Understanding ground and structural response to tunnelling through interpretation of monitoring data

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11TH INTERNATIONAL SYMPOSIUM
FIELD MONITORING IN GEOMECHANICS
IMPERIAL COLLEGE LONDON
4TH–8TH SEPTEMBER 2022

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Lecture content

Lectures largely based on lessons learnt from tunnelling / field monitoring research on Jubilee Line Extension (JLE), Channel Tunnel Rail Link (CTRL) and Crossrail projects.

1) Objectives of the monitoring / research.

2) Monitoring methodology.

3) Steps in processing and analysing data.

4) Interpretation of the data in relation to tunnelling activities.

5) Conclusions and thoughts for the future.

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Monitoring at full scale correlates to London becoming a giant laboratory!

Field instruments and monitoring open new dimensions helping us to understand how the ground and structures respond to tunnelling and deep excavations

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1) Research objectives: Gaps in knowledge

JLE

- Subsidence trough
- Ground-structure interaction
- Protective measures
- Damage
- Remedial measures
- Long-term behaviour

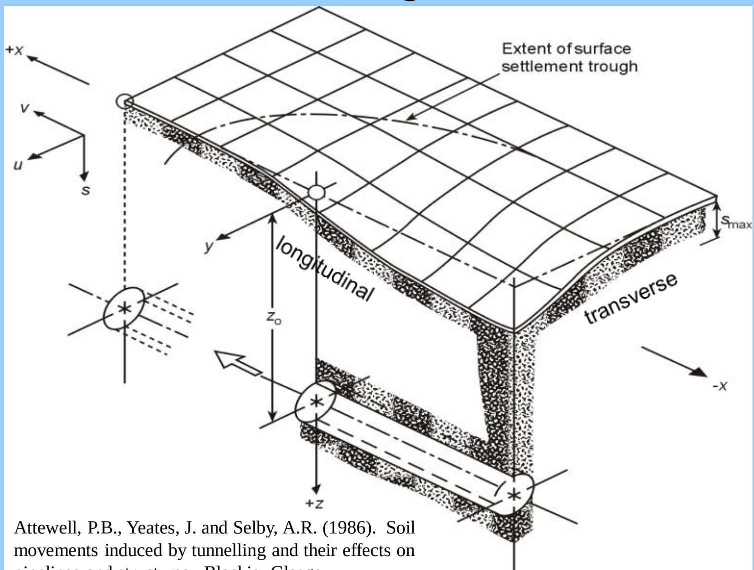
CTRL

- Effect of tunnelling on piles and piled foundations

Crossrail

- Effect of tunnelling on existing tunnels

Surface settlement trough above an advancing tunnel



Attewell, P.B., Yeates, J. and Selby, A.R. (1986). Soil movements induced by tunnelling and their effects on pipelines and structures. Blackie, Glasgow.

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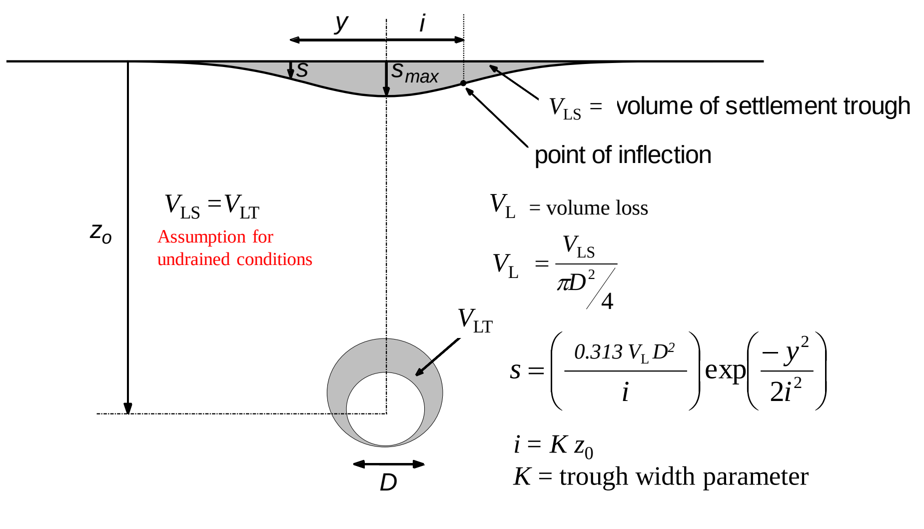
Transverse vertical displacements (settlement trough) and volume loss



V_L = volume loss

$$V_L = \frac{V_{LS}}{\pi D^2/4}$$

$$s = \left(\frac{0.313\, V_L D^2}{i}\right)\exp\left(\frac{-y^2}{2i^2}\right)$$

$i = K z_0$

K = trough width parameter

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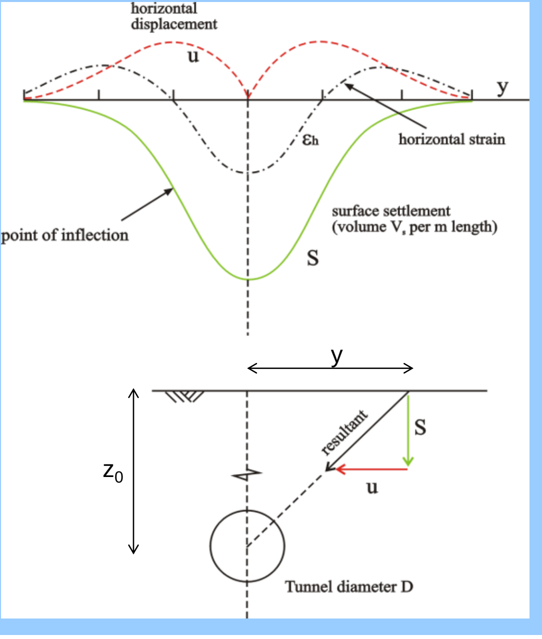
Transverse horizontal displacements



- point sink assumption
- resultant vector of displacement points towards tunnel axis
- allows horizontal displacements to be determined

$$u = \frac{s.y}{z_o}$$

- differentiate to obtain horizontal strain, ε_h

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2) Monitoring methodology

- What to measure?
- How? Which instruments and techniques?
- Required measurement resolution?
- Redundancy?
- Stable datum?
- Manual versus automatic readings?
- Where and in what concentration?
- Sign convention?
- Surface and subsurface?
- 2-D vs 3-D?
- Supplementary monitoring?
- Frequency (transient vs final)?
- Need for long-term measurements?

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2) Monitoring methodology

- The whole process should be optimised as far as possible.
- Interpretation of data strongly influenced by methodology adopted.
- Level of interpretation very much depends on depth of understanding required.
- At the same time monitoring methodology is being considered, it is essential to consider how construction activities are to be recorded.

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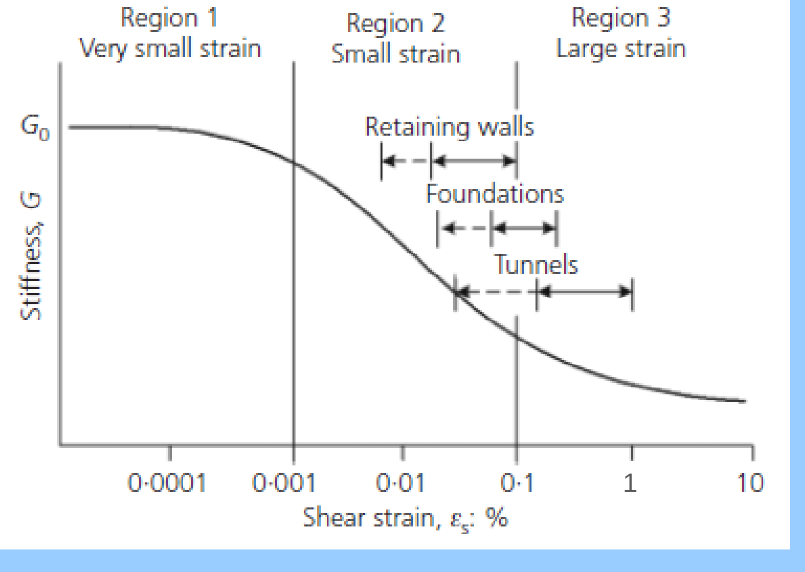
2) Monitoring methodology – strain levels of interest



(after Atkinson and Sälfors, 1990)

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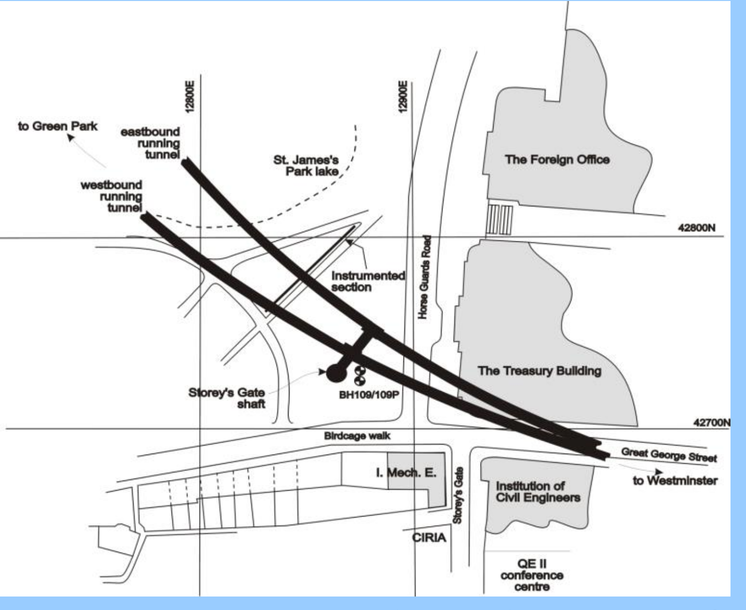
2) Monitoring methodology – SJP example



St James's Park instrumented greenfield reference site (Nyren, 1998)

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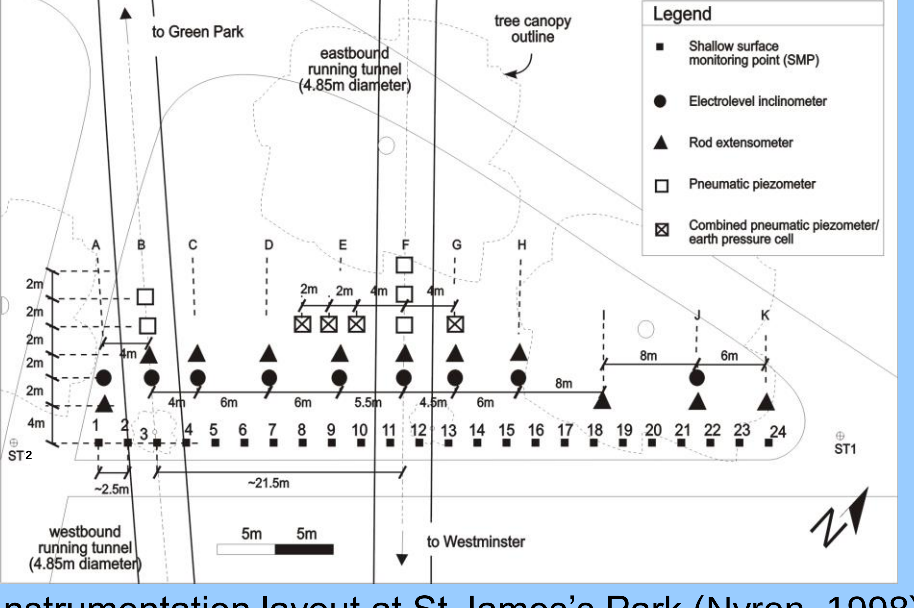
2) Monitoring methodology – SJP example



Instrumentation layout at St James's Park (Nyren, 1998)

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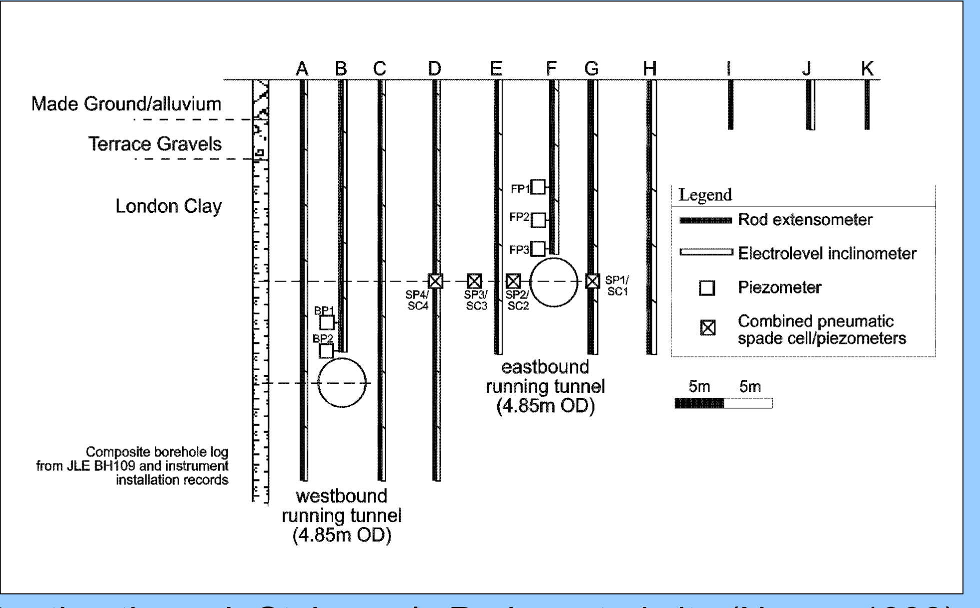
2) Monitoring methodology – SJP example



Section through St James's Park control site (Nyren, 1998)

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2) Recording / monitoring construction activities

- As tunnelling is usually linear, recording times and dates of each ring build is usually straightforward.
- With modern TBMs a multitude of other information and data are also collected (operating variables: e.g. face pressure, thrust, grouting pressures and volumes).
- Essential need for recording events that do not conform with normal routine activities.
- Recording spatial data for deep excavations is much more challenging, especially when underground (not exposed at surface).

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2) Elizabeth House, Waterloo – EH example

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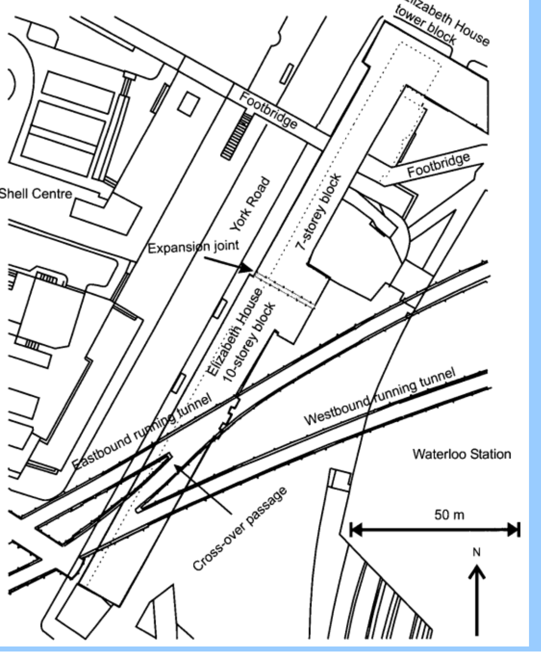
2) Recording / monitoring construction activities



JLE tunnel construction at Elizabeth House: running tunnels and cross-over passage

(Standing, 2001)

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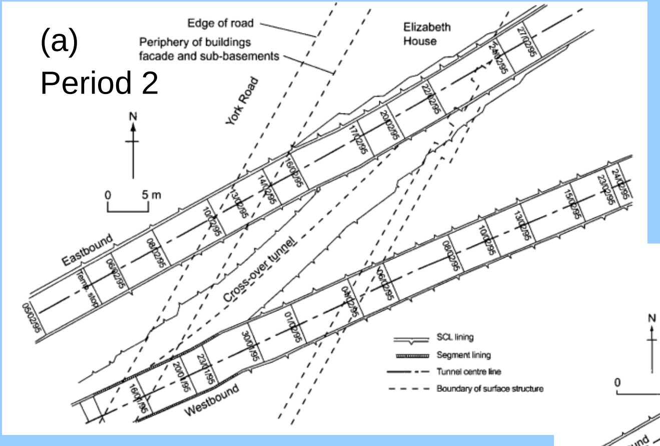
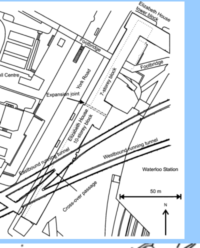
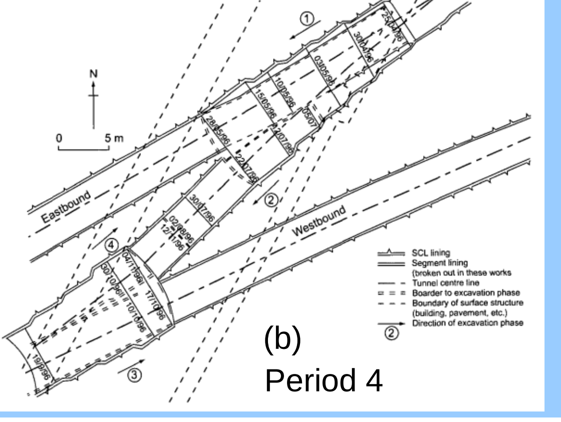
2) Recording / monitoring construction activities







JLE tunnel construction progress at Elizabeth House
(a) running tunnels
(b) cross-over passage

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3) Steps in processing and analysing data

- Check data in their raw form.
- Inspect data vs time plots, looking for drifts and jumps, malfunctioning instruments and to gain an idea about accuracy.
- Particularly important to assess base reading period which should start well in advance of the works (ideally to capture seasonal responses).
- Try to isolate background responses (e.g. thermal, tidal, humidity changes).
- Start splicing monitoring data with construction activities (in a broad sense).

