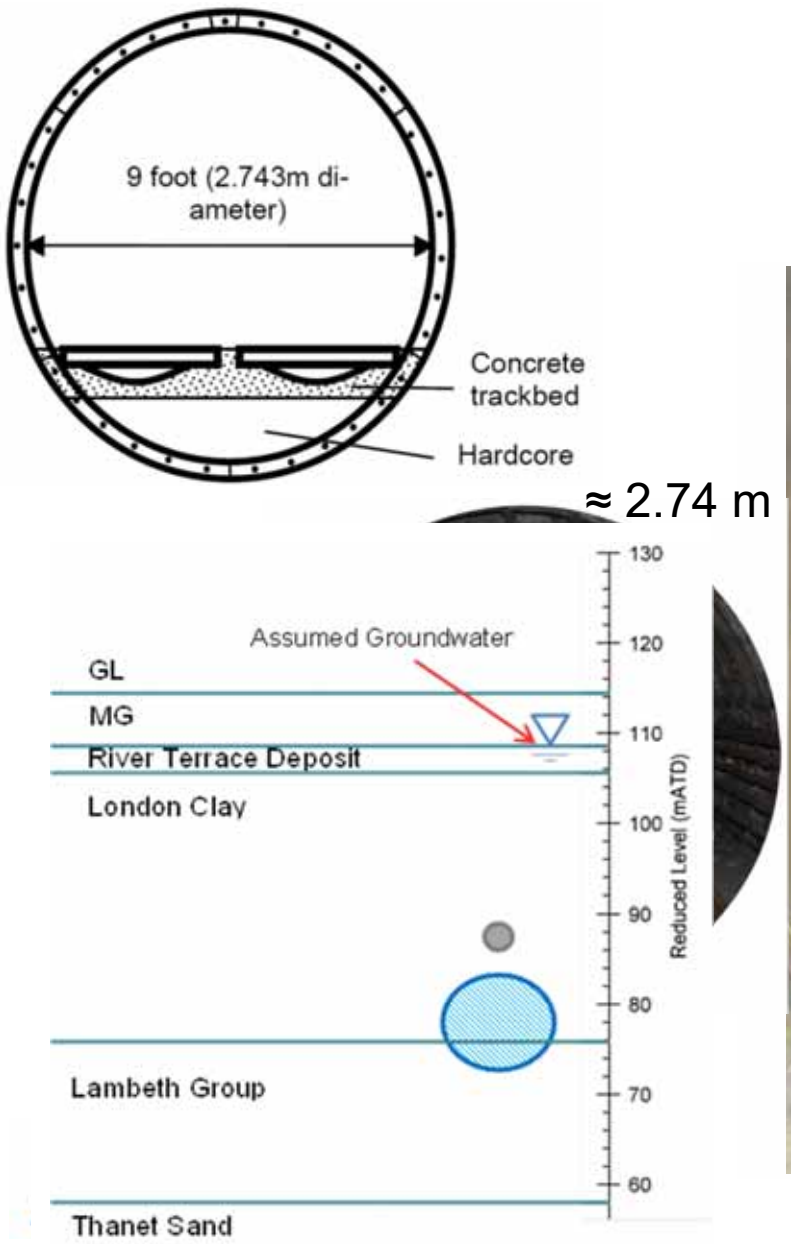

34

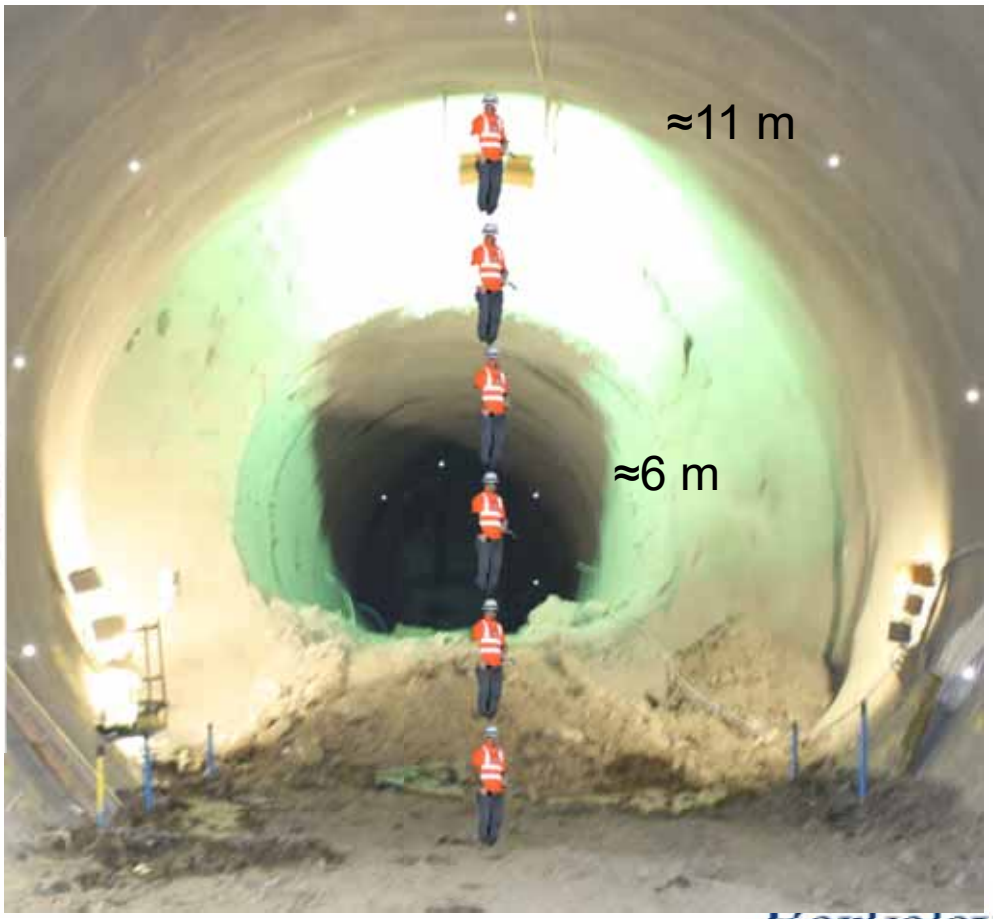
How Big Is It?

Constructed: 1917 - 1923

Made of cast iron

Suspended: 2003





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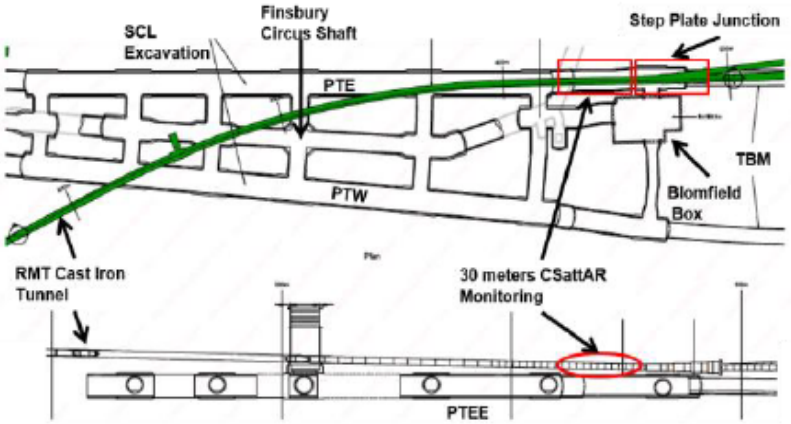
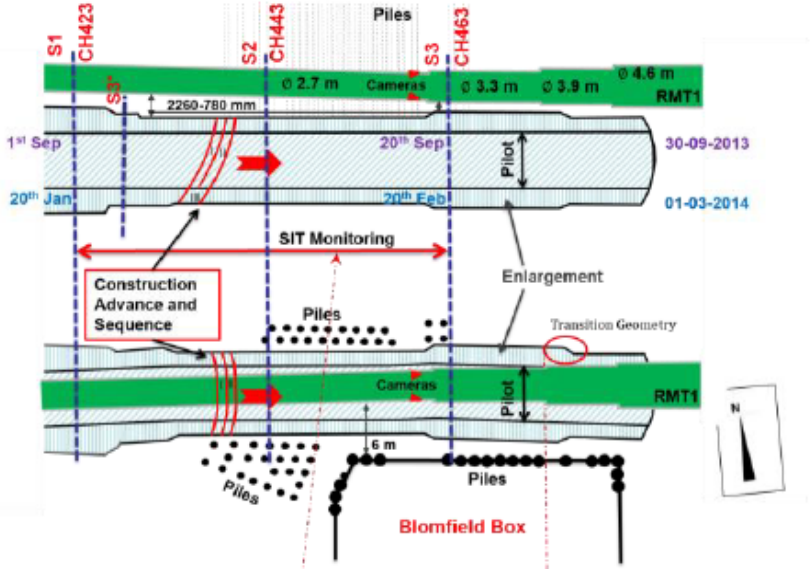
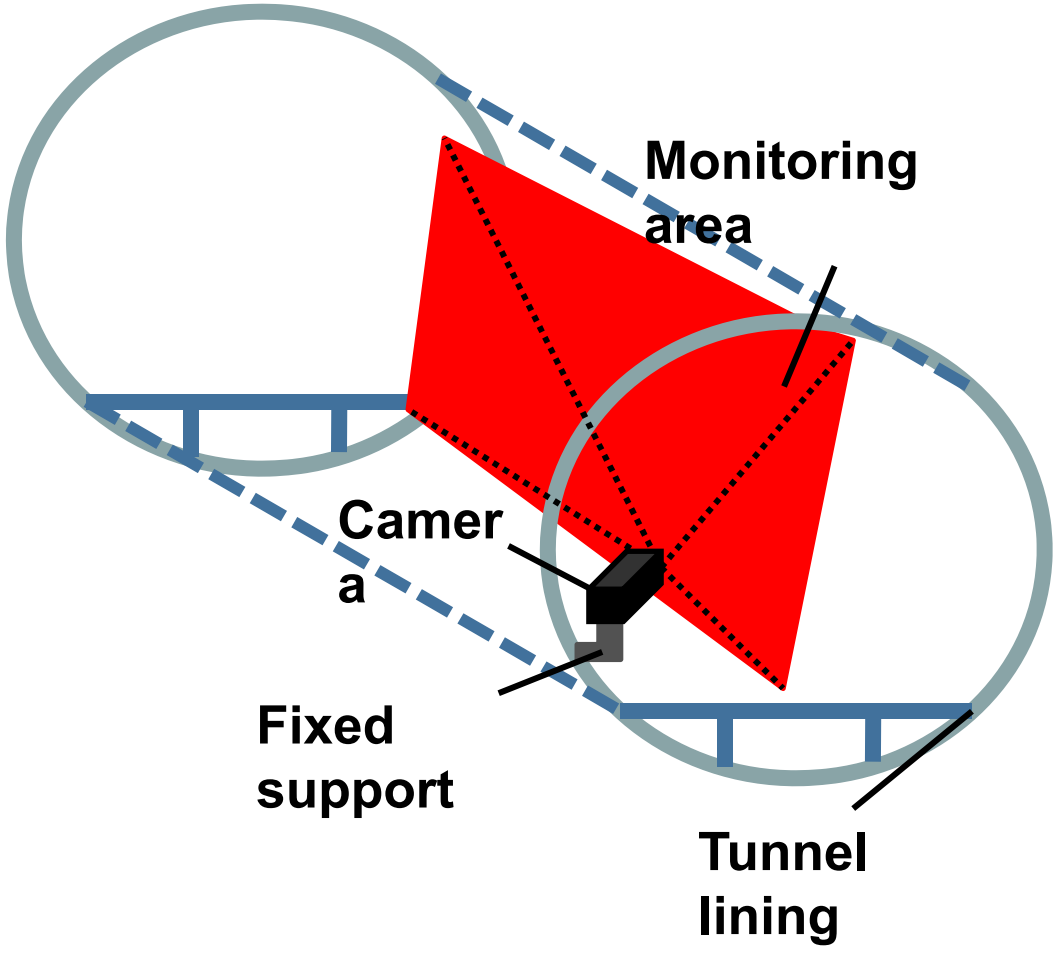
- Site Overview





- Camera setup



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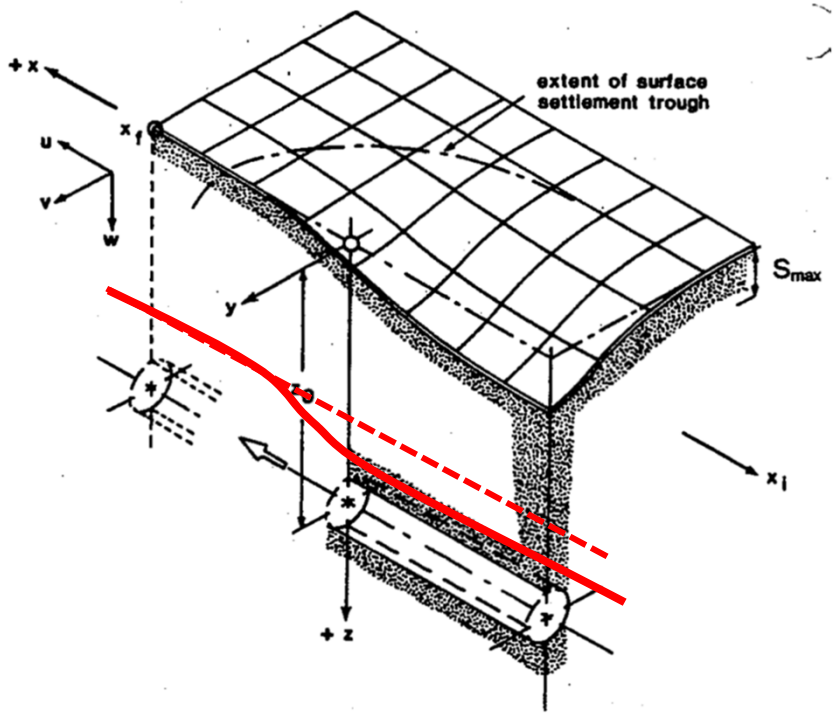
Low frequency motion

Bending or Shearing?



(After Attewell, 1986)

Matthew Wilcock

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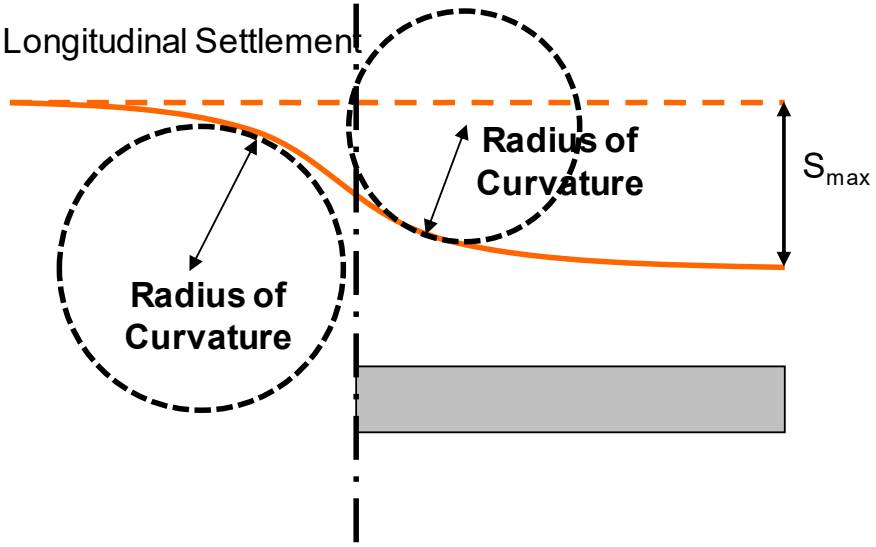
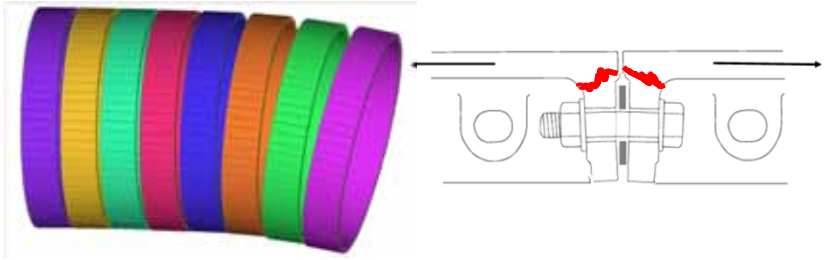
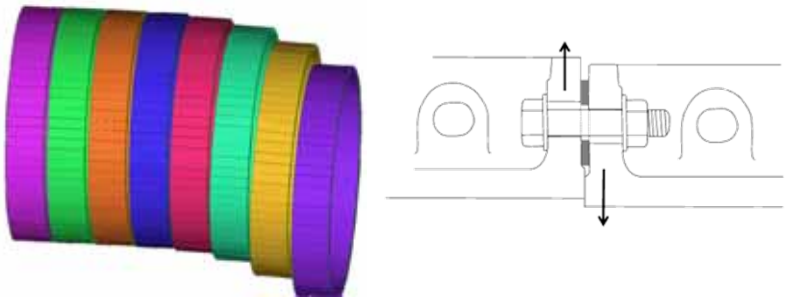


Bending Mode

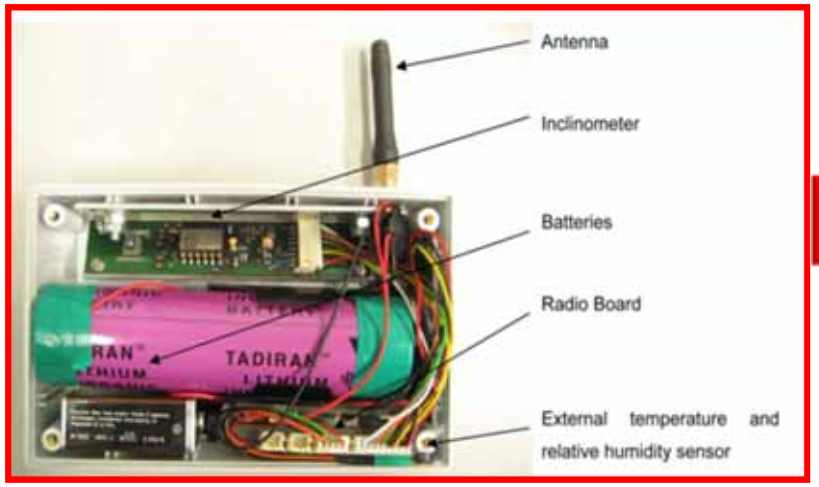


Shearing Mode



Arup – M. Devriendt

Berkeley UNIVERSITY OF CALIFORNIA



2009

2012

wisen innovation

2015

UtterBerry™

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power

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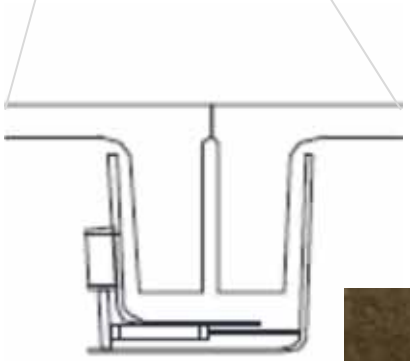
Shear LPDT Orientation

Expected settlement profile



Compressive (-ve) when ring nearest tunnelling approach shifts downward with respect to neighbouring ring!

Data for these sensors above sign reversed in data processing.

New Tunnel

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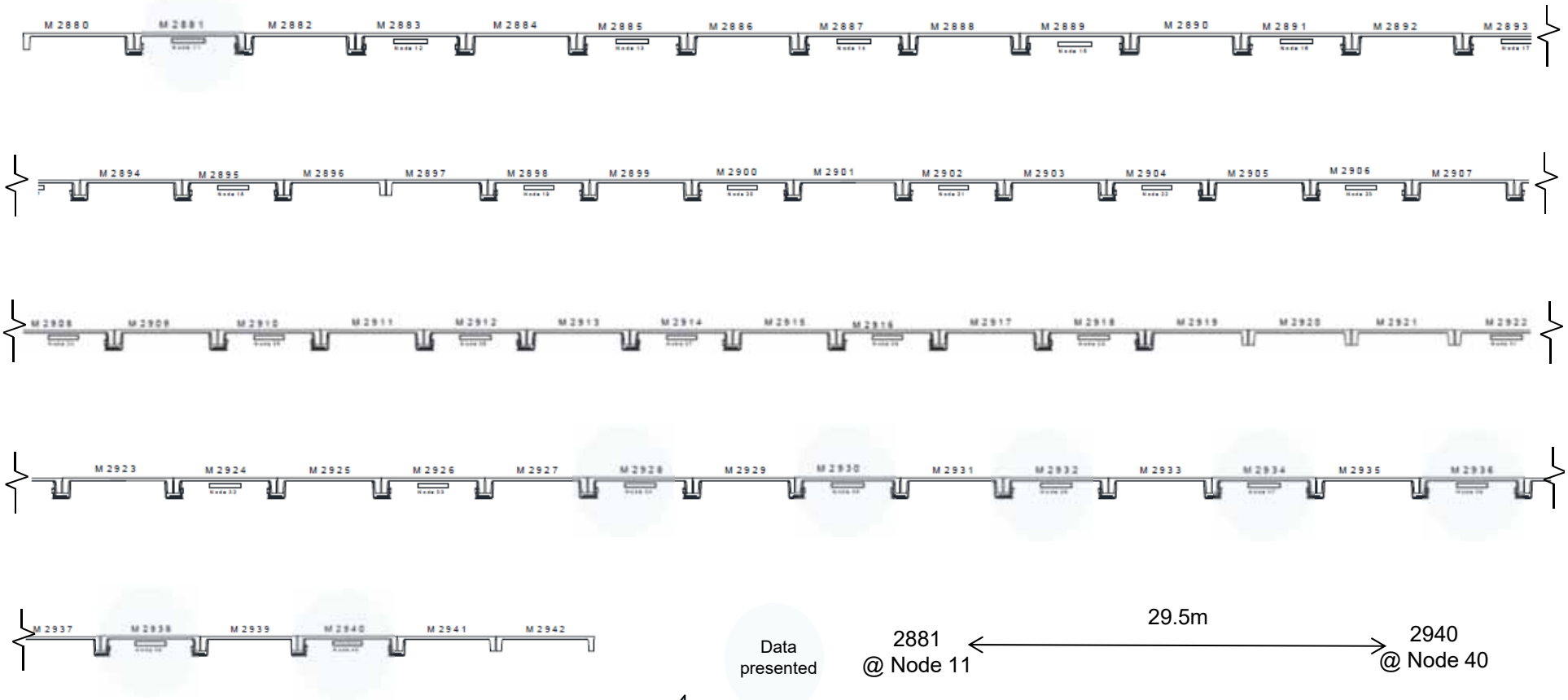
Layout of Sensors & Location of Sensors 11, 34-40

120 Wireless Sensors to monitor movements of 60 joints



Data presented

29.5m

2881 @ Node 11

2940 @ Node 40

New Tunne

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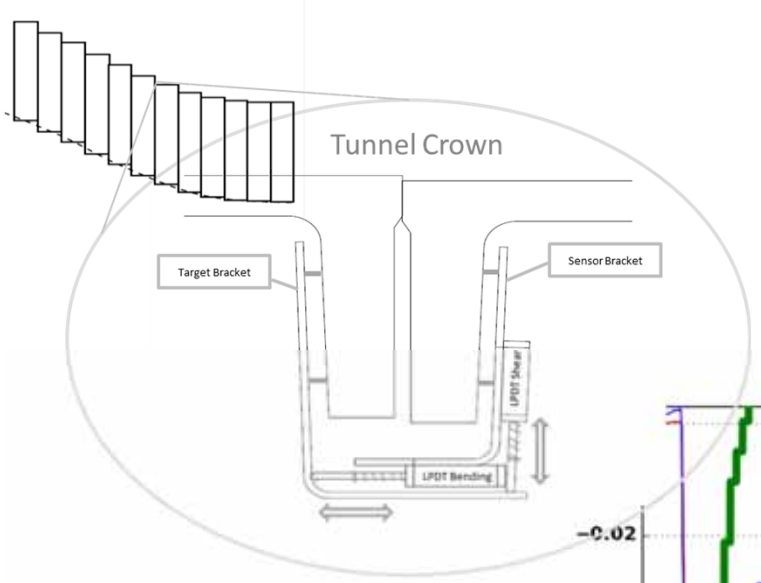
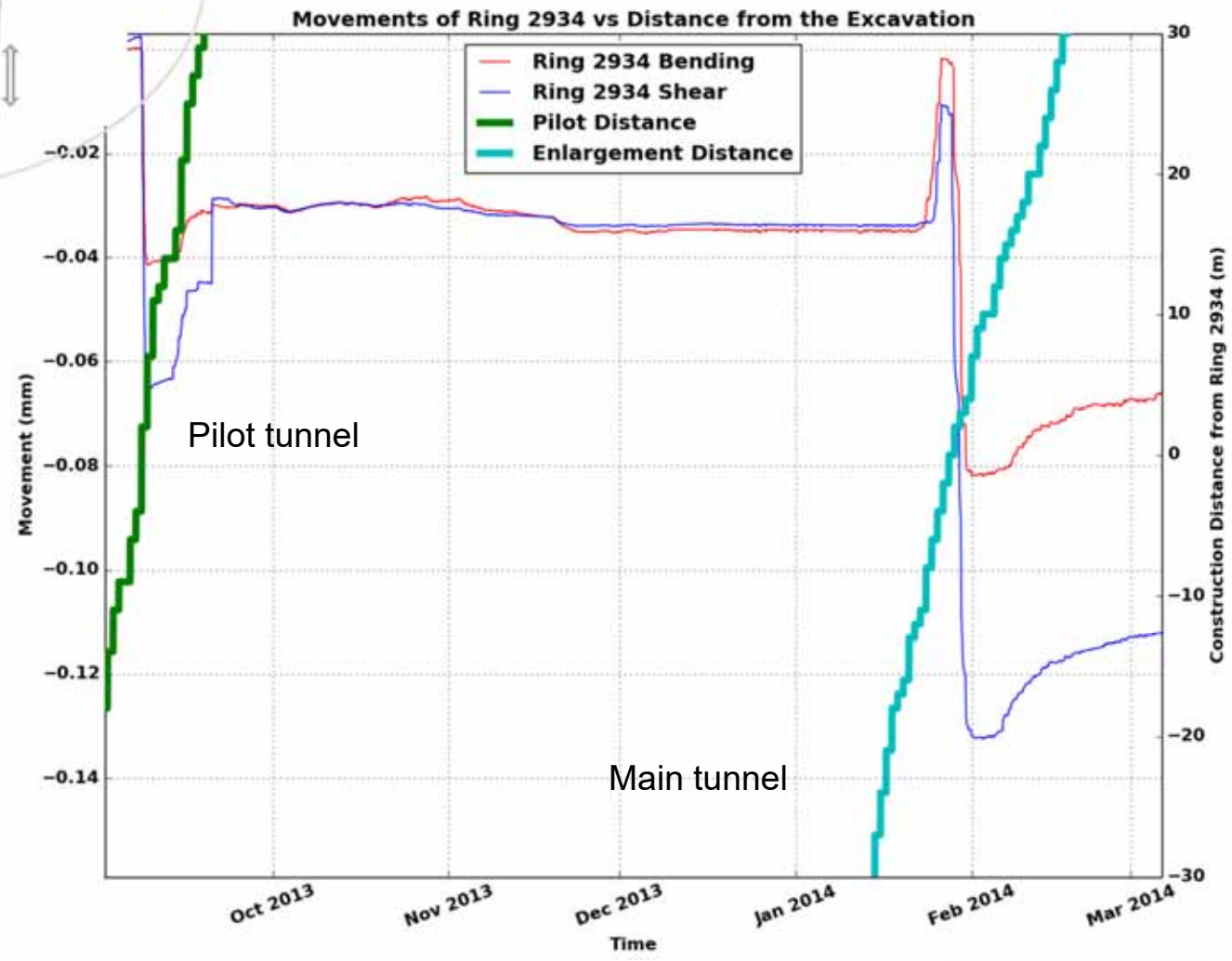
Wilcock





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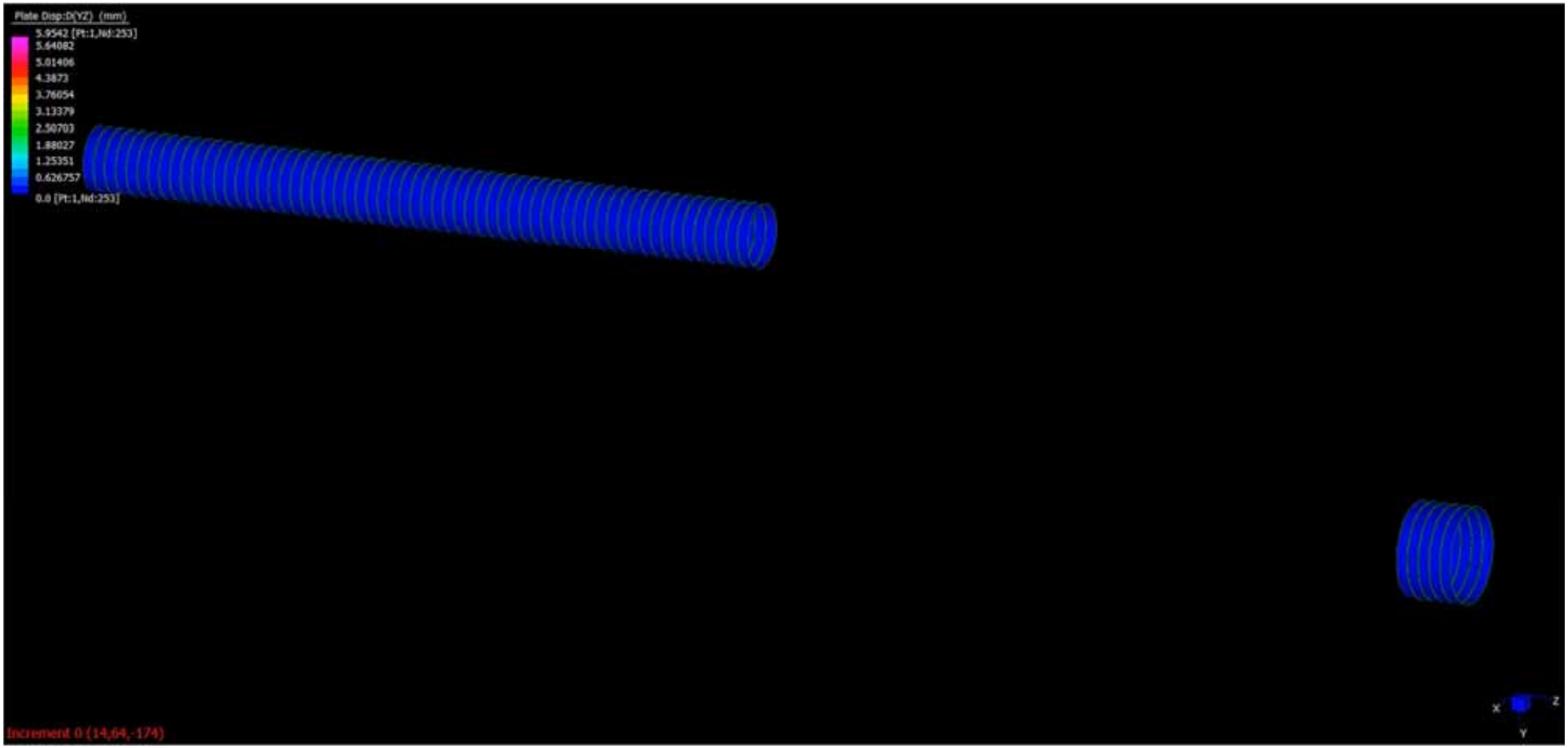

