# Long-term effects of geotechnical processes

Hokkaido University

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Reader in Geomechanics

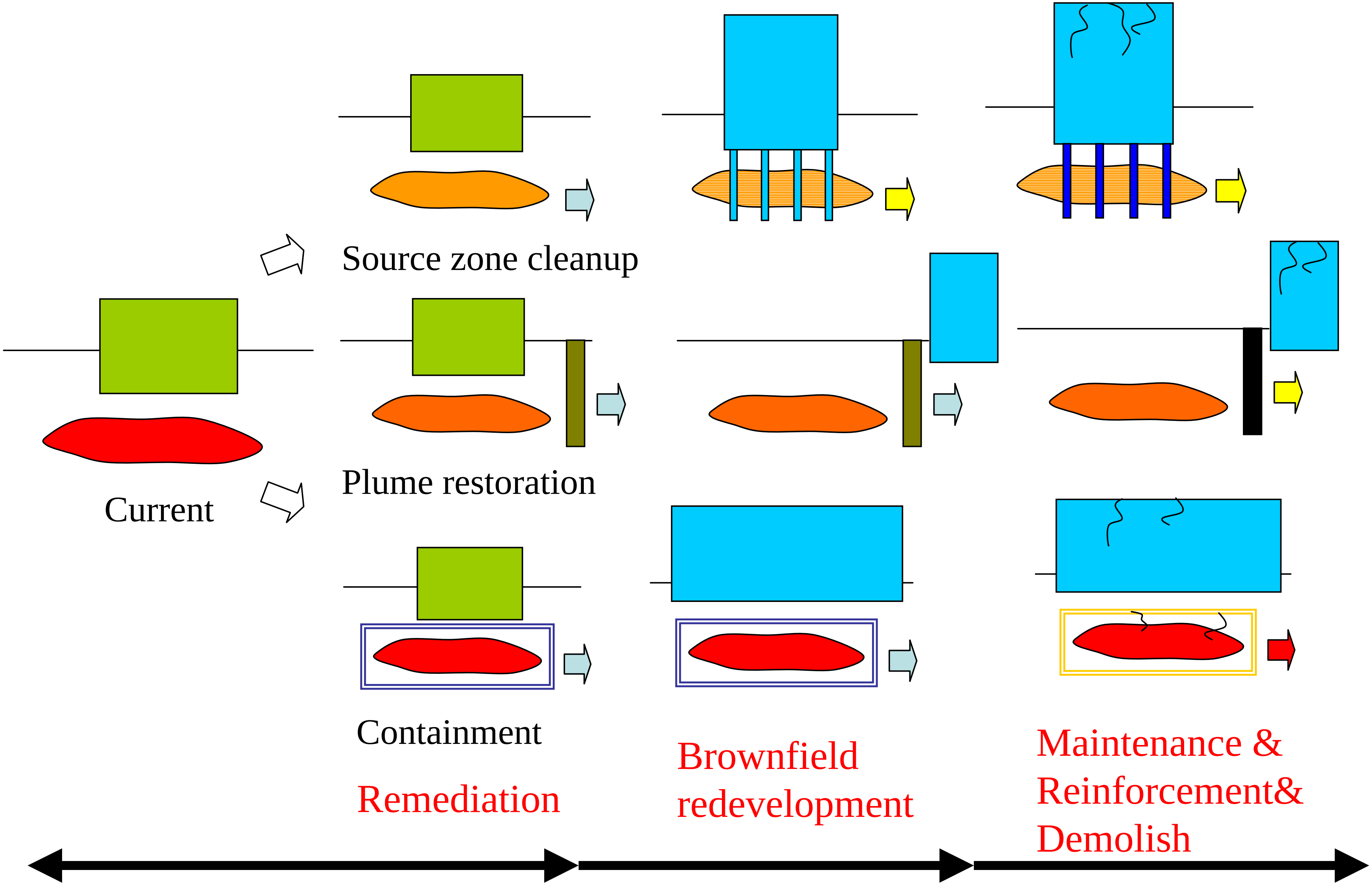
UNIVERSITY OF CAMBRIDGE

## Lunch Box (Bento)

- Appearance
- Price
- Expiration date
- Calorie

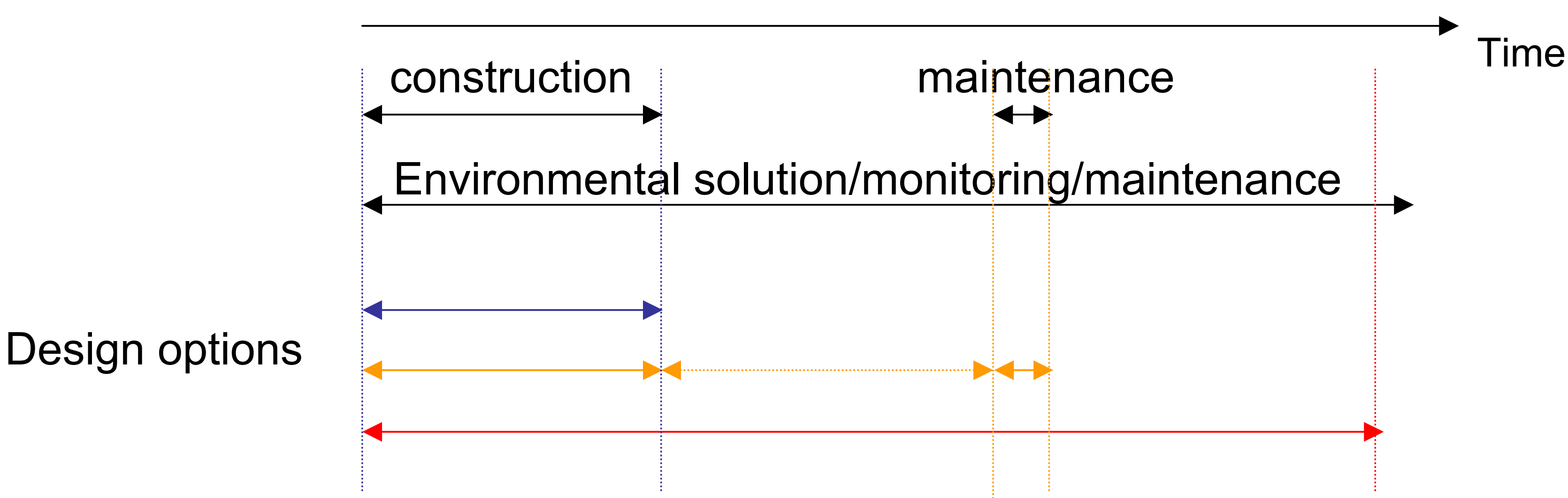
## Geotechnical Construction

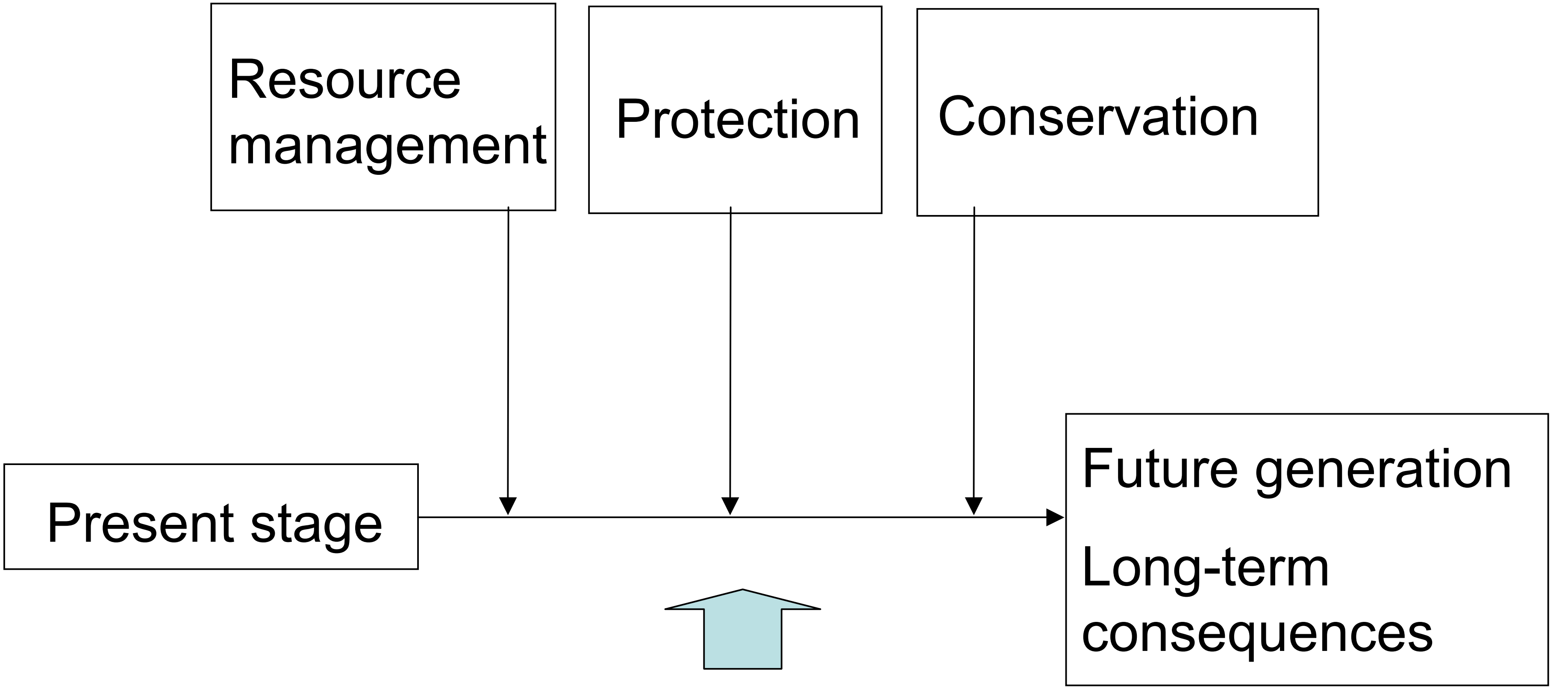
- Design
- Cost
- Sustainability/Maintenance
- Embodied Energy


Source zone cleanup
Current
Plume restoration
Containment
Remediation
Brownfield
redevelopment
Maintenance &
Reinforcement&
Demolish

# Design options

- Construction – short period
  - Design codes
- Maintenance – periodical, some uncertainty
  - Life-cycle cost analysis, system performance
- Long-term solution – rather slow. Large uncertainty.
  - Embodied energy evaluation, Life cycle environmental impact analysis






- Understand **long term effects** (geotechnical processes, embodied energy calculation)
- "Systematic" **monitoring** to deal with uncertainty in evaluating long-term effects
- Interpretation of data (direction and rate of change)
- Engineering ideas and solutions

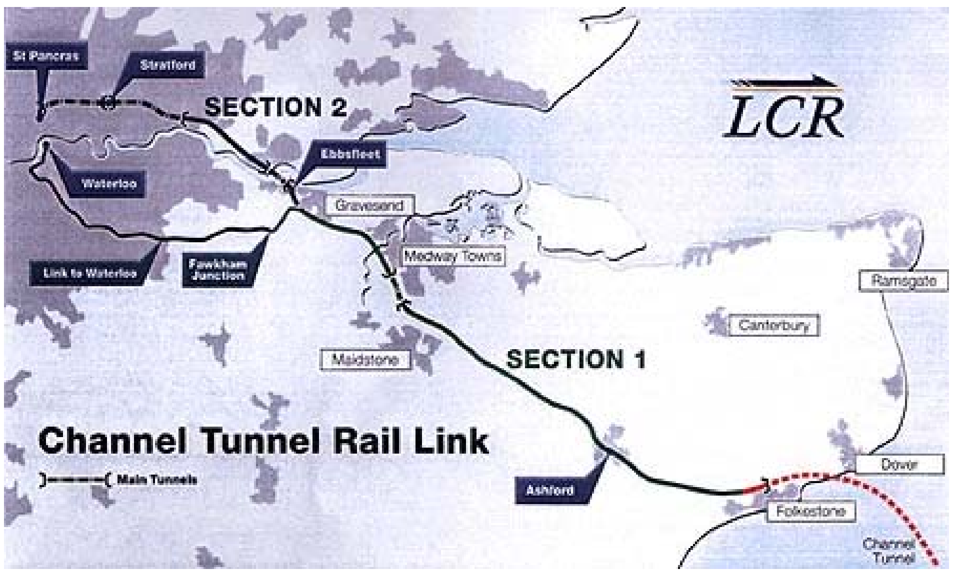
# Questions

- Does the construction process affect the long-term performance of geotechnical infrastructure?
- How much energy do we use to make a geotechnical structure? How much energy is used for its operation?
- What are the essential soil parameters and key indicators and how can we measure them?
- What long-term monitoring strategy should we adopt and at what scale?
- What are the emerging technologies that can be used for long-term monitoring?

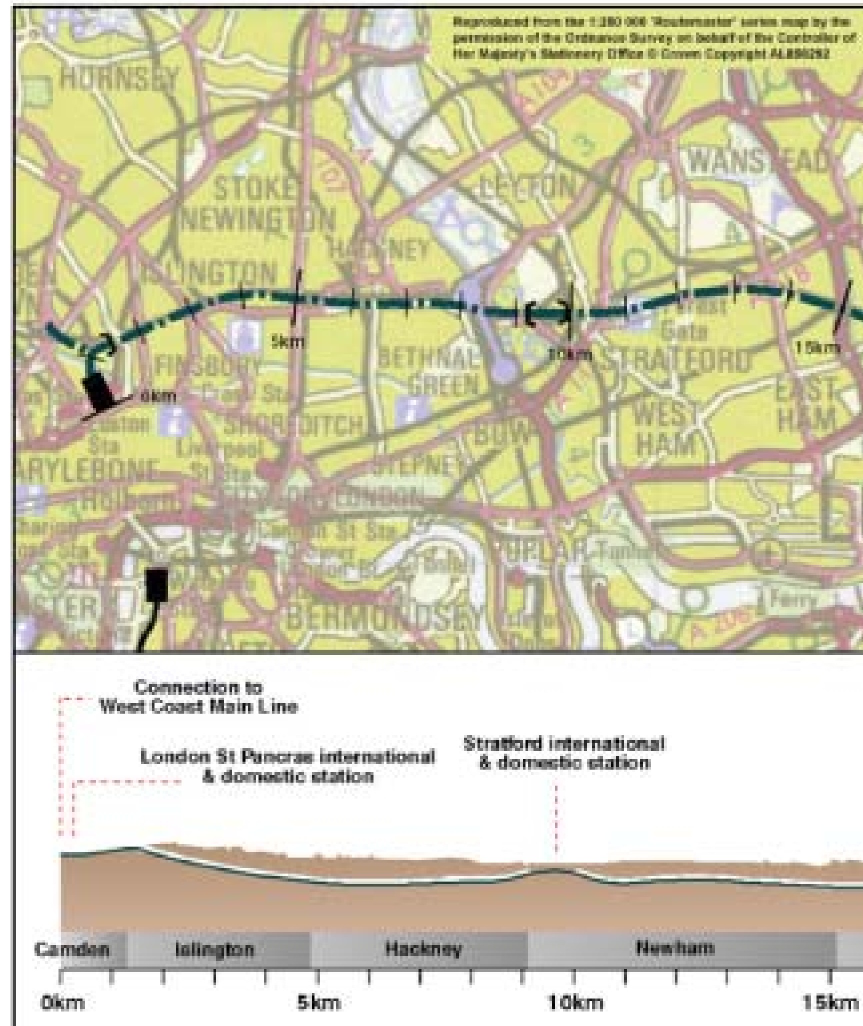
# Today’s Bento Menu

- Long-term effects of tunnel construction
- Long-term effects of compensation grouting
- Long-term effects of piling
- Innovation in monitoring

# Embodied Energy of Channel Tunnel Rail Link Contract 220

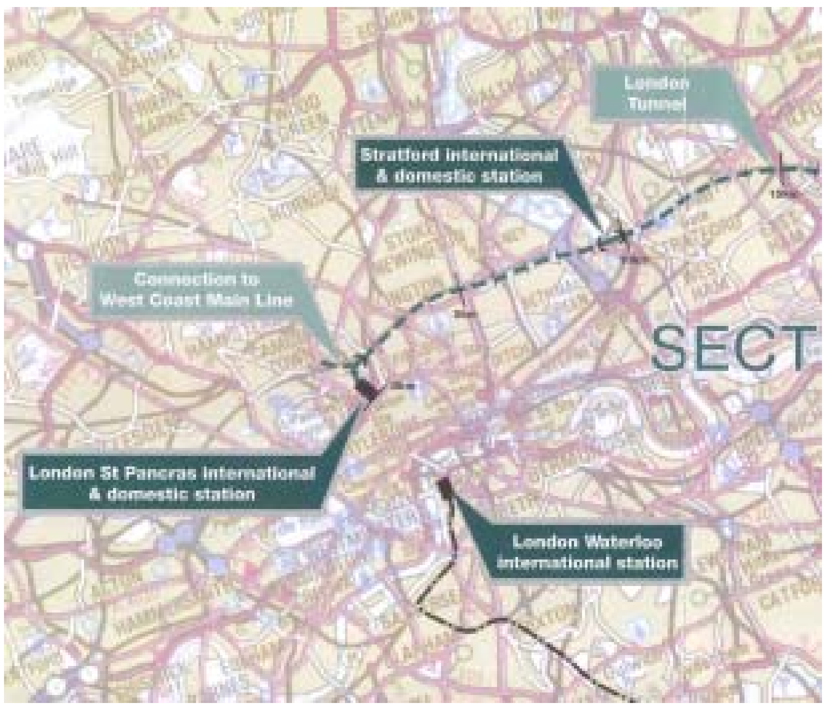



Kilometre Points: 0-15



# Case Study: CTRL

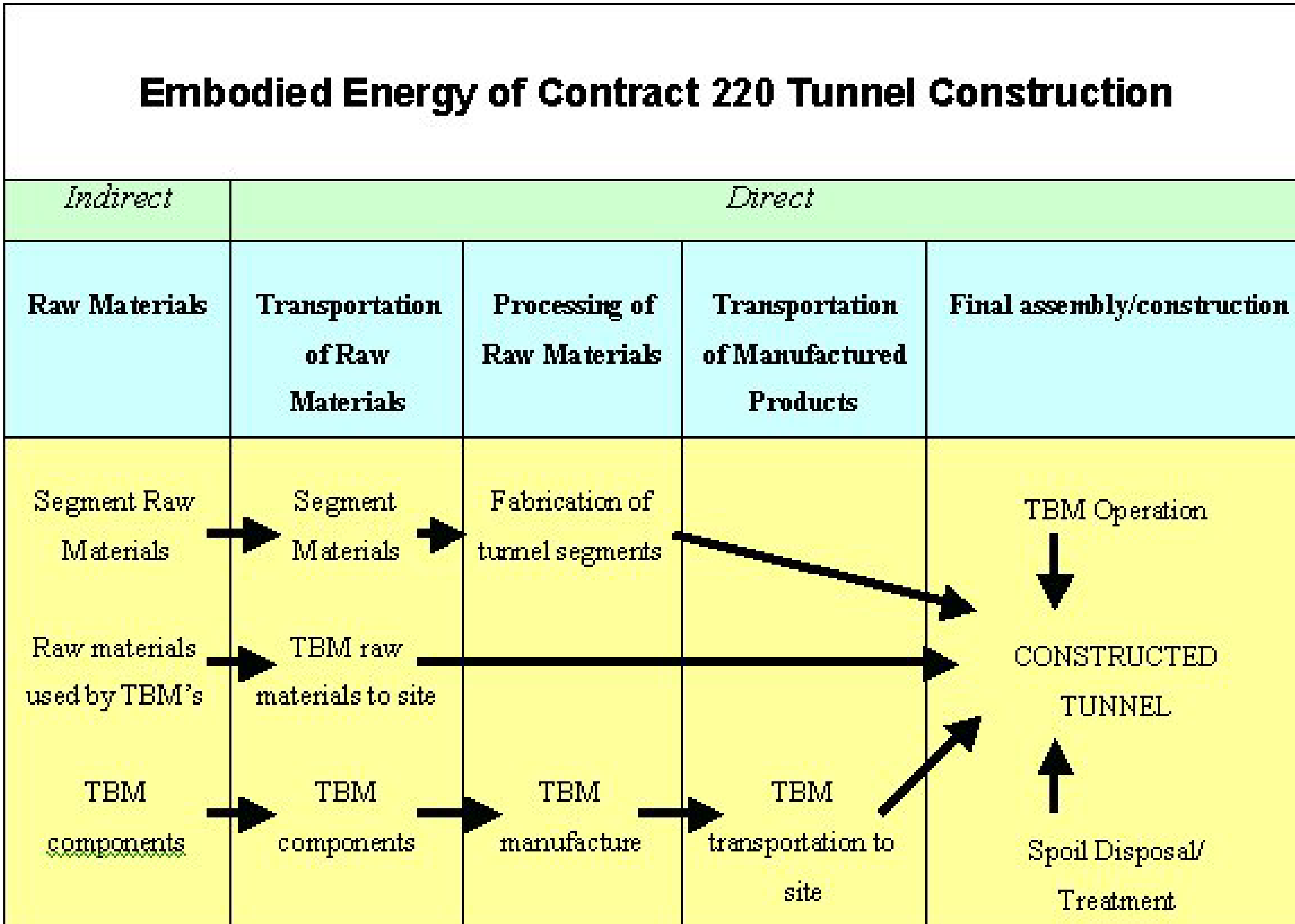
- CTRL contract 220 drive.



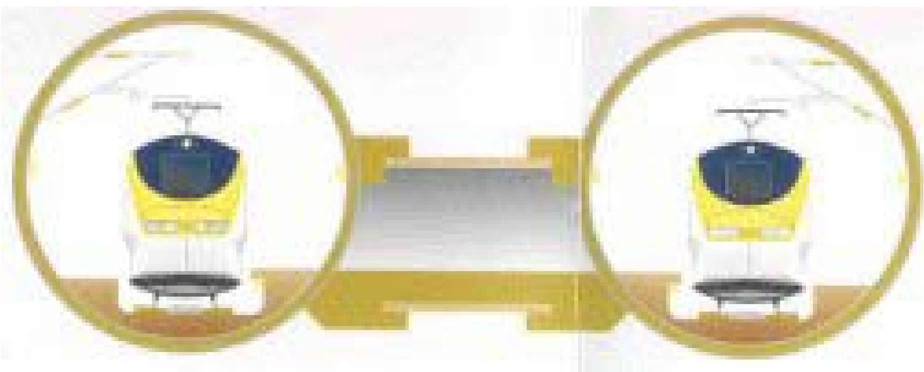

Tunnel Map Stratford to London St. Pancreas

Stratford Box

# Data Collection



# Construction

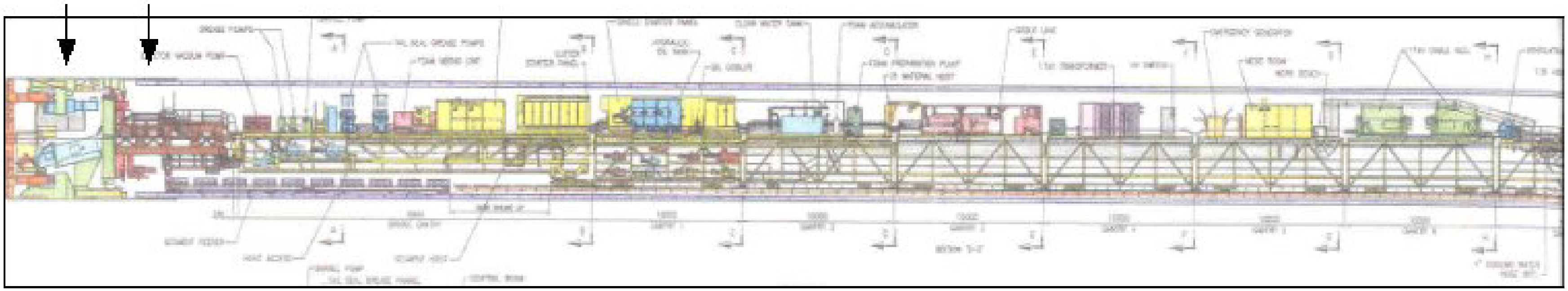


Twin Bore Tunnel

Segment Loading

TBM and Gantries

TBM Tail Seal

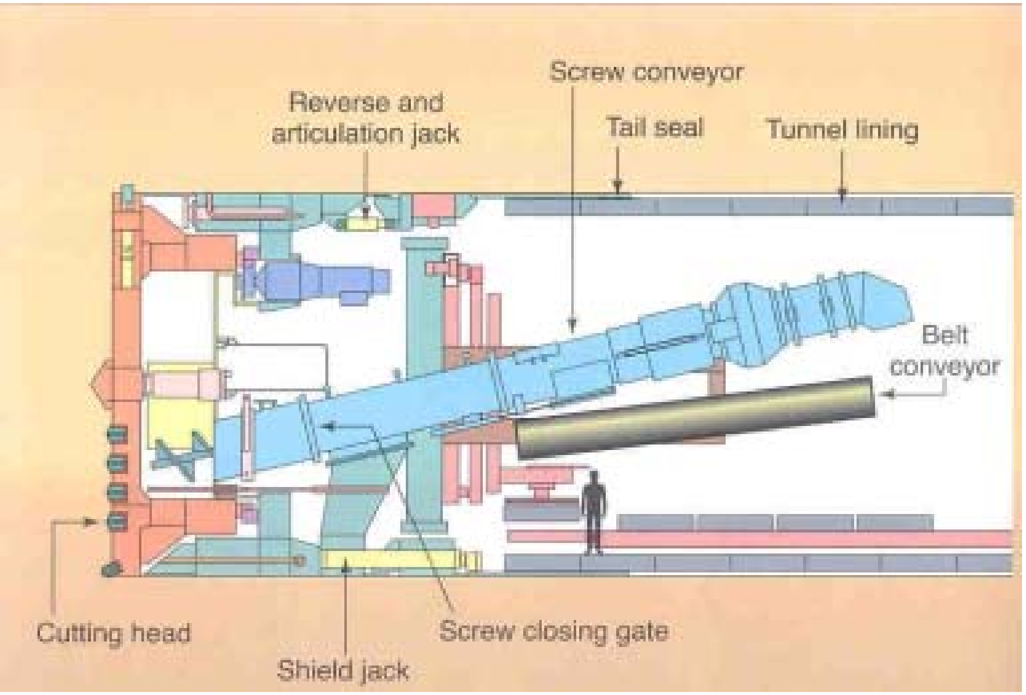


# Construction

Segment Factory

Spoil Disposal at Stratford

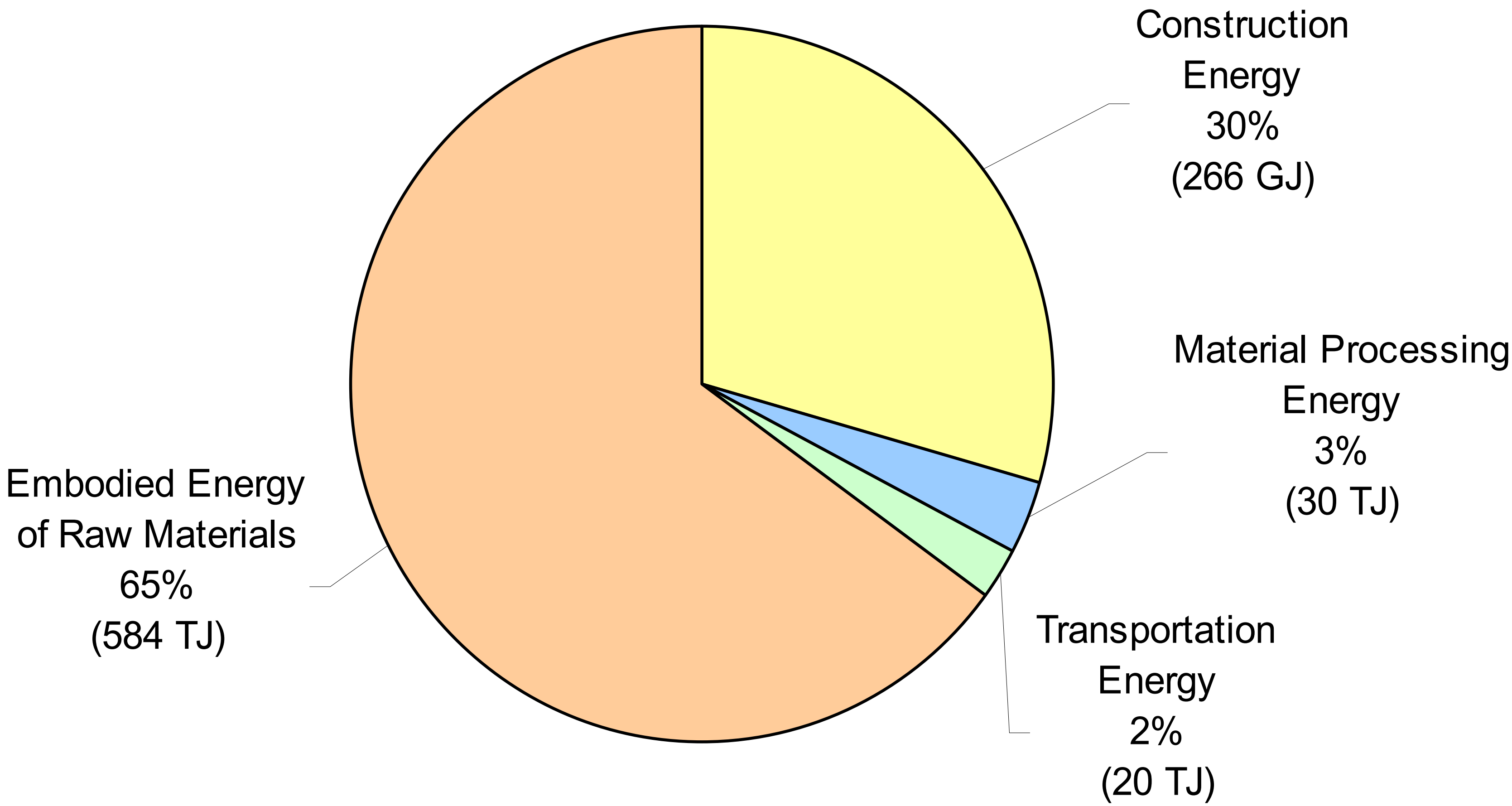
# Kawasaki TBM




Cross-section of TBM

TBM in Harima Works, Japan

Breakdown of Tunnel Embodied Energy of CTRL 220 Construction

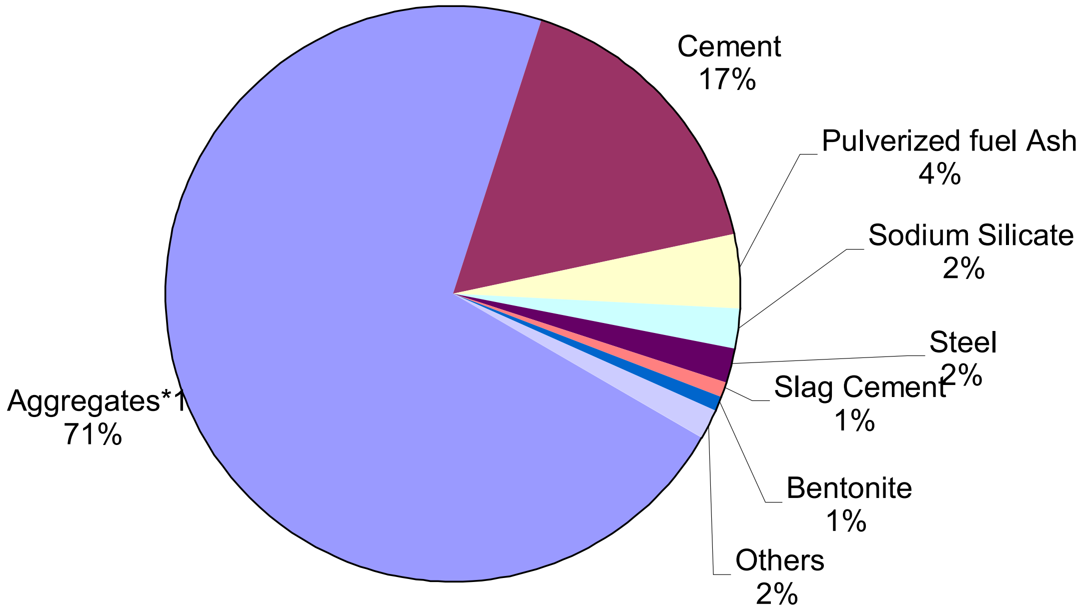



Equivalent CO2 Emission is 97.8 tonnes.