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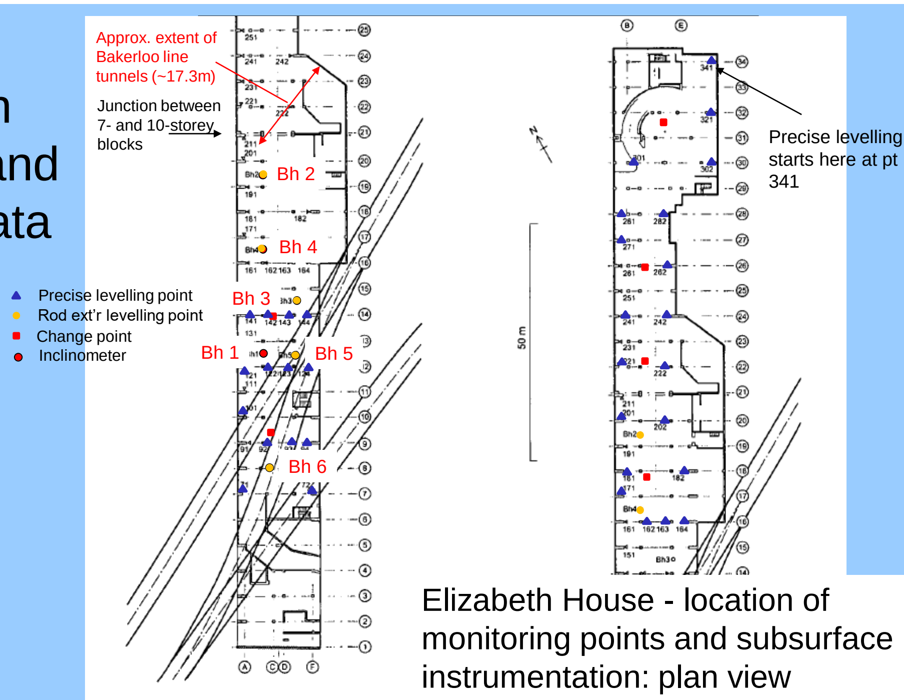
3) Steps in processing and analysing data



Elizabeth House - location of monitoring points and subsurface instrumentation: plan view

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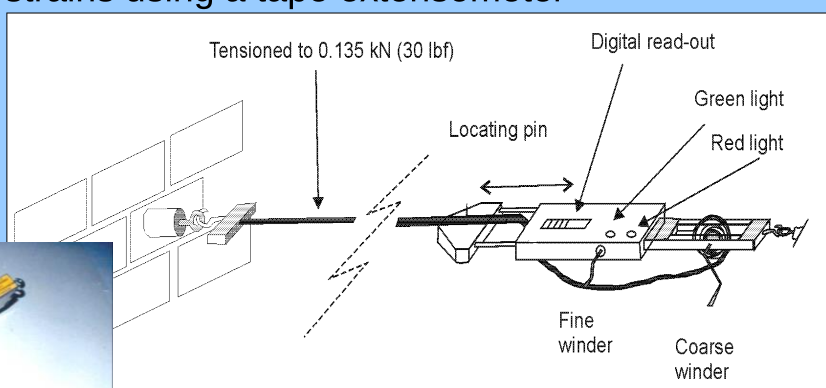
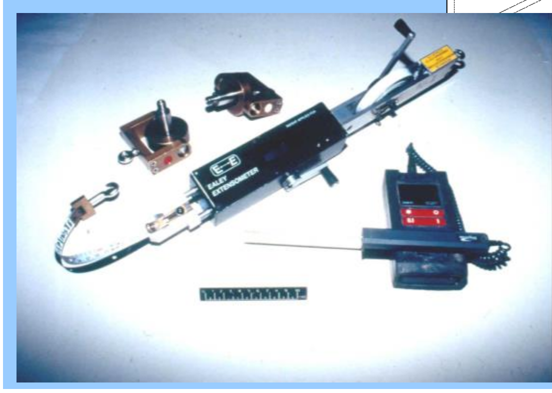
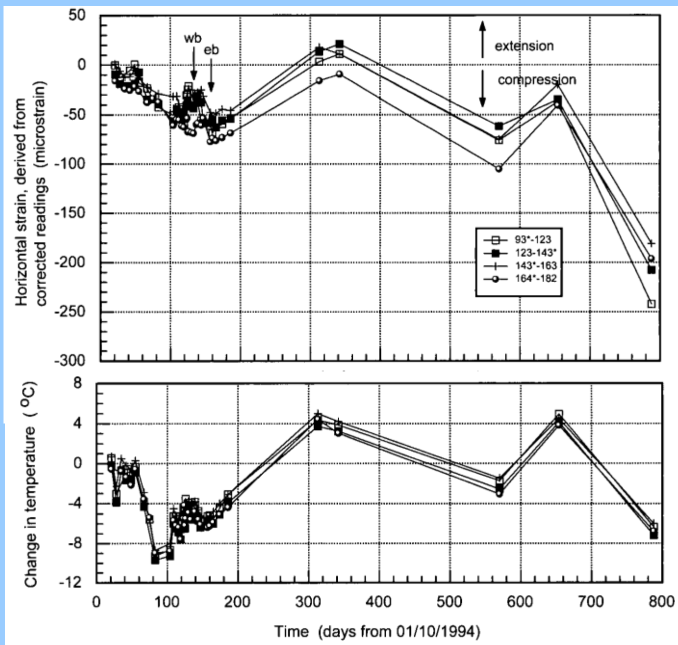
2) Monitoring methodology – Elizabeth house

Measuring horizontal strains using a tape extensometer





3) Steps in processing and analysing data



Elizabeth House tape extensometer data, showing influence of temperature (and tunnelling).

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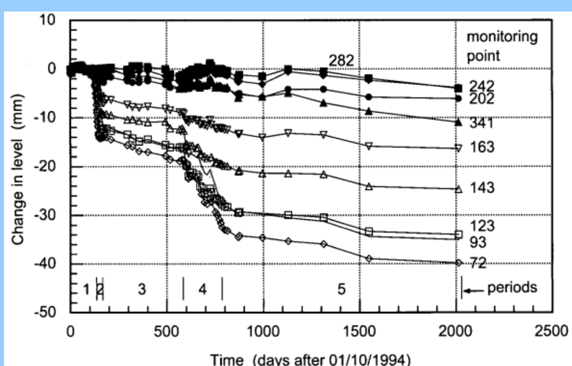
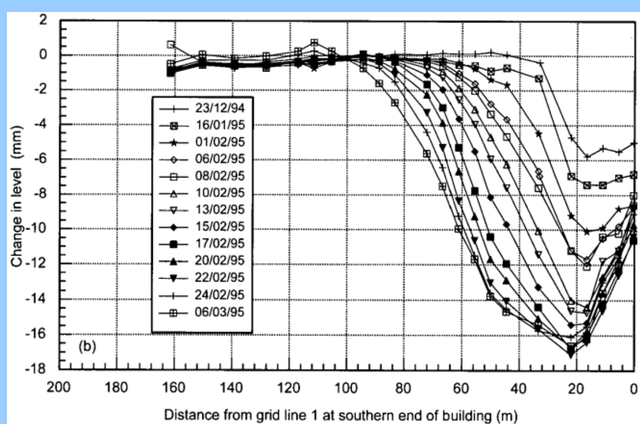
3) Steps in processing and analysing data



Change in level versus time for selection of precise levelling points within Elizabeth House.



Vertical displacement profiles along building length (York Road) for Period 2.

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3) Steps in processing and analysing data

Some questions to think about:

Did we need all these monitoring points?
Would it have been better to have more surveys?
Was accuracy sufficiently good?
Could we have used better techniques?
Was the datum used ok?

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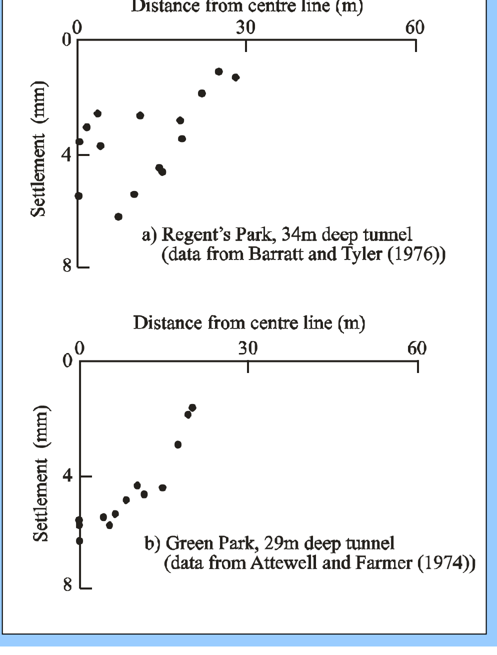
3) Steps in processing and analysing data



Precise levelling data
from the 1970s
(construction of Jubilee &
Victoria line tunnels).

Can we improve on these profiles?
Potential causes of data scatter?
- Instrument used?
- Small magnitudes?
- Insufficient base readings?
- Datum point affected by works?

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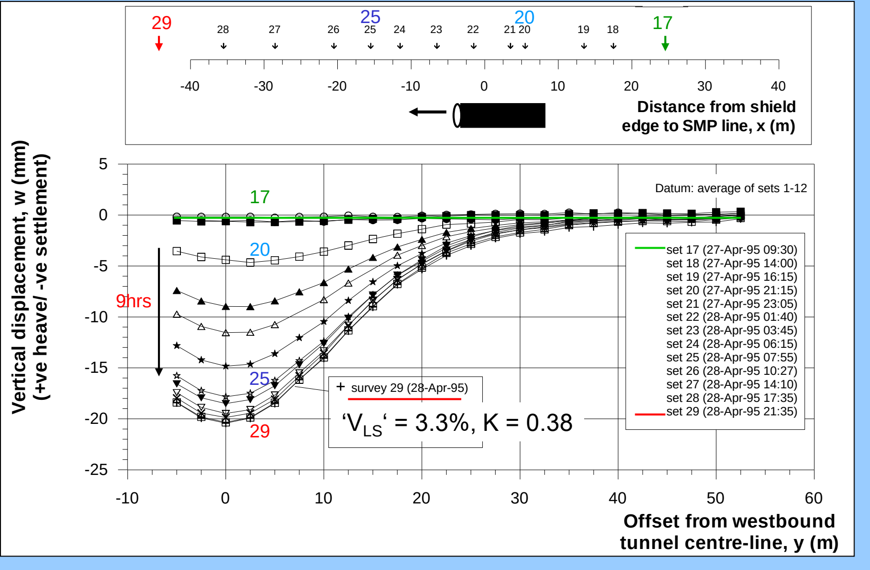
3) Steps in processing and analysing data



Vertical surface displacements at St James's Park from construction of WB running tunnel (Nyren, 1998)

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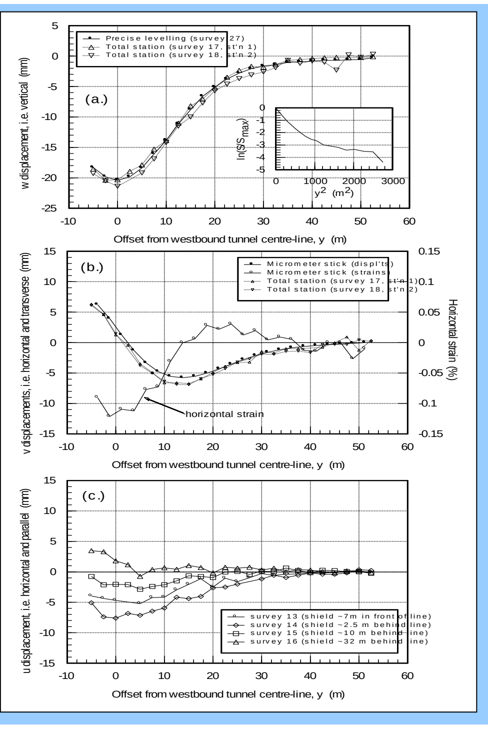

3) Steps in processing and analysing data

Displacement profiles from WB running tunnel (vertical and two horizontal) (Nyren et al., 2001)

Confidence in data measurement and accuracy through redundancy

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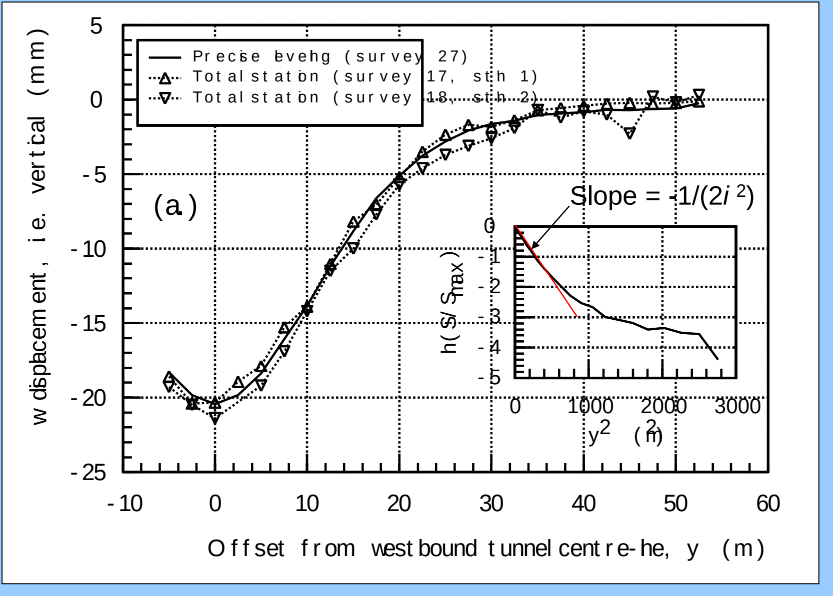
3) Steps in processing and analysing data