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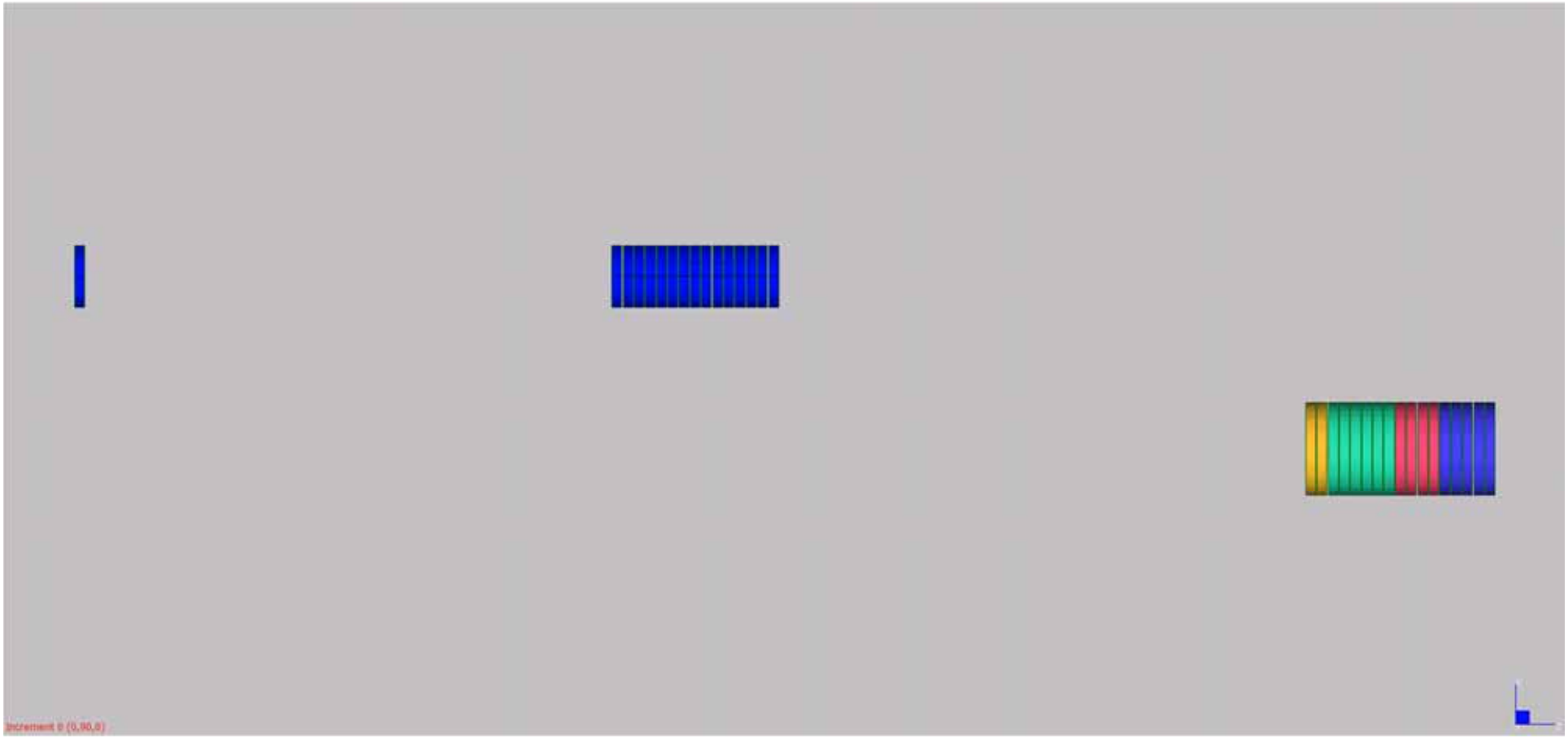

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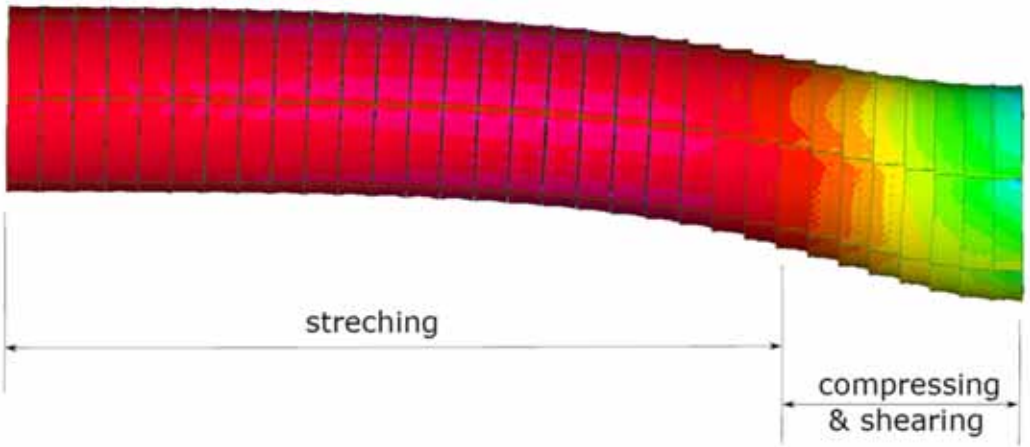

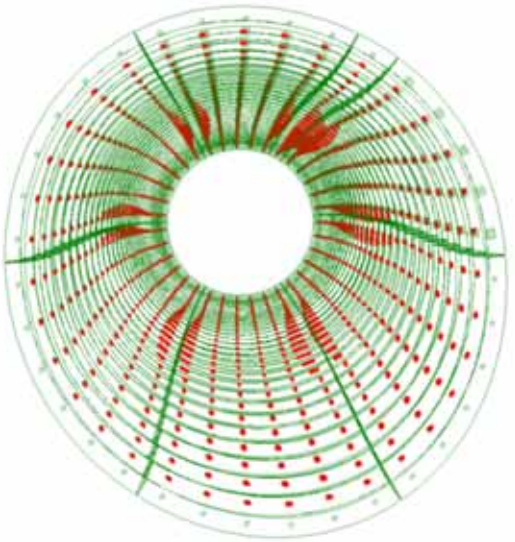

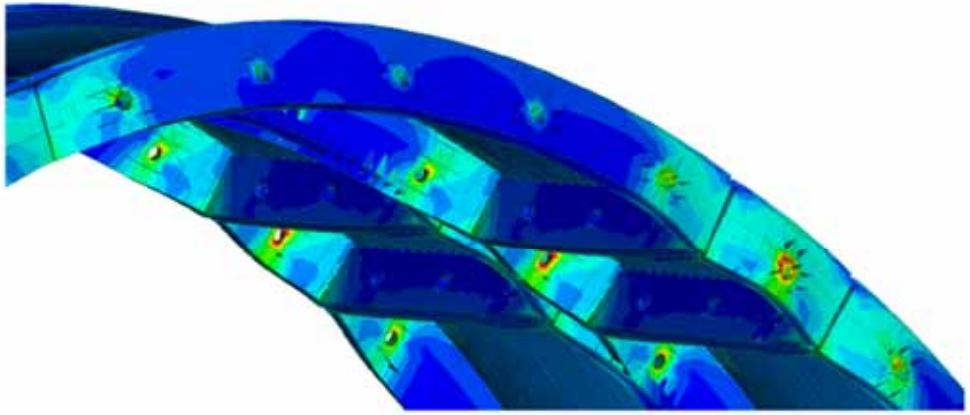

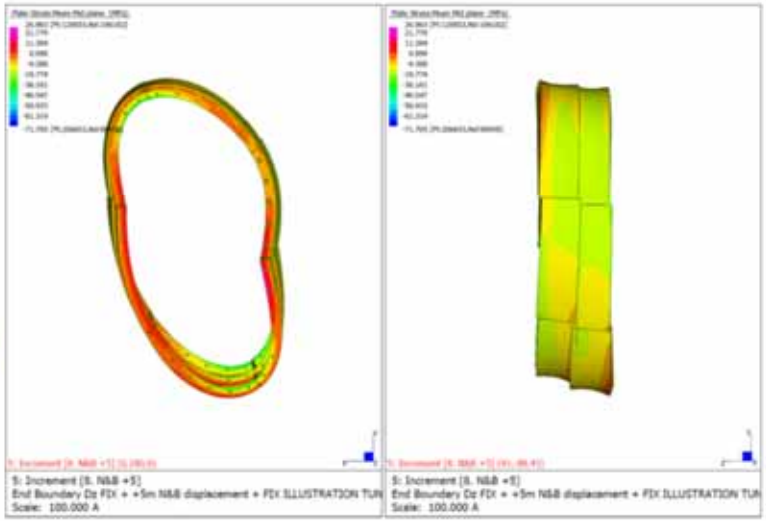

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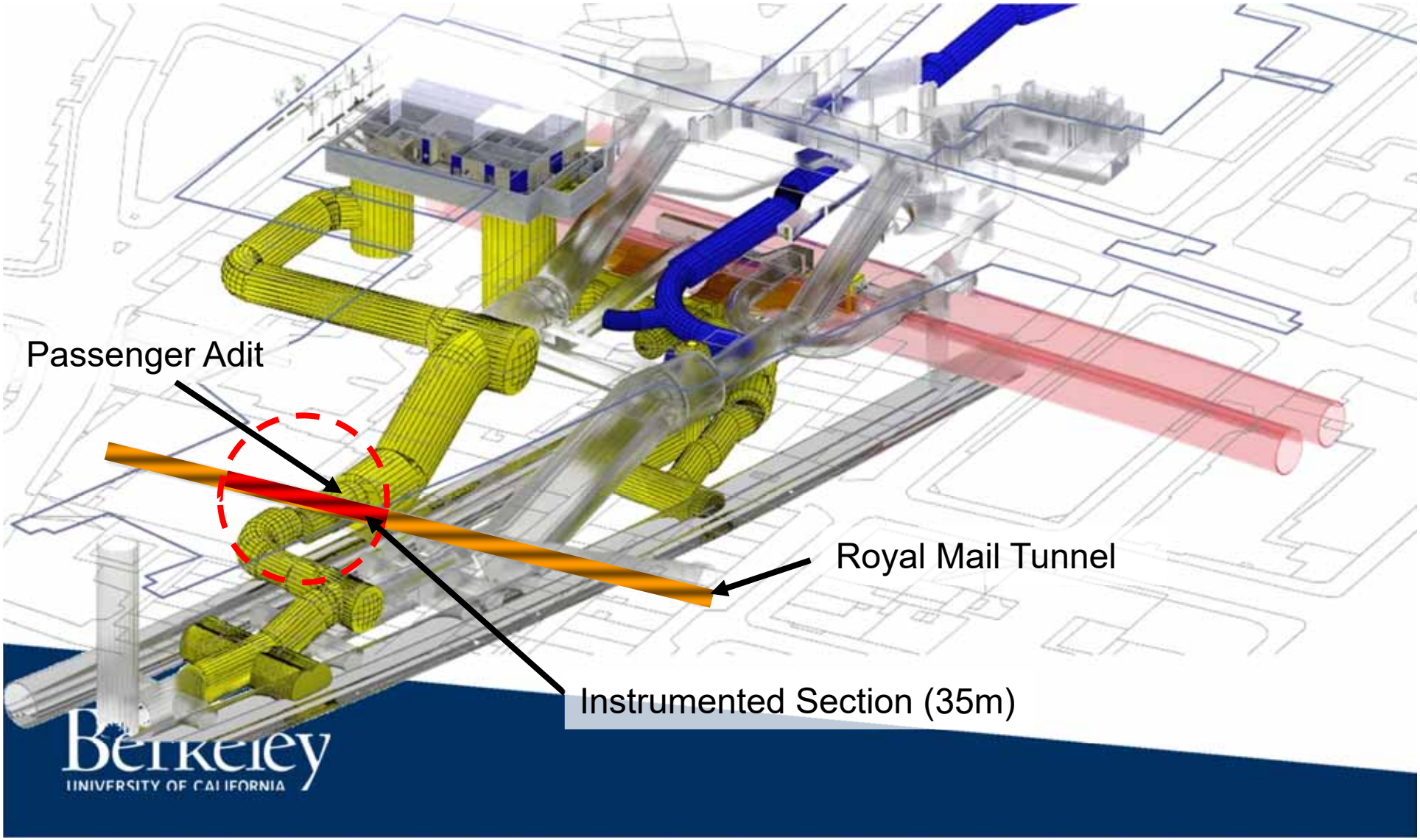
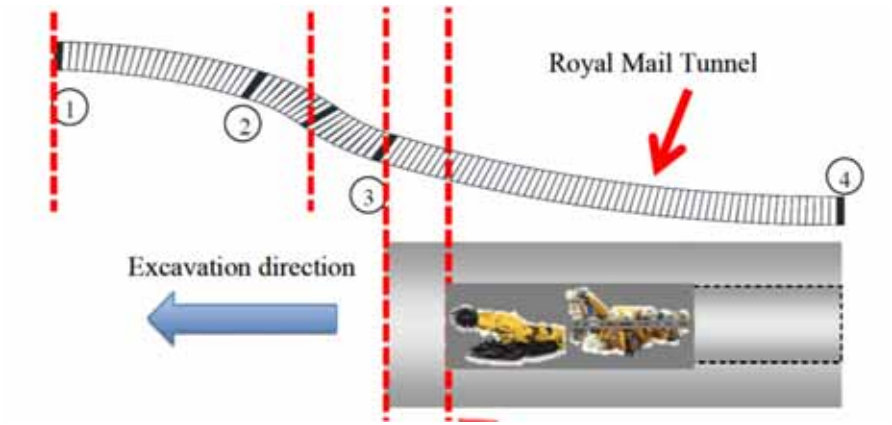
Bond Street – LUL Station



The two case studies show that the cast-iron tunnels are more tolerable to bending (i.e. can accommodate smaller Radius of Curveture (ROC))

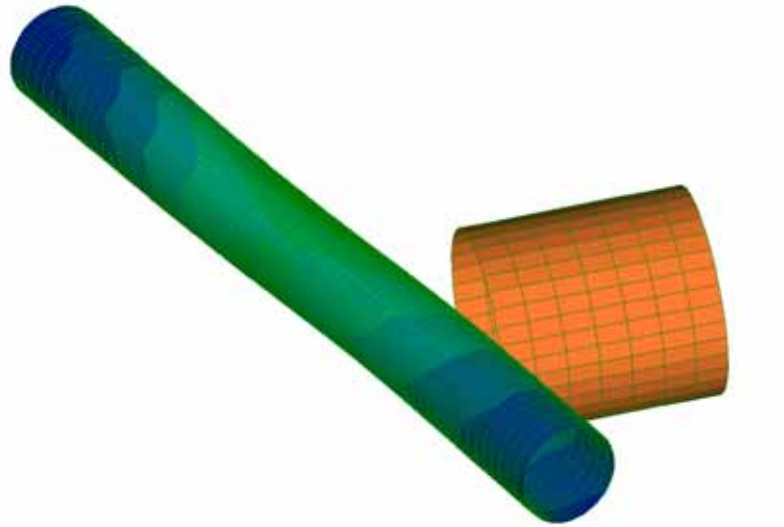
Longitudinal crossing

Bending > Shearing

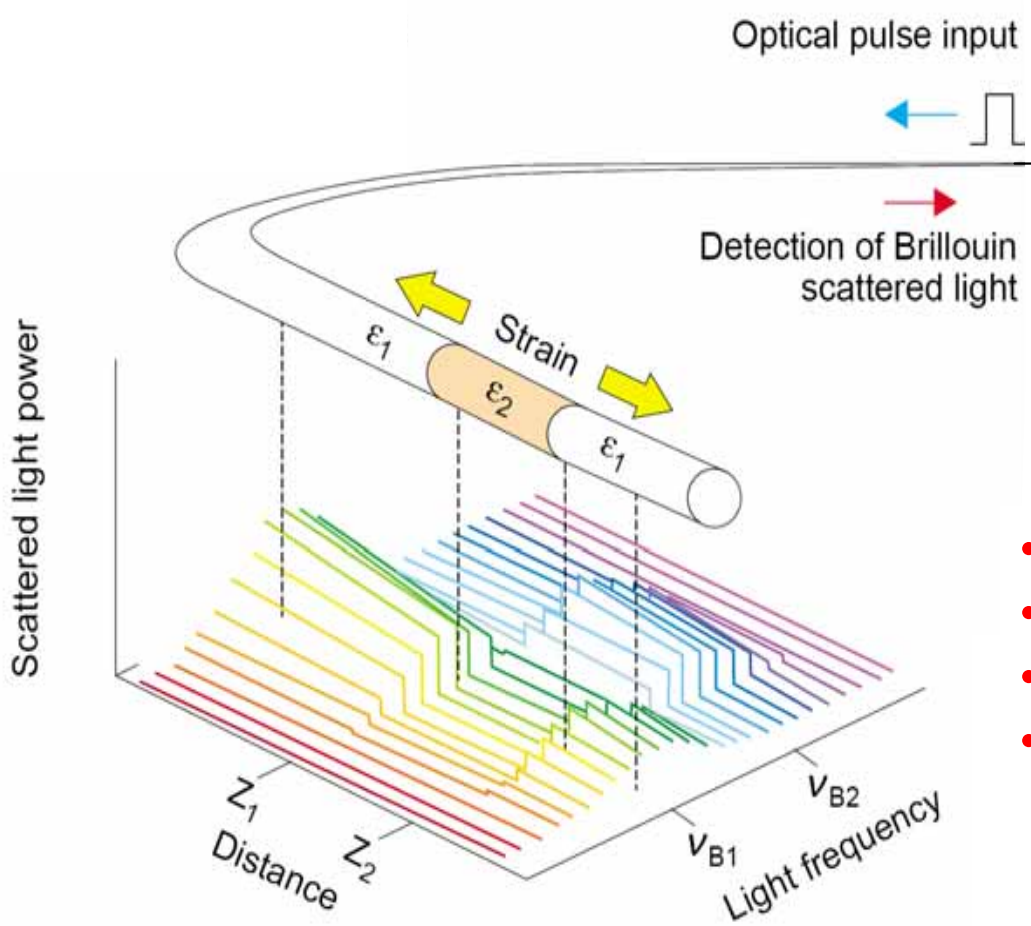


Transverse crossing

Shearing > Bending

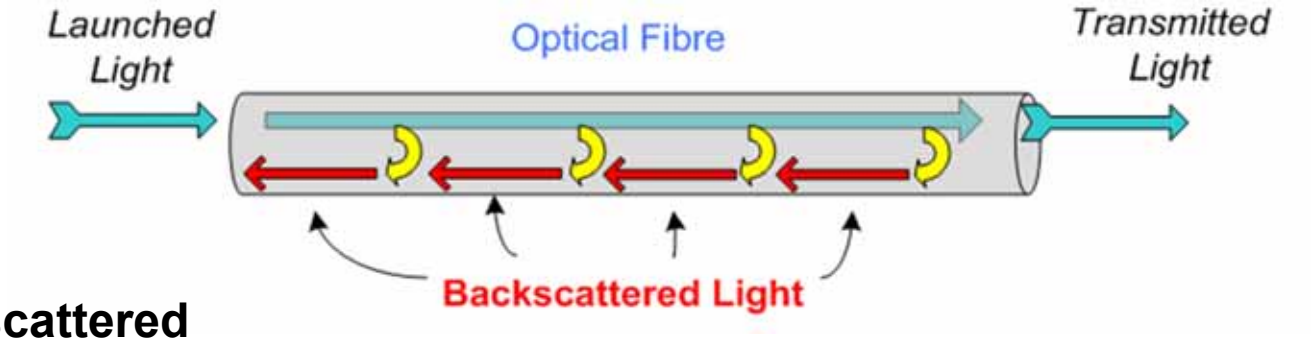


Distributed Sensing providing "Continuous Strain/temperature/vibration Profile" along the fibre optic cable

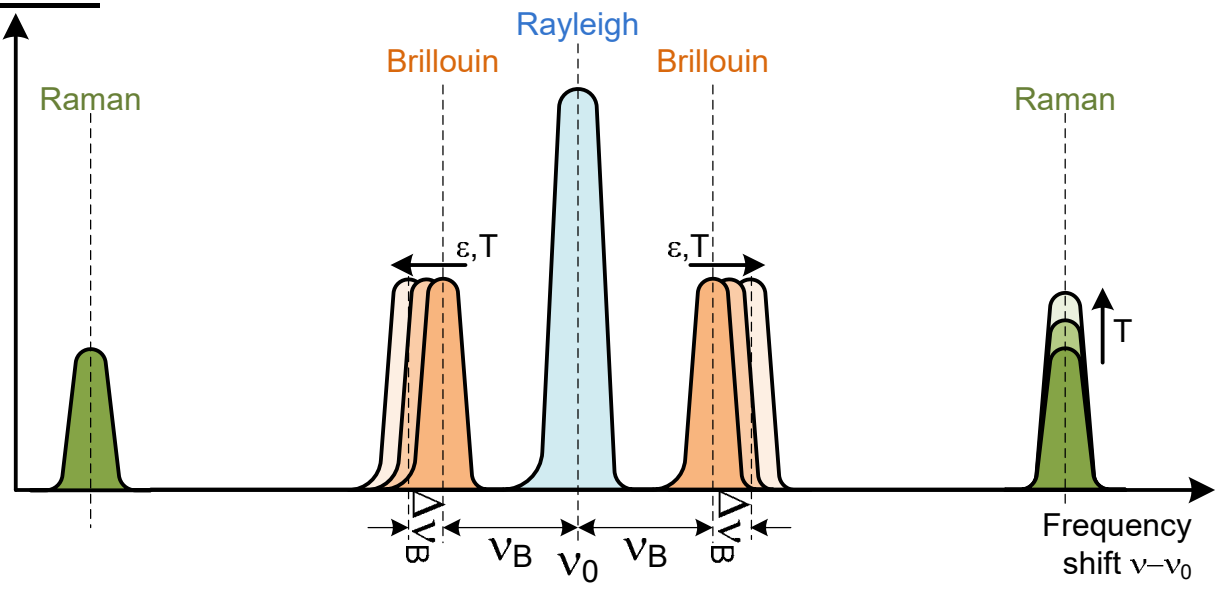


The frequency shift of the Brillouin scattered light is proportional to the strain.

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

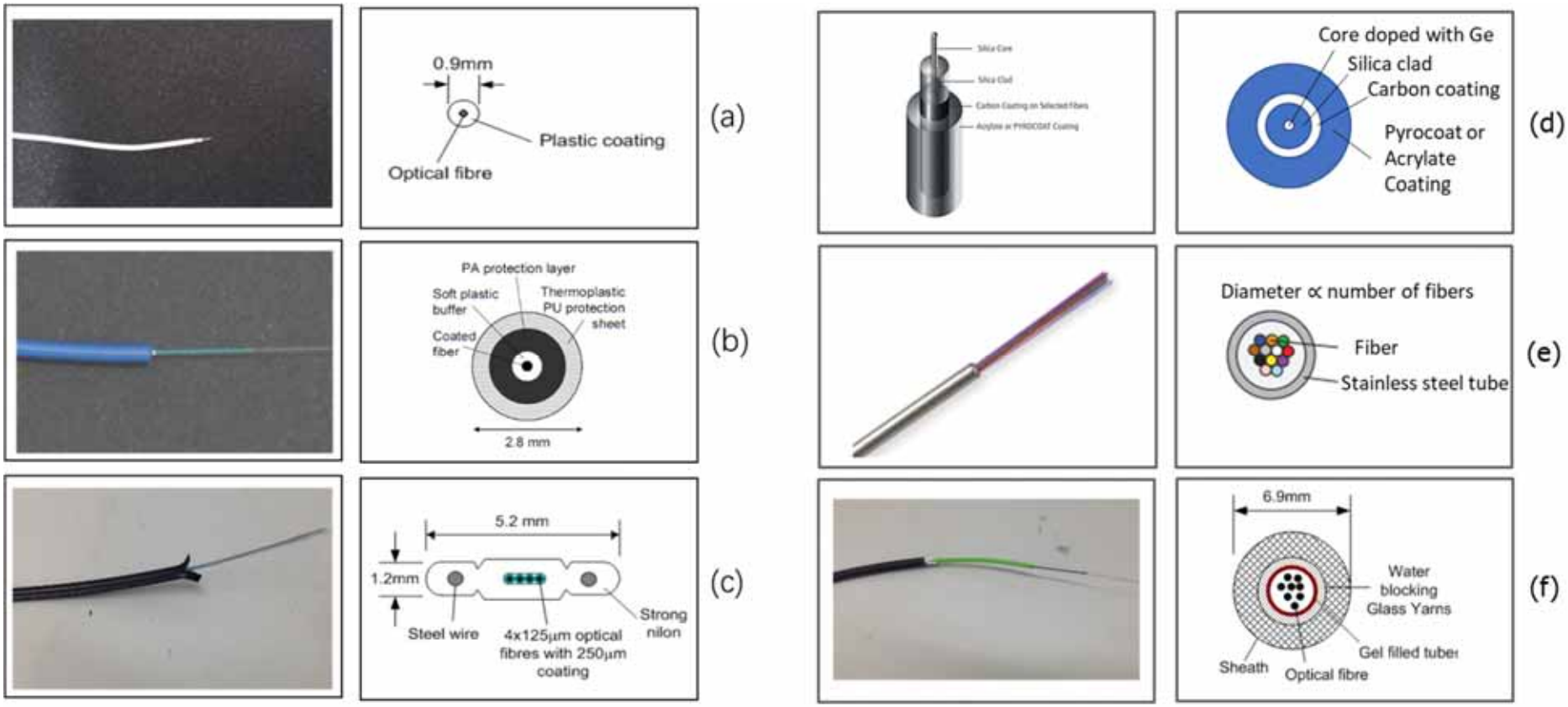


Backscattered spectrum



1. Send light through the fibre and detect the back scattered light
2. Identify the location of back scattering from the time interval
3. Measure Frequency shift due to strain (ΔF)
4. Translate ΔF to strain: $\varepsilon = f(\Delta F)$
5. Obtain the strain profile: ε(x) over the whole length of the cable

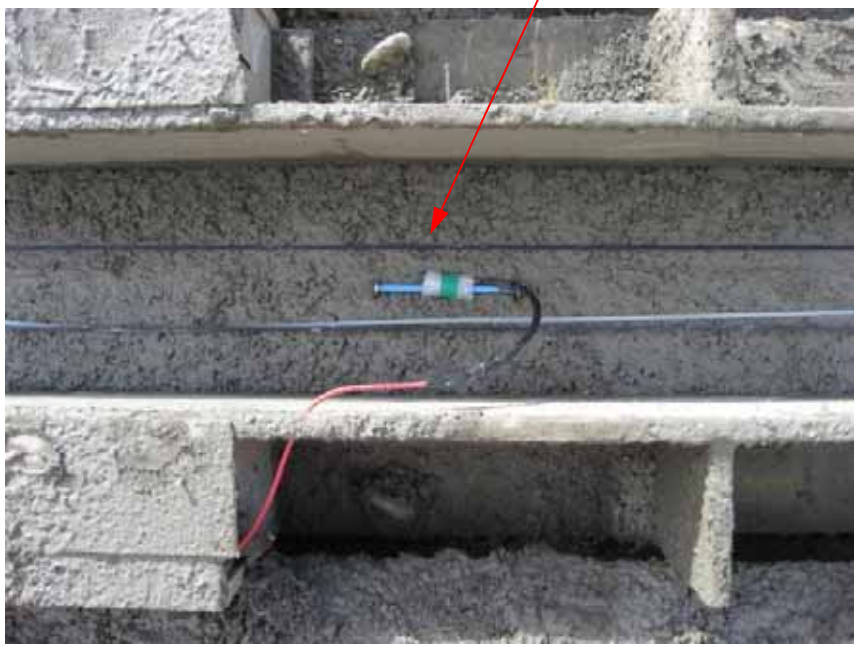
Sensing cables

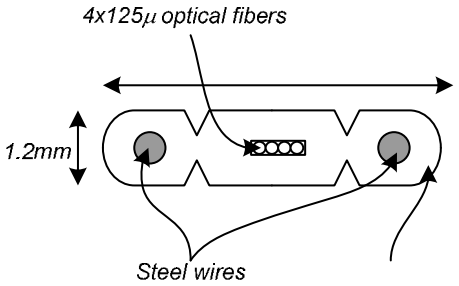


(a-d) Strain/acoustic sensing
(e-f) Temperature sensing

Robustness

Fujikura Reinforced
Fibre Optic Cable





FUJIKURA SM 4
Reinforced

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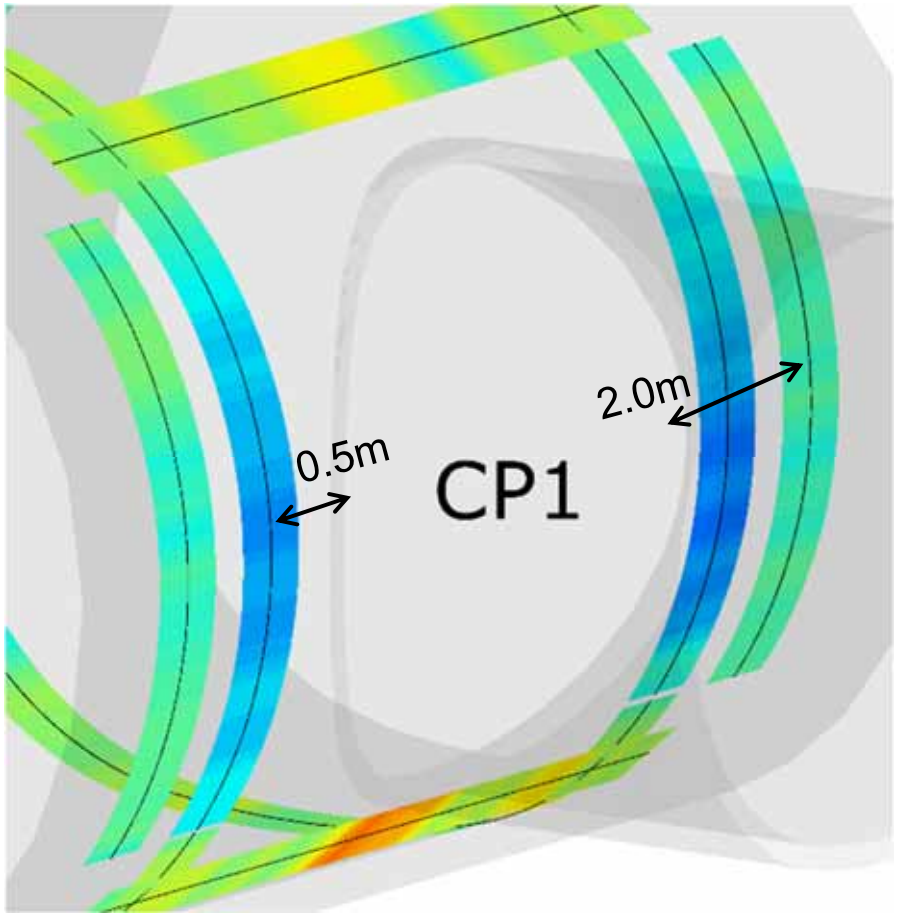
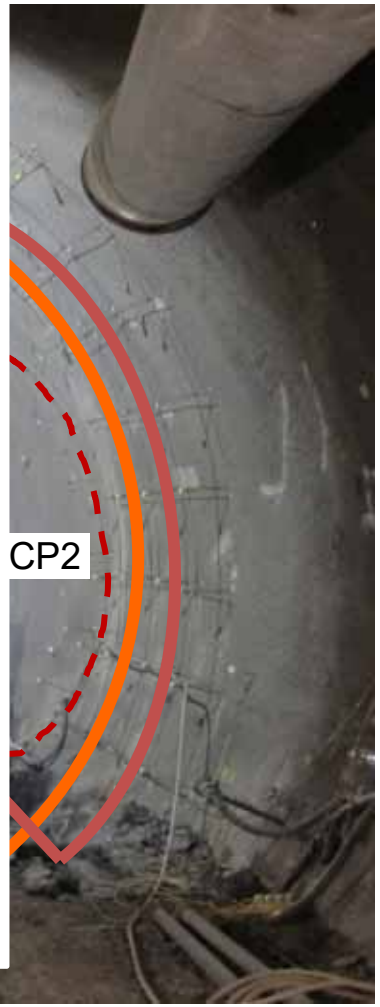
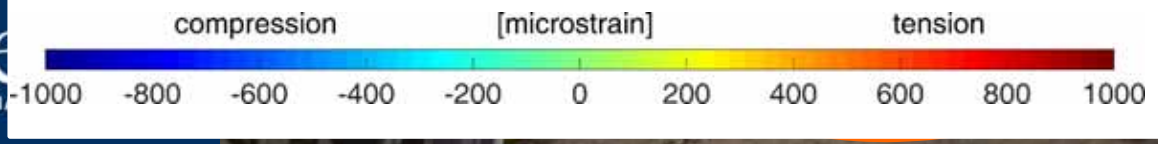
Sprayed concrete lining
Performance during cross passage opening