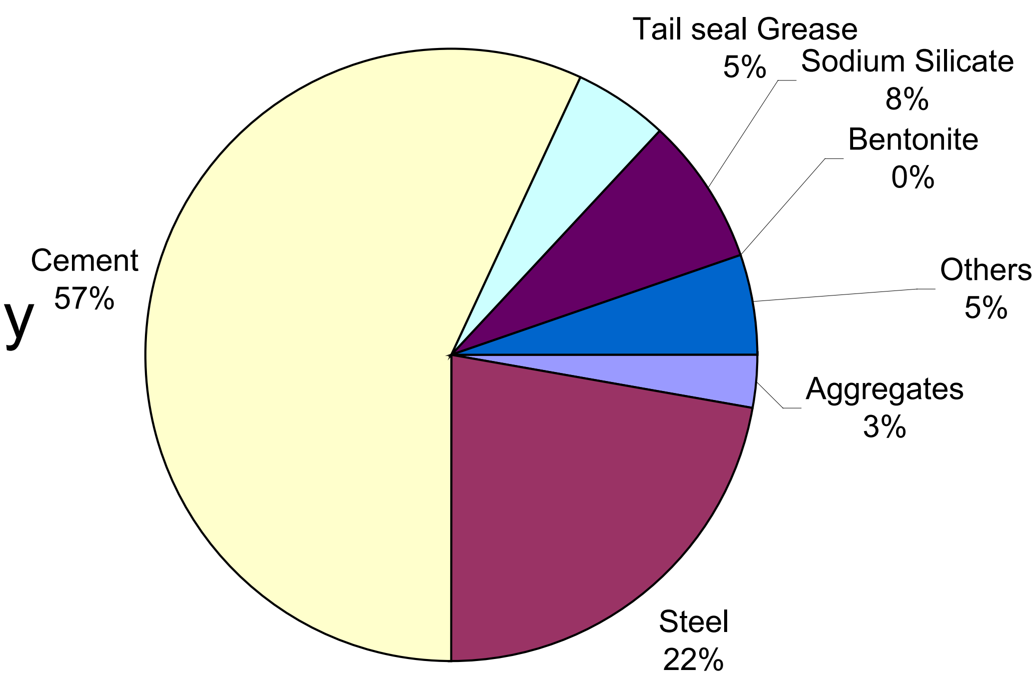
0.000059% of total UK greenhouse emissions in 2002

2.1% of all emissions associated with the UK construction industry in 1999.

## Total Mass

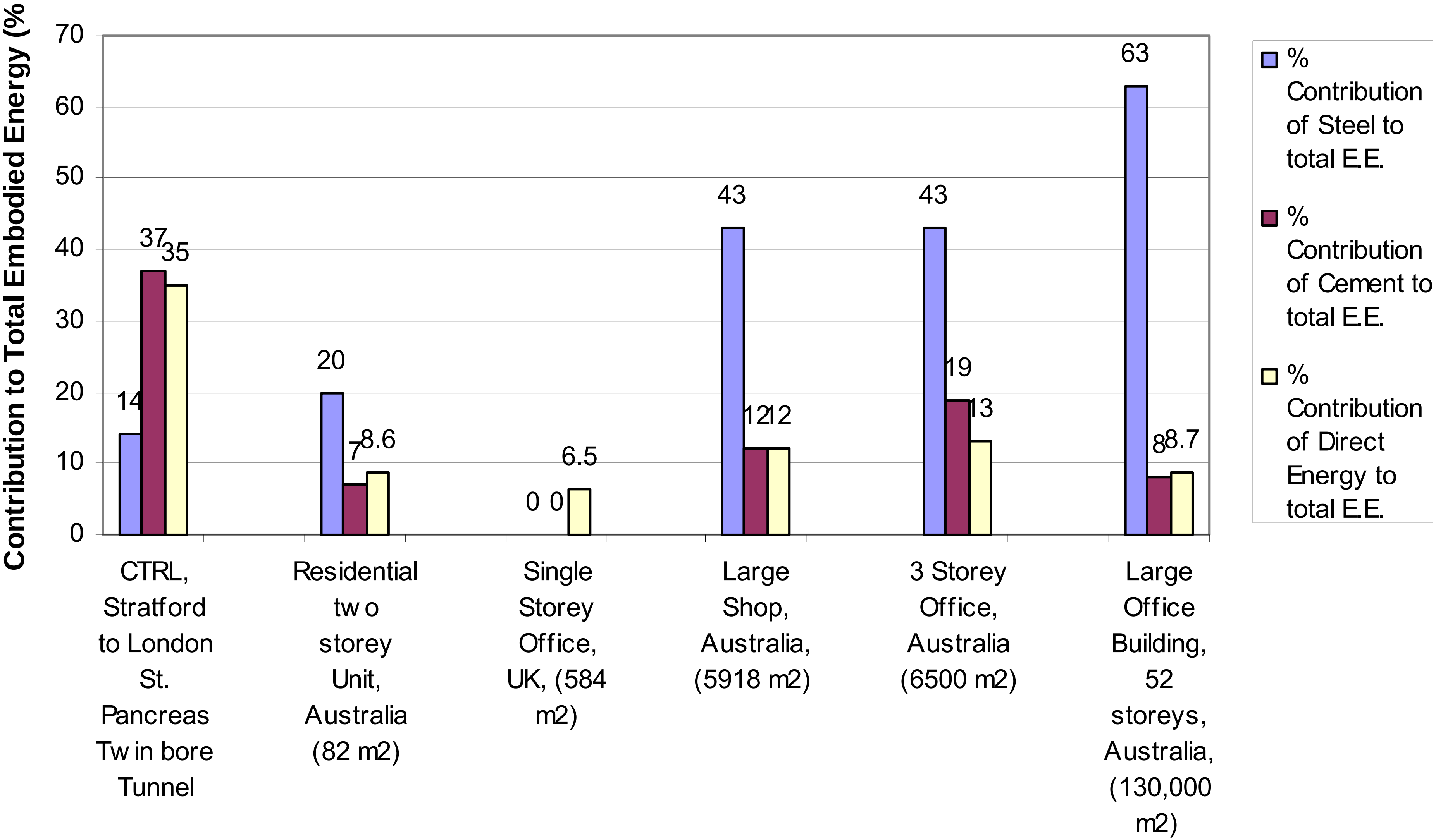



## Embodied Energy



# Comparison of the embodied energy of selected structures.

| Building | Source ref. | Embodied Energy (GJ) | $\frac{Tunnel E.E.}{Building E.E.}$ |
|---|---|---|---|
| CTRL, Stratford to London St. Pancreas Twin bore Tunnel | [This project] | 899,410 | 1 |
| Typical UK Masonry house (100m$^2$) | [12] | 414 | 2172 |
| Average House, Australia (125 m$^2$) | [13] | 625 | 1450 |
| Standard New US Home, Michigan, USA (227 m$^2$) | [16] | 942 | 927 |
| Residential attached two storey Unit, Australia (82 m$^2$) | [14] | 1,240 | 749 |
| Standard Home, Toronto, Canada | [15] | 2,350 | 382 |
| Single Storey Office, UK (584 m$^2$) | [17] | 2,494 | 361 |
| Large Shop, Australia (5918 m$^2$) | [14] | 60,837 | 15 |
| 3 Storey Office, Australia (6500 m$^2$) | [14] | 69,875 | 13 |
| Large Office Building, 52 storeys, Australia, (130,000 m$^2$) | [14] | 2,589,400 | 0.35 |

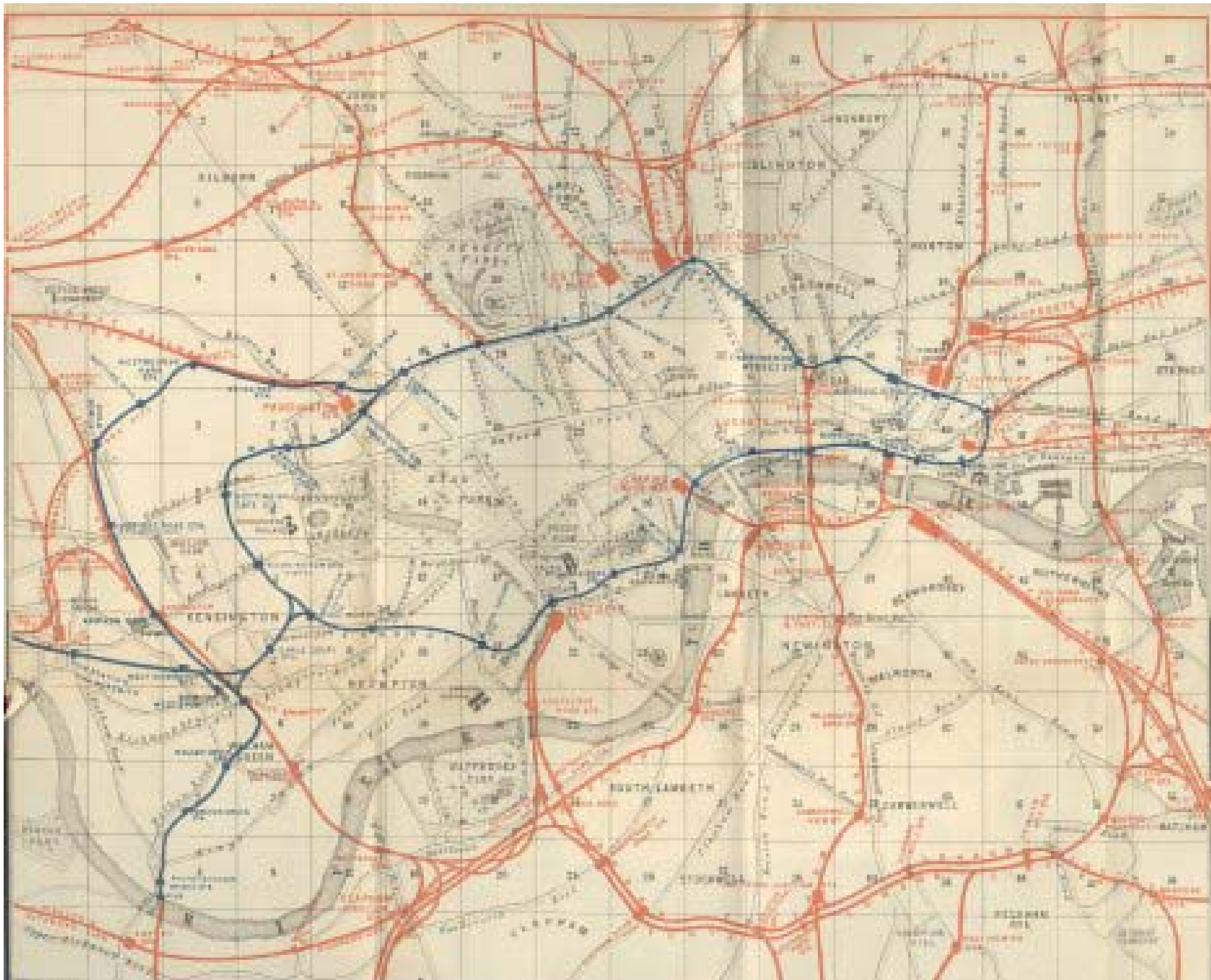

Contribution to Total Embodied Energy (%
70
60
50
40
30
20
10
0
14
37
35
20
7
8.6
0
0
6.5
43
12
12
43
19
13
63
8
8.7
CTRL, Stratford to London St. Pancreas Tw in bore Tunnel
Residential tw o storey Unit, Australia (82 m2)
Single Storey Office, UK, (584 m2)
Large Shop, Australia, (5918 m2)
3 Storey Office, Australia (6500 m2)
Large Office Building, 52 storeys, Australia, (130,000 m2)
% Contribution of Steel to total E.E.
% Contribution of Cement to total E.E.
% Contribution of Direct Energy to total E.E.

UNDERGROUND

# THE LONDON UNDERGROUND TUBE NETWORK

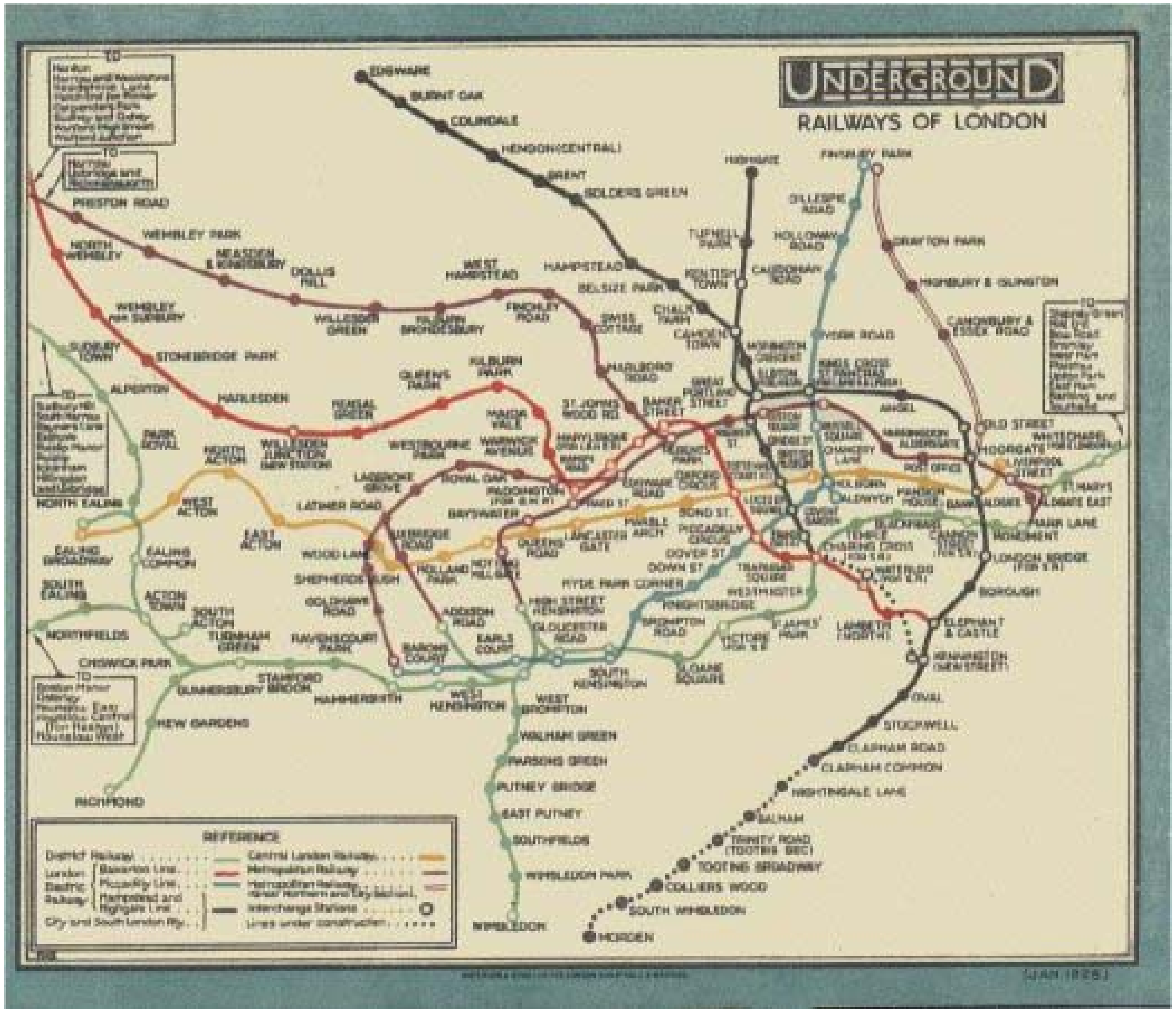
- Area served: 3240km$^2$
- 45km N-S   72km E-W
- line length: 392km
- 35% (140km) in deep tunnels
- 80% (110km) cast iron
- Deepest tunnel 67.4m bgl
- Average tunnel depth 24.5m bgl
- 2.5million passengers/ day

# 1889



# 1908

# 1926

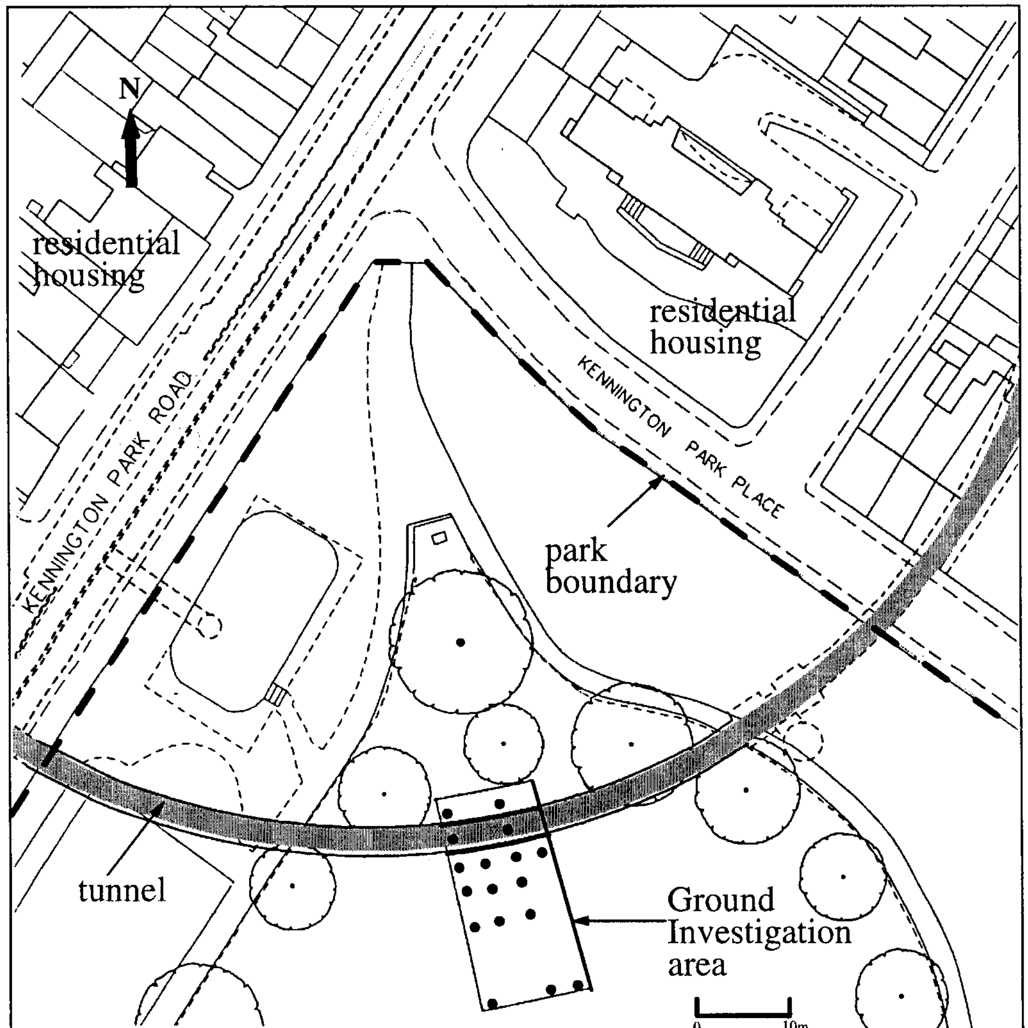

UNDERGROUND
RAILWAYS OF LONDON
EDGWARE
BURNT OAK
COLINDALE
HENDON (CENTRAL)
BRENT
GOLDERS GREEN
HAMPSTEAD
BELSIZE PARK
PRESTON ROAD
WEMBLEY PARK
NORTH WEMBLEY
STONEBRIDGE PARK
HARLESDEN
WILLESDEN JUNCTION
KILBURN PARK
FINCHLEY ROAD
HIGHGATE
FINSBURY PARK
DRAYTON PARK
HIGHBURY & ISLINGTON
CANONBURY & ESSEX ROAD
MOORGATE
LIVERPOOL STREET
ALDGATE EAST
MARK LANE
MONUMENT
LONDON BRIDGE
BOROUGH
ELEPHANT & CASTLE
KENNINGTON
OVAL
STOCKWELL
CLAPHAM ROAD
CLAPHAM COMMON
NIGHTINGALE LANE
BALHAM
TRINITY ROAD (TOOTING BEC)
TOOTING BROADWAY
COLLIERS WOOD
SOUTH WIMBLEDON
MORDEN
NORTH EALING
EALING BROADWAY
EALING COMMON
SOUTH EALING
NORTHFIELDS
CHISWICK PARK
KEW GARDENS
RICHMOND
HAMMERSMITH
WEST KENSINGTON
WEST BROMPTON
WALHAM GREEN
PARSONS GREEN
PUTNEY BRIDGE
EAST PUTNEY
SOUTHFIELDS
WIMBLEDON PARK
WIMBLEDON
SOUTH KENSINGTON
SLOANE SQUARE
HYDE PARK CORNER
BOND ST.
MARBLE ARCH
LANCASTER GATE
BAYSWATER
WOOD LANE
SHEPHERDS BUSH
REFERENCE
Central London Railway
Metropolitan Railway
Interchange Stations
Lines under construction
(JAN 1926)


Key to lines
Key to symbols
Restricted services

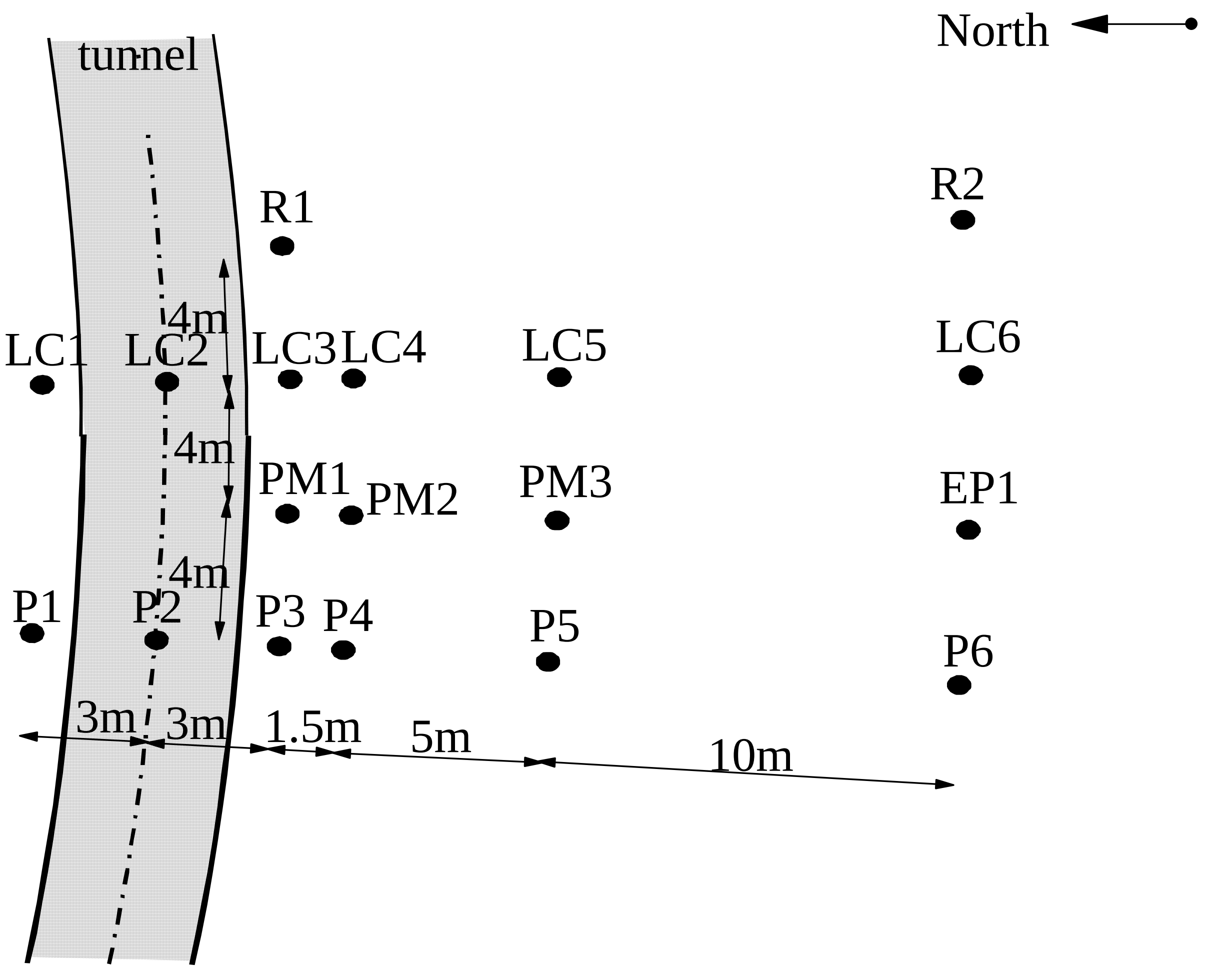
# Existing Tunnels

- New construction interactions
  - pile driving nearby
  - neighbouring tunnel construction
- Long-term survival: what is the unexpired life?
  - chemical environment
  - earth and water pressures create ground loading
  - affected by construction, consolidation, creep, ageing
  - loads on lining must change as groundwater changes
- Design of new works
  - what ground actions to assume in what design life?
  - what influence from new construction activities?