JLEP WB running tunnel transverse vertical surface displacements



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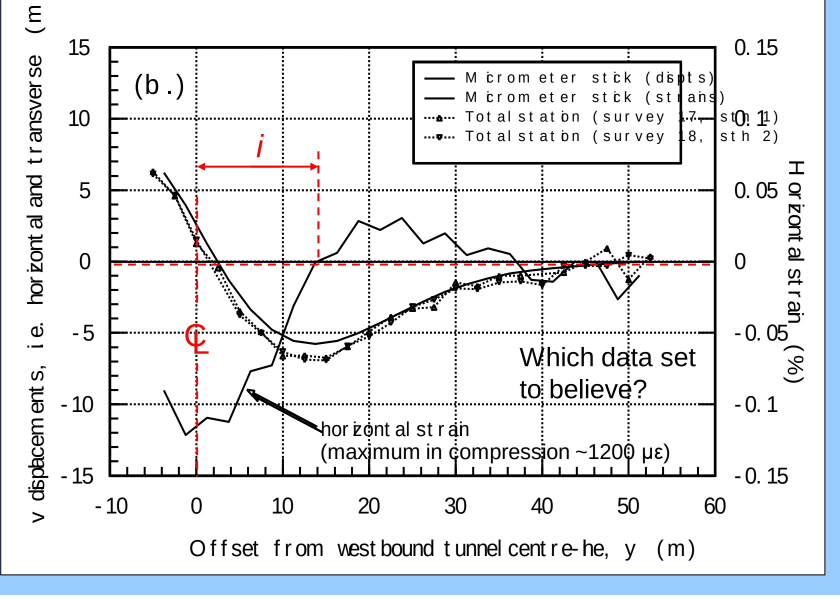
3) Steps in processing and analysing data

JLEP WB running tunnel transverse horizontal surface displacements



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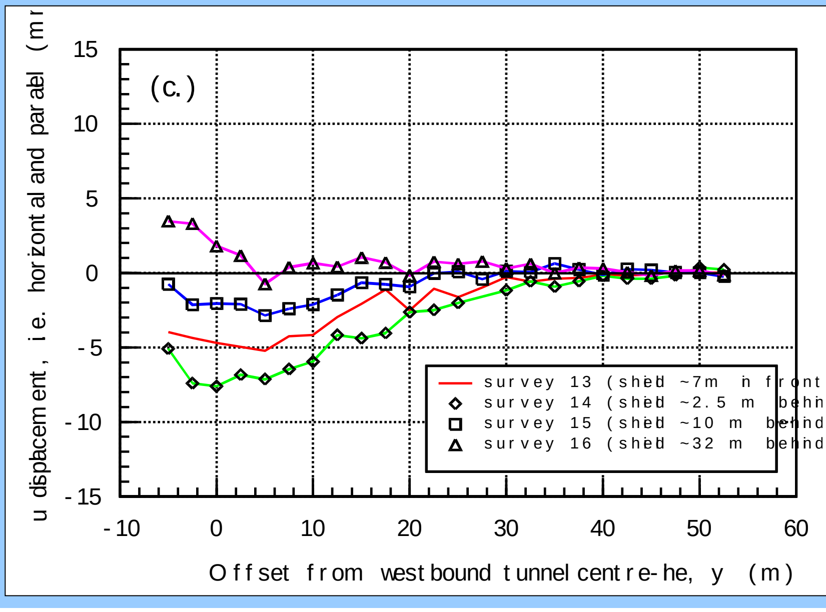
3) Steps in processing and analysing data

JLEP WB running tunnel longitudinal horizontal surface displacements



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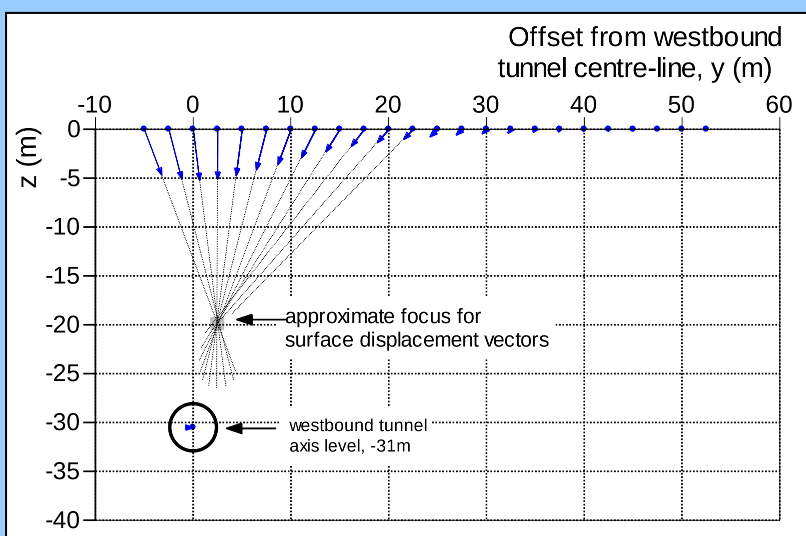
3) Steps in processing and analysing data

Surface displacement vectors after construction of WB running tunnel at St James's Park (Nyren, 1998)



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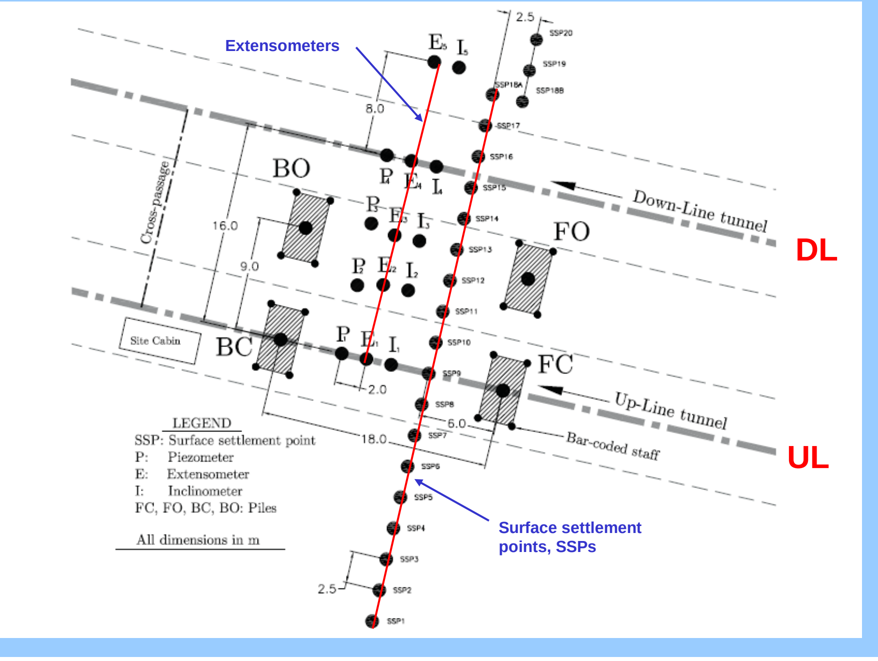
3) Steps in processing and analysing data – CTRL example

Layout of CTRL research site and instrumentation (Selemetas, 2005)



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3) Steps in processing and analysing data – CTRL example

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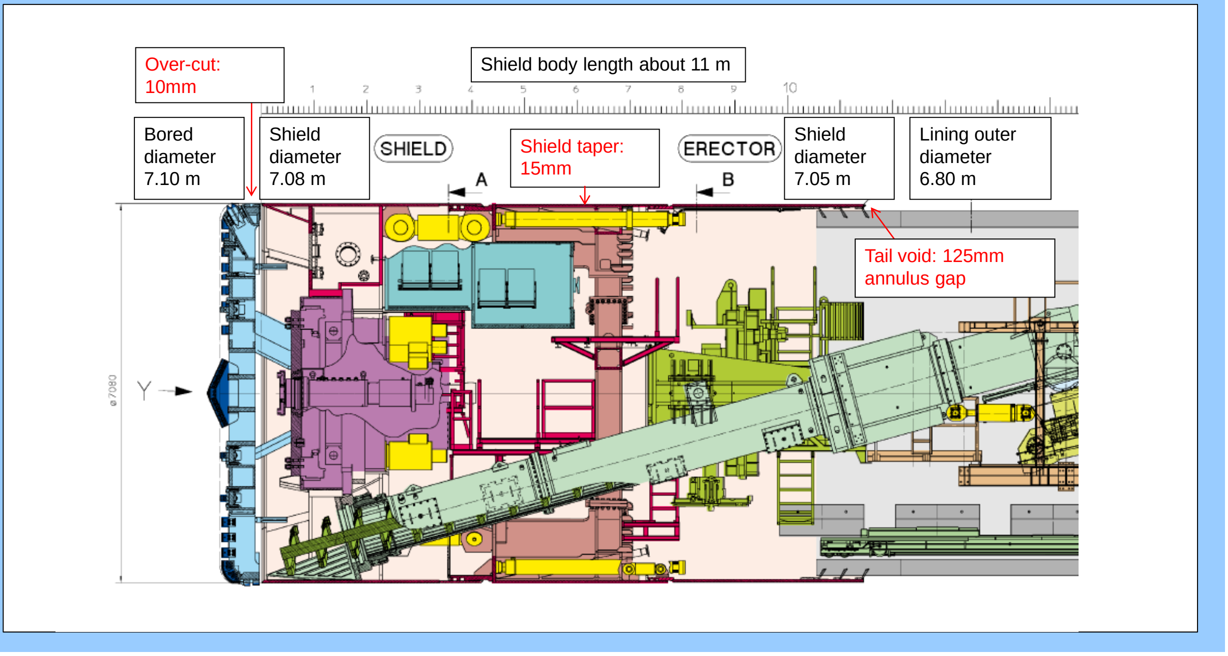
Earth-Pressure-Balance Tunnel Boring Machine



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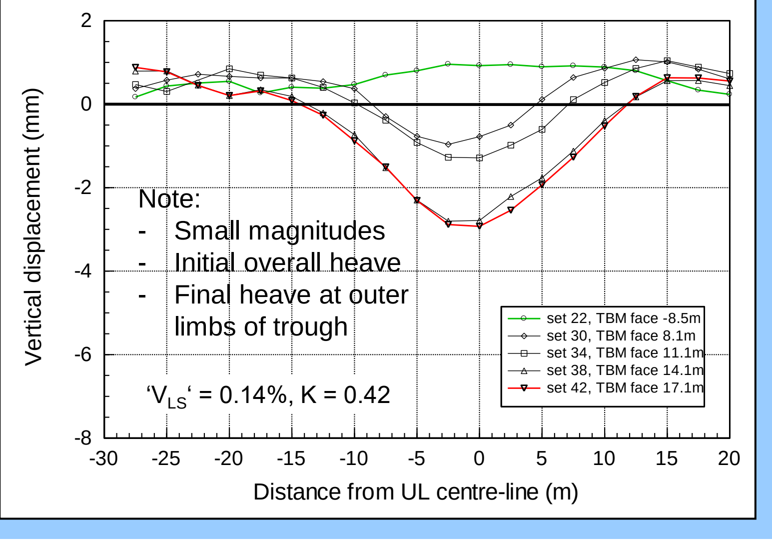
3) Steps in processing and analysing data

Progressive transverse settlement troughs for Up-line (UL) tunnel drive

Results from CTRL research site Dagenham Dock (Standing and Selemetas, 2013)



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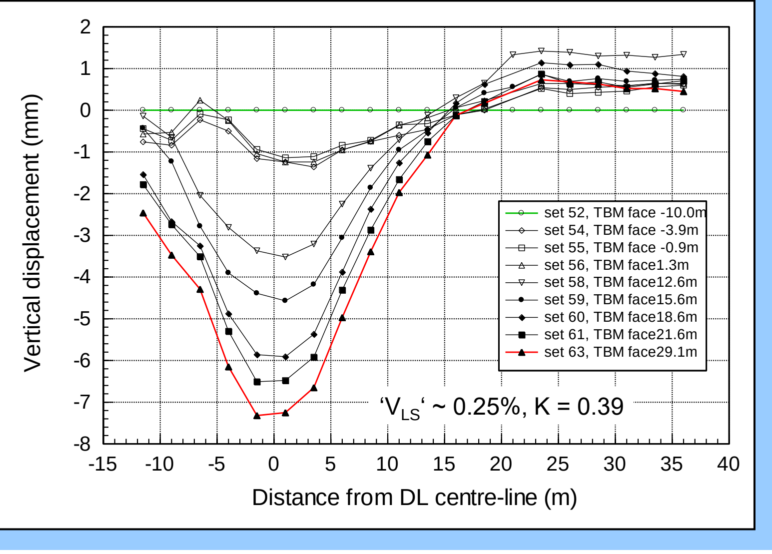
3) Steps in processing and analysing data

Progressive transverse settlement troughs for Down-line (DL) tunnel drive

Results from CTRL research site Dagenham Dock



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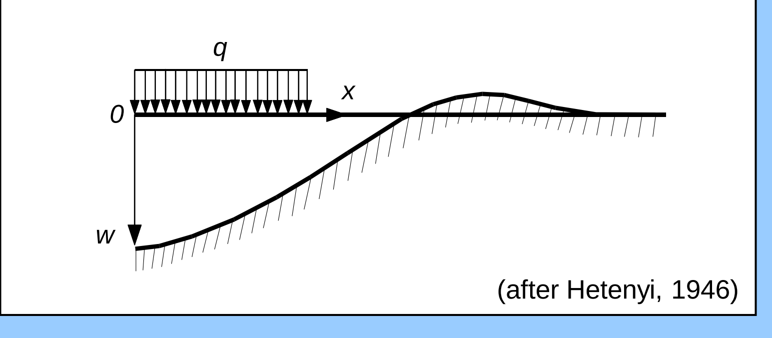
3/4) Steps in processing, analysing and interpretating the data

Response of an elastic beam on an elastic medium subjected to a uniform distributed load



Influence of continuous concrete slab beneath the tarmac'd surface of the ground.

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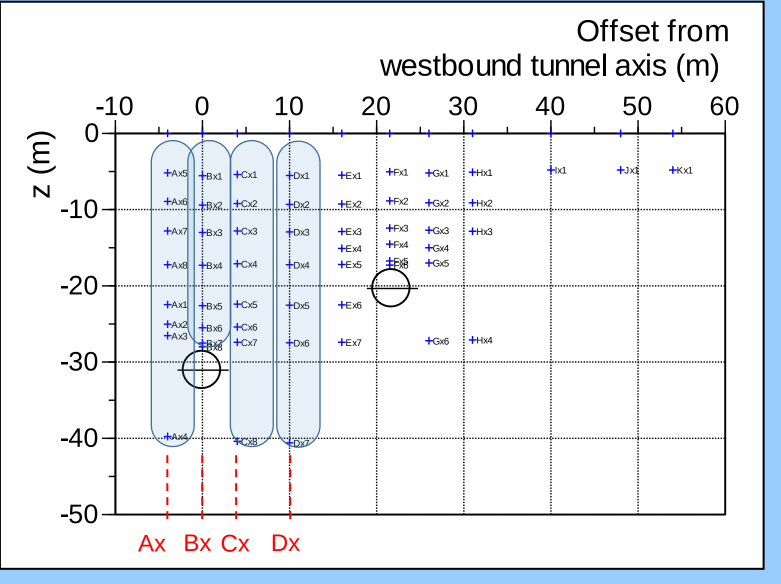
3) Steps in processing and analysing data

Arrangement of **subsurface** rod extensometers (vertical displacements)

Section through JLE control site St James's Park (Nyren, 1998)



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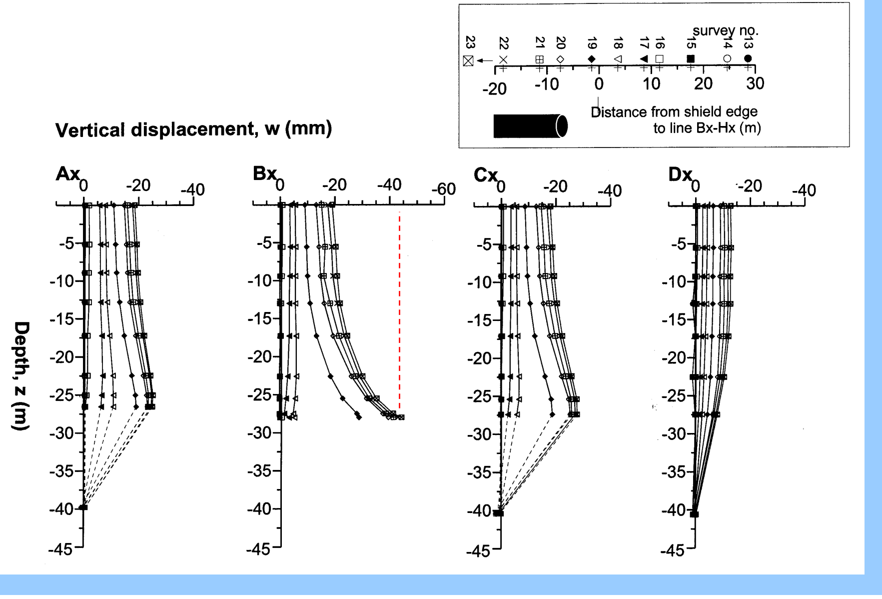
3) Steps in processing and analysing data

