

# MUIR WOOD LECTURE 2011

TUNNELLING IN URBAN AREAS  
AND EFFECTS ON INFRASTRUCTURE  
Advances in research and practice.

**Robert MAIR**

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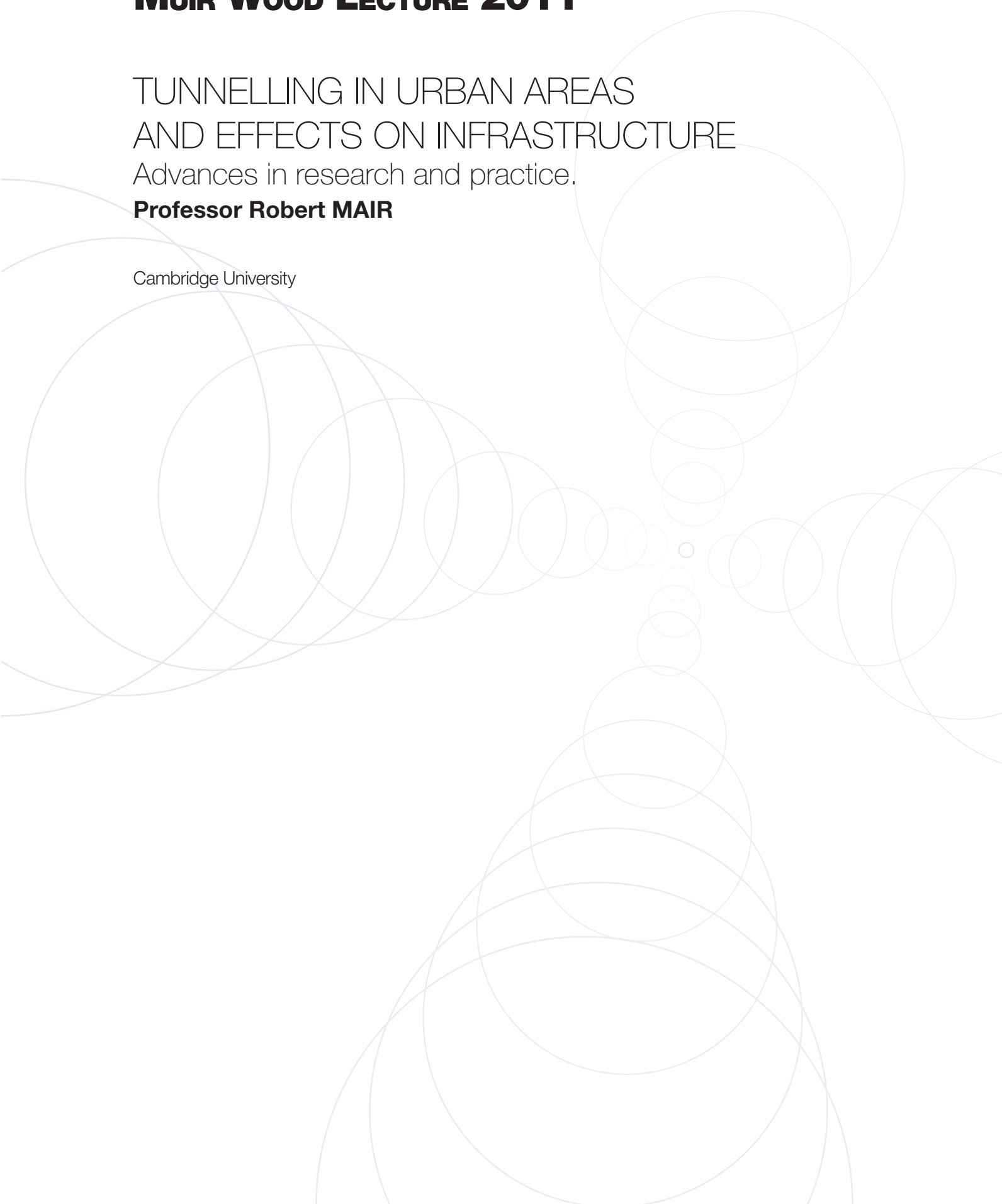
# MUIR WOOD LECTURE 2011

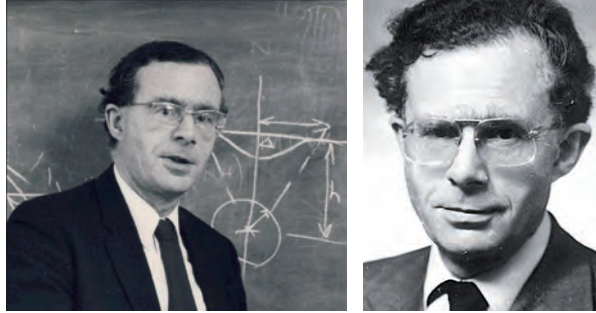
## TUNNELLING IN URBAN AREAS AND EFFECTS ON INFRASTRUCTURE

Advances in research and practice.

**Professor Robert MAIR**

Cambridge University





**Distinguished tunnelling engineer  
Founding President & Honorary Life President  
International Tunnelling Association 1973-2009**

*"It has been said that a tunnel is a long cylindrical hole through the ground, with a geologist at one end and a group of lawyers at the other."*

*"Yet more dire is the present day phenomenon of lawyers at each end."*

*"Uncertainty is a feature that is unavoidable in tunnelling. But it can be understood and controlled so that it does not cause damaging risk."*

Sir Alan Muir Wood was an inspirational engineer who had a great influence on tunnelling and geotechnics. I benefitted hugely from working with him on a wide variety of projects. We had many inspiring conversations.

He made many astute observations about tunnelling, some of which are reproduced on this slide. His comment about uncertainty in tunnelling being understood and controlled, so that it does not cause damaging risk, is a key theme of this Lecture.

#### OUTLINE OF LECTURE

##### **Effects of tunnelling on buildings: research advances**

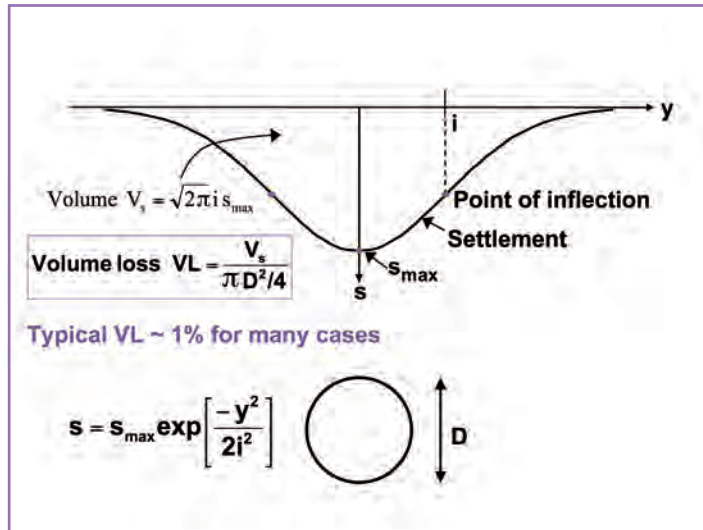
- centrifuge modelling and case histories
- field data of performance of buildings
- proposed new design method

##### **Recent innovations in field monitoring**

- optical fibre measurements
- wireless sensors
- future developments for 'smart' tunnelling

# 1 >> TUNNELLING-INDUCED GROUND MOVEMENTS AND BUILDING RESPONSE

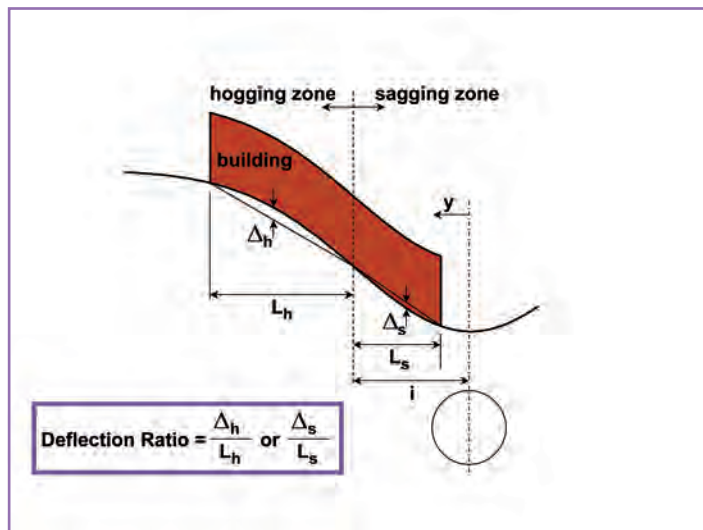
## TRANSVERSE SETTLEMENT TROUGH AND VOLUME LOSS



A key parameter of major importance in soft ground tunnelling is volume loss. Extensive field measurements have shown that the settlement trough can be well characterised by the Gaussian distribution (Peck, 1969; Rankin, 1988; Mair and Taylor, 1997).

Typical volume losses for tunnelling in soft ground are generally around 1% for many cases under well controlled conditions, and can often be well below 1% (Mair, 2008).

