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Fibre optic strain measurement for field monitoring of soil-structure interaction

Robert Mair

Cambridge University

ISFMG, Imperial College, 7 September 2022

Outline of Lecture

- **Innovative fibre optic sensing for field measurements**
- **Circular shafts**
- **Tunnel linings**
  - sprayed concrete
  - TBM precast linings
- **Early warning detection of impending geotechnical instability**
  - slopes
  - sinkholes

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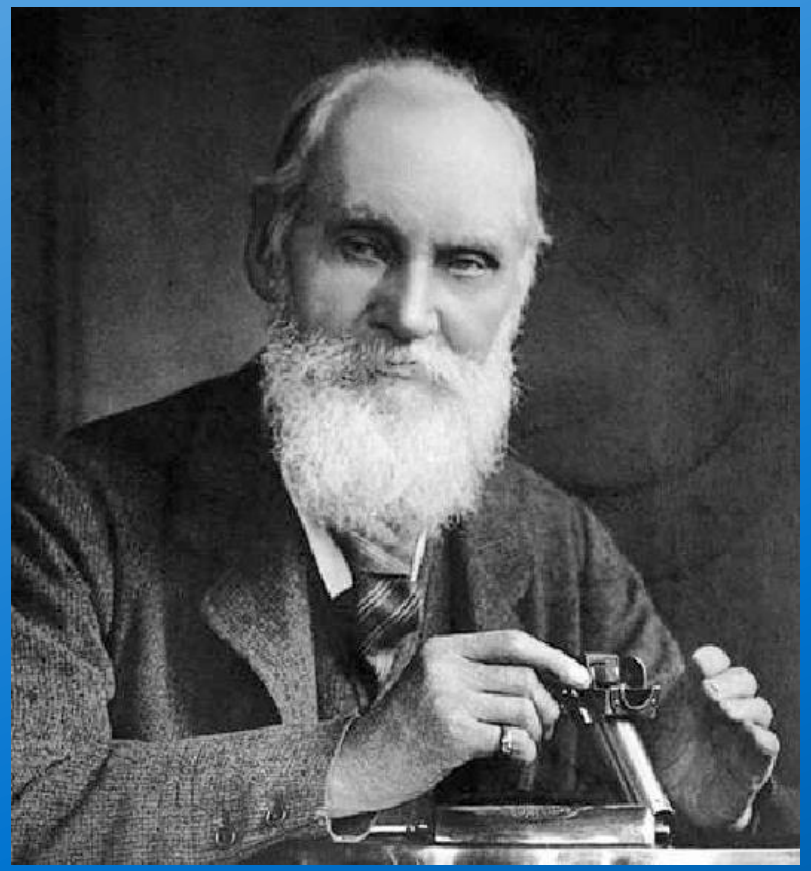

“If you cannot measure it, you cannot improve it.”

Lord Kelvin

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CSIC Mission:

“Transform the future of infrastructure enabling better decision-making through smarter information”

CSIC Vision:

- Enable step changes in construction practice
- Extend asset life & reduce management costs

Phase 1 – 2011-2016 Phase 2 – 2016-2023

www.centreforsmartinfrastructure.com @CSIC_IKC

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CSIC: £22m over 12 years from UK Government and Industry

Infrastructure Clients (Owners and Operators)

Consultants, contractors and asset managers

Technology & information supply chain

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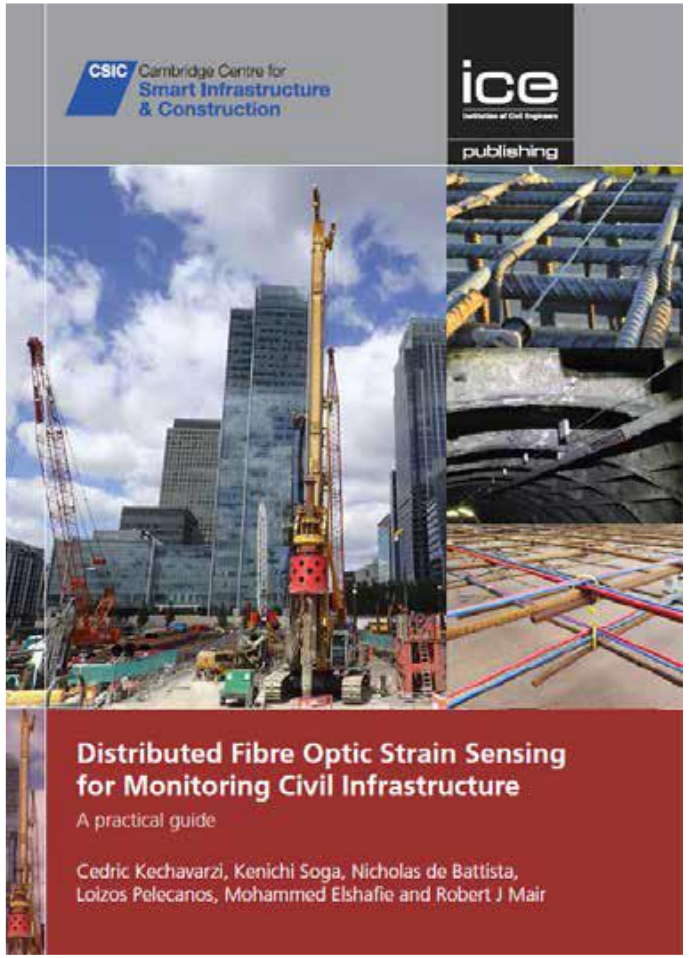
Field demonstrations & case studies

CSIC has deployed novel sensors on over 100 construction sites

A CSIC practical guide published by the ICE



Distributed Fibre Optic Strain Sensing for Monitoring Civil Infrastructure

Kechavarzi, C. et al (2016)

- **General concepts**
- **Practical considerations**
- **Data processing, analysis and interpretation**
- **Case studies in geotechnical applications**
  - tunnels
  - piles
  - diaphragm walls
  - slopes and embankments

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Innovative Fibre Optic Sensing

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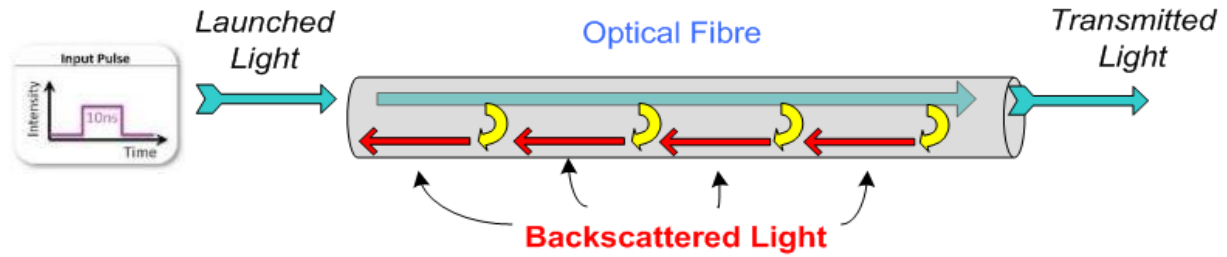
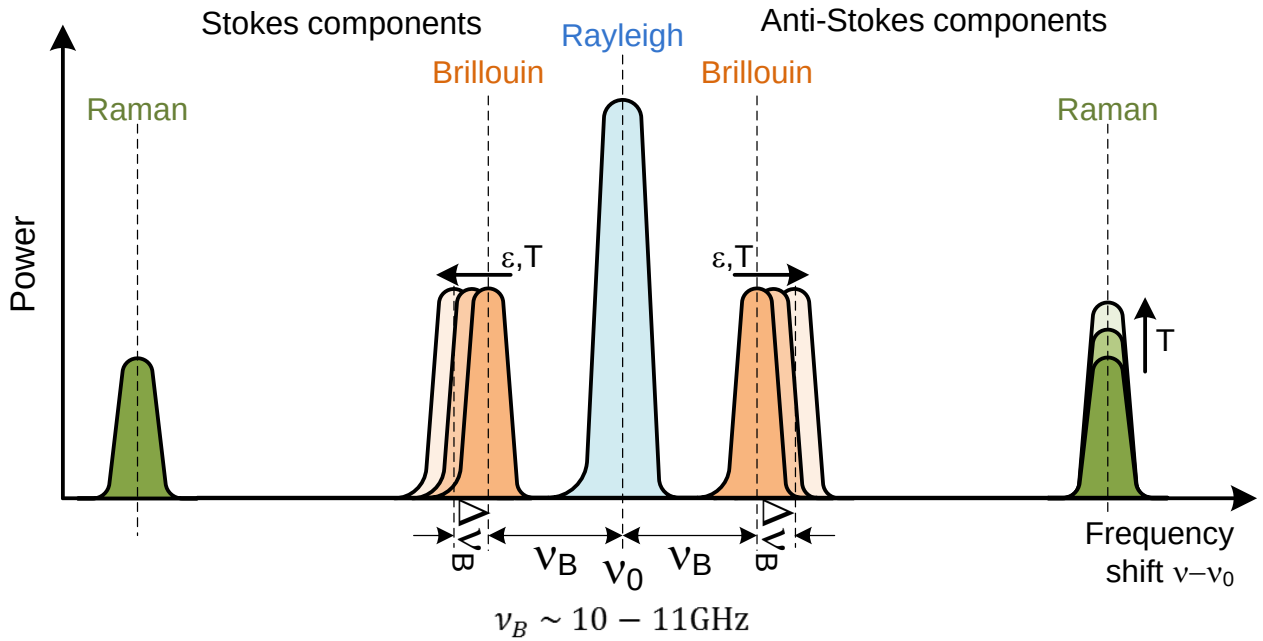
Instrumentation

Distributed (Brillouin) fibre optic strain (DFOS) sensing





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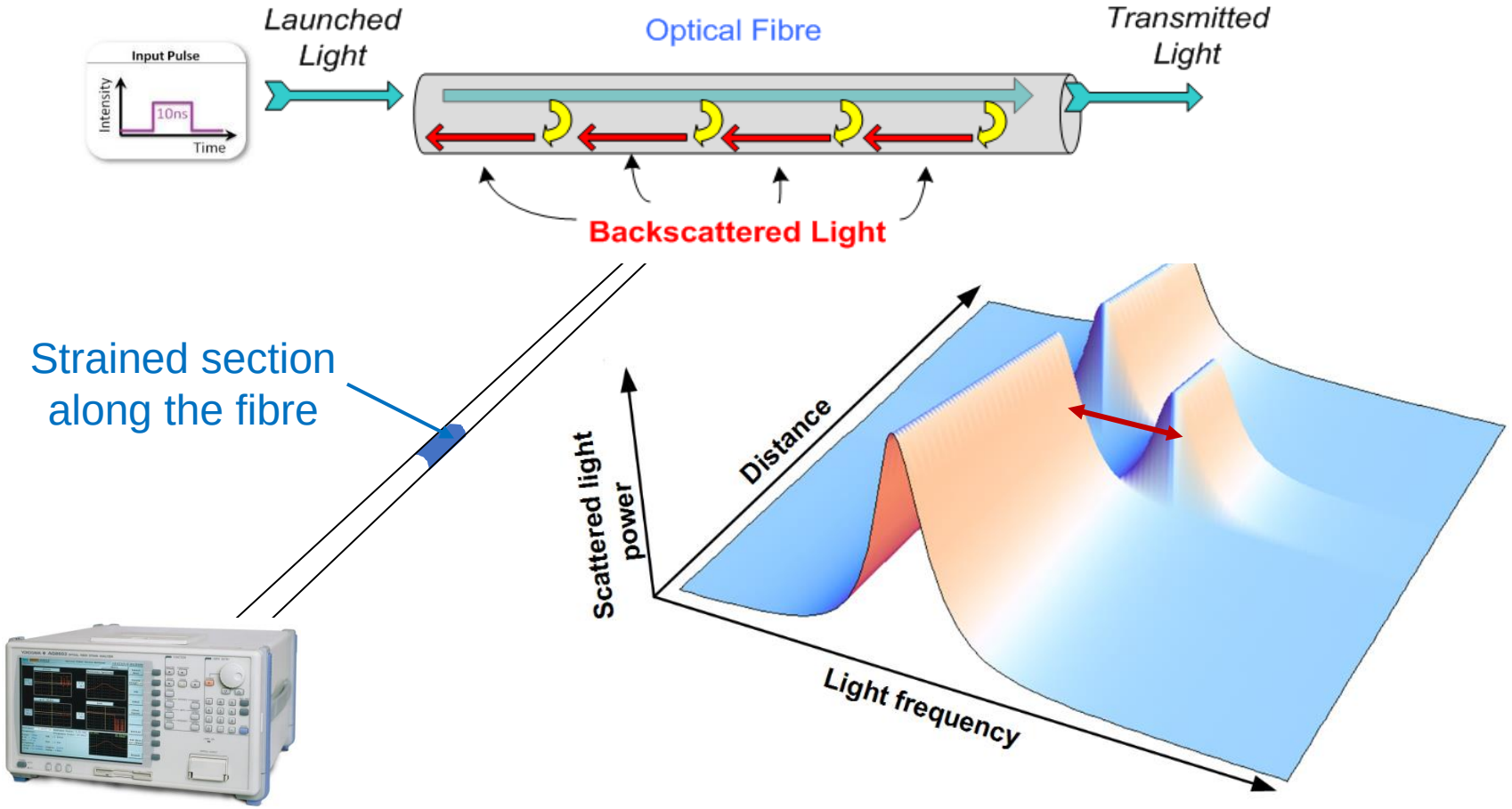
Innovative fibre optic sensing