Vertical subsurface displacements during WB tunnel construction

Results from JLE control site St James's Park (Nyren, 1998)



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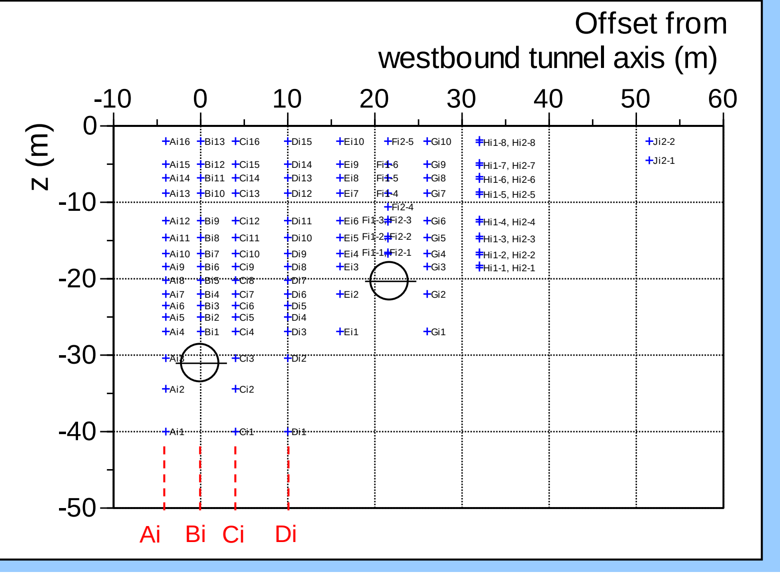
3) Steps in processing and analysing data

Arrangement of subsurface electrolevel inclinometers (horizontal displacements)

Section through JLE control site St James's Park (Nyren, 1998)



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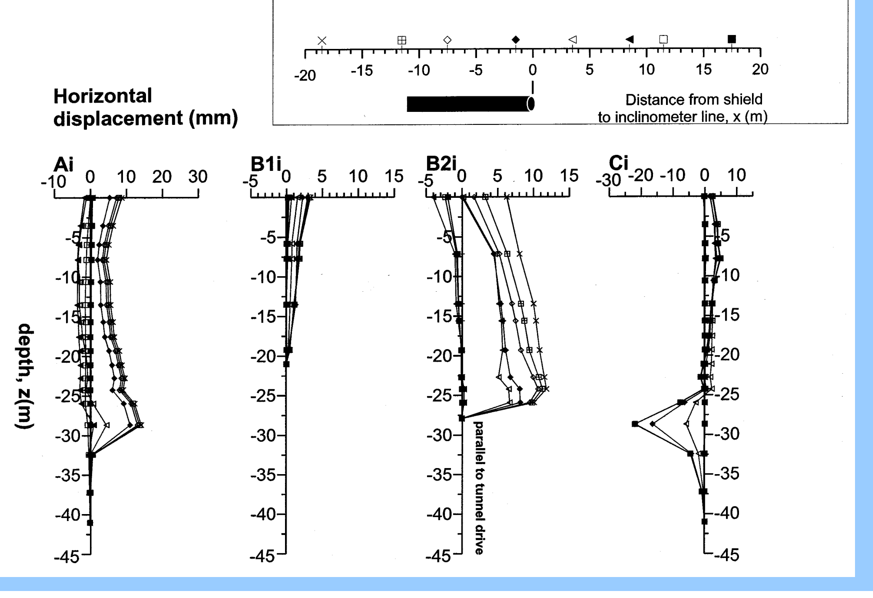
3) Steps in processing and analysing data

Horizontal subsurface displacements during WB tunnel construction

Results from JLE control site St James's Park (Nyren, 1998)



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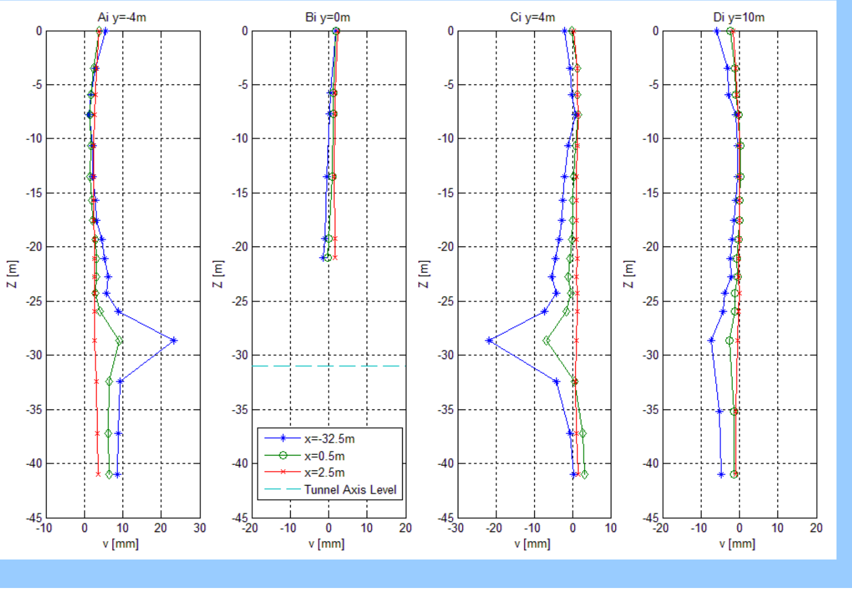
3) Steps in processing and analysing data

Horizontal subsurface displacements during WB tunnel construction

Results from JLE control site
St James's Park
(Crow, 2013)



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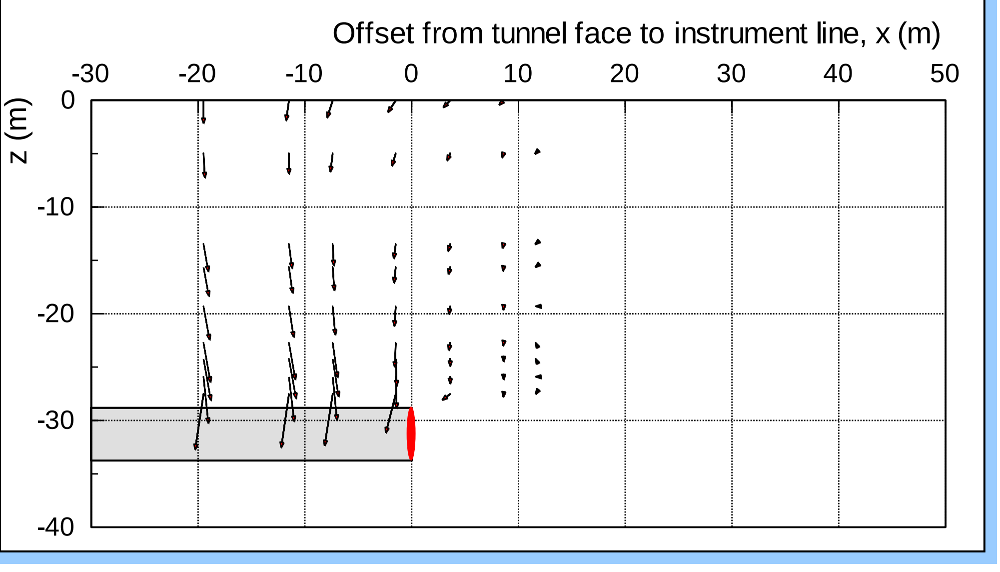
3/4) Steps in processing, analysing & interpretation of data

Subsurface longitudinal displacement vectors during WB tunnel construction

Results from JLE control site
St James's Park
(Nyren, 1998)



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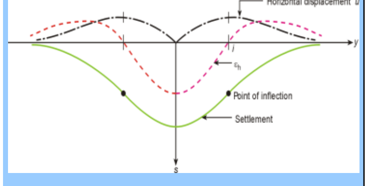
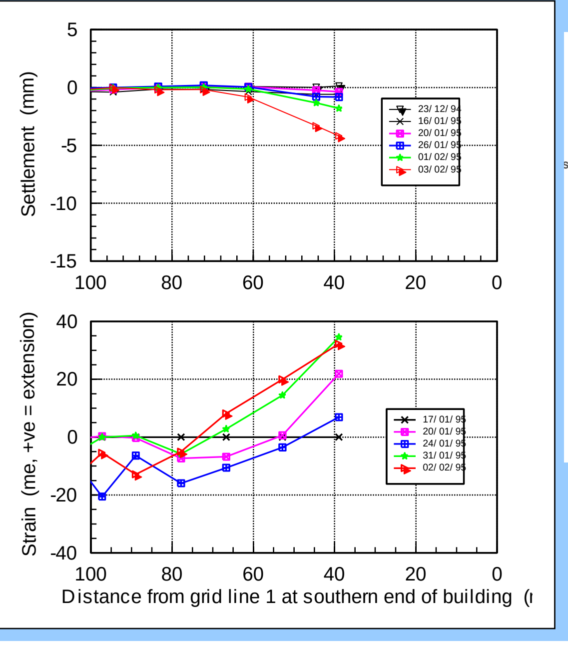
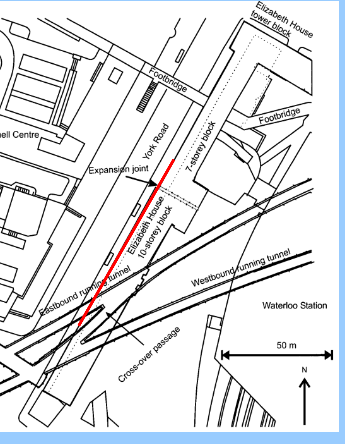
3/4) Steps in processing, analysing & interpretation of data

Elizabeth House: settlements and horizontal strains during **WB** tunnel construction

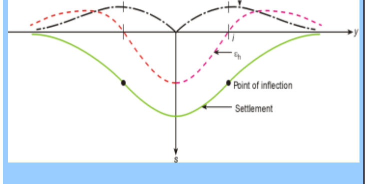


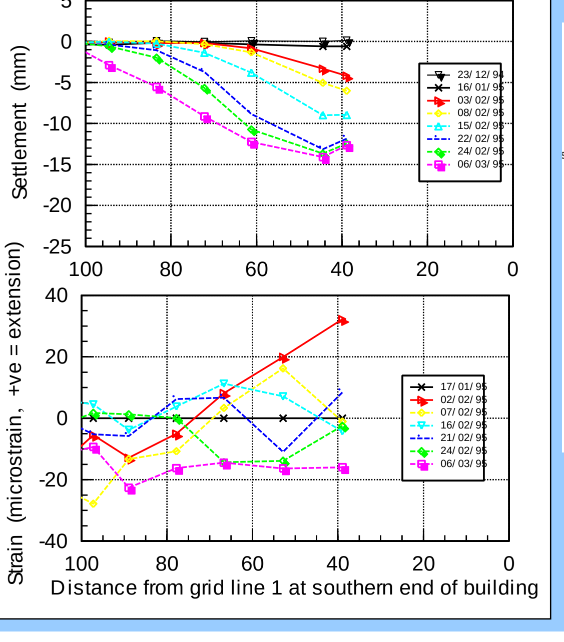


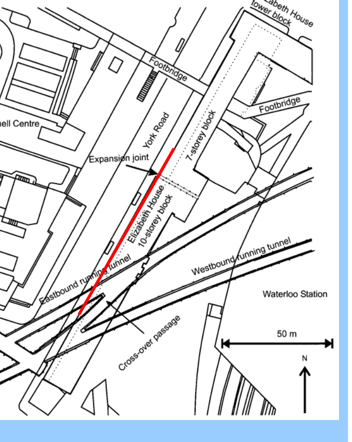


3/4) Steps in processing, analysing & interpretation of data

Elizabeth House: settlements and horizontal strains during **EB** tunnel construction



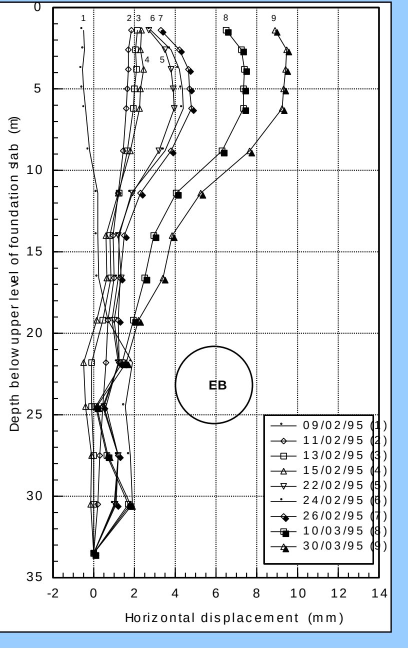




3/4) Steps in processing, analysing & interpretation of data

Elizabeth House: horizontal displacements from in-place subsurface electrolevels

- horizontal displacements of up to about 5mm measured (~ 1330 με)
- comparable with strains measured at St James's Park greenfield reference site
- restrained displacement beneath slab



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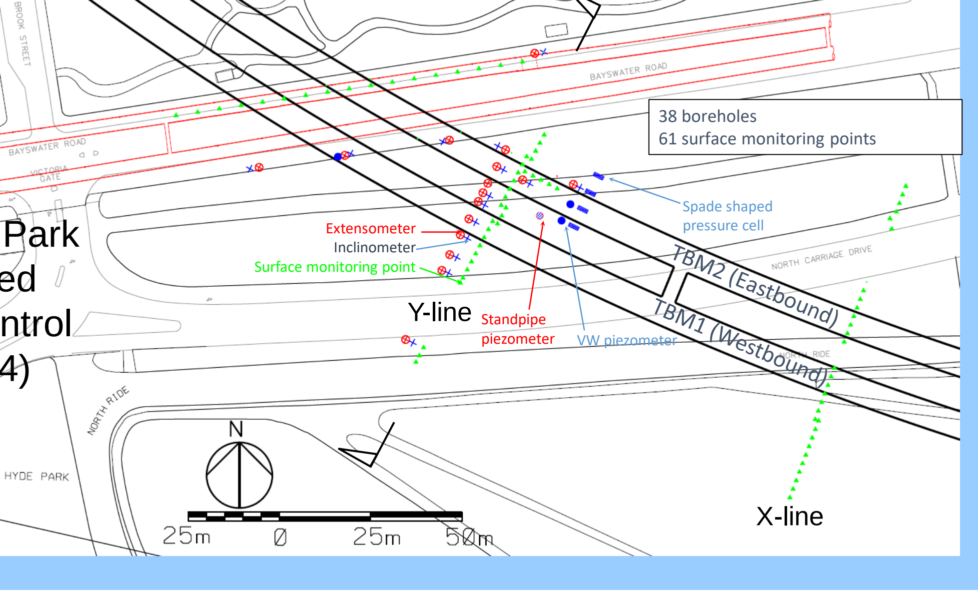
2) Monitoring methodology – Hyde Park example

Instrumentation layout plan

Plan of Hyde Park instrumented greenfield control (Wan, 2014)