## DEFORMATION OF BUILDING ABOVE A TUNNEL

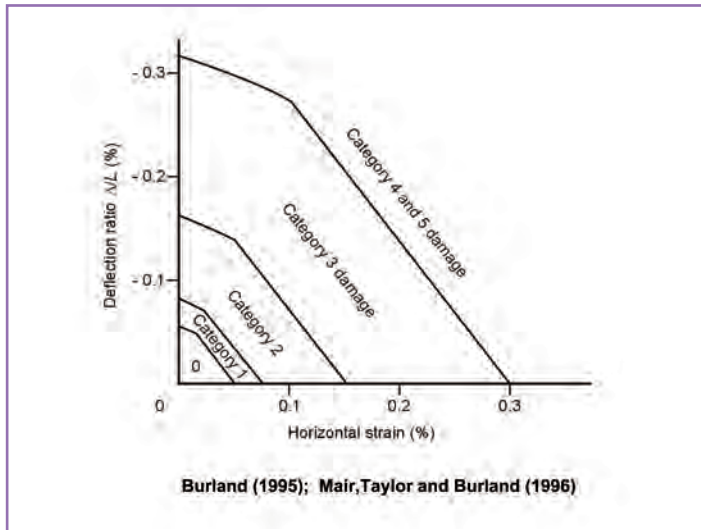


It is often assumed that the building follows the 'greenfield site' settlement trough. It is also convenient to consider the building separately either side of the point of inflexion, ie in the hogging or sagging zone.

The deflection ratio is a measure of the curvature of the building and the strains induced in the building are directly related to the deflection ratio (Burland and Wroth, 1974; Burland et al, 1977; Mair et al, 1996)

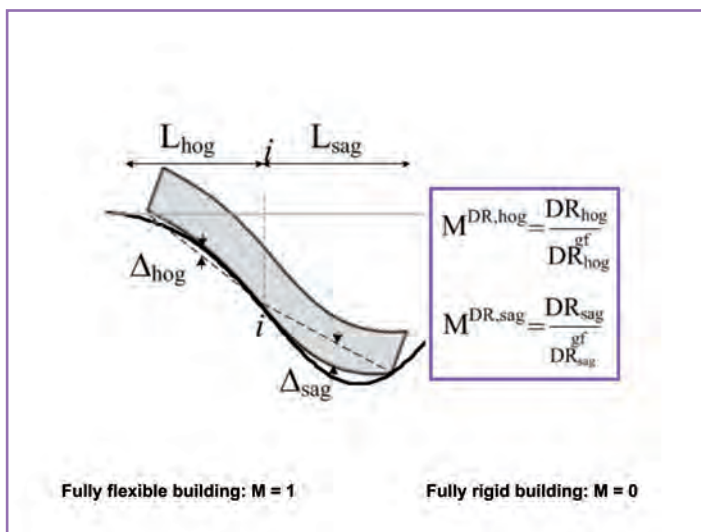
# 1 >> TUNNELLING-INDUCED GROUND MOVEMENTS AND BUILDING RESPONSE

## RELATIONSHIP OF BUILDING DAMAGE CATEGORY TO DEFLECTION RATIO AND HORIZONTAL STRAIN



Building damage can be related directly to the magnitude of tensile strain induced in the building (Boscardin and Cording, 1989) and simple design charts can be used relating deflection ratio and horizontal strain (Burland, 1995; Mair, Taylor and Burland, 1996).

## MODIFICATION OF SETTLEMENT SHAPE BY STIFFNESS OF BUILDING



The inherent stiffness of buildings may mean that they do not always follow the 'greenfield settlement' profile.

Modification factors (Potts and Addenbrooke, 1977) are a useful way of quantifying this effect.

## 2 >> CENTRIFUGE MODELLING OF TUNNELLING EFFECTS ON BUILDINGS

### 10 METRE BEAM CENTRIFUGE AT CAMBRIDGE



**Centrifuge modelling scaling laws:**  
 **$1/N^{\text{th}}$  scale at  $Ng$  gives same stresses as at full scale.**  
**Typically  $N=75$ :**  
**60mm diameter tunnel models 4.5m dia.**

Centrifuge modelling has been carried out on the 8m diameter beam centrifuge at the University of Cambridge to investigate the influence of building stiffness on response to tunnelling induced ground movements (Farrell, 2010).

### CENTRIFUGE MODELLING OF TUNNELLING AND SOIL-STRUCTURE INTERACTION

**Instrumentation**

- Dense fine sand
- Tested at 1/75 scale at 75g
- Prototype scale:
  - 6.15m diameter tunnel
  - 8.25m cover

**Instrumentation to measure soil displacements**

- Lasers
- Displacement transducers
- Particle Image Velocimetry (PIV)

**Farrell (2010)**

**Model Structure**

**Model Tunnel**

**Camera for PIV**

**Strain Gauges**

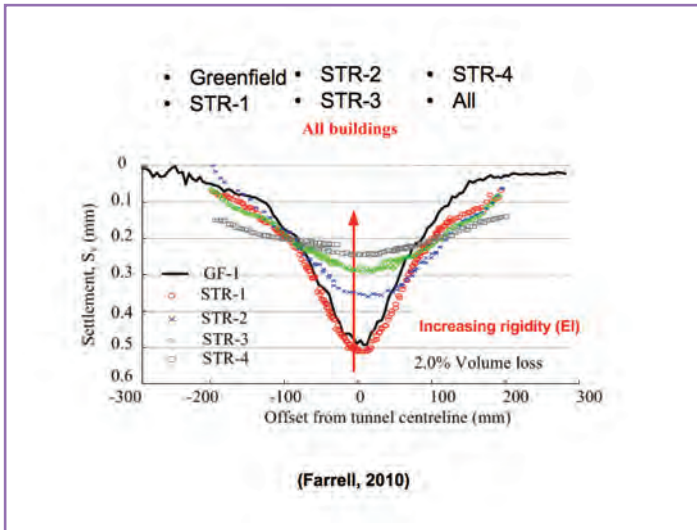
**Dimensions:**  
C=110mm, B=40mm, D=80mm, Tunnel

The tunnel volume loss can be progressively increased in the model tunnel and the ground and building movements observed using particle image velocimetry (PIV) and digital photography together with lasers and instrumentation.



## 2 >> CENTRIFUGE MODELLING OF TUNNELLING EFFECTS ON BUILDINGS

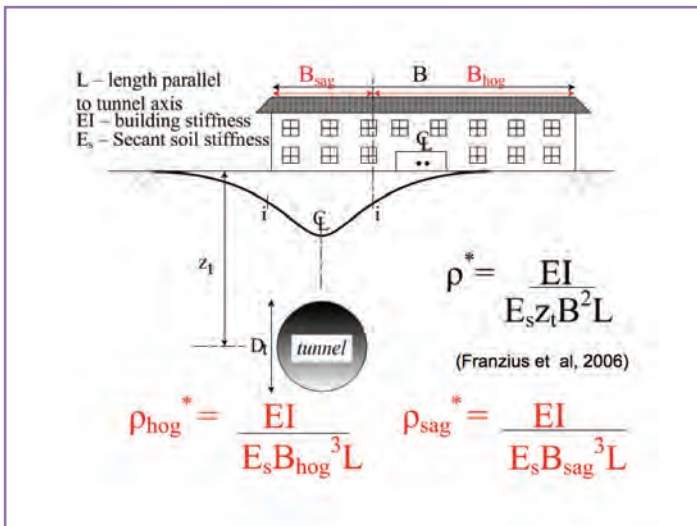
### RESPONSE OF DIFFERENT STIFFNESS MODEL BUILDINGS TO TUNNELLING



The settlement response of buildings is highly dependent on their bending stiffness. For a given soil stiffness, buildings with a low bending stiffness or rigidity ( $EI$ ) respond flexibly and settle in close agreement with the greenfield settlement profile.

Buildings with higher bending stiffness modify the greenfield settlement profile and are subjected to much smaller distortions (and hence strains).

