NEW ZEALAND GEOTECHNICAL SOCIETY inc.

An NZGS 1 day short course

NEW ZEALAND GEOTECHNICAL SOCIETY inc.

Ground movement control

Tunnelling

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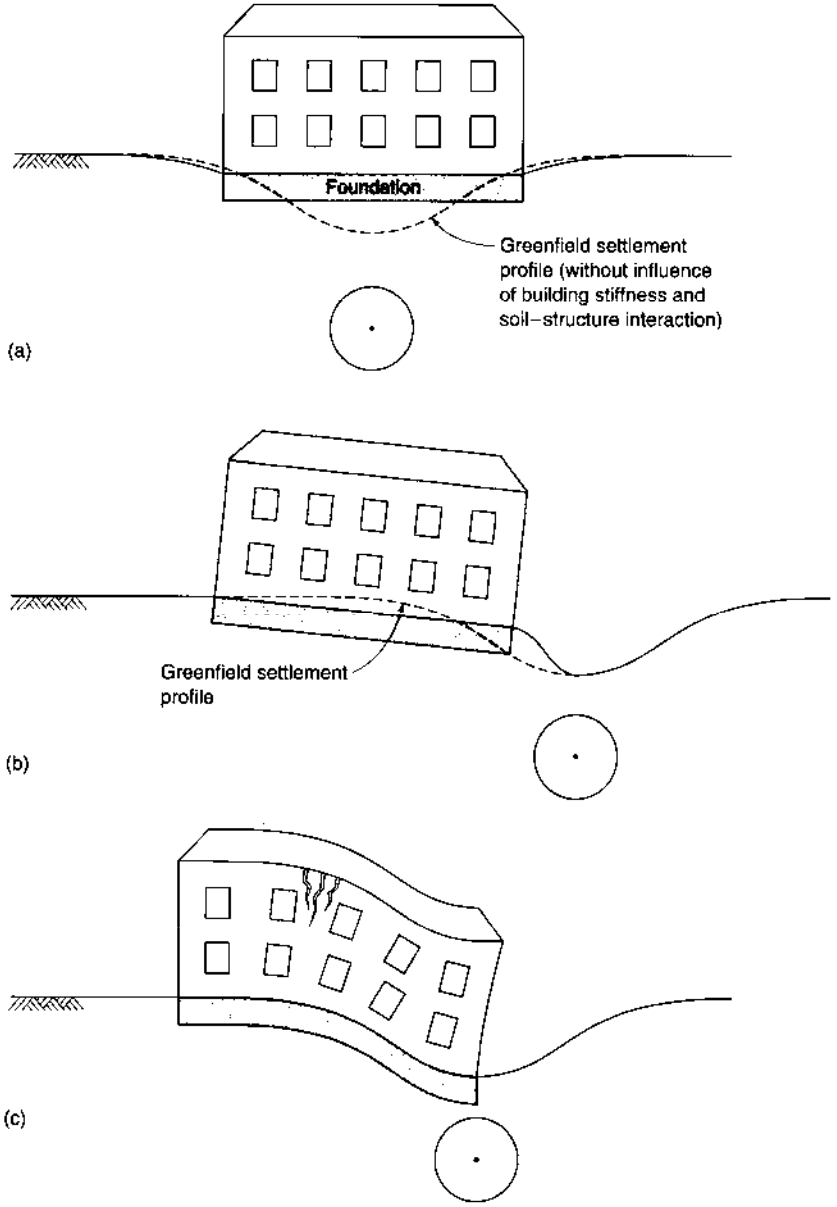
Outline

- Introduction
- Ground movements generated by tunnelling
- Procedures for ground movement control
  - General
  - Tunnelling procedure (TBMs)
  - Screen (curtain) walls
  - Structural movement compensation
  - Compensation grouting
- Final remarks

Introduction

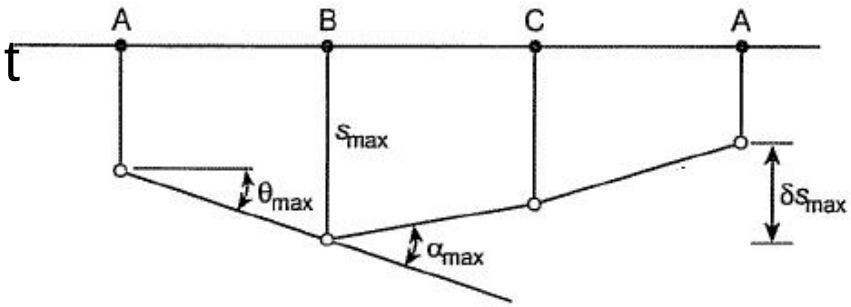
General remarks

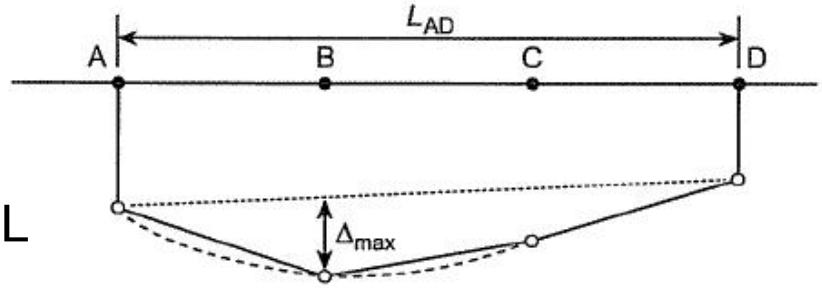
- Any tunnelling activity causes ground movements
- Ground movements must be controlled to ensure that they are within requirements
- In the last few years, there is an increasing sensibility of public opinion concerning ground movements caused by civil engineering works, especially tunnelling and deep excavations
- This lecture focuses on ground movements caused by tunnelling

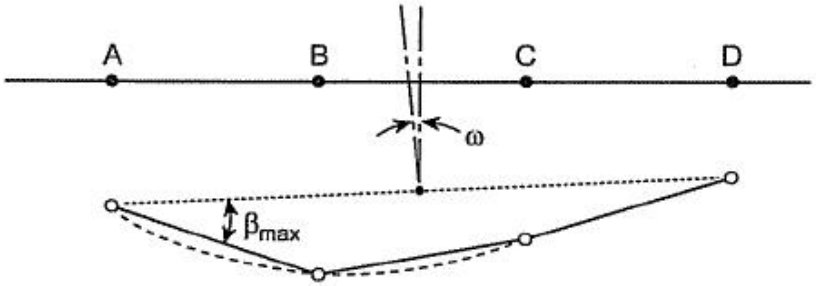


Introduction

- Ground and foundation movement
  - *Rotation or slope*, θ
  - *Angular strain (distortion),* α
  - *Relative deflection*, Δ
  - *Deflection ratio*, Δ/L
  - *Tilt*, ω
  - *Relative rotation*, β
  - *Average horizontal strain*, $\varepsilon_h=\delta l/L$