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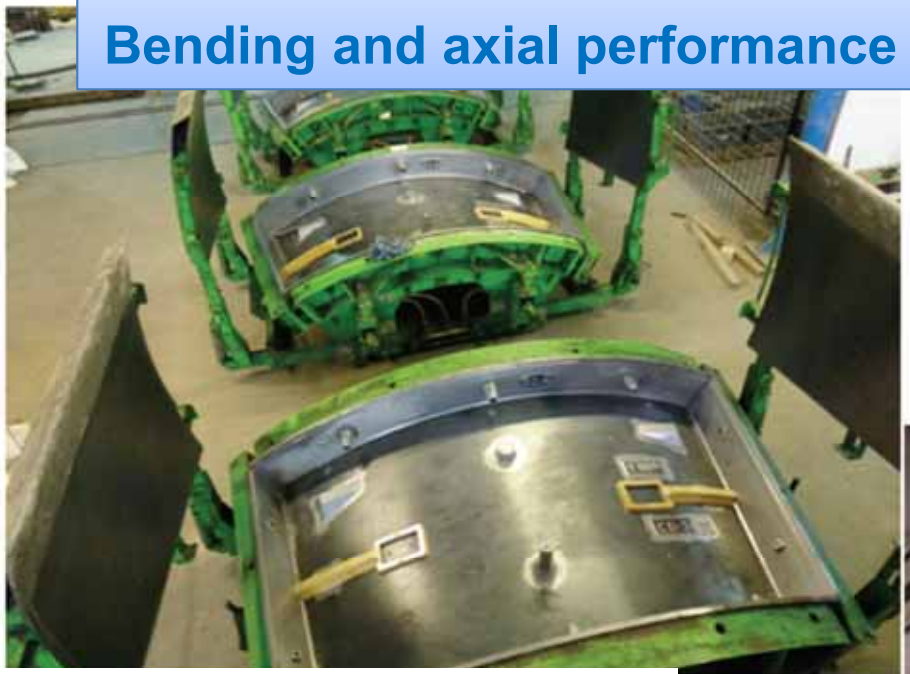
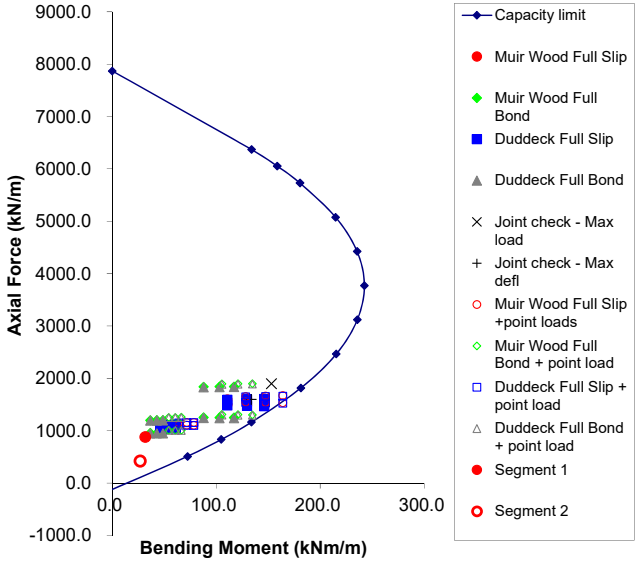
Tunnel lining

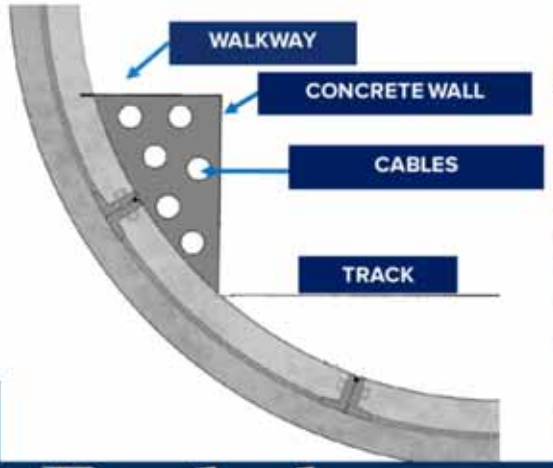
Bending and axial performance during construction and in long term

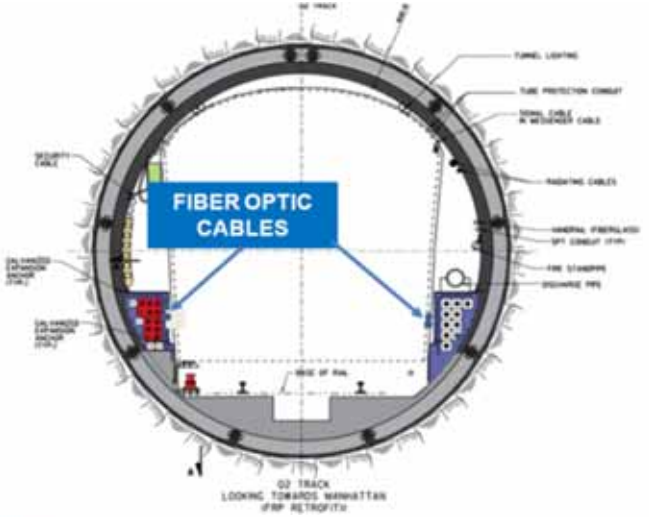




In January this year, New York Governor Cuomo announced a plan to prevent the 15-month-long L-train shutdown set to begin in April.

The Canarsie Tunnel, which opened in 1924, has shown deterioration after flooding from Hurricane Sandy in 2012.





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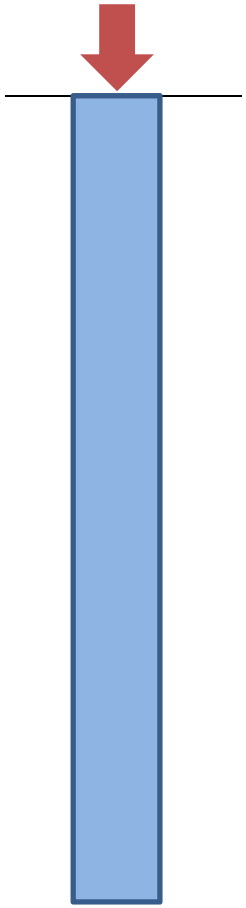
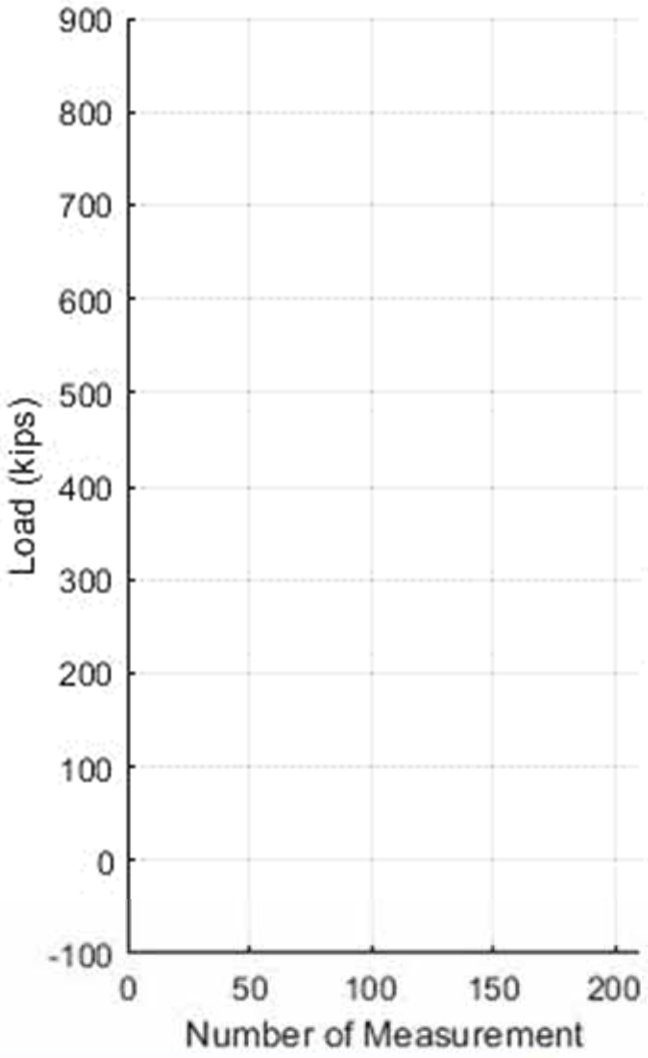
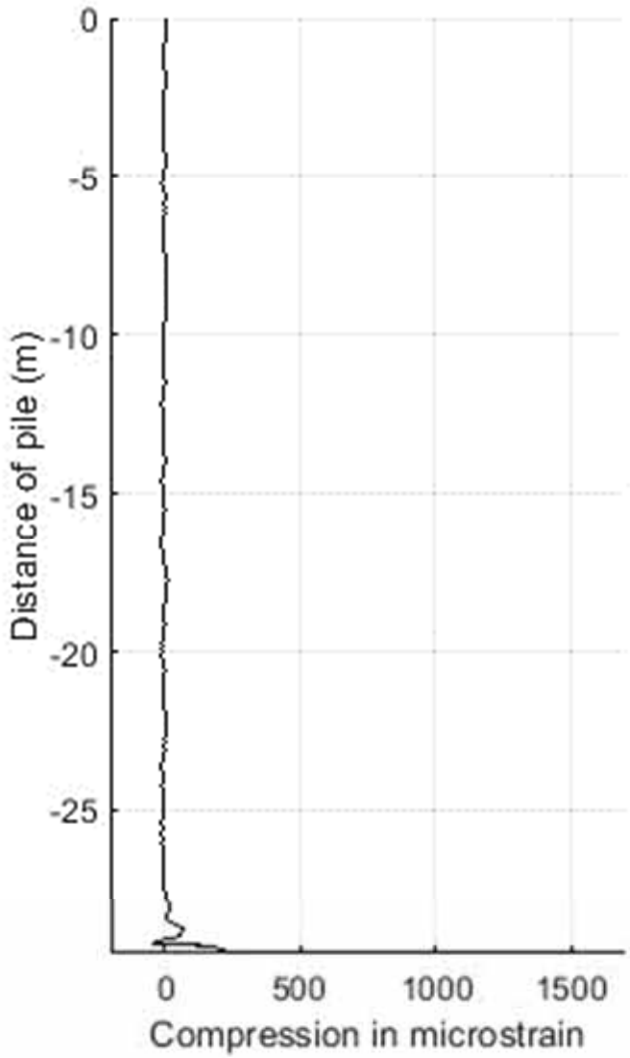
A pile loading test…







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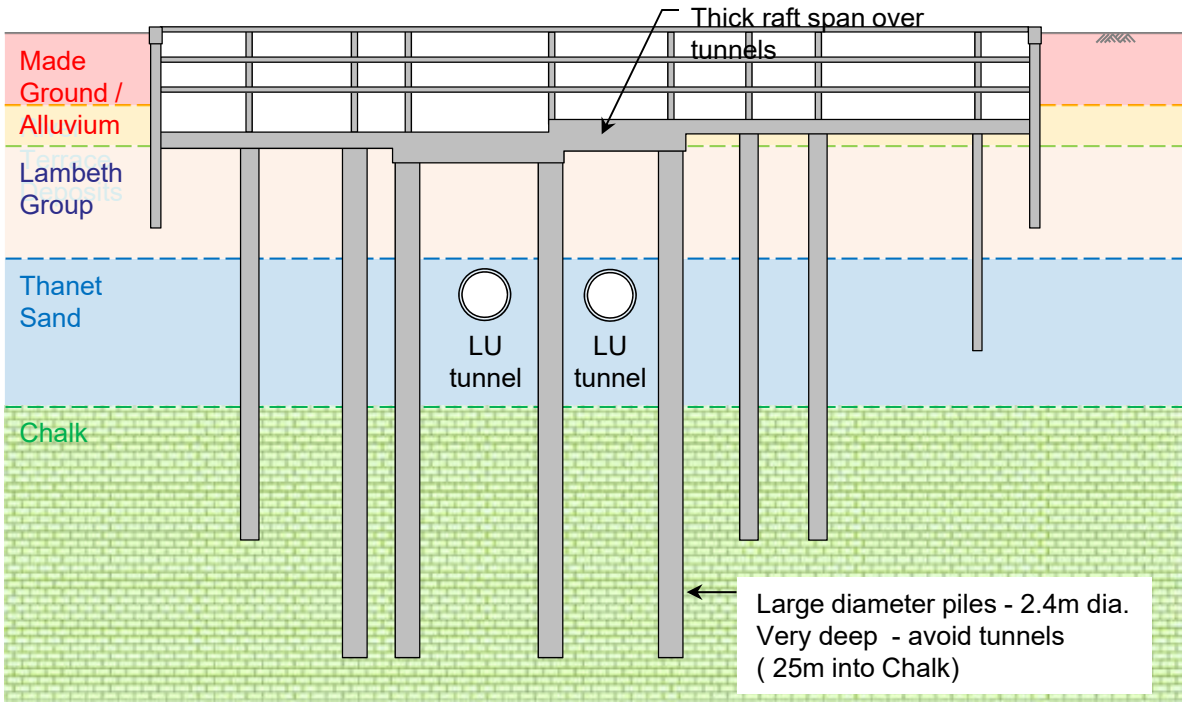
A building construction at the Isle of Dog, London



ARUP

Echo Ouyang

Musa Chunge

Cedric Kechavarzi

Loizos Pelecanos

Vivien Kwan

Duncan Nicholson

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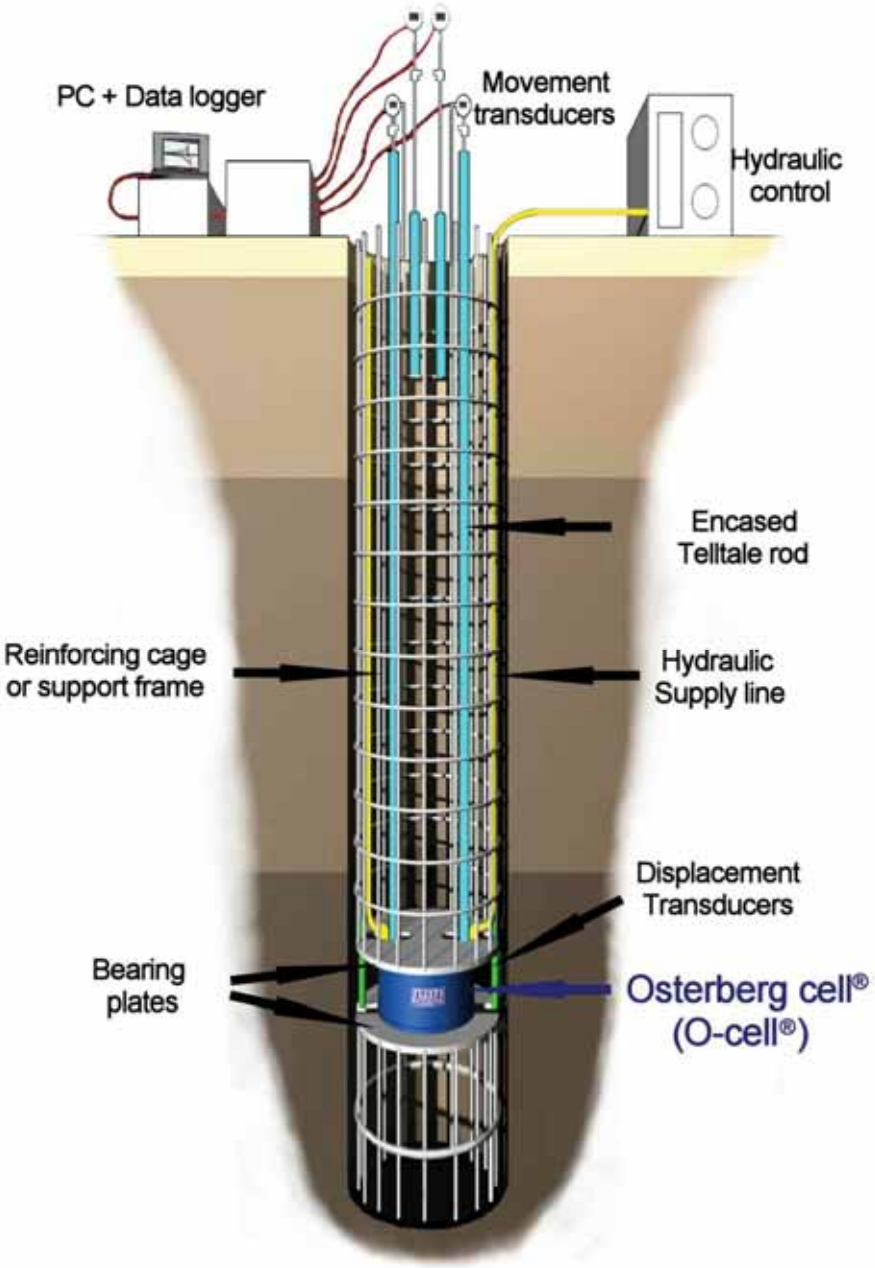
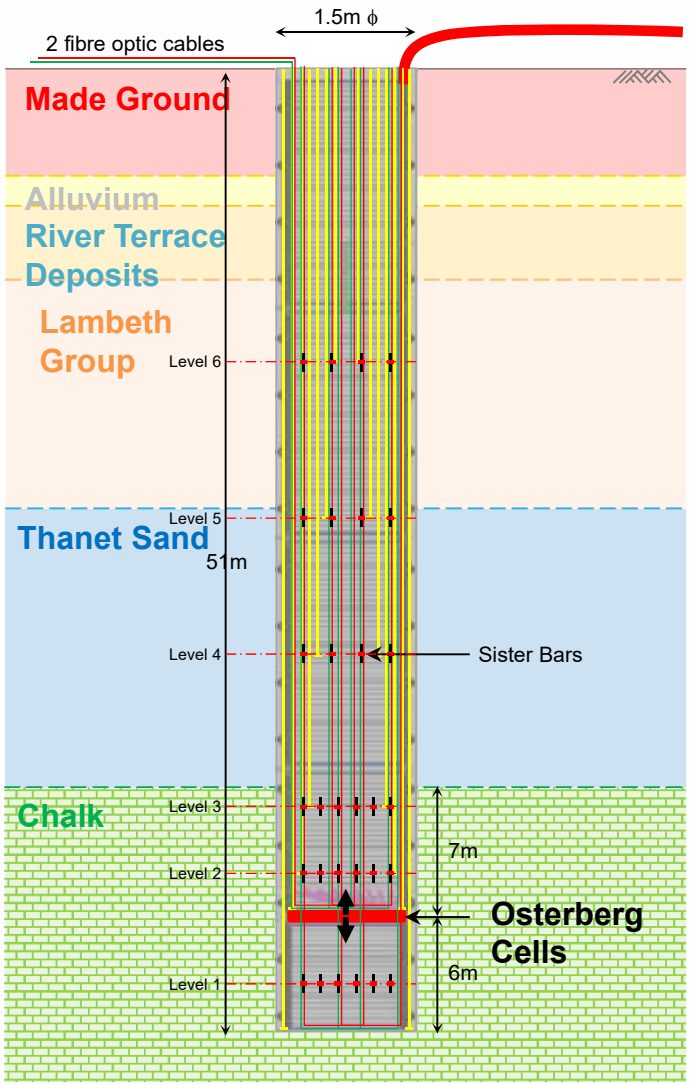
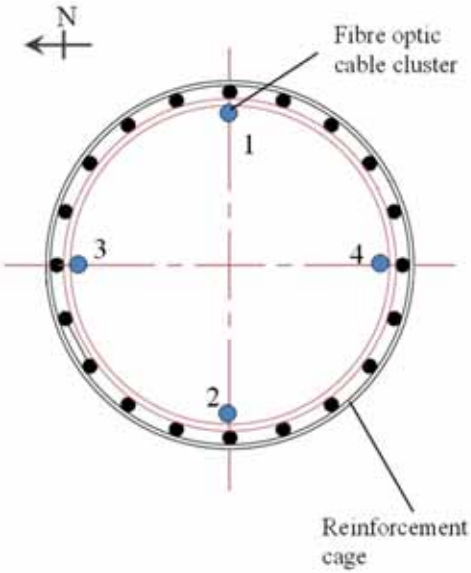
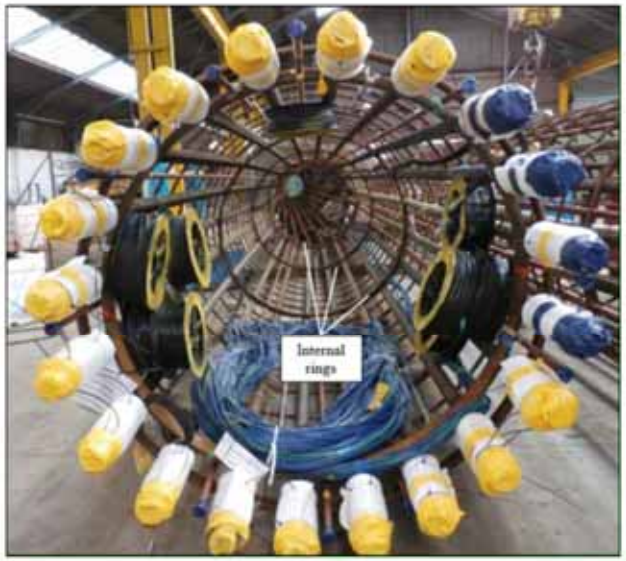
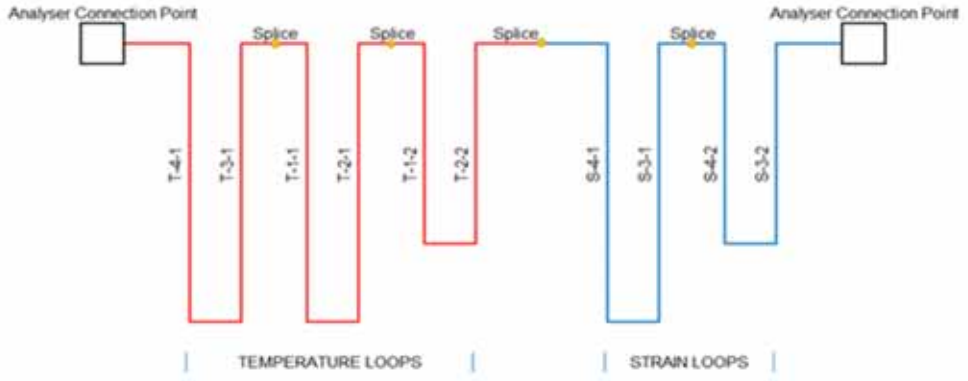
O-Cells

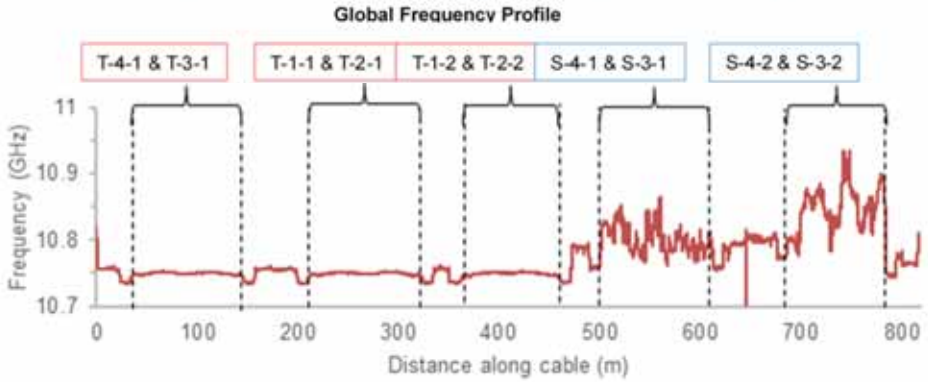

PC + Data logger
Movement transducers
Hydraulic control
Encased Telltale rod
Reinforcing cage or support frame
Hydraulic Supply line
Displacement Transducers
Bearing plates
Osterberg cell®
(O-cell®)











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

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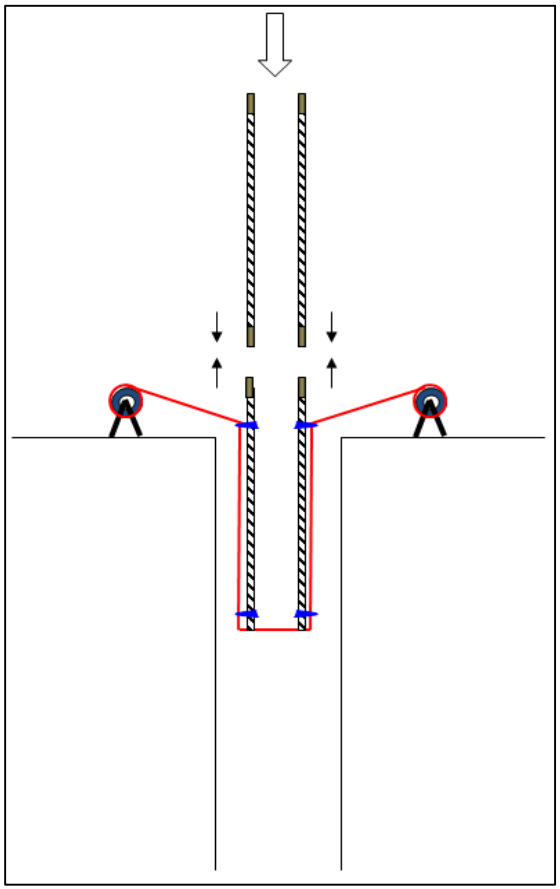
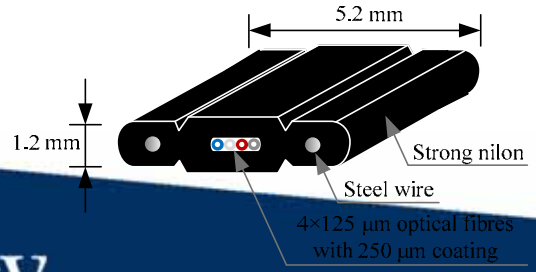
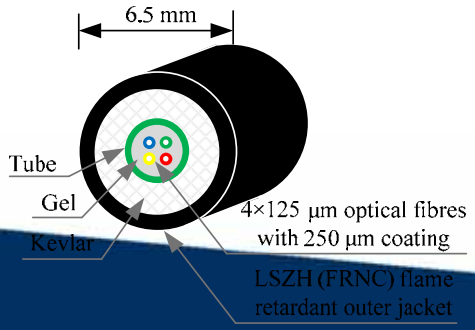
No disturbance to actual construction operations







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Conventional Strain Gauge System

Distributed FO system

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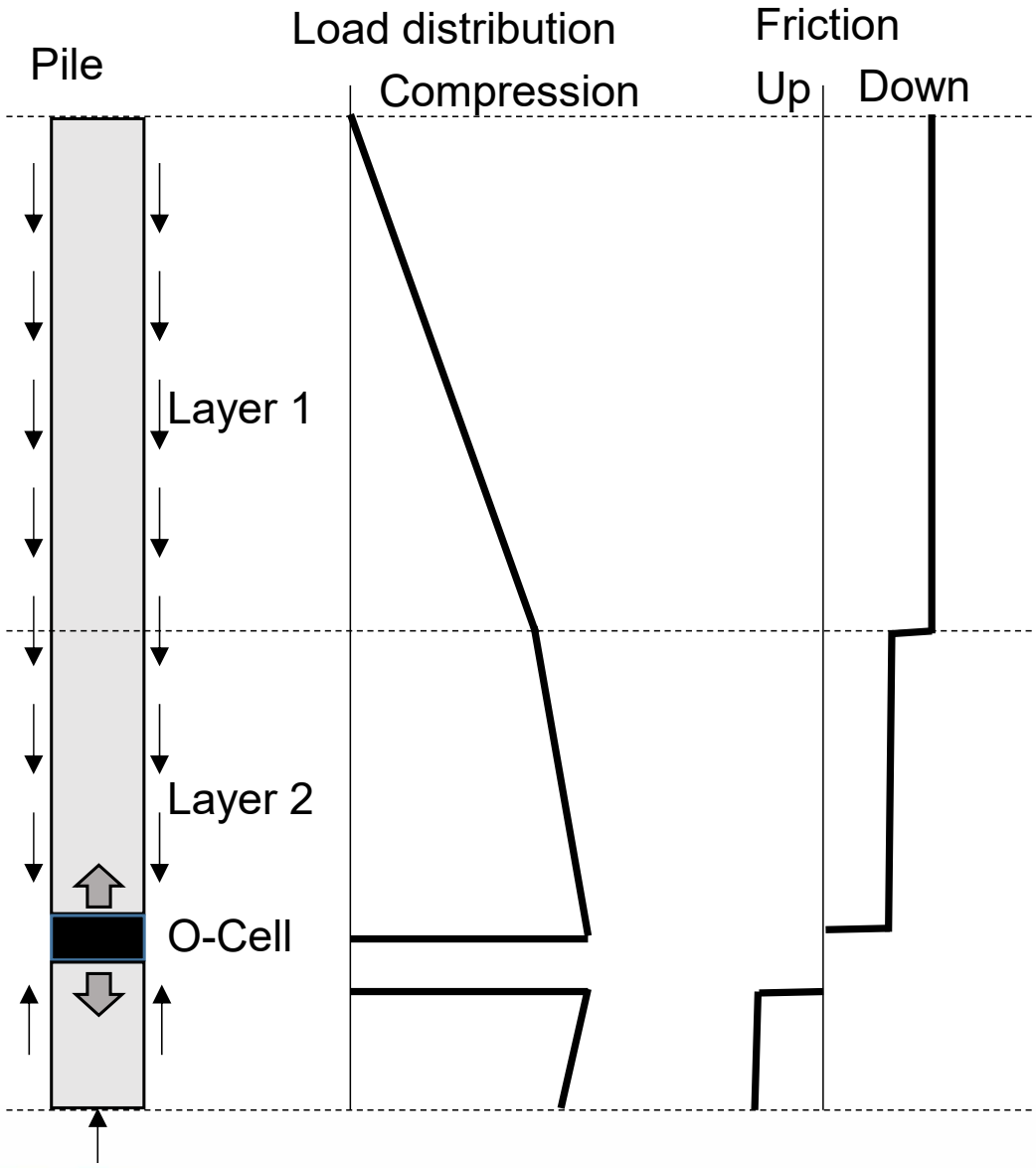
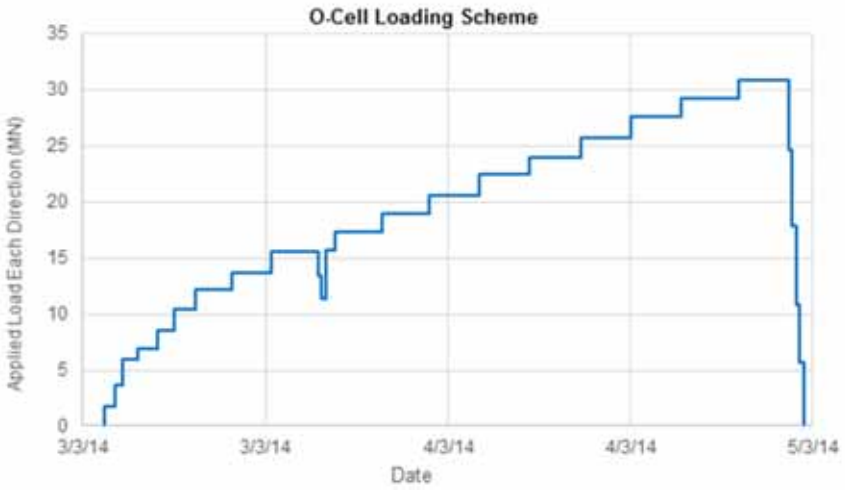
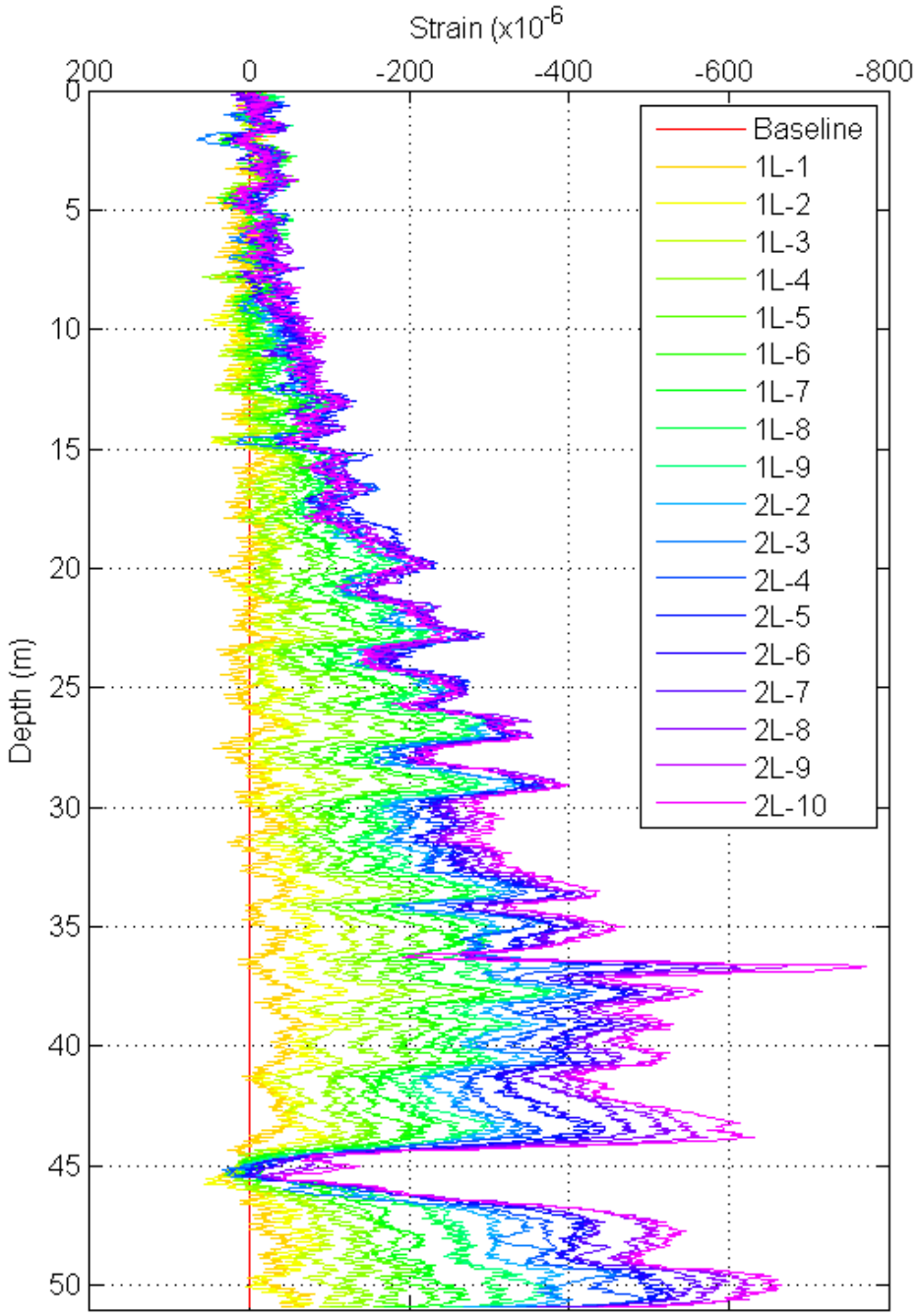
Mechanism of O-cell testing