Distributed (Brillouin) fibre optic strain (DFOS) sensing



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Shafts

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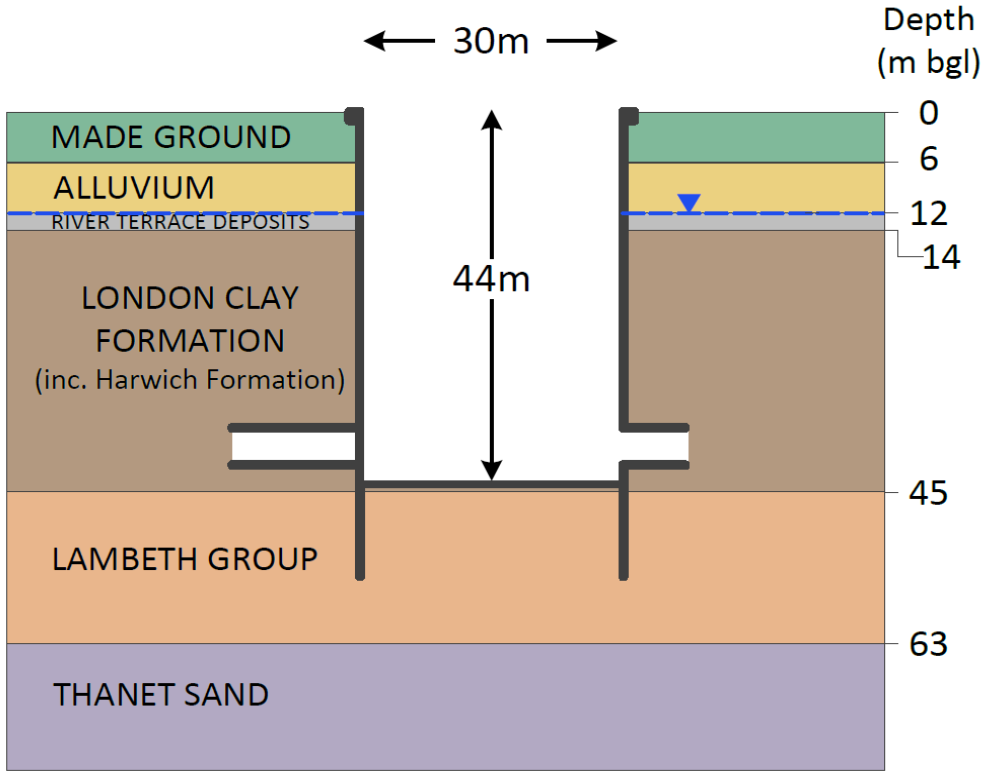
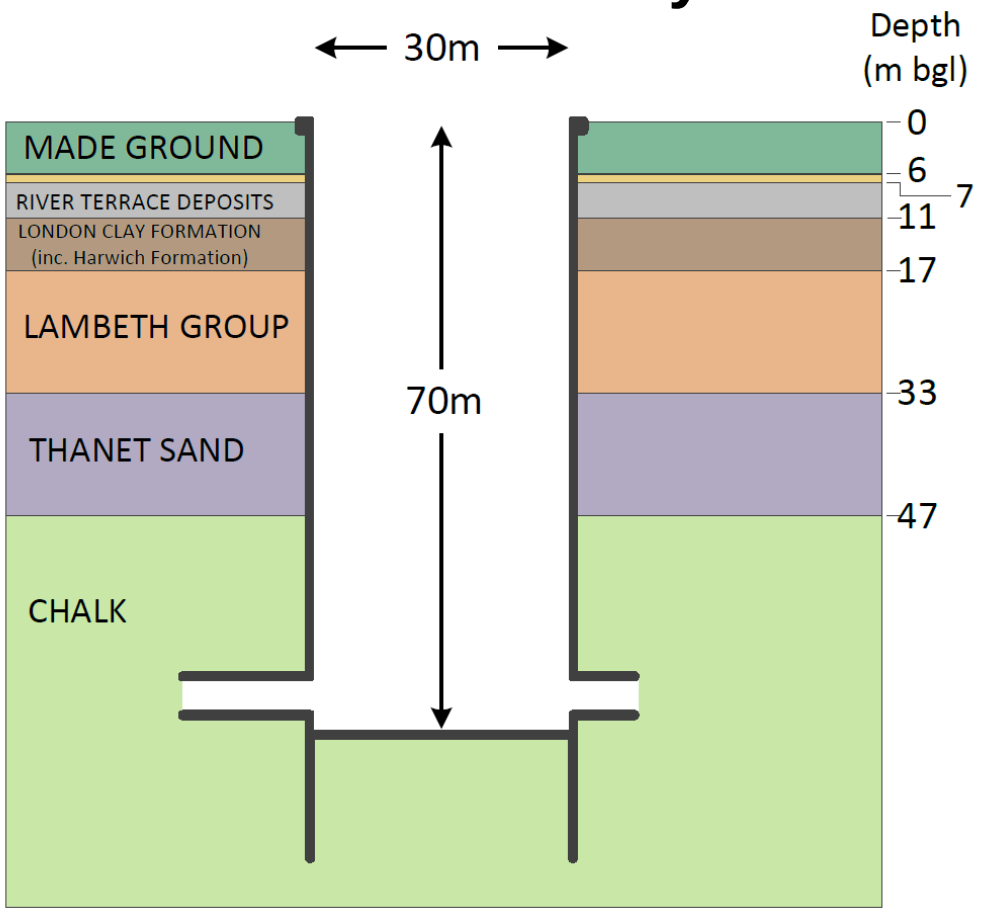
Fibre optics installed in Crossrail and Thames Water shafts

Crossrail: Limmo



Thames Water: Abbey Mills



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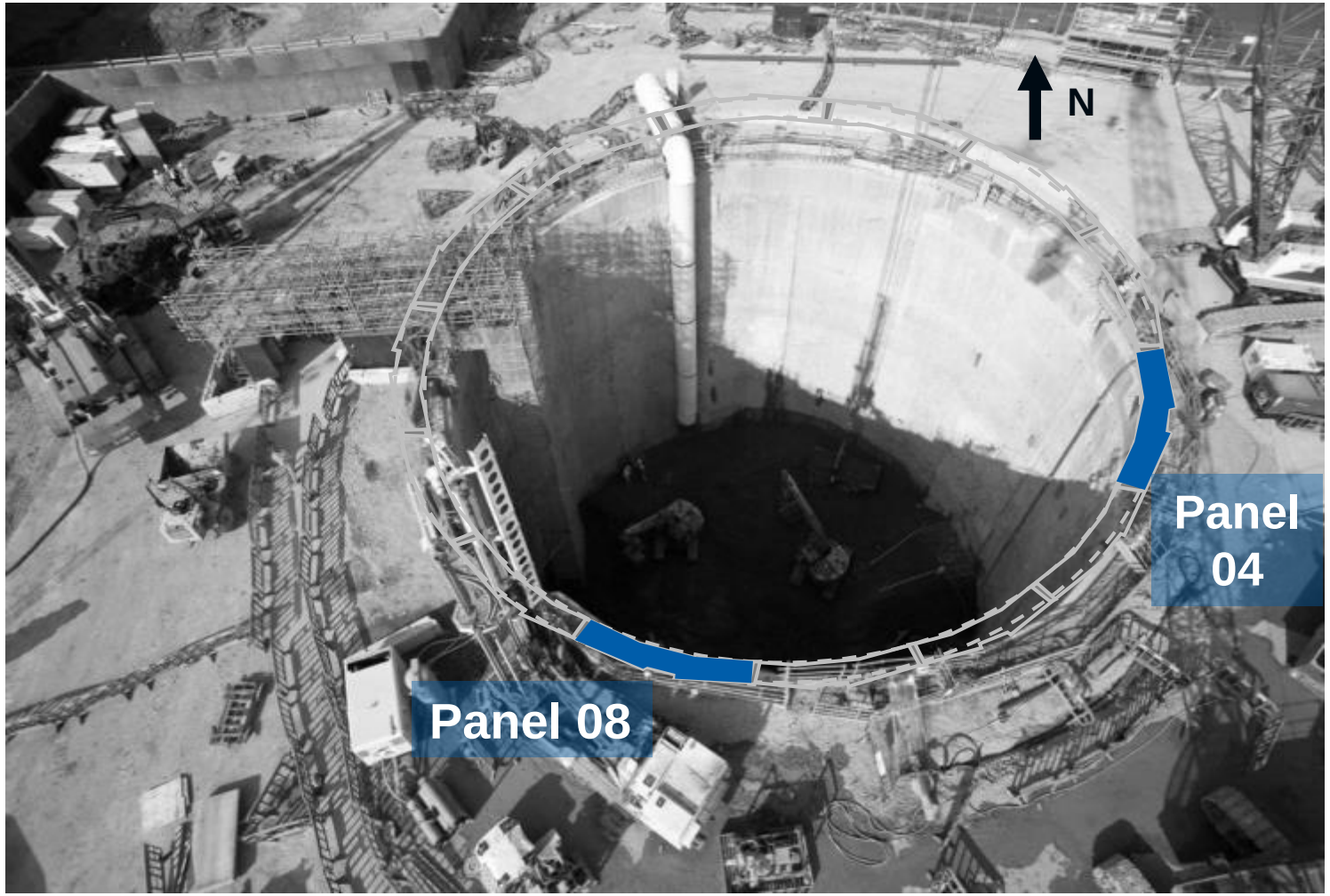
Fibre optic monitoring – Crossrail Limmo Peninsula main shaft



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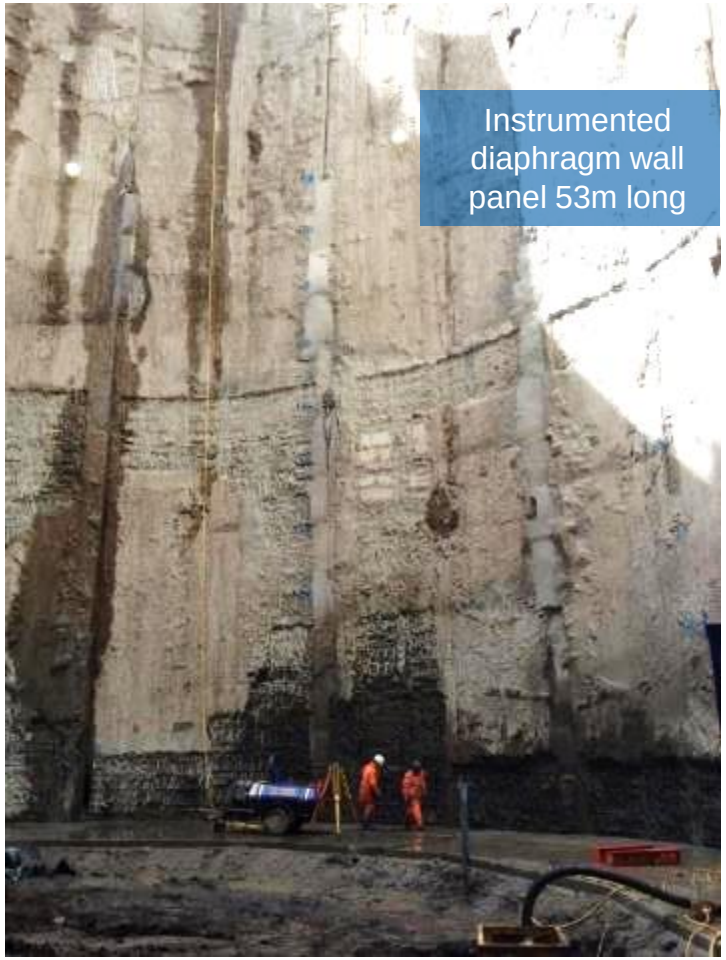
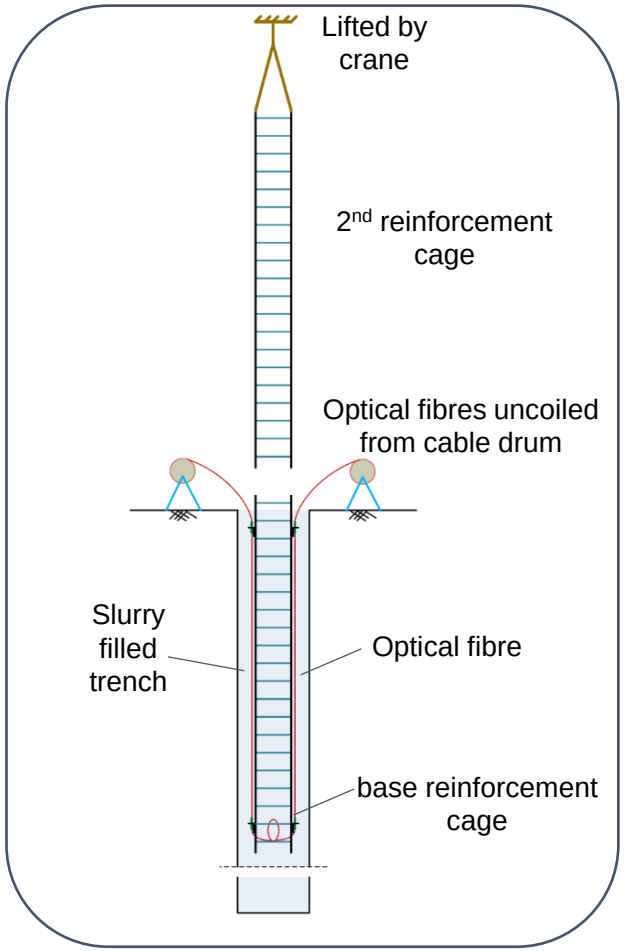
Fibre optic monitoring – Crossrail Limmo Peninsula main shaft