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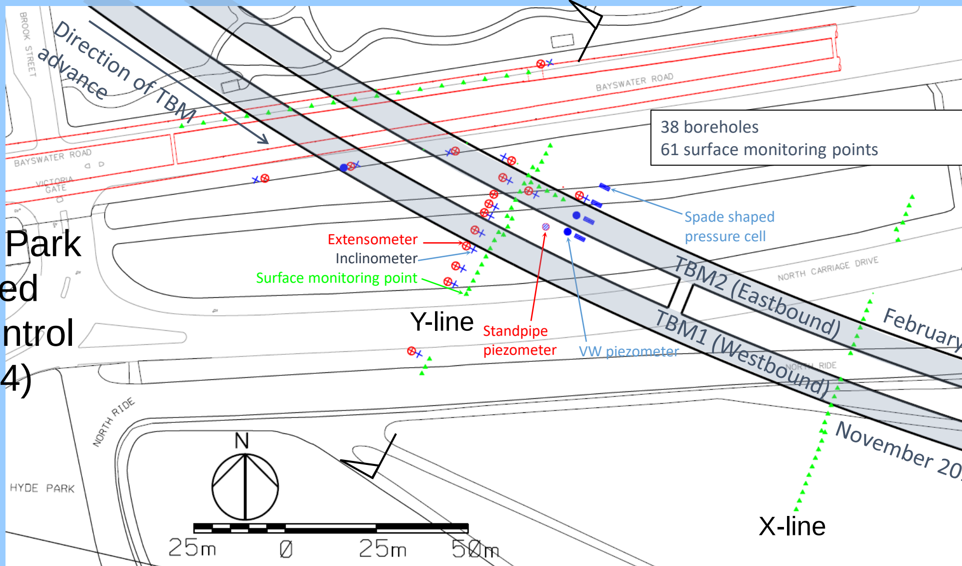
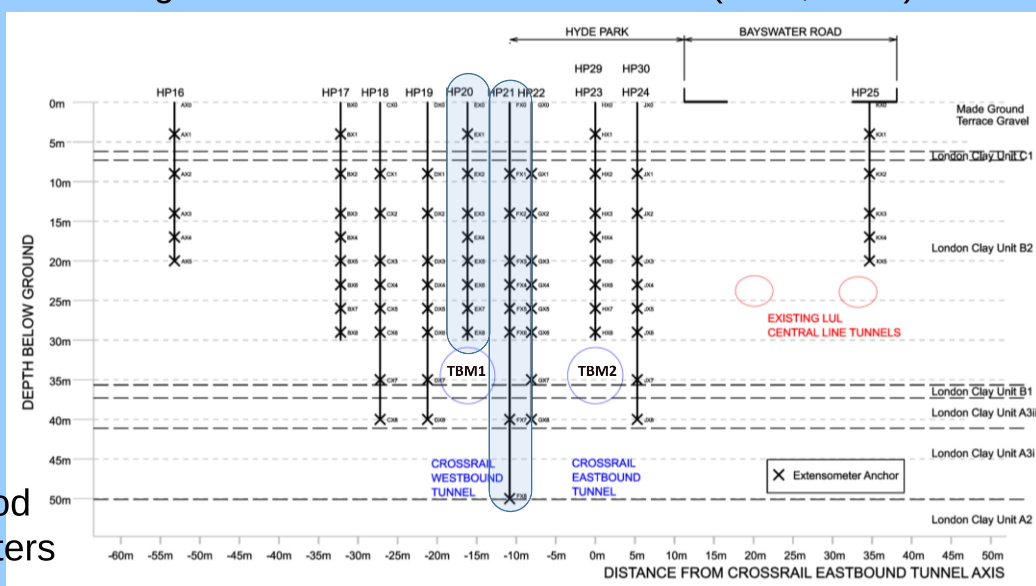


2) Monitoring methodology – Hyde Park example

Section through Crossrail research control site (Wan, 2014)



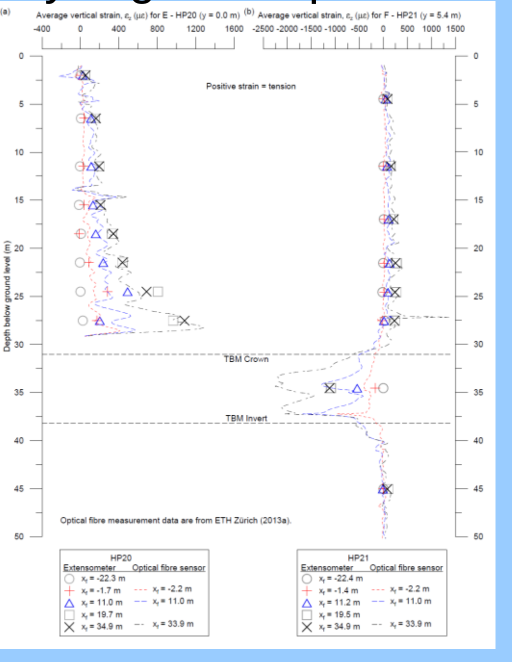
Array of rod extensometers

3/4) Steps in processing, analysing & interpretation of data

Crossrail TBM1 EPBM tunnelling, Hyde Park (Wan, 2014)

Comparison of subsurface vertical ***strains*** determined from rod extensometer and optical fibre (swept wave interferometry) measurements.

Influence of spatial resolution.



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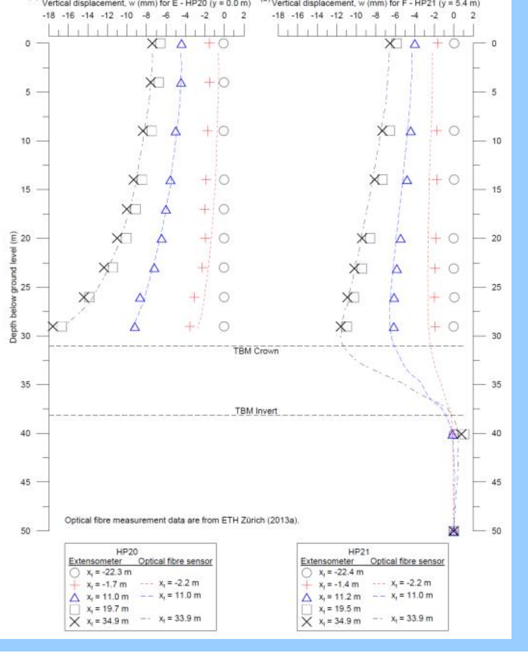
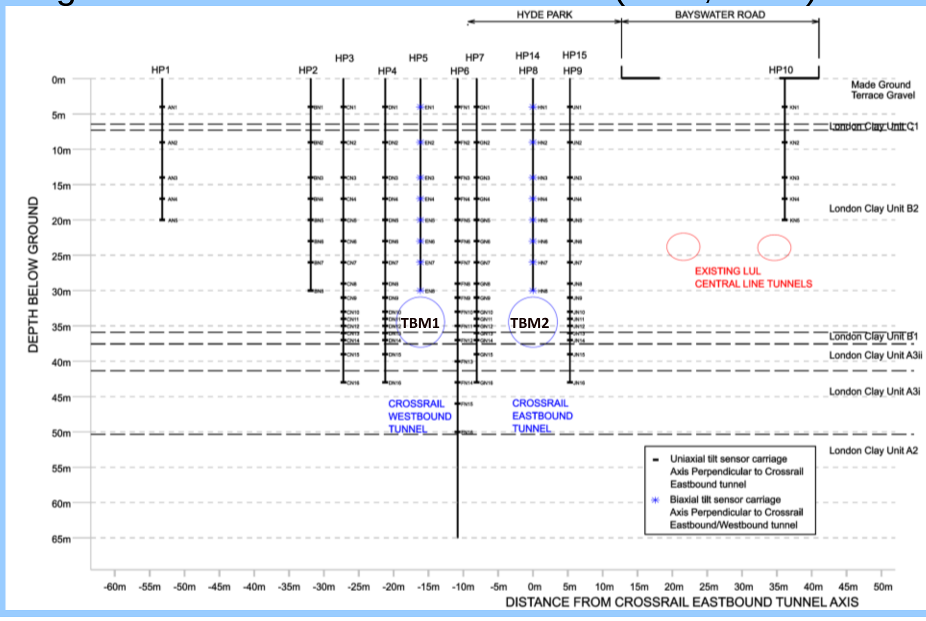


2) Monitoring methodology – Hyde Park example

Section through Crossrail research control site (Wan, 2014)

Array of in-place inclinometers



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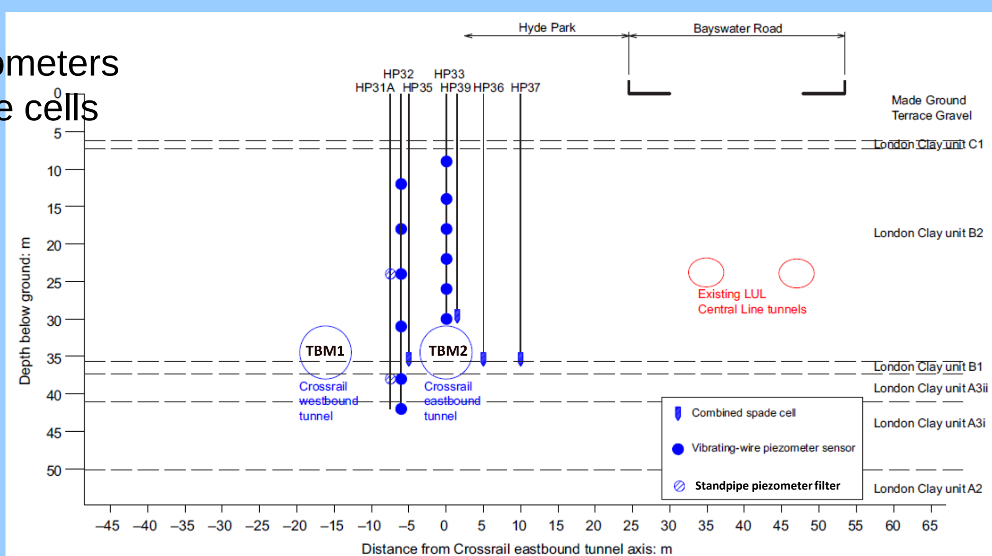
2) Monitoring methodology – Hyde Park example

Section through Crossrail research control site (Wan, 2014)

Array of piezometers and pressure cells



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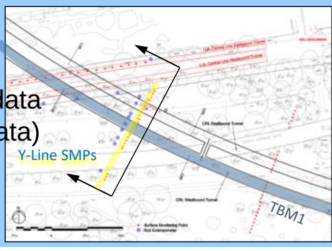
4) Interpretation of the data in relation to tunnelling activities

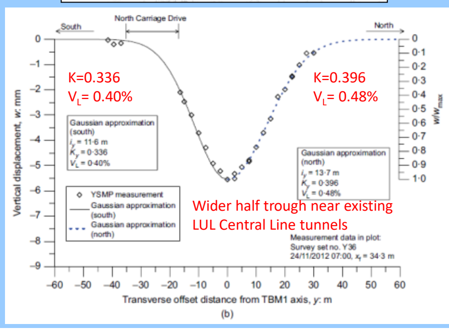
Greenfield ***surface*** settlement troughs

Westbound drive (TBM1) for **Y-Line**

Precise levelling data
(no total station data)

Hyde Park





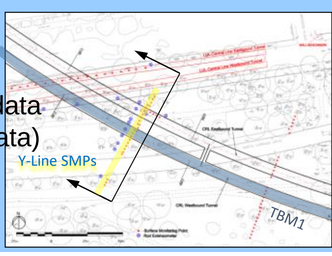
4) Interpretation of the data in relation to tunnelling activities

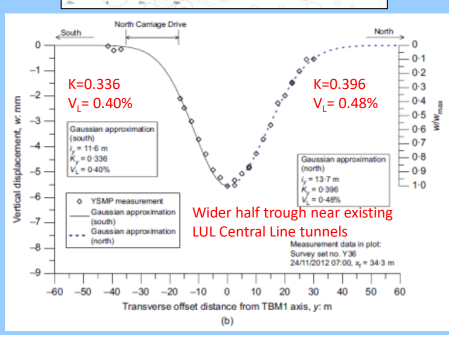
Greenfield ***surface*** settlement troughs (Wan et al., 2017a)

Westbound drive (TBM1) for **Y-Line**

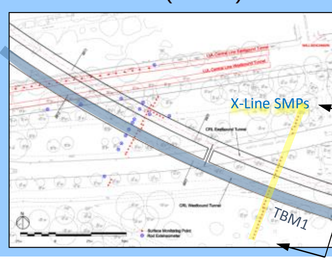
Precise levelling data
(no total station data)

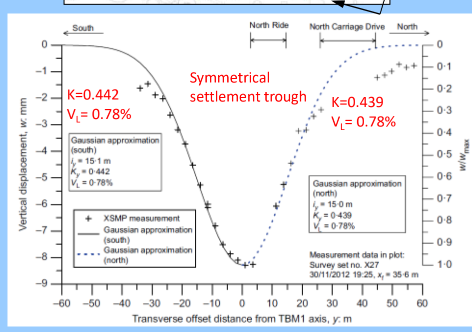
Hyde Park





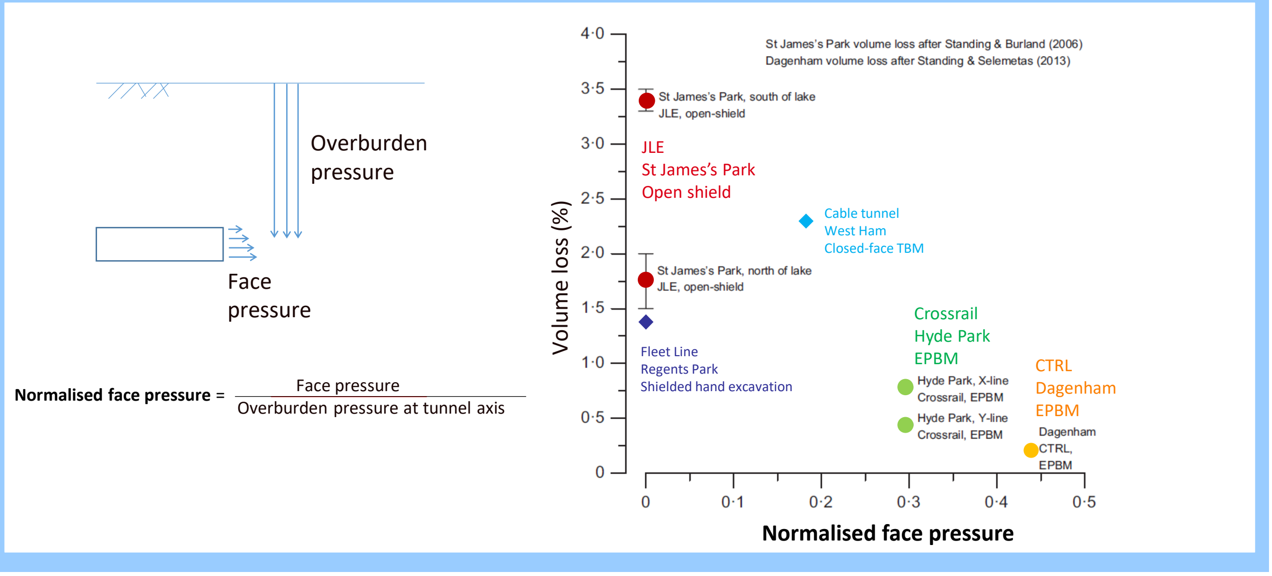
Westbound drive (TBM1) for **X-Line**





4) Interpretation of the data in relation to tunnelling activities

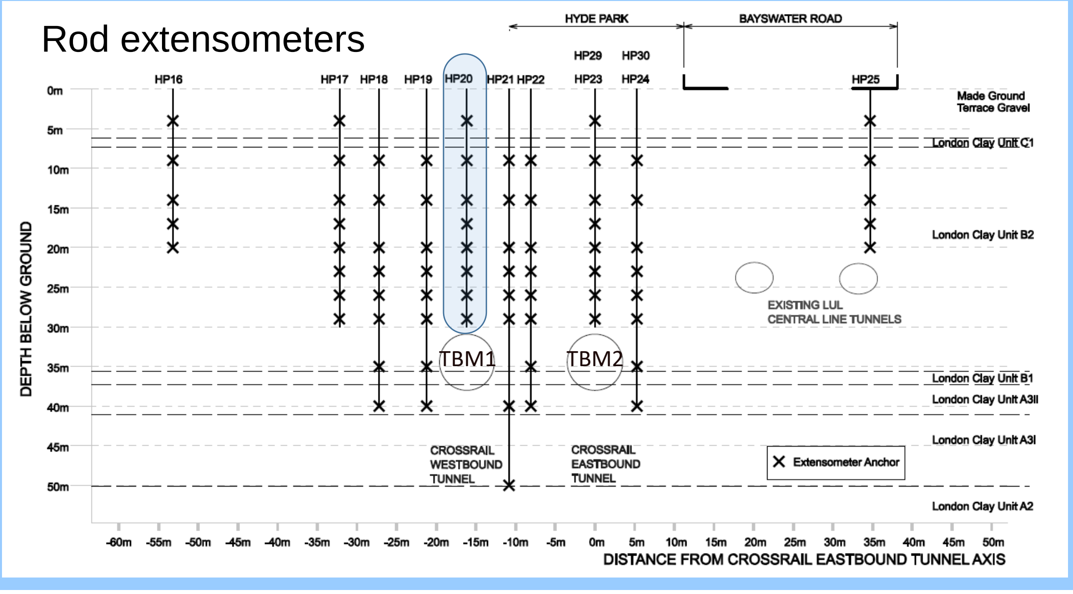
Greenfield ***surface*** movements at London Clay sites (volume loss)