### DEFINITION OF RELATIVE STIFFNESS (STIFFNESS OF THE BUILDING RELATIVE TO THE SOIL STIFFNESS)

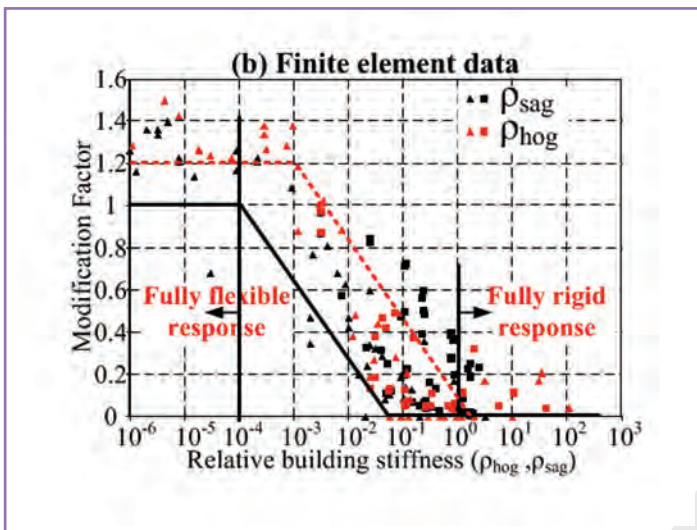
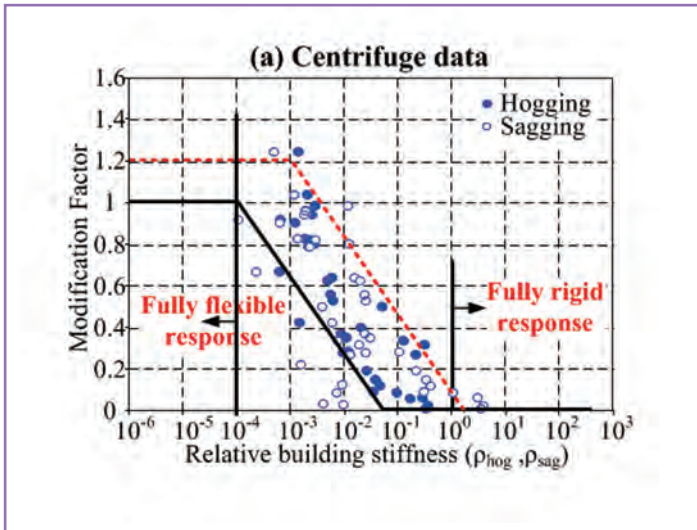


A new definition of stiffness can be defined in terms of the widths of the building in the sagging and hogging parts of the 'greenfield' settlement trough,  $B_{sag}$  and  $B_{hog}$  respectively (Goh, 2010).



## 2 >> CENTRIFUGE MODELLING OF TUNNELLING EFFECTS ON BUILDINGS

### SUMMARY OF CENTRIFUGE MODEL TEST RESULTS



Centrifuge model tests and finite element analyses both show that the relationship between modification factors and relative building stiffness fall into a relatively well defined envelope.

Most centrifuge model test results fall within a narrow envelope

Finite element analyses of wide variety of simplified buildings indicate similar trends (Potts and Addenbrooke, 1997; Franzius et al, 2006)

Fully rigid response ( $M=0$ )  
if  $\rho^*_{hog}$  or  $\rho^*_{sag} > 1$


Fully flexible response ( $M = 1$ )  
if  $\rho^*_{hog}$  or  $\rho^*_{sag} < 10^{-4}$

Potential for reducing need for protective measures.

### 3 >> CASE HISTORY OF BUILDING RESPONSE TO TUNNELLING

#### CASE STUDY – ITALY - FARRELL, MAIR, SCIOTTI, PIGORINI & RICCI (2011)

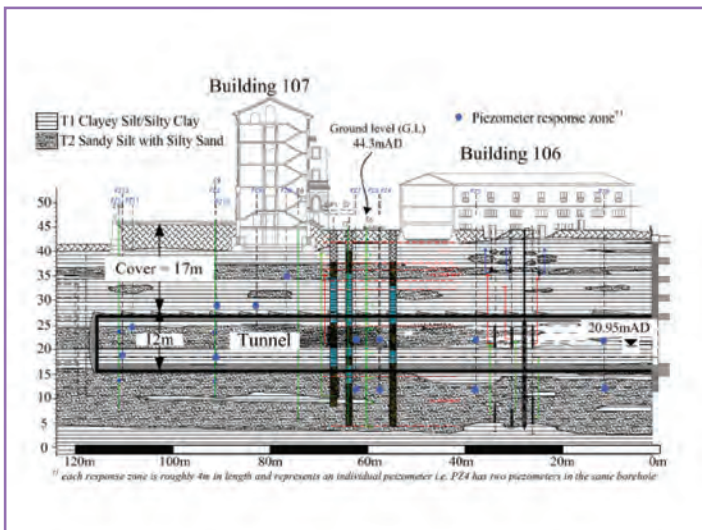
- 12m diameter SCL tunnel
- Stiff silty clay/clayey silt with silty sandy lenses
- Passes beneath two load bearing masonry buildings
  - Building 106: 2 storeys
  - Building 107: 5 storeys
- Extensive protective measures
  - Jet grouting from surface
  - Jet grouting from within tunnel
  - Compensation grouting
  - Forepoling
  - Face anchors
  - Drains installed in tunnel face



**Very different response of two buildings to tunnelling**

The tunnel in this case history passes beneath two buildings of very different stiffness. The 12m tunnel was constructed using the sprayed concrete lining (SCL) method, as part of a high speed railway line.

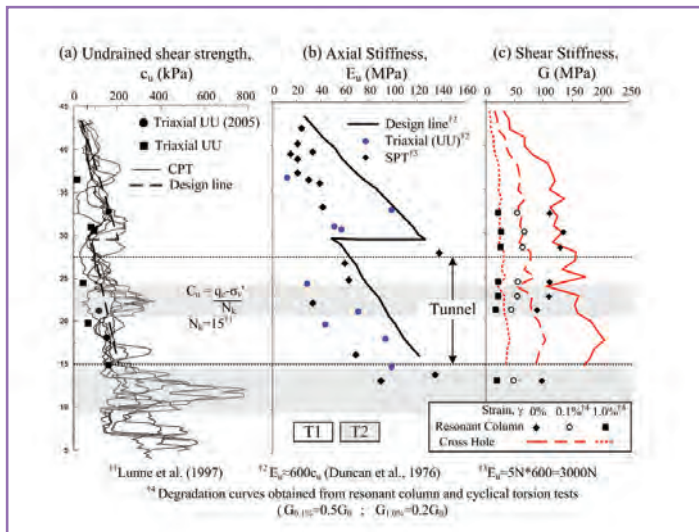
#### CASE STUDY – ITALY - FARRELL, MAIR, SCIOTTI, PIGORINI & RICCI (2011)



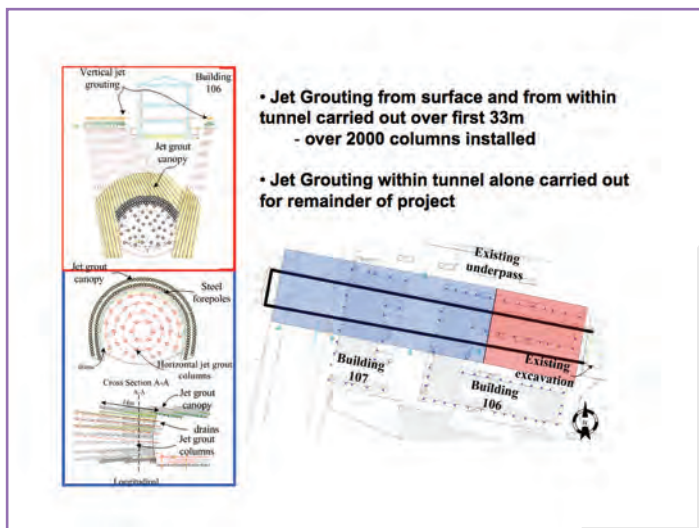
The ground conditions generally encountered by the tunnel consisted of a stratified stiff to very stiff silty clay with sandy silt lenses.

### 3 >> CASE HISTORY OF BUILDING RESPONSE TO TUNNELLING

#### GROUND CONDITIONS



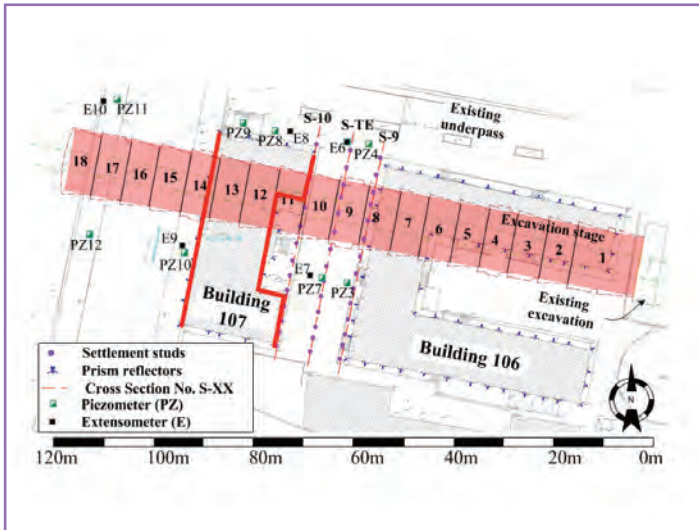
#### CASE STUDY – ITALY - FARRELL, MAIR, SCIOTTI, PIGORINI & RICCI (2011)



Extensive jet grouting was undertaken: for the early part of the tunnel from the ground surface and from within the tunnel, for the remainder of the tunnel from within the tunnel alone.