Introduction

- Damage criteria

Table 2.2 Relationship between category of damage and limiting tensile strain (ϵ_{lim}) (after Boscardin and Cording, 1989)

Category of damage	Normal degree of severity	Limiting tensile strain ϵ_{lim} (%)
0	Negligible	0–0.05
1	Very slight	0.05–0.075
2	Slight	0.075–0.15
3	Moderate[a]	0.15–0.3
4 to 5	Severe to very severe	>0.3

[a] Boscardin and Cording describe the damage relating to ϵ_{lim} in the range of 0.15–0.3% as 'moderate to severe'. However, none of their case studies exhibits severe damage for this range of strains. There is no evidence to suggest that tensile strains up to 0.3% cause severe damage

Boscardin & Cording (1989)

Introduction

- Damage criteria

Table 2.1 Classification of visible damage to walls with particular reference to ease of repair of plaster and brickwork or masonry

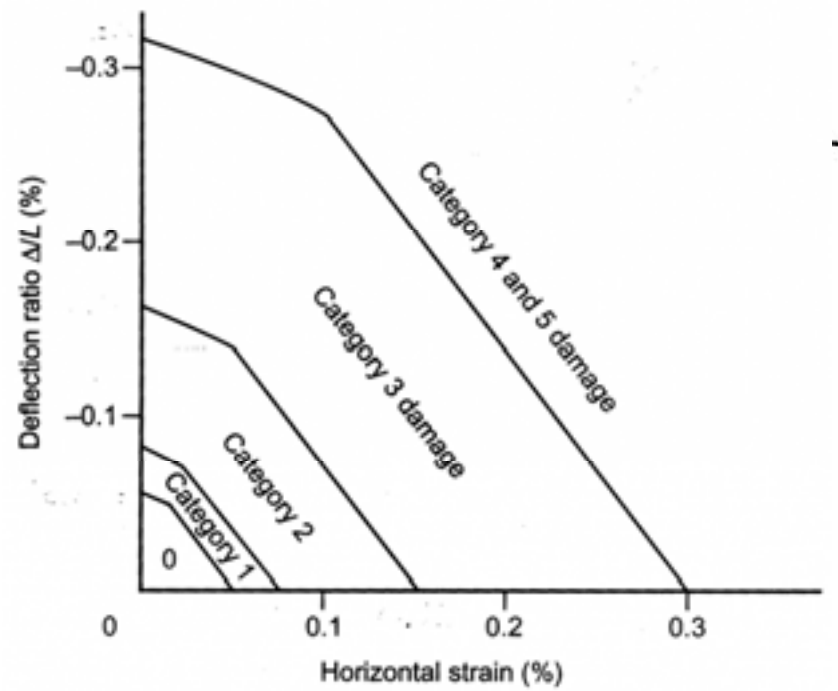
Category of damage	Normal degree of severity	Description of typical damage[a]
0	Negligible	Hairline cracks less than about 0.1 mm
1	Very slight	*Fine cracks which are easily treated during normal decoration.* Damage generally restricted to internal wall finishes. Close inspection may reveal some cracks in external brickwork or masonry. Typical crack widths up to 1 mm.
2	Slight	*Cracks easily filled. Redecoration probably required. Recurrent cracks can be masked by suitable linings.* Cracks may be visible externally and *some repointing may be required to ensure weathertightness.* Doors and windows may stick slightly. Typical crack widths up to 5 mm.
3	Moderate	*The cracks require some opening up and can be patched by a mason. Repointing of external brickwork and possibly a small amount of brickwork to be replaced.* Doors and windows sticking. Service pipes may fracture. Weathertightness often impaired. Typical crack widths are 5 to 15 mm or there are several greater than 3 mm.
4	Severe	*Extensive repair work involving breaking-out and replacing sections of walls, especially over doors and windows.* Windows and door frames distorted, floor sloping noticeably.[b] Walls leaning[b] or bulging noticeably, some loss of bearing in beams. Service pipes disrupted. Typical crack widths are 15 to 25 mm but also depends on the number of cracks.
5	Very severe	*This requires a major repair job involving partial or complete rebuilding.* Beams lose bearing, walls lean badly and require shoring. Windows broken with distortion. Danger of instability. Typical crack widths are greater than 25 mm but depends on the number of cracks.

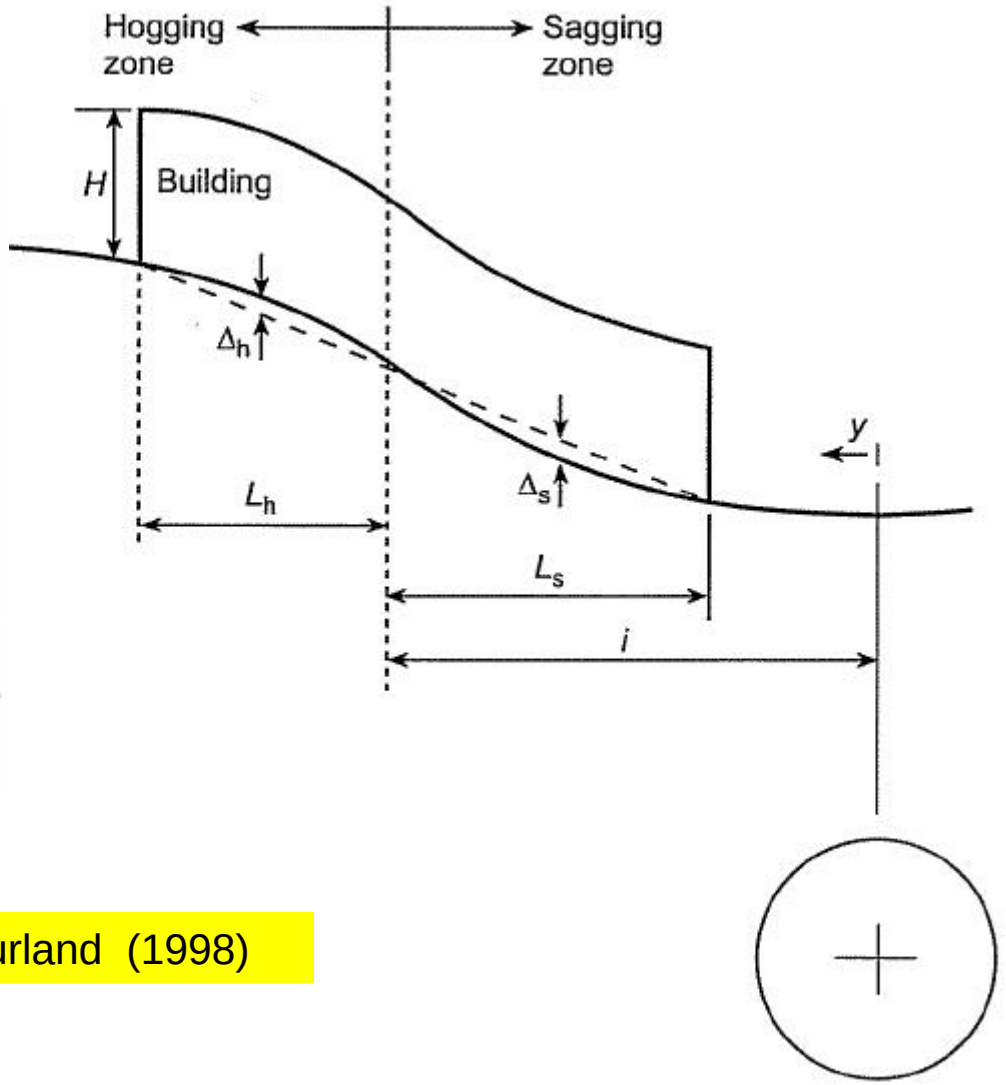
Ease of repair is given in italics

Burland et al. (1977)