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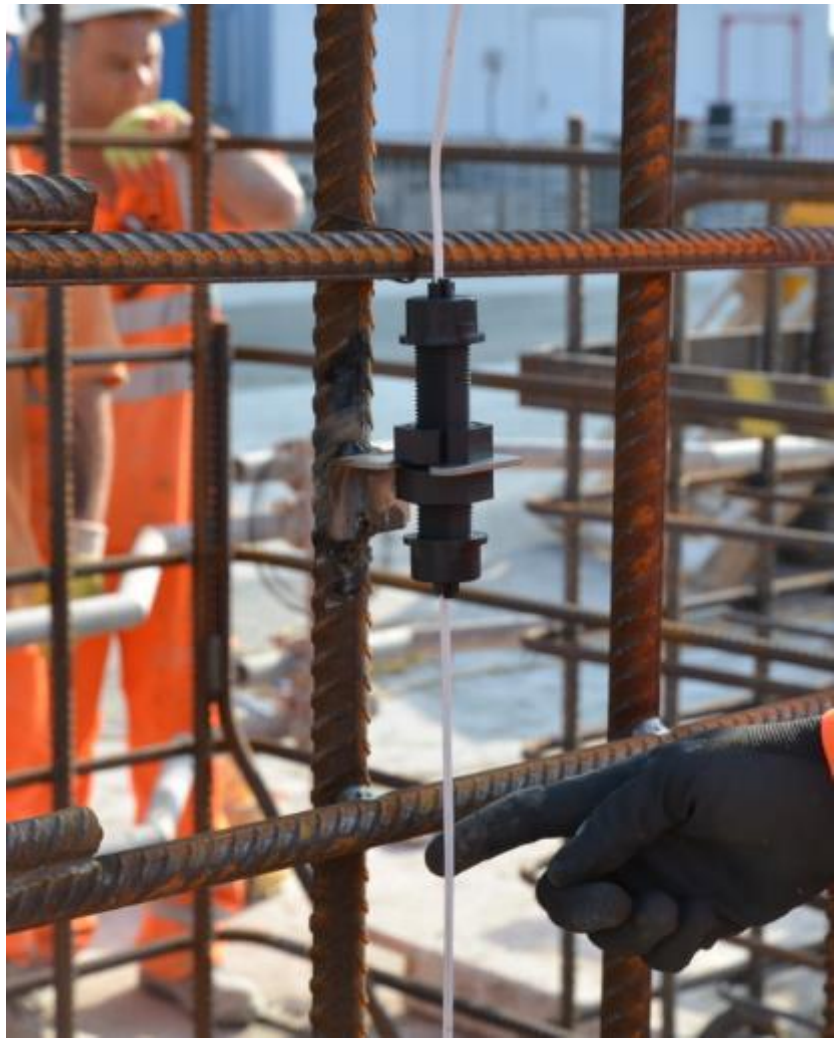
Installation of instrumented reinforcement cage

Fibre optic connection to steel reinforcement



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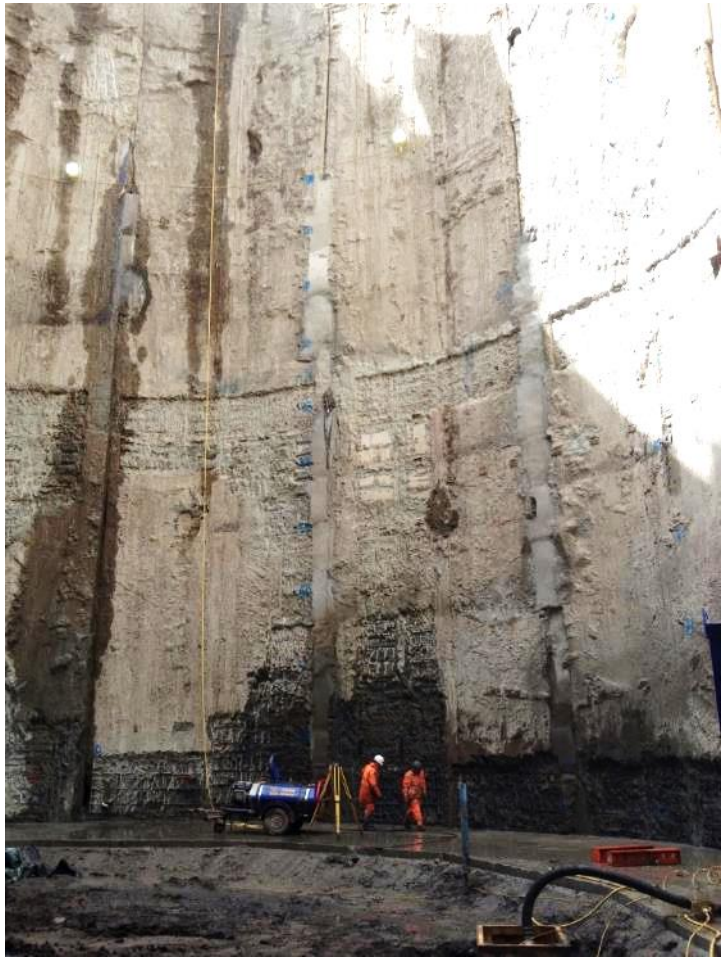
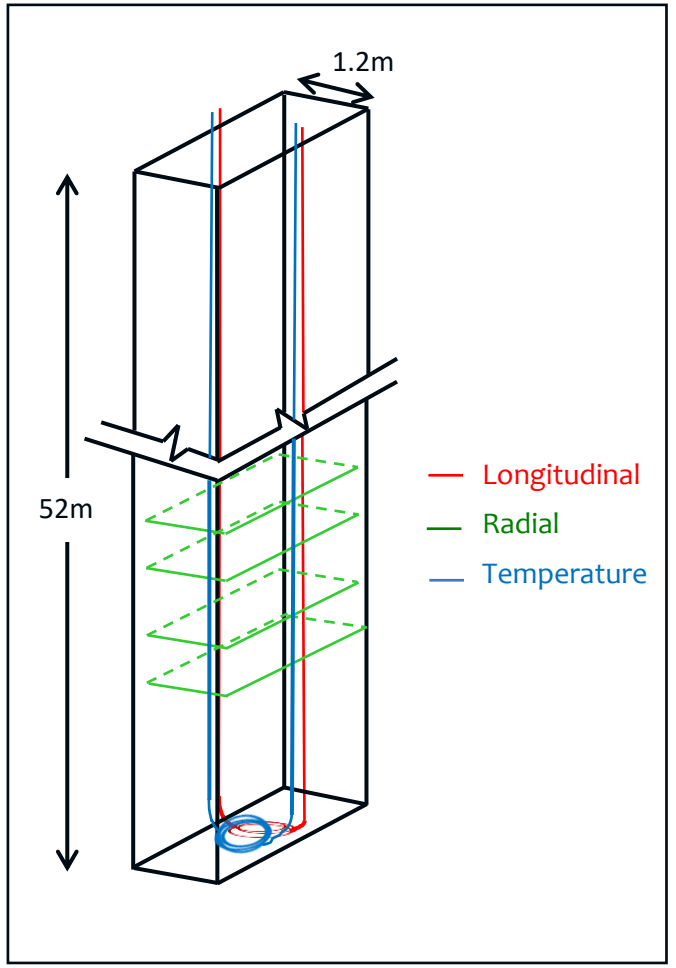
Fibre optic monitoring – Crossrail Limmo Peninsula main shaft





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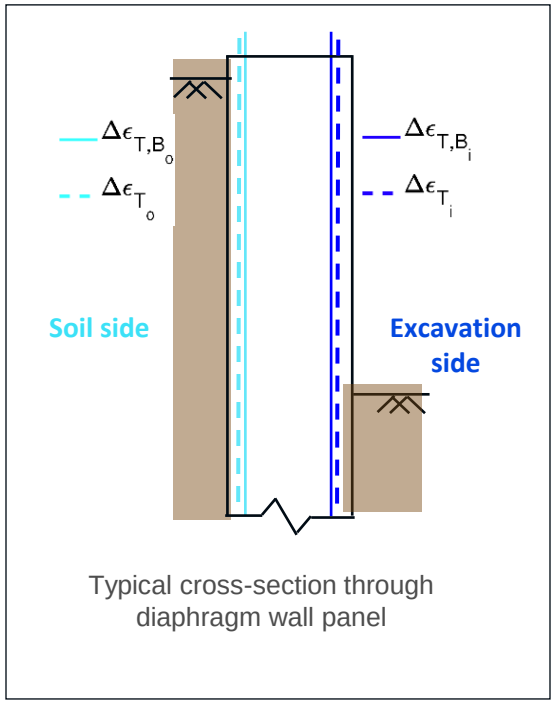
Instrumented reinforcement cage – hoop strains

Data acquisition on site

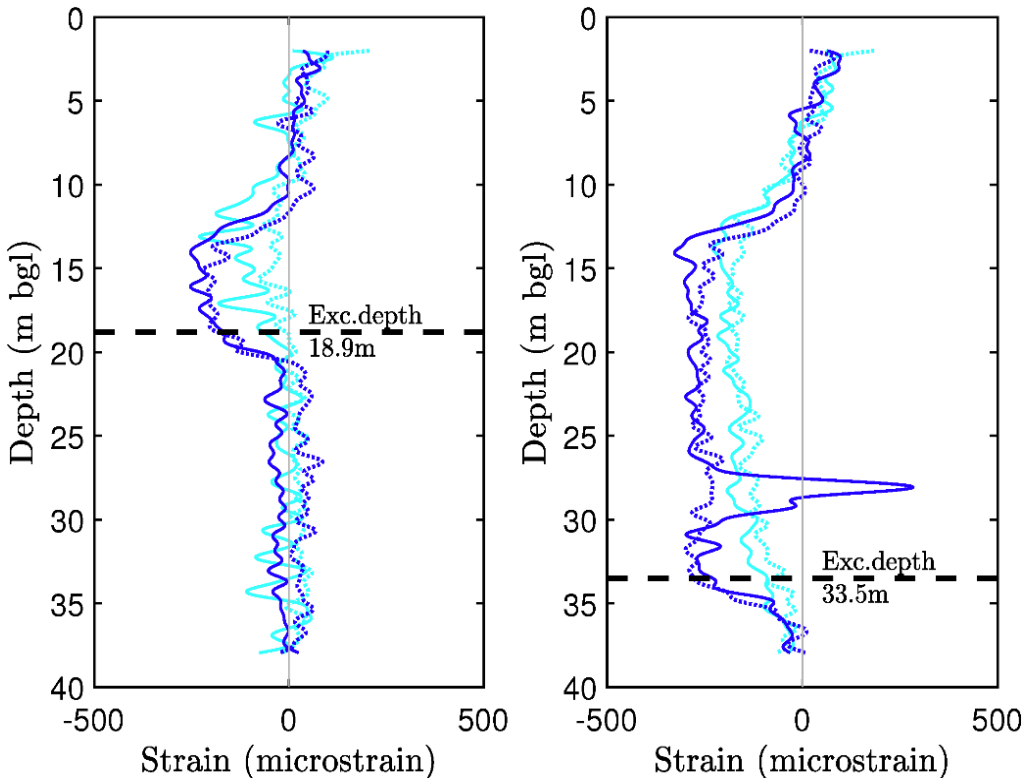
Mechanical and thermal induced strain (Panel 4)



Typical cross-section through diaphragm wall panel

$\Delta\varepsilon_T$ – Temp. induced strain

$\Delta\varepsilon_{T,B}$ – Temp. + mechanically-induced strain



Sign convention:

-ve : compressive strain

+ve : tensile strain

Strains due to bending are very small, strains are dominated by temperature

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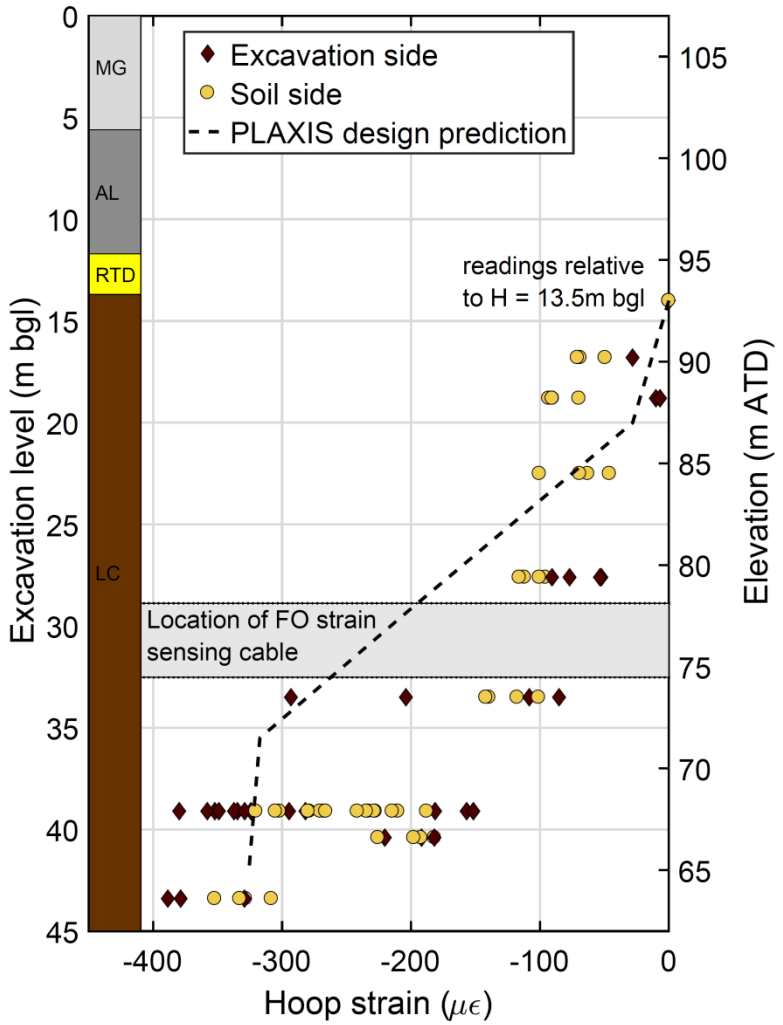
Measured hoop strain in a 1.2m thick and 53m deep diaphragm wall panel



Sign convention:

-ve : compressive strain

+ve : tensile strain

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Shafts - Lessons learned

- **Fibre optics successfully measured strains in shafts**
- **Compressive hoop strains much more significant than longitudinal bending strains, which are very small**
- **Reinforcement for longitudinal bending could be substantially reduced**
- **Temperature strains more significant than bending strains**