### 3 >> CASE HISTORY OF BUILDING RESPONSE TO TUNNELLING

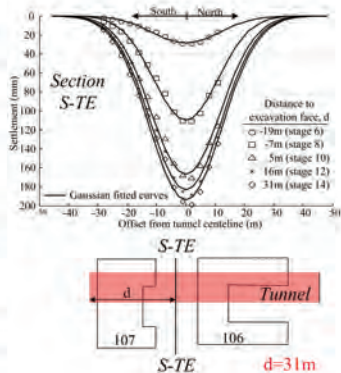
#### MONITORING INSTRUMENTATION



Extensive monitoring instrumentation was installed, both in the ground between the buildings to measure the 'greenfield' response, and also on the buildings themselves.

#### OBSERVED GREENFIELD RESPONSE

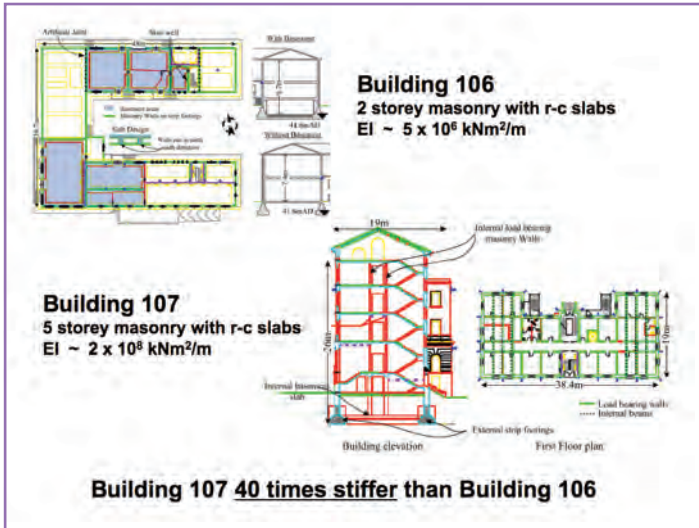
- Significant proportion of settlements occur ahead of face
- Settlements conform to a Gaussian distribution
- Very large settlements observed (200mm)
- Volume loss of 5% (mainly caused by jet grouting)





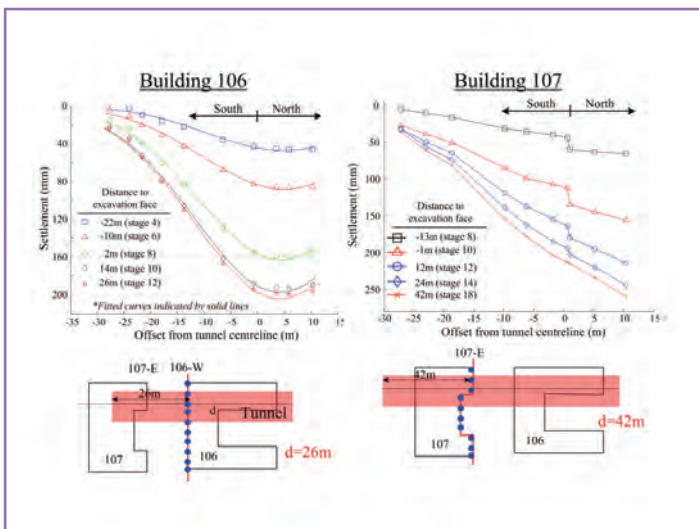
### 3 >> CASE HISTORY OF BUILDING RESPONSE TO TUNNELLING

CASE STUDY – ITALY - FARRELL, MAIR, SCIOTTI, PIGORINI & RICCI (2011)



The 5 storey Building 107 was assessed to have a bending stiffness ( $EI$ ) of around 40 times that of the 2 storey Building 106.

### RESPONSE OF BUILDINGS TO TUNNELLING

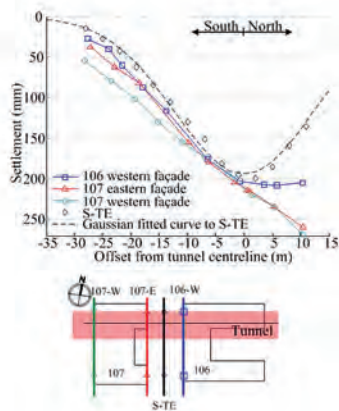


Building 106 behaved almost fully flexibly, whereas Building 107 behaved in an almost fully rigid manner, exhibiting tilt but very little curvature.

### 3 >> CASE HISTORY OF BUILDING RESPONSE TO TUNNELLING

#### COMPARISON OF RESPONSE OF BUILDINGS

- **Building 106 responds relatively flexibly – similar to 'greenfield' S-TE array**
- **Building 107 responds fully rigidly**



## 4 >> FIELD DATA OF BUILDING PERFORMANCE IN RESPONSE TO TUNNELLING

THE RESPONSE OF A WIDE VARIETY OF BUILDINGS TO TUNNELLING HAVE BEEN MONITORED IN DETAIL:



### **Elizabeth House London**

A reinforced concrete framed 10 storey building constructed in the 1960s (Mair and Taylor, 2001; Standing, 2001)



### **Moodkee Street London**

Three storey buildings of load bearing brick on shallow strip foundations (Withers, 2001)



### **2 storey and 5 storey buildings Italy**

With basements, reinforced concrete slabs and load bearing masonry walls founded on strip footing foundations (Farrell, Mair, Sciotti, Pigorini & Ricci, 2011)



### **The Treasury London**

A stone-clad brick-masonry building constructed at the beginning of the 20th century, comprising a sub-basement, a basement, a sub-ground floor, and four storeys above ground level, with a light concrete slab foundation with localised pads and strip footings (Viggiani and Standing, 2001)



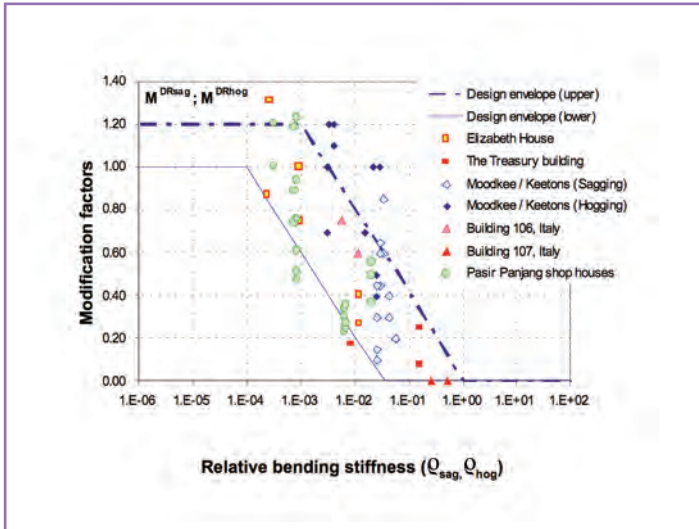
### **Pasir Panjang shophouses Singapore**

Two-storey, reinforced-concrete framed buildings with brick infill, founded on shallow foundations of individual footings on wooden piles (Goh and Mair, 2011)



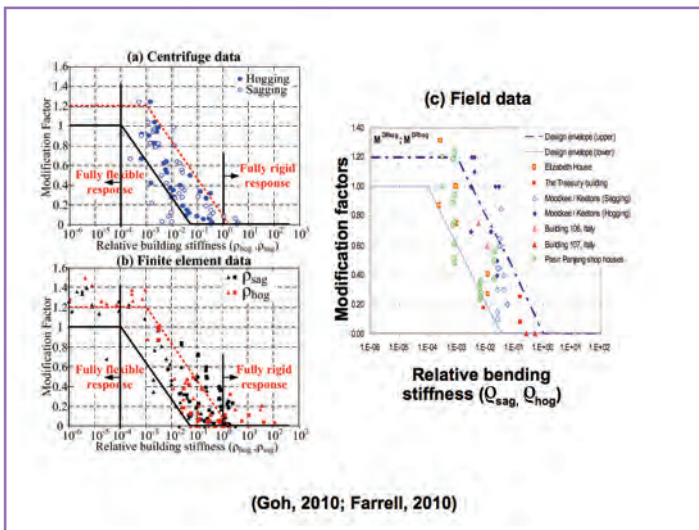
## 4 >> FIELD DATA OF BUILDING PERFORMANCE IN RESPONSE TO TUNNELLING

### FIELD DATA OF BUILDINGS INFLUENCED BY TUNNELLING (GOH, 2010; FARRELL, 2010)



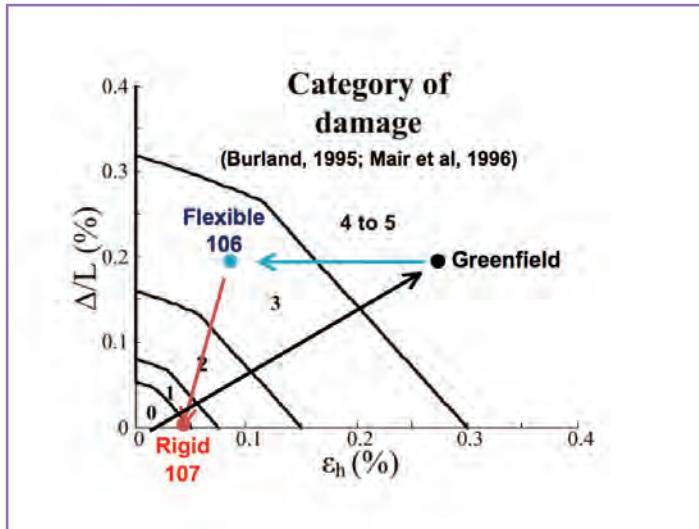
The majority of the data from all of the observed buildings fall into the same envelope of modification factor versus relative bending stiffness as found from centrifuge model tests and finite element analyses. This envelope can be used for design. By estimating the relative bending stiffness of the building, the modification factor can be estimated, and this will indicate whether the building is likely to behave fully flexibly, partially flexibly or fully rigidly.