55

4) Interpretation of the data in relation to tunnelling activities

Section through Crossrail research control site (Wan, 2014)



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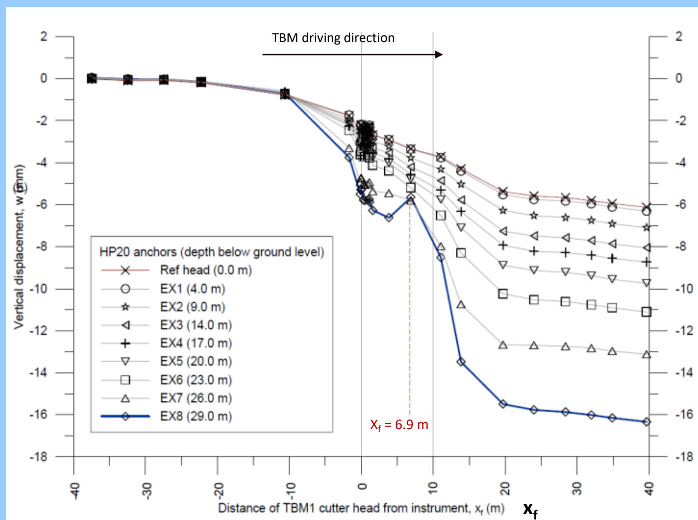
4) Interpretation of the data in relation to tunnelling activities

Greenfield ***subsurface*** movements at Hyde Park

Centre-line rod extensometers

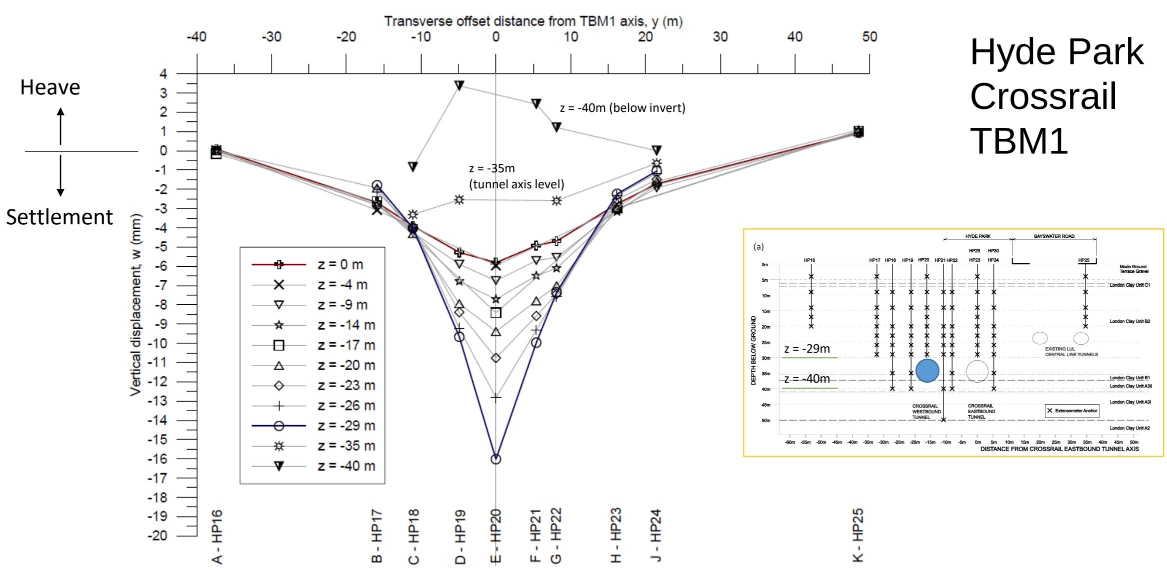
Subsurface vertical displacements – development as TBM passes Westbound Crossrail drive (TBM1)



4) Interpretation of the data in relation to tunnelling activities

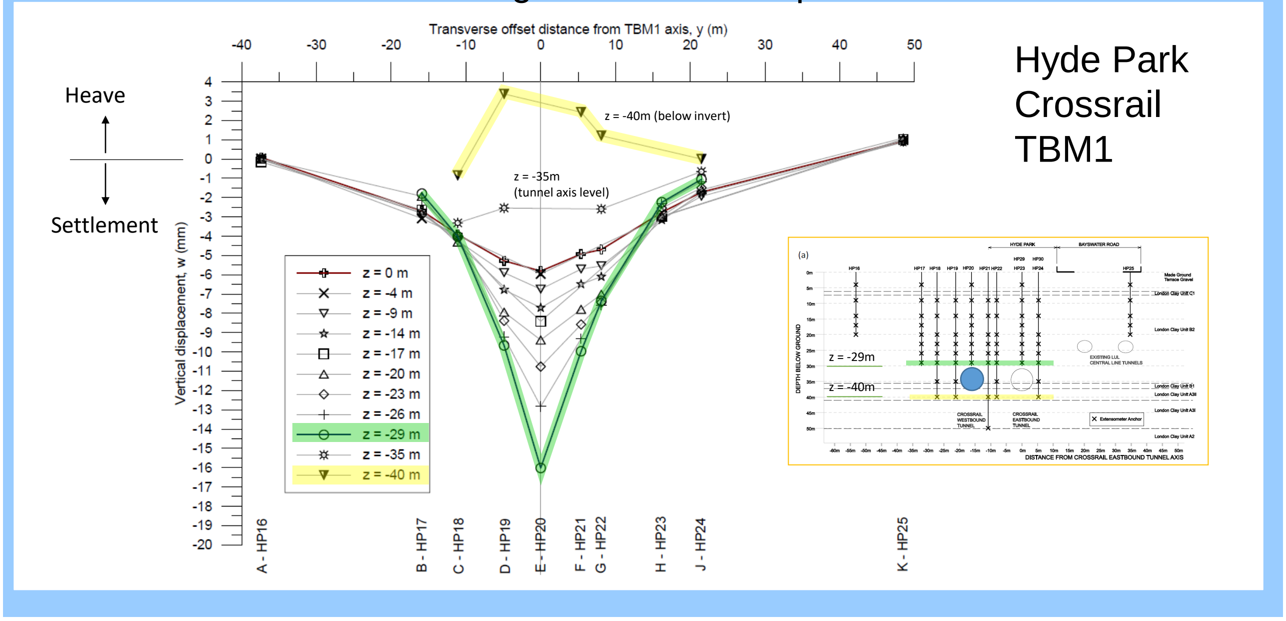
Subsurface settlement troughs at various depths (Wan et al., 2017b)

Hyde Park Crossrail TBM1



4) Interpretation of the data in relation to tunnelling activities

Subsurface settlement troughs at various depths



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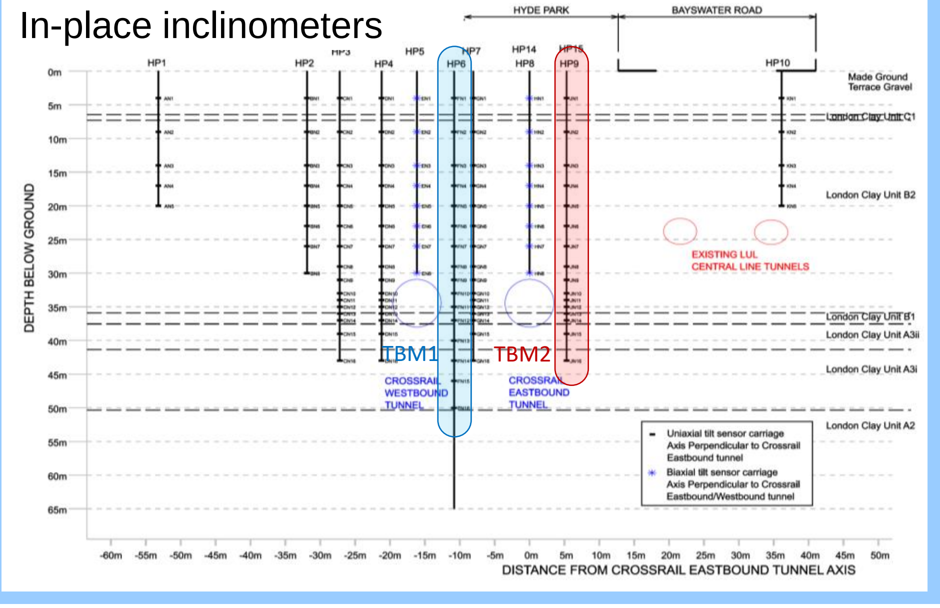
4) Interpretation of the data in relation to tunnelling activities

Subsurface horizontal displacements



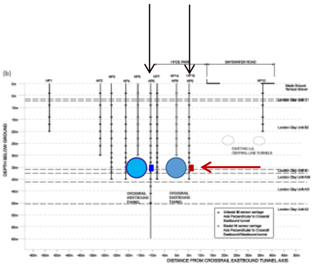
60

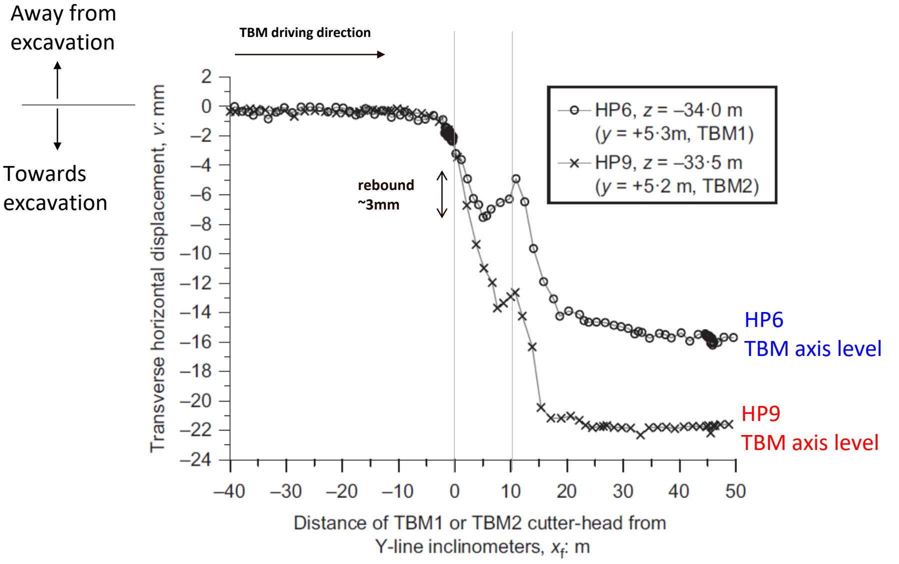
4) Interpretation of the data in relation to tunnelling activities

Subsurface horizontal displacements for TBM1 and TBM2

Hyde Park Crossrail

HP6 HP9





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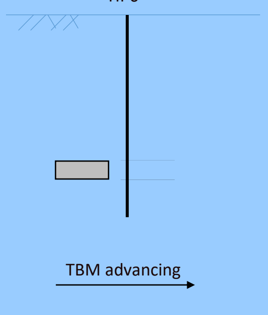
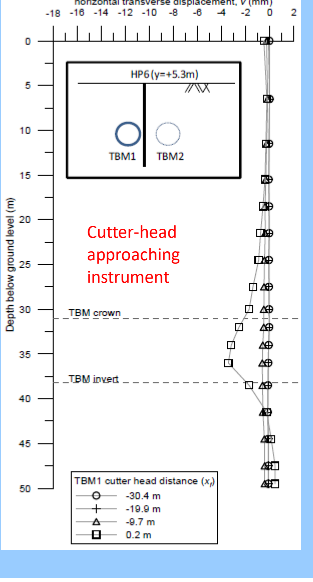
4) Interpretation of the data in relation to tunnelling activities

Development of subsurface horizontal displacements for TBM1



Hyde Park Crossrail



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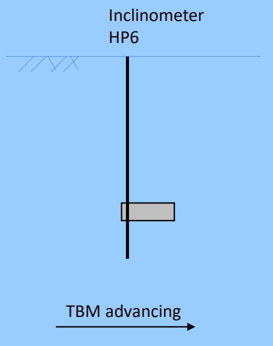
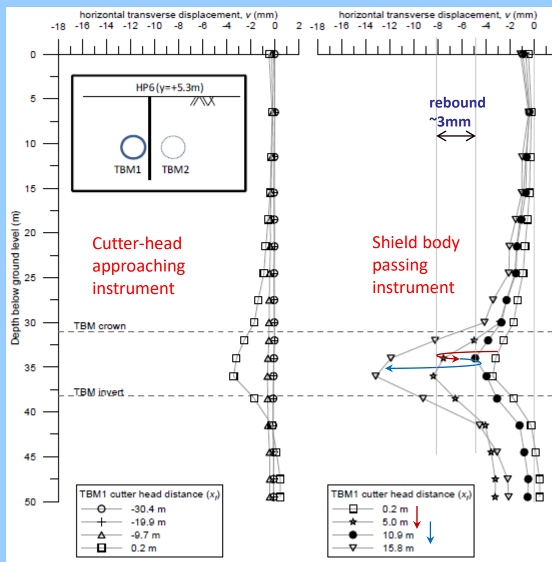
4) Interpretation of the data in relation to tunnelling activities

Development of subsurface horizontal displacements for TBM1





Hyde Park Crossrail

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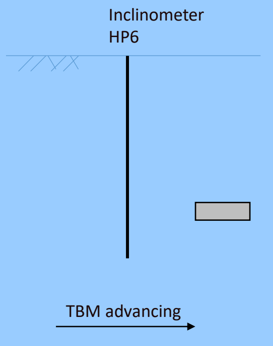
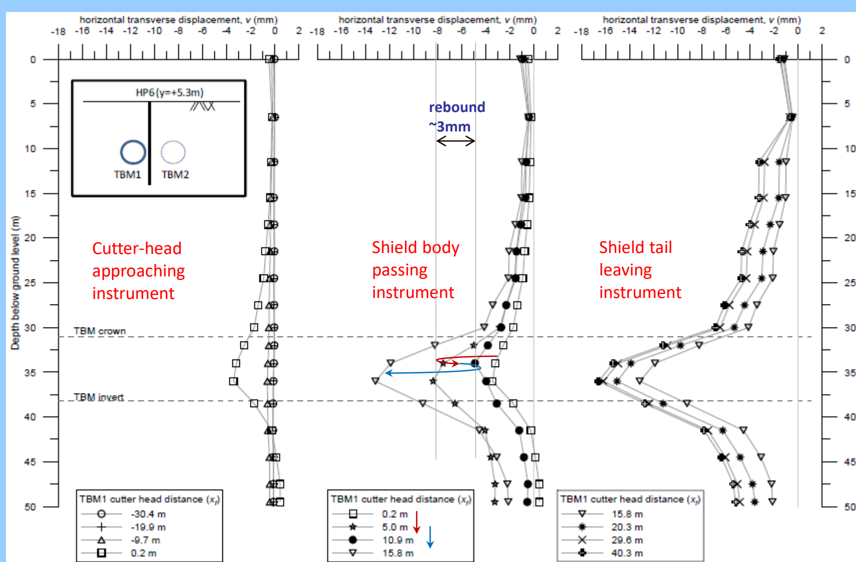
4) Interpretation of the data in relation to tunnelling activities