Introduction

- Damage criteria

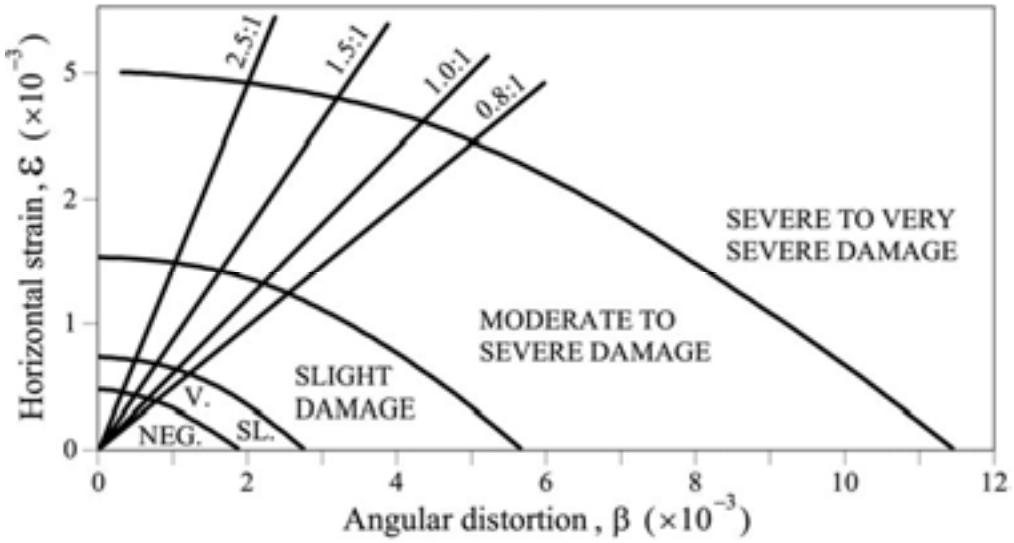




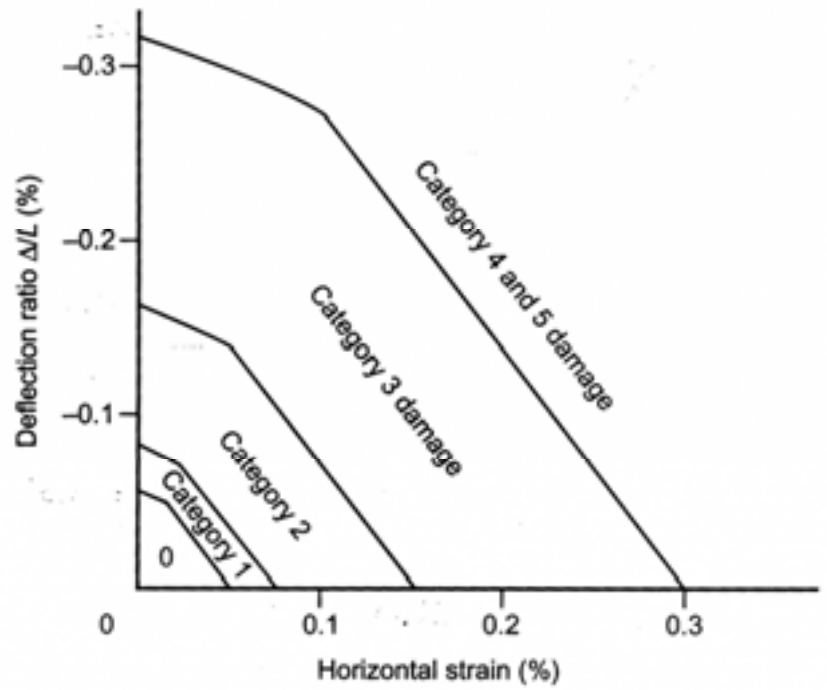
Burland (1998)

Introduction

- Damage criteria



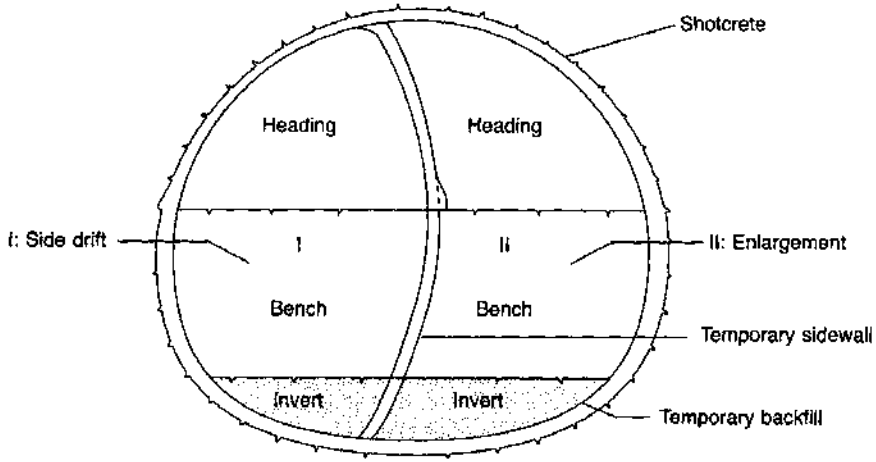
Boscardin & Cording (1989)