### CENTRIFUGE MODEL TESTS, FE RESULTS AND FIELD DATA OF BUILDINGS INFLUENCED BY TUNNELLING



## 4 >> FIELD DATA OF BUILDING PERFORMANCE IN RESPONSE TO TUNNELLING

### IMPLICATIONS FOR DESIGN



Assuming the buildings to conform to 'greenfield' ground movements may very often be overly conservative.

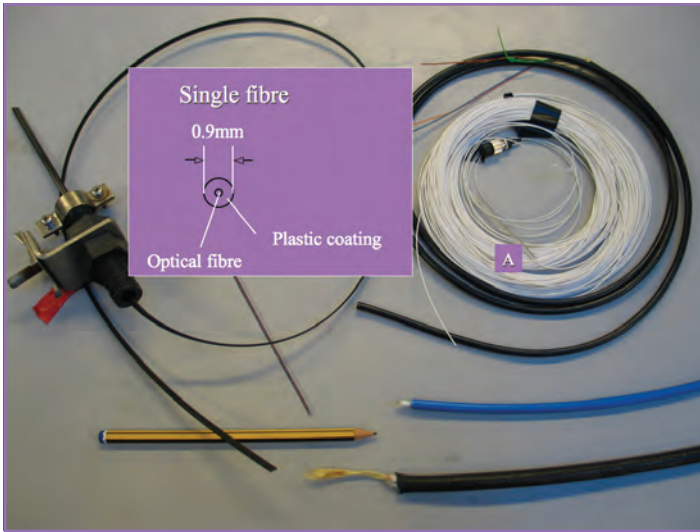
Building category damage 4/5 ('Severe' to 'Very Severe') would have been predicted for Buildings 106 and 107 in Italy if they are assumed to be fully flexible. In reality, most buildings, however flexible in bending, experience significantly smaller horizontal strain (Mair, 2003). Building 106 was almost fully flexible in bending but experienced smaller horizontal strains (most of these being associated with jet grouting). Building 107 was almost completely rigid, and as a consequence experienced very small deflection ratio and hence very little damage was observed.

### SUMMARY

- Centrifuge modelling provides new insights into building response to tunnelling
- Consistent with field data of building performance
- Relative building stiffness a very important parameter
  - stiff buildings experience much less differential settlement than flexible buildings
  - in such cases expensive protective measures not necessary
- In many cases very small horizontal strain induced in buildings
- New design approach proposed - takes account of relative building stiffness – verified by centrifuge model tests and field data of building performance

## 5 >> OPTICAL FIBRE MONITORING

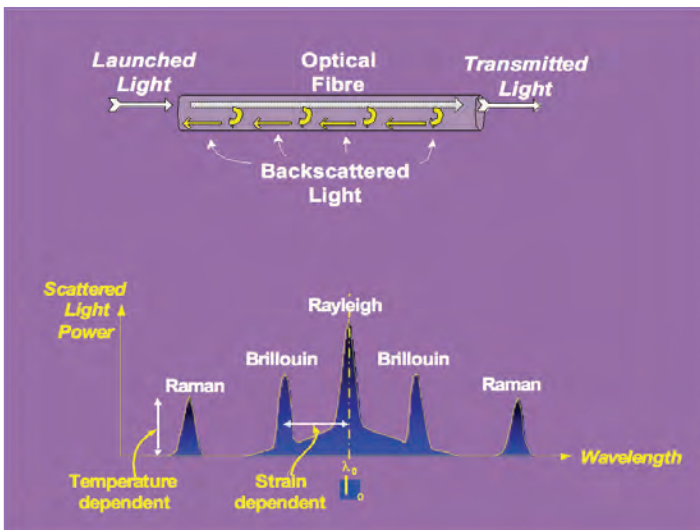
### OPTICAL FIBRE



A recent subject of research at Cambridge University, led by Professor Kenichi Soga, is a novel technique which uses distributed optical fibre strain sensing (Bennett et al, 2006; Klar et al, 2006; Vorster et al, 2006; Mohamad et al, 2007; Mohamad, 2008; Mair,2008).

This direct measurement of strain is of considerable potential for many geotechnical and structural applications. The distributed strain sensing technique is based on Brillouin optical time domain reflectometry (BOTDR). A major advantage of the system is that the sensing fibre is often standard single optical fibre encased with a 0.9 mm plastic cover.

### PRINCIPLE OF DISTRIBUTED OPTICAL FIBRE SENSING

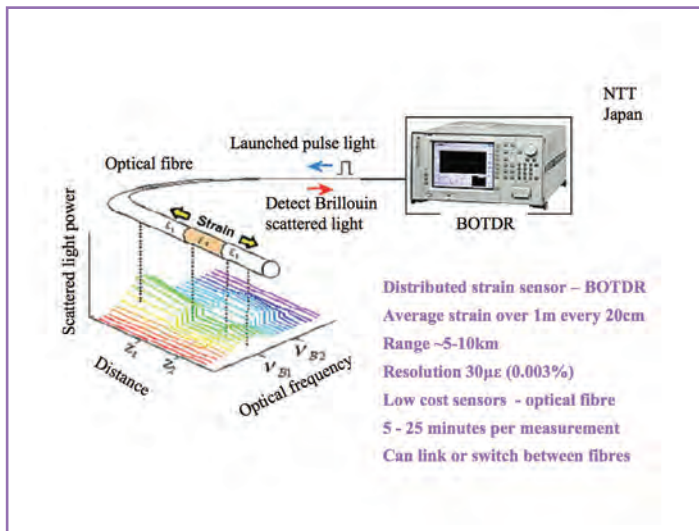


Strains and deformations alter the refractive index and geometry of the optical fibre material. These changes perturb the intensity, phase, and polarisation of the lightwave propagating along the probing fibre. If a pulse of light is launched through the fibre, the majority travels through but a small fraction is scattered back.

Different components of light power, each with distinctive peaks at certain wavelengths, can be identified. In the case of Brillouin scattering, the frequency of the backscattered light is shifted by an amount linearly proportional to the strain applied at the scattering location. By resolving the backscattered signal in time and frequency, a complete strain profile along the full length of the fibre can be obtained.

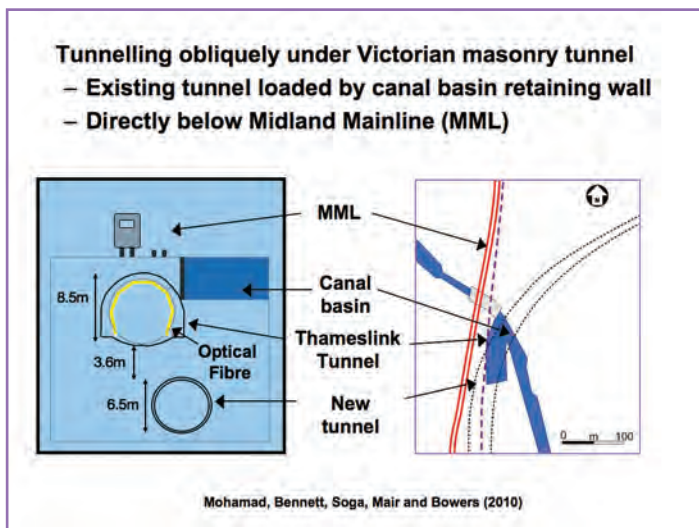
## 5 >> OPTICAL FIBRE MONITORING

### BRILLOUIN OPTICAL TIME DOMAIN REFLECTOMETRY (BOTDR)



Strain can be measured along the full length (up to 10km) of a suitably installed optical fibre by attaching a BOTDR analyser to one end of the fibre.