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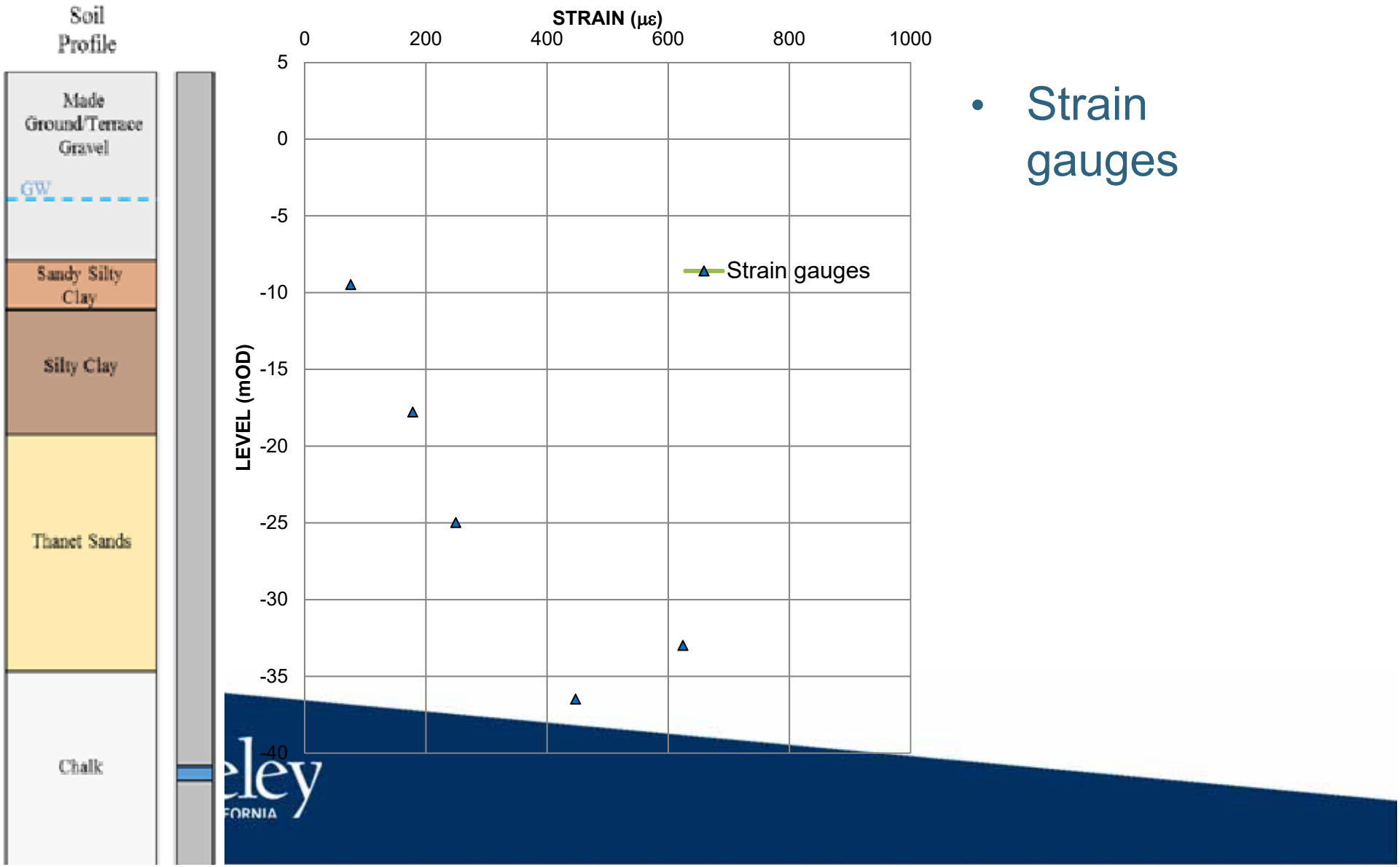
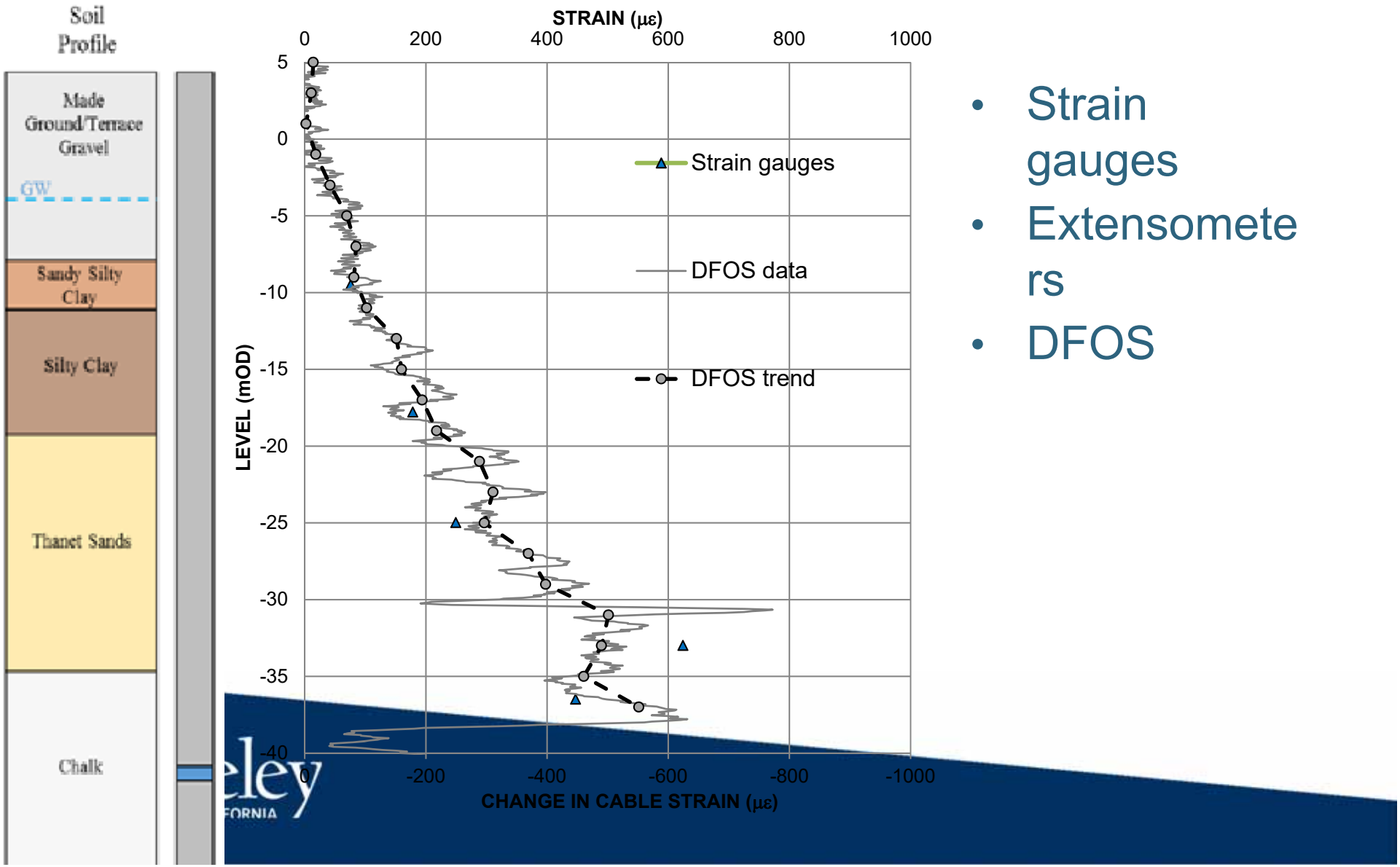


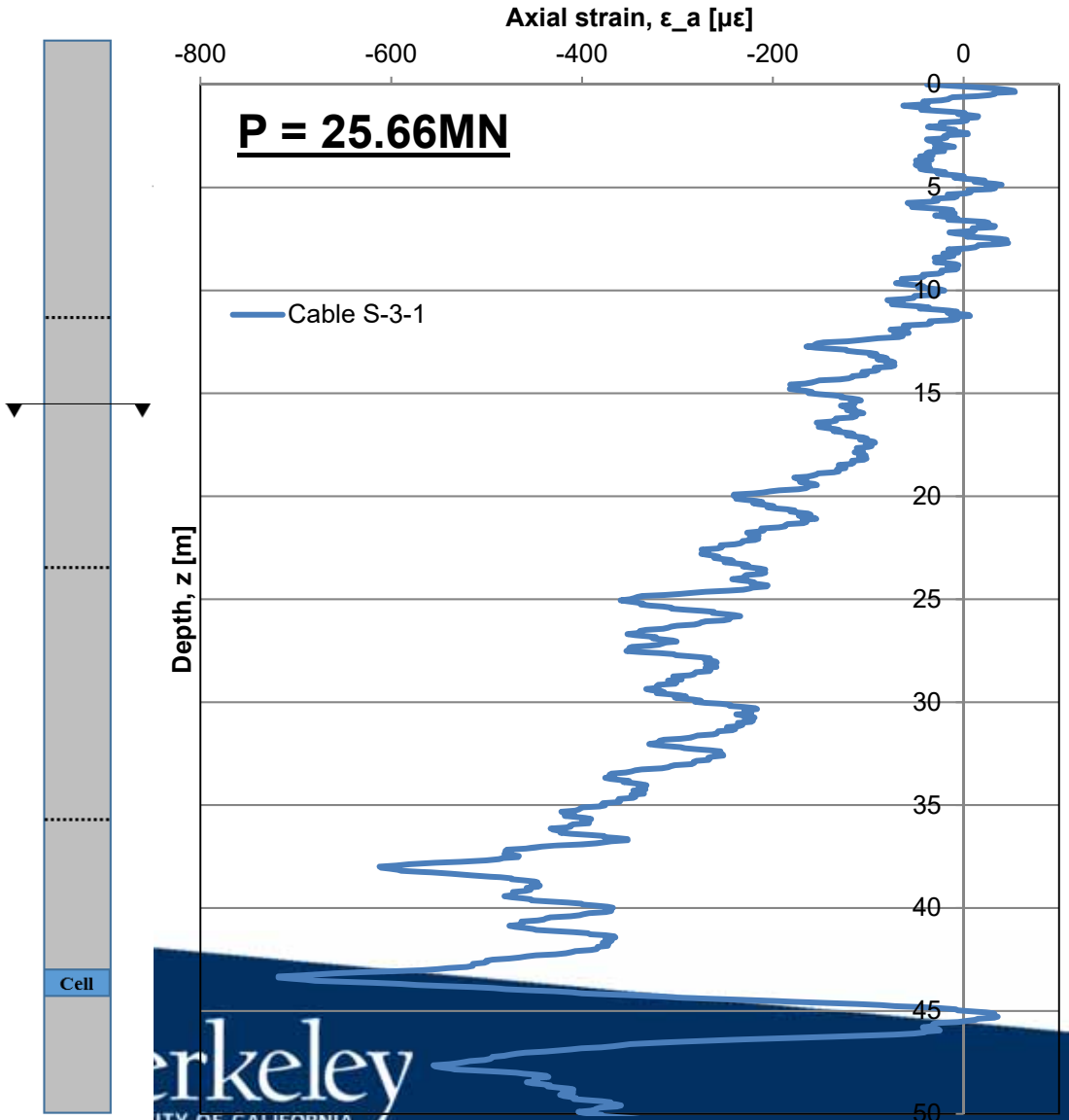
- Strain gauges

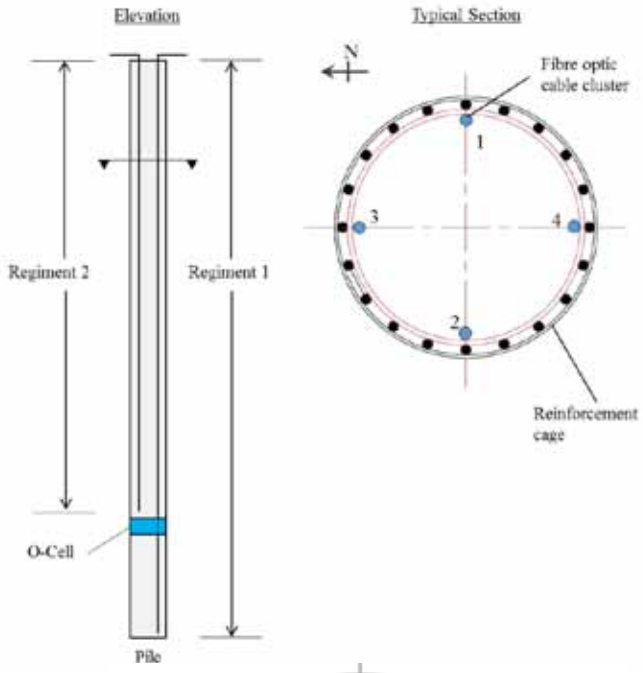
Axial strain
Instrument comparison

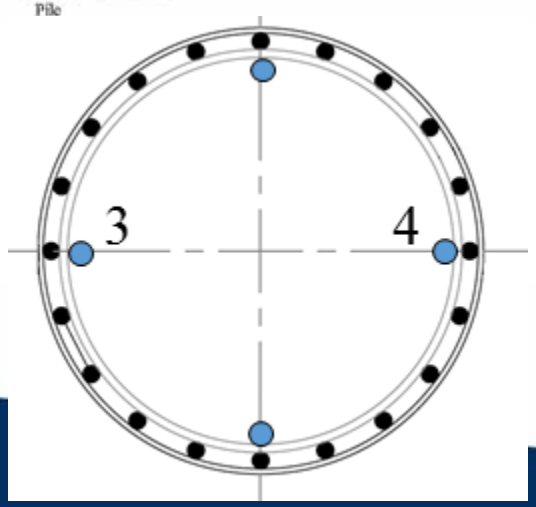


- Strain gauges
- Extensometers
- DFOS

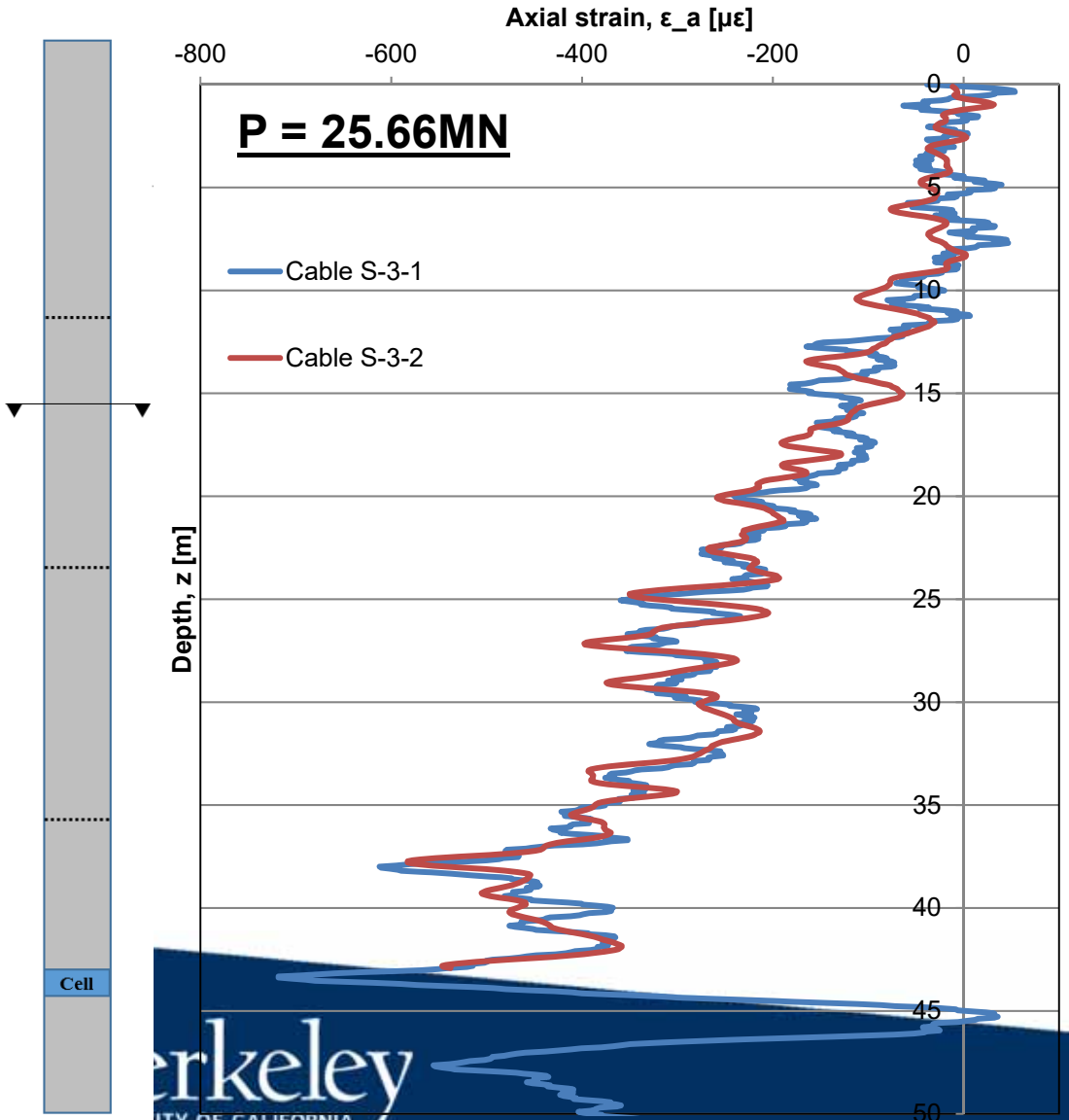
Axial strain
Different FO cable comparison

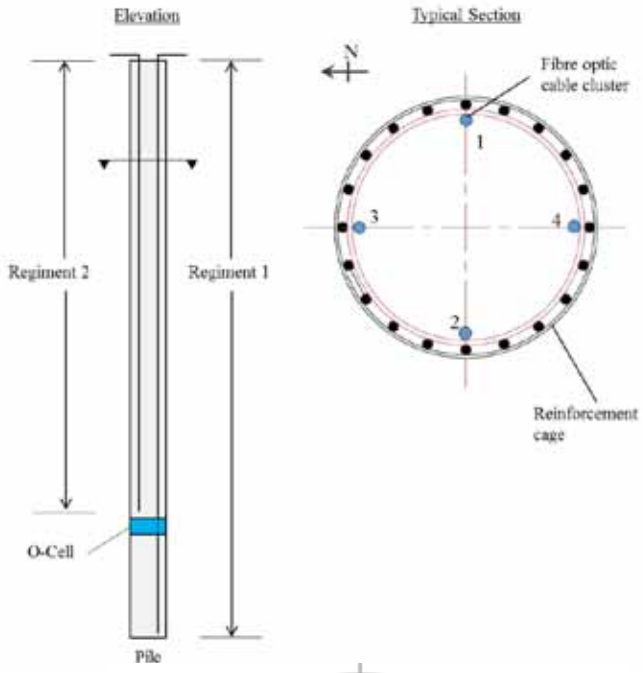


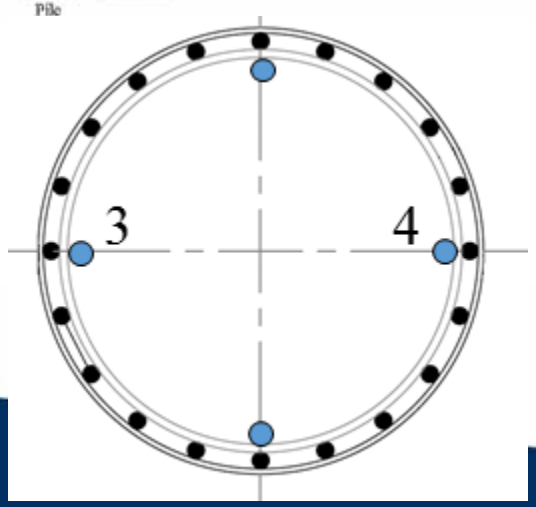




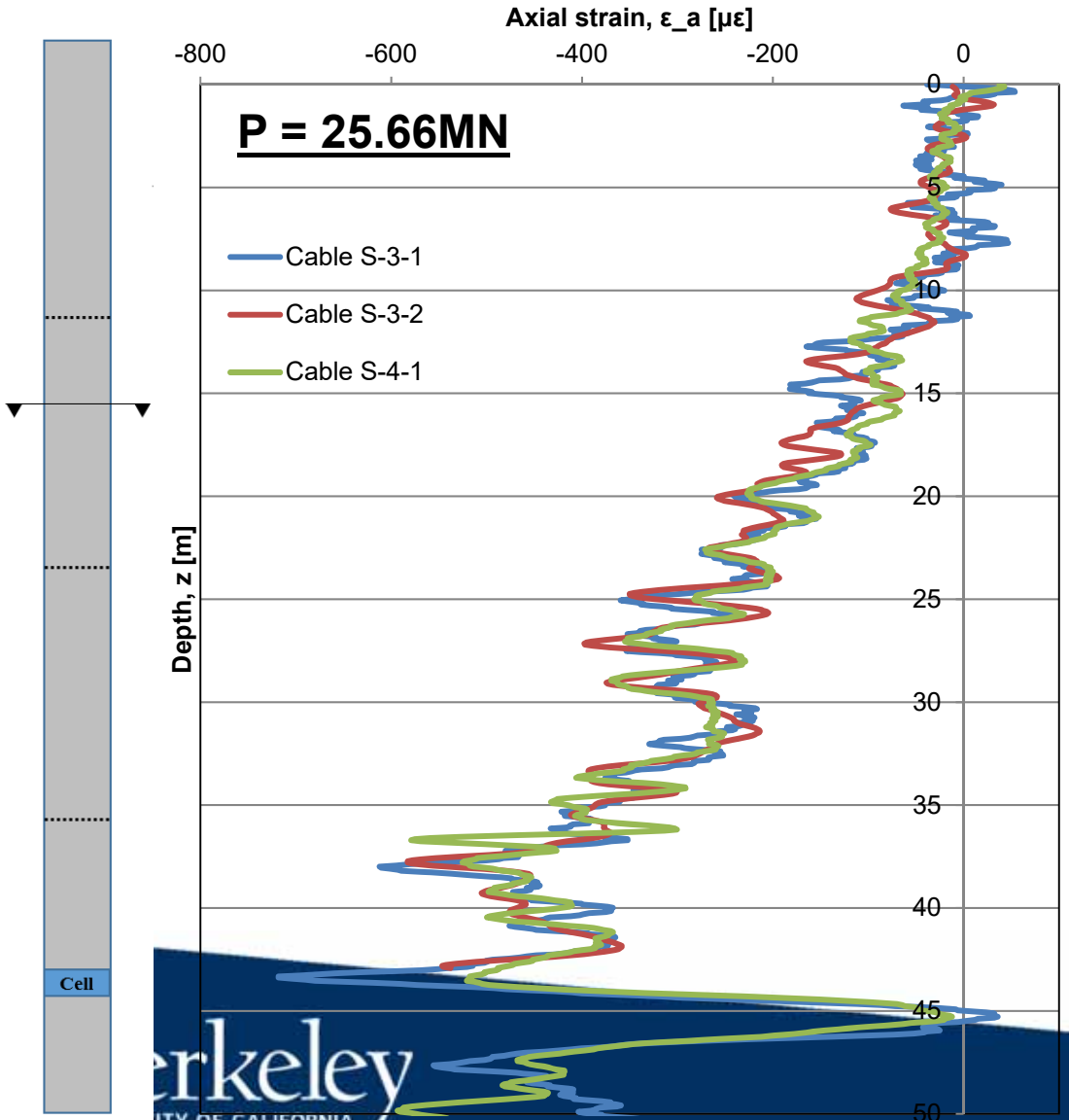
Axial strain
Different FO cable comparison

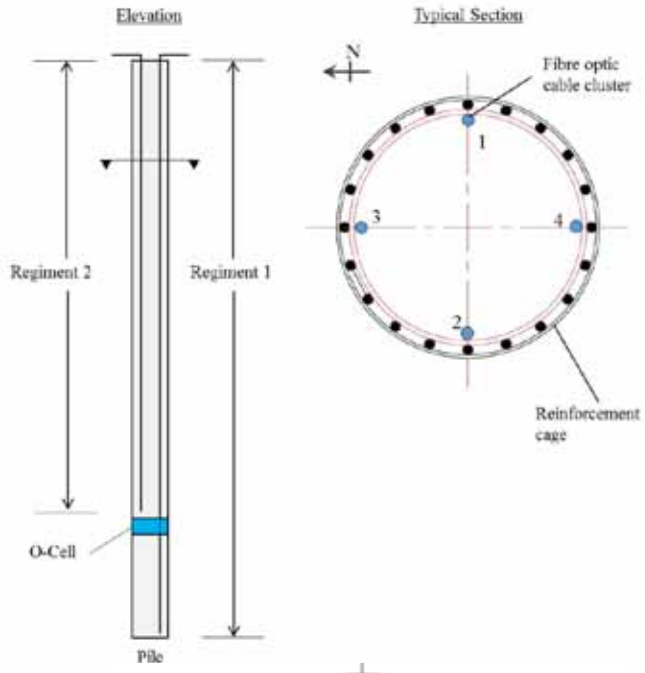


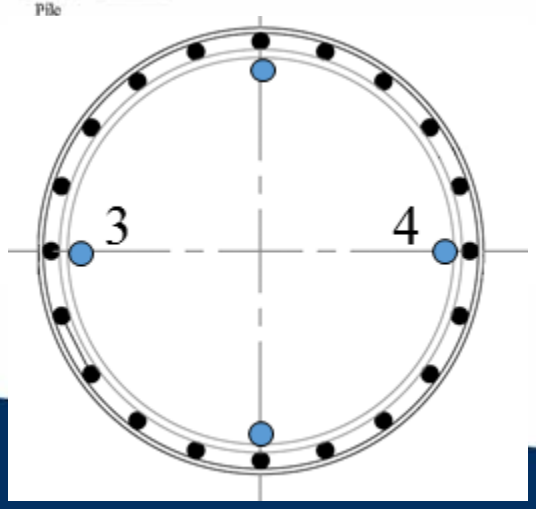




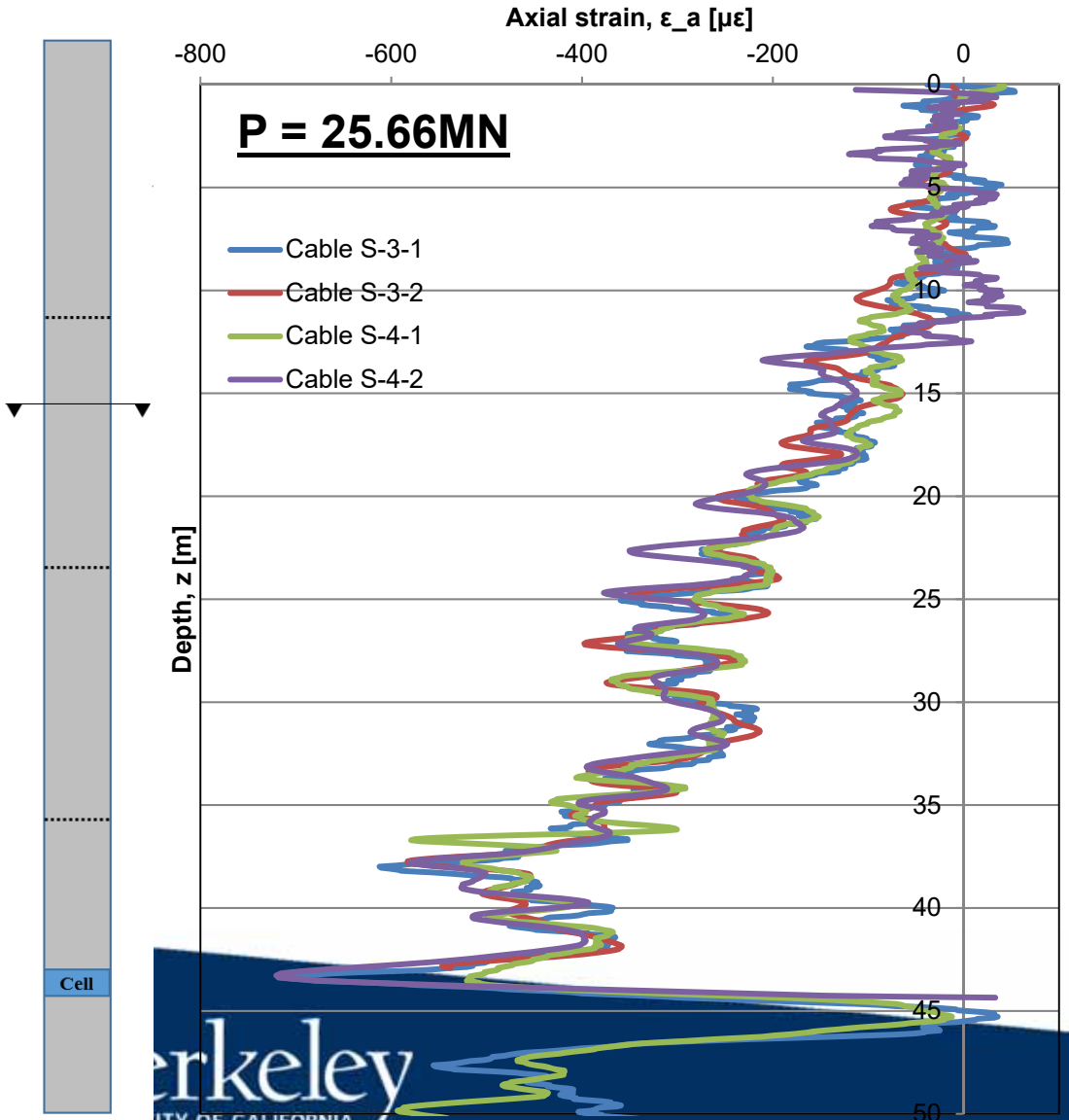
Axial strain
Different FO cable comparison