Tunnels

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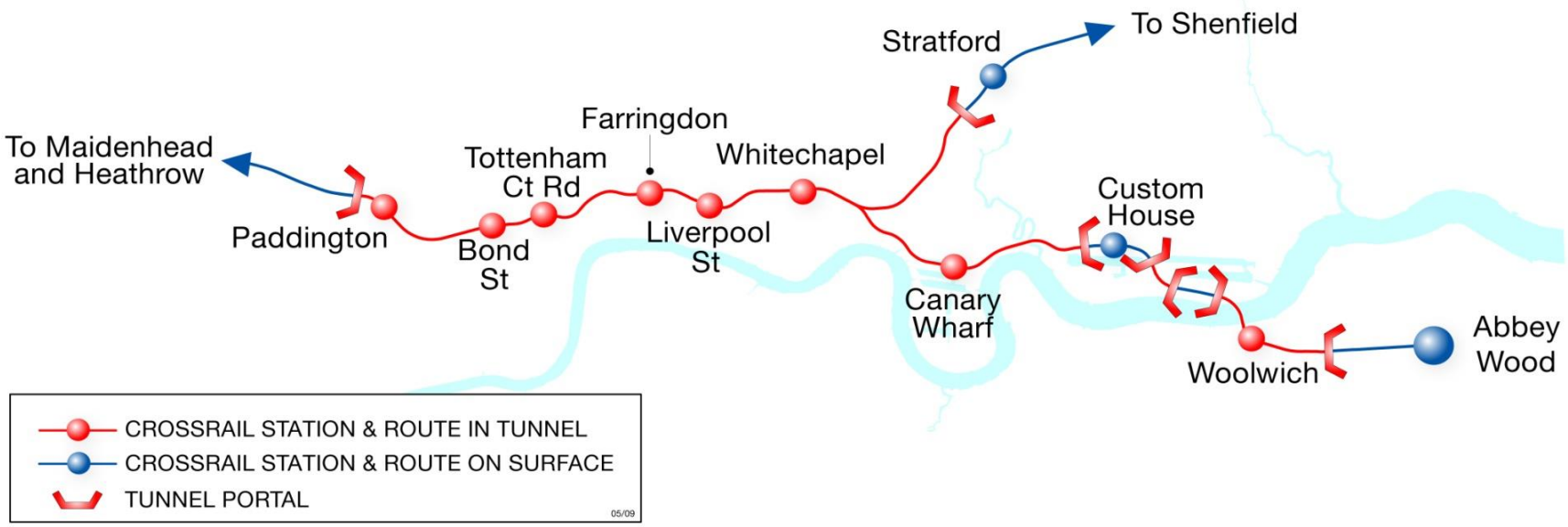
CROSSRAIL (now ELIZABETH LINE)

21 km of new sub-surface twin-bore railway through London



8 new sub-surface stations

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Innovative fibre optic sensing

Crossrail Liverpool Street Station

De Battista et al (2015)

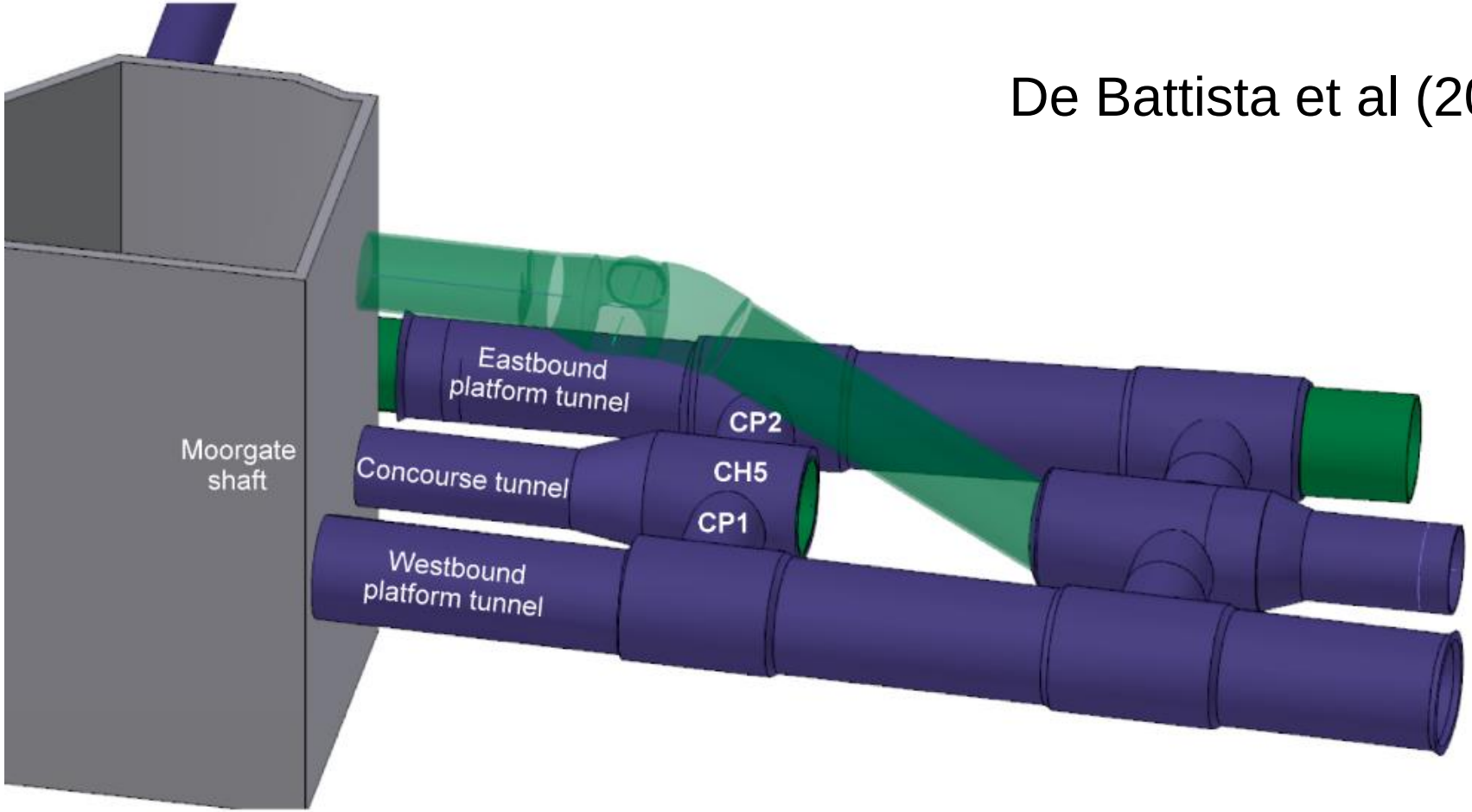

Image credit: Crossrail

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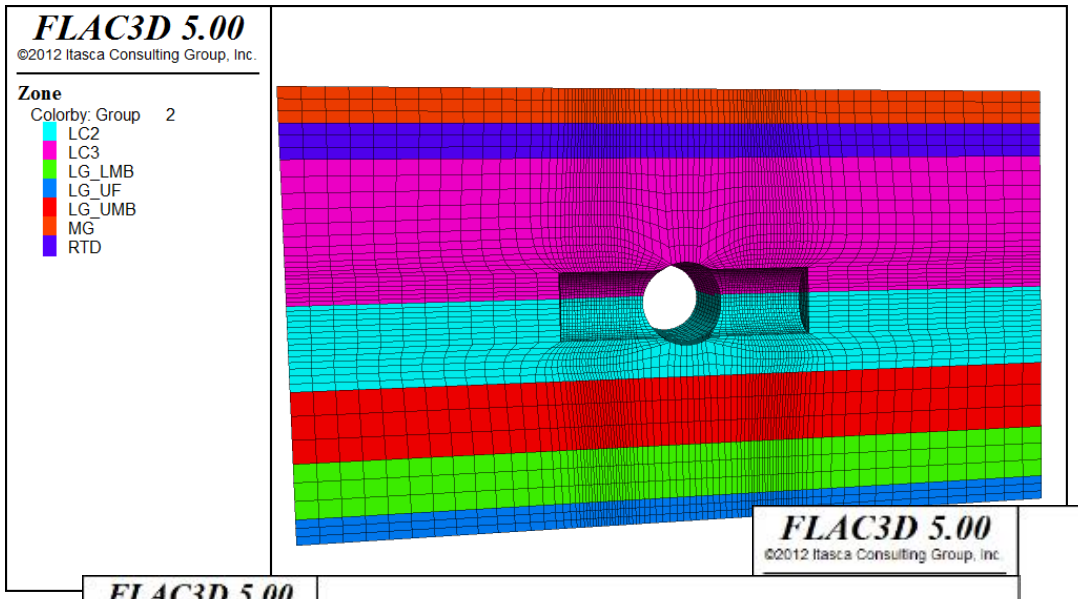
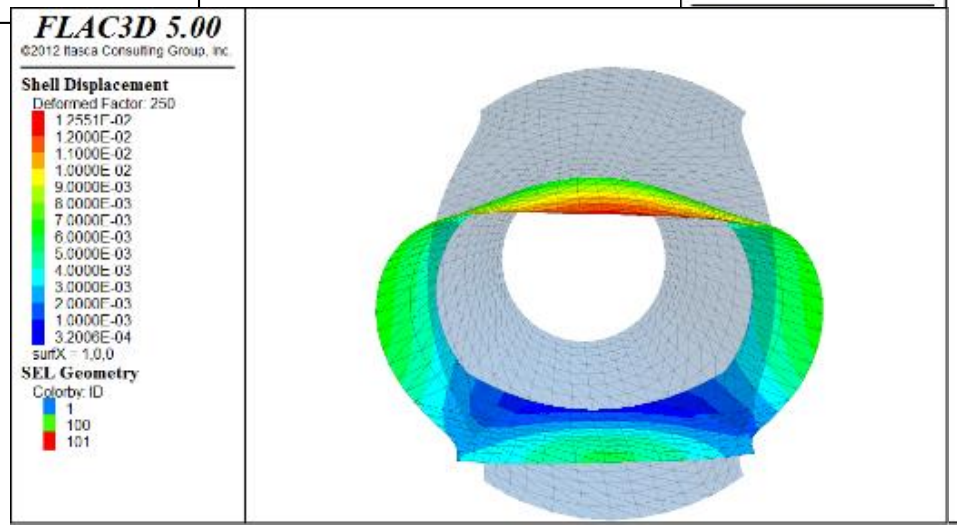


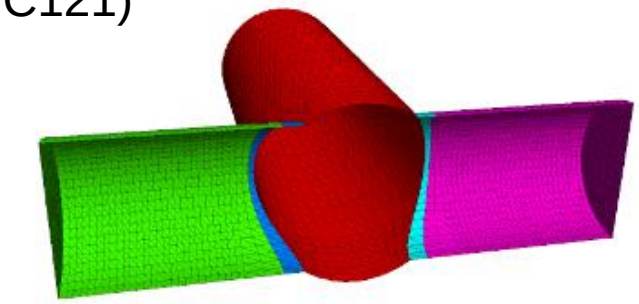


3D Finite Element analysis of tunnel junctions

- sprayed concrete properties time-dependent, complex

- soil properties highly non-linear

(Mott MacDonald, Crossrail C121)



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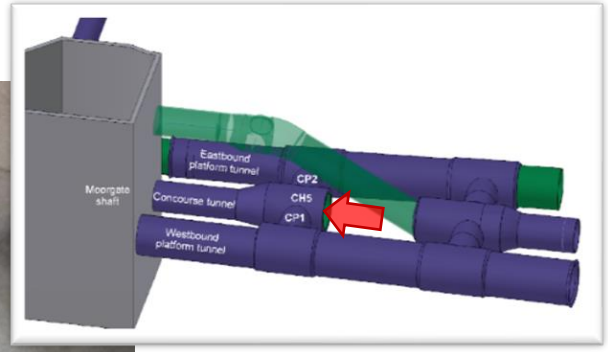
Innovative fibre optic sensing