### MONITORING OF THAMESLINK TUNNEL

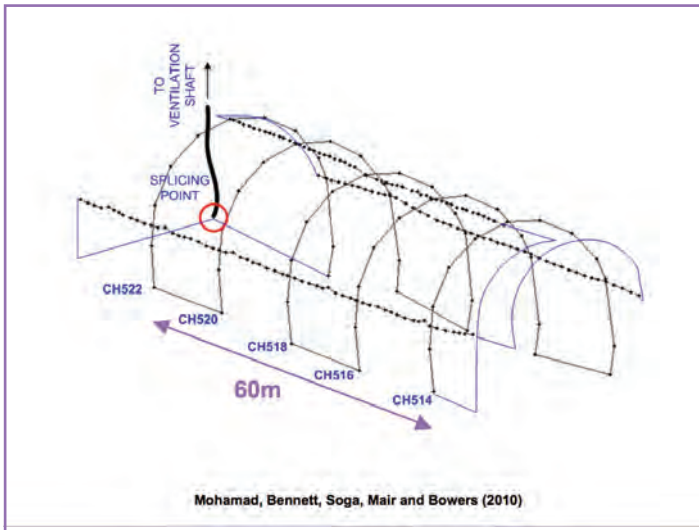


The BOTDR technique was applied to the monitoring of strains of the Thameslink Tunnel during construction of the new Thameslink 2000 tunnel beneath it, shown in Figure 70 (Mohamad et al, 2010). The Thameslink Tunnel is an old masonry tunnel of diameter 8.5m constructed between 1865 and 1868 using the cut and cover method. In 2005, the new twin Thameslink 2000 Tunnels (TL2K) were constructed as part of the Channel Tunnel Rail Link's (CTRL) Section 2 Contract 103 (C103). The new tunnels are of 6m internal diameter (6.5m OD) and the northbound tunnel passes underneath the Thameslink Tunnel with the Midland Main Line (MML) running at ground level. The minimum clearance from the crown of the new tunnel to the invert of the brick-lined tunnel was 3.6m.



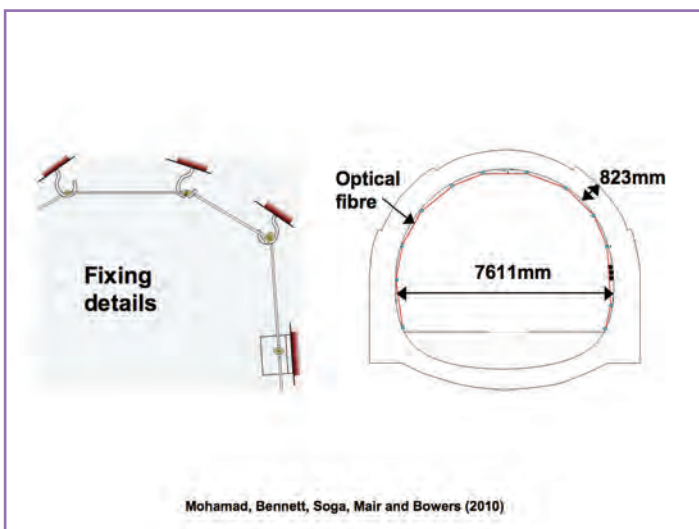
## 5 >> OPTICAL FIBRE MONITORING

### MONITORING OF THAMESLINK TUNNEL



The optical fibre was attached at three longitudinal sections (crown and west and east springlines) and five circumferential sections (CH514 to CH522) spaced over a 60m length.

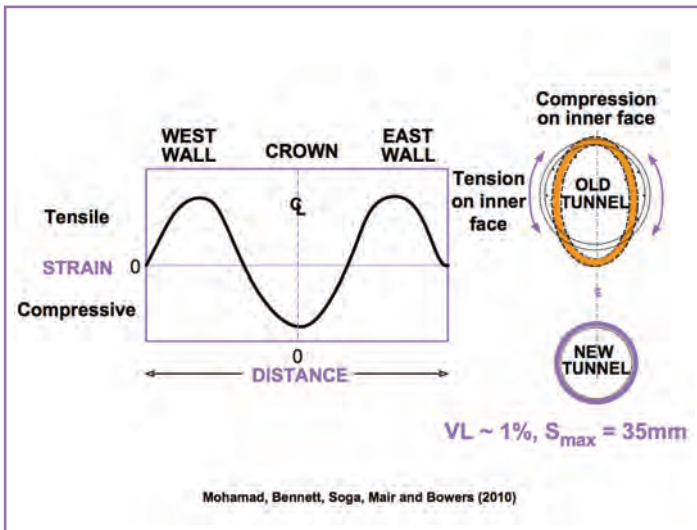
### MONITORING OF THAMESLINK TUNNEL



The optical fibre was attached to the brick-work by means of hooks and epoxy resin, having first been pre-tensioned to 2000-3000 microstrain. Full details of the project are given by Mohamad et al (2010).

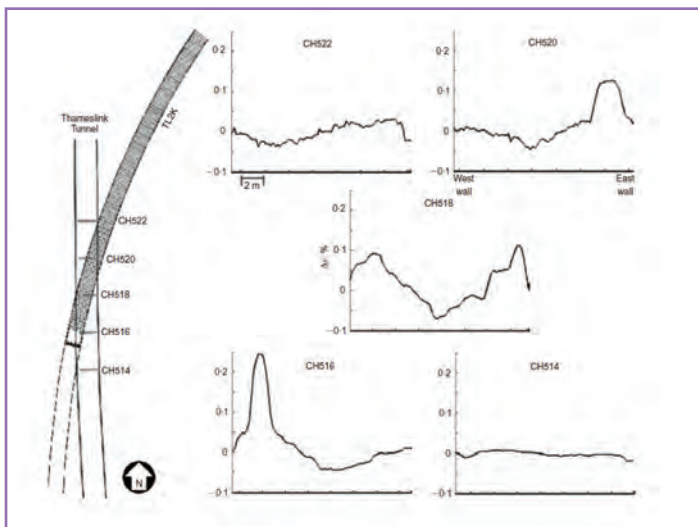
## 5 >> OPTICAL FIBRE MONITORING

### MONITORING OF THAMESLINK TUNNEL



The expected strain around the inner face of the old tunnel as a consequence of constructing a new tunnel beneath it is of a sinusoidal form: compression around the crown and tension in the walls. The settlement records indicated that the volume loss associated with the new tunnel construction was around 1% and the maximum settlement experienced by the masonry tunnel was 35mm.

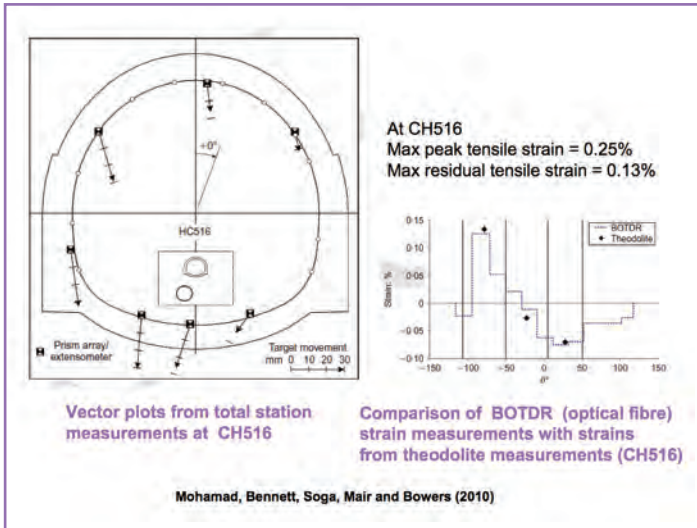
### STRAIN RECORDED WHEN NEW TUNNEL IS DIRECTLY BENEATH WEST WALL OF THAMESLINK TUNNEL (TENSILE STRAIN POSITIVE)



Measurements were made from the west wall at track level around the tunnel to the east wall at track level (Mohamad et al, 2010). A complete record of the development of strain was obtained as the new tunnel approached, was beneath the masonry tunnel and passed beyond it.

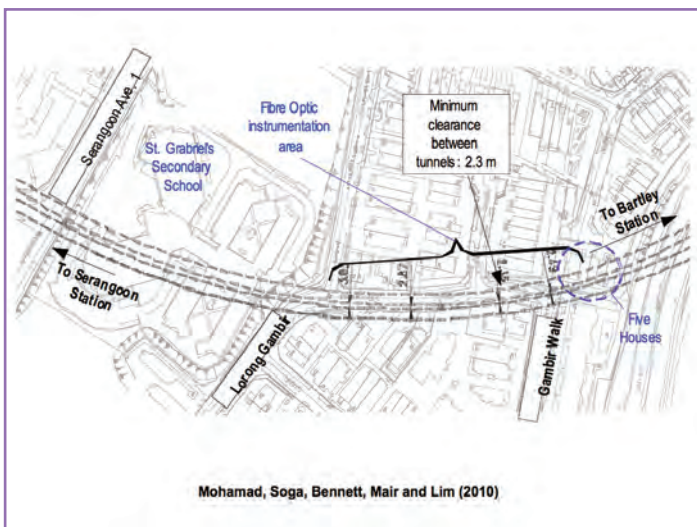
## 5 >> OPTICAL FIBRE MONITORING

### MONITORING OF THAMESLINK TUNNEL



Very good agreement was obtained between the tensile strains inferred from theodolite (total station) measurements and the BOTDR (optical fibre) measurements.