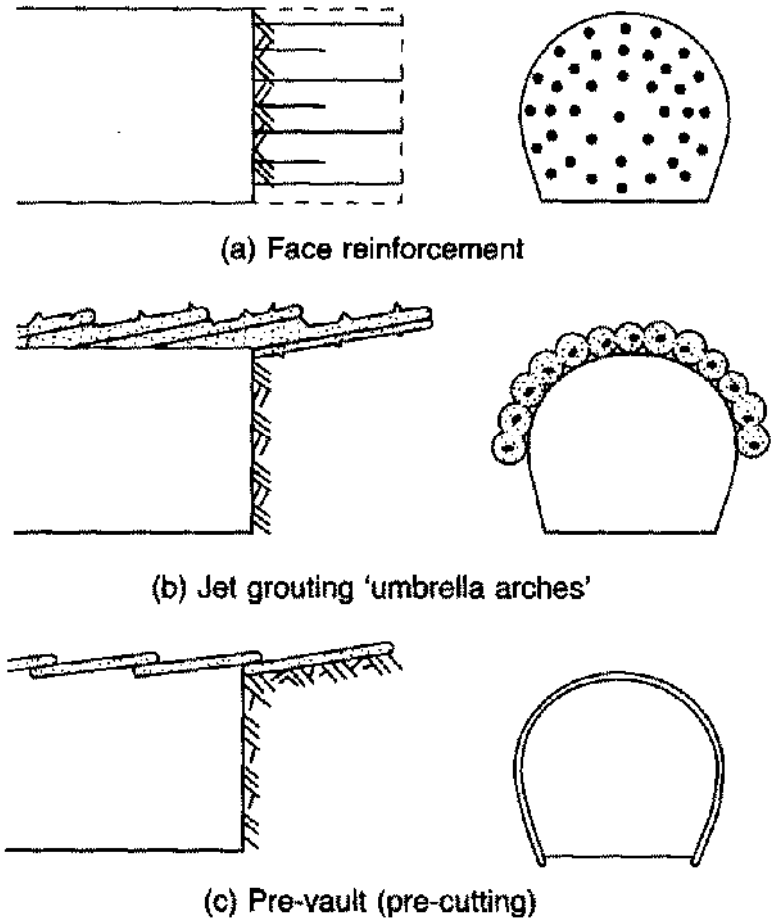
Burland (1998)