# LUL Kennington



# LUL Kennington




R rotary cored borehole

P cable percussion borehole

LC self-boring load cell pressuremeter tests

EP self-boring expansion pressuremeter tests

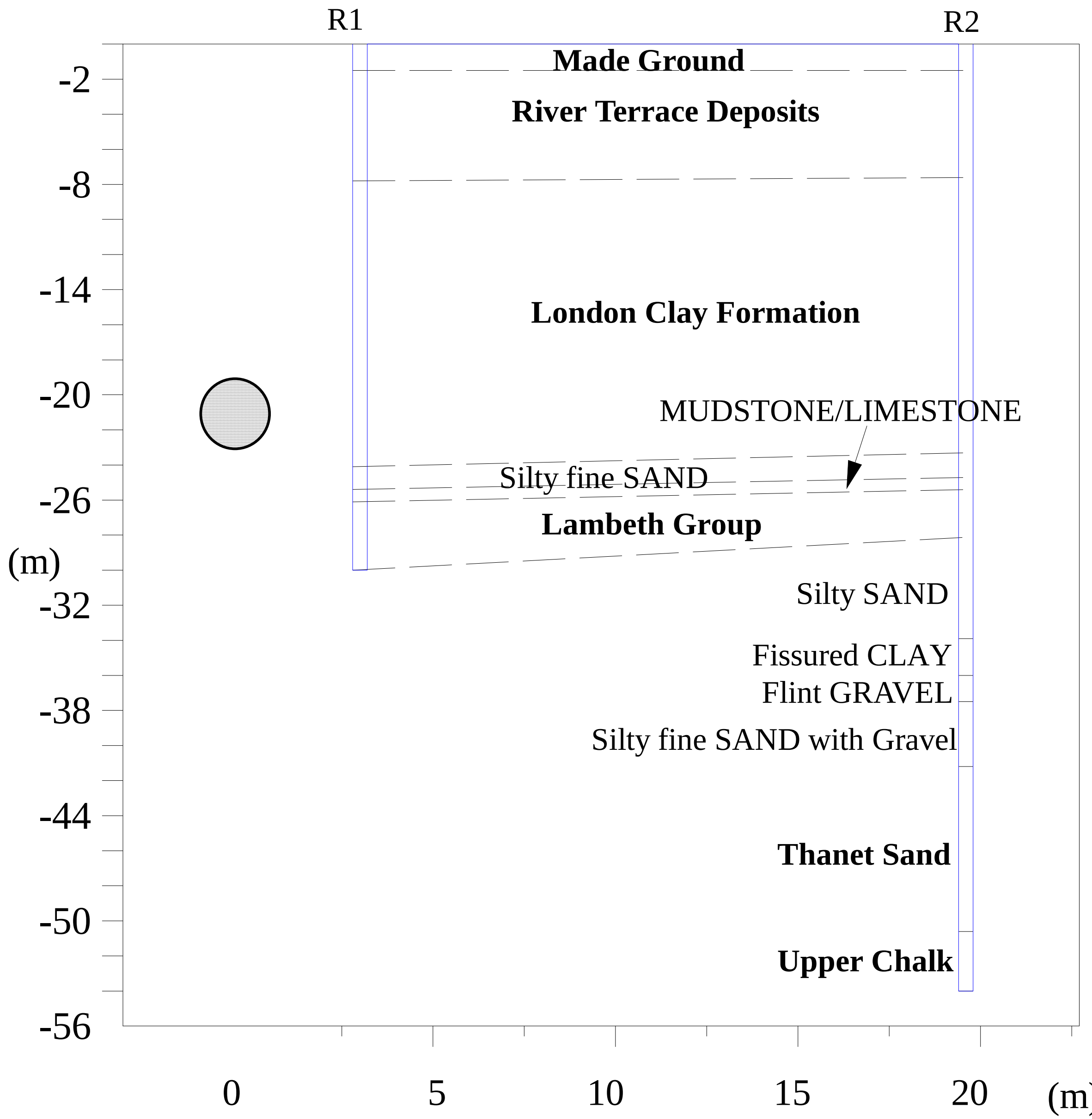
PM self-boring permeameter tests

# EPSRC / LUL Project

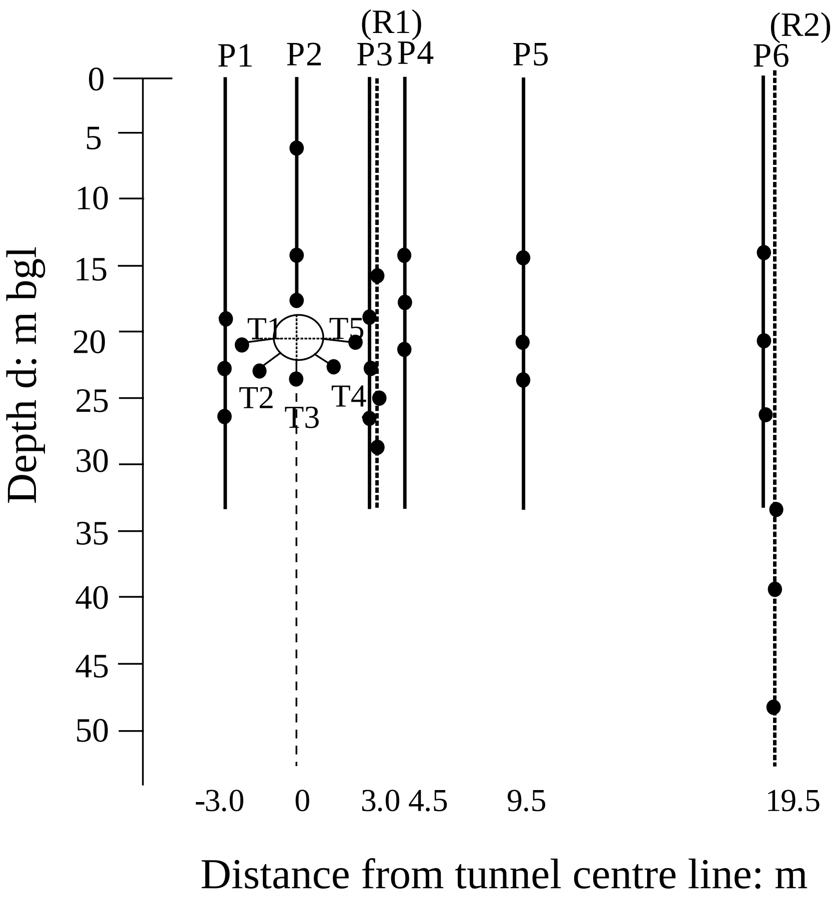
- London northern line at Kennington
  - 75 year old tunnel
  - ground investigation, in situ measurements, cores
- Piezometric conditions
  - pressure profiles, in situ self-boring permeameter
  - degree of drainage into tunnel
- Comparison of ground near and far from tunnel
  - lateral pressure; self-boring load cells and pressuremeter tests
  - very high quality cores; stiffness, and strength
- Predicted response to rising ground-water
  - FE based on in situ conditions and trends

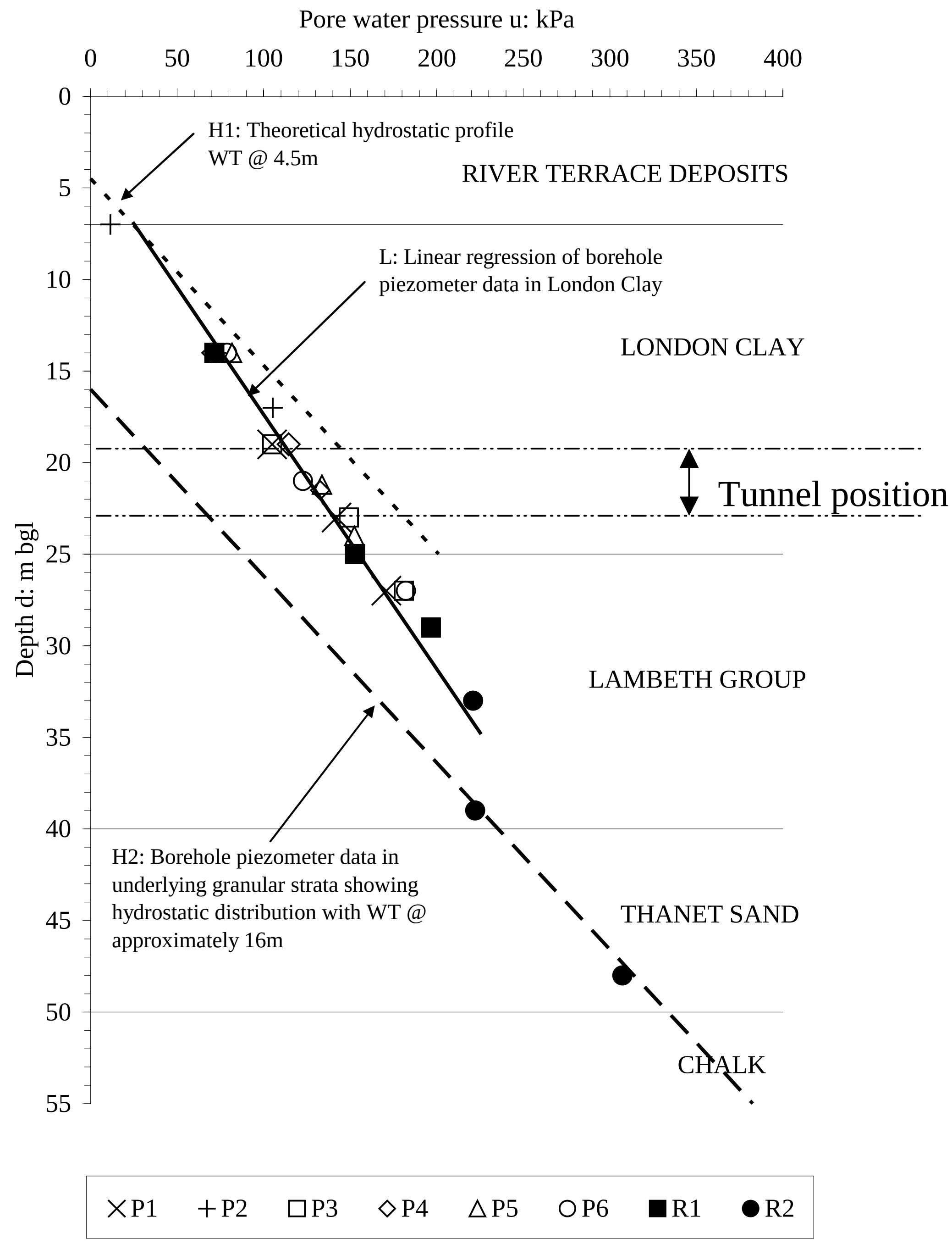

Ground Investigation Works
Kennington Loop
No - we are not building anything here!
London Underground Limited is carrying out research into the behaviour of all its tunnels as part of its commitment to keep London moving.
As part of this study, we are investigating the ground conditions around one of our tunnels which runs beneath Kennington Park. This involves drilling boreholes, and taking and testing soil samples.
The research is being carried out in collaboration with Cambridge University and the Geotechnical Consulting Group.
The contractors are Soil Mechanics Limited with specialist sub-contractors Cambridge Insitu.
The work starts in early January and is expected to be completed by the end of March. On completion of the works the park will be reinstated as before.
For further information contact Nick Burgess, LUL Project Engineer, 4/13, 30 The South Colonnade, Canary Wharf, E14 5EU

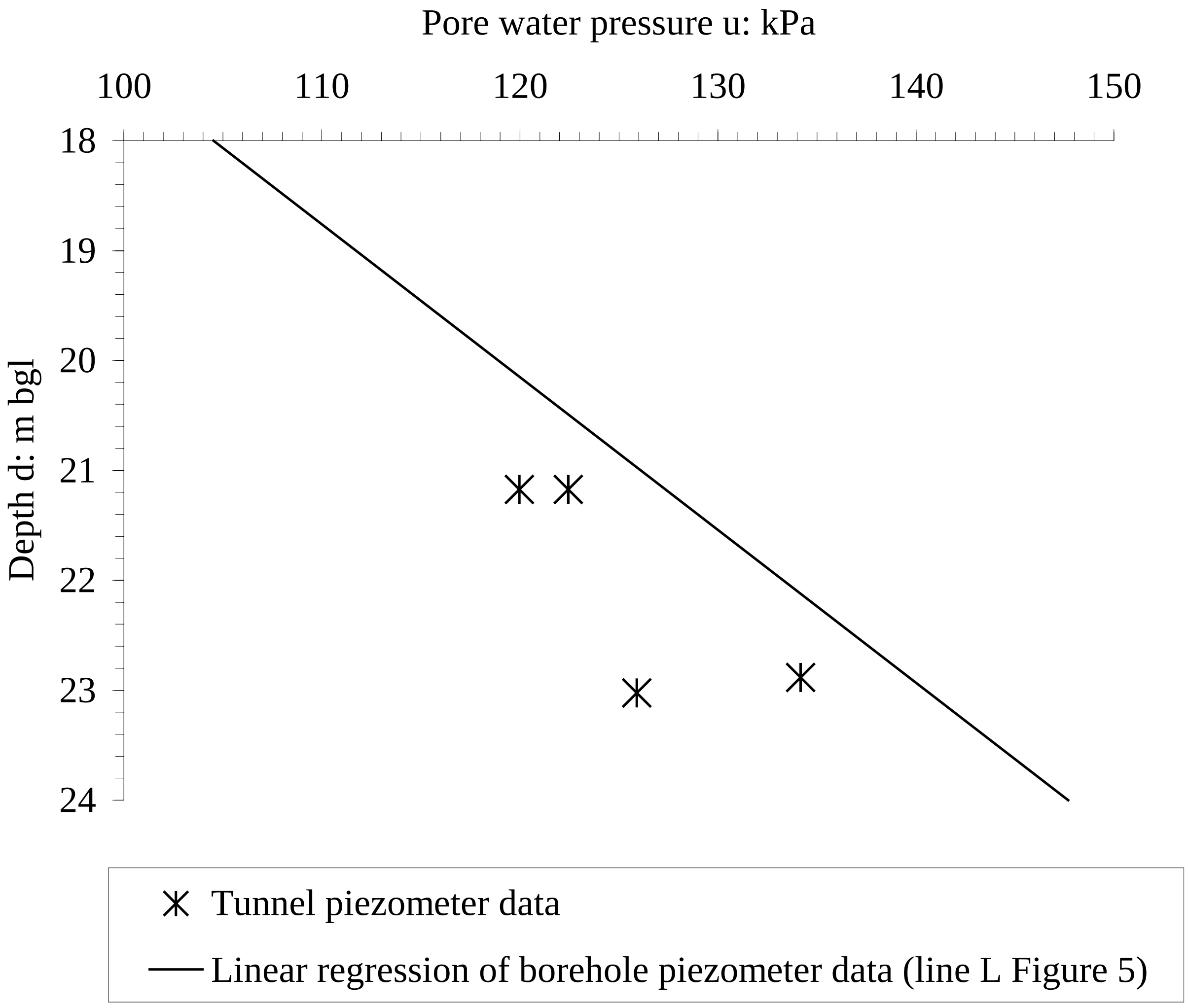
# LUL Kennington stratigraphy



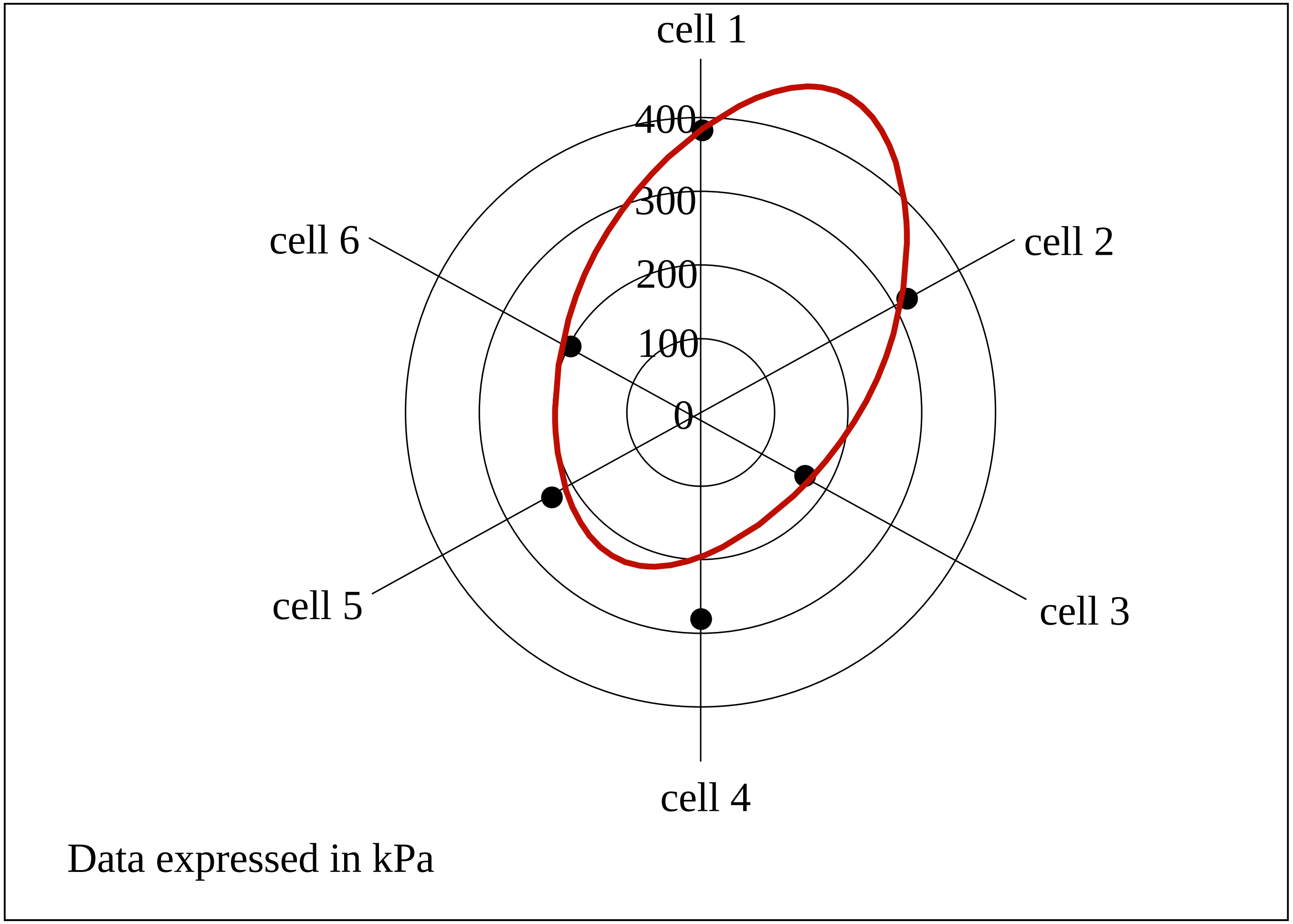
# Pore water pressures



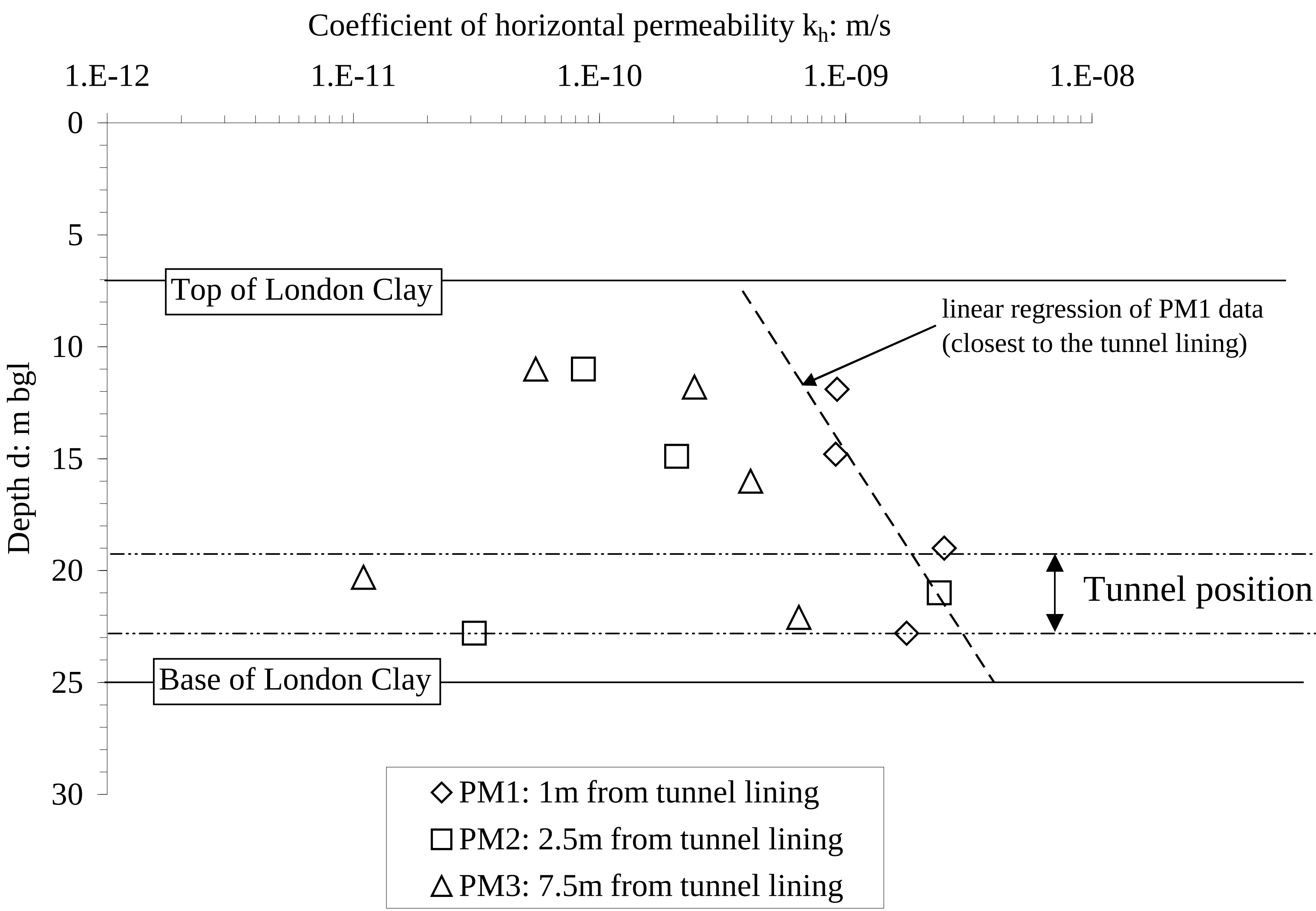




Pore water pressure u: kPa
100
110
120
130
140
150
18
19
20
21
22
23
24
Depth d: m bgl
Tunnel piezometer data
Linear regression of borehole piezometer data (line L Figure 5)