### SINGAPORE CIRCLE LINE 3, CONTRACT 852 FIBRE OPTIC MONITORING OF CLOSE PROXIMITY TUNNELLING

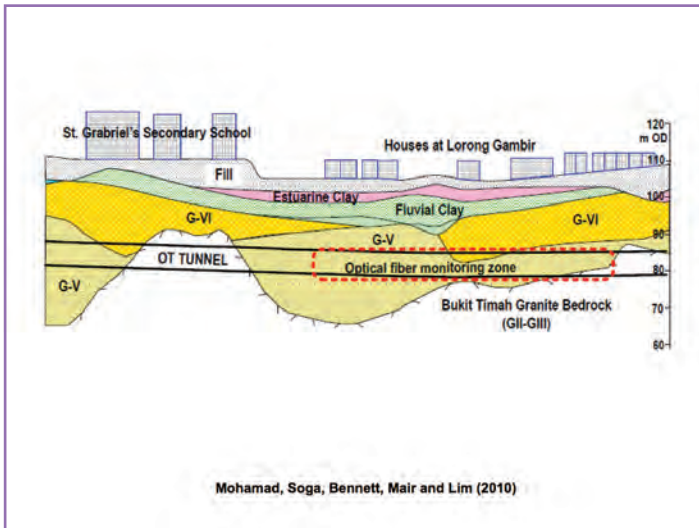


The newly constructed Circle Line in Singapore consists of twin circular bored tunnels of 6.35m outer diameter. In one part of the alignment, the tunnels were constructed less than one tunnel diameter apart in order to avoid the piled foundations of adjacent buildings. The length of close proximity tunnelling is about 580m with the minimum clear separation of the twin tunnels being 2.3m



## 5 >> OPTICAL FIBRE MONITORING

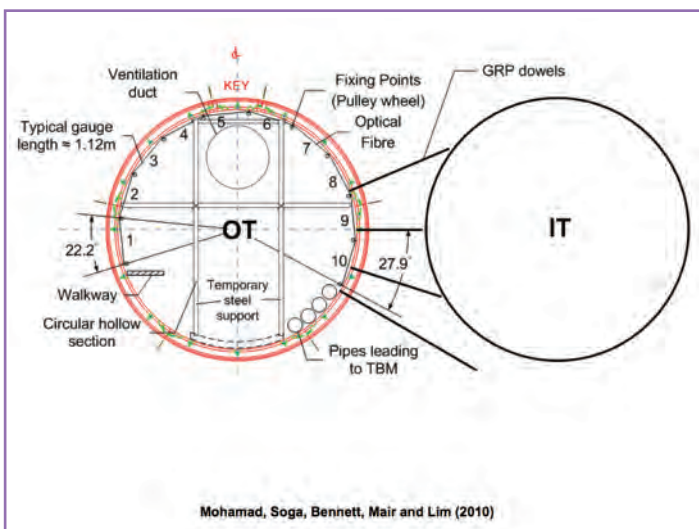
### SINGAPORE CIRCLE LINE 3, CONTRACT 852 LONGITUDINAL GEOLOGICAL PROFILE



The twin tunnels were bored in the Bukit Timah Formation granitic residual soils of various degrees of weathering. Depending on the mineral content of the parent rock, the residual soils comprise clayey or sandy silt. Maximum surface settlements recorded for the first tunneling drive (the Outer Tunnel) were generally up to about 25 mm (corresponding to a volume loss of about 2%).

However in some locations surface settlements as large as 50 mm were recorded. Horizontal ground movements as high as 60mm were also recorded at tunnel axis level by inclinometers located 0.7-1.5m from the outside of the tunnel. Consequently there were concerns about the effect of constructing the second tunnel on the first tunnel in close proximity (2.3m).

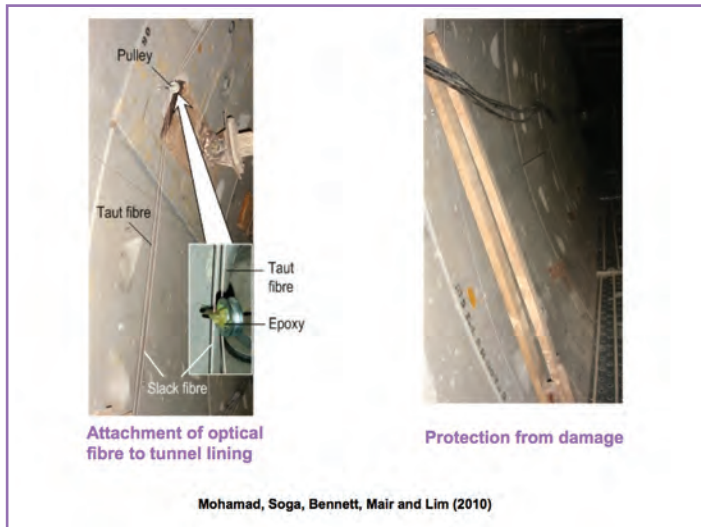
### SINGAPORE CIRCLE LINE 3, CONTRACT 852 FIBRE OPTIC MONITORING OF CLOSE PROXIMITY TUNNELLING



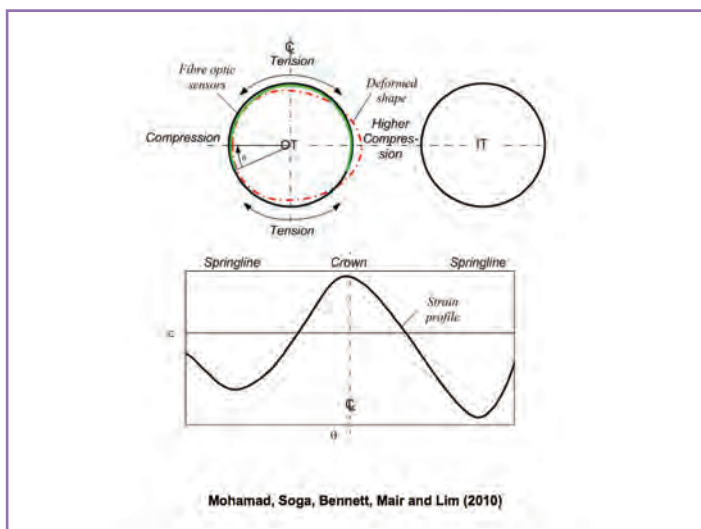
The soils between the two tunnels (i.e. the tunnels' pillar) were reinforced with glass reinforced polymer (GRP) dowels, which were drilled through the Outer Tunnel (OT) concrete segments and grouted prior to the arrival of the second TBM constructing the Inner Tunnel (IT). A temporary steel bracing support system was erected in the Outer Tunnel as a precaution. Optical fibre was fixed around the perimeter of the Outer Tunnel. The movements of the Outer Tunnel were also monitored daily by means of surveying with theodolites and tape extensometer readings.

# 5 >> OPTICAL FIBRE MONITORING

## OPTICAL FIBRE INSTALLATION

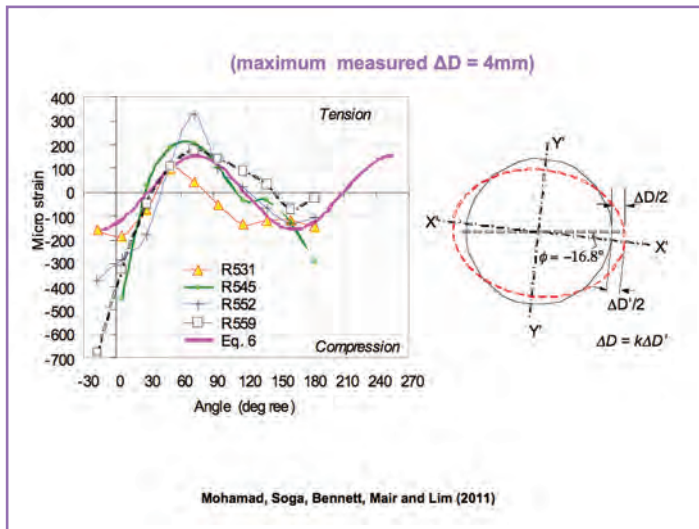


## PATTERN OF STRAINS INDUCED ON INTRADOS OF TUNNEL LINING



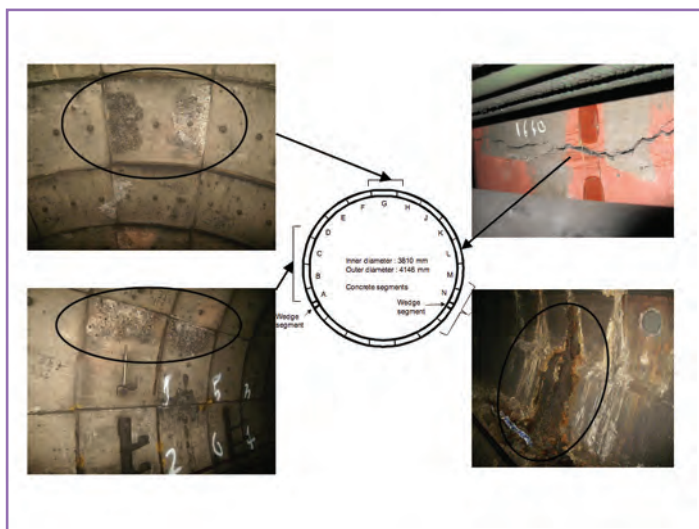
## 5 >> OPTICAL FIBRE MONITORING

### MEASURED STRAINS ON INTRADOS OF TUNNEL LINING



The strain distribution across the circumference of the tunnel rings shows a generally similar profile between them. Maximum compressive strains located just below the tunnel springline on the side of the excavated tunnel were found to be larger than the maximum tensile strains measured at the tunnel crown, such that the deformed oval shape of the tunnel was found to follow an eggshaped distorted shape. The highest measured compressive strain was 0.067% and the highest tensile strain was 0.035%. These strains were very low, and correspond to small tunnel diameter changes (the maximum recorded being less than 5mm). These small strains and movements are consistent with the generally low values of volume loss (0.5-0.9%) reported for construction of the InnerTunnel.