Tunnelling methods

- Open-face tunnelling

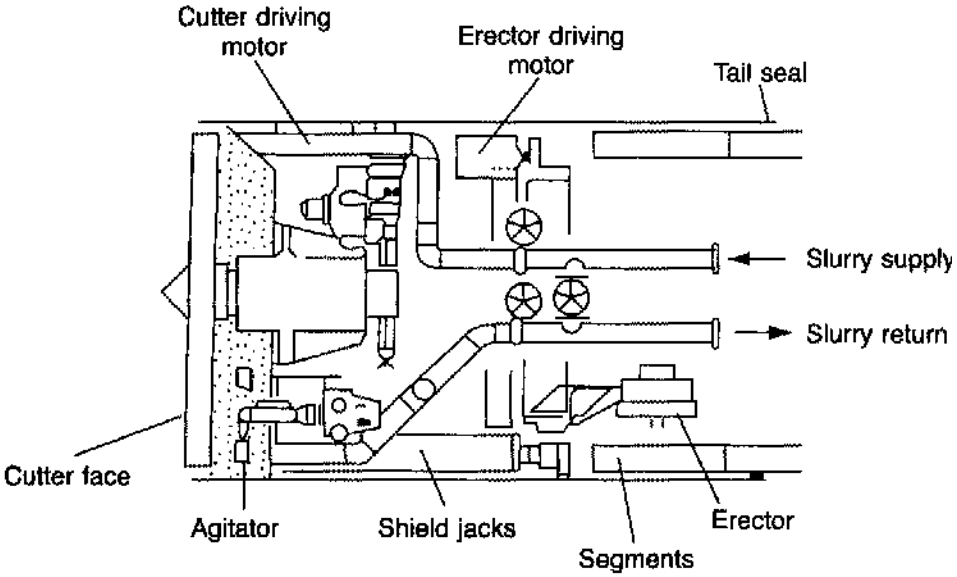


NATM or SCL

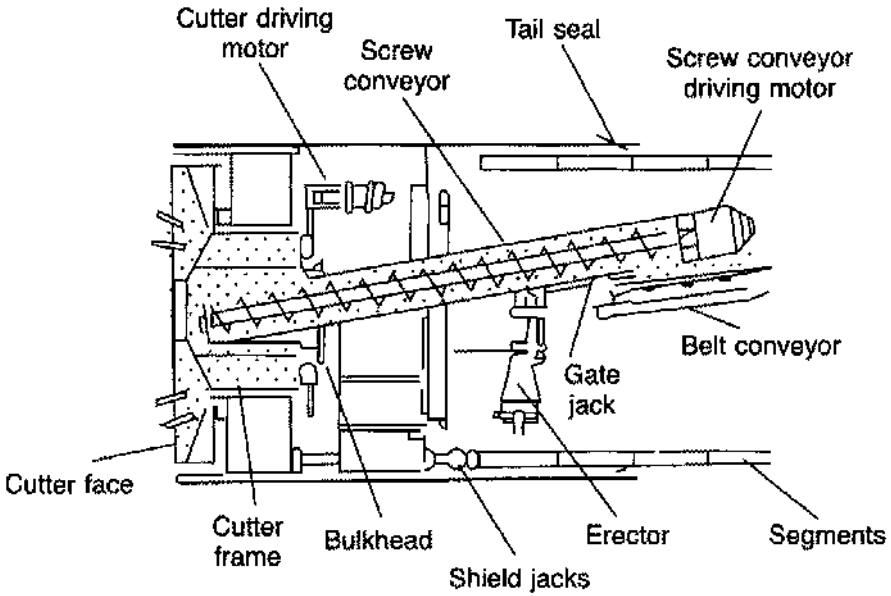


Tunnelling methods

- Closed-face tunnelling



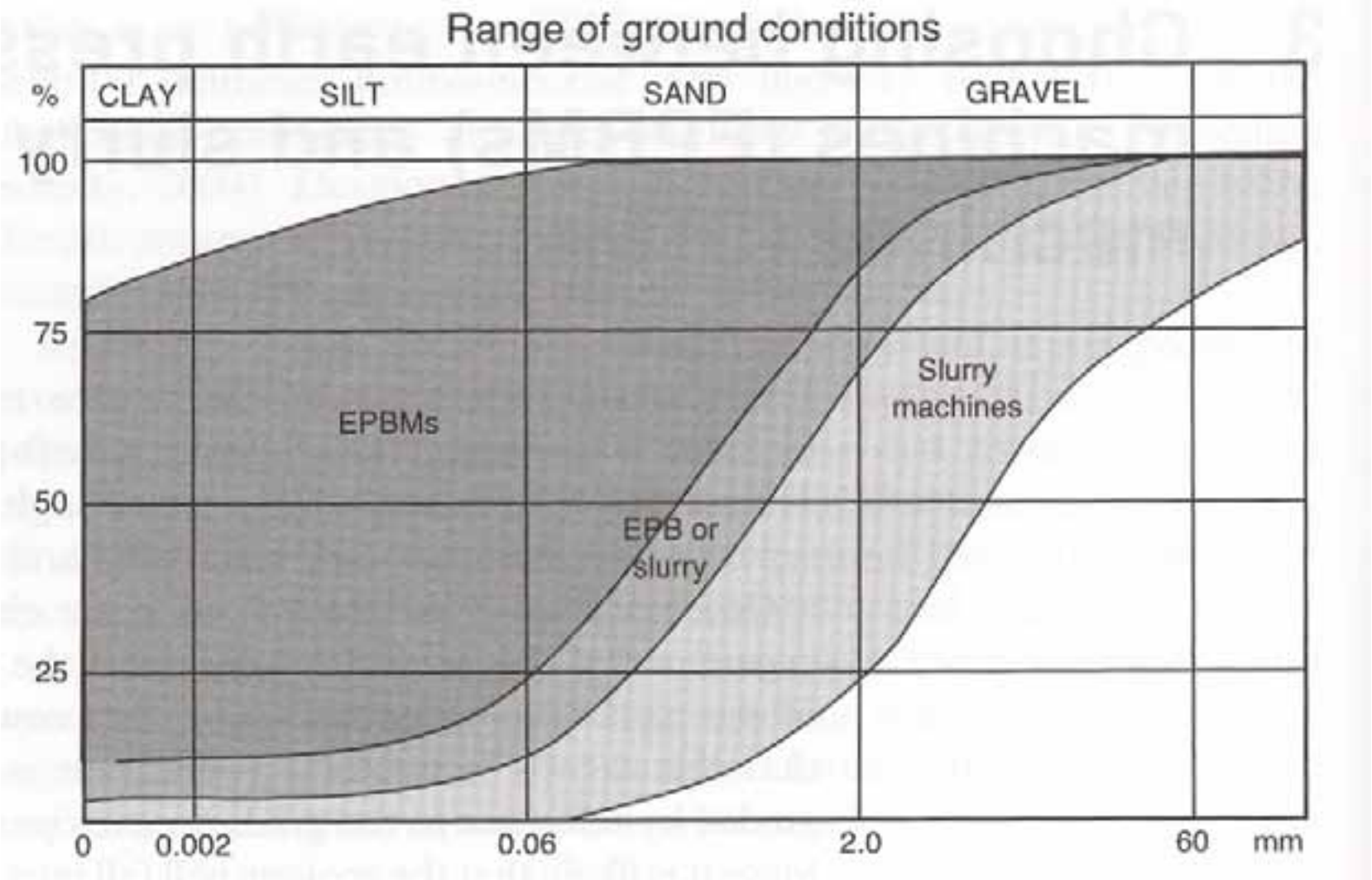
Slurry shield (SS)



Earth pressure balance (EPB)

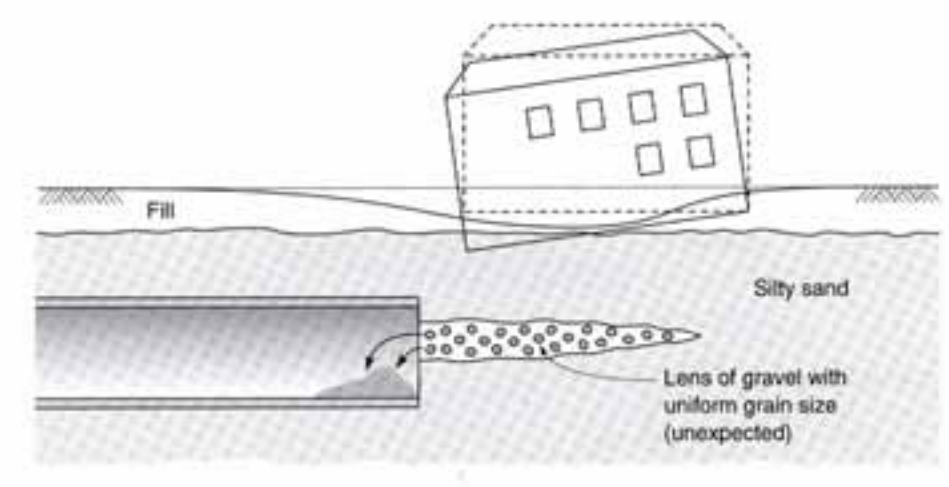
Tunnelling methods

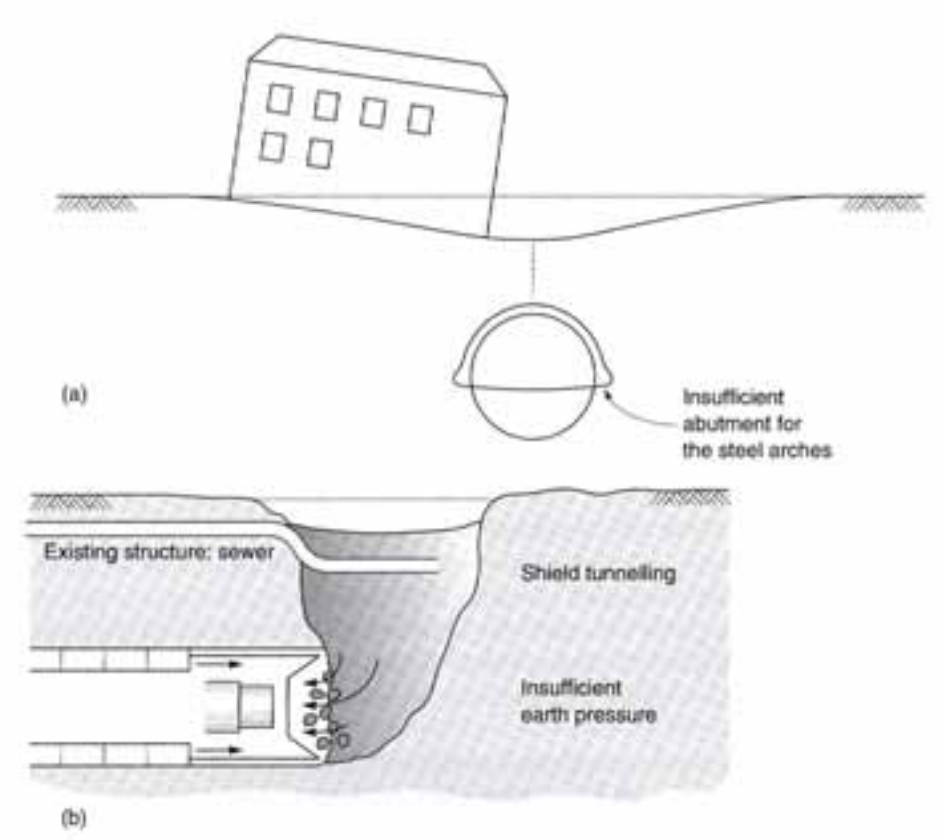
- Selection of closed-face tunnelling method