Development of subsurface horizontal displacements for TBM1





Hyde Park Crossrail

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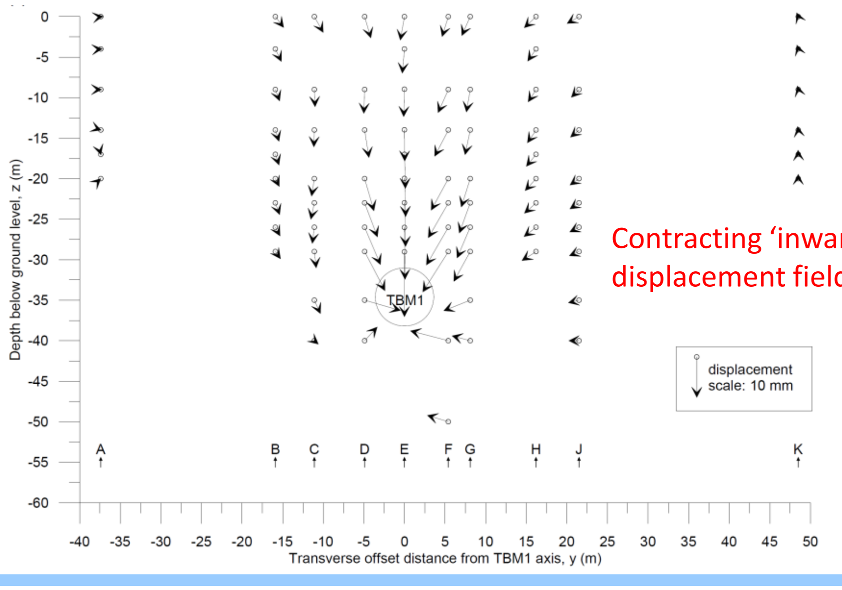
4) Interpretation of the data in relation to tunnelling activities

Resultant vectors of subsurface displacement for TBM1

Hyde Park Crossrail



Contracting 'inward' displacement field near EPBM

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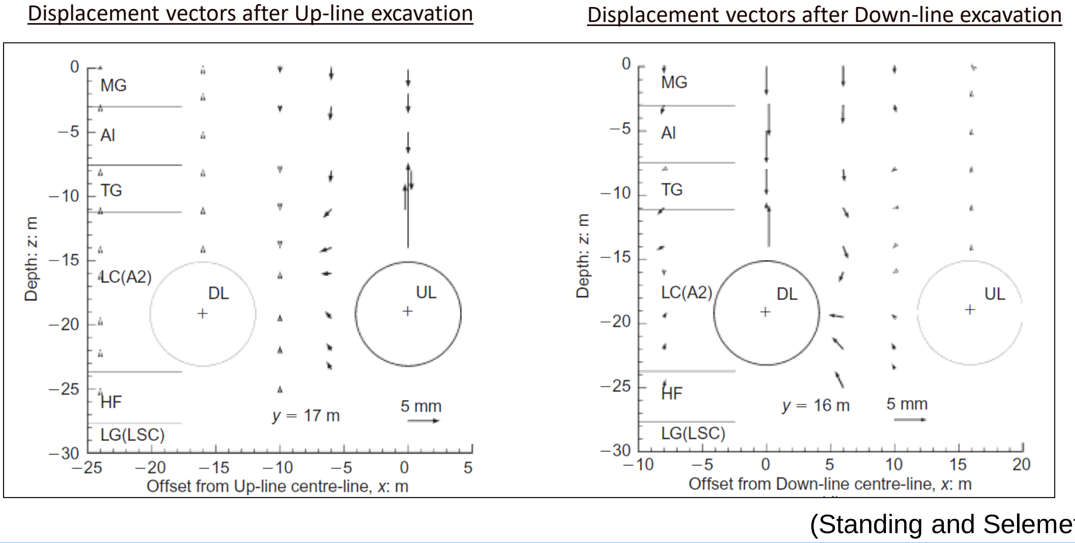
4) Interpretation of the data in relation to tunnelling activities

Resultant vectors of incremental subsurface displacement for CTRL UL and DL tunnel drives at Dagenham

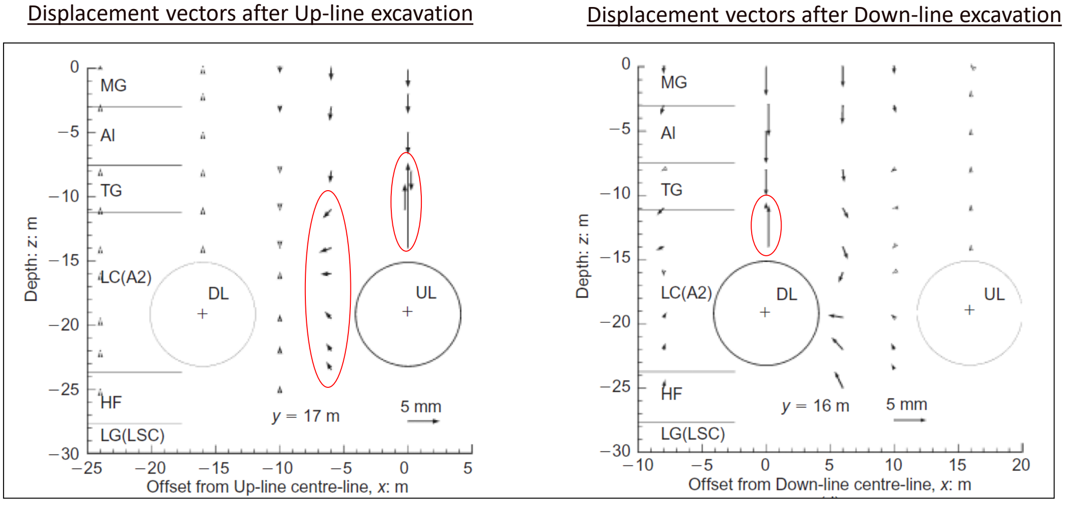


(Standing and Selemetas, 2013)

66

4) Interpretation of the data in relation to tunnelling activities

Resultant vectors of incremental subsurface displacement for CTRL UL and DL tunnel drives at Dagenham



Expanding 'outward' displacement field near EPBM (Standing and Selemetas, 2013)

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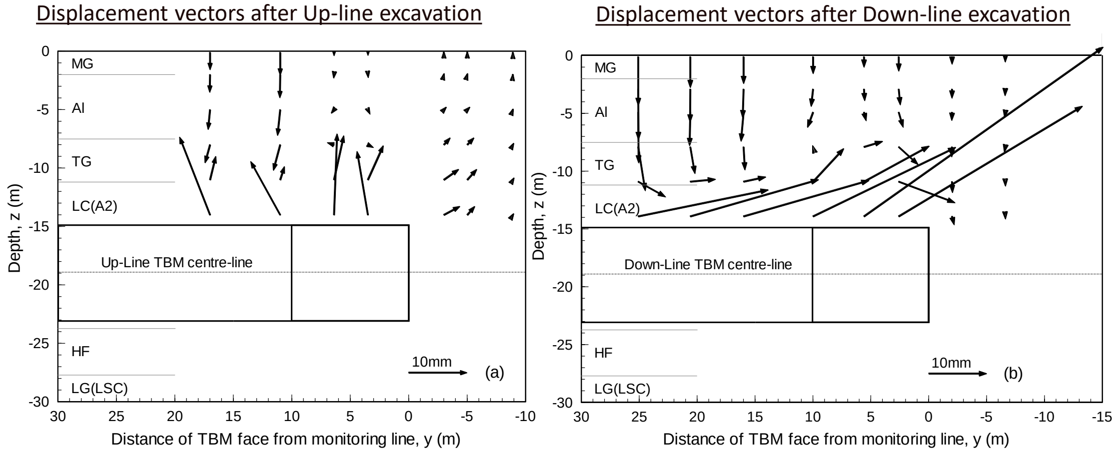
4) Interpretation of the data in relation to tunnelling activities

Resultant vectors of incremental subsurface displacement for CTRL UL and DL tunnel drives at Dagenham



Expanding 'outward' displacement field near EPBM (Standing and Selemetas, 2013)

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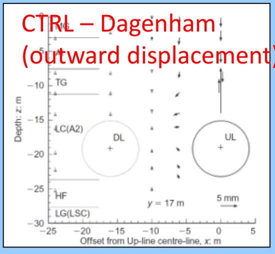
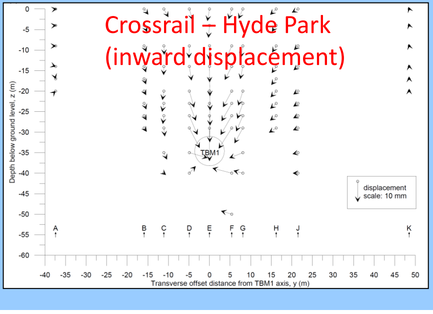
4) Interpretation of the data in relation to tunnelling activities

Average face pressure and tail grout pressures at CTRL and Crossrail sites



CTRL at Dagenham	Up-Line	Down-Line
Tunnel axis depth	19 m	19 m
Overburden pressure (σ_o) at tunnel axis	360 kPa	360 kPa
Average **face pressure**	150 kPa (**41% σ_o**)	200 kPa (**55% σ_o**)
Average **tail grout pressure**	200 kPa (**55% σ_o**)	160 kPa (**44% σ_o**)



Crossrail at Hyde Park	Westbound	Eastbound
Tunnel axis depth	35 m	35 m
Overburden pressure (σ_o) at tunnel axis	665 kPa	665 kPa
Average **face pressure**	190 kPa (**28% σ_o**)	200 kPa (**30% σ_o**)
Average **tail grout pressure**	90 kPa (**13% σ_o**)	140 kPa (**21% σ_o**)

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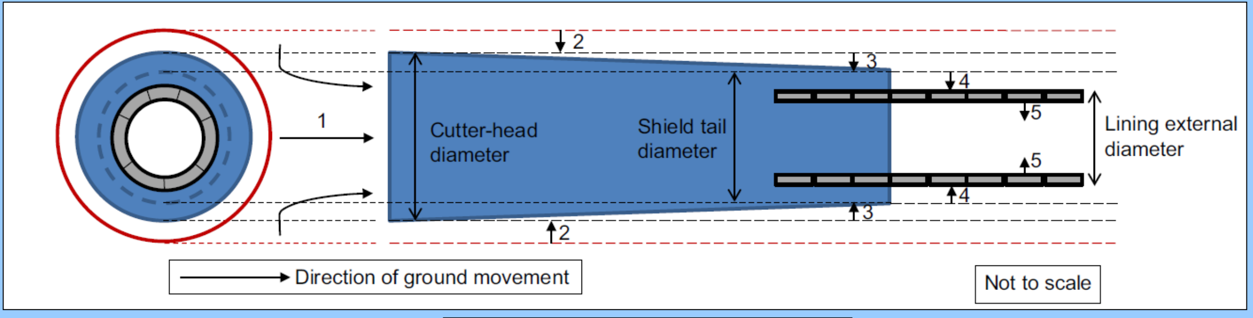
4) Interpretation of the data in relation to tunnelling activities

Source of short-term volume loss – five components



Components of short-term ground loss:
1. face movement
2. over-excavation
3. shield tapering
4. tail void closure
5. lining deformation/grout shrinkage

(Wan et al., 2017b)

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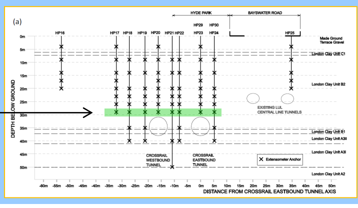
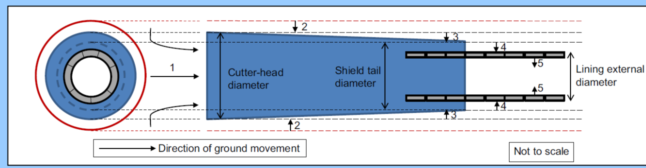
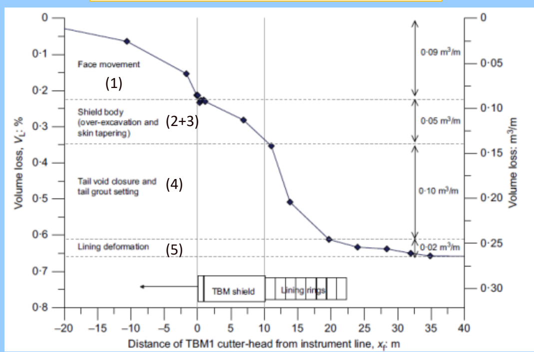
4) Interpretation of the data in relation to tunnelling activities

Source of short-term volume loss – V_L at 2m above tunnel crown

Anchors at 2m approx. above TBM crown







(Wan et al., 2017b) **TBM1**

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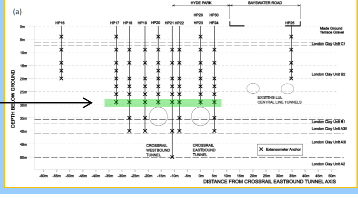
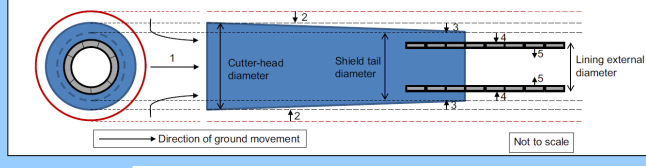
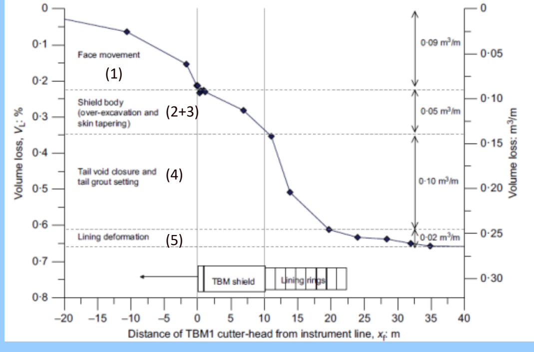
4) Interpretation of the data in relation to tunnelling activities

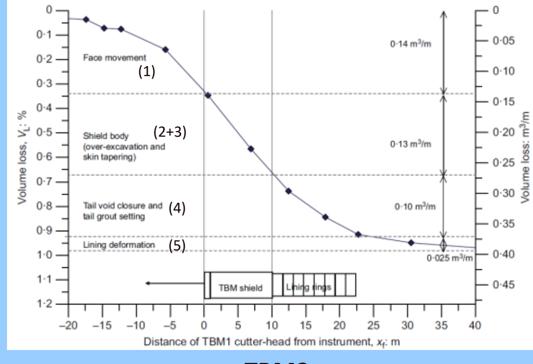
Source of short-term volume loss – V_L at 2m above tunnel crown