Sprayed concrete lining (SCL) tunnel construction



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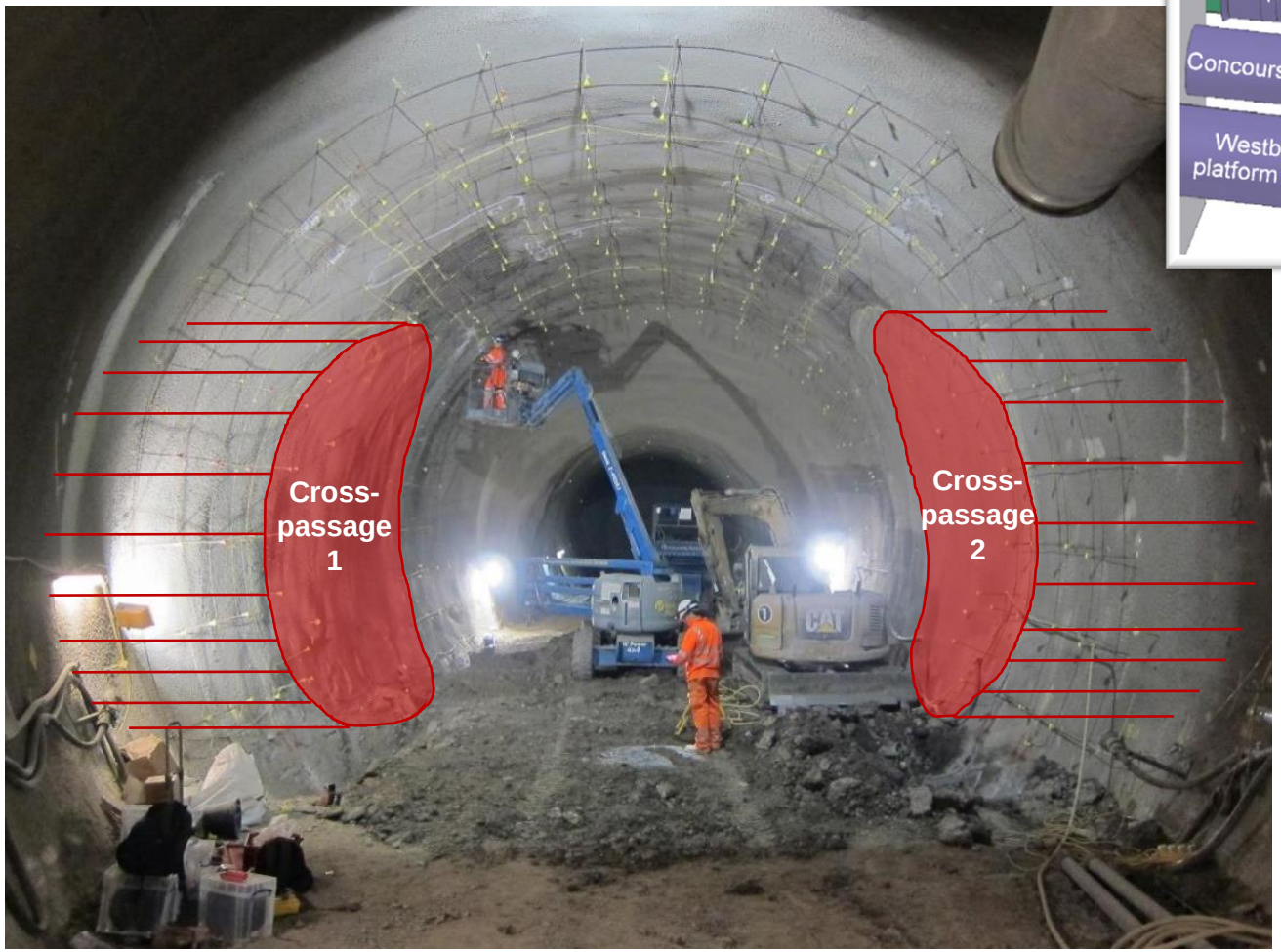
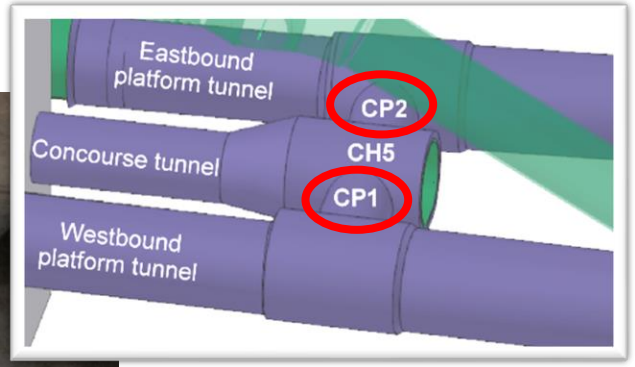
Innovative fibre optic sensing

Cross-passage excavation





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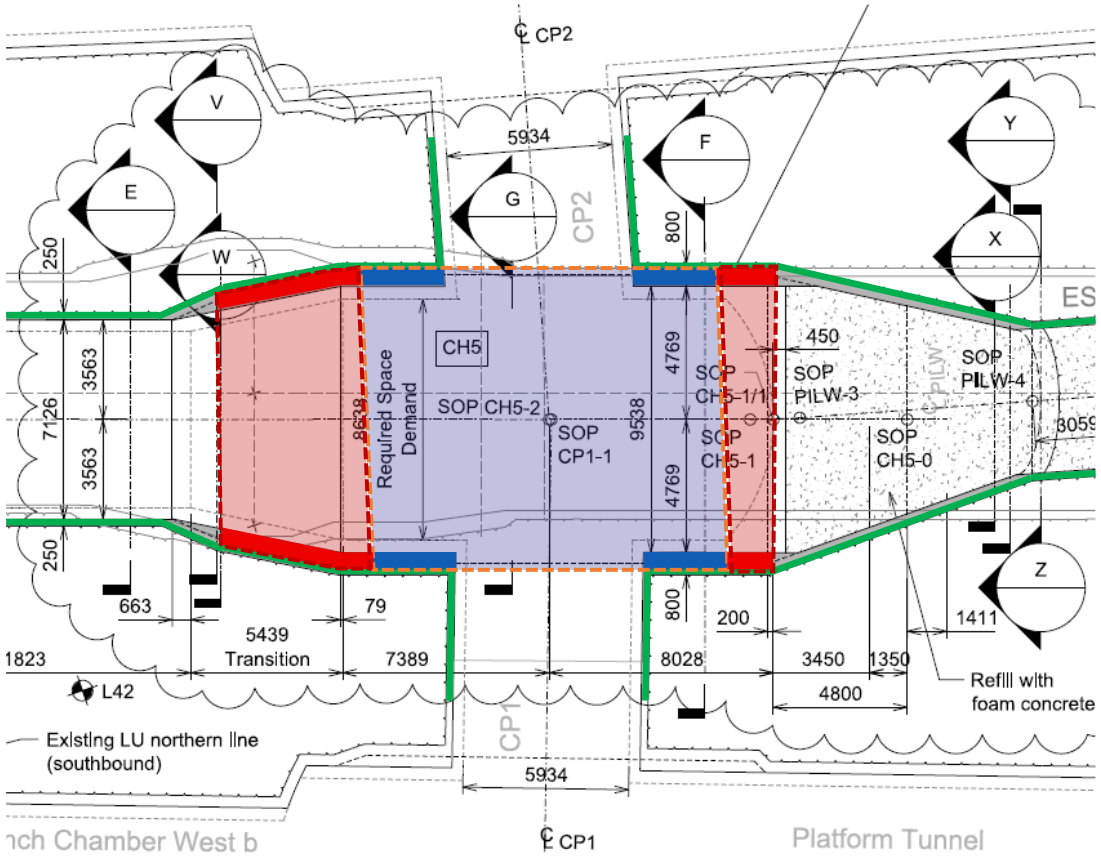
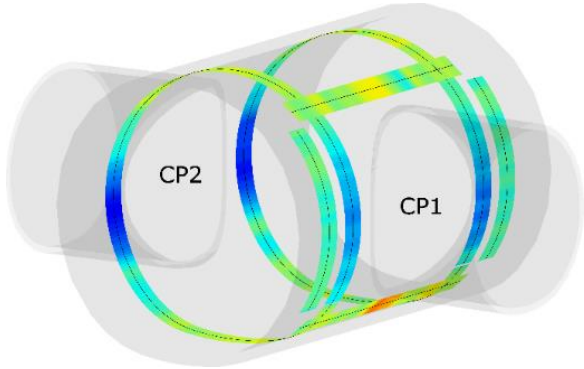
Monitoring results

Localised strain effects demonstrated by fibre optics





3m on either side of CPs

Excess thickening SCL (~1/3)

Improvements:

- Less material (~1350 m³ SCL)
- Less excavation
- Less time
- Safer construction

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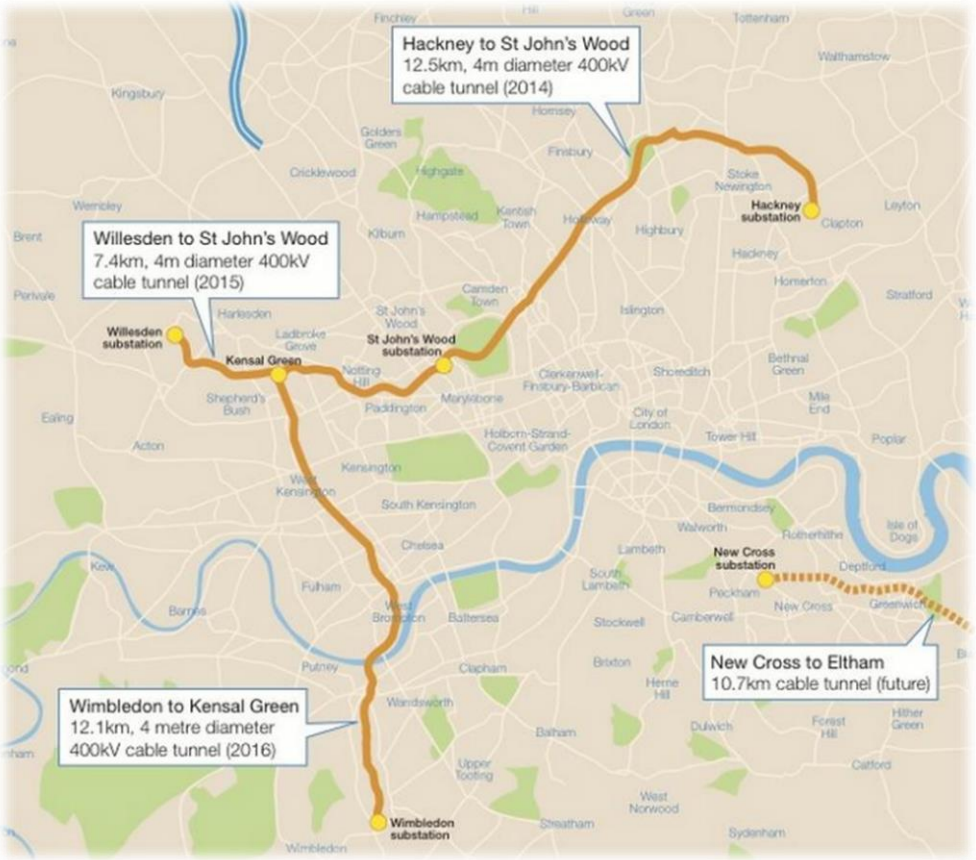
National Grid London Cable Replacement Tunnels

- **32km of new TBM driven segmental concrete tunnel lining from Willesden to Hackney, and Kensal Green to Wimbledon**

- **Tunnelling from 2011-2014.**
- **All concrete linings**

- **12km of 4m trapezoidal lining**
- **16km of 3.2m expanded lining**
- **4km of 3m bolted tunnel lining**



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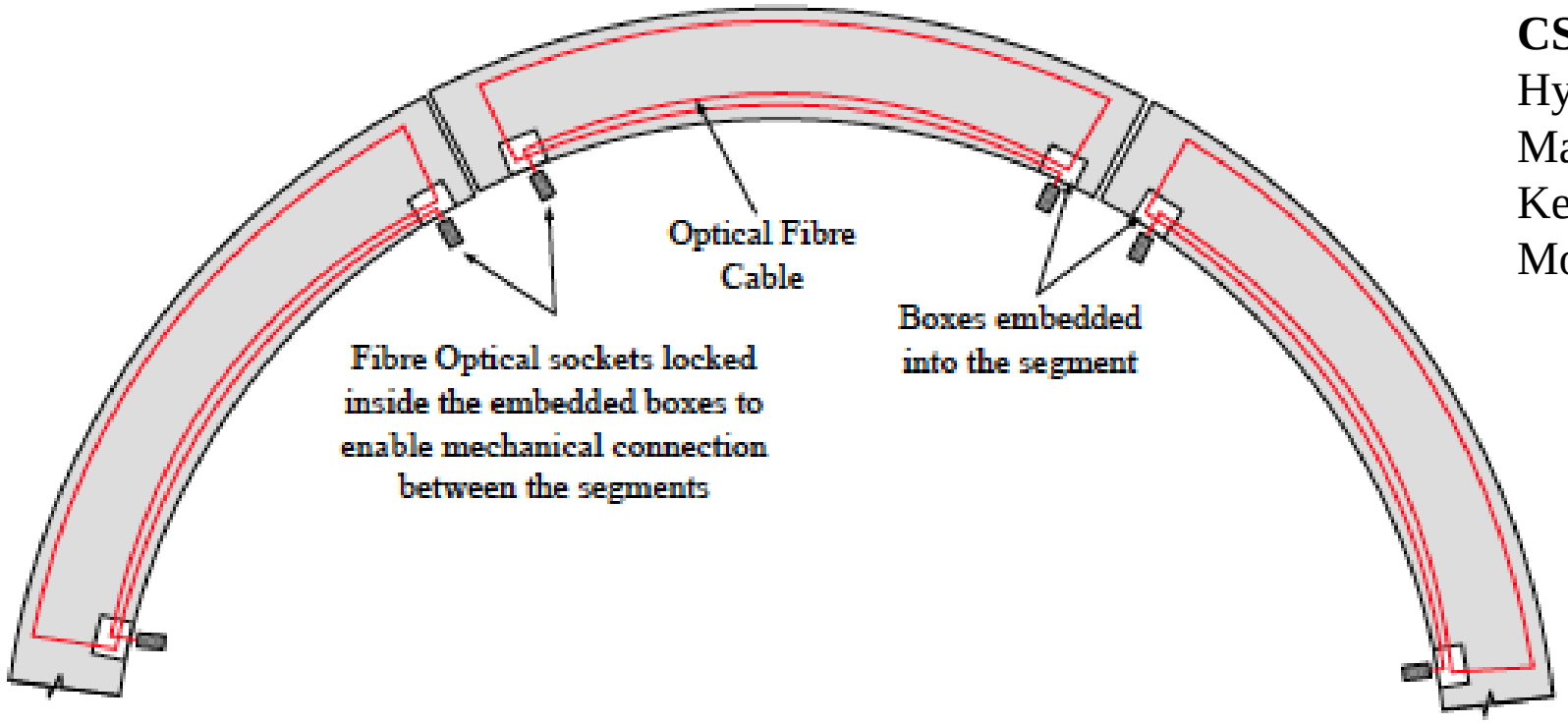
Fibre optic instrumented tunnel segments

Innovative fibre optic installation in concrete tunnel segments for National Grid London Power tunnels in collaboration with Costain



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Installing fibre optics in precast concrete lining segments (steel fibre reinforced)

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National Grid Power Tunnels: fibre optic instrumented tunnel lining segments erected at back of tunnel boring machine

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National Grid Power Tunnels
Two adjacent rings of fibre optic instrumented tunnel lining segments