Tunnelling methods

- Movements caused by tunnel instability





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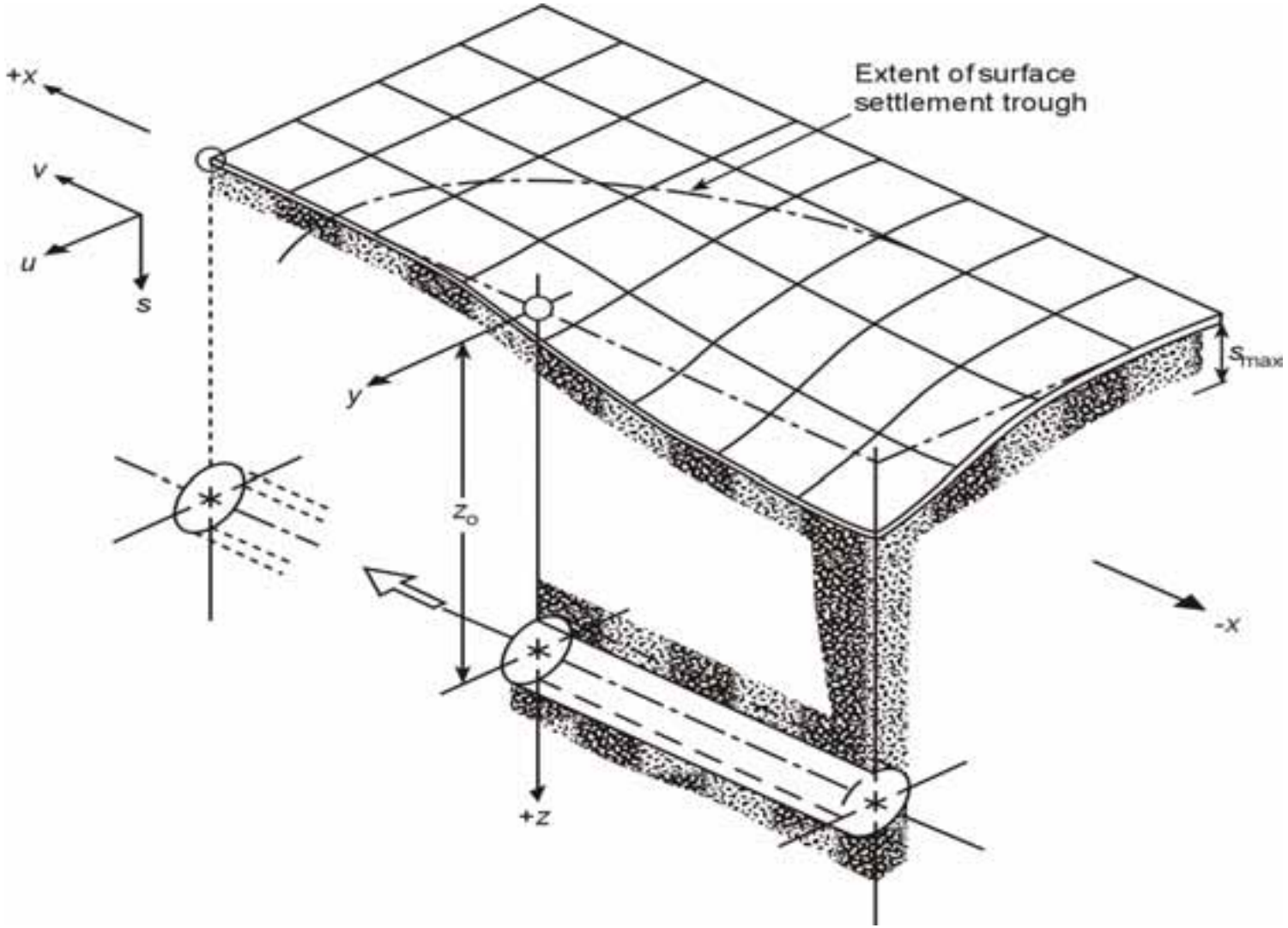
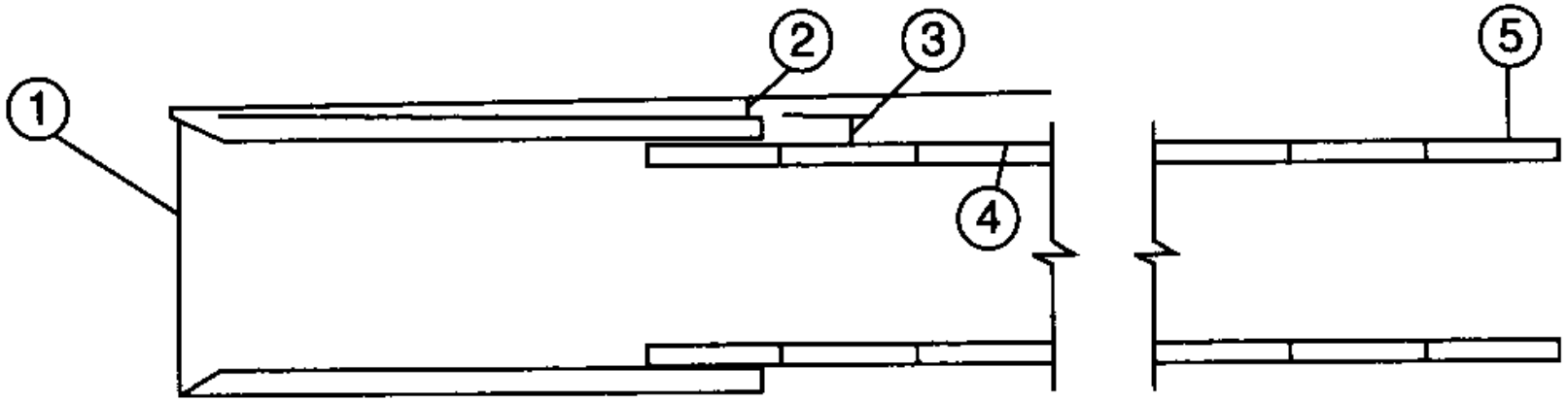
Ground movements caused by tunnelling

- Settlement trough



Ground movements caused by tunnelling

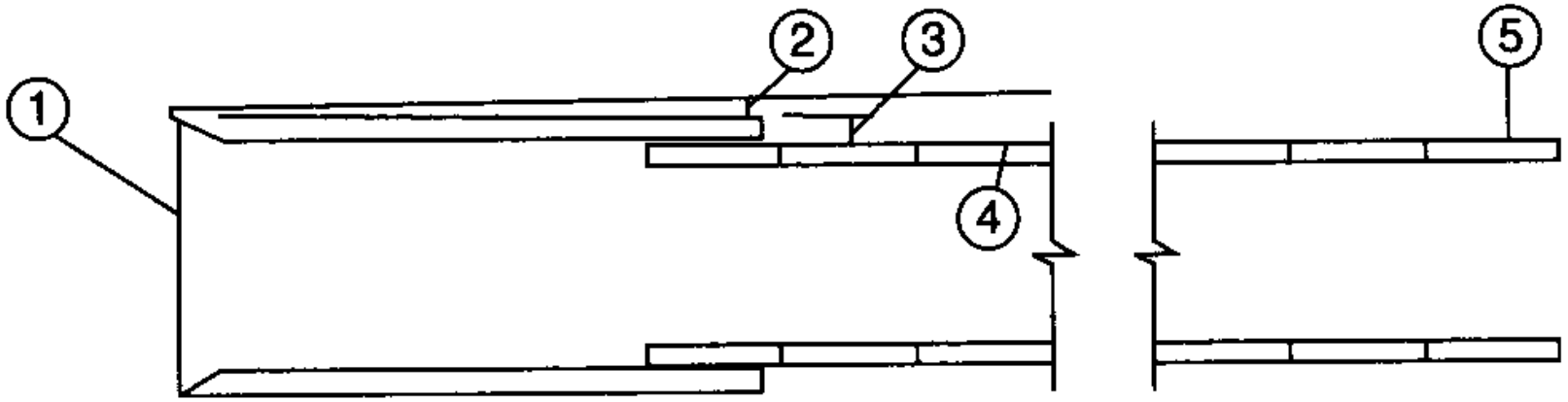
- Ground movements generated by (closed-faced) tunnelling