### ASSESSMENT OF LONDON UNDERGROUND TUNNEL



Fibre optic strain measurement has also been used by Cambridge University for monitoring joint movement and other deterioration effects in a London Underground tunnel (Cheung et al, 2010).

### OPTICAL FIBRE INSTALLATION BY CAMBRIDGE UNIVERSITY TO MONITOR JOINT MOVEMENT IN LONDON UNDERGROUND TUNNEL



The tunnel joint movements were captured by measuring the strain along the fibre across the segment joints. The results showed that there is good agreement between the joint movements evaluated from the optical fibre sensor system and those measured by conventional vibrating wire strain gauges.

#### BOTDR FIBRE OPTIC TECHNOLOGY FOR MONITORING SUMMARY

- Provided valuable strain data for Thameslink masonry tunnel and Singapore close proximity tunnels
- Continuous strain profile a big advantage
- Low cost installation
- Promising new development for monitoring of tunnels and many other geotechnical applications

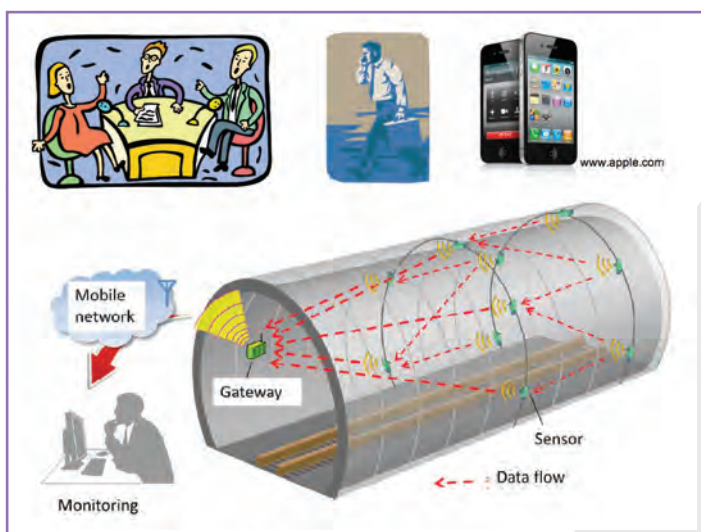
## 6 >> WIRELESS SENSORS

### WIRELESS SENSOR TECHNOLOGY



The use of wireless sensor technology opens up many opportunities for structural monitoring of infrastructure, including tunnels.

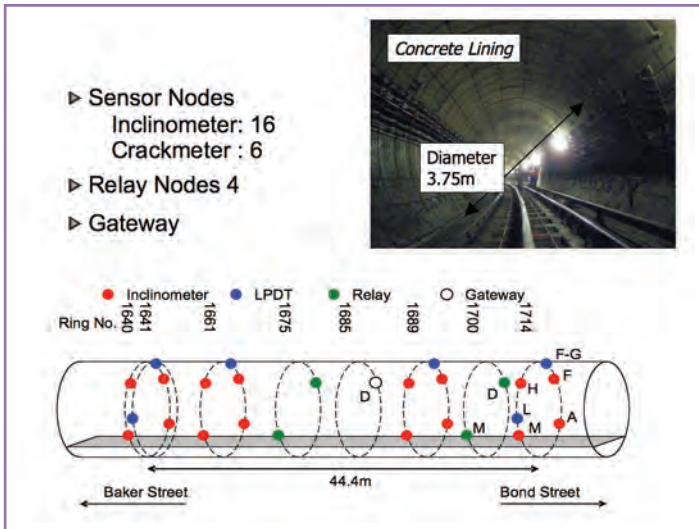
### WIRELESS SENSOR NETWORK





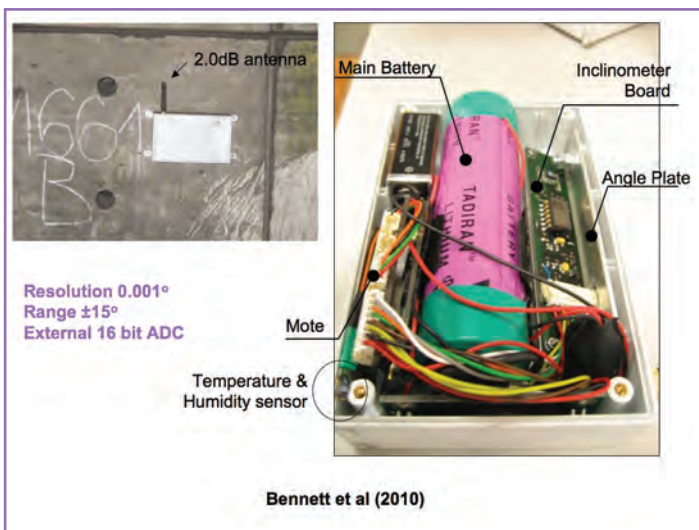
## 6 >> WIRELESS SENSORS

### SENSOR LOCATIONS



Research at Cambridge University, led by Professor Kenichi Soga, has resulted in the development of hybrid wireless sensor network systems for structural monitoring of tunnels (Bennett, Kobayashi, Soga and Wright, 2010). Structural monitoring of a London Underground tunnel has been undertaken.

### INCLINOMETER

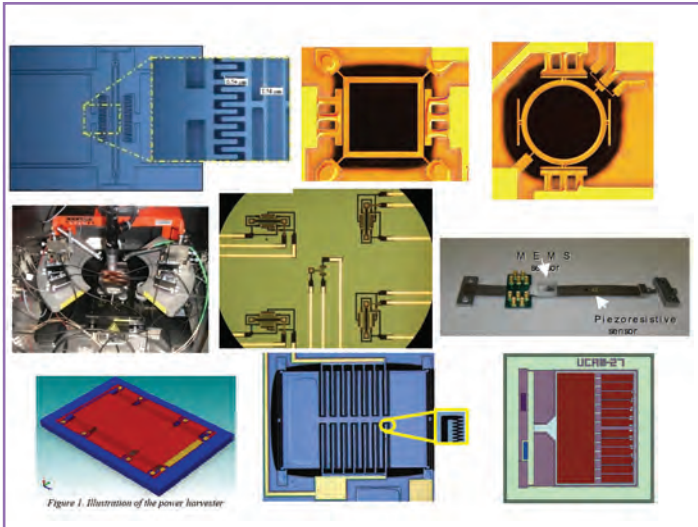






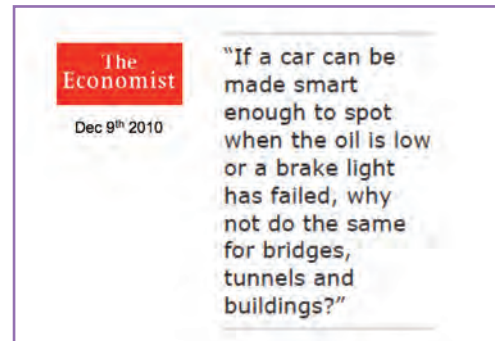
## 6 >> WIRELESS SENSORS & ACKNOWLEDGEMENTS

### MEMS SENSORS AND POWER HARVESTERS



MEMS or Micro Electro Mechanical Systems are small integrated devices that combine electrical and mechanical components varying in size from micrometers to millimeters. These can merge the function of computation and communication with sensing and actuation to produce a system of miniature dimensions. Recent research at Cambridge University is developing MEMS strain sensors for application to monitoring civil engineering infrastructure, including tunnels (Soga et al, 2010).

Recent developments in sensor technologies provide huge opportunities for the tunnelling industry



### SUMMARY

- New insights into response of buildings to ground movements caused by tunnelling
  - relative stiffness of building important
  - new design method for predicting response
  - reduced need for protective measures
- BOTDR fibre optic technology – promising new strain monitoring technique for tunnelling and many other geotechnical applications
- Wireless sensors provide exciting new opportunities for monitoring tunnel infrastructure throughout design life – ‘smart’ tunnels

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Cambridge University Geotechnical Research Group, especially

- Kenichi Soga
- Mohammed Elshafie

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