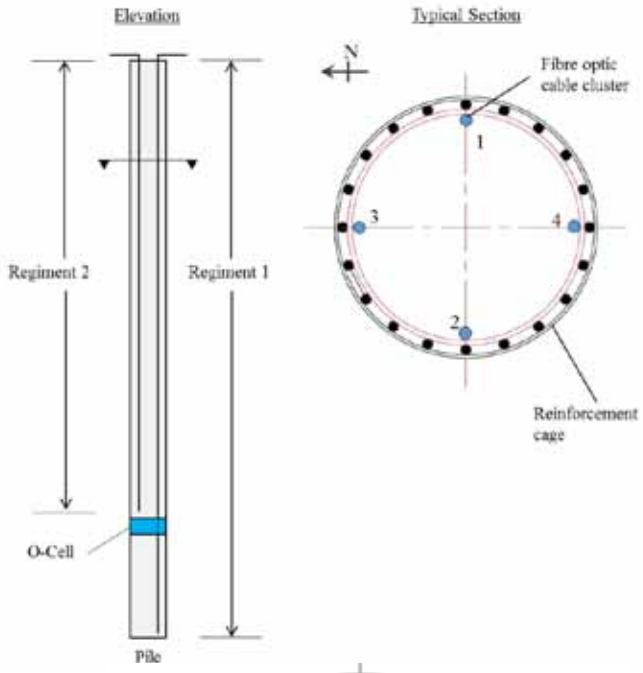


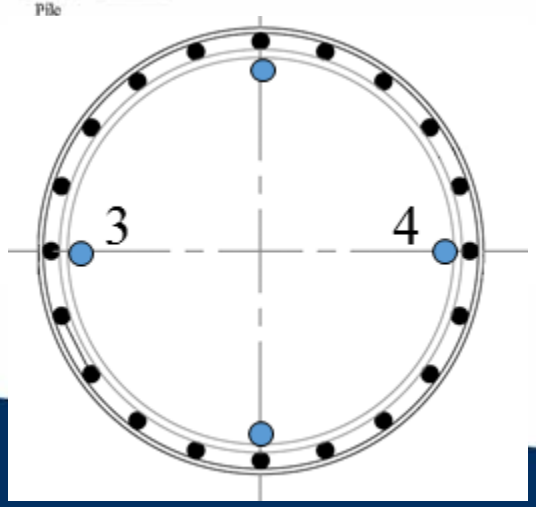




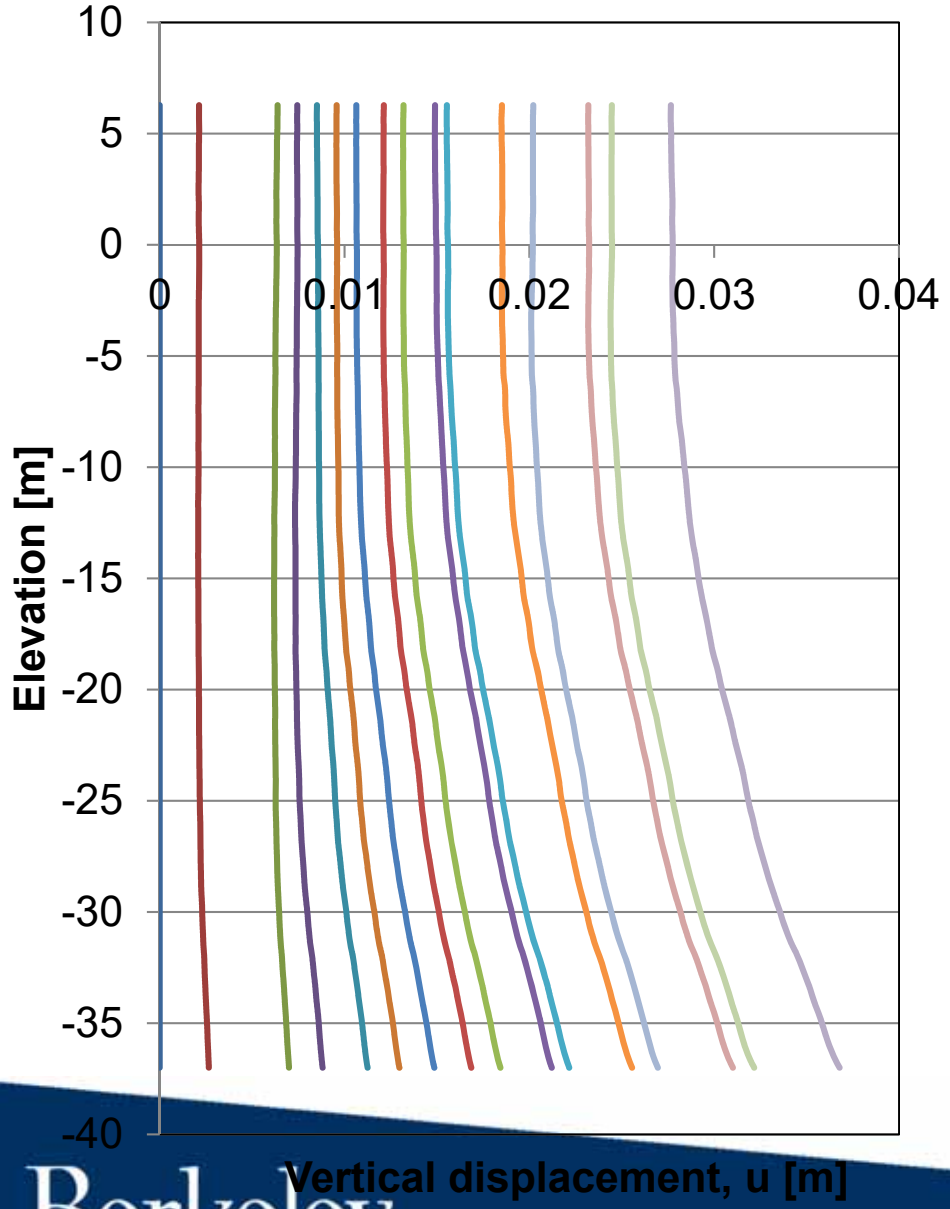
Axial strain
Different FO cable comparison

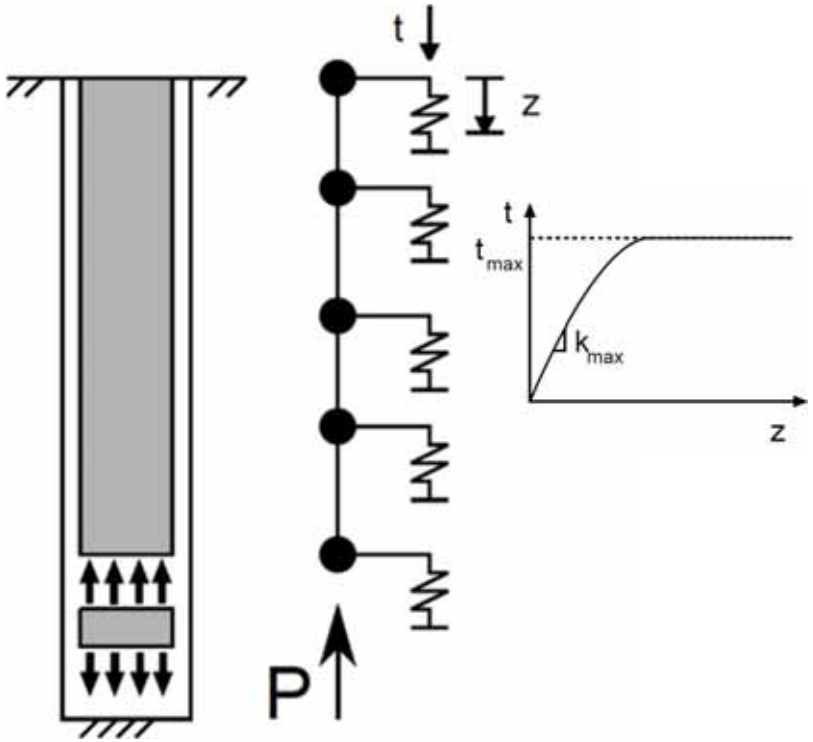




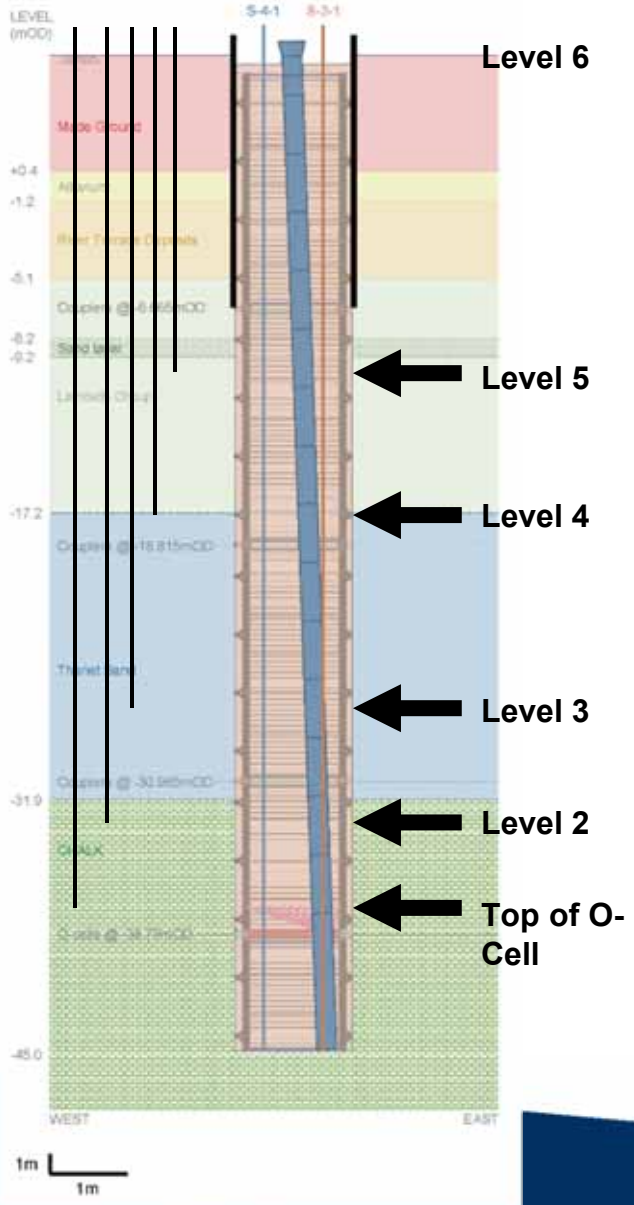


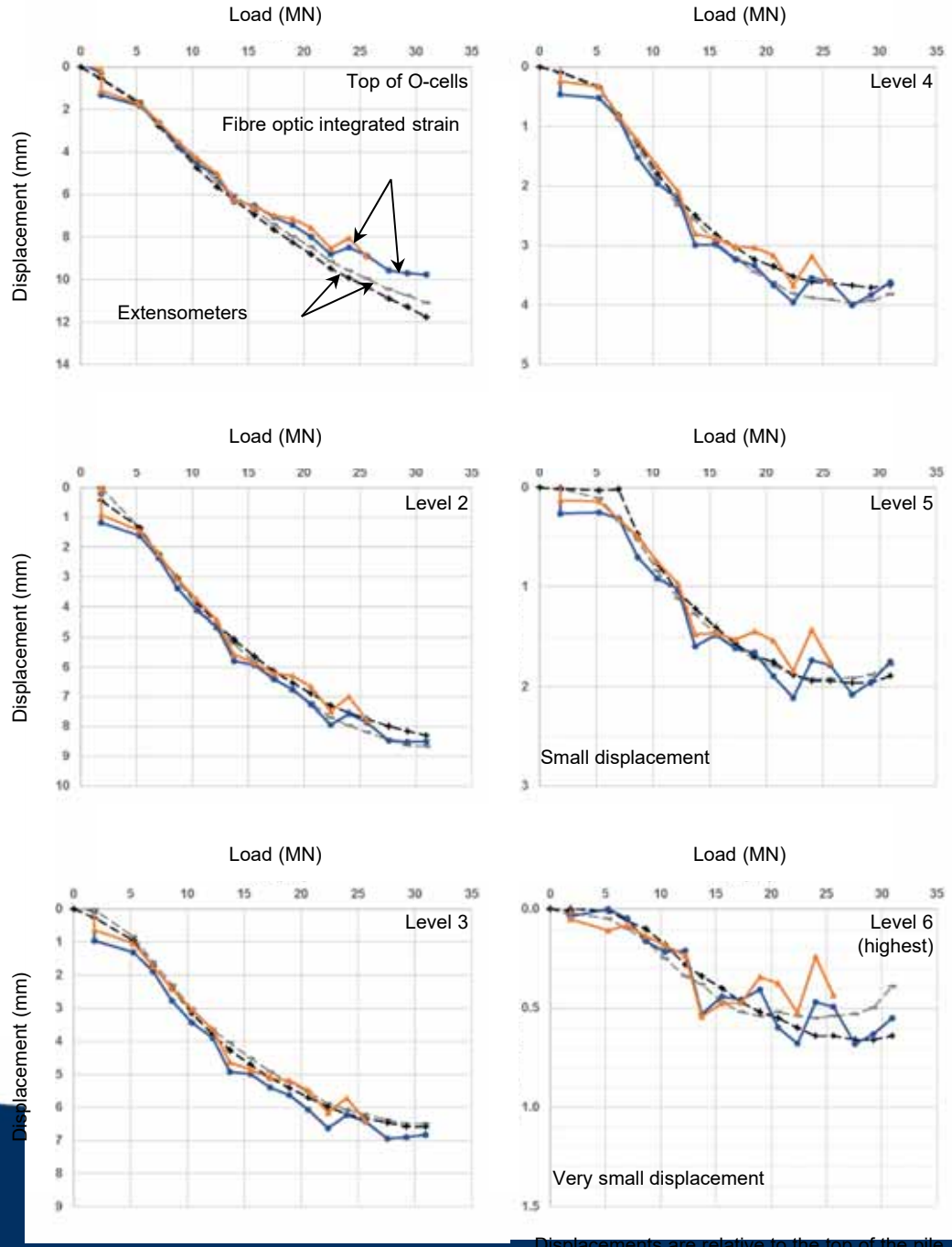
Vertical Displacement Profiles

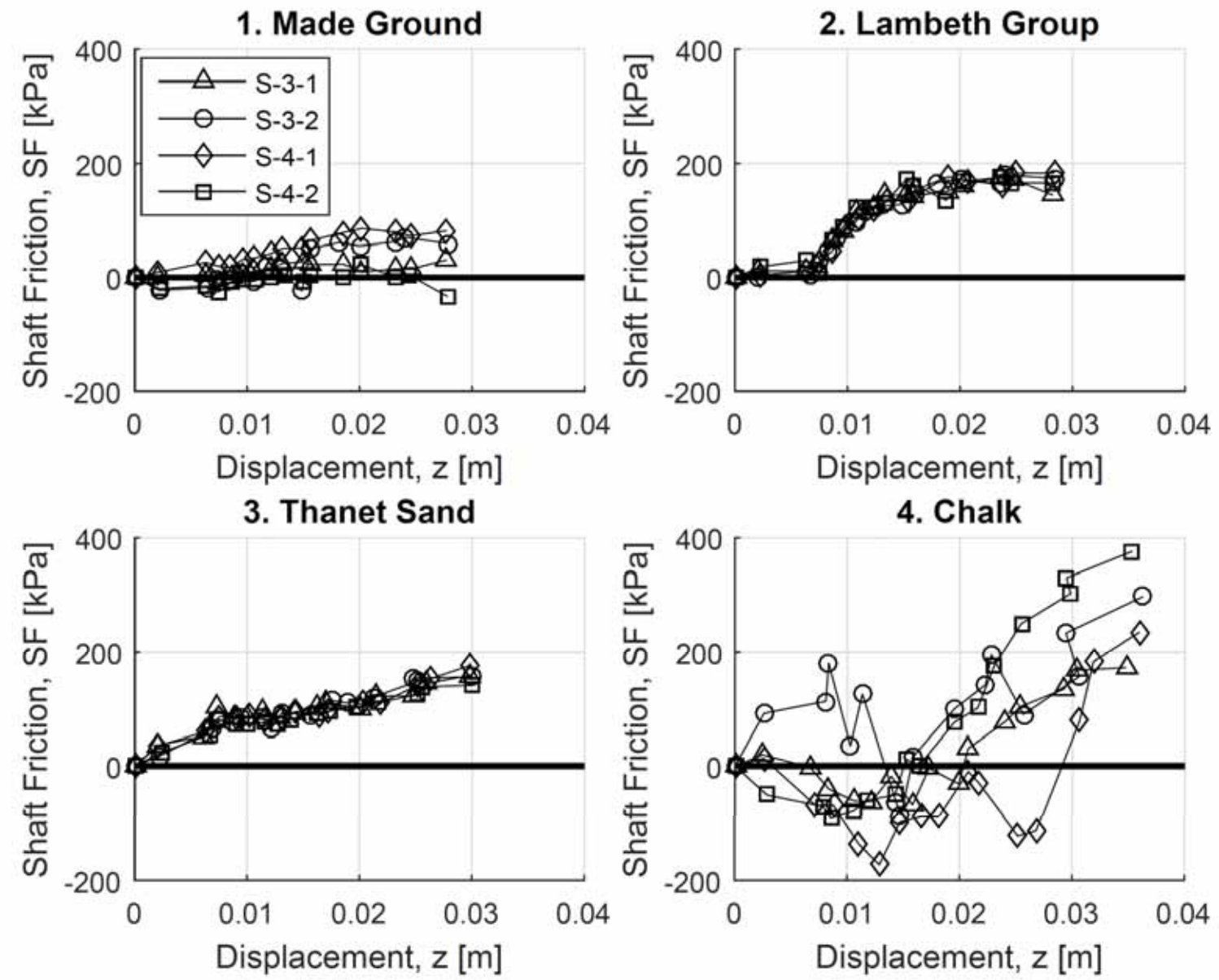




Extensometer







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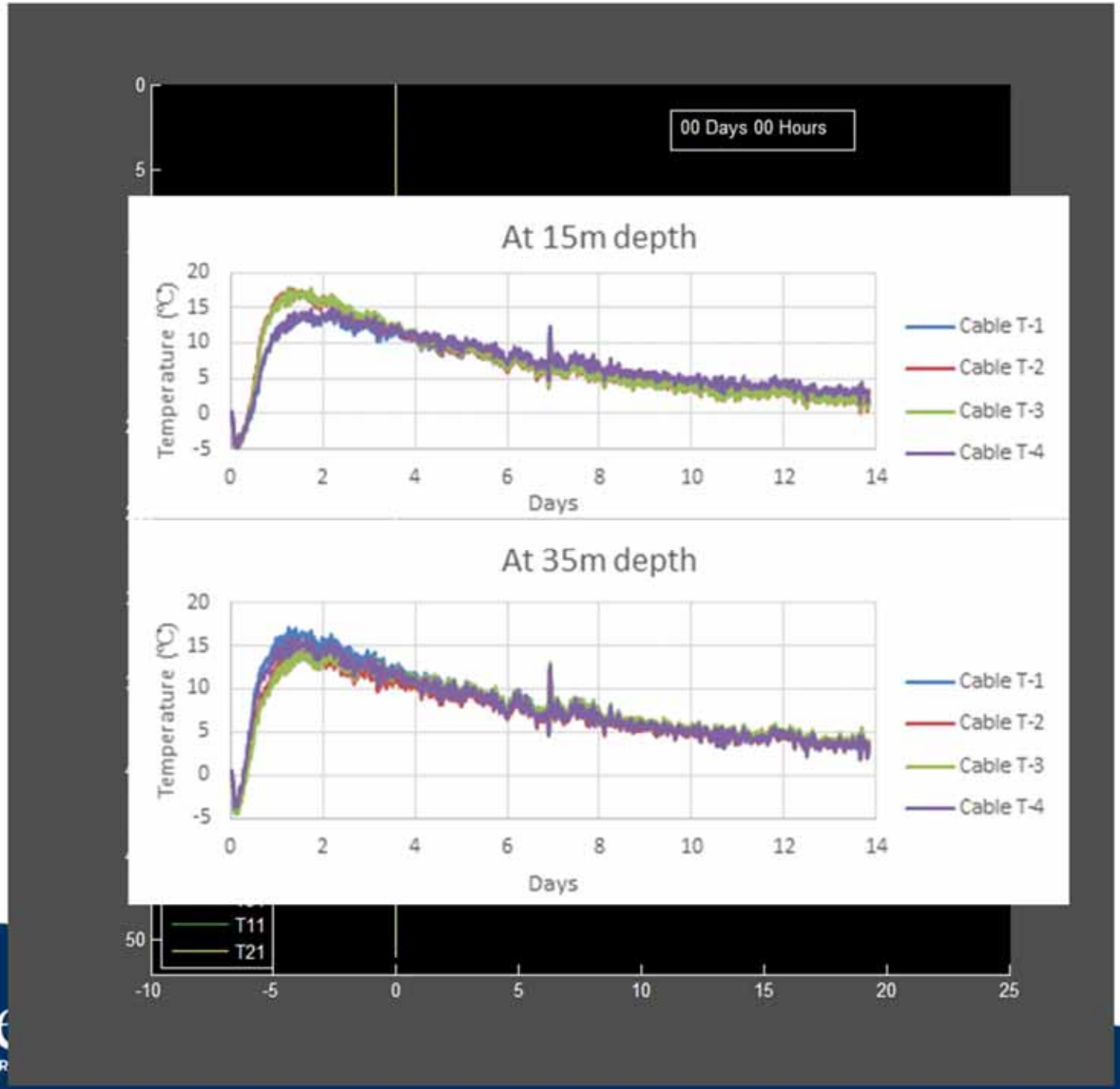
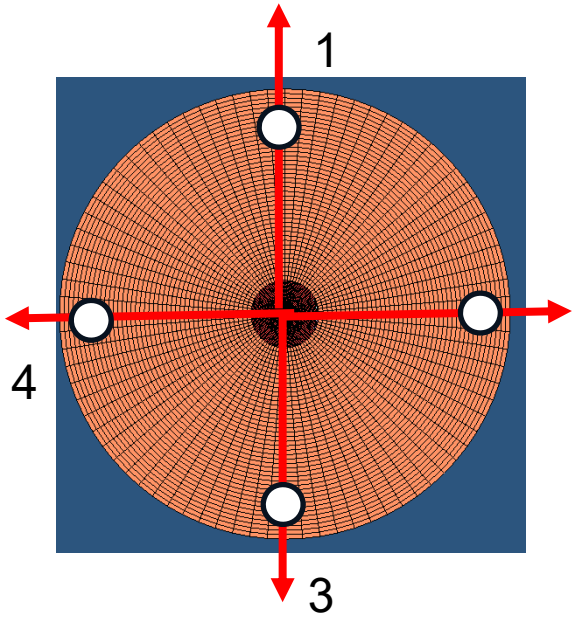
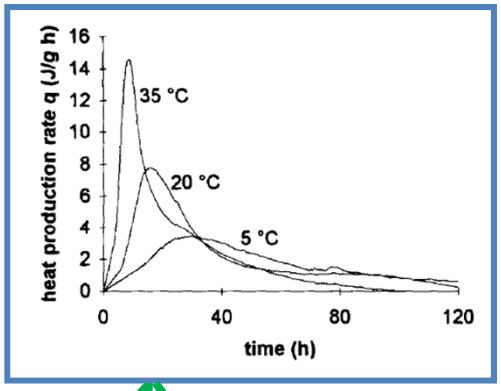
PROBLEMS WITH PILE CONSTRUCTION

- ✓ 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.

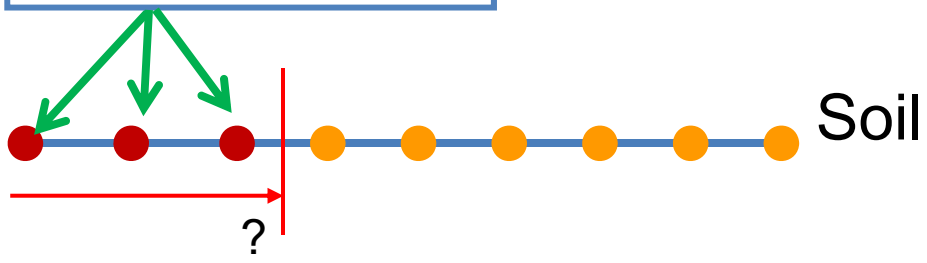

00 Days 00 Hours
At 15m depth
Temperature (°C)
Days
Cable T-1
Cable T-2
Cable T-3
Cable T-4
At 35m depth
Temperature (°C)
Days
Cable T-1
Cable T-2
Cable T-3
Cable T-4
T11
T21



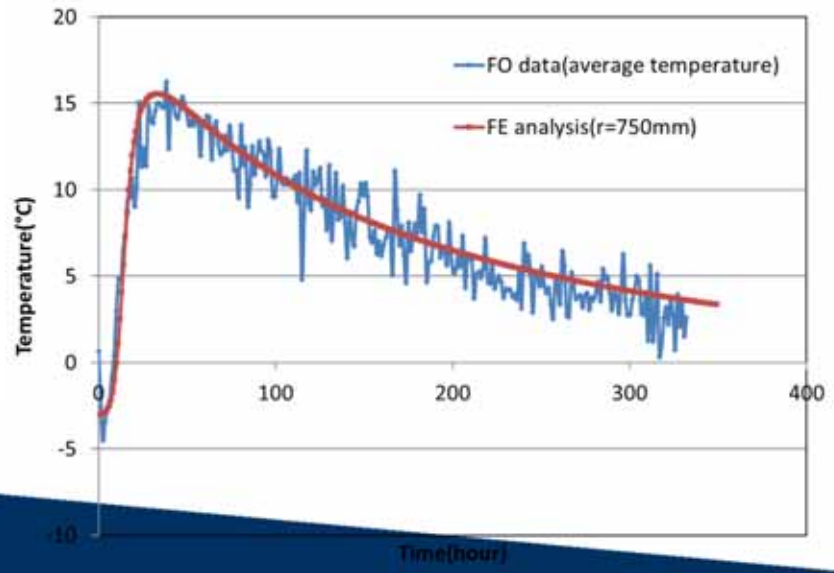


Source of concrete heating

2



Find the pile radius which match the temperature profile (20 x 4 x 50 = 4000 data sets)



Rui Yi Cedric Kechvarzi

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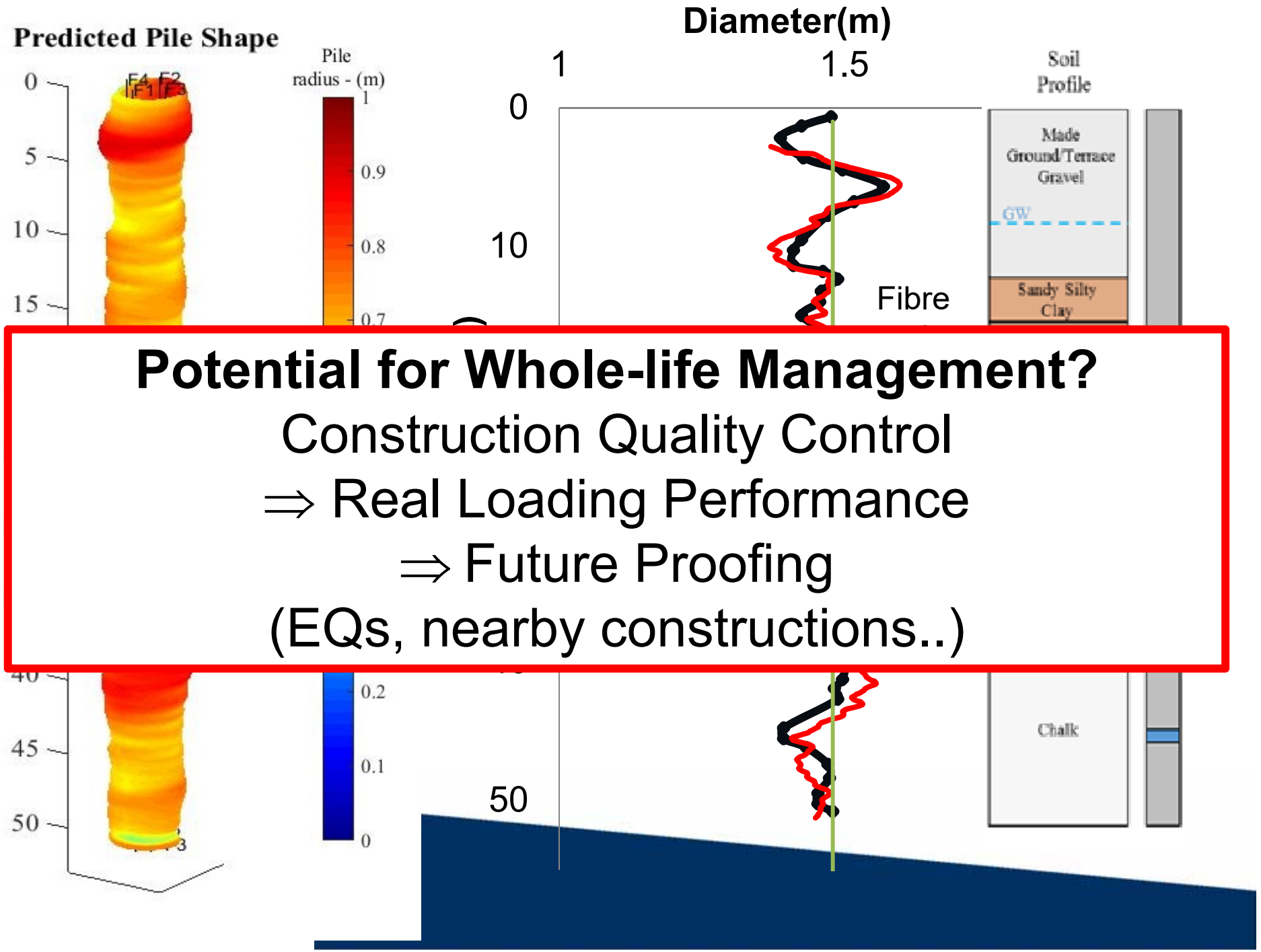


Potential for Whole-life Management?