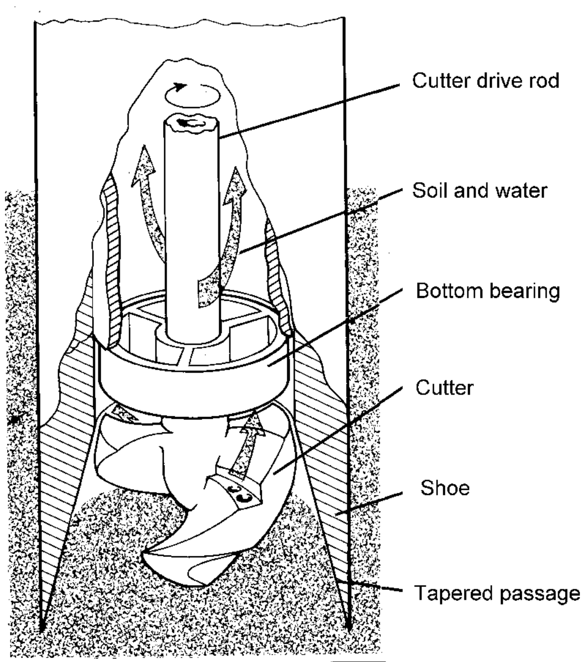
# LUL Kennington: load cell data



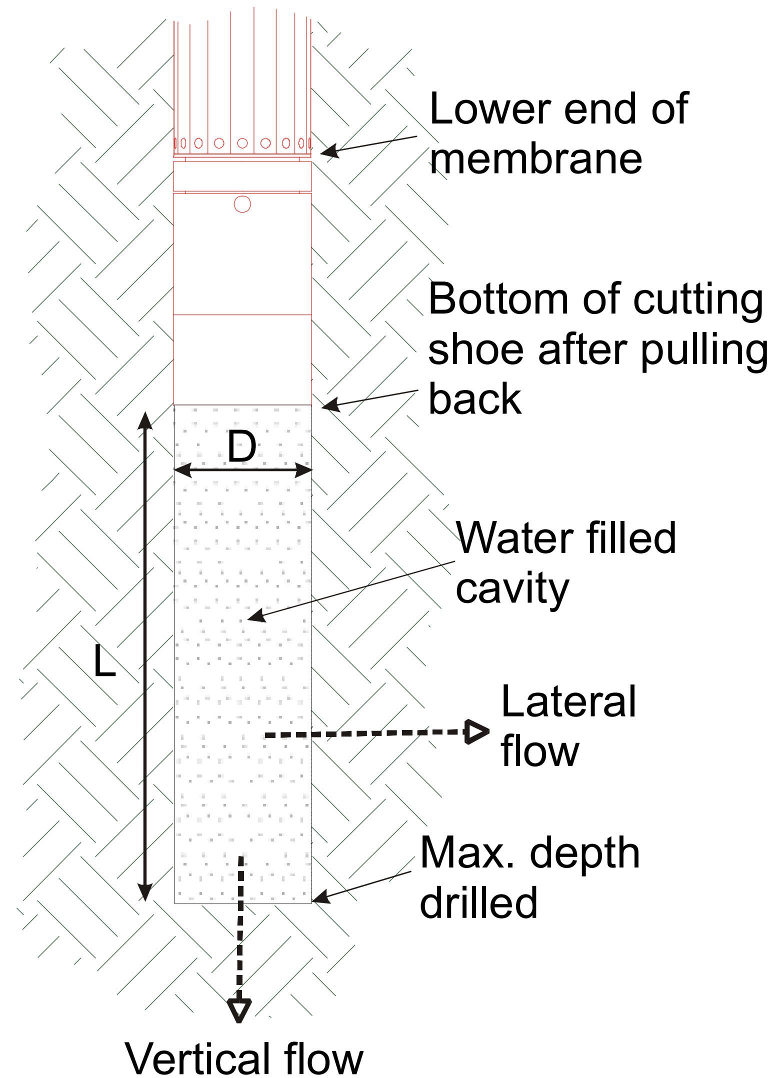
# Permeability

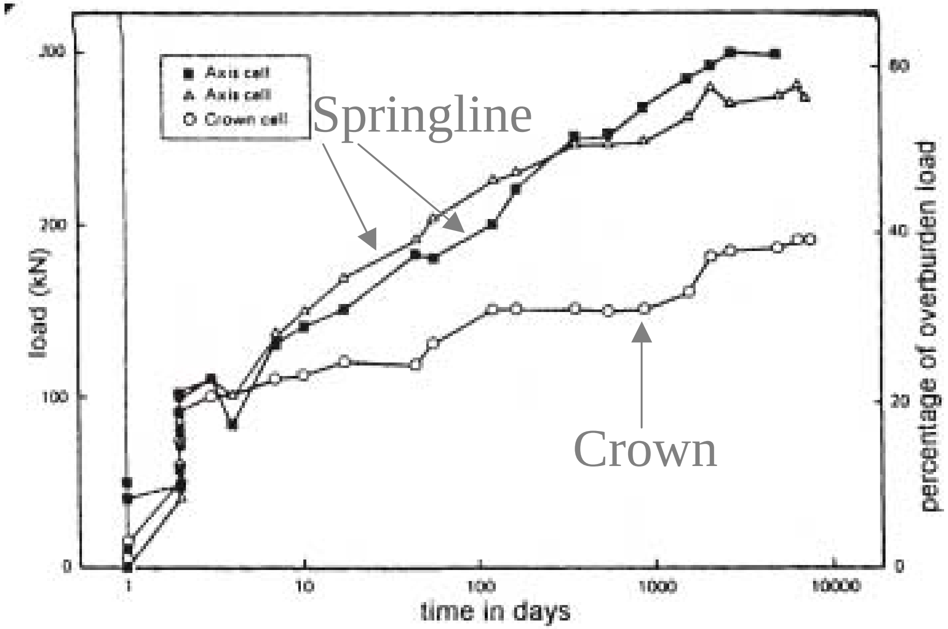


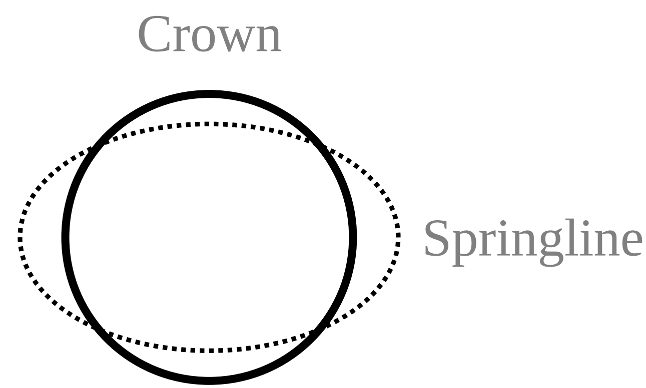
# Field Permeability Measurement

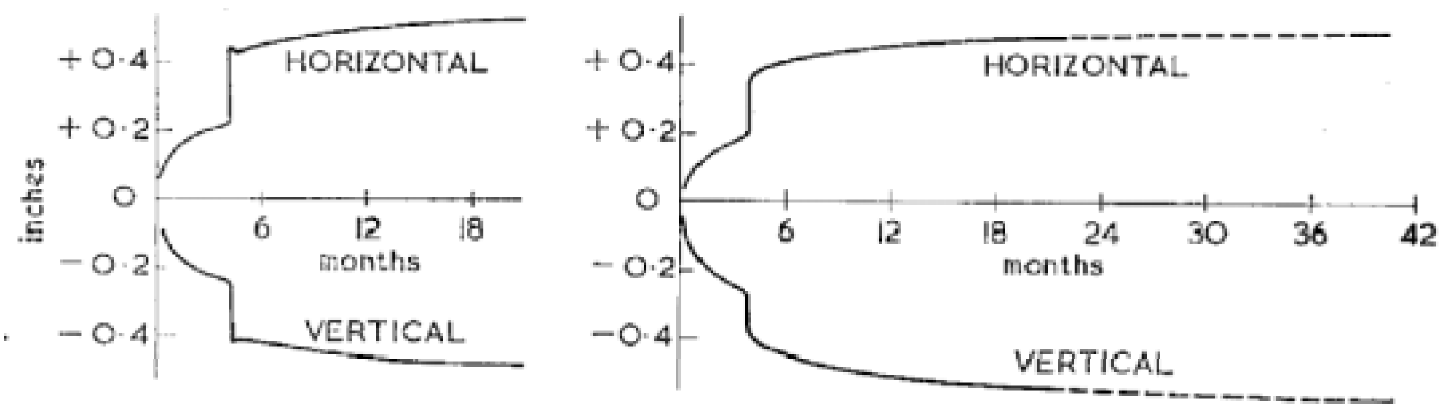



LOW DISTURBANCE DRILLING SYSTEM



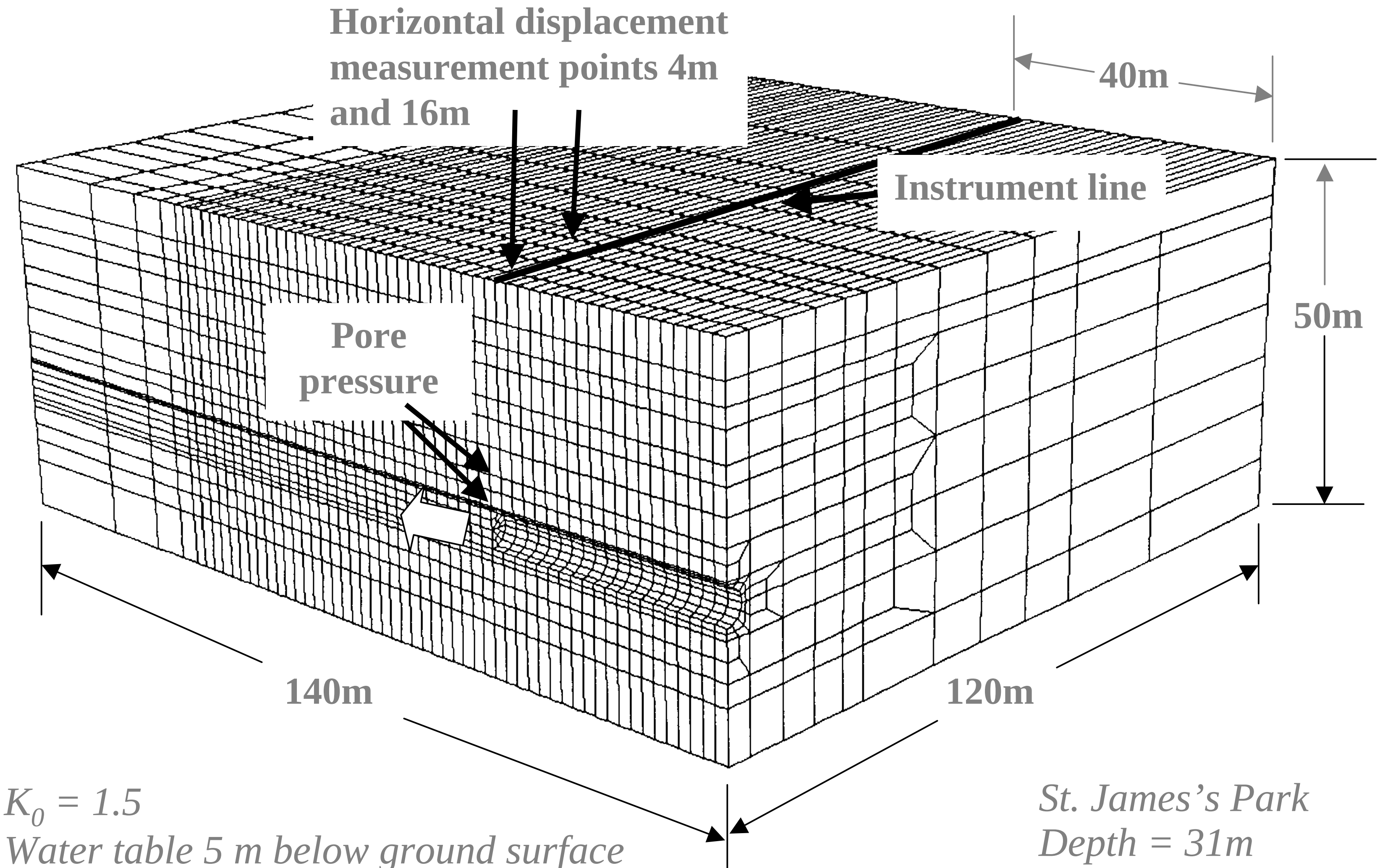



Ward and Thomas (1965)

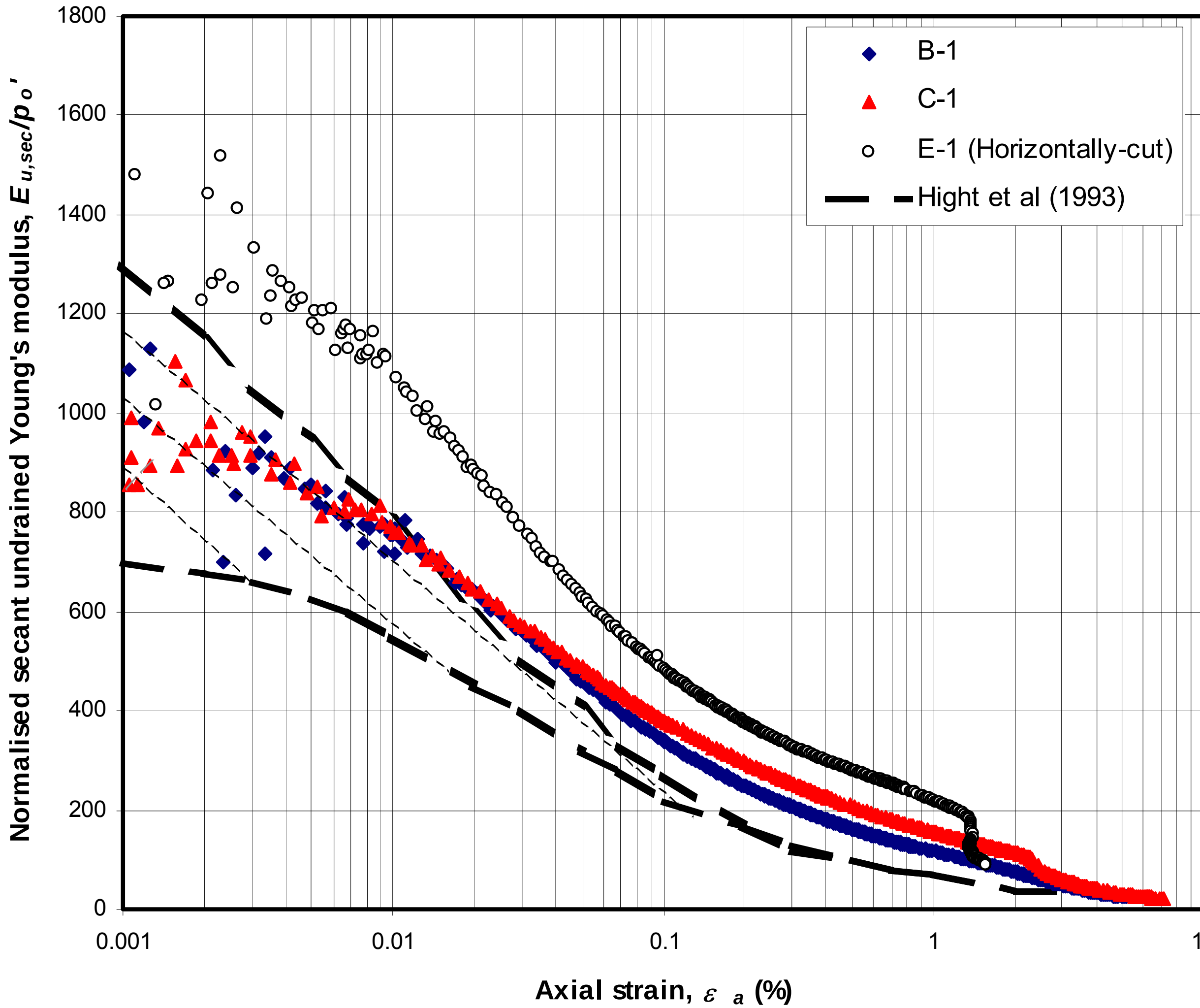
# Long term effect of tunnel construction processes




*$K_0$ = 1.5*
*Water table 5 m below ground surface*
*Hydrostatic*

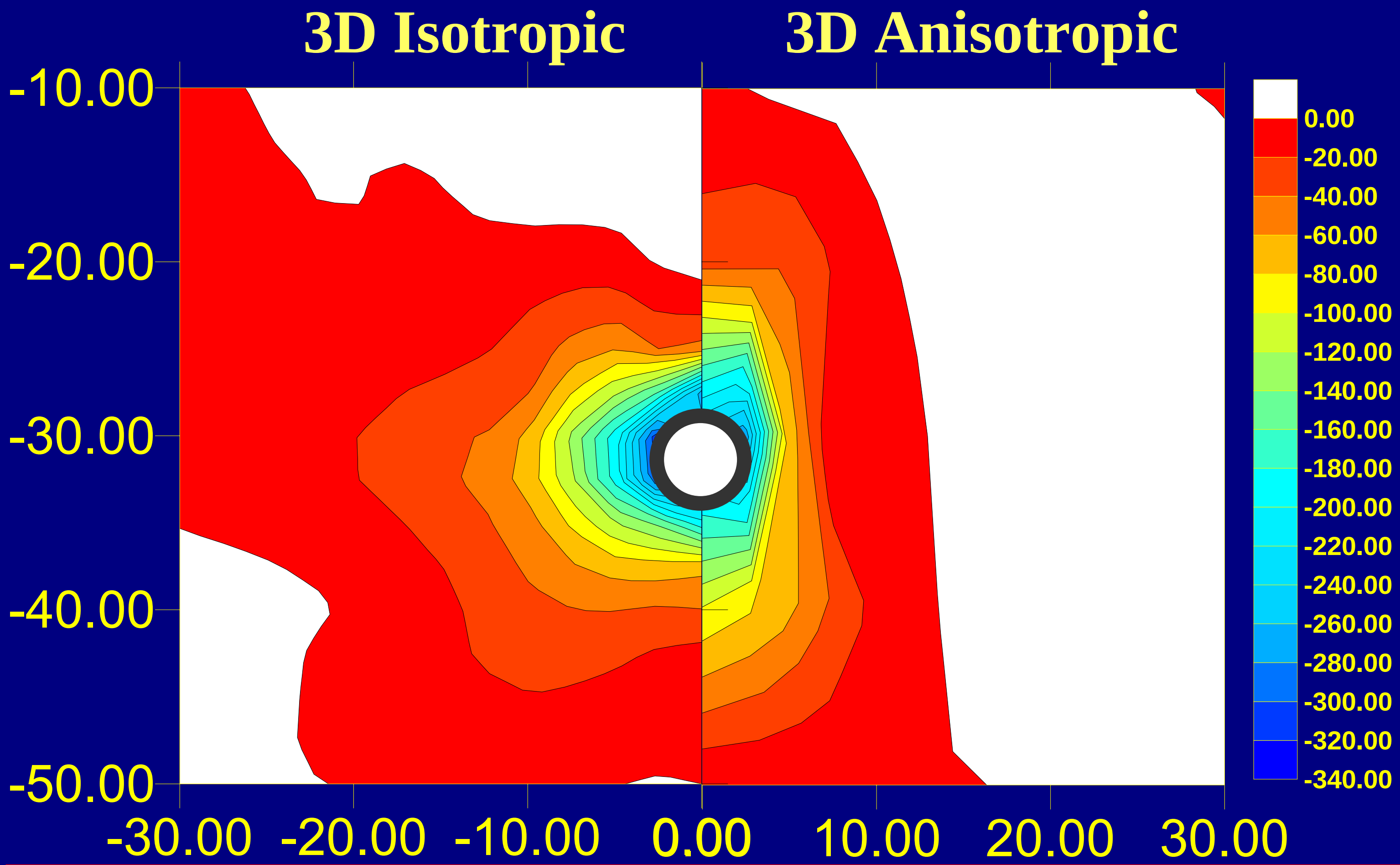
*St. James's Park*
*Depth = 31m*
*Diameter = 4.85m*

# Anisotropy



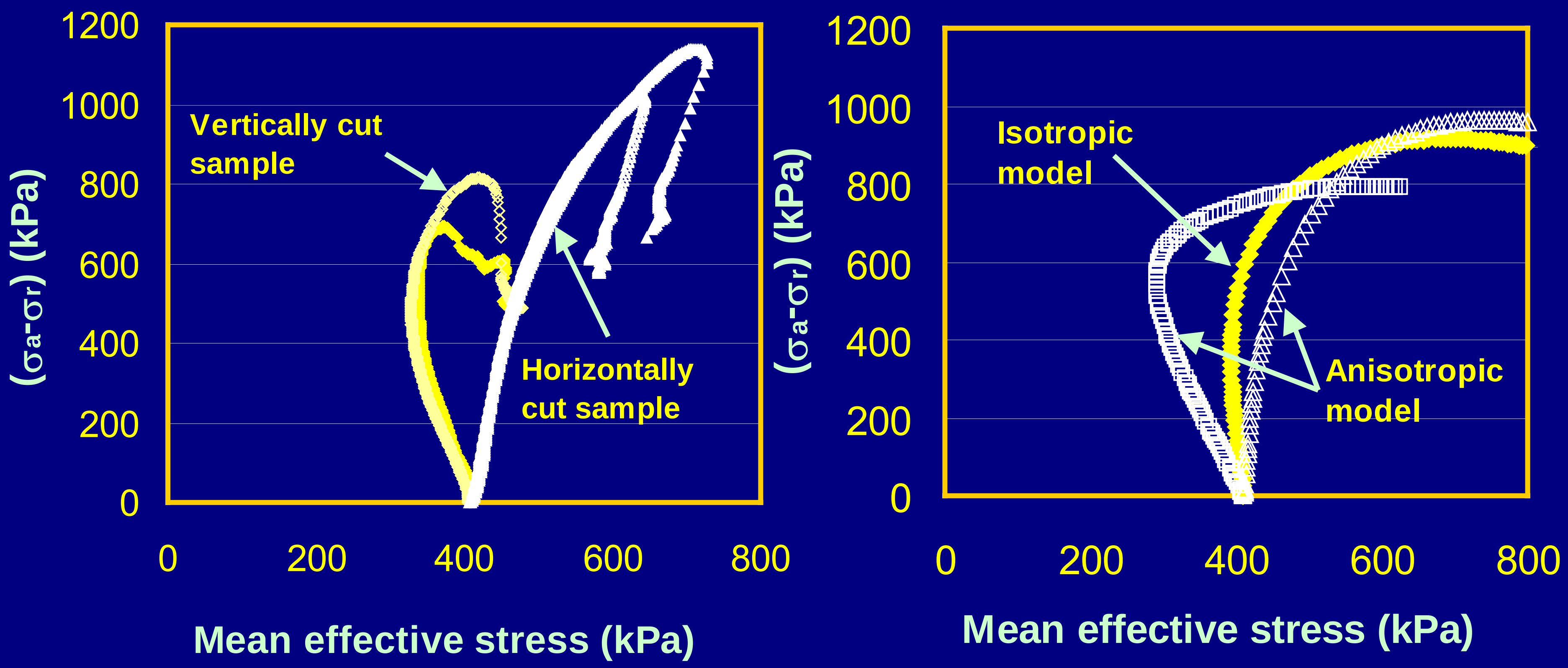
B-1
C-1
E-1 (Horizontally-cut)
Hight et al (1993)
Normalised secant undrained Young's modulus, $E_{u,sec}/p_o'$
Axial strain, $\varepsilon_a$ (%)
0
200
400
600
800
1000
1200
1400
1600
1800
0.001
0.01
0.1
1
10

# Excess Pore Pressure Contour (kPa)



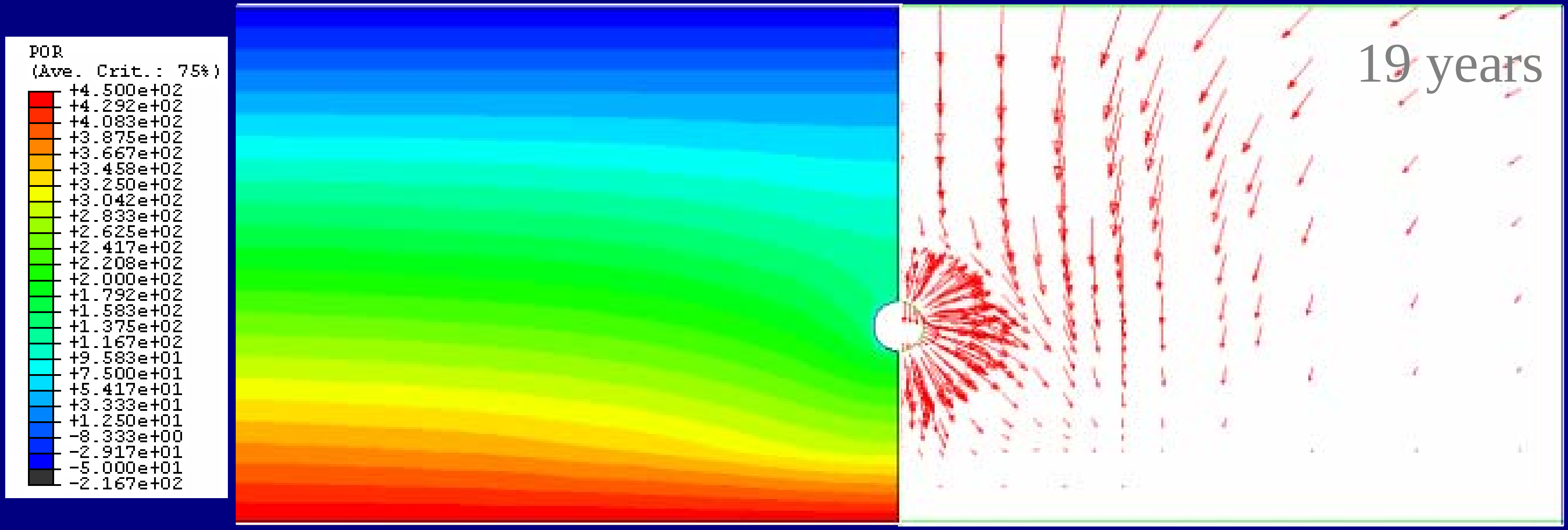

- Similar pattern but different magnitude between 2D and 3D
- Different pattern between isotropic and anisotropic soil because of difference in stress path directions

# Undrained Effective stress paths



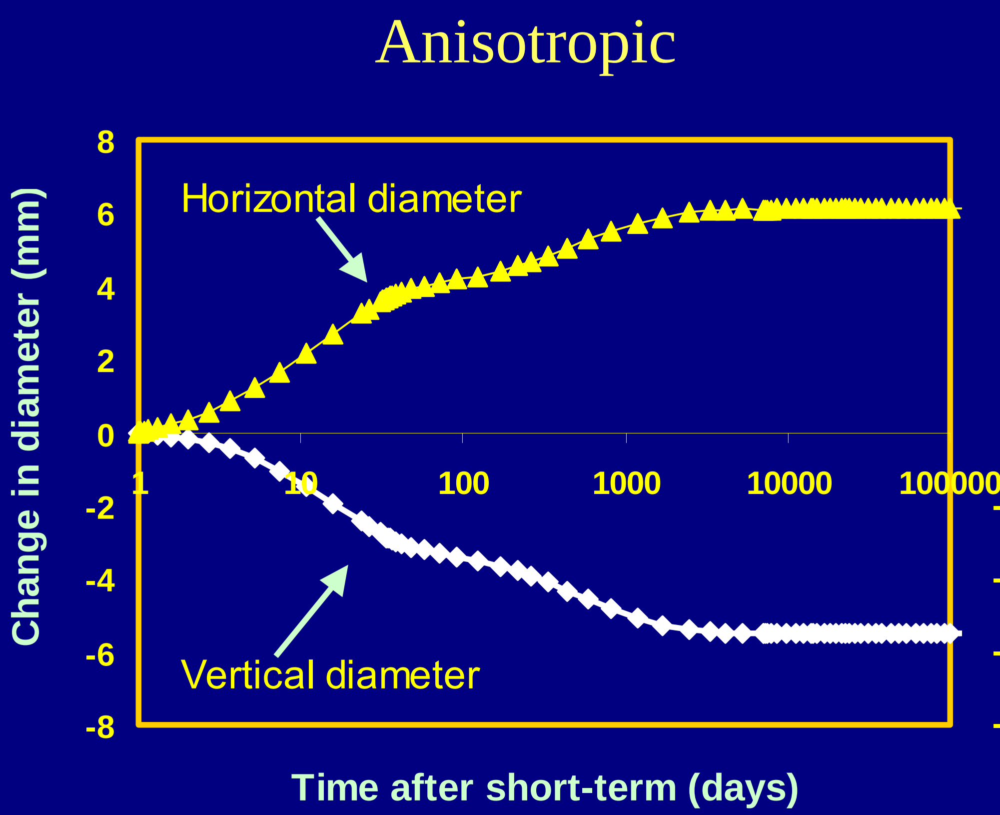

**Excess pore pressure generations will be different**

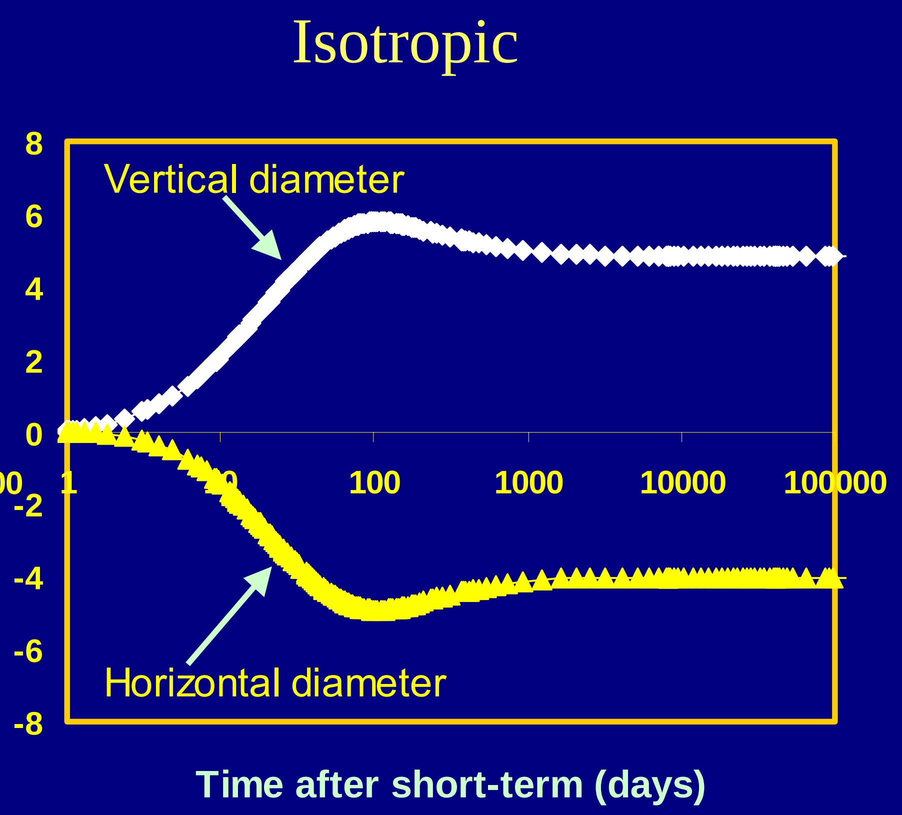
# Long-term

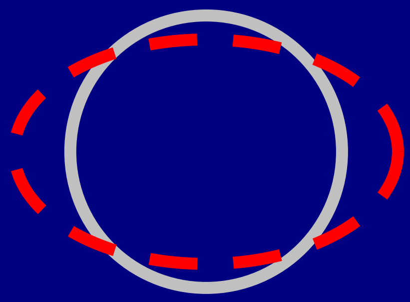


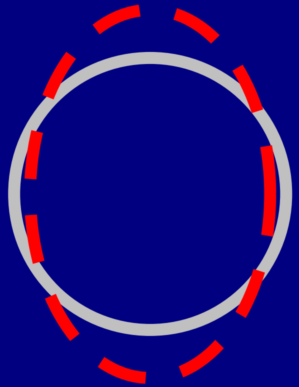

- Permeable tunnel lining leads to further settlement with time
- There will be slightly outward displacement around the tunnel