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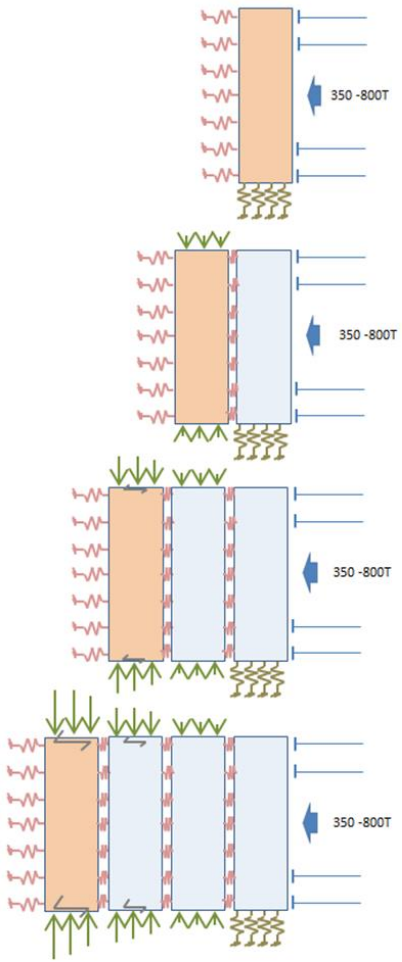
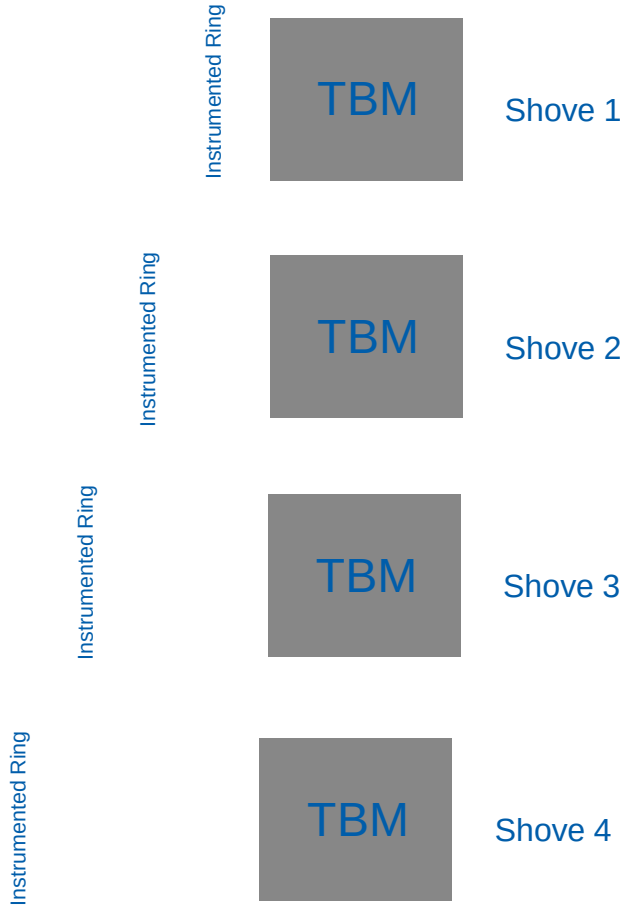
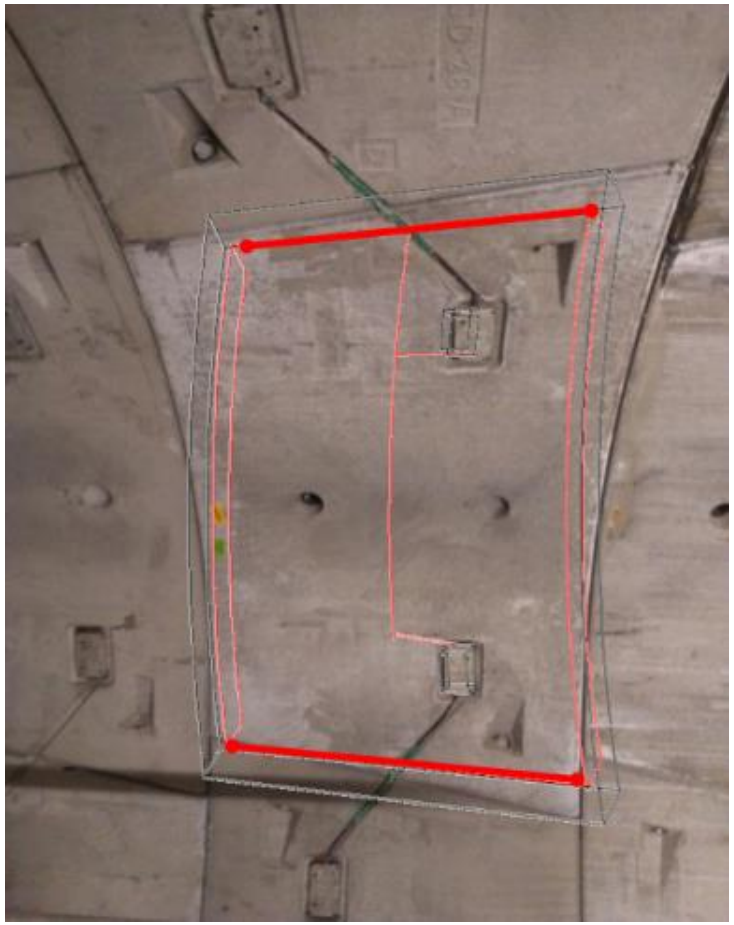
Short-term monitoring of longitudinal thrusts







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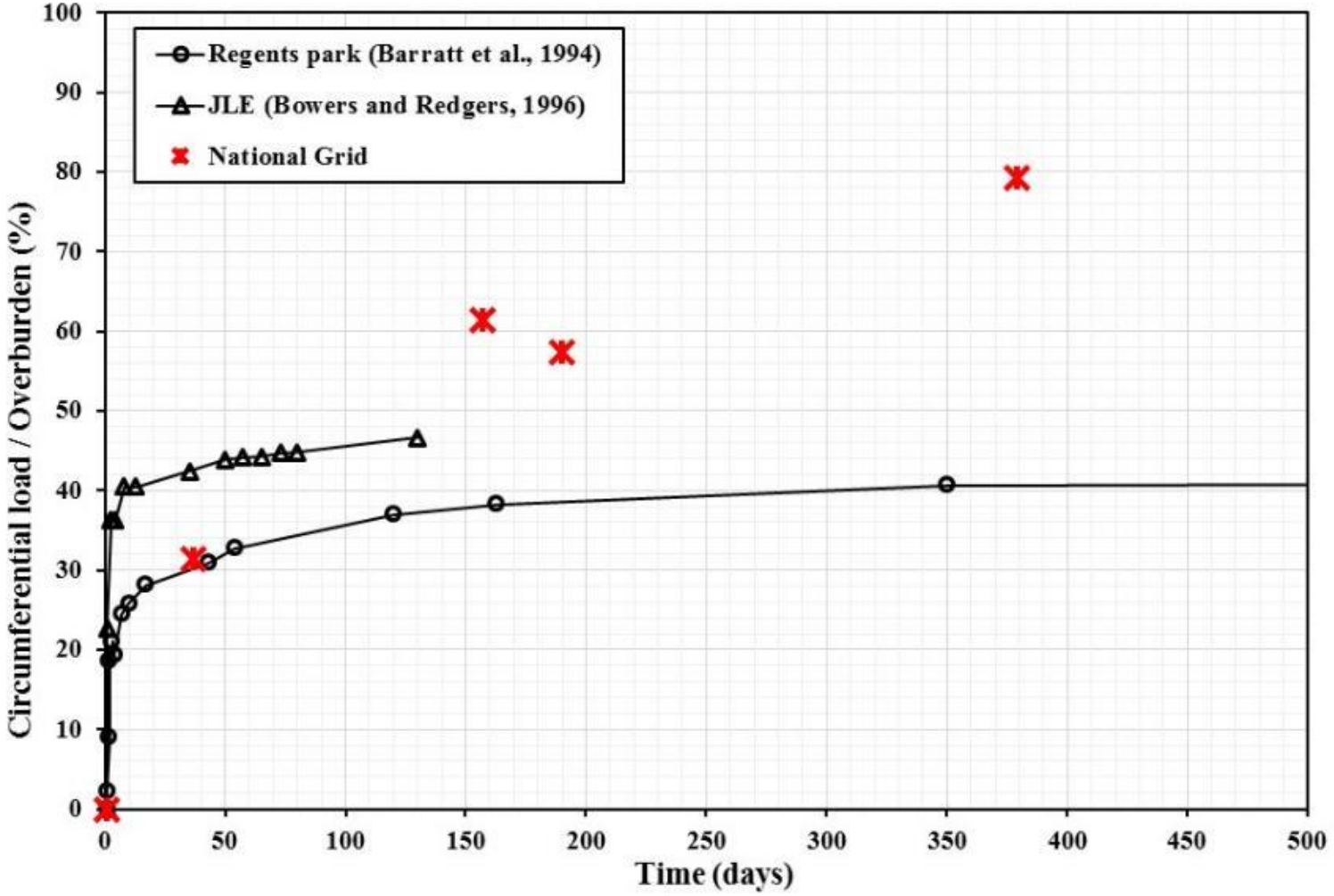
Time-dependent build-up of ground loading



Regents Park (1994) & JLE (1996)
Load cells between segments
Open face tunnelling

National Grid (2012)
Fibre optic strain gauges
EPB tunnelling

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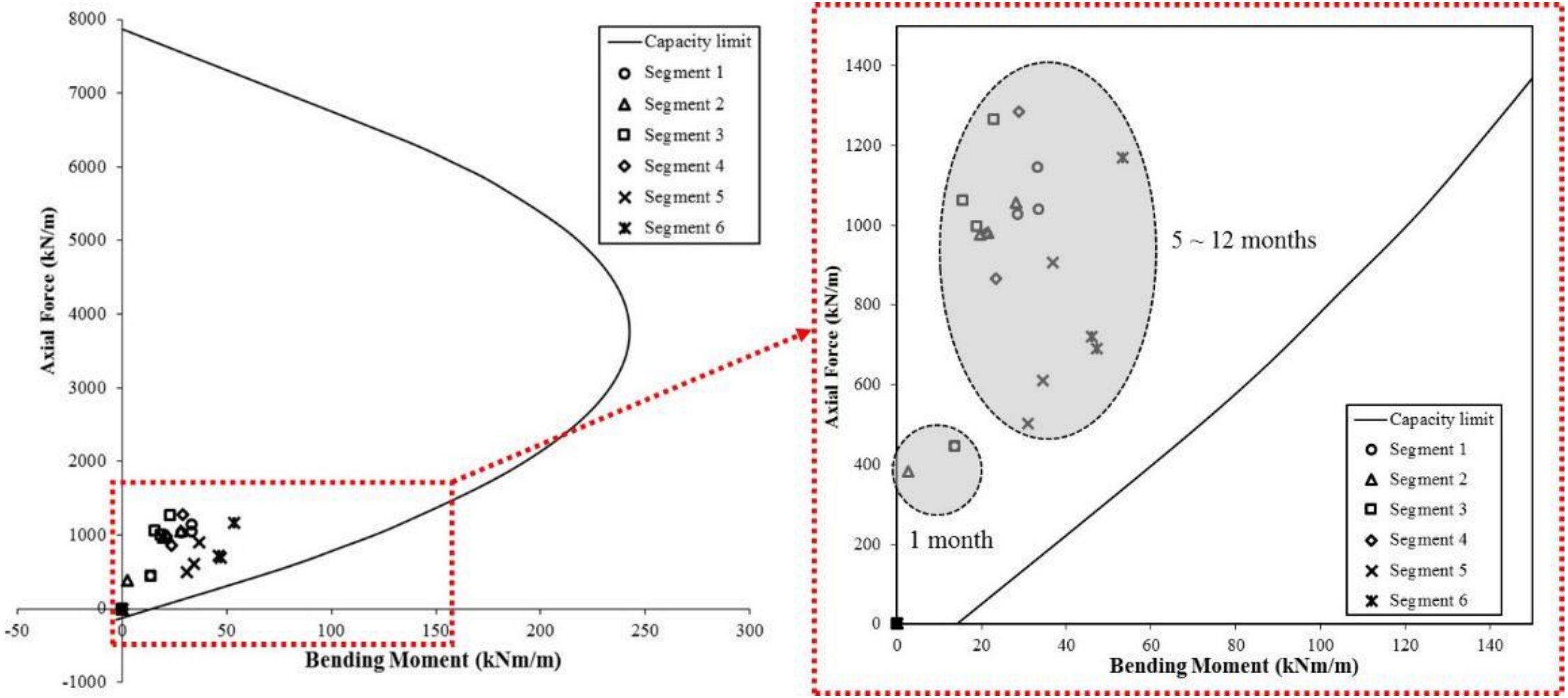
Axial forces and bending moments in steel-fibre reinforced concrete linings



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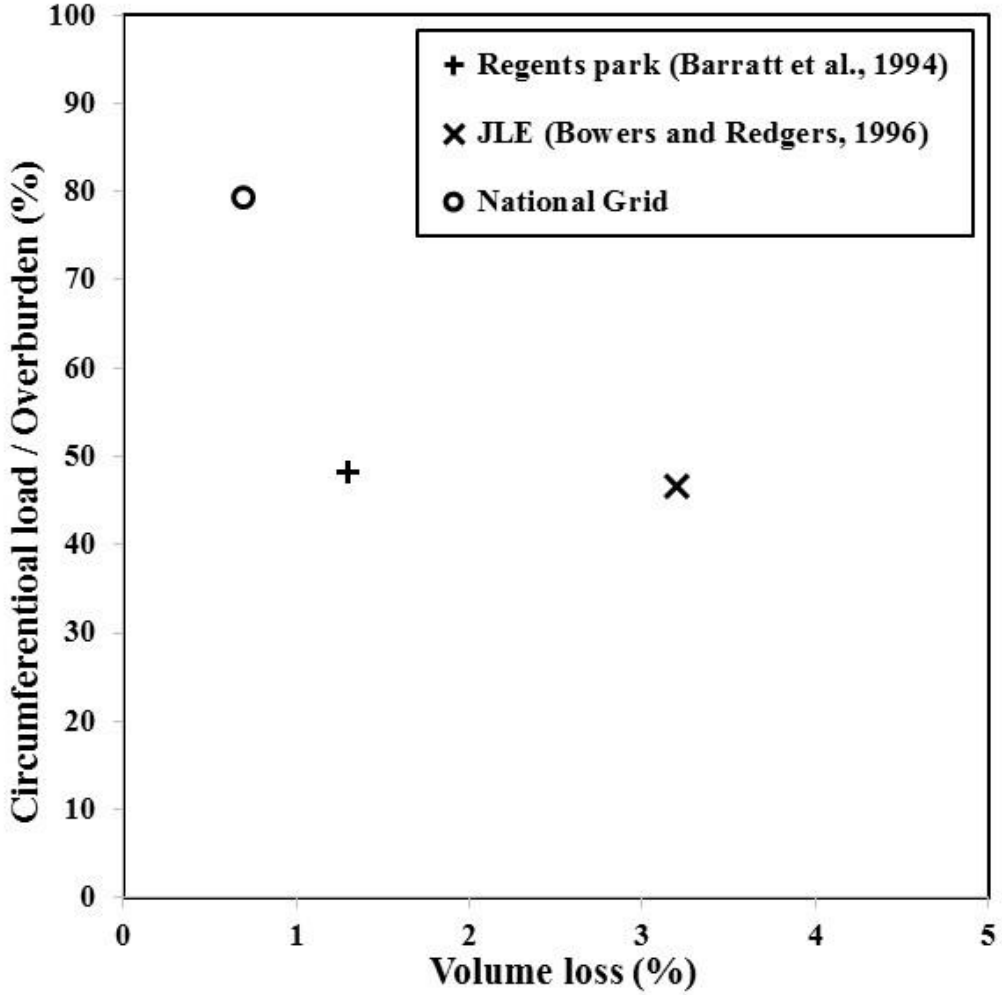
Normalised axial loads in London Clay tunnels