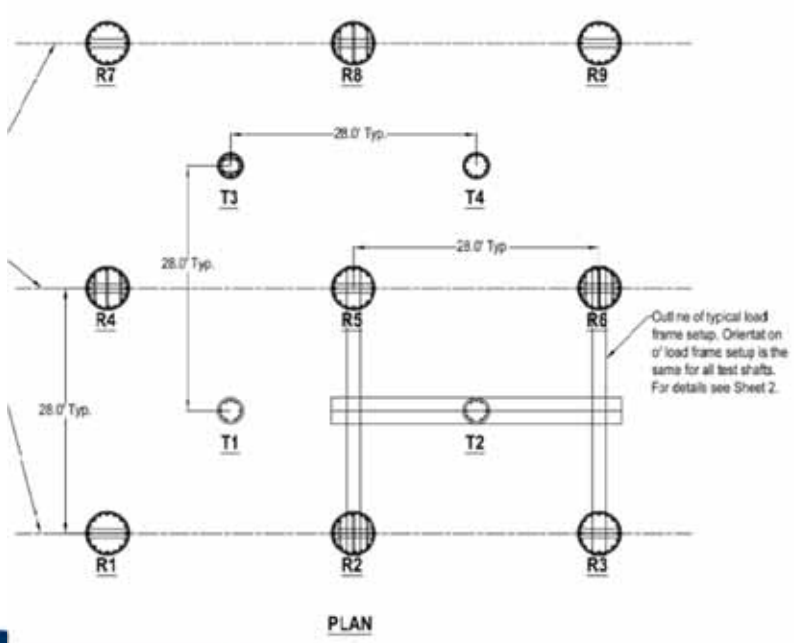
Construction Quality Control

$\Rightarrow$ Real Loading Performance

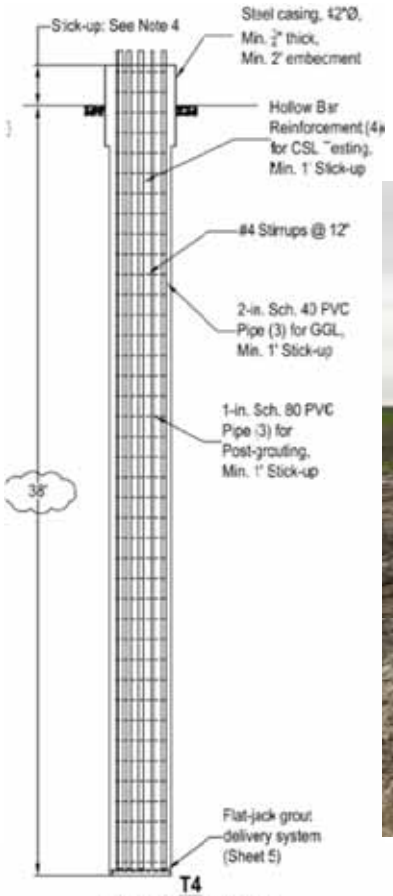
$\Rightarrow$ Future Proofing

(EQs, nearby constructions..)

Deployment of Post Grouting Technique to improve Drilled Shaft End-Bearing Resistance



PLAN



Post-grouted Shaft: Flat-jack System

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Abbey Mills Shaft
Fibre Optics Monitoring

Tina Schwamb

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Thames Water

Lee Tunnel
Creating a cleaner, healthier River Thames

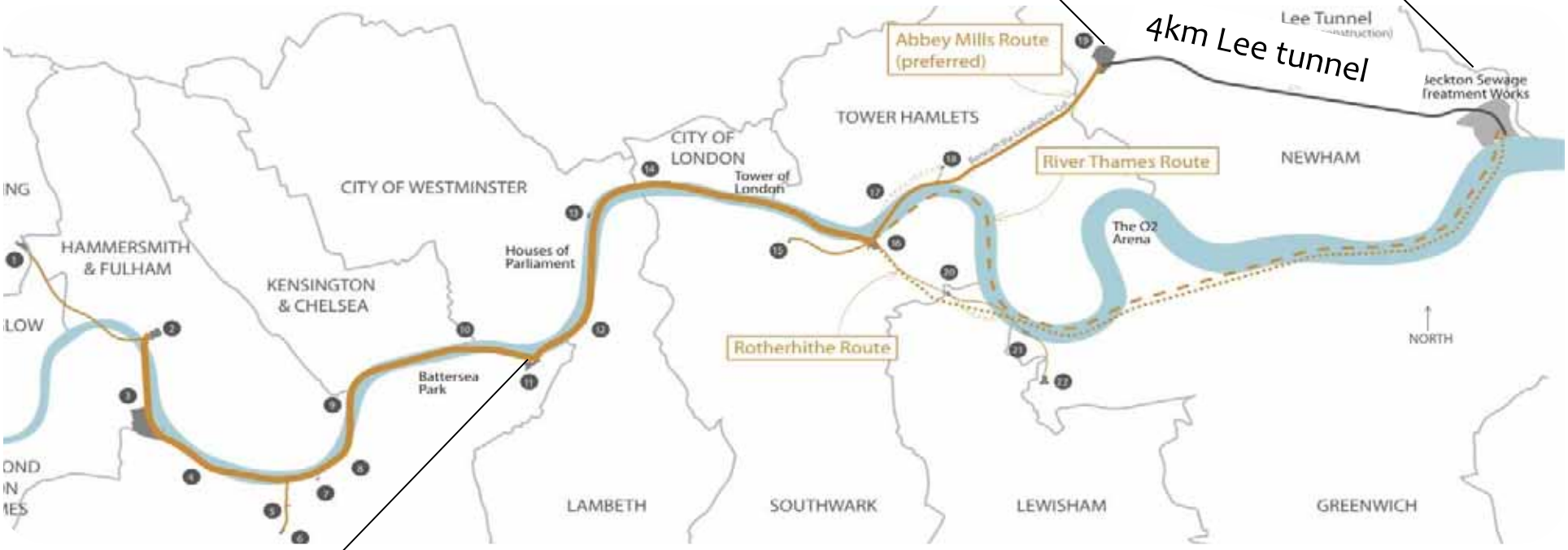
mvb

Engineering and Physical Sciences Research Council

Innovate UK
Technology Strategy Board

Abbey Mills Pumping station
(Captures 39 million tonnes of sewage a year)

Beckton sewage treatment plant



Thames Tunnel

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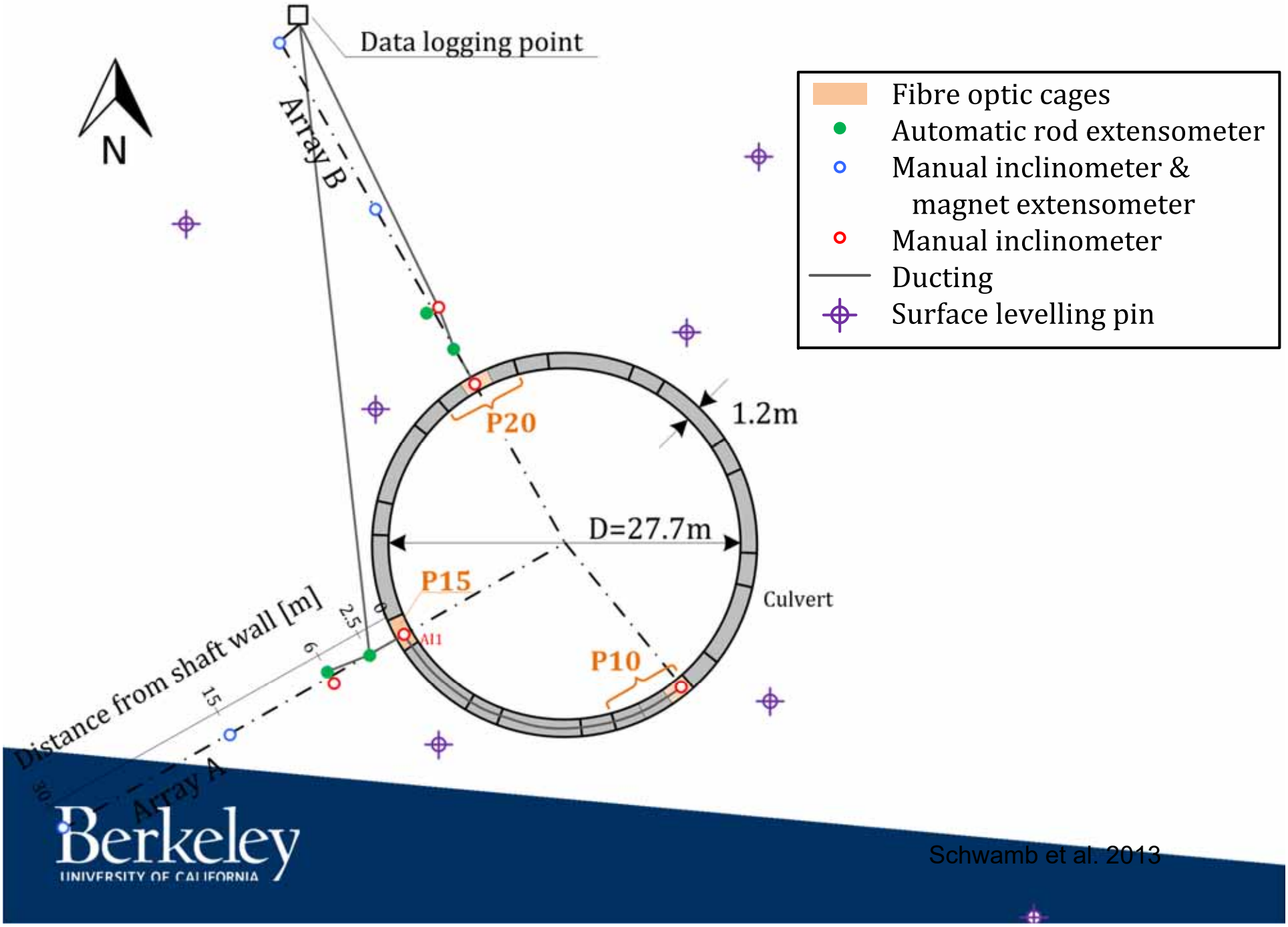
(Schwamb et al., 2014)

Shaft F Details

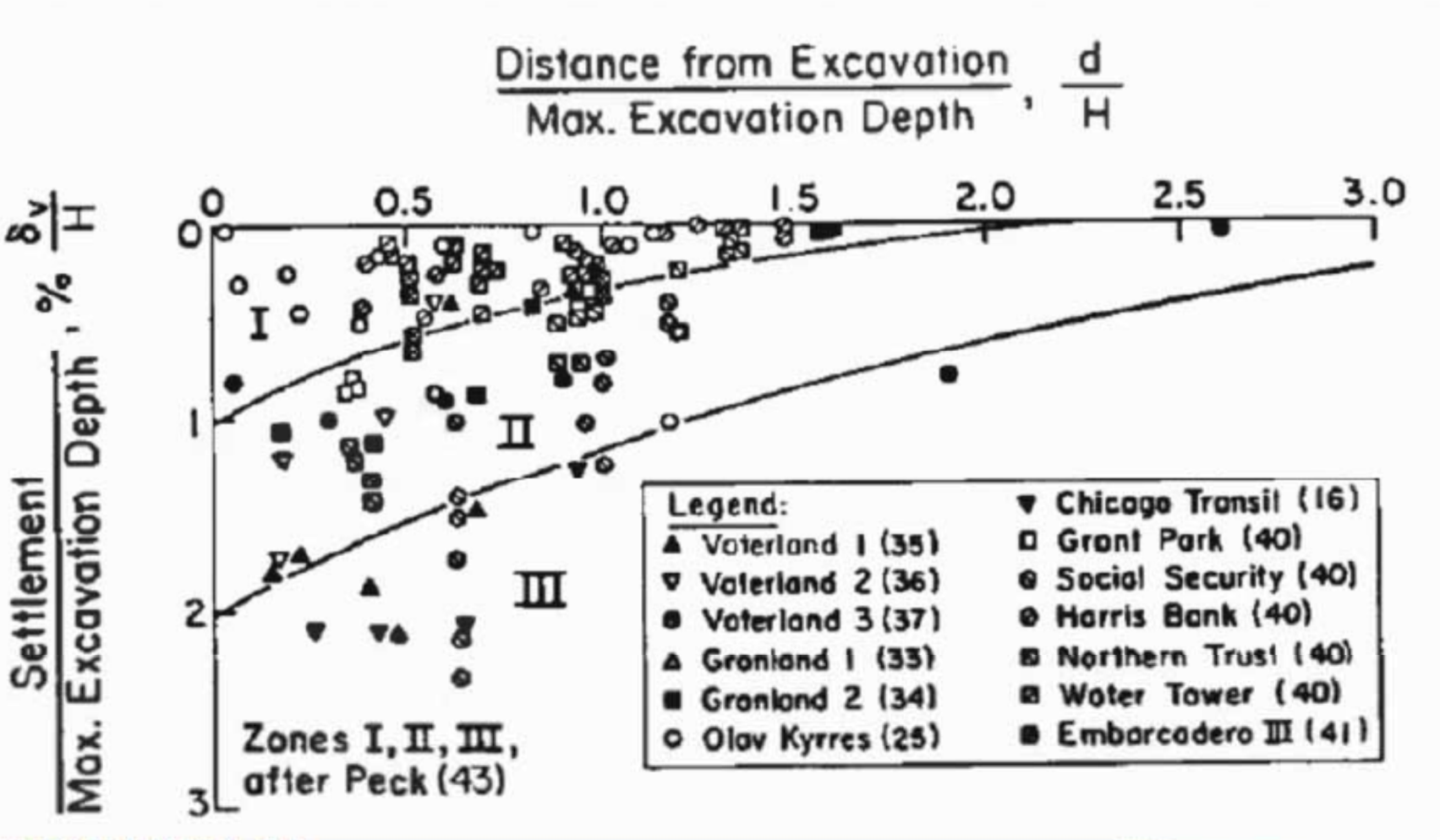
- Abbey Mills shaft:
  - 30m ext. diameter
  - 70m deep
- Diaphragm walls:
  - 20 panels
  - 1.2m thick
  - 84m deep

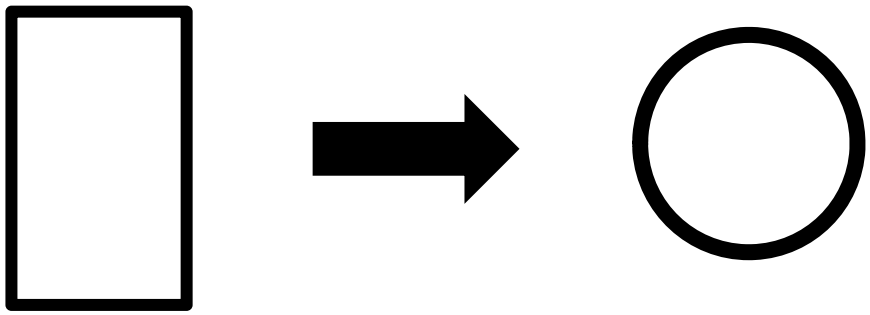


Schwamb et al. 2013

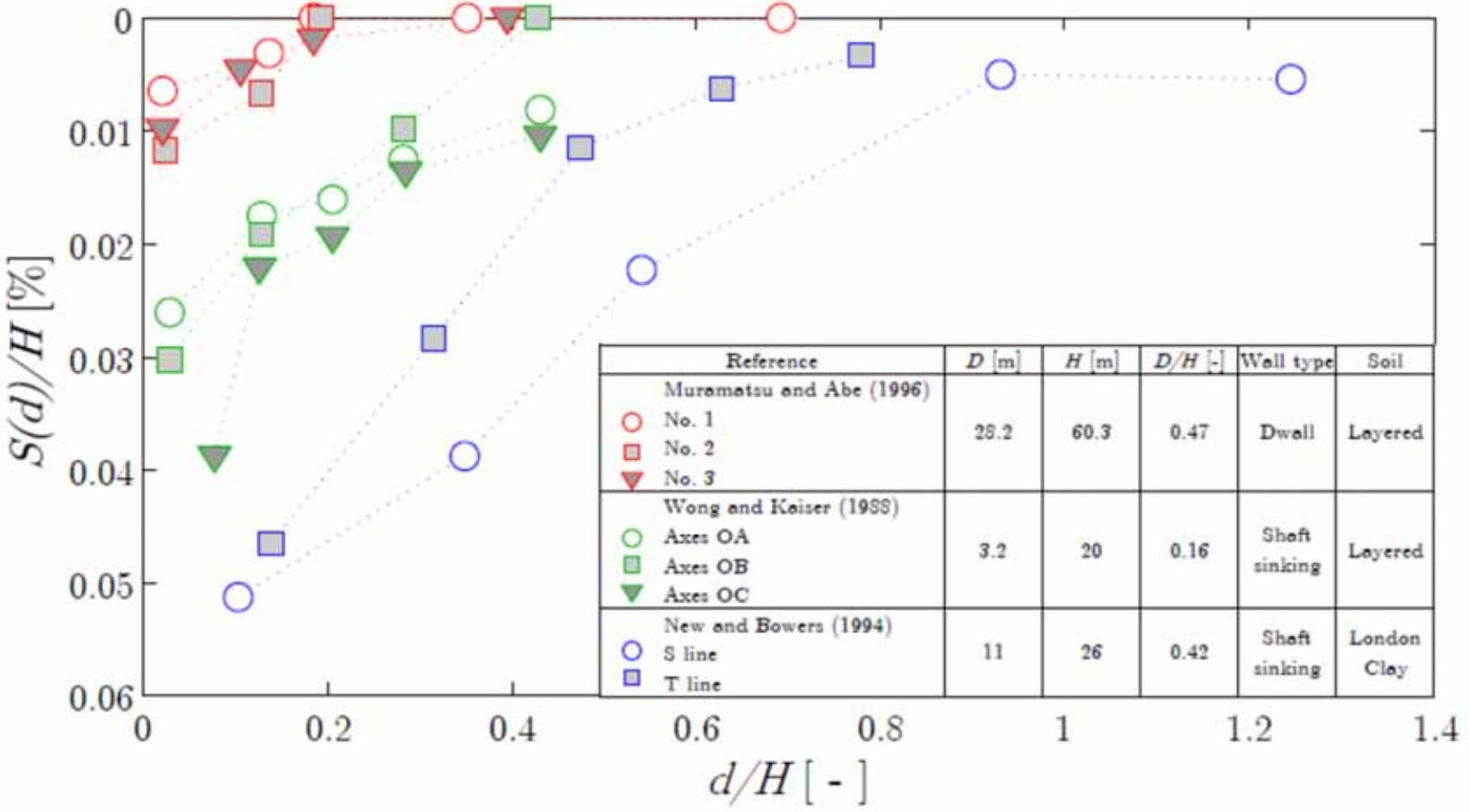
Peck (1969)

Clough and O'Rourke (1990)

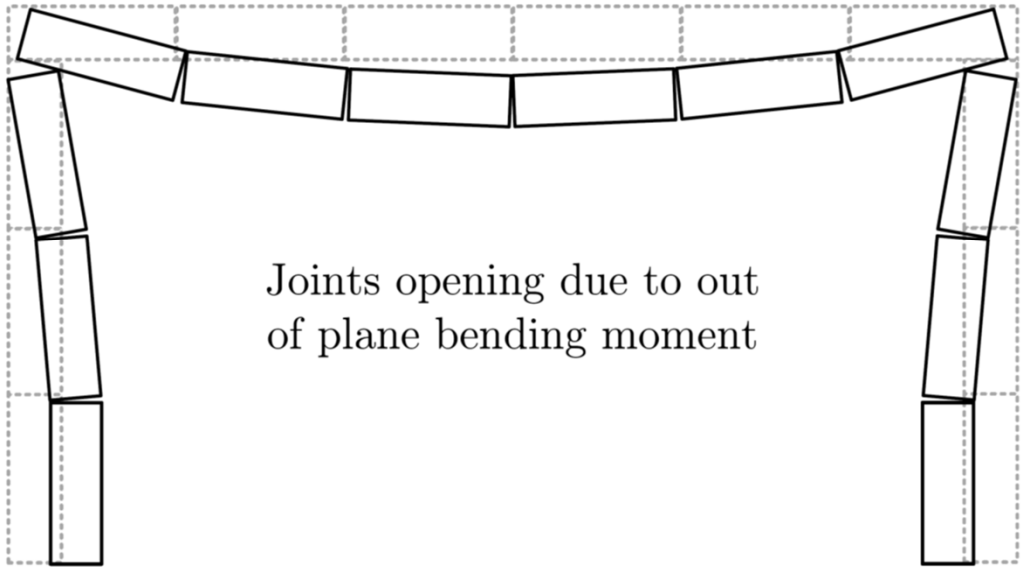


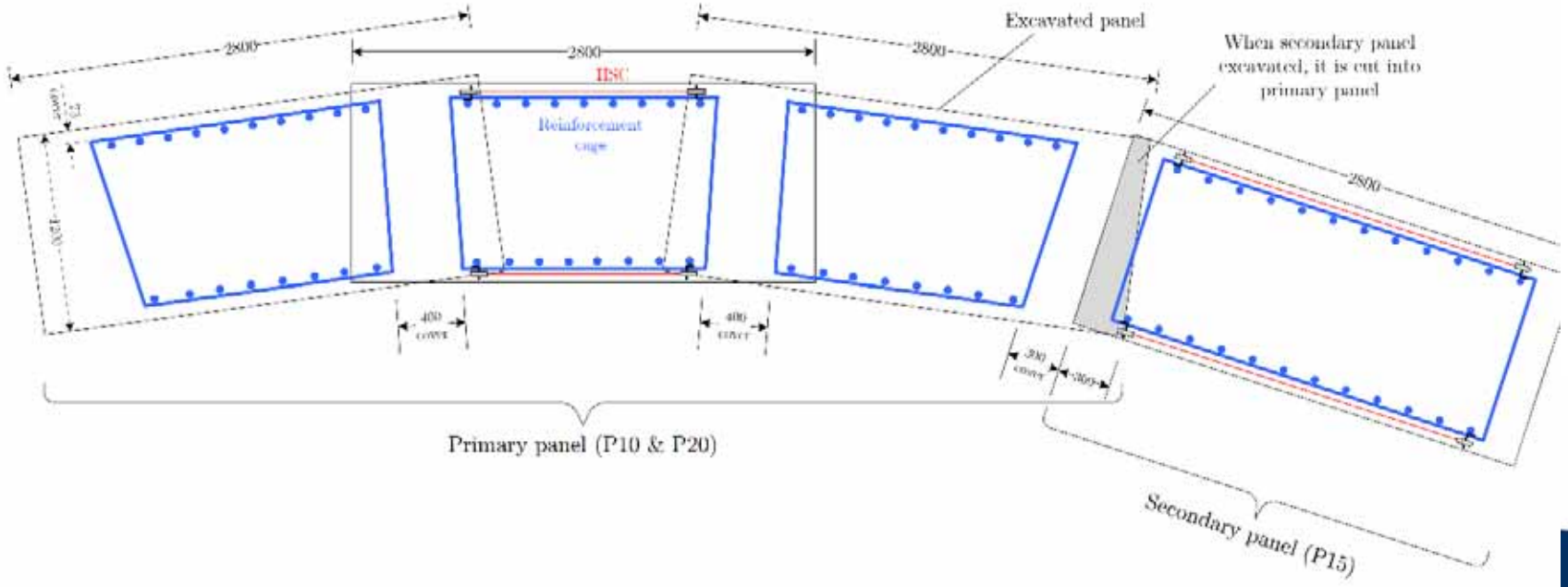


"plane strain" shafts Circular shafts



Reference	D [m]	H [m]	D/H [-]	Wall type	Soil
Muramatsu and Abe (1996) No. 1 No. 2 No. 3	28.2	60.3	0.47	Dwall	Layered
Wong and Kaiser (1988) Axes OA Axes OB Axes OC	3.2	20	0.16	Shaft sinking	Layered
New and Bowers (1994) S line T line	11	26	0.42	Shaft sinking	London Clay

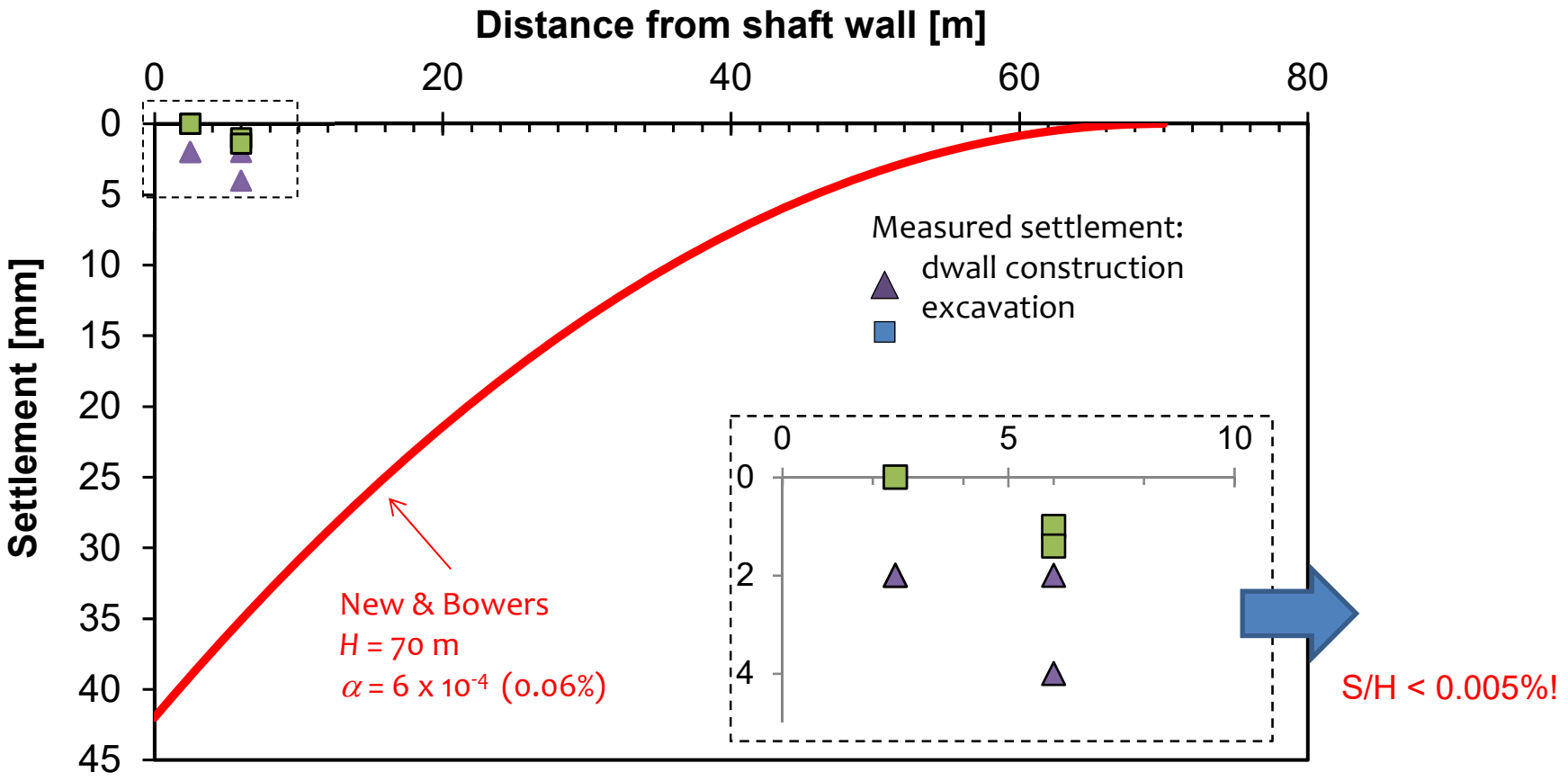

Joints opening due to out
of plane bending moment


2800
2800
2800
IBC
Reinforcement
cage
Excavated panel
When secondary panel
excavated, it is cut into
primary panel
2800
400
400
300
300
Primary panel (P10 & P20)
Secondary panel (P15)

New & Bowers (1994)
Study at Heathrow shaft of
D = 11 m, H = 26 m

$$S(d) = \frac{\alpha(H-d)^2}{H}$$

H = shaft depth
d = distance from shaft
S = settlement
α = 6 x 10^{-4} (empirical factor)



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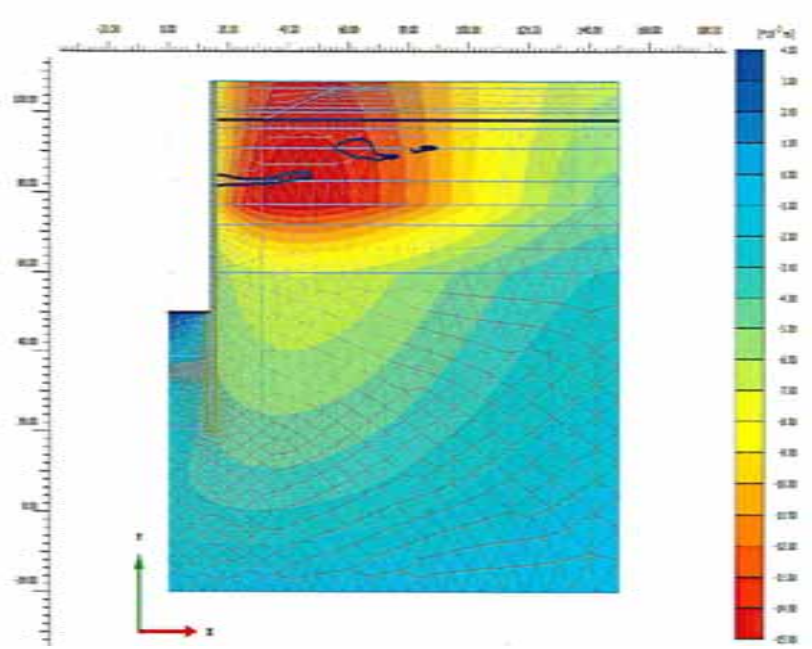
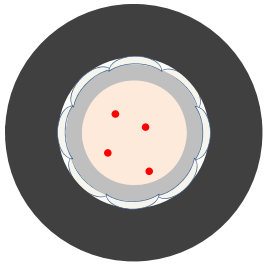
Original design considerations

- Reference Design PLAXIS analysis – 7mm
- Reference Design – modified New & Bowers – 13mm
- Hard to justify approach taken without any empirical data
- Potential cost and risk implications Tideway Tunnel

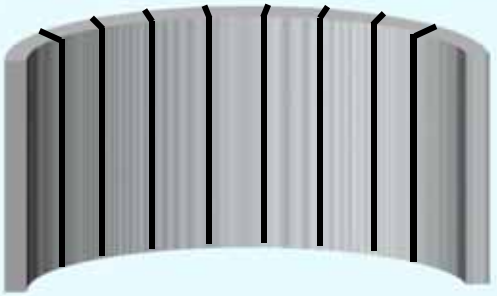


Fibre Optics Installation

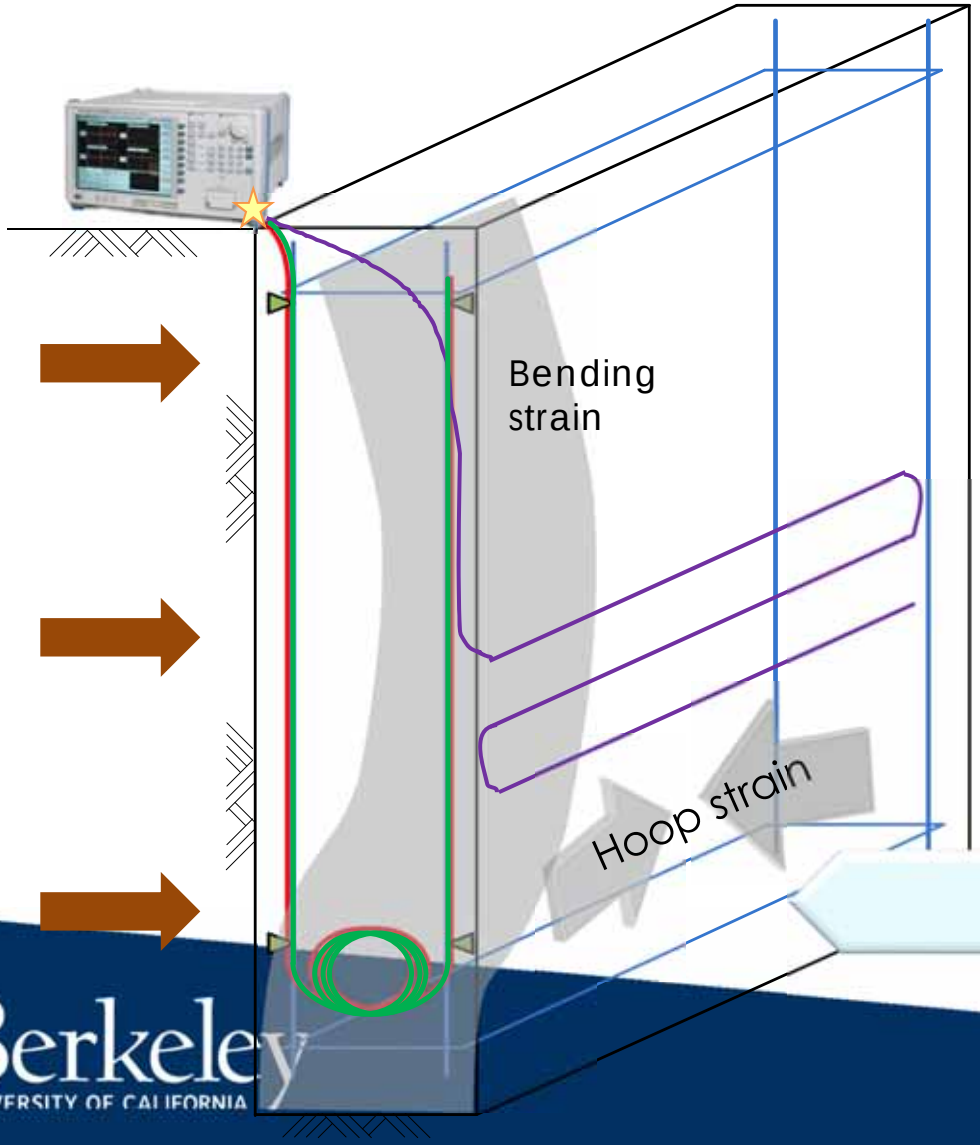
Strain cable



Temperature cable



- Diaphragm walls
- Joints between panels
- Reduced cirumferential stiffness???