# Performance of the tunnel lining

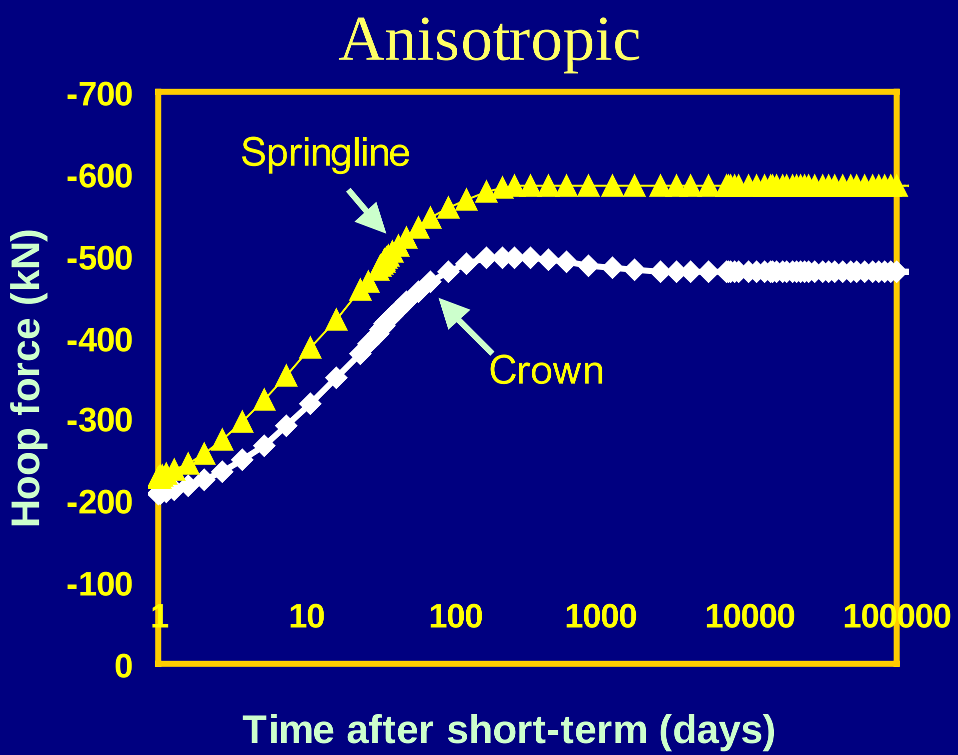


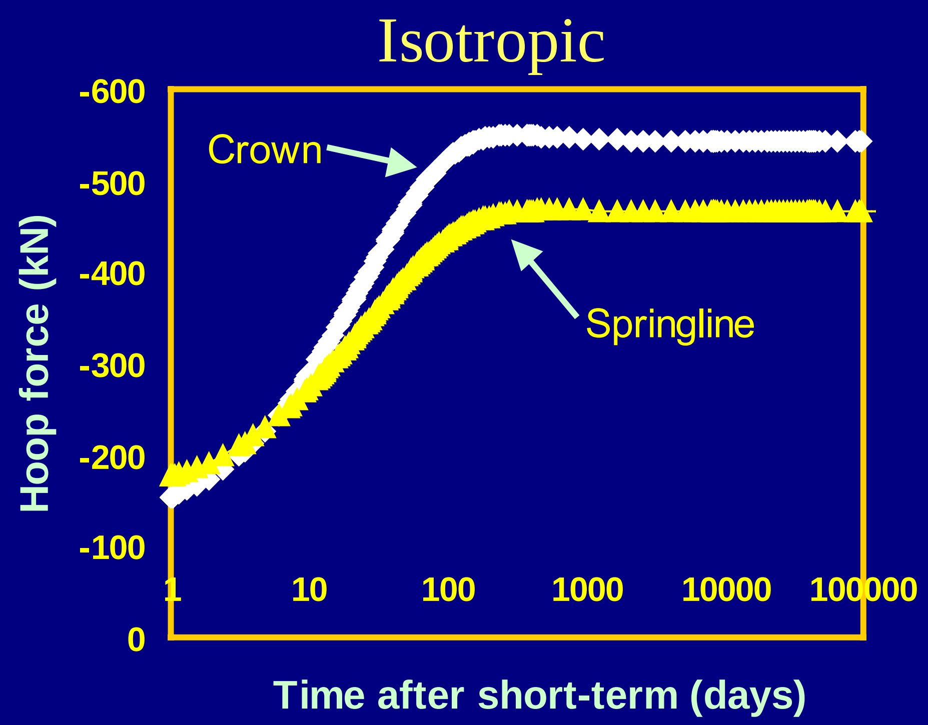



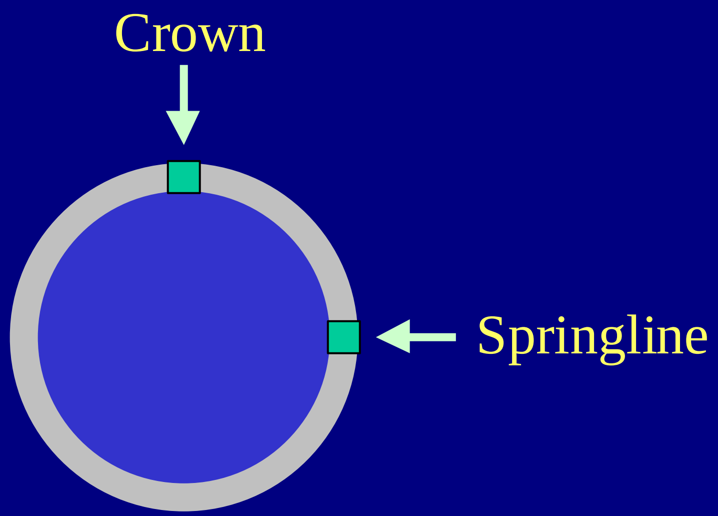



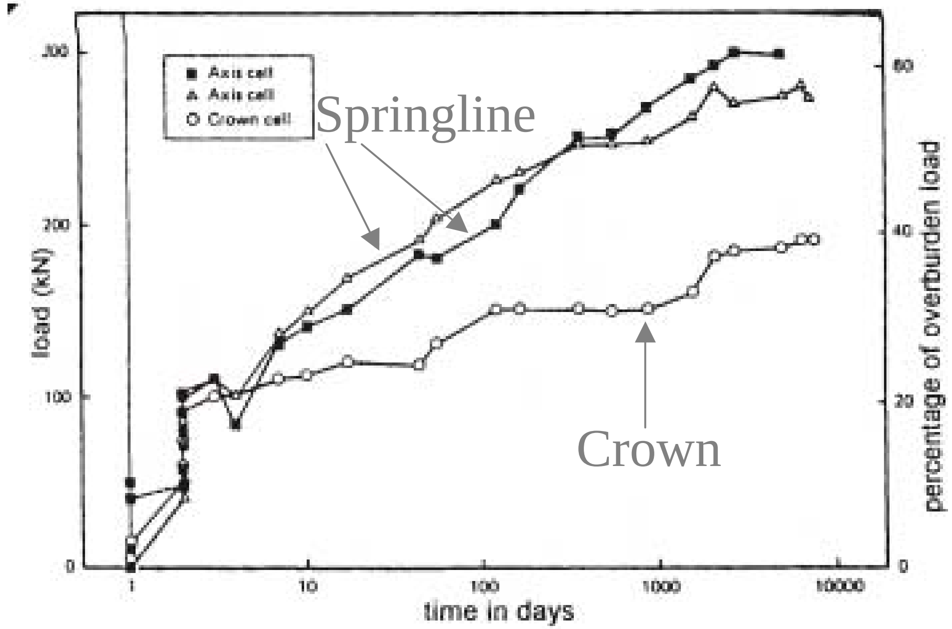


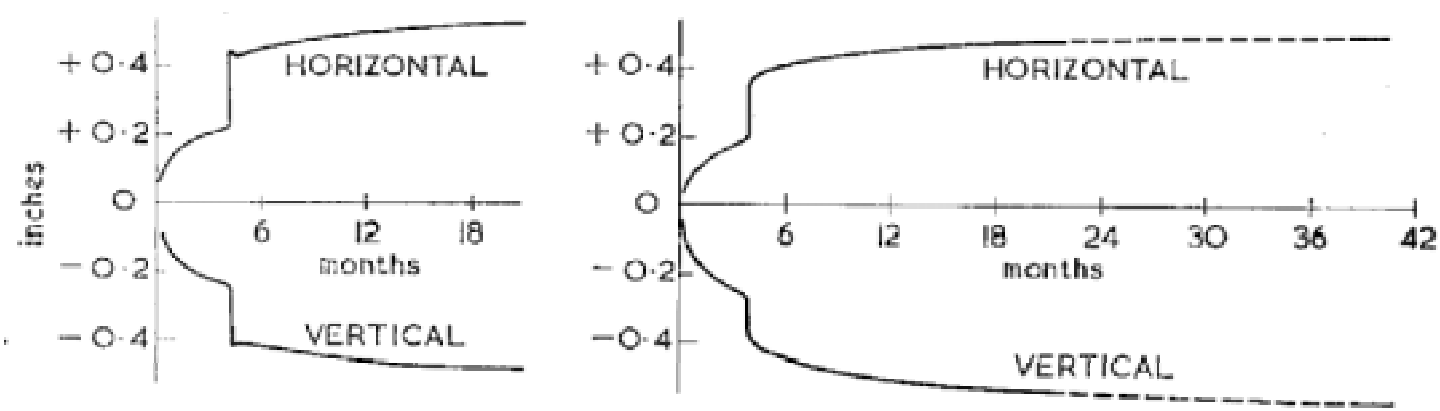
# Performance of the tunnel lining



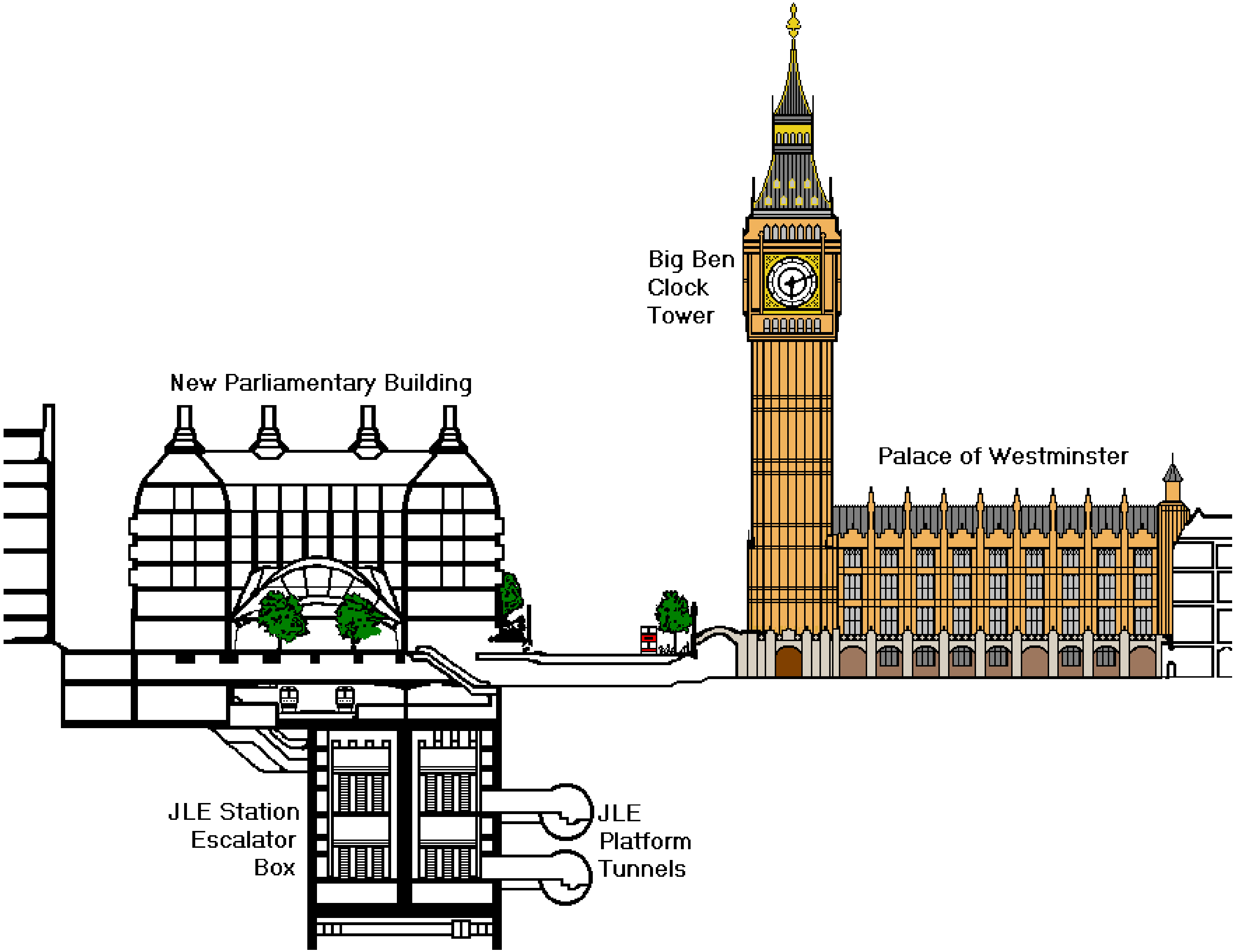





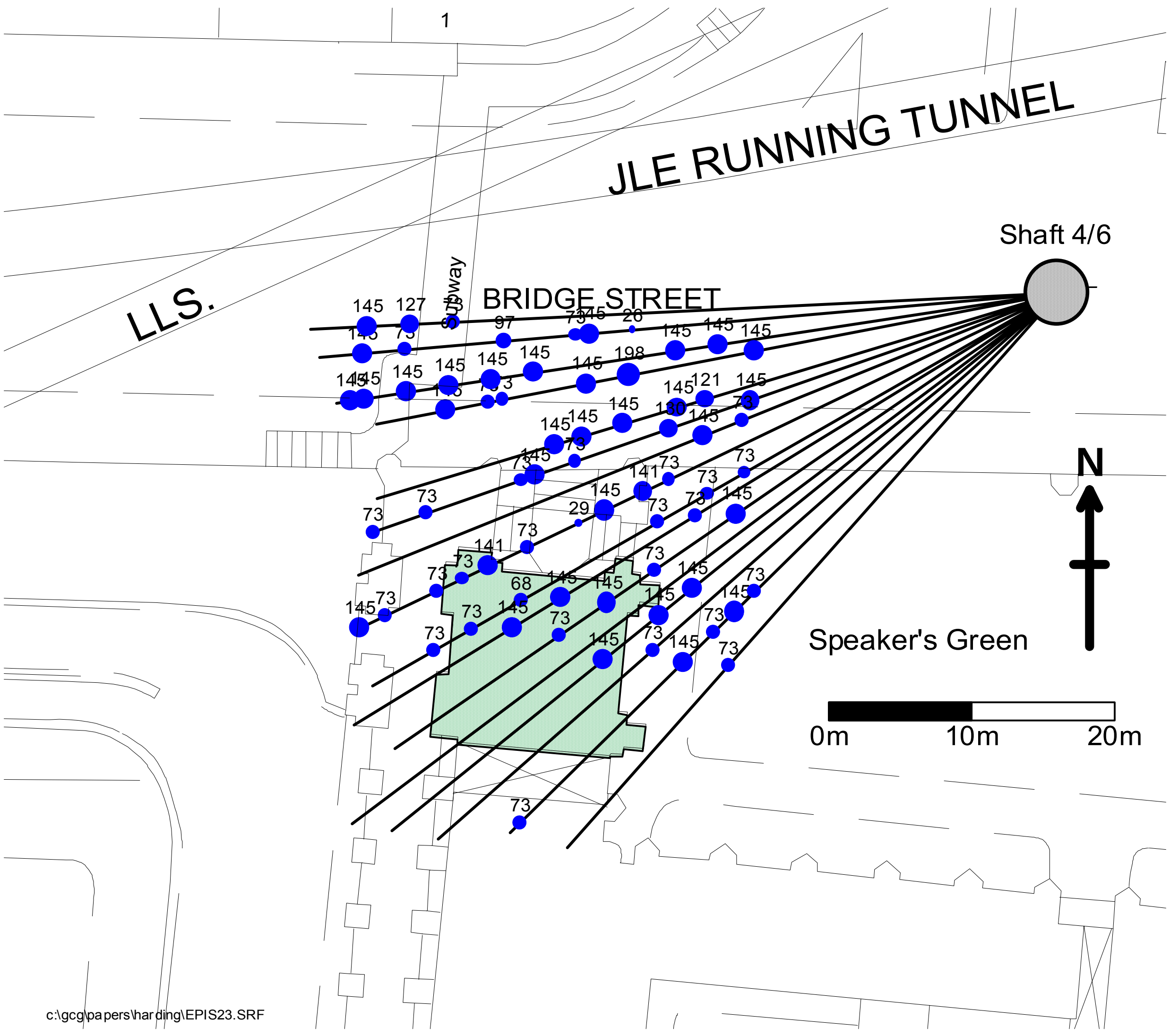




Ward and Thomas (1965)


Big Ben
Clock
Tower
New Parliamentary Building
Palace of Westminster
JLE Station
Escalator
Box
JLE
Platform
Tunnels

# Grout Injections : Episode 23

**16 June 1997 to 20 June 1997**
**Scale 1:500**

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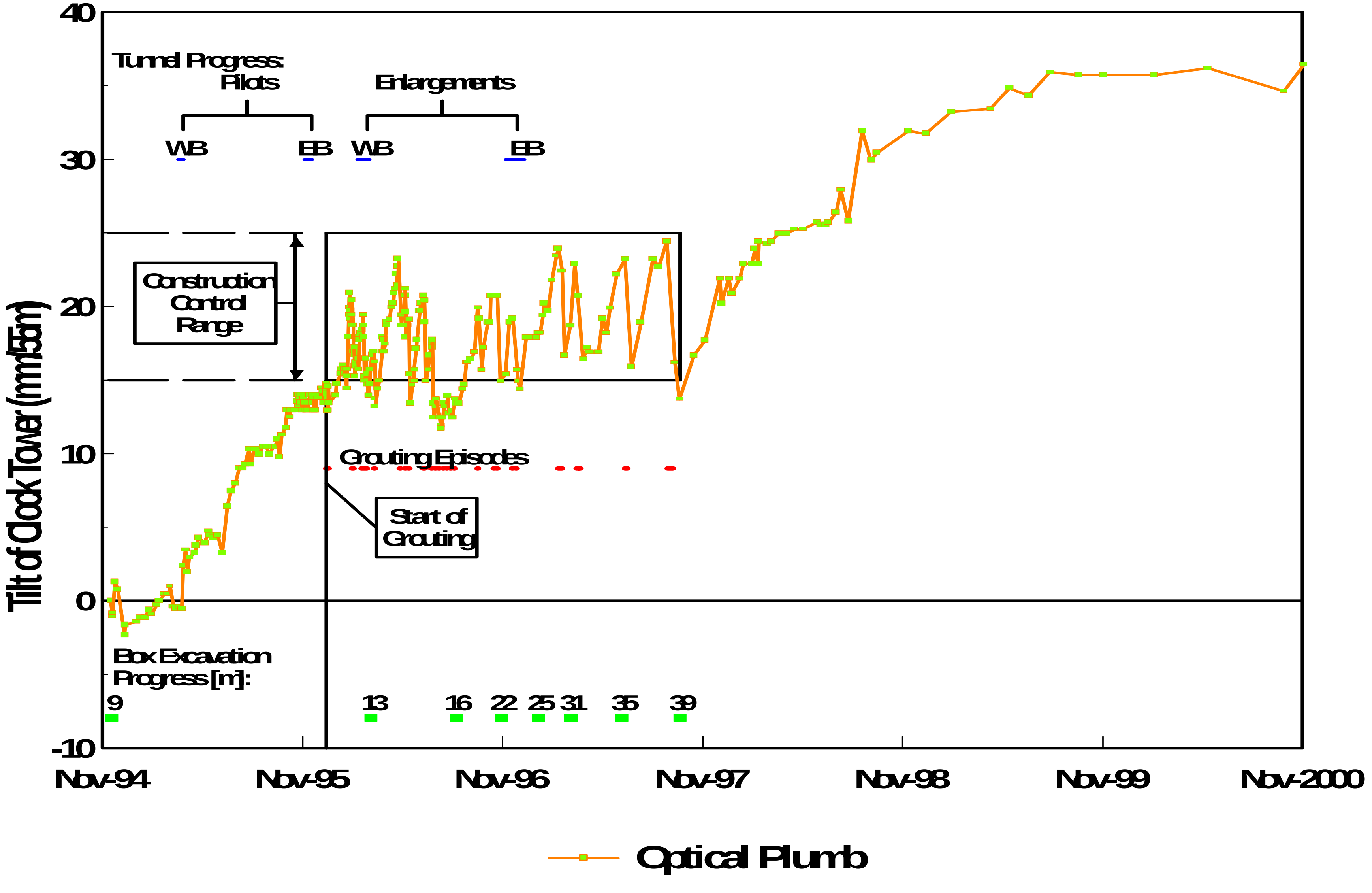
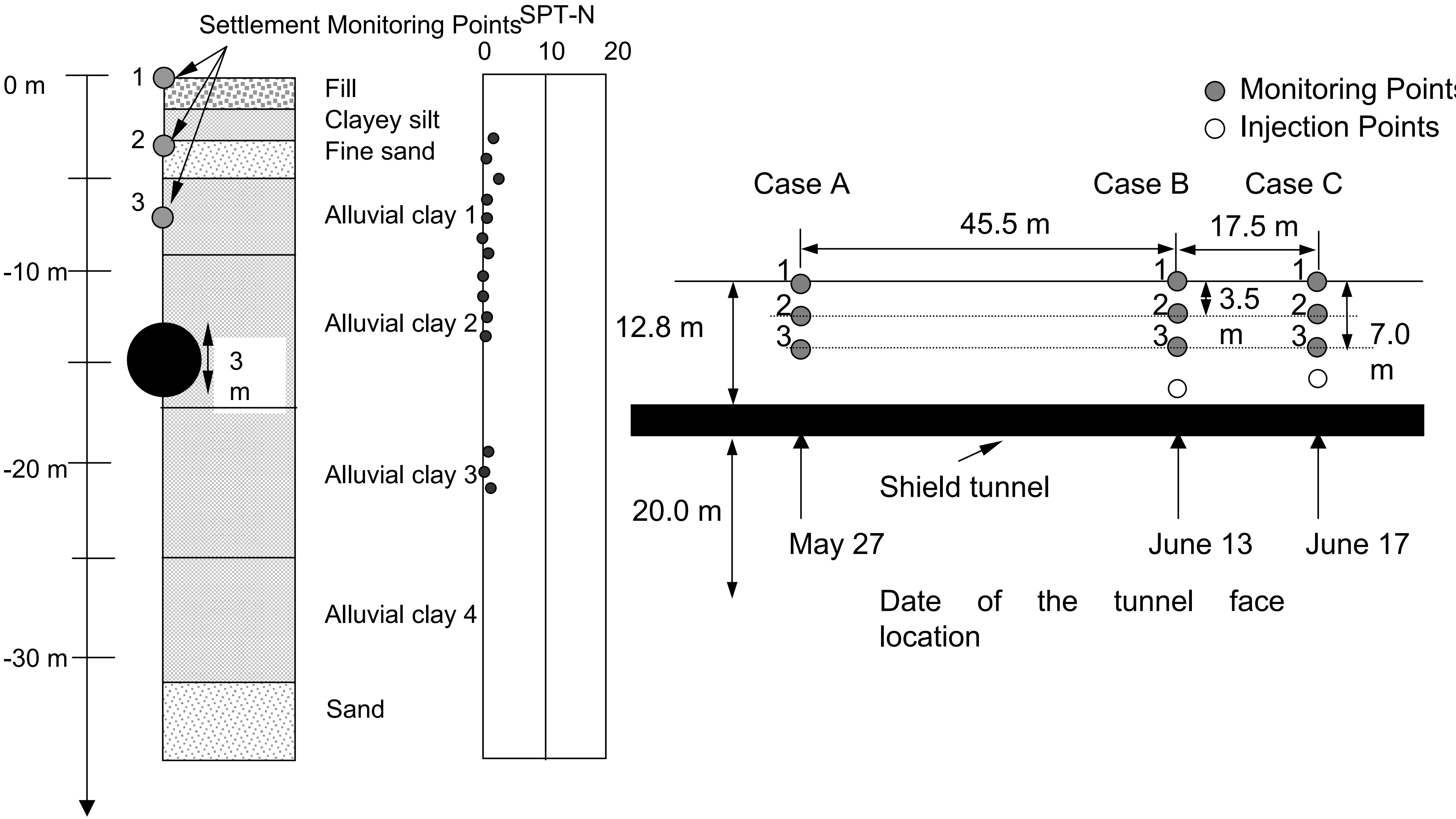
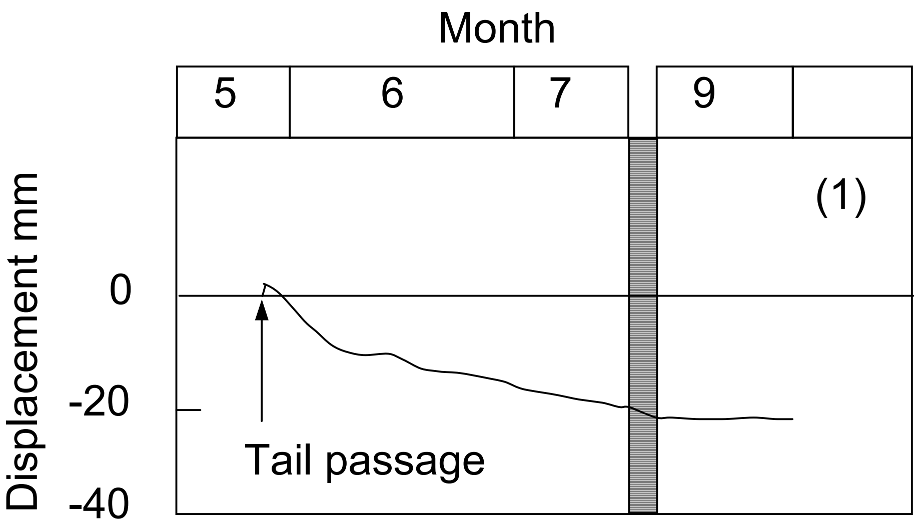


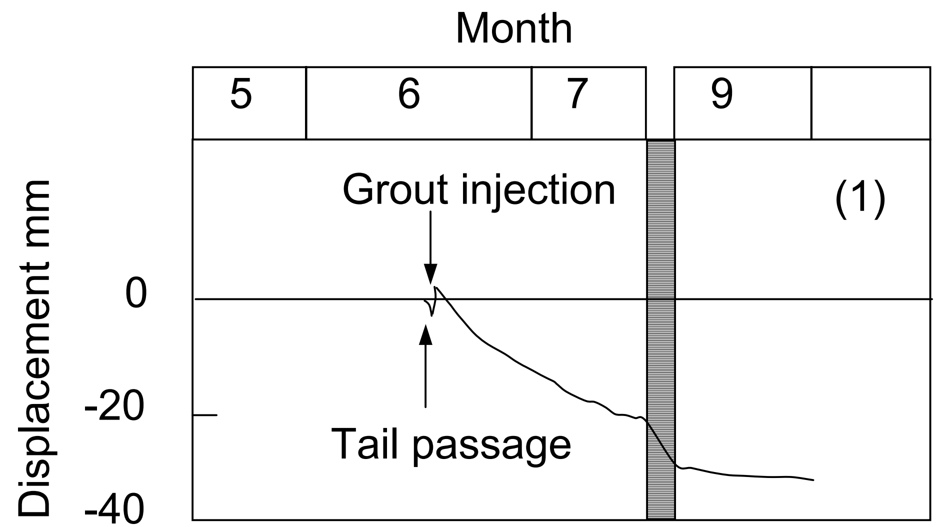
40
30
20
10
0
-10
Tilt of Clock Tower (mm/55cm)
Tunnel Progress:
Pilots
Enlargements
WB
EB
WB
EB
Construction Control Range
Grouting Episodes
Start of Grouting
Box Excavation Progress [m]:
9
13
16
22
25
31
35
39
Nov-94
Nov-95
Nov-96
Nov-97
Nov-98
Nov-99
Nov-2000
Optical Plumb



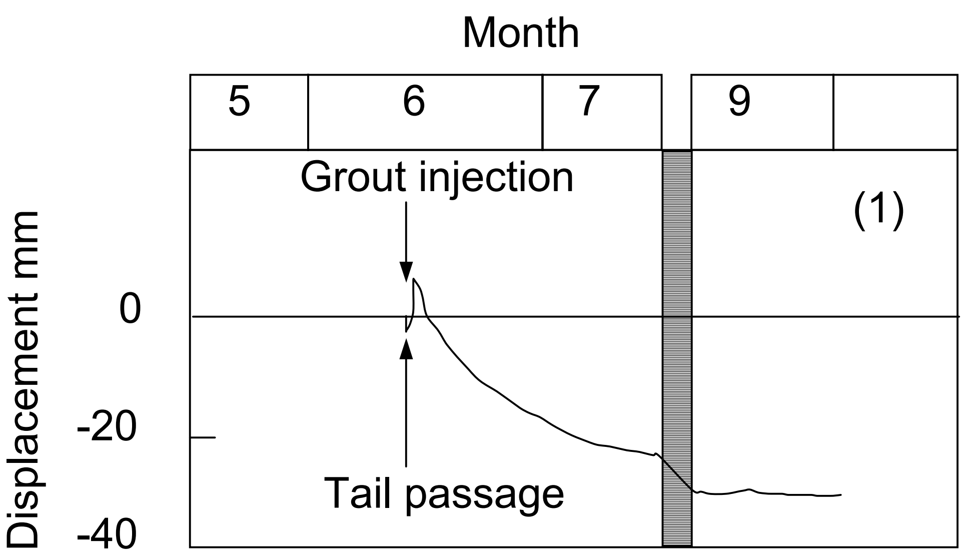
Settlement Monitoring Points
SPT-N
0
10
20
0 m
-10 m
-20 m
-30 m
1
2
3
Fill
Clayey silt
Fine sand
Alluvial clay 1
Alluvial clay 2
3 m
Alluvial clay 3
Alluvial clay 4
Sand
Monitoring Points
Injection Points
Case A
Case B
Case C
45.5 m
17.5 m
3.5 m
7.0 m
12.8 m
20.0 m
Shield tunnel
May 27
June 13
June 17
Date of the tunnel face location