Regents Park (1994) & JLE (1996)
Load cells between segments
Open face tunnelling

National Grid (2012)
Fibre optic strain gauges
EPB tunnelling

Strain measurement for early warning detection of impending geotechnical instability

- slopes
- sinkholes

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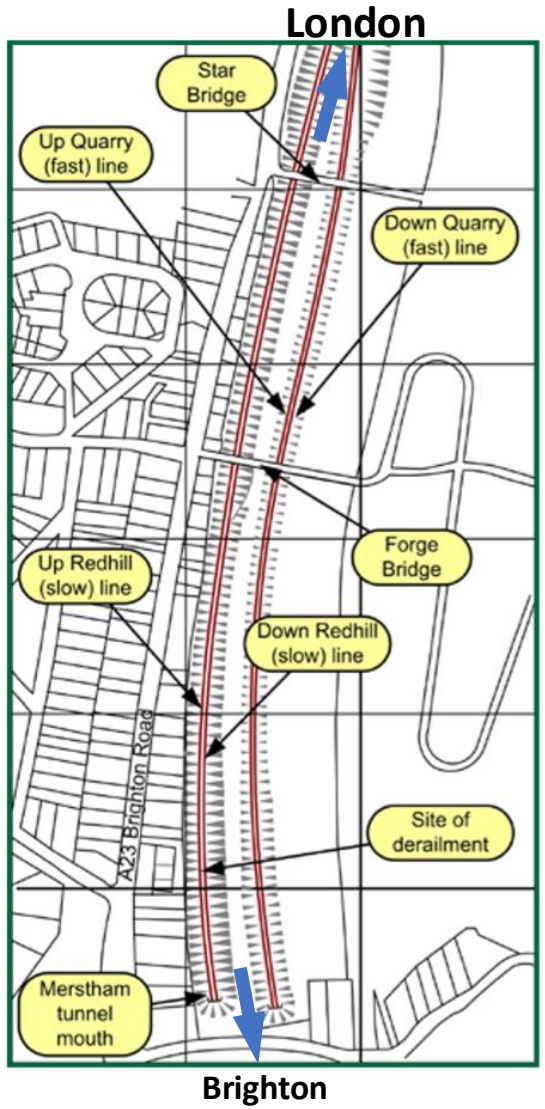
Rockfall Detection on Hooley Railway Cutting

30m deep cutting in Chalk, 25km south of London



Fibre optic sensing trial in 100m of cutting

CSIC, Network Rail, Bam Nuttall, Bam Ritchies

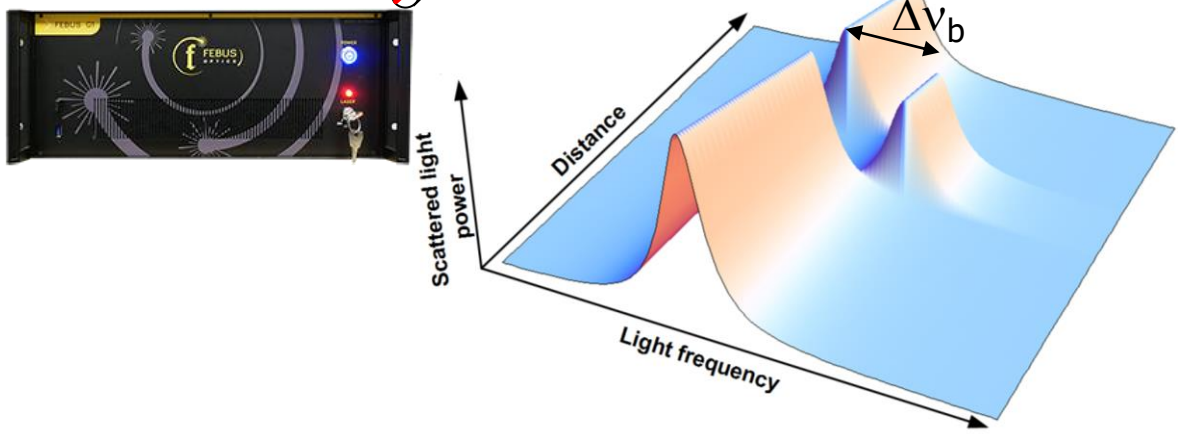
Fibre optic sensing technologies used

Distributed fibre optic sensing (DFOS)

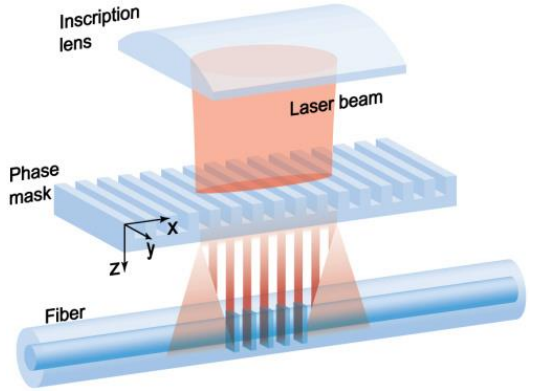
Strained section along the fibre

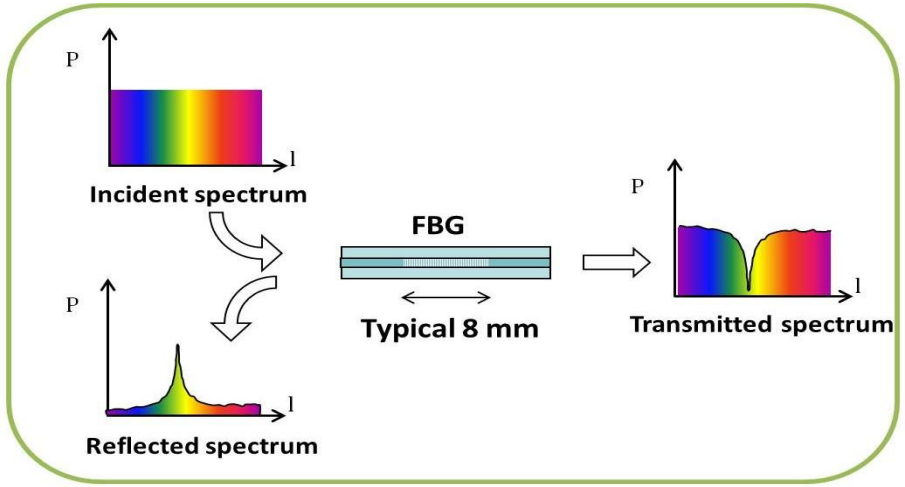
$$L = \frac{Time}{2} \cdot \frac{c}{n}$$

L



Fibre Bragg grating (FBG)



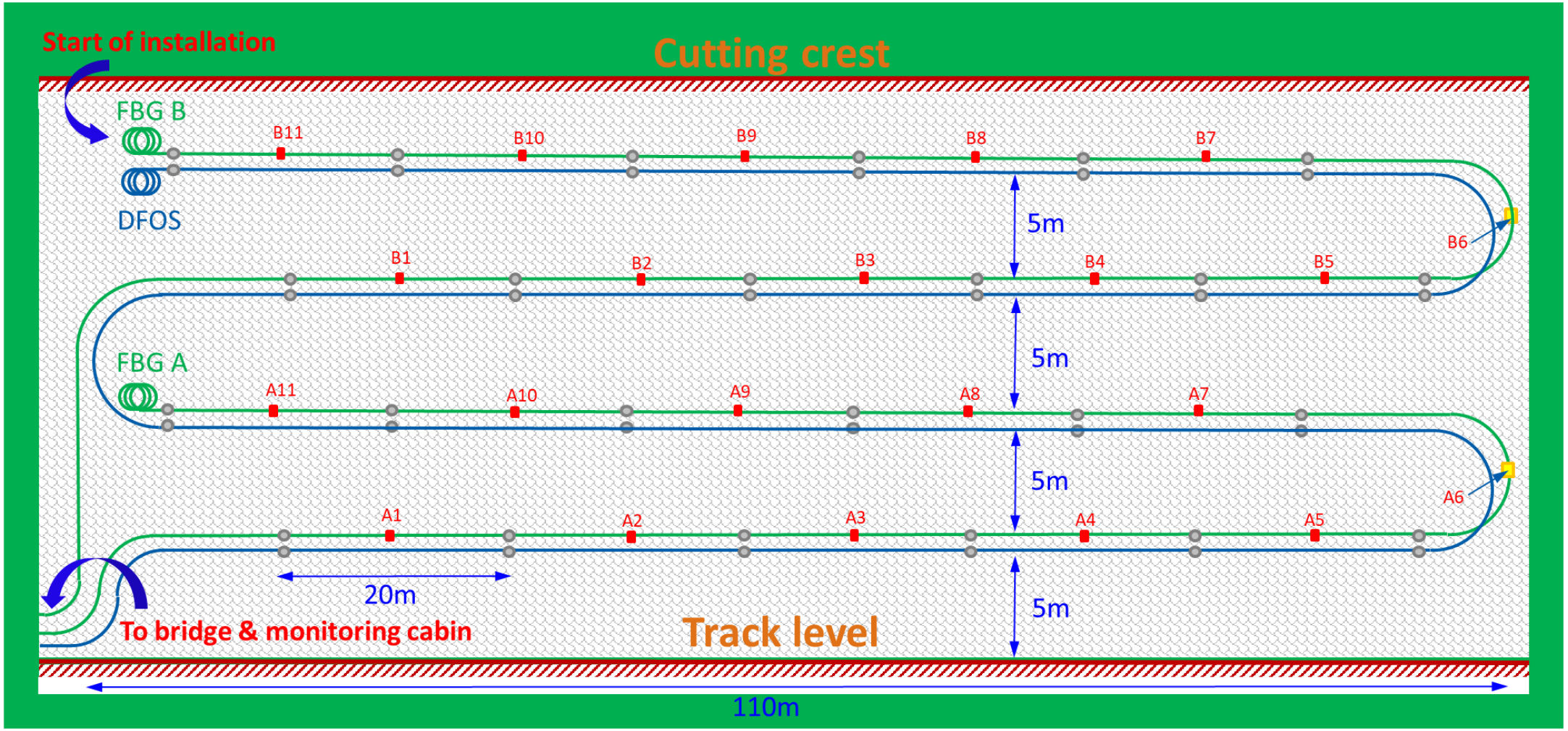


System installation

Fibre optic cables attached to rockfall mesh and fixed to ground anchors drilled into cutting face at 20m centres

System installation

Cables installed at four different heights along the cutting. Both DFOS and FBG cables attached to each clamp - allowing both systems to be attached at the same time



FO instrumented geogrid for ground movement detection – Tilehouse Lane Cutting (HS2)