- Components of ground movement
  - Deformation of the ground towards the face resulting from stress relief
  - Passage of the shield, effect of overcutting edge (plus machine plough or yaw)
  - Tail void, ground filling the gap around the lining
  - Deflection of the lining as ground loading develops
  - Consolidation movements (pore pressure dissipation + drainage)

Ground movements caused by tunnelling

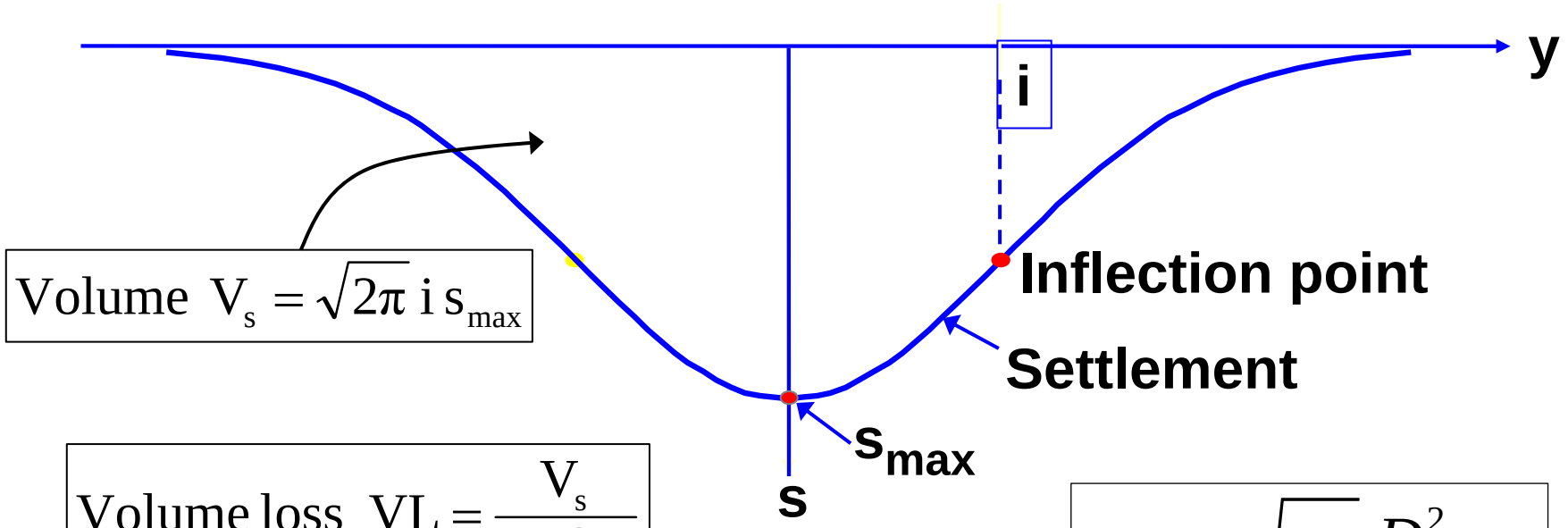
- Ground movements generated by (open-faced) tunnelling



- Components of ground movement
  - Deformation of the ground towards the face resulting from stress relief
  - Passage of the shield, effect of overcutting edge (plus machine plough or yaw)
  - Tail void, ground filling the gap around the lining
  - Deflection of the lining as ground loading develops
  - Consolidation movements (pore pressure dissipation + drainage)

Ground movements caused by tunnelling

- Settlement trough: volume loss

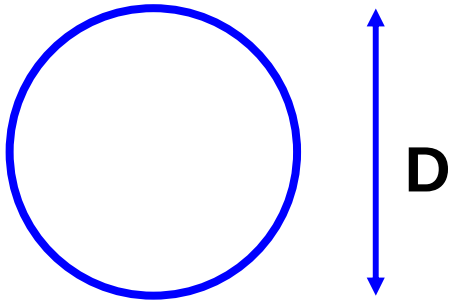


$$\text{Volume } V_s = \sqrt{2\pi}\, i\, s_{max}$$

$$\text{Volume loss } VL = \frac{V_s}{\pi D^2/4}$$

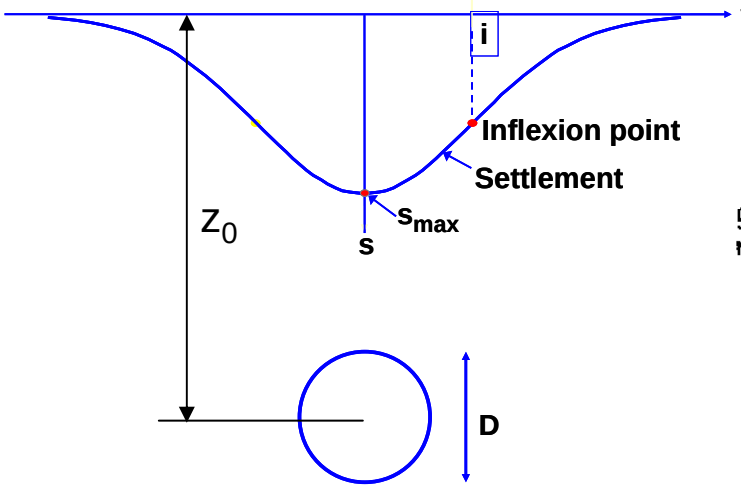
$$s_{max} = \sqrt{\frac{\pi}{32}}\frac{D^2}{i}VL$$