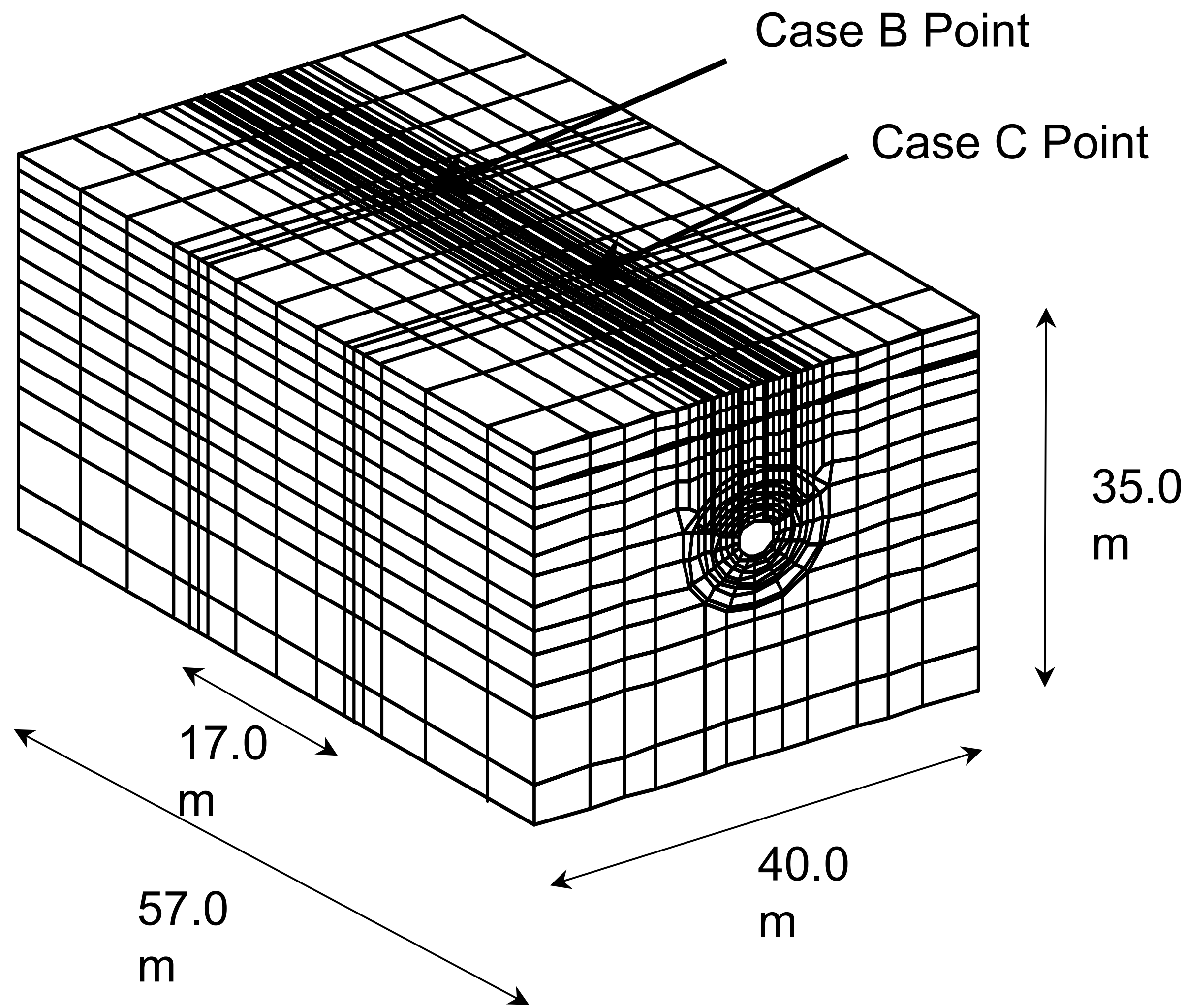

Case A

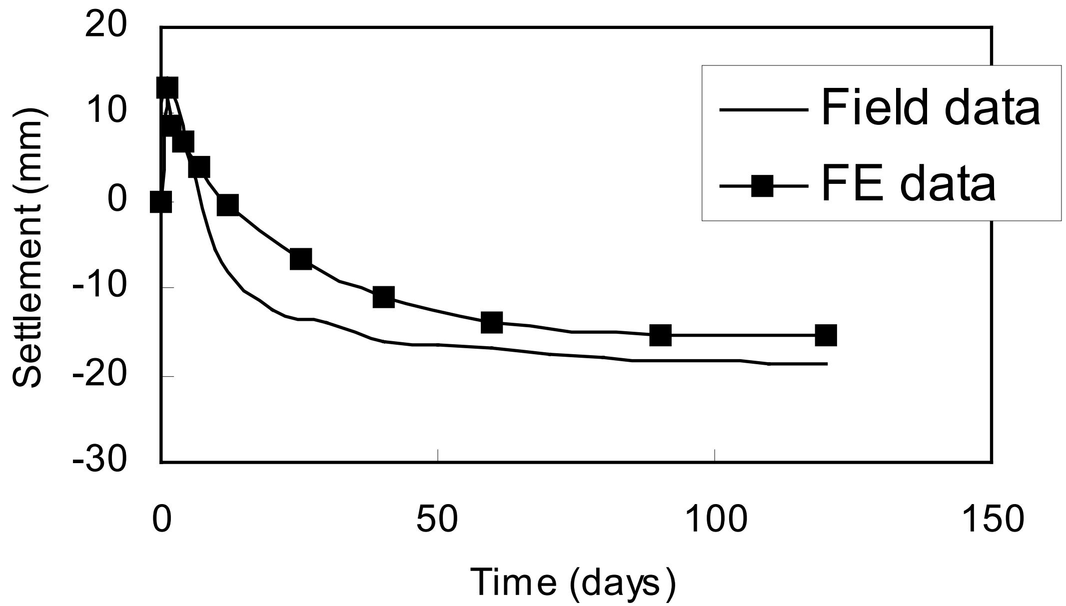



Case C



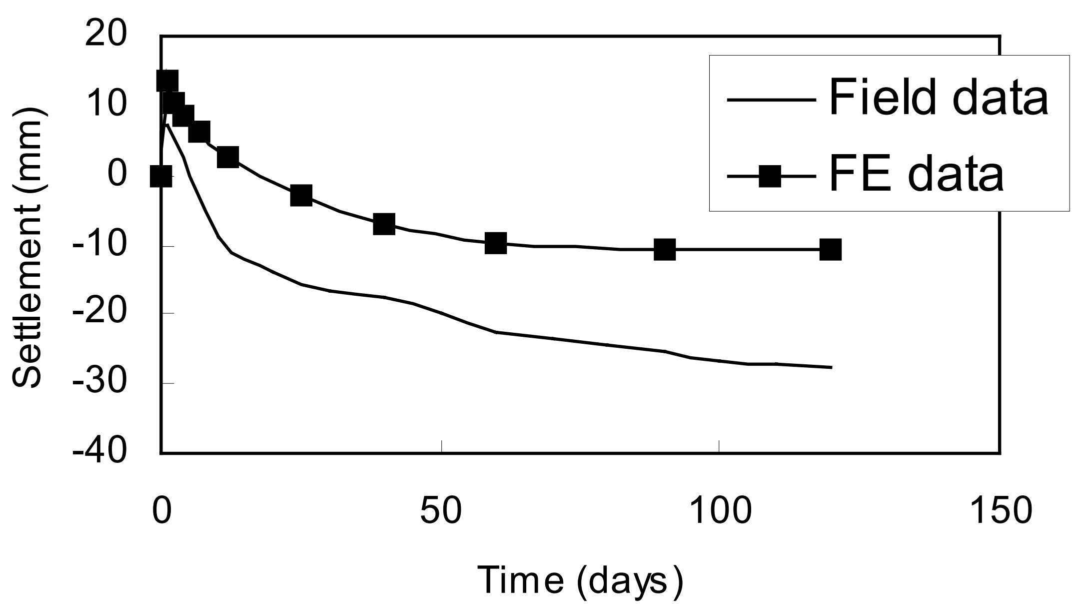

Case B


Case B Point
Case C Point
35.0
m
17.0
m
40.0
m
57.0
m



Field data
FE data
Settlement (mm)
Time (days)
20
10
0
-10
-20
-30
0
50
100
150


Case B



Field data
FE data
Settlement (mm)
Time (days)
20
10
0
-10
-20
-30
-40
0
50
100
150


Case C

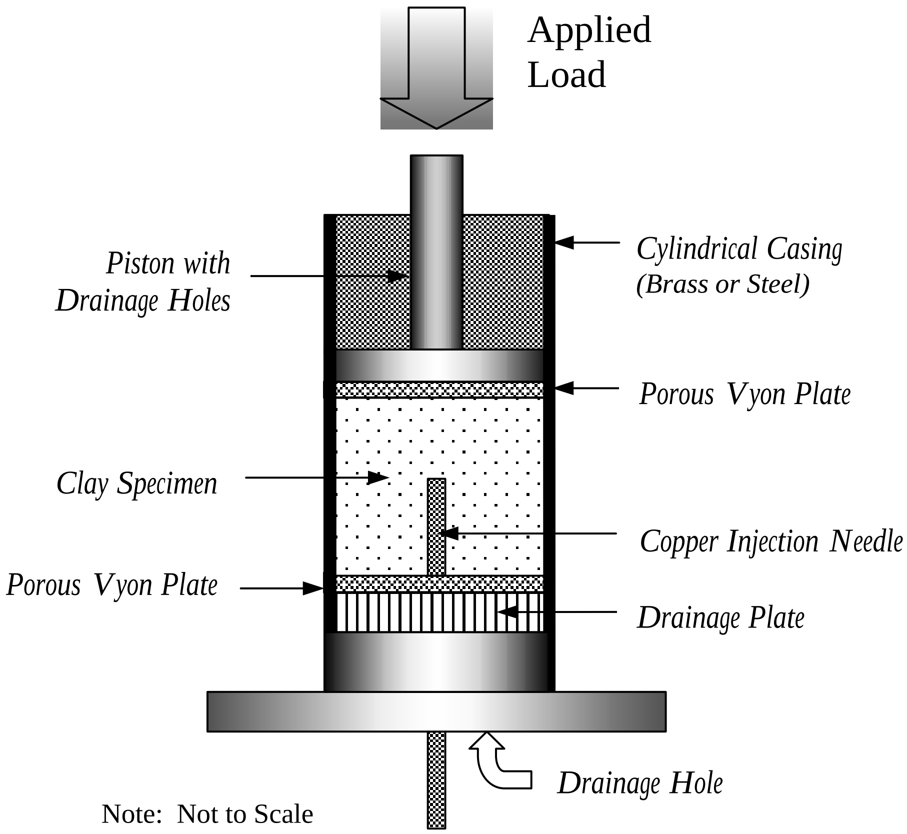
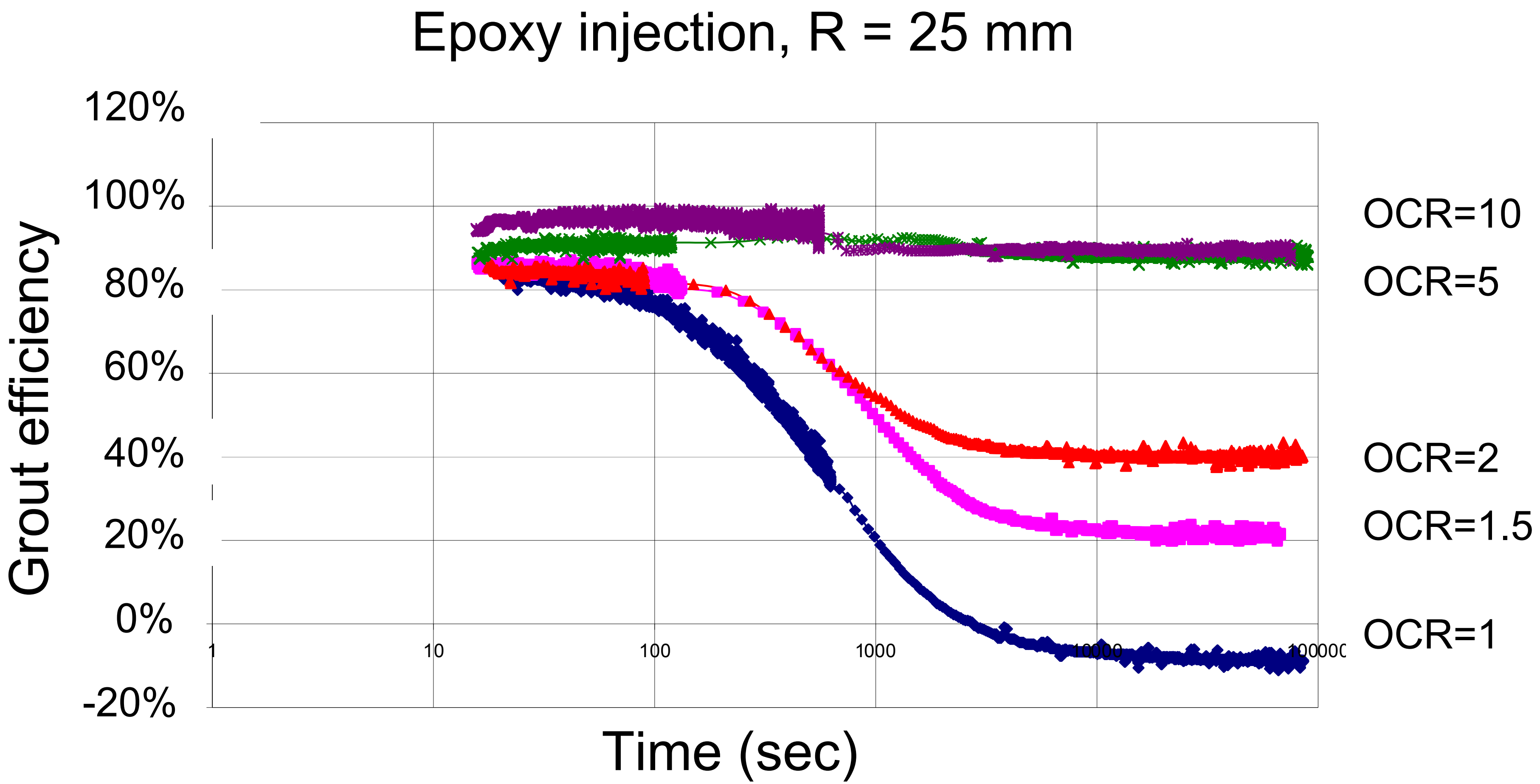



Figure 4.3 Section of Modified Consolidometer

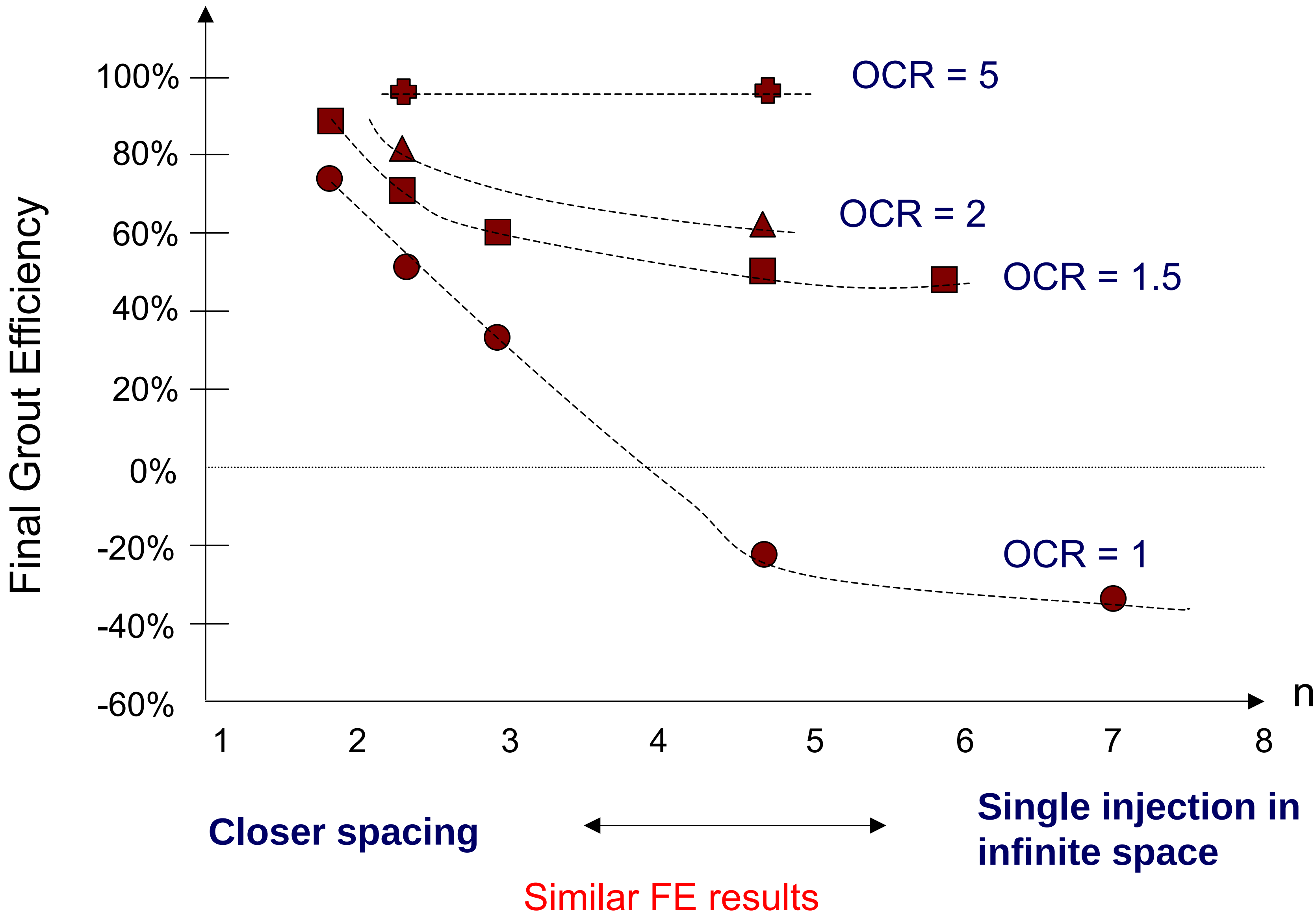
Different diameter specimens – simulate simultaneous injection at different spacings

# Effect of OCR on Compensation Efficiency

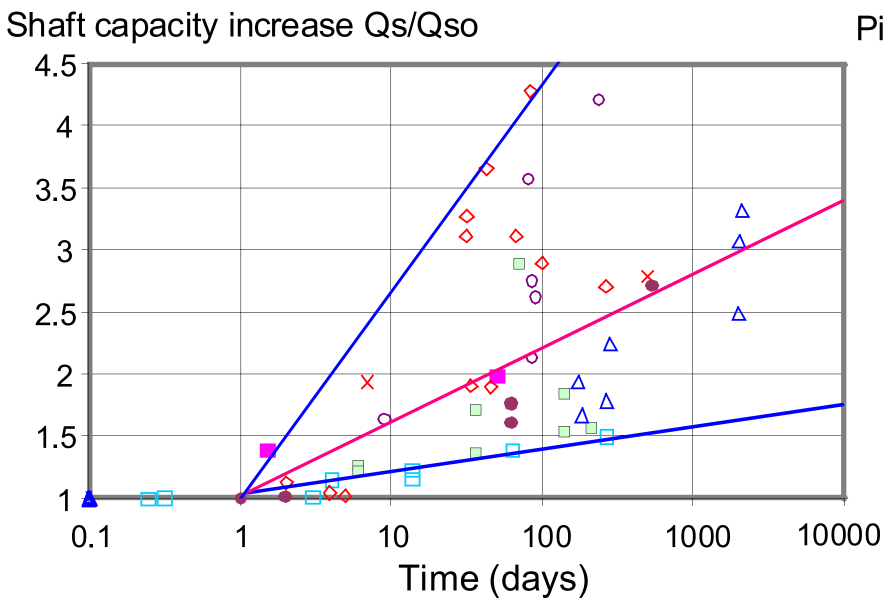


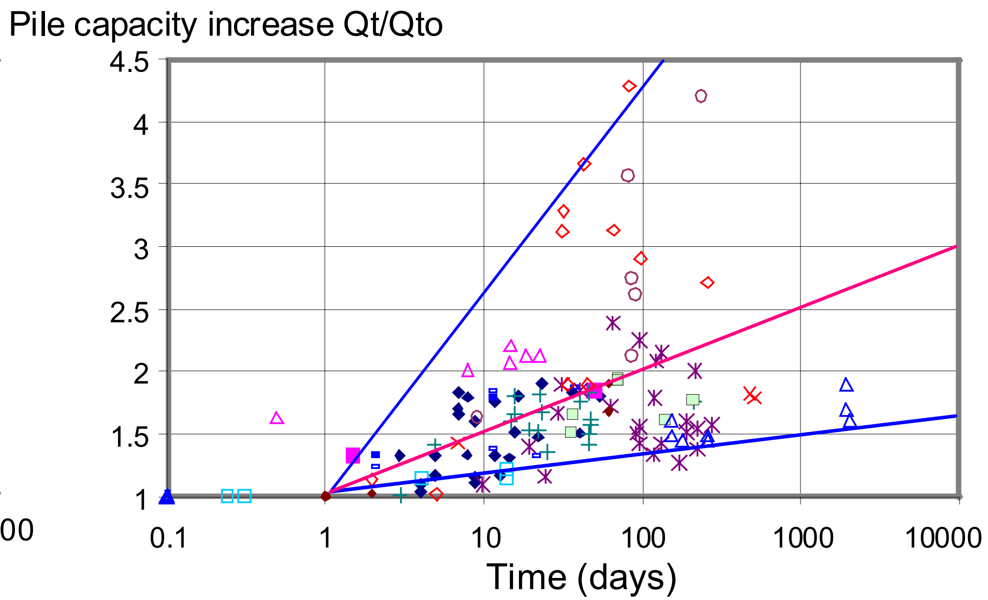

Very low efficiency in NC clays confirmed by field trials

# Effect of Grout Spacing



# Pile set-up - Field Observation



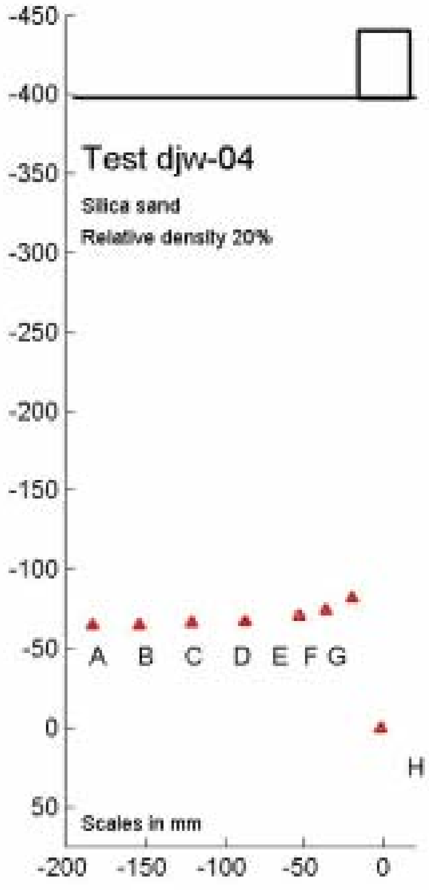



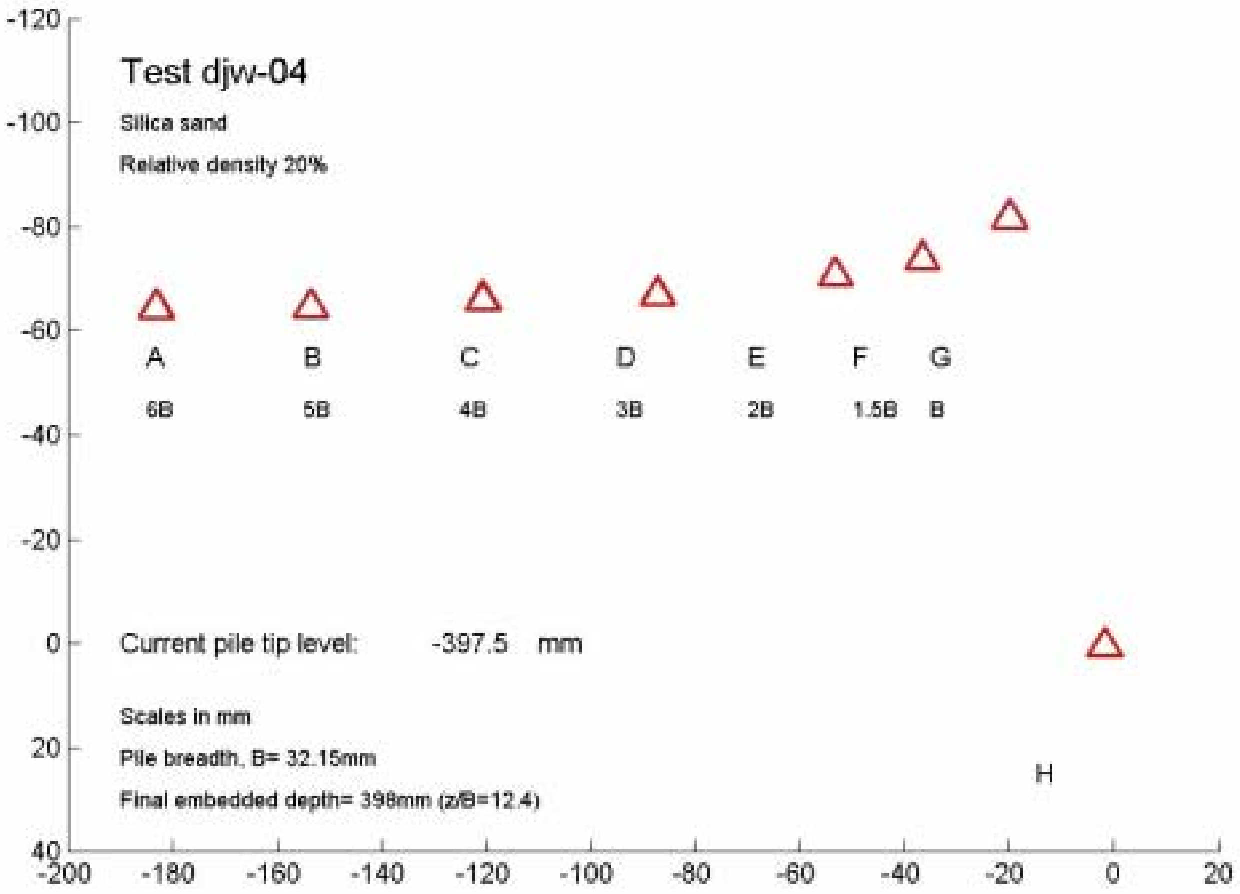

- Driven piles in sand exhibit shaft capacity increases of typically 60% per log cycle time, though highly variable (20-170% per log cycle).
- Greater set up appears to occur in denser sands, with saturated and dry sands and not above 3m.
- References: Chow et al (1998), Jardine & Standing (1999)

# Observation of soil movement during pile driving

Model pile is jacked into calibration chamber.
Digital images captured through reinforced window.
This example: silica sand, base resistance = 14 - 17 MPa.