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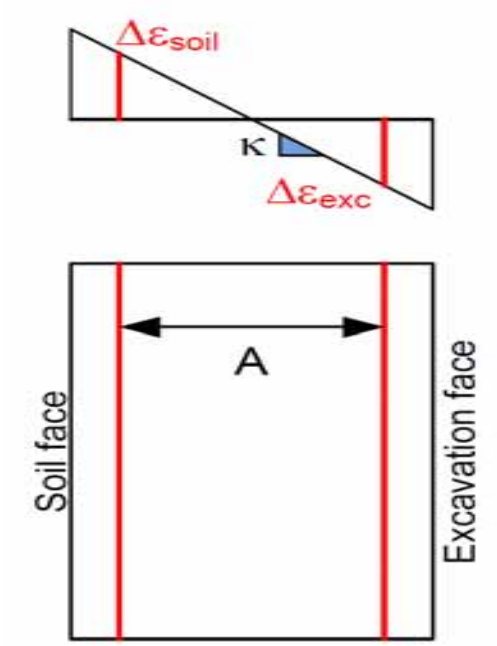
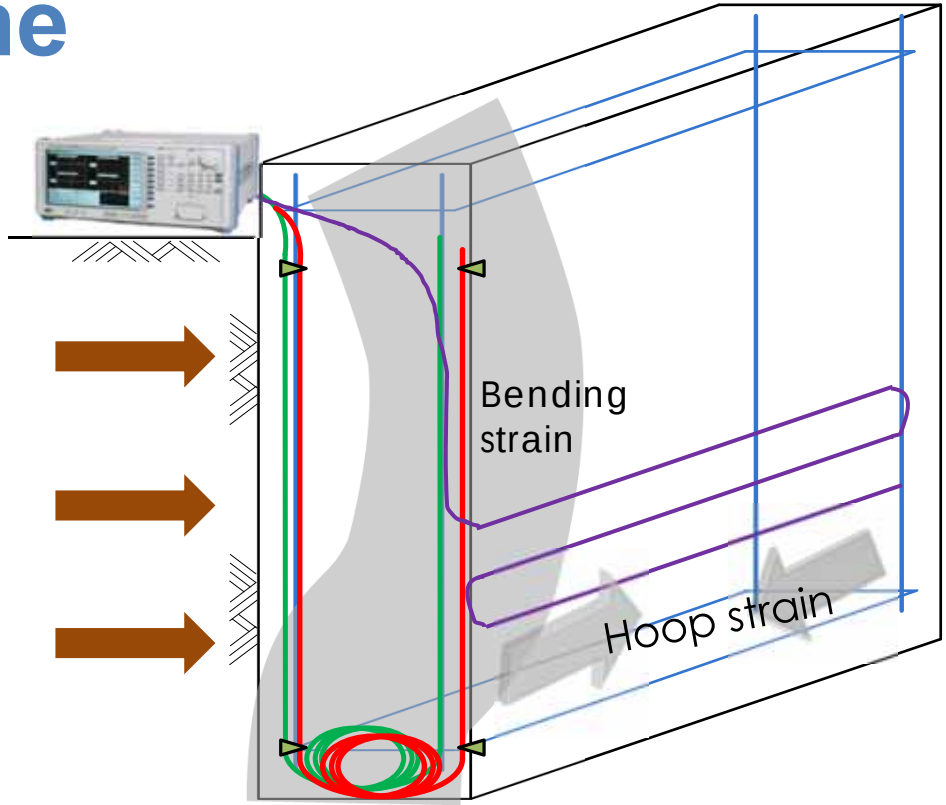
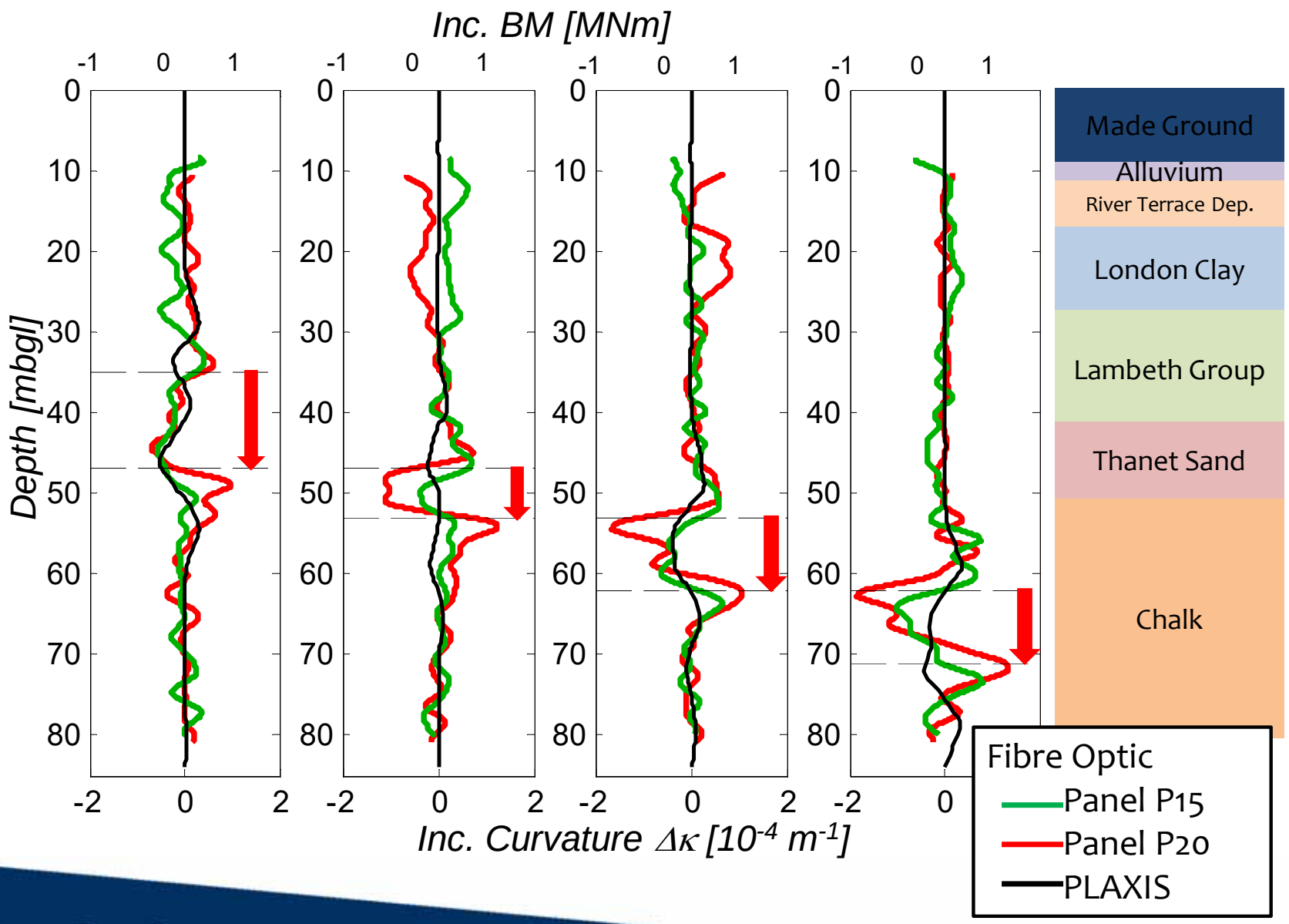
Monitoring Scheme







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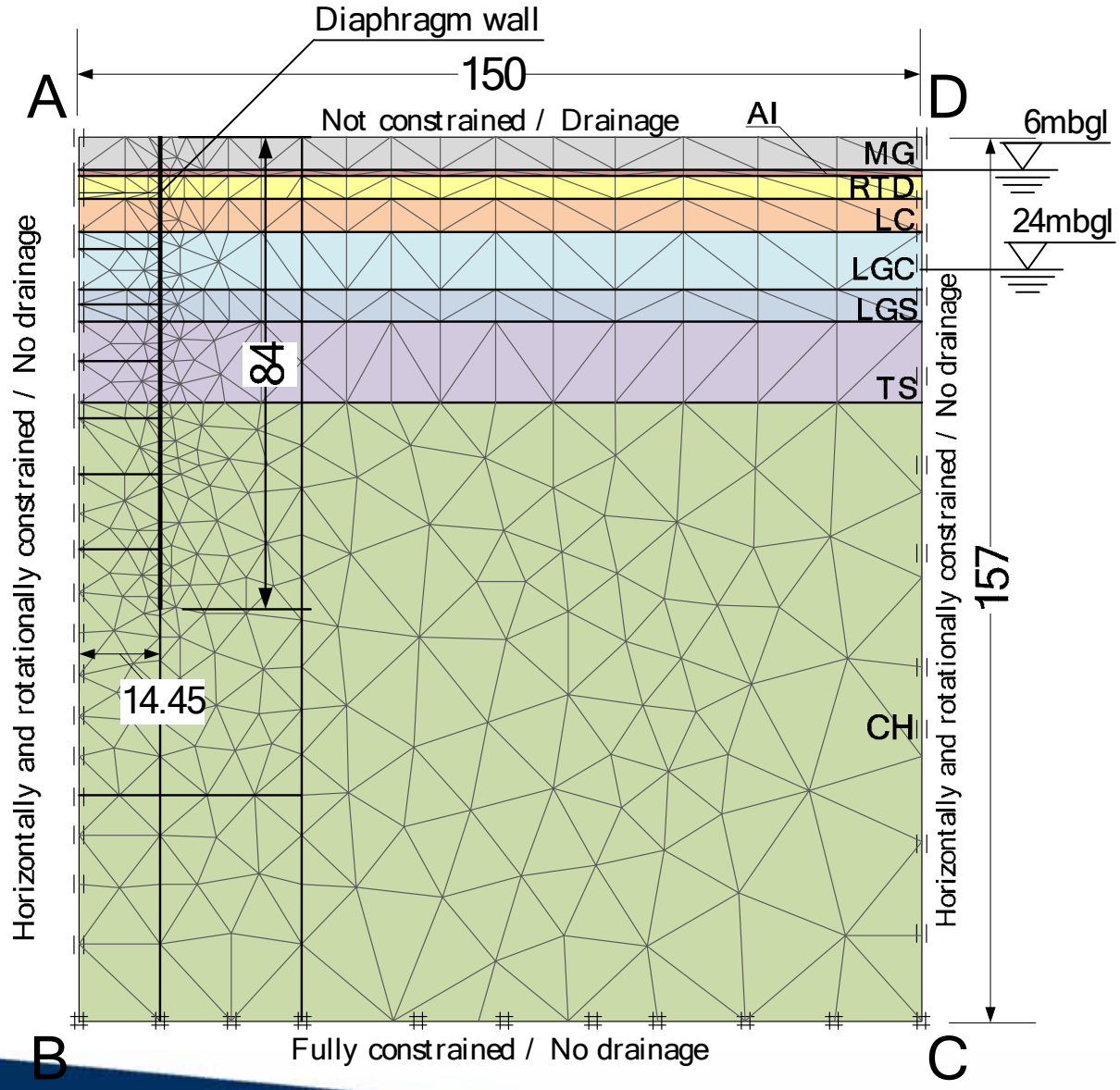

- 2D axisymmetric mode
- Mohr-Coulomb soil model
- Wall:
  - concrete C50/60
  - E = 37 GPa (short-term)
  - thickness = 1.2 m
- Wall installation effects are considered with reduced K_o values (WIP)
- For comparison use serviceability limit state (SLS) results

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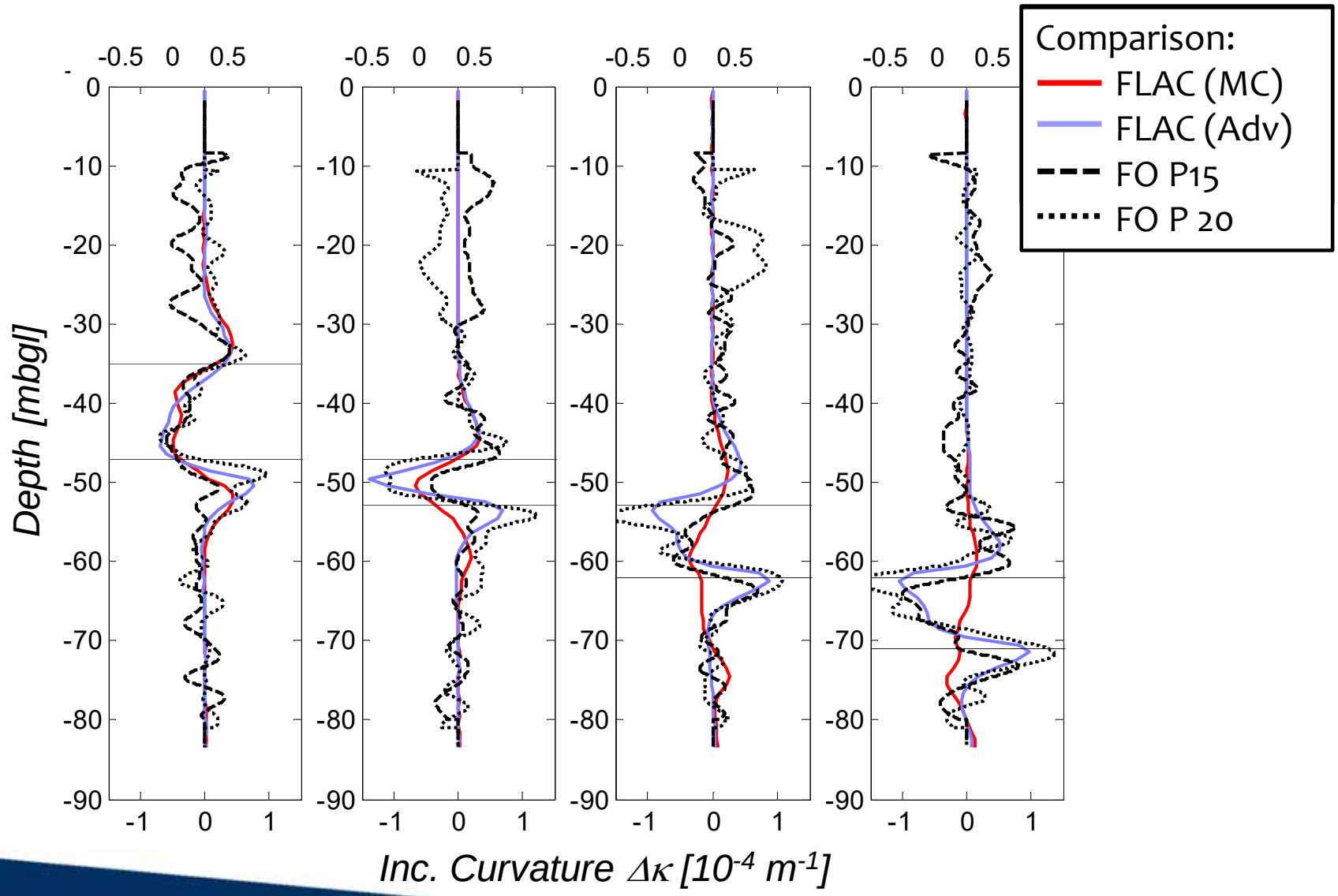

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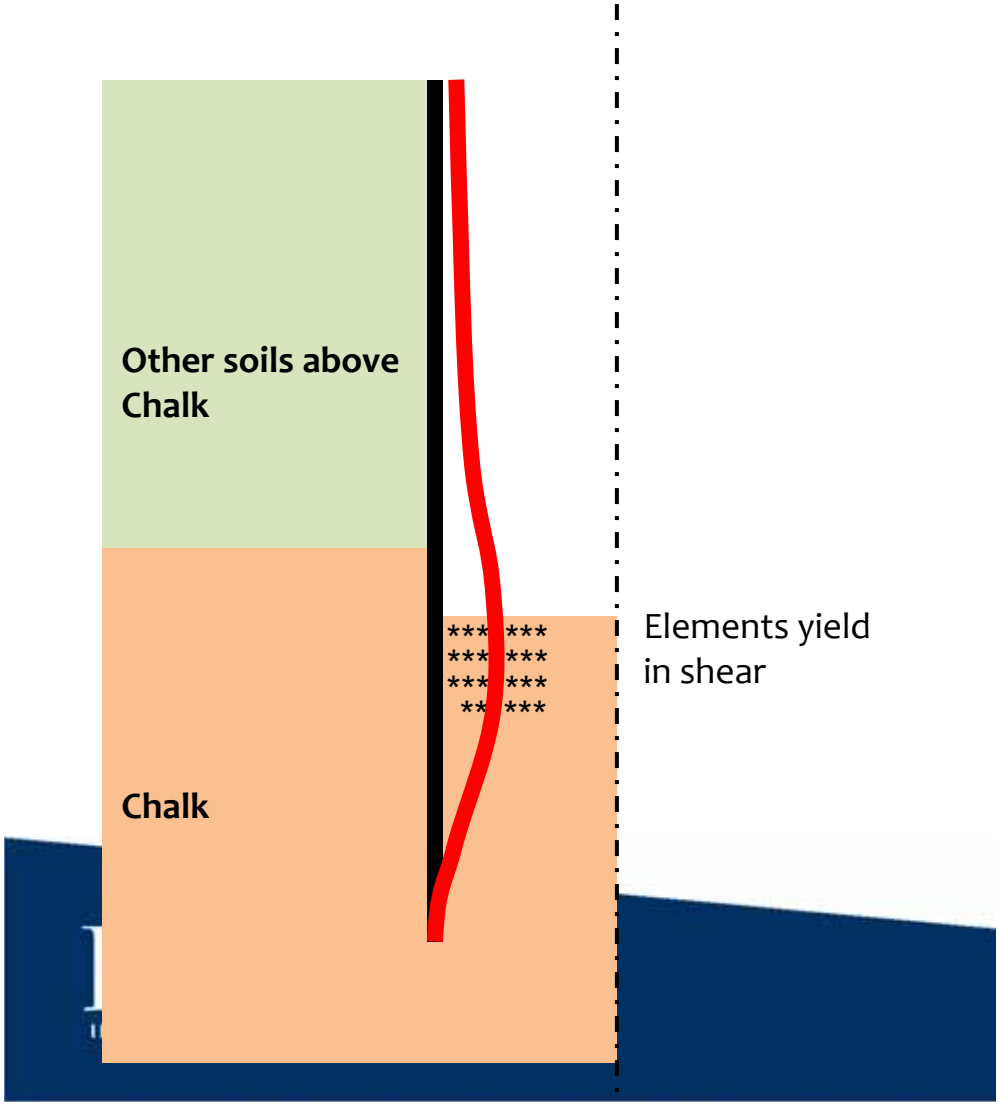
Soil models

FLAC model

Mohr Coulomb for CHALK:

K = 1000 MPa | G = 600 MPa | E = 1500 MPa

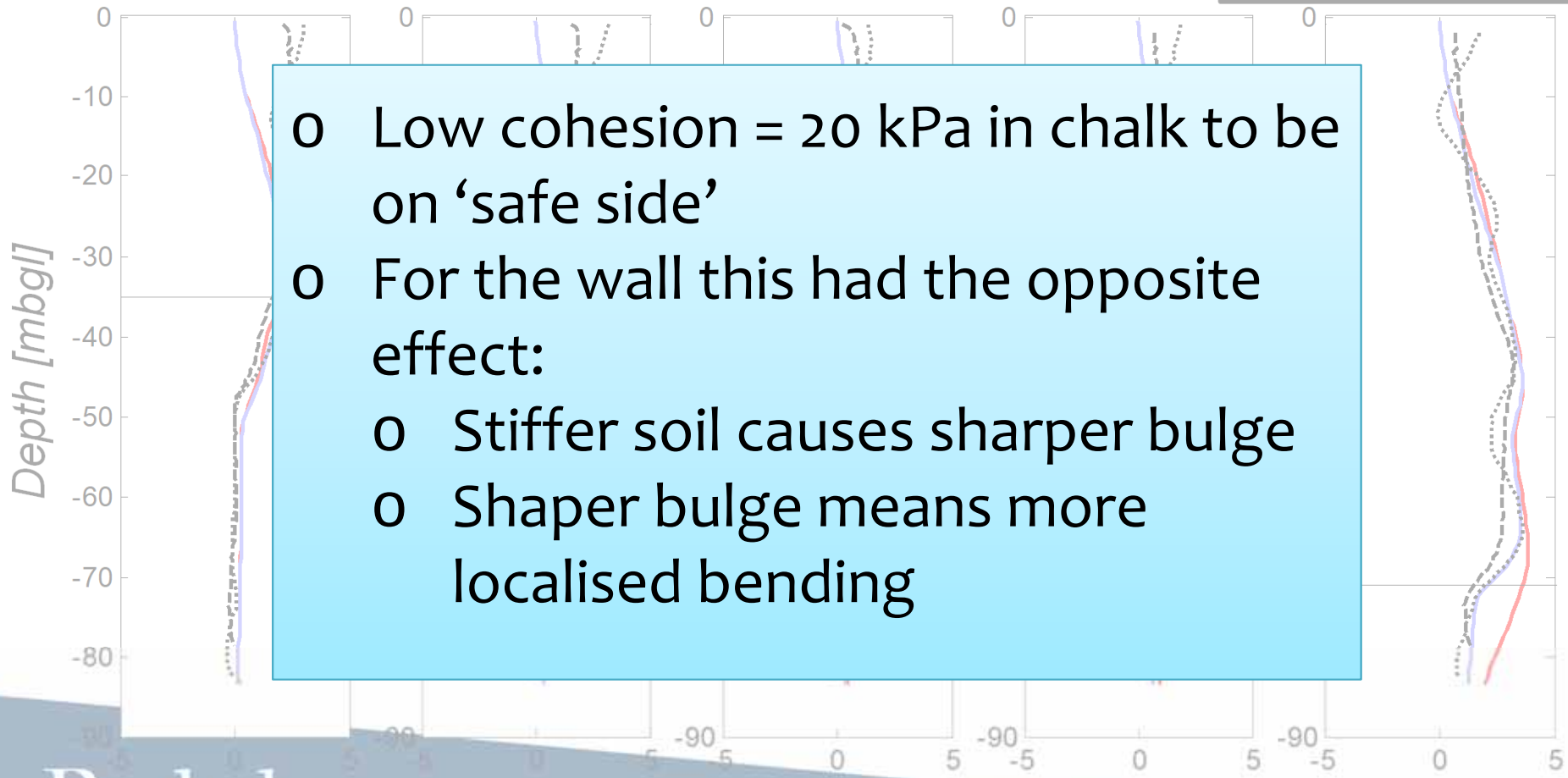
ϕ' = 35° | c' = 20 kPa



Soil models

FLAC model

Comparison:
- FLAC (MC)
- FLAC (Adv)
- Inc P10
- Inc P 20



- Low cohesion = 20 kPa in chalk to be on 'safe side'
- For the wall this had the opposite effect:
  - Stiffer soil causes sharper bulge
  - Shaper bulge means more localised bending

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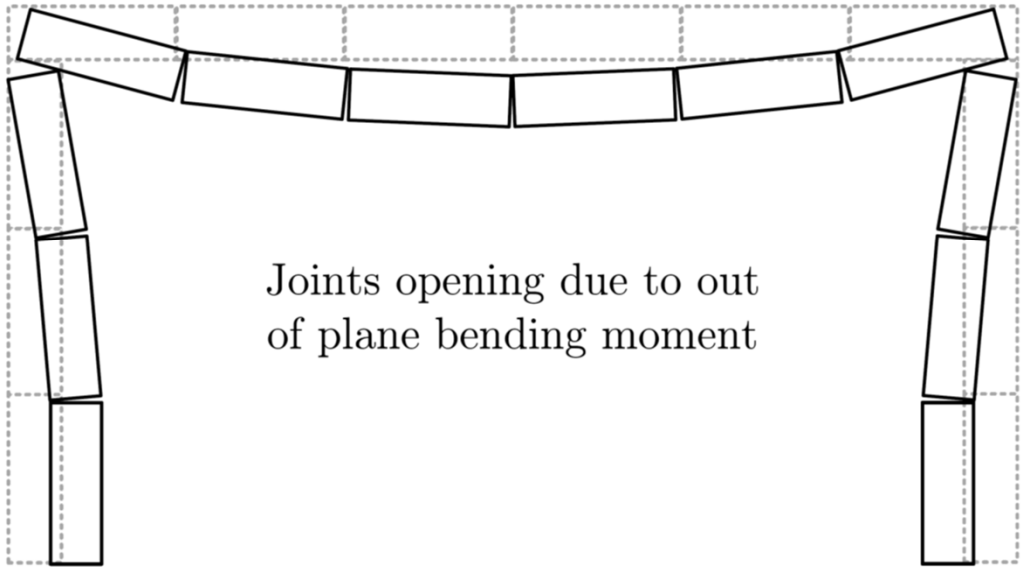
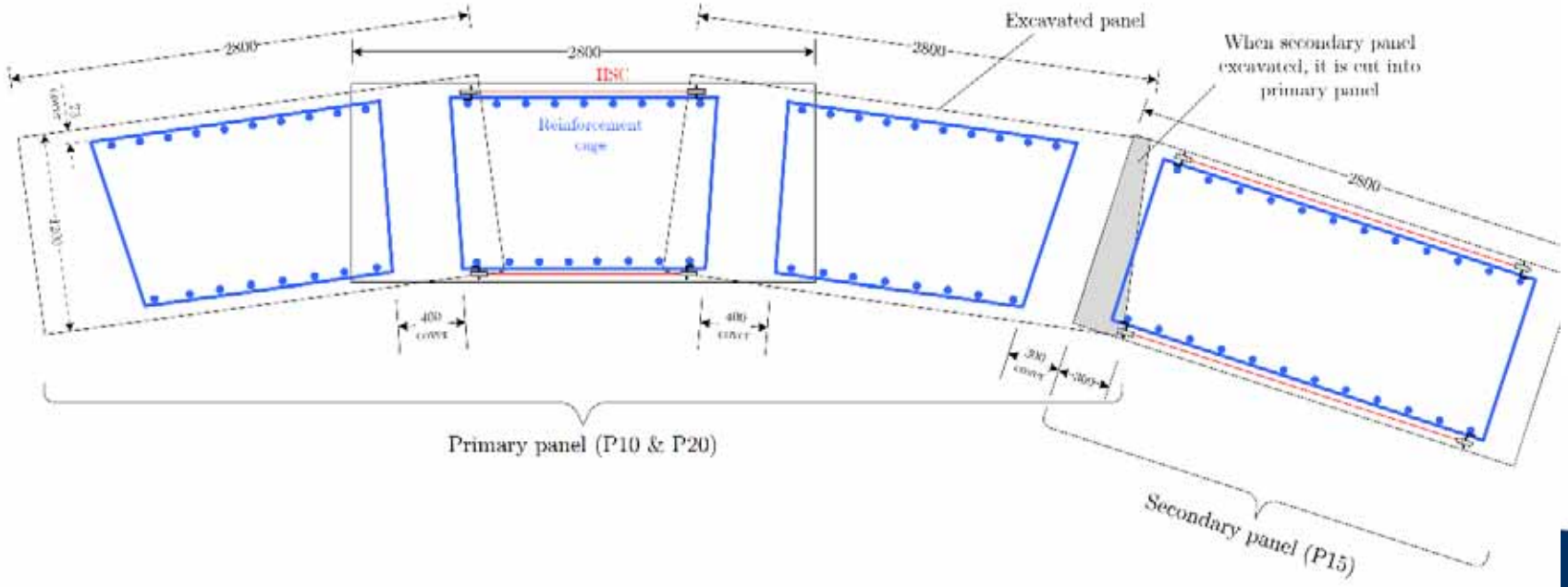
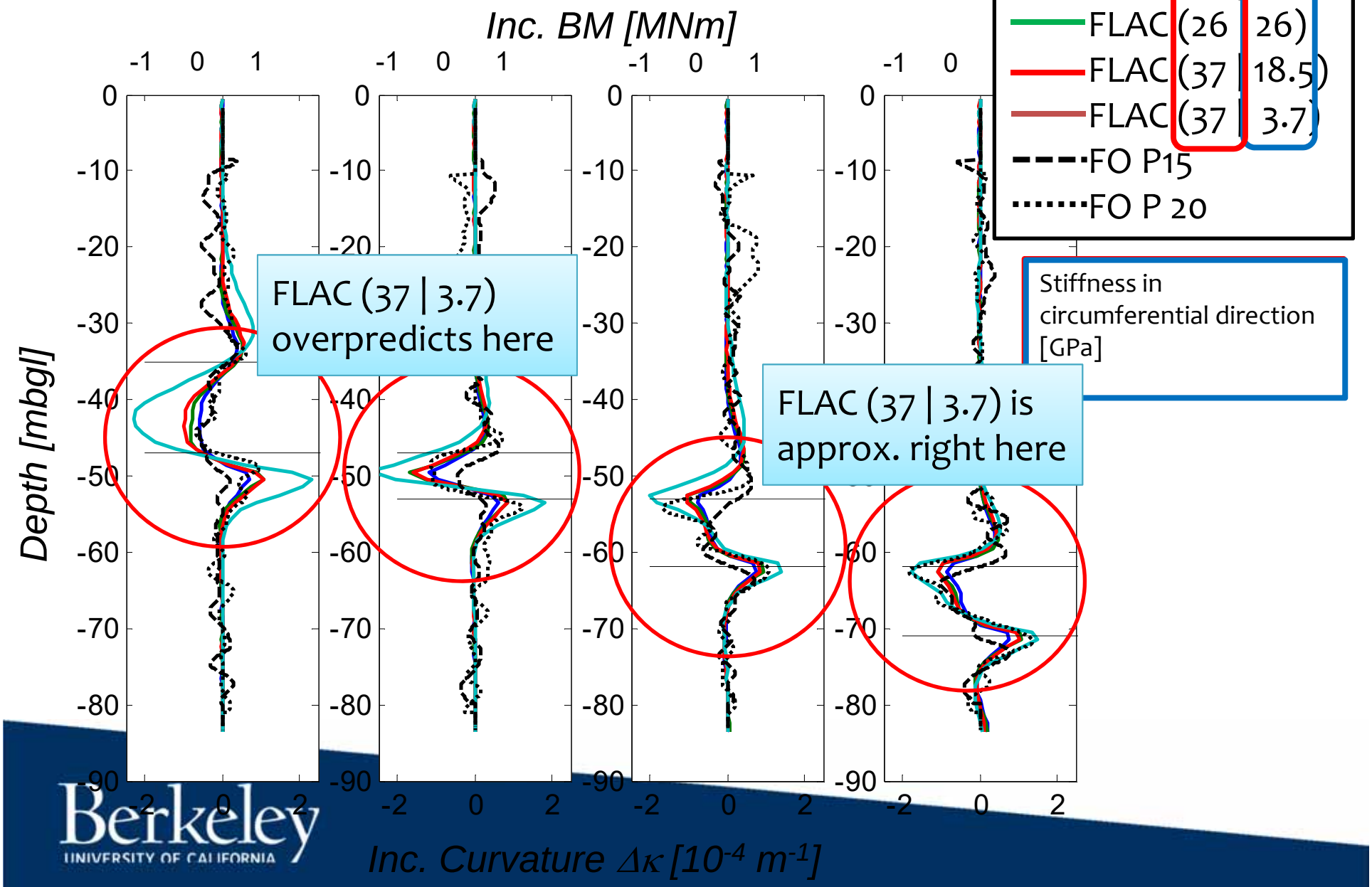