Xiaomin Xu et al (2022) – paper to this conference

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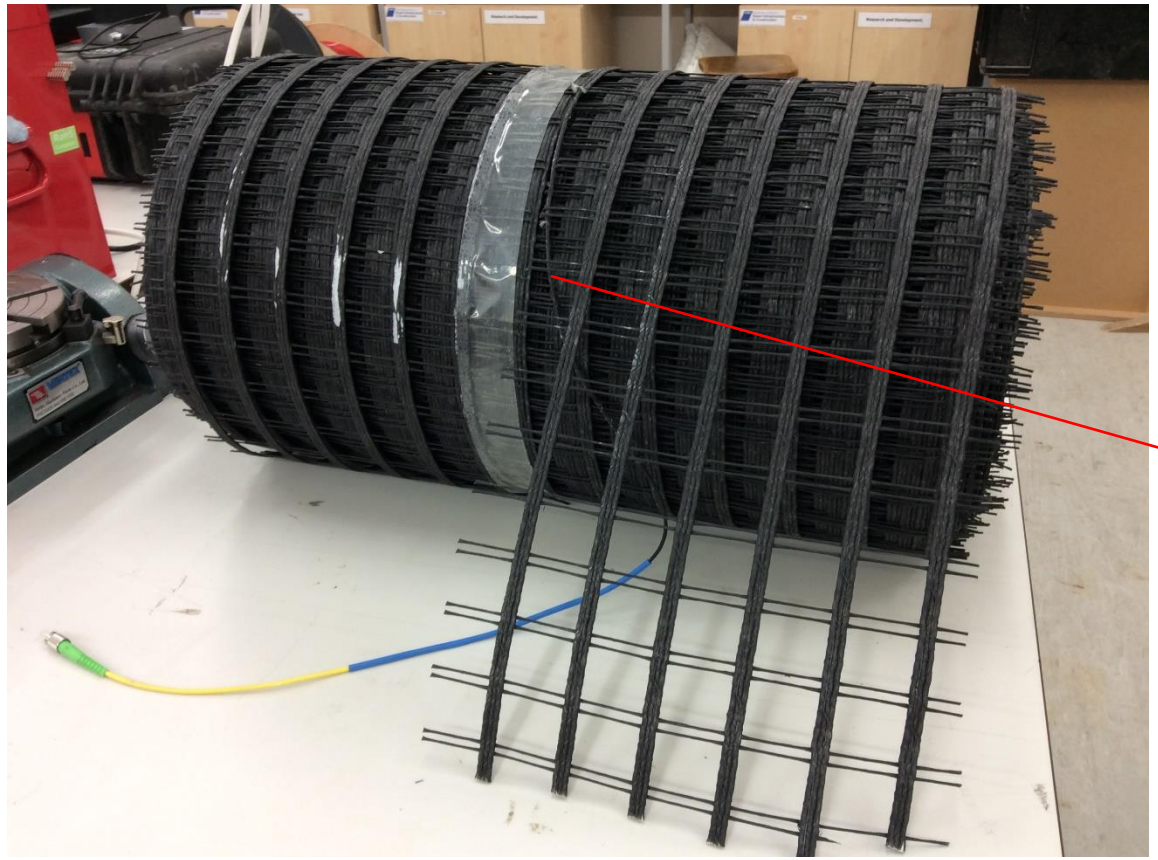
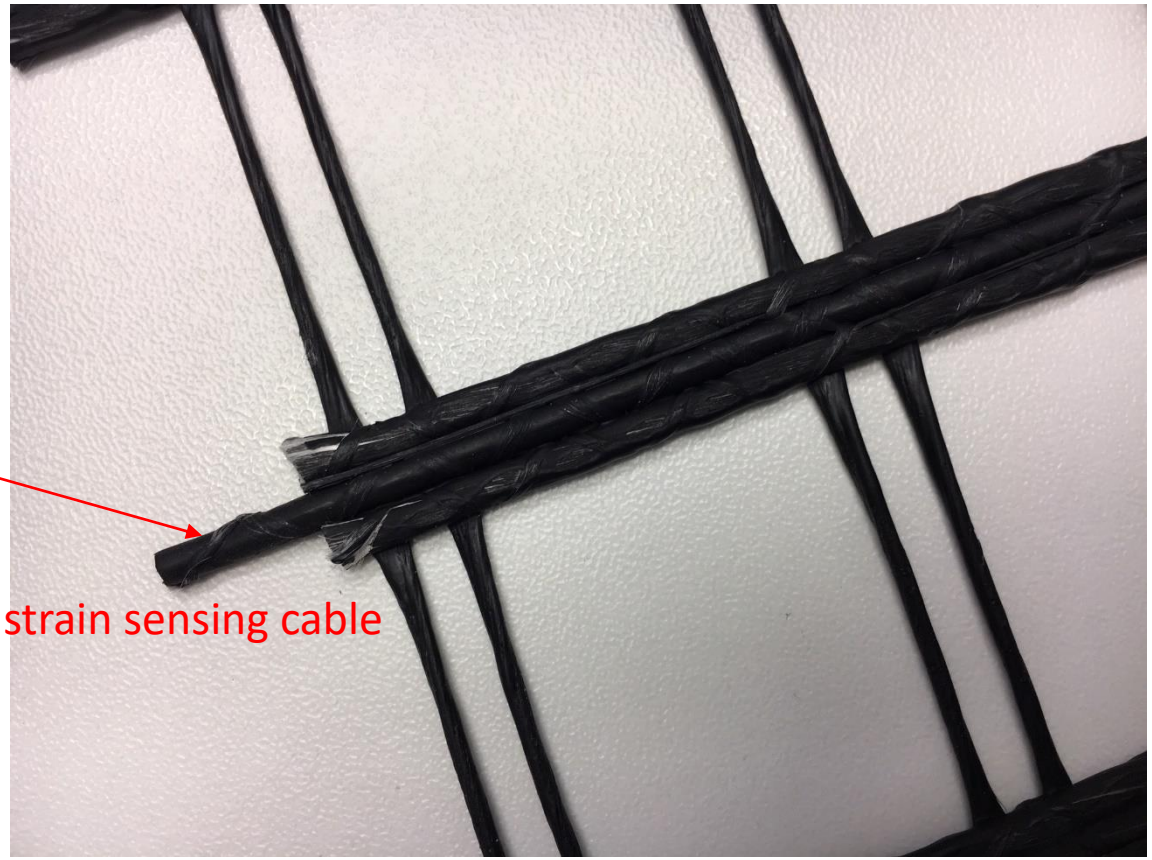
Development of DFOS instrumented geogrid

CSIC, Huesker and Epsimon





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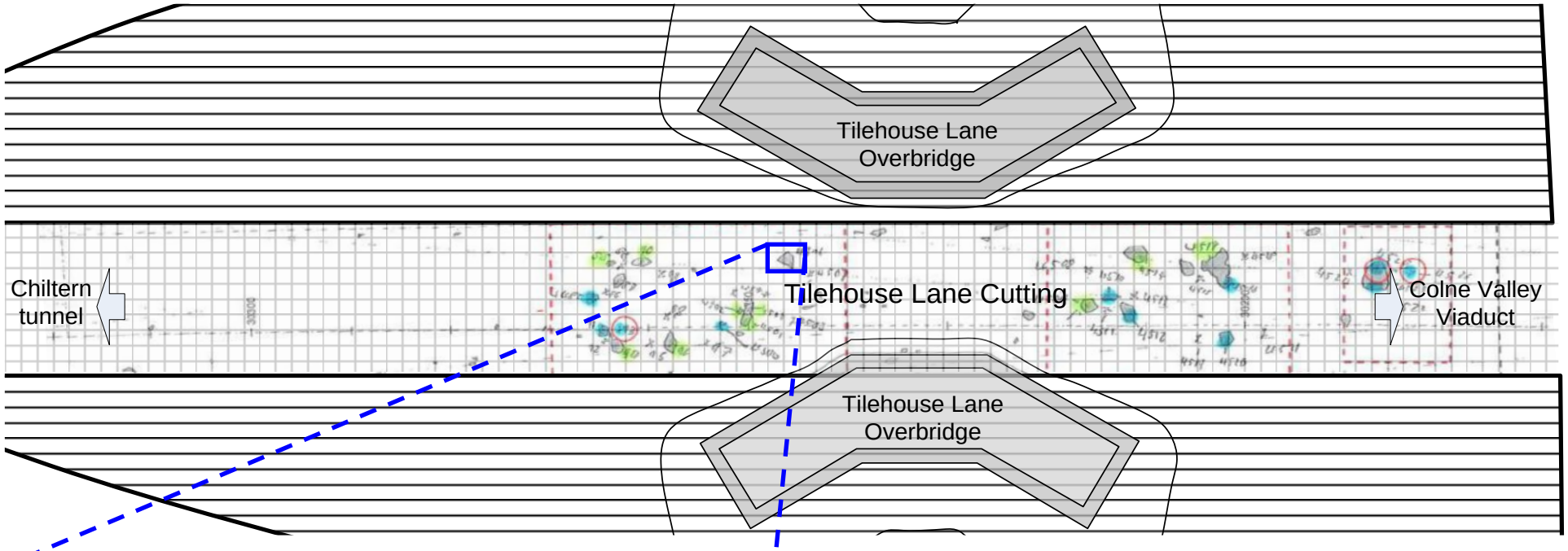
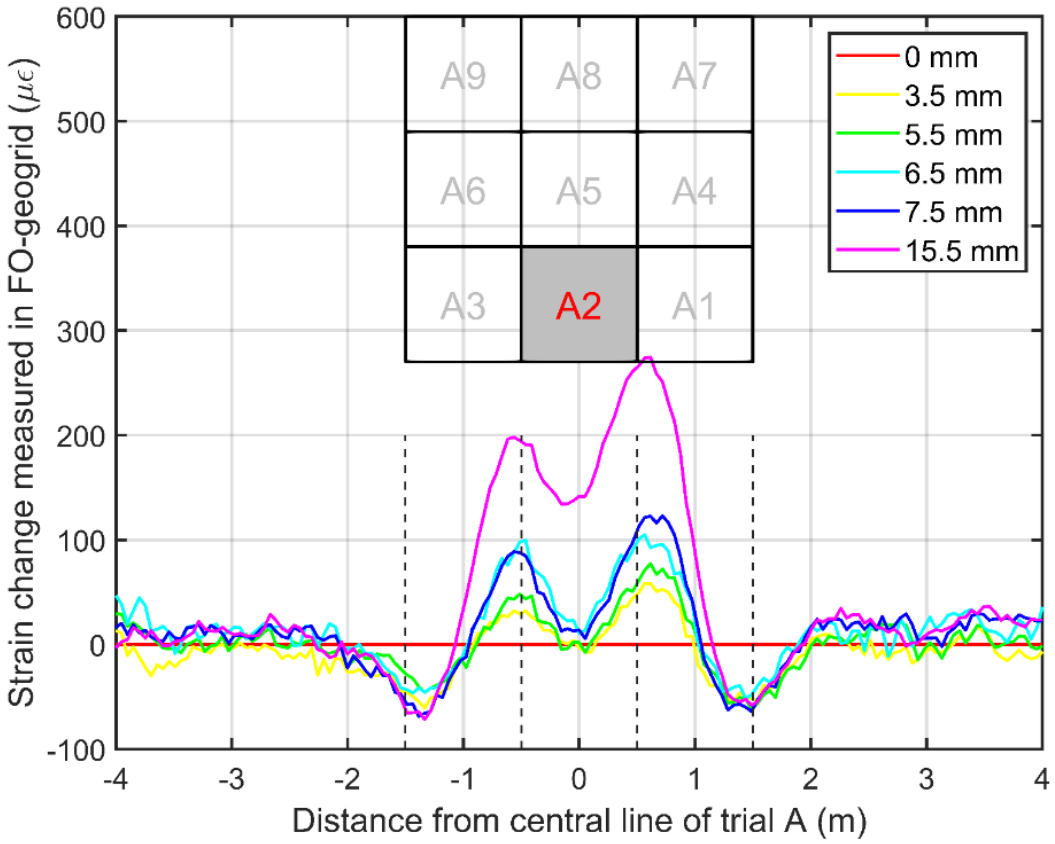
FO instrumented geogrid for early warning detection

CSIC, Jacobs, Huesker, Epsimon, Align, HS2 (Xu, X et al, 2022)

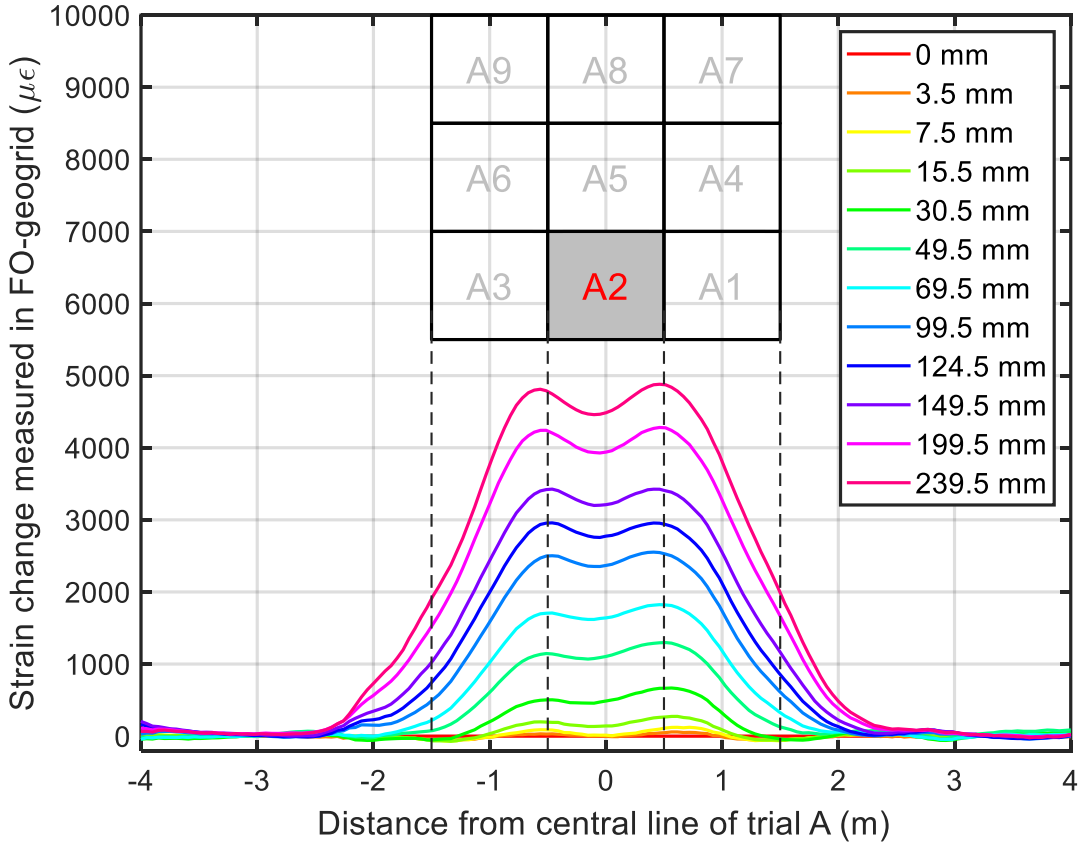


Preliminary field tests on instrumented geogrids

Xu, X et al, 2022



Small displacements



Large displacements

Large scale installation of Sensorgrid (100m long, 10m wide)

Xu, X et al (2022)

Summary

- **Fibre optic sensor monitoring: huge potential for strain measurement for monitoring soil-structure interaction**
- **Circular shafts**
  - **Hoop compressive strains much more significant**
  - **Longitudinal bending strains very small**
- **Tunnels**
  - **Sprayed concrete linings: strains induced around openings**
  - **TBM precast concrete linings: improved understanding of induced loads**
- **Early warning detection of impending geotechnical instability**
  - **Slopes**
  - **Sinkholes**

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