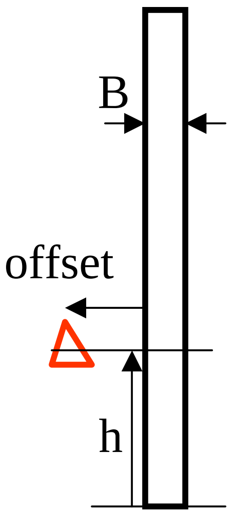
# Deformation of soil element around a pile

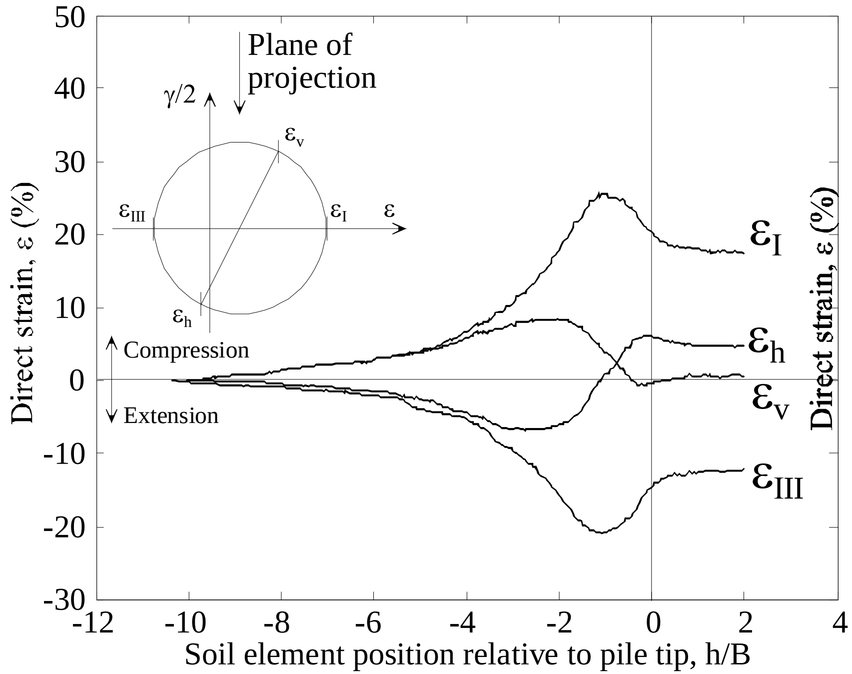


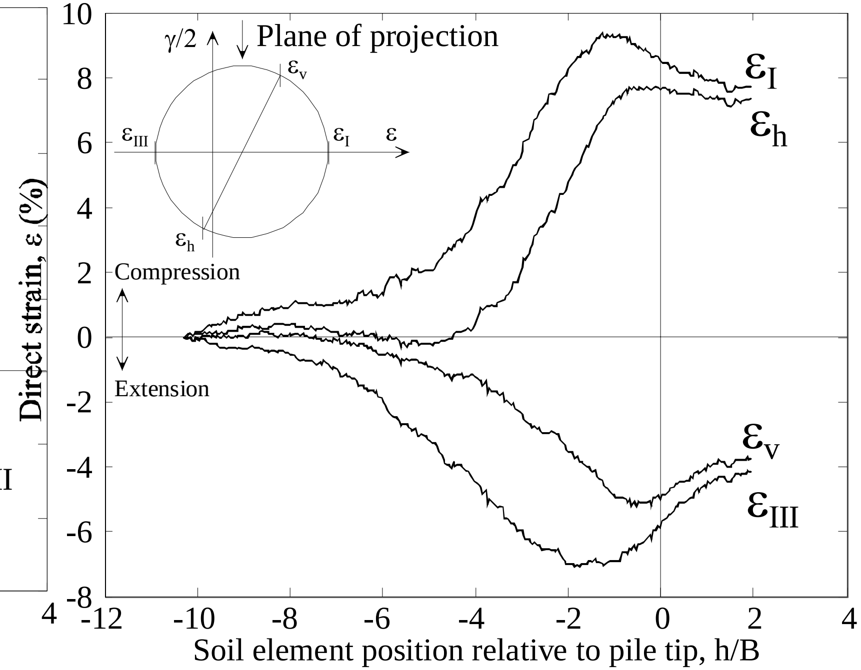




Images converted to displacement measurements using Particle Image Velocimetry (PIV) and close-range photogrammetry.

# Measured strain paths




Near the pile (offset = 1.5B)

Far from the pile (offset = 3.5B)

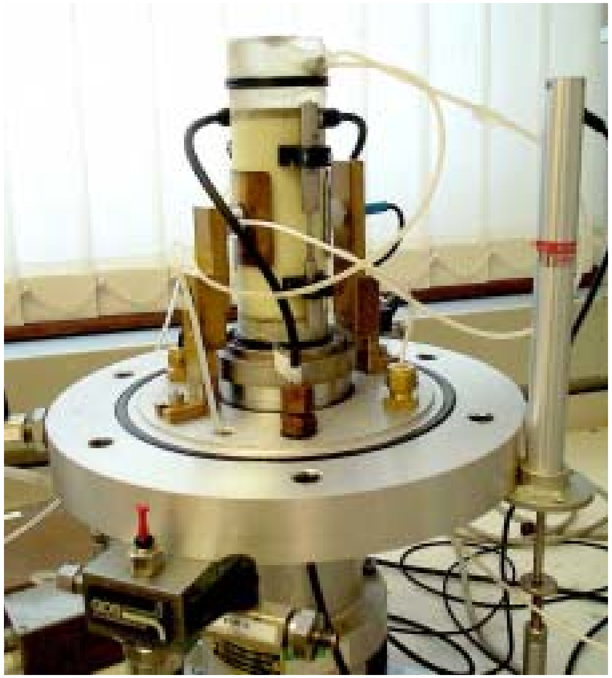
Tests on silica sand and carbonate sand showed similar behaviour, but carbonate sand produced large strains and lower stresses.

# Triaxial tests

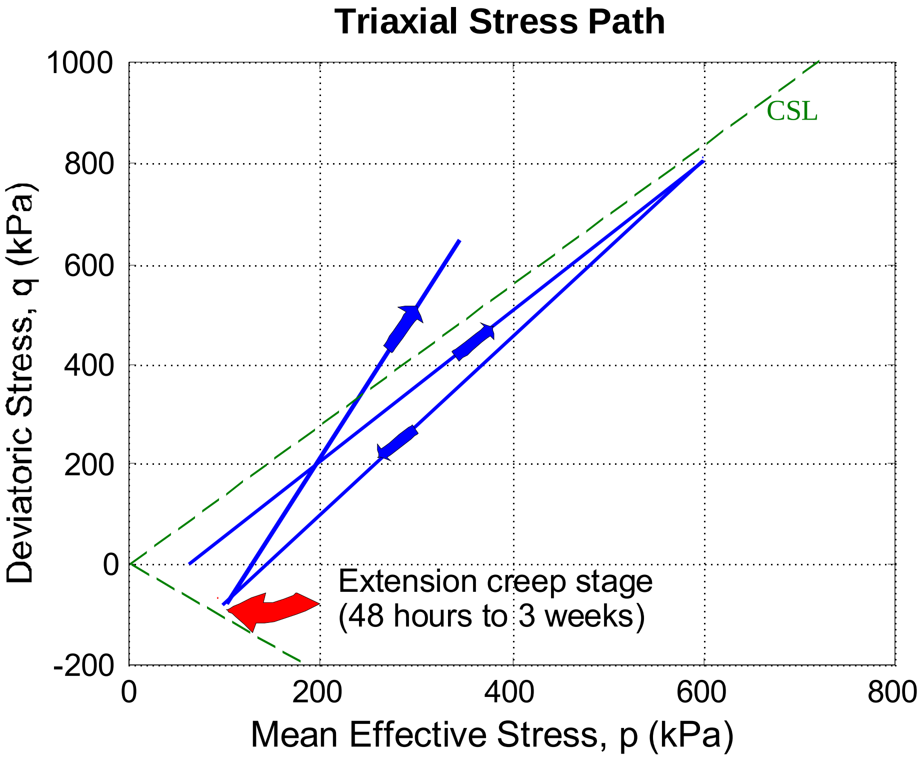
• The stress path was determined based on the pile driving mechanism. Creep was performed at various stages of the stress path.

•Note that an approximation was made to convert the 3D stress conditions to triaxial condition.

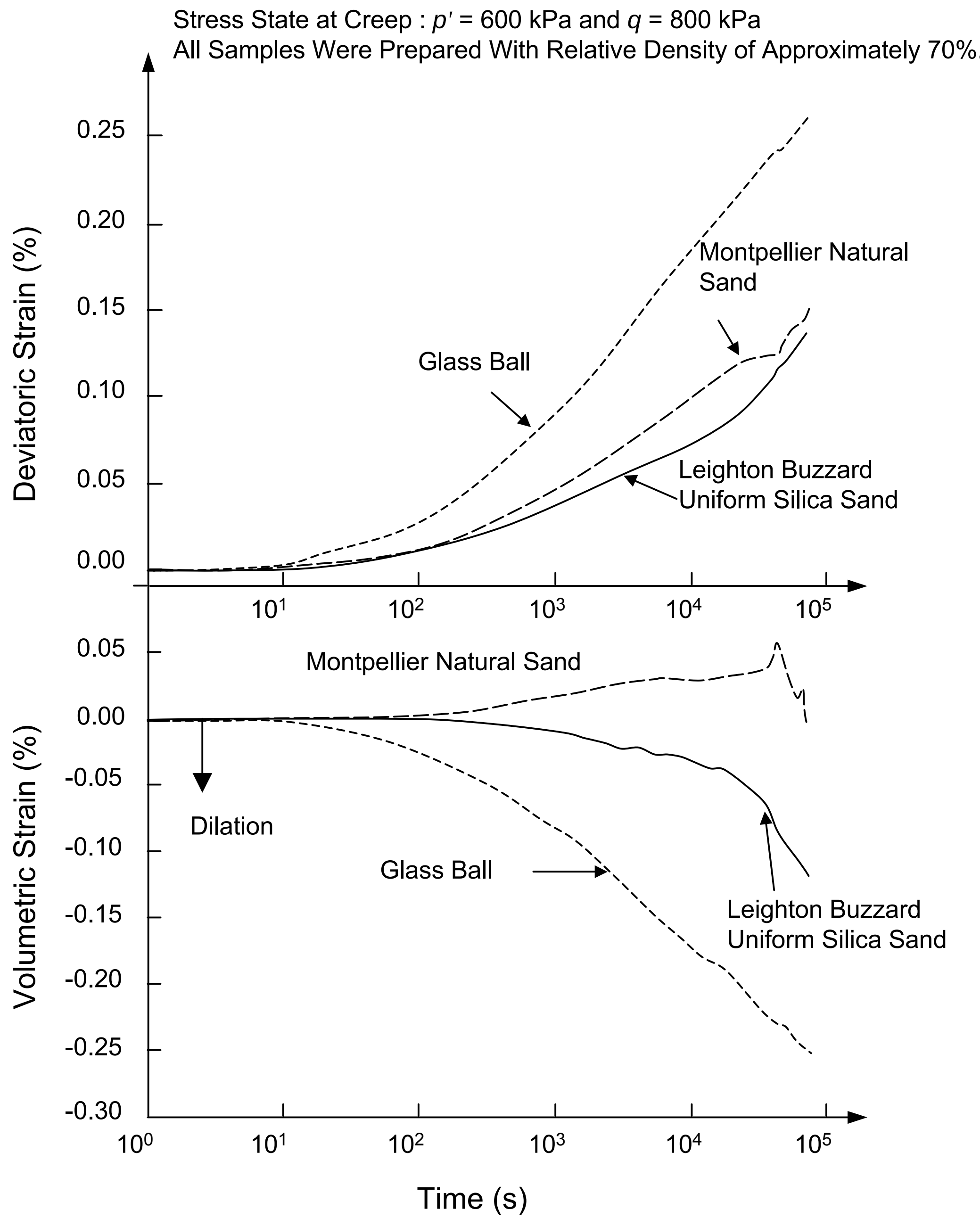
•A variety of granular materials (two silica sands, glass balls, glass shards) were tested to examine the effect of shape and particle strength.



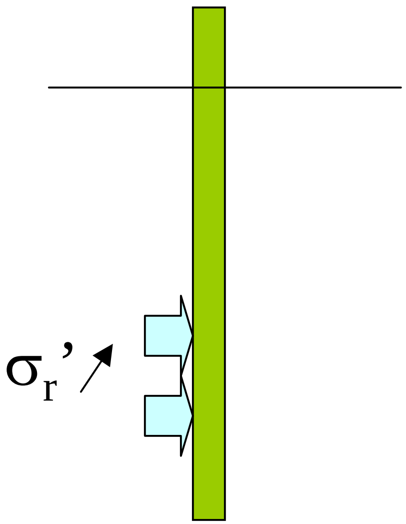
Soil element with local strain devices



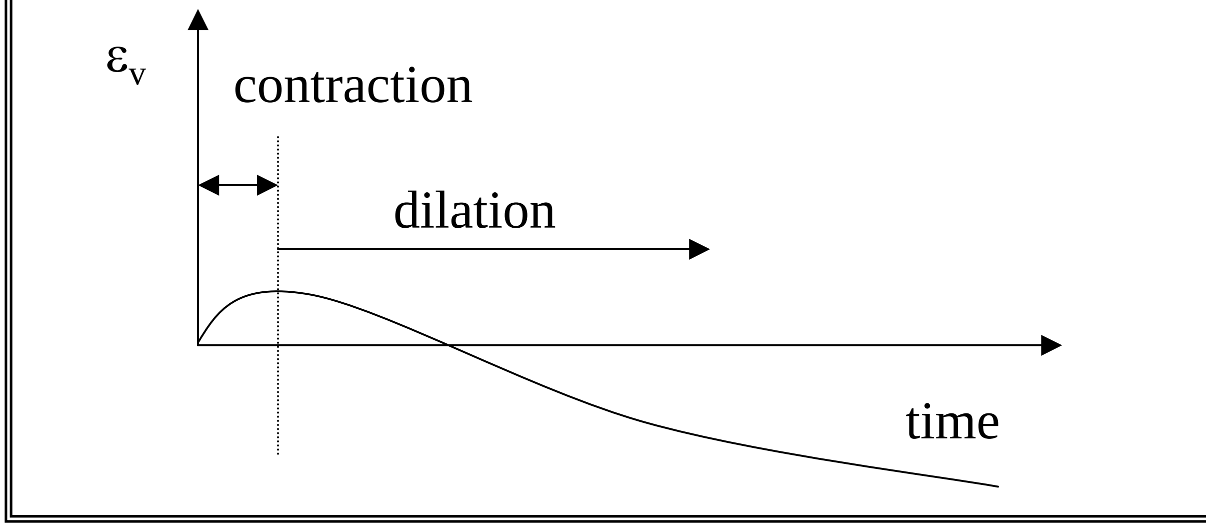
# Triaxial test data



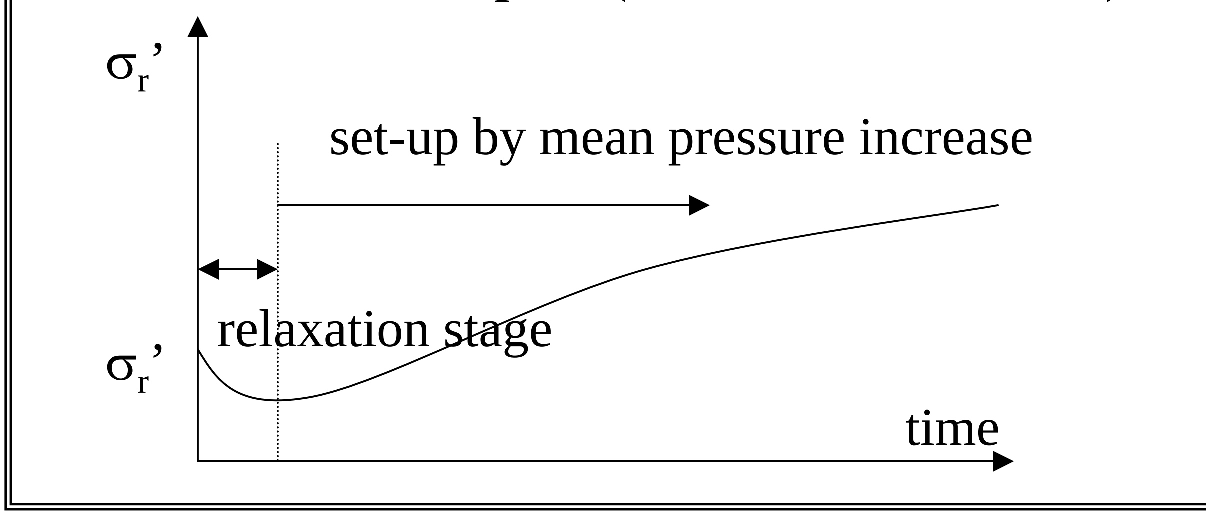
# Pile-set-up due to dilatant creep



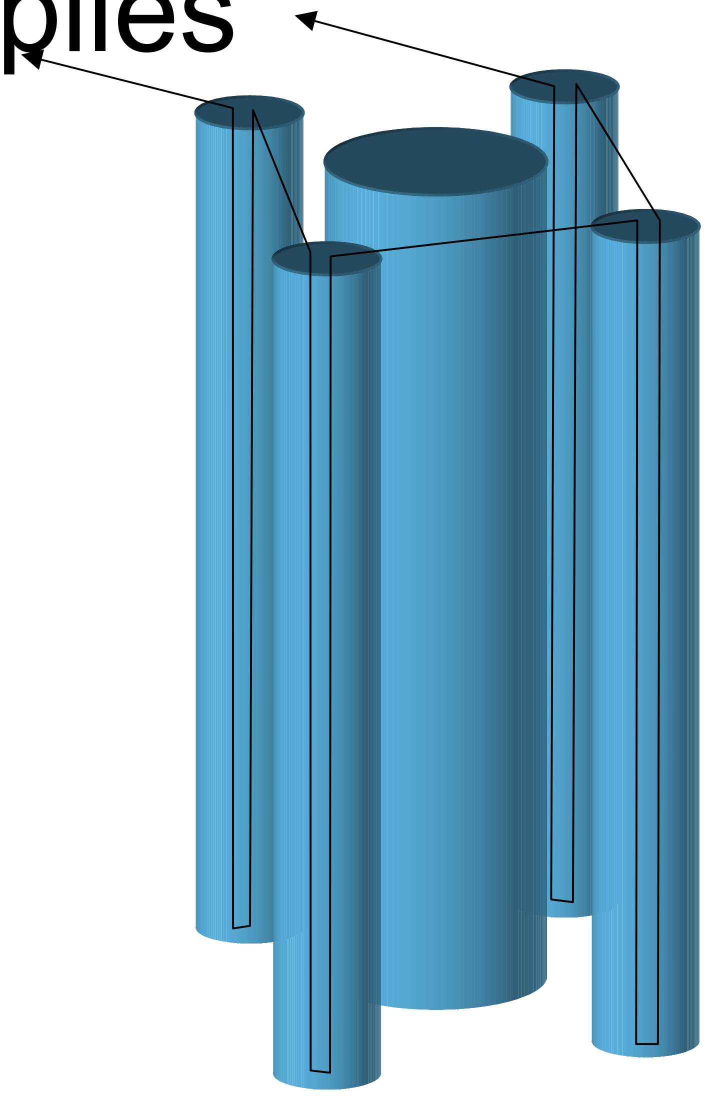

1. Triaxial creep test (stress constant)




2. Soil around a pile (kinematic restraint)



# Fibre optic strain sensing in piles



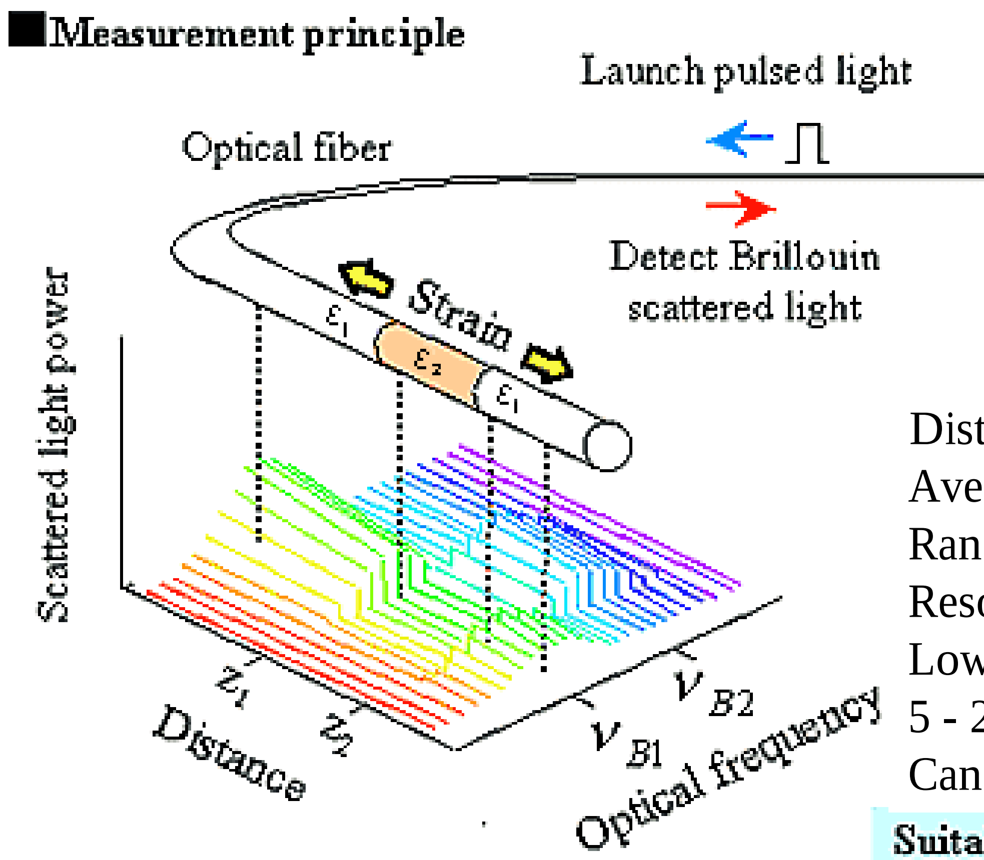
- Installed at BRE test site, Chattenden
- Monitor minipiles in group during load tests
- Attached to rebar
- Optical fibre pretensioned
- Comparison with and complementary to vibrating wire strain gauges

Depth 7m, Minipiles 143mm dia, Central pile 300mm dia, 1.2m cube pile cap

# Strain sensor technology comparison

| | Vibrating wire | FBG (eg. Ando FB200) | BOTDR (eg. Ando AQ8603) |
|---|---|---|---|
| Sensor | Vibrating wire | Fibre Bragg grating | Optical fibre |
| Measurement | Discrete | Discrete | Distributed |
| Strain resolution | 0.5-1$\mu\varepsilon$ | 0.1-10$\mu\varepsilon$ | 30$\mu\varepsilon$ |
| Limit of spatial resolution | 50-250mm | ~2-20mm (length of grating) | 1m |
| No. of measurements | 1 per copper cable | Typically 40 sensors | 1 measurement every 20cm<br>Range 10km (max 20,000) |
| Measurement time | Real time | Real time | 4-25 minutes |
| Detected physical quantity | Change of resonance in wire | Bragg reflection frequency shift | Brillouin gain spectrum frequency shift |
| Maximum strain | 3,000$\mu\varepsilon$ | ~10,000$\mu\varepsilon$ | ~10,000$\mu\varepsilon$ |
| Cost | Analyser ~£1-10k<br>Sensor £80-250 | Analyser £20k<br>Gratings ~£50-300 each | Analyser £50k<br>Fibre ~£.0.1-10/m |
| Features | Established technique | High strain accuracy | Distributed measurement |

# Brillouin optical time domain reflectometry (BOTDR)




BOTDR

Distributed strain sensor – BOTDR
Average strain over 1m every 20cm
Range ~5-10km
Resolution 30με (0.003%)
Low cost sensors - optical fibre
5 - 25 minutes per measurement
Can link or switch between fibres