Joints opening due to out
of plane bending moment


2800
2800
2800
IBC
Reinforcement
cage
Excavated panel
When secondary panel
excavated, it is cut into
primary panel
2800
400
400
300
300
Primary panel (P10 & P20)
Secondary panel (P15)

Wall stiffness

FLAC model



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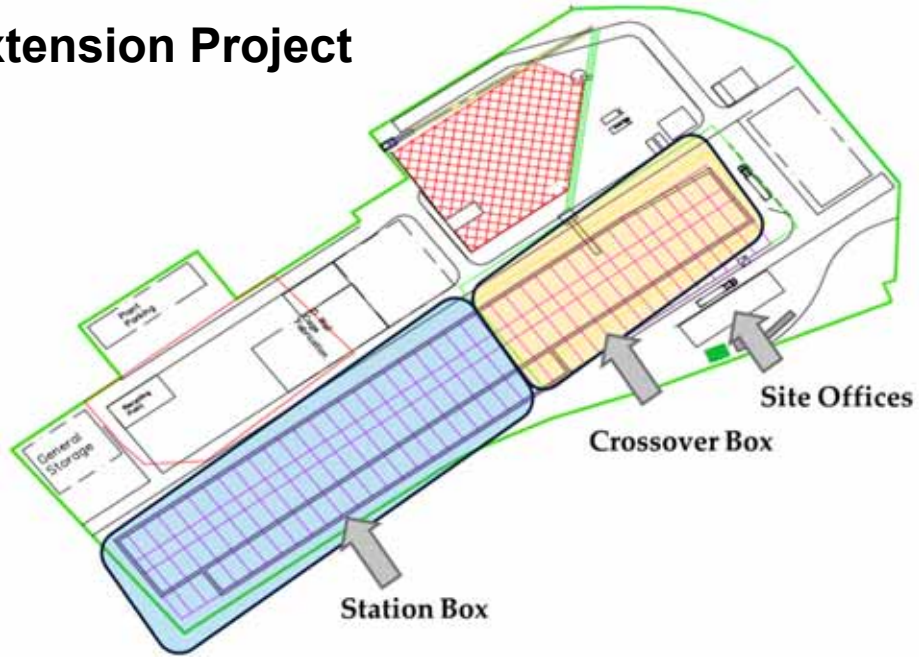
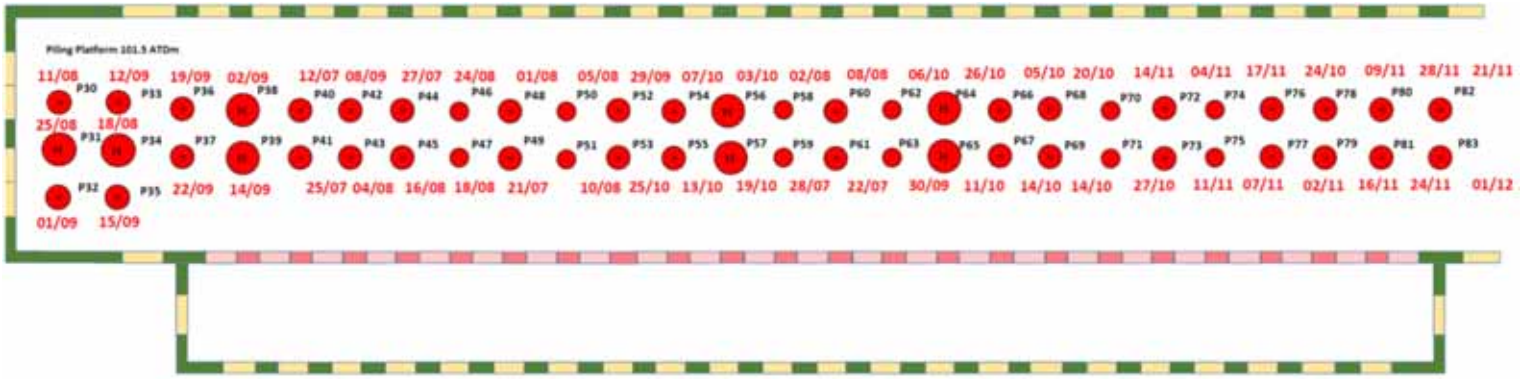
Cementation

SKANSKA

Northern Line Extension Project





Thermal Integrity FO monitoring of 100 Panels and 74 Piles, replacing other methods such as sonic logging.

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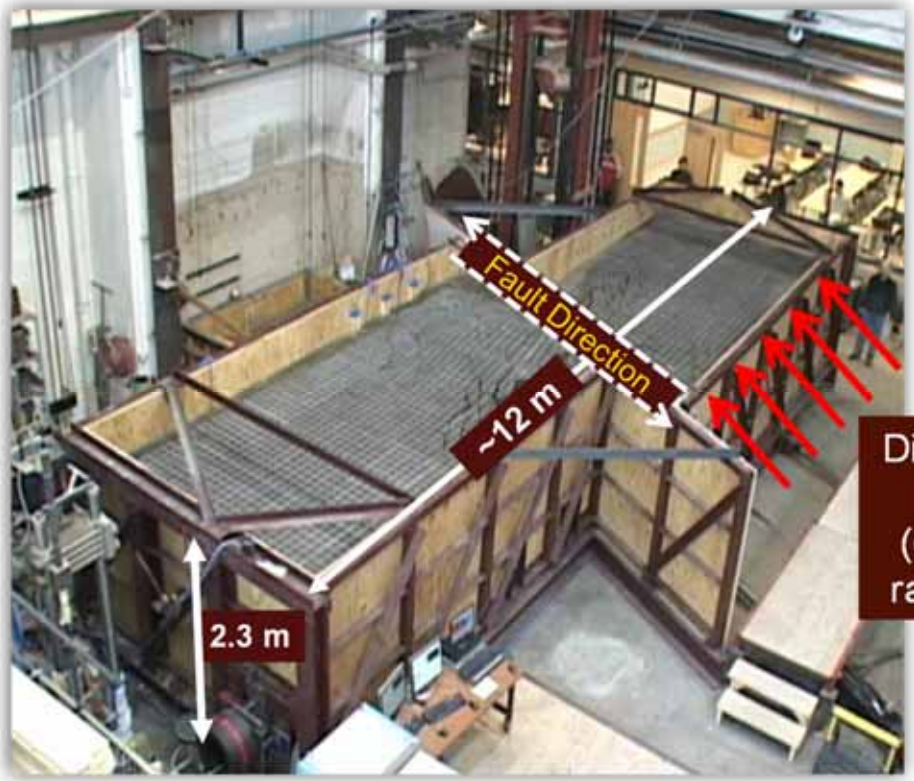
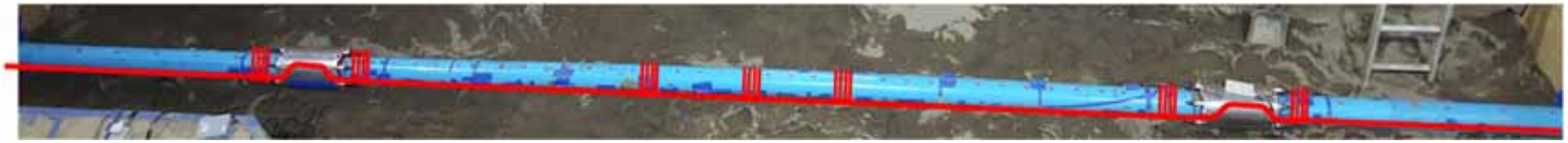
Prof Tom O'Rourke
Dr Brad Wham



Cornell University

Direction of Box Movement (displacement rate = 2 in/min)



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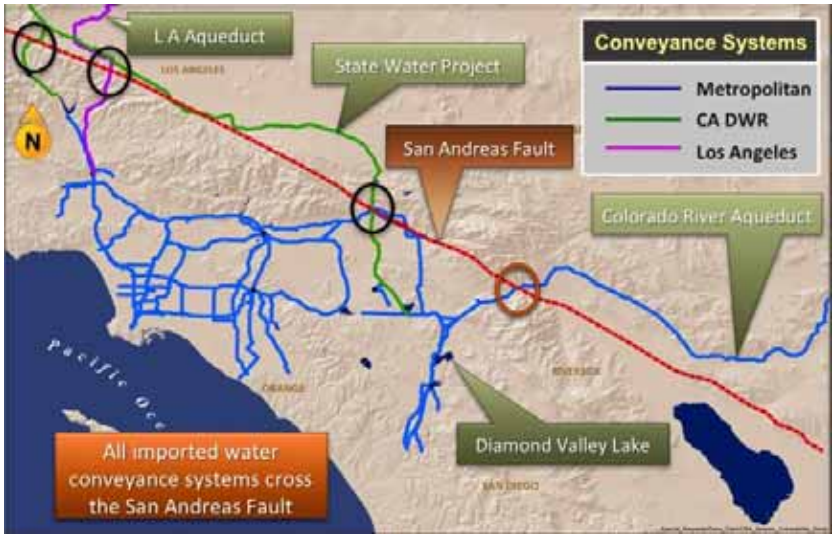
Elizabeth tunnel
Los Angeles Department of Water and Power



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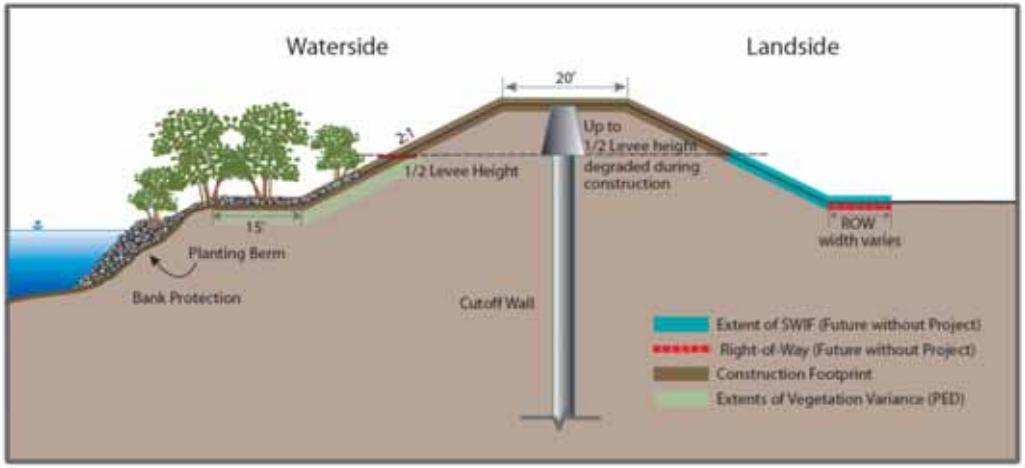
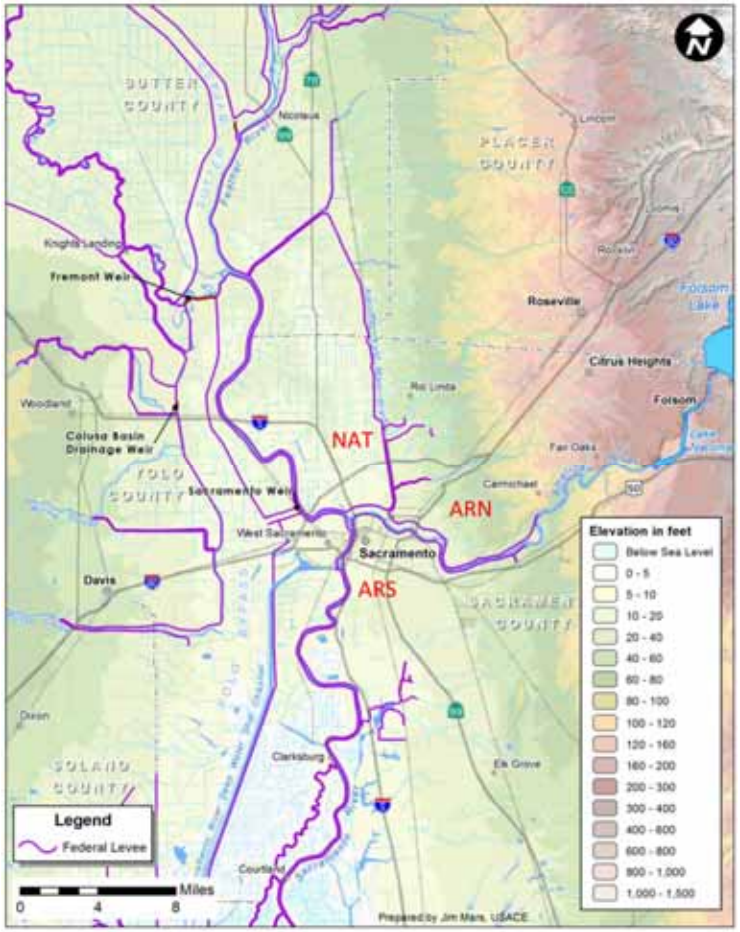
American River Levee Upgrade Project

- 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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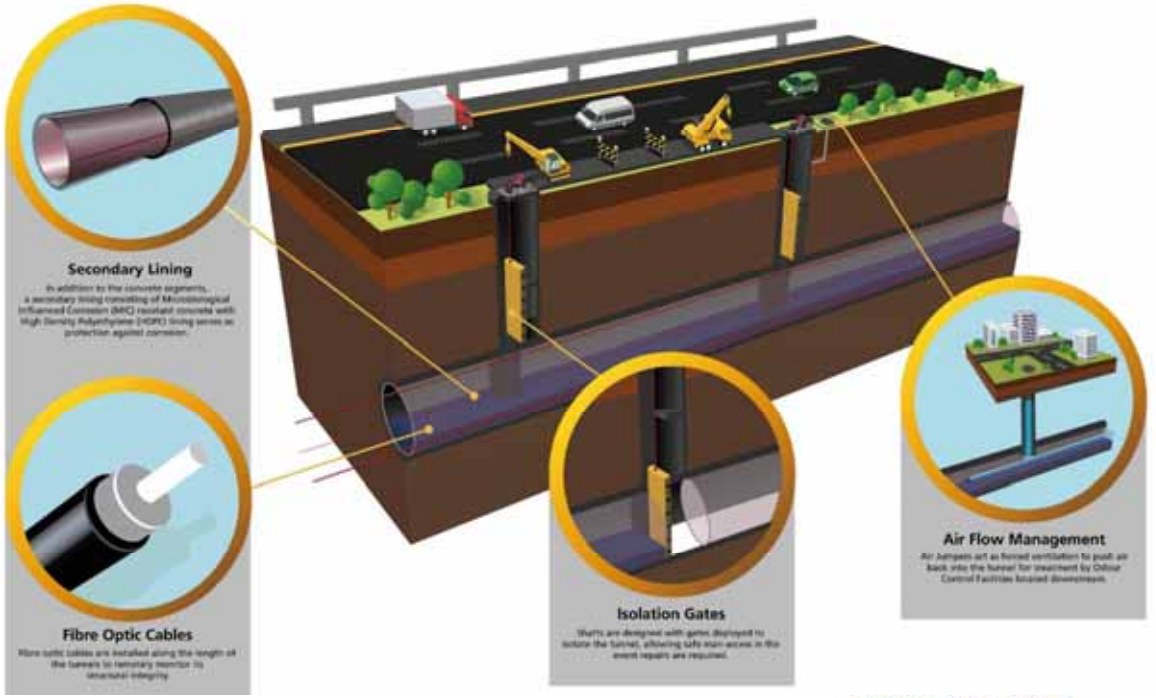
51 km Smart Tunnel
Singapore's Deep Tunnel Sewerage System (DTSS)



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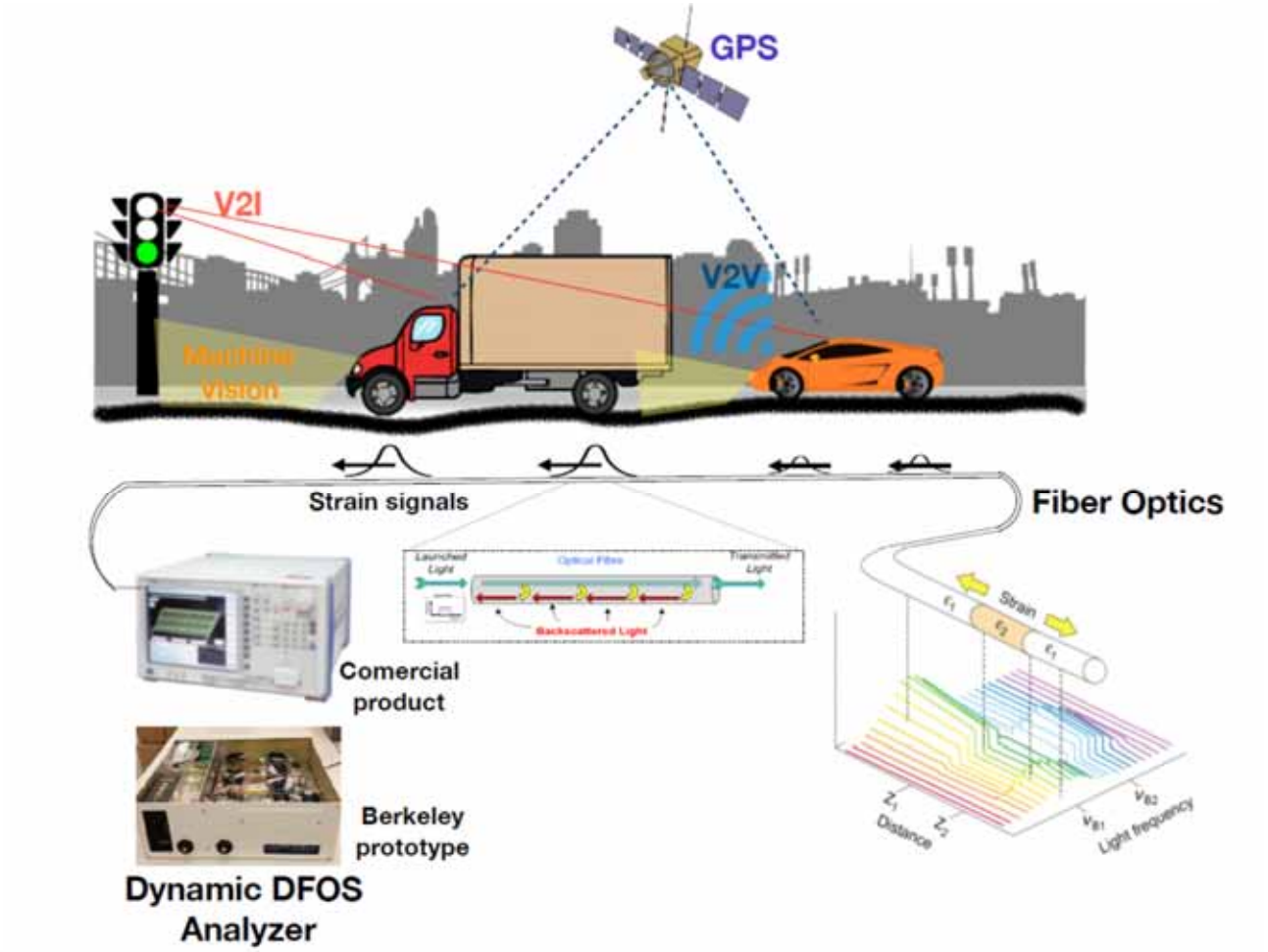
Smart Road Corridors by Meso-Scale In-Pavement Distributed Infrastructure Sensing



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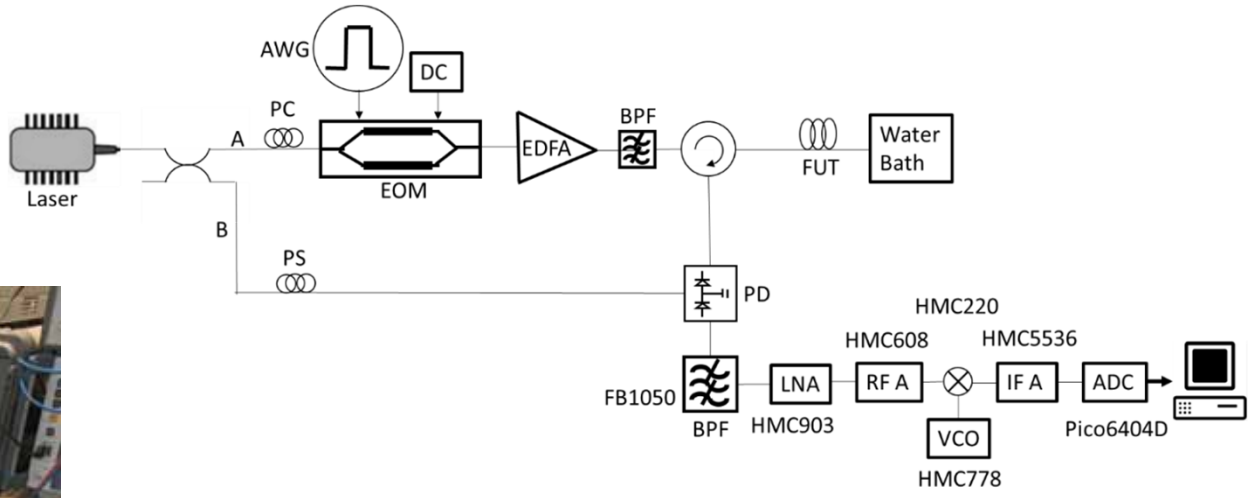

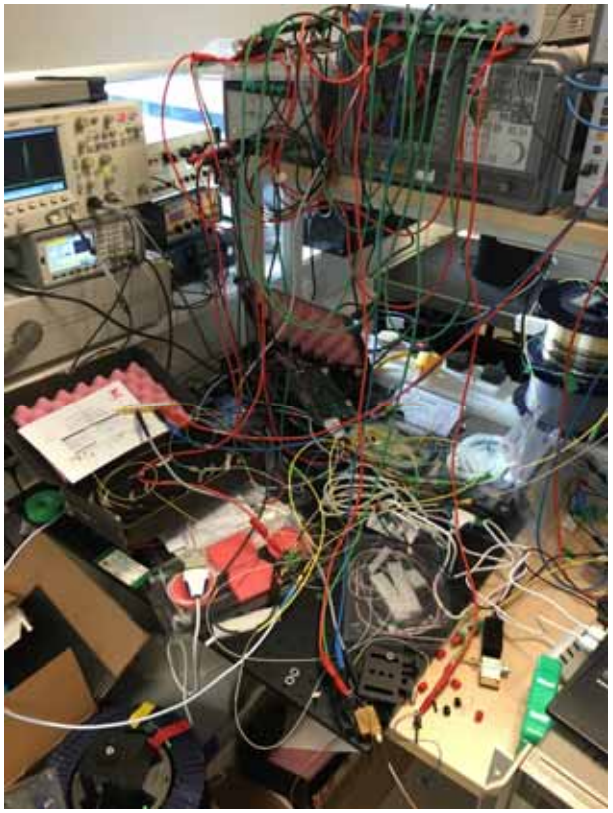

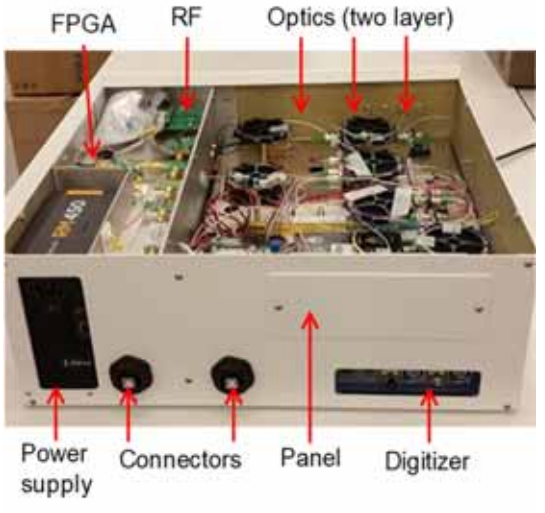

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Review

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http://dx.doi.org/10.1098/rsfs.2016.0023

One contribution of 8 to a theme issue 'Sensors in technology and nature'.

Subject Areas:

Infrastructure sensing

Kenichi Soga[1] and Jennifer Schooling[2]

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Design, construction, maintenance and upgrading of civil engineering infrastructure requires fresh thinking to mini
labour. This can only be achieved by u
the infrastructure, both during its constr
life, through innovative monitoring. Adv
guing possibilities to radically alter met
monitoring of infrastructure. In this pa
future of infrastructure relies on smarter
obtained from embedded sensors within
for new design, construction, operation a
grated infrastructure systems linked dire
Some examples of emerging sensor tech
are given. They include distributed fibr
wireless sensor networks, low-power
energy harvesting and citizens as sensor

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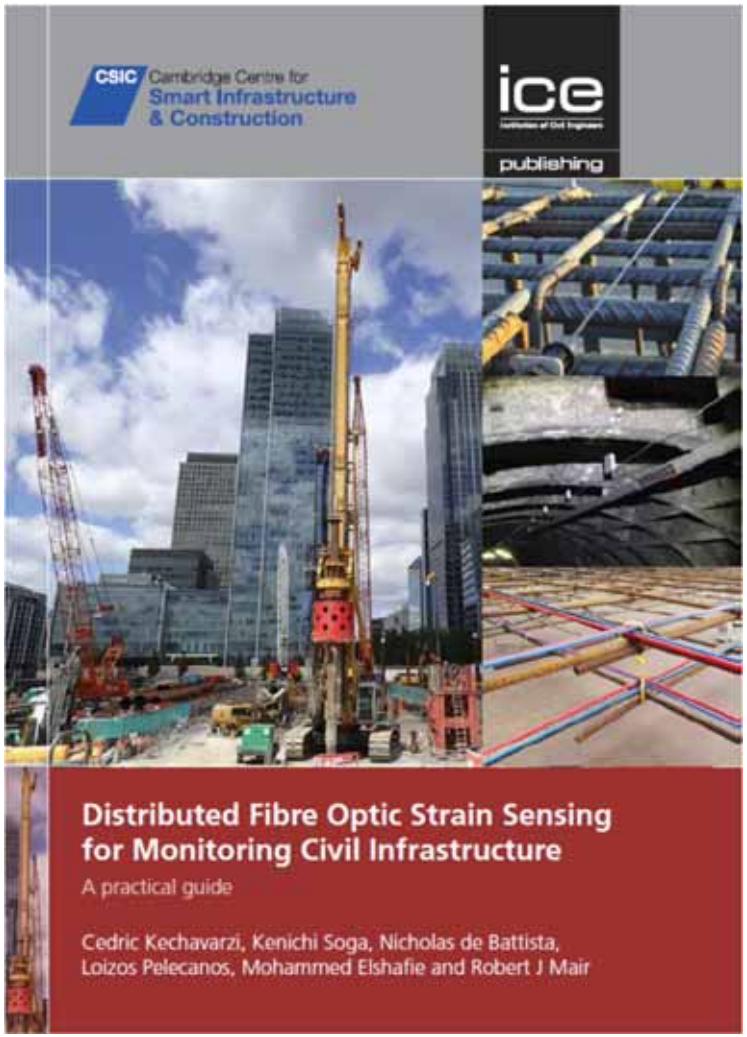
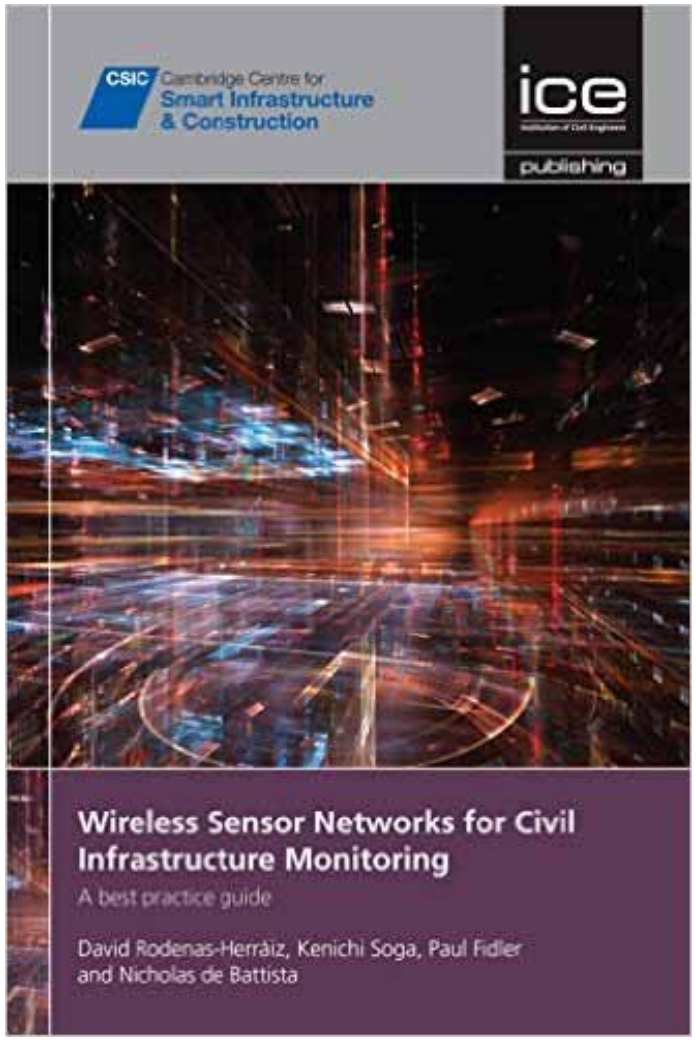
Best Practice Guides for Monitoring Civil Infrastructure



Distributed Fibre Optics Sensing



Wireless Sensor Networks

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Summary

- Innovation in sensors as part of Internet of Things
  - Exciting opportunities for Geotechnical Engineering to understand the real performance of infrastructure and construction.

- For example, distributed fibre optics (especially embedded) can give useful strain data that no other sensors can give.

- Monitoring system should be an integral part of the construction package
  - Quality Control
  - Maintenance
  - Reuse

- This leads to Performance-design, construction and maintenance.


Thank you