Anchors at 2m approx. above TBM crown









(Wan et al., 2017b) **TBM1** **TBM2**

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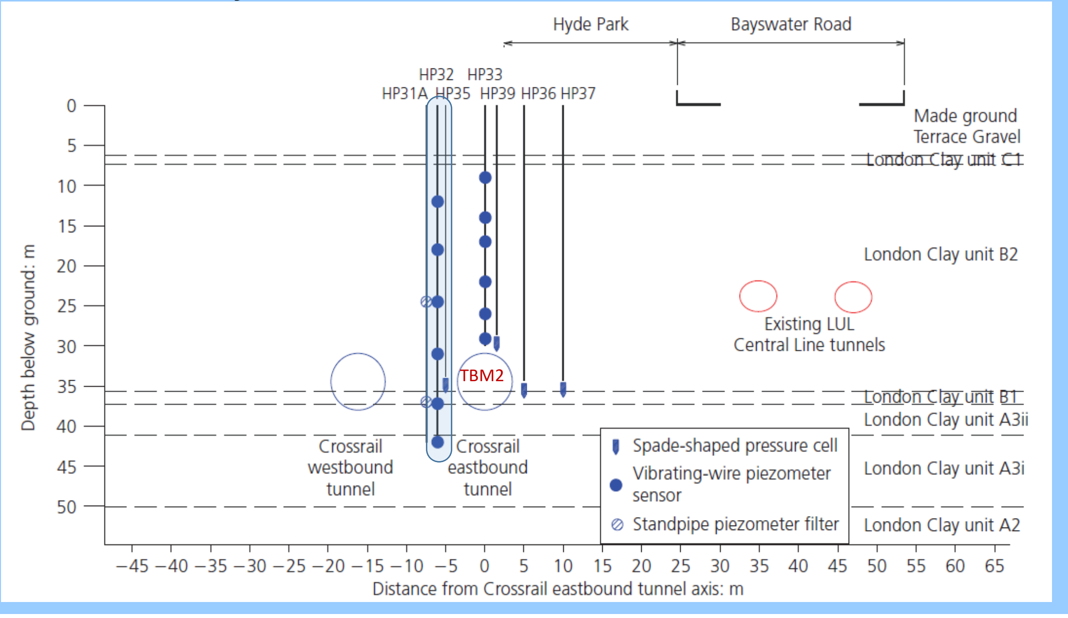
4) Interpretation of the data in relation to tunnelling activities

Piezometers at Hyde Park



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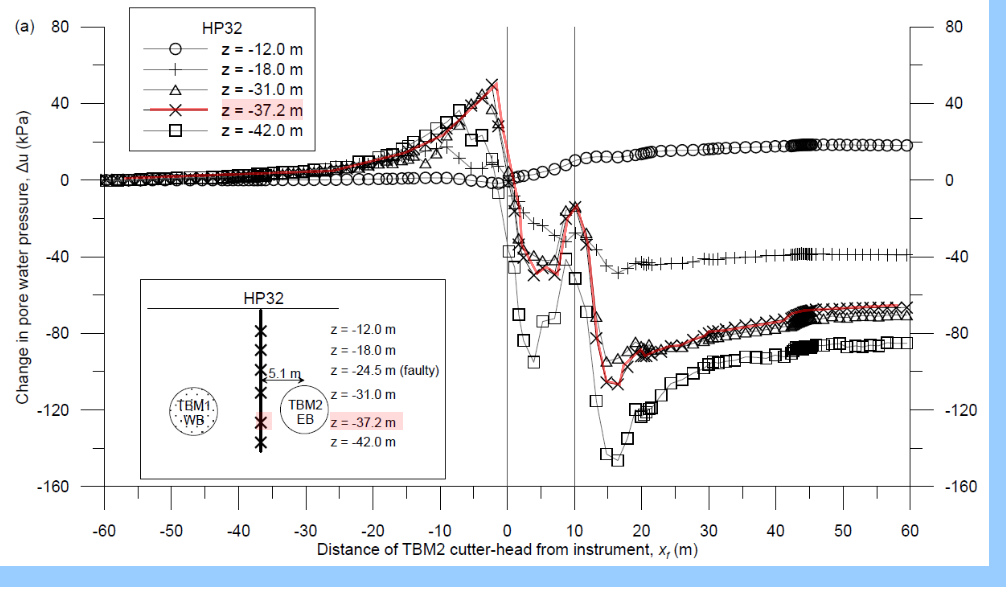
4) Interpretation of the data in relation to tunnelling activities

Pore water pressure measurements: during Crossrail TBM2 passage

Hyde Park



(Wan et al., 2019)

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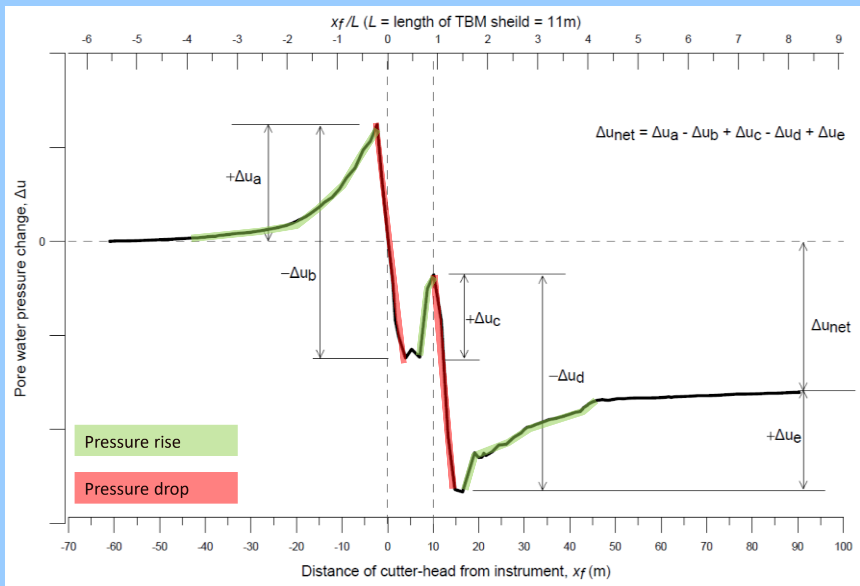
4) Interpretation of the data in relation to tunnelling activities

Typical pwp response in close vicinity of EPBM



(Wan et al., 2019)

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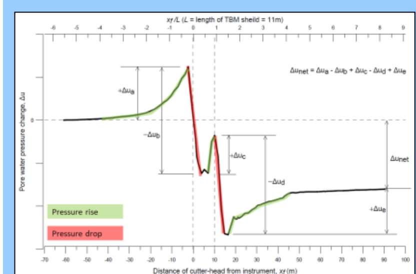
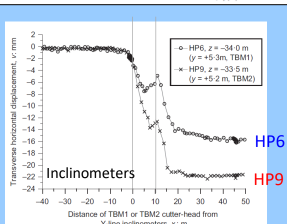
Development of ground arching around advancing EPBM





(Wan et al., 2019)

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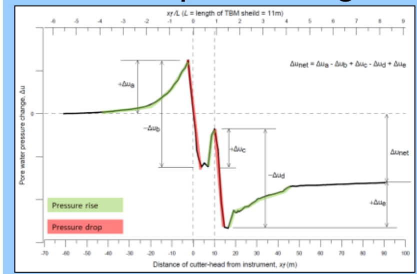
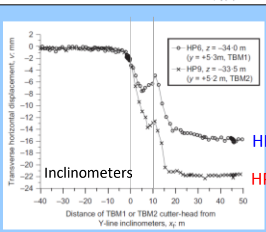
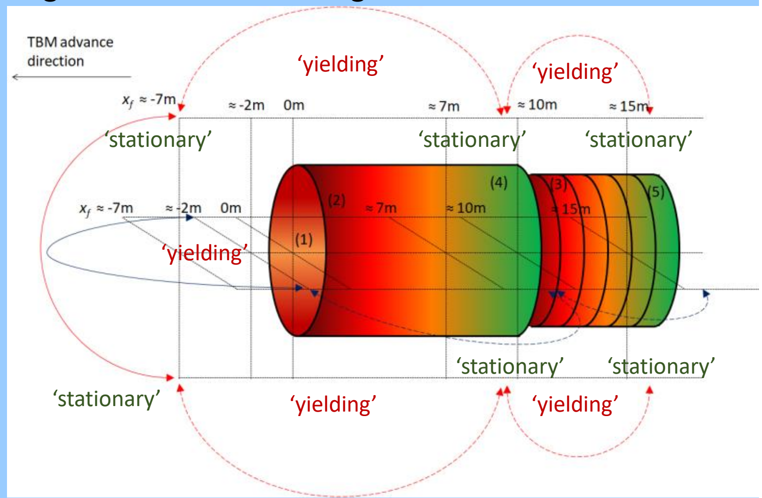
4) Interpretation of the data in relation to tunnelling activities

Development of ground arching around advancing EPBM







Area where significant ground loss originates: (1) face movement; (2) Over-cutting; (3) Tail void closure

Area where the ground gains support: (4) Tail grout pressure; (5) Grout gaining stiffness

(Wan et al., 2019)

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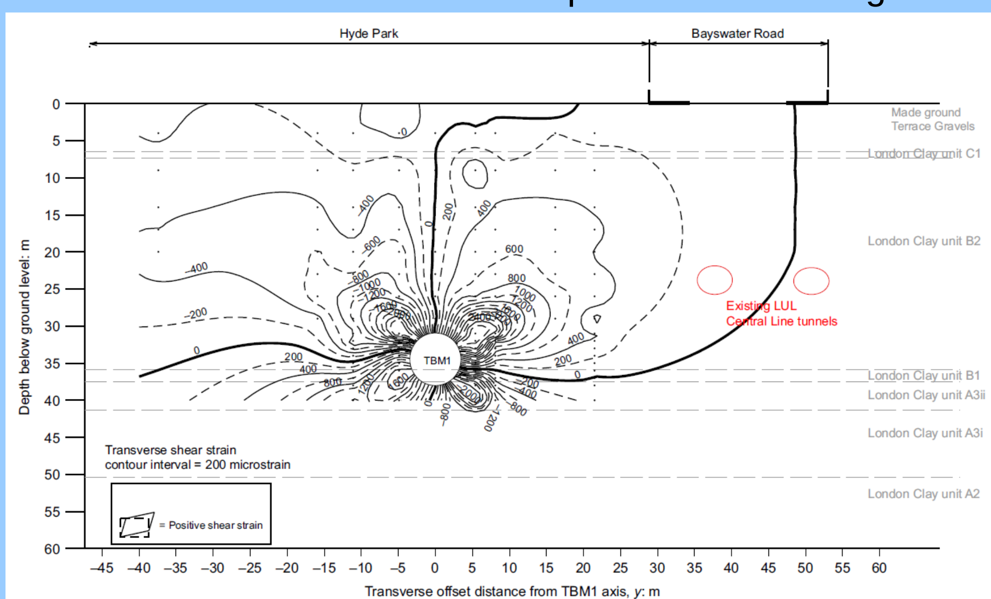
4) Interpretation of the data in relation to tunnelling activities

Contours of incremental shear strains developed from tunnelling

Hyde Park



(Wan et al., 2017b)

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Long-term displacements

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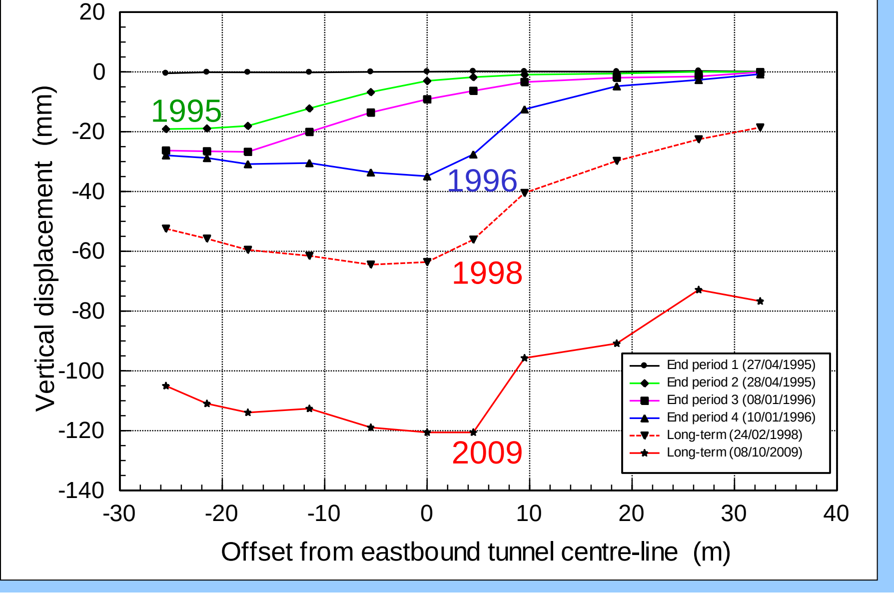
4) Interpretation of the data in relation to tunnelling activities

Long-term settlements from JLE site (measurements at depth of 5m)

St James's Park



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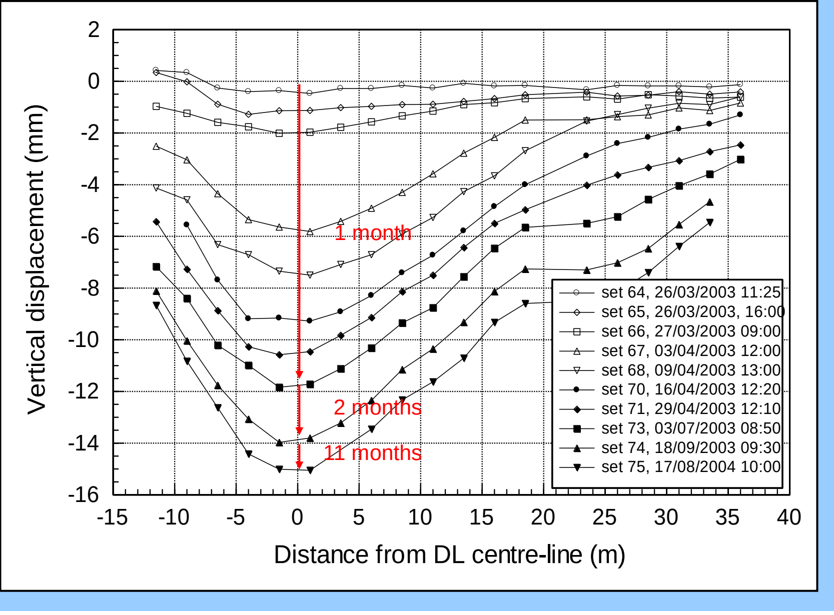
4) Interpretation of the data in relation to tunnelling activities

Long-term settlements from CTRL site

Dagenham Dock



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Conclusions

- Careful thought required when considering monitoring methodology: optimize for costs, accuracy & interpretation.
- Those doing the interpretation should be very conversant with instruments used, their installation (influence of grouts used, precautions taken, cell-action effects etc.) and the measurements themselves.
- Base readings vital for understanding accuracy and isolating non-construction related influences (e.g. tides, trees, temperature, malfunctioning of instruments).
- Recording of construction / excavation activities a vital component of interpretation. Try to establish a recording methodology before works start.
- Without a detailed analysis and interpretation of the basic/ raw/early field monitoring data, there is uncertainty in all subsequent more complex analyses.

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Conclusions

- Primary emphasis has been on displacement measurements in vertical and horizontal senses. From these, detailed contoured displacement and strain fields can be determined. Beware of effects of spatial resolution when contouring.
- Measurements of pore water pressure and total stress more challenging but they allow ground response interpretations to be taken to another level (e.g. identification of arching mechanisms).
- Monitoring of pore water pressures often provides advanced warning of imminent ground response before changes in displacement observed.
- Generally there are four primary periods of monitoring in tunnelling projects: base readings; transient (while construction underway); short term (after tunnel has passed); long term.

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Conclusions

- Frequently the primary focus is on base readings and short-term monitoring. Interpretation of transient ground response can be challenging but is important to understand fully the whole mechanism.
- Long-term monitoring is also very challenging but for different reasons: longevity of instruments and monitoring system; choice of datum; finance / commitment to continue monitoring (especially if over a period of many years / decades); interpretation of the data.

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Thoughts for the future…

- Monitoring technology is advancing very rapidly, especially in terms of automatic logging and transfer of data. We should think carefully about appropriate frequency of data collection, especially regarding interpretation.
- It is seemingly possible to measure quantities to higher and higher resolution. Think carefully about what is realistic, bearing in mind factors such as temperature and the magnitudes that are of engineering (and scientific) concern.
- Machine learning and Artificial Intelligence are powerful approaches that can provide great benefits to the interpretation of data. Applying such methodology should be very carefully supervised by those with in-depth experience of interpreting field monitoring data.
- It is important not to forget what we have learnt in the past and the ways that we used to interpret data. These have been applied for decades and require careful thought.

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  - Graham Taylor
  - Michael Wan
  - Jessica Yu
  - Shawn Xue
  - Jaime Wills Sanin

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Many thanks for coming,
listening and your attention

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