**Suitable for monitoring various large scale constructions**

Diagram courtesy of ntt.co.jp/news

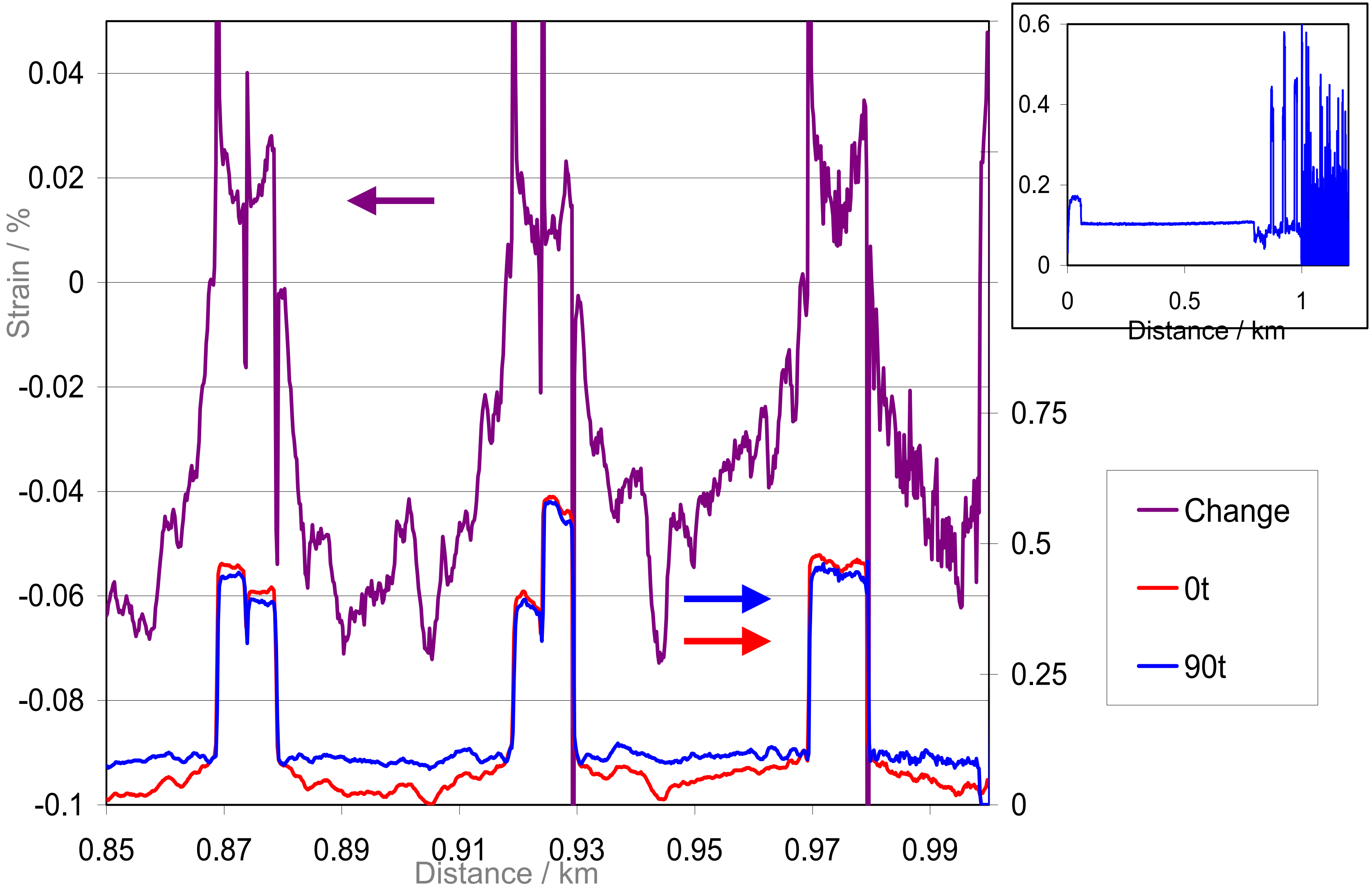
# Field installation

BRE

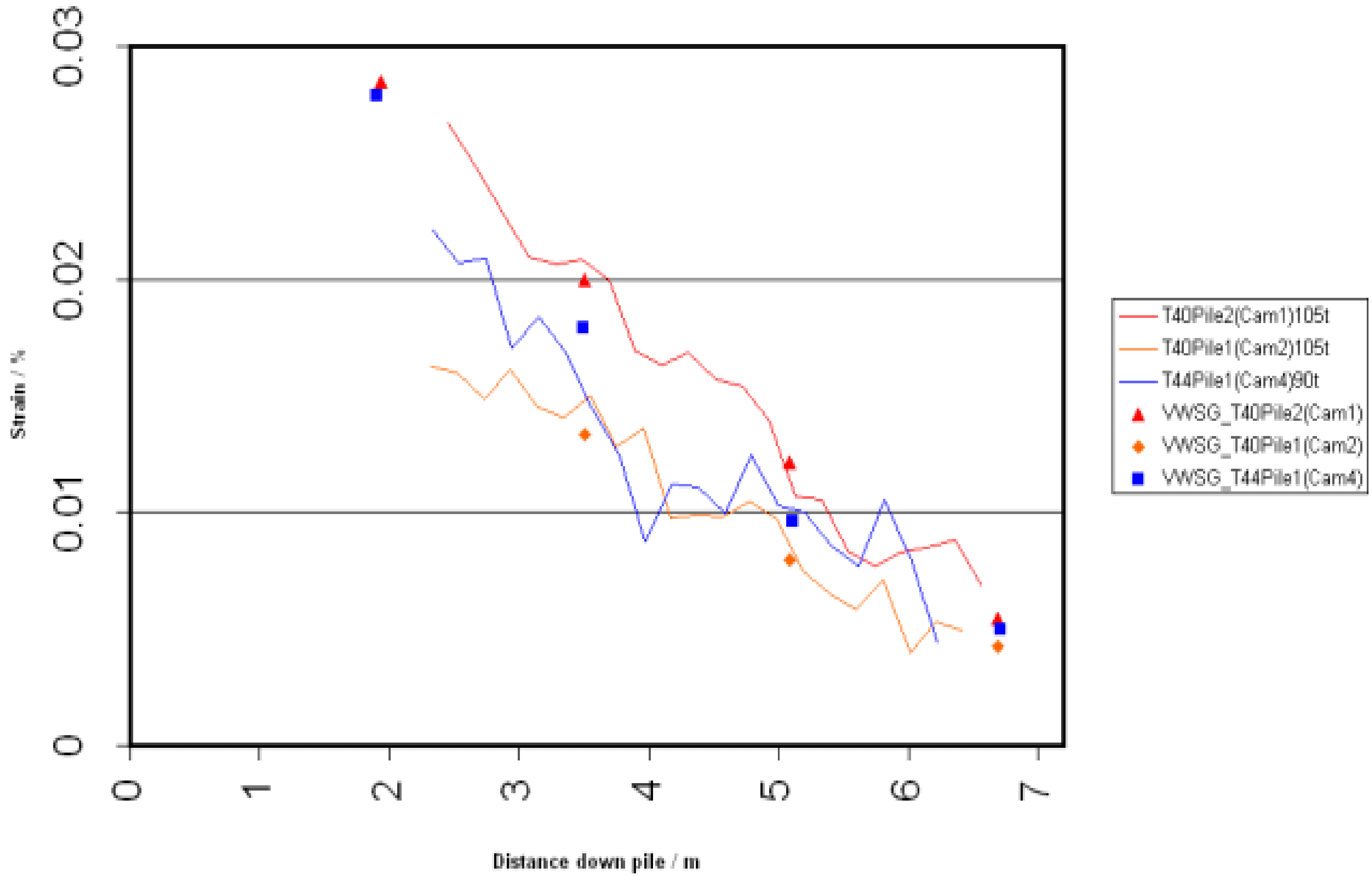
Cementation Foundations

SKANSKA

# Monitoring strain during load tests

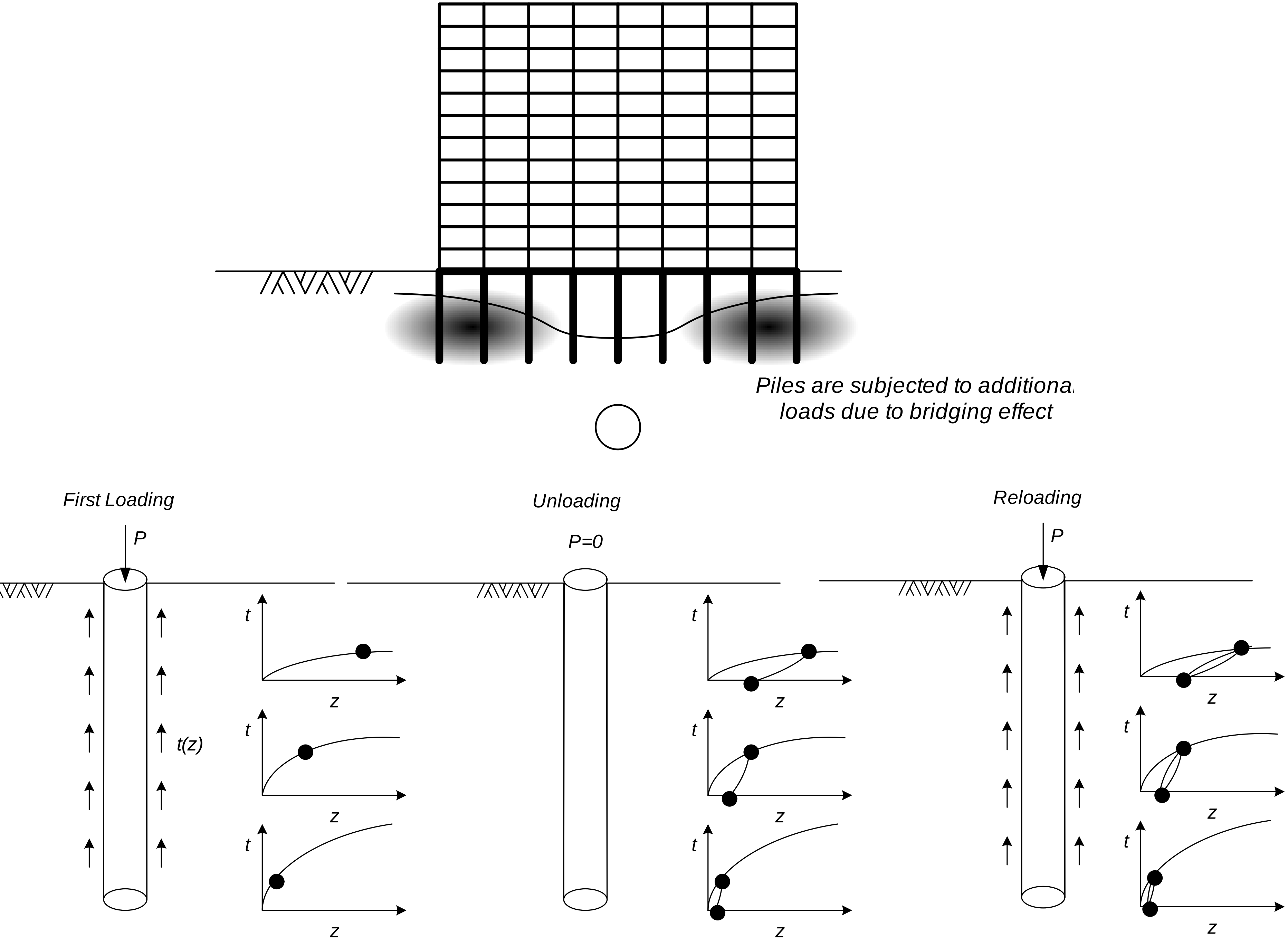


# Comparison with vibrating wire strain gauges (VWSG)



# What can it be used?

- Research
  - Load tests – construction of load transfer functions
  - Clearer understanding of pile group behavior
- Monitoring lifespan of the structure (part of smart structures approach)
  - Post-earthquake diagnostic of a structure
  - Behavior due to long-term changes, (consolidation, capacity increase with time etc.)
- Adaptive Design
  - Tunnel excavation below an existing structure.
  - Changes in building designation.
  - Additional floors/adding removing walls.
- Reuse of old piles
  - Increased pile capacity due to kinematic hardening



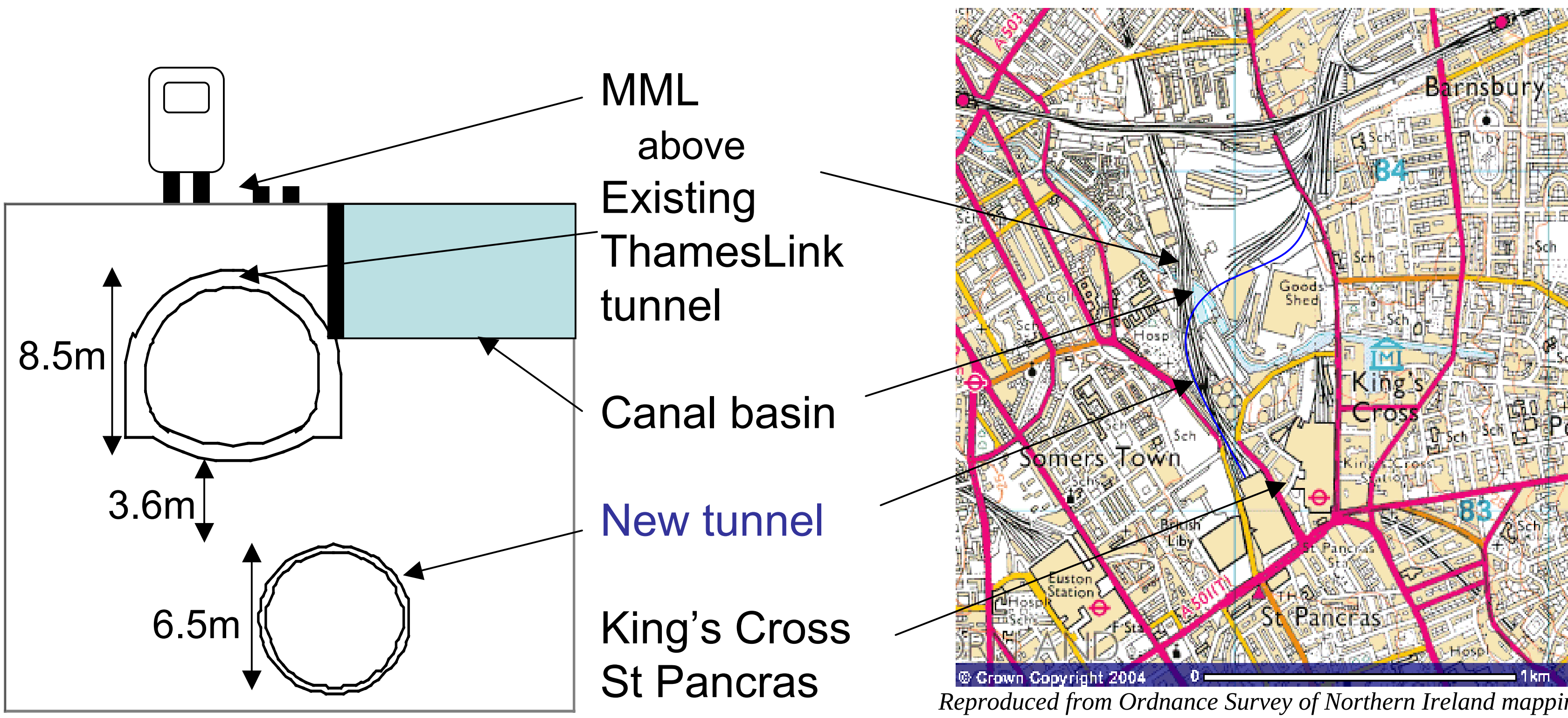
Piles are subjected to additiona
loads due to bridging effect
First Loading
P
t(z)
t
z
Unloading
P=0
Reloading
P

# Bankside123 Installation

- Long term bearing pile monitoring
  - $\phi$1.6m, 50m deep piles, Strain sensors: BOTDR, vibrating wire, FBG

# Monitoring of existing ThamesLink tunnel

- Tunnelling obliquely under Victorian masonry tunnel
  - Existing tunnel loaded by canal basin retaining wall
  - Directly below Midlands Main Line (MML)

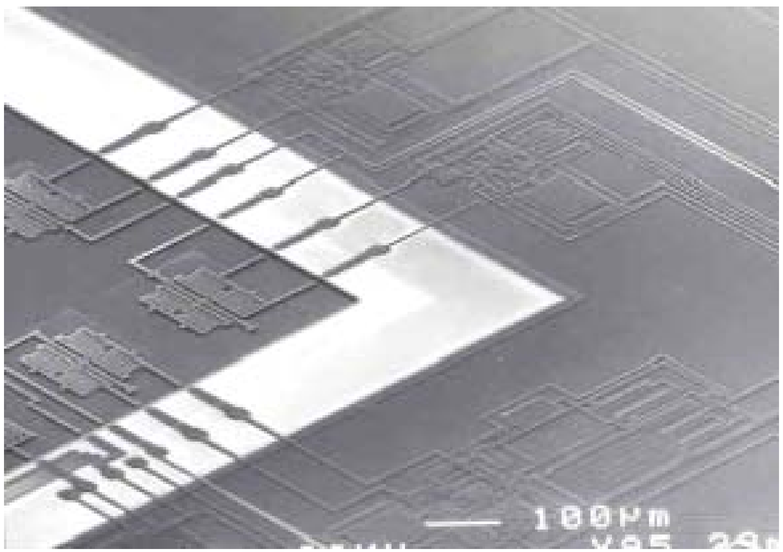



*Reproduced from Ordnance Survey of Northern Ireland mapping with the permission of the Director and Chief Executive, © Crown Copyright.*

# Innovation in Monitoring of Aging Infrastructure

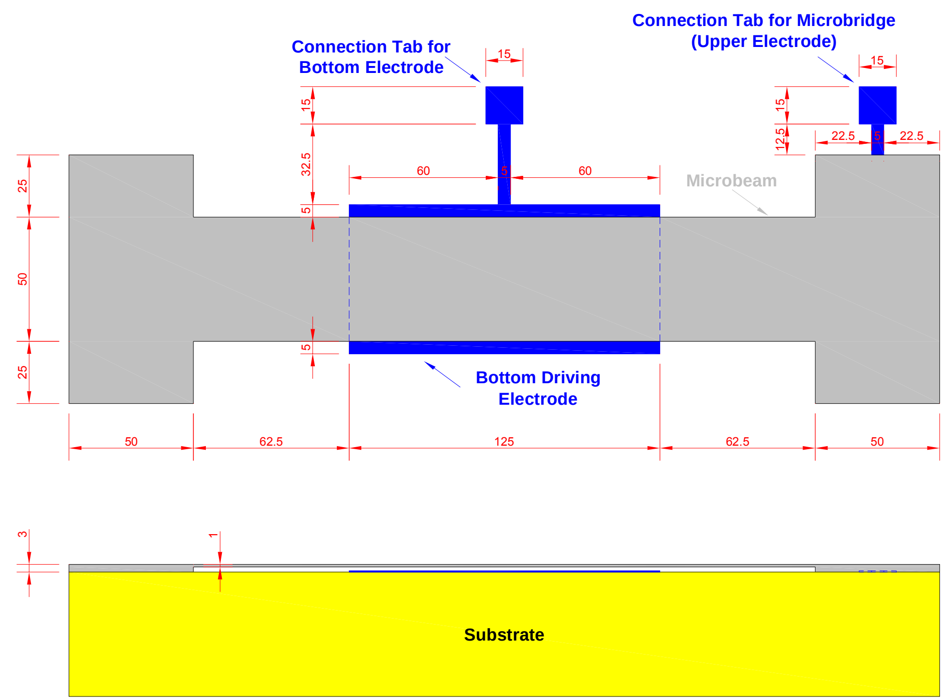
- Fiber optics
- Micro Electro Mechanical Sensors (MEMS)
- Wireless Network Systems

# MEMS



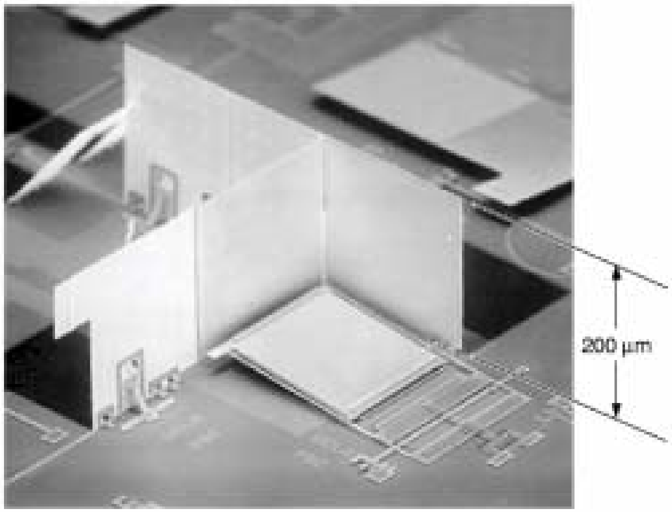

**Note:**

1. Electrostatic excitation and capacitive detection tecnhique is adopted.
2. Microbeam thickness is 1 micrometer.
3. Gap between microbeam and bottom electorde is at least 1.5 micrometer.

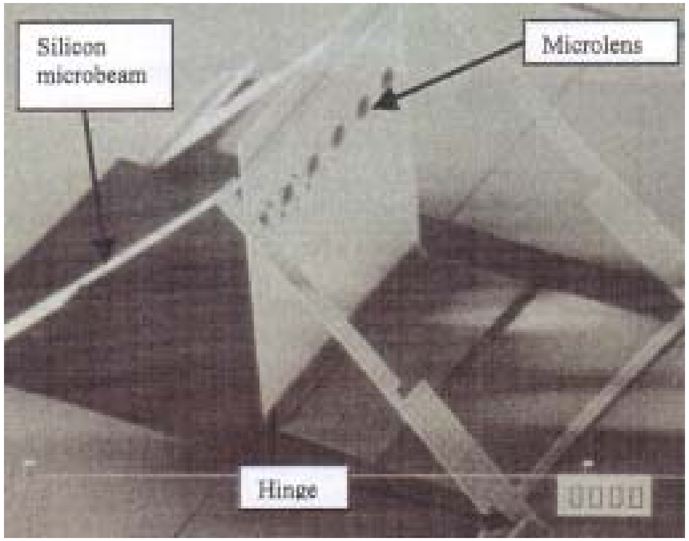



**Schematic drawing of a mircobeam (all units in micrometer)**

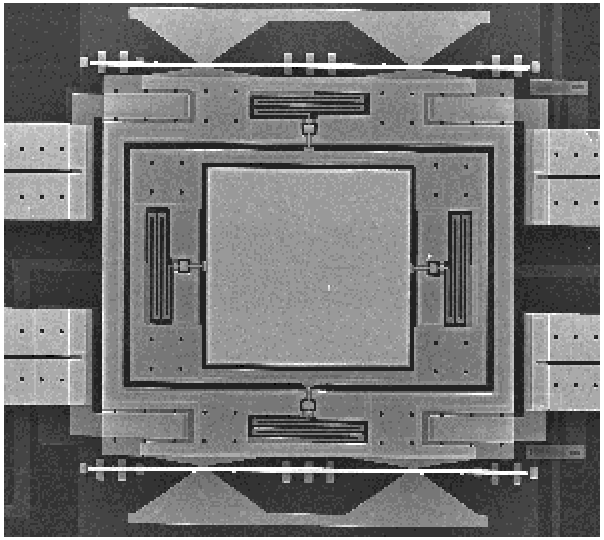
# Micro-machined Reflectors



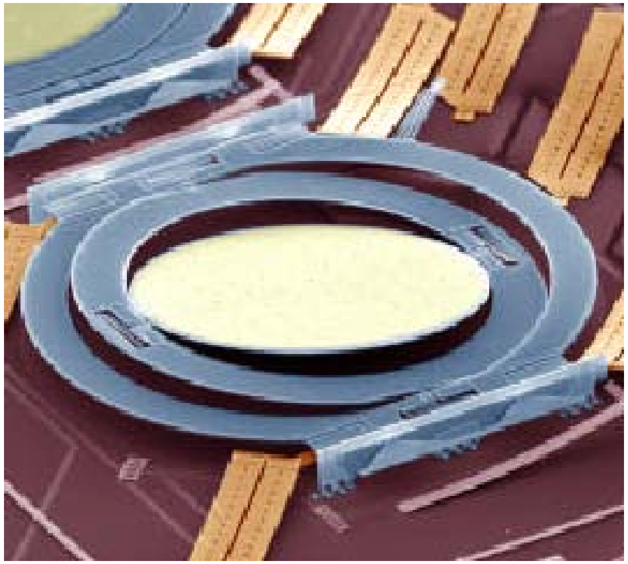

Warnecke et al., 2001




From David Moore (CUED)

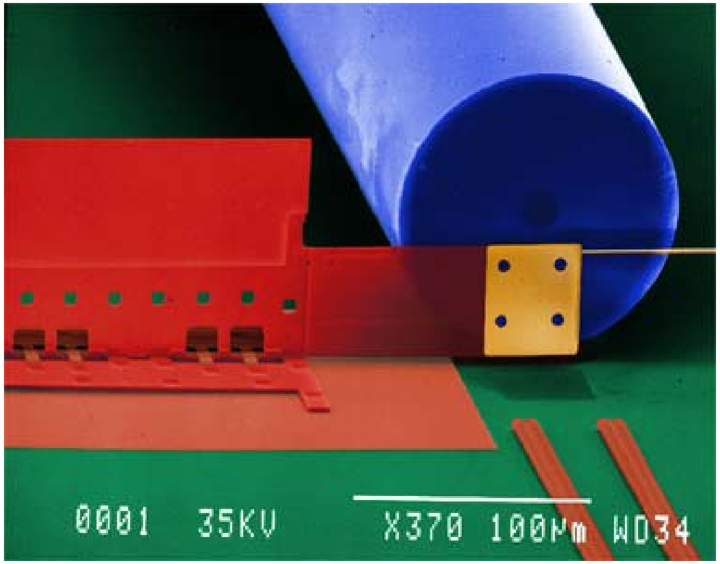


Lucent Technologies

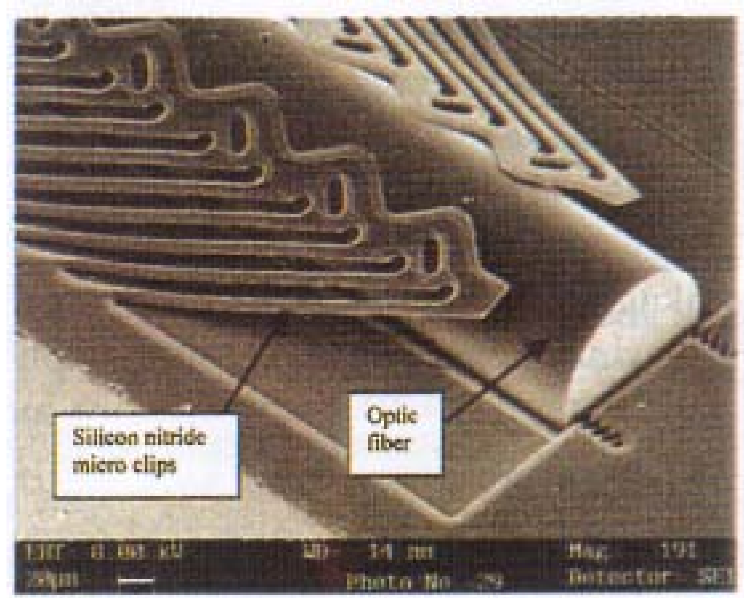


Lucent Technologies

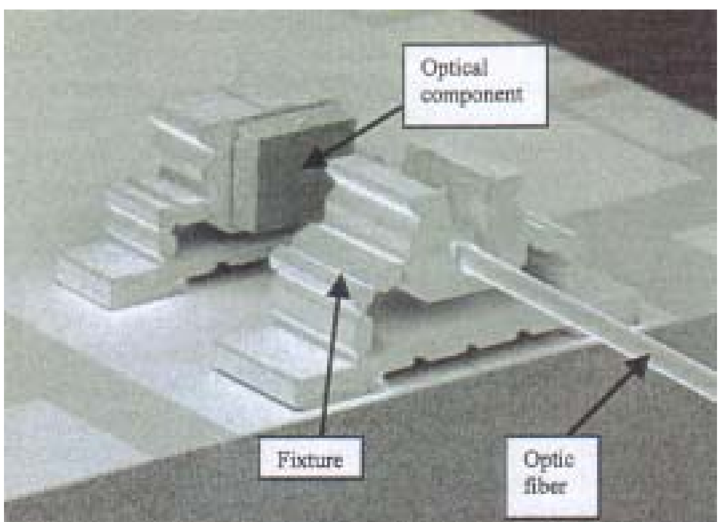
# Fibre optics MEMS



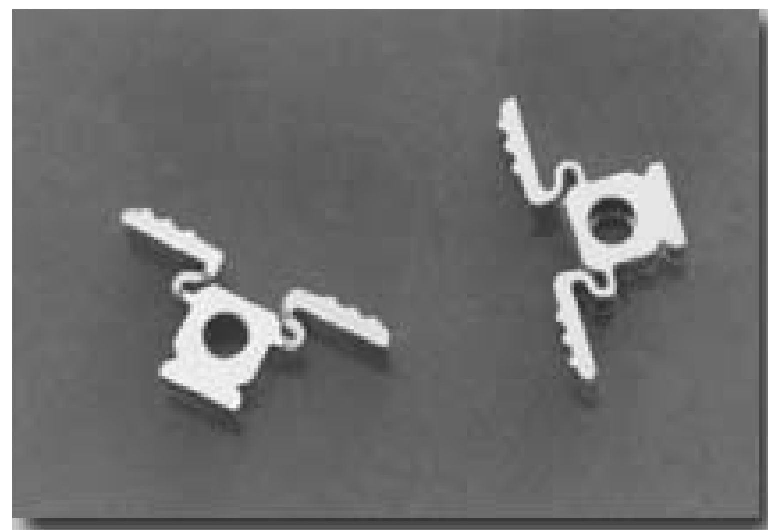

Lucent Technologies




David Moore (CUED)

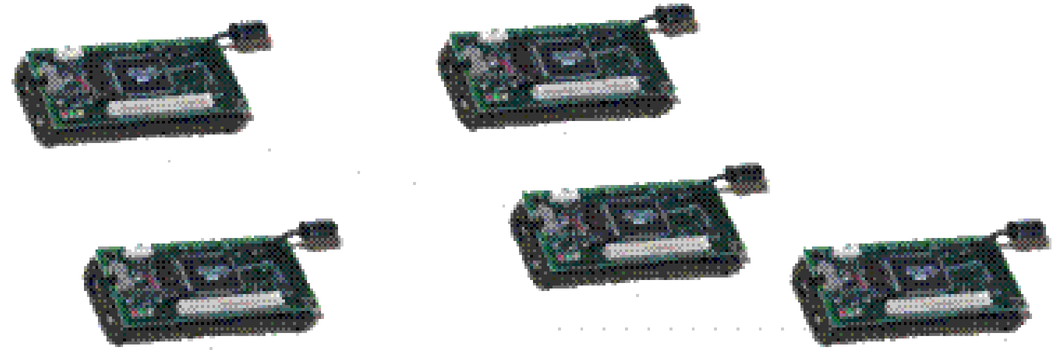


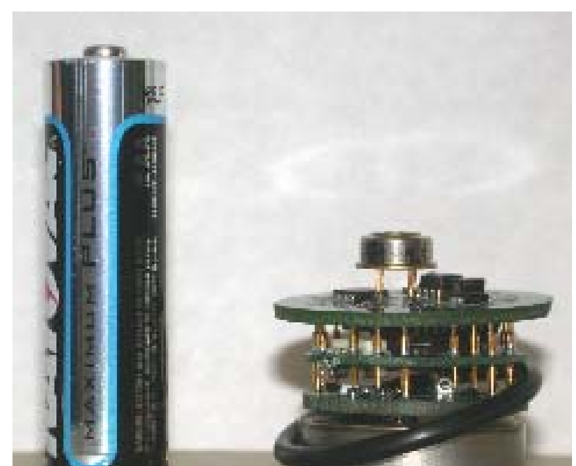

Axsun.com/David Moore (CUED)



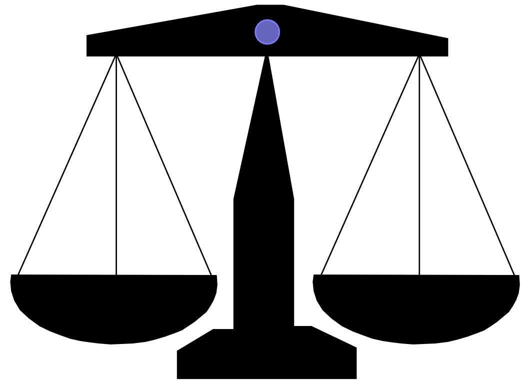
Axsun.com

# Wireless Network Systems





Modelling (Better understanding of long-term soil behaviour



Monitoring (optimum number of measurements)

Important soil properties?

- Permeability
- Undrained-partially drained-drained behavior
- Stiffness anisotropy

Boundary conditions

- Interface permeability

Key Performance Indicators?

- Ground or structure movements
- Crack developments

# Future of Geotechnical Engineers?

- Need to perform life cycle assessment and embodied energy evaluation of geotechnical structures/construction
- Requires risk assessment (social, environmental, economic)
- Long-term prediction and monitoring
- How can we incorporate this into design?
- Do we have enough technical knowledge on predicting (uncertain) long-term future events?

Thank you