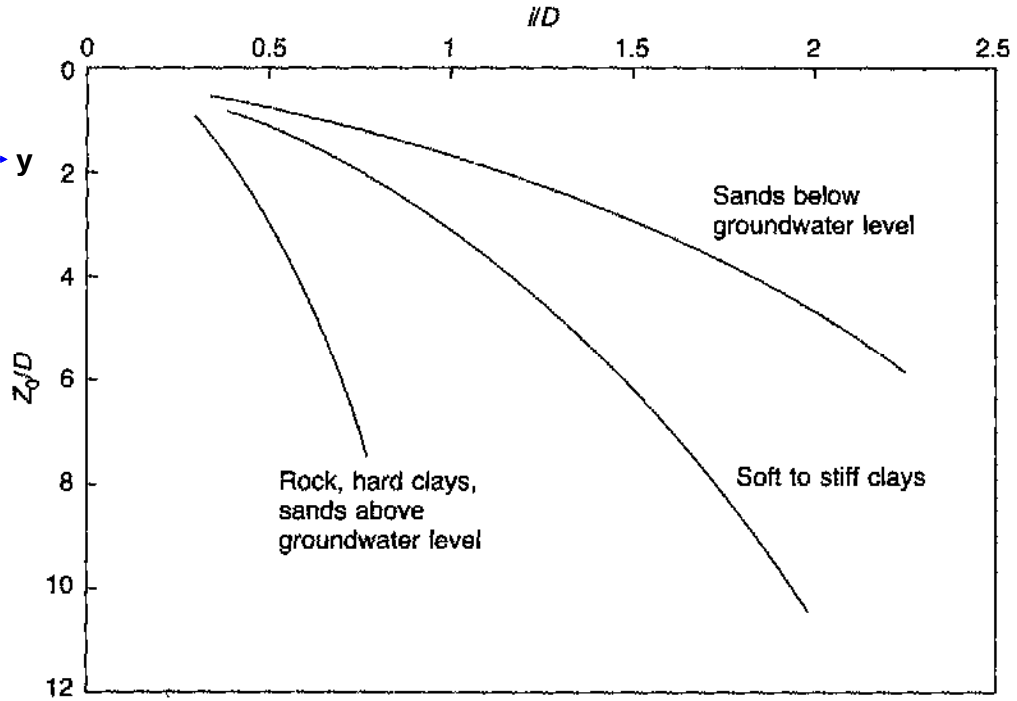
$$s = s_{max}\exp\left[\frac{-y^2}{2i^2}\right]$$



Ground movements caused by tunnelling

- Settlement trough width



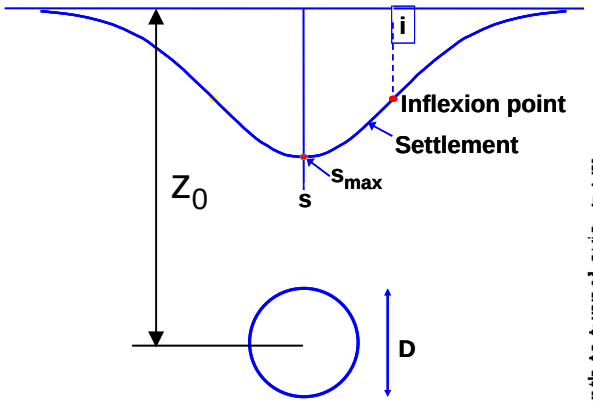


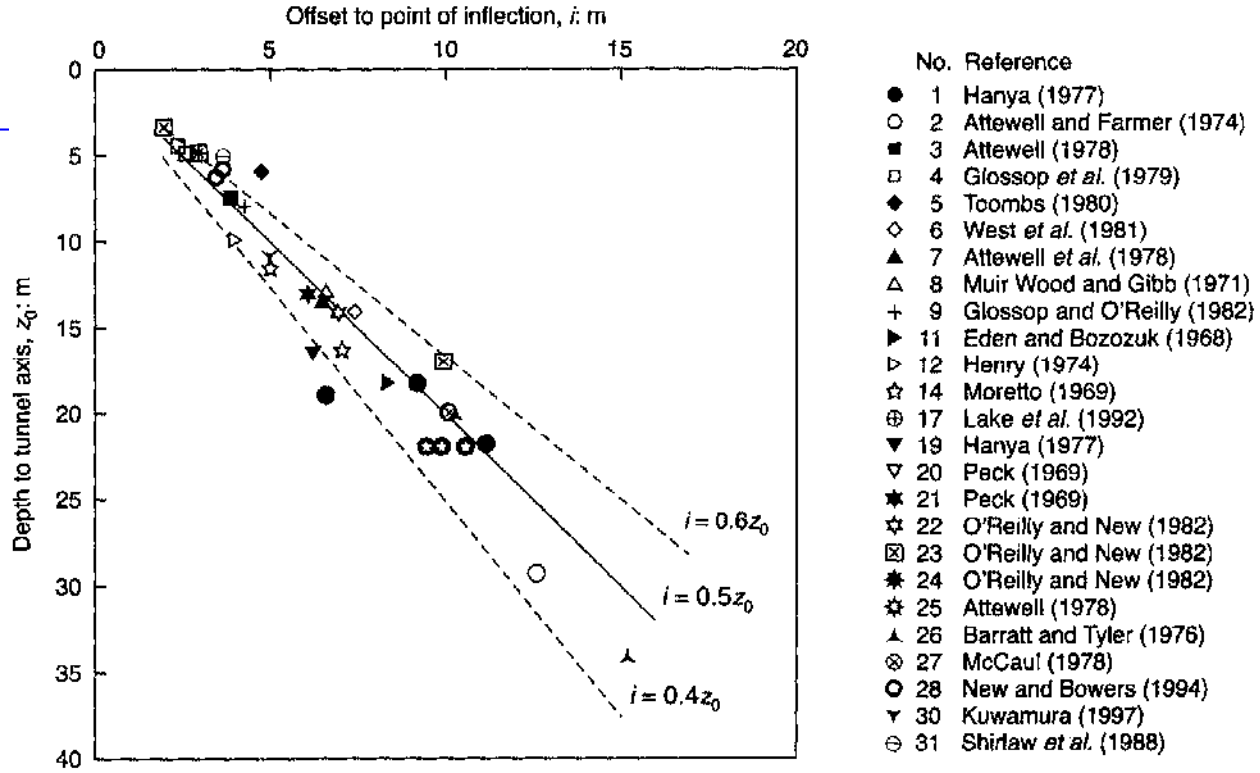
Peck (1969)

Ground movements caused by tunnelling

- Settlement trough width: clays

$$i = Kz_o$$





- K = = 0.5 in clays

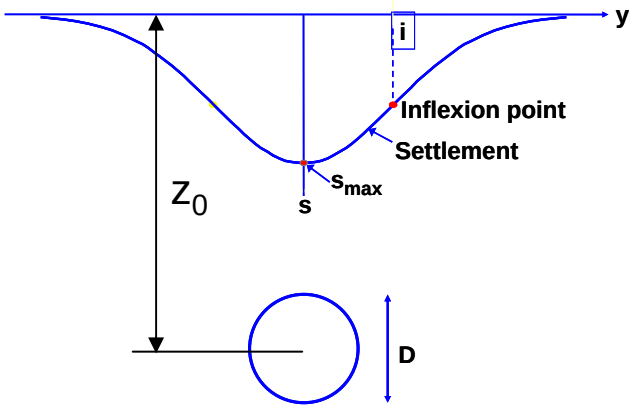
  O'Reilly & New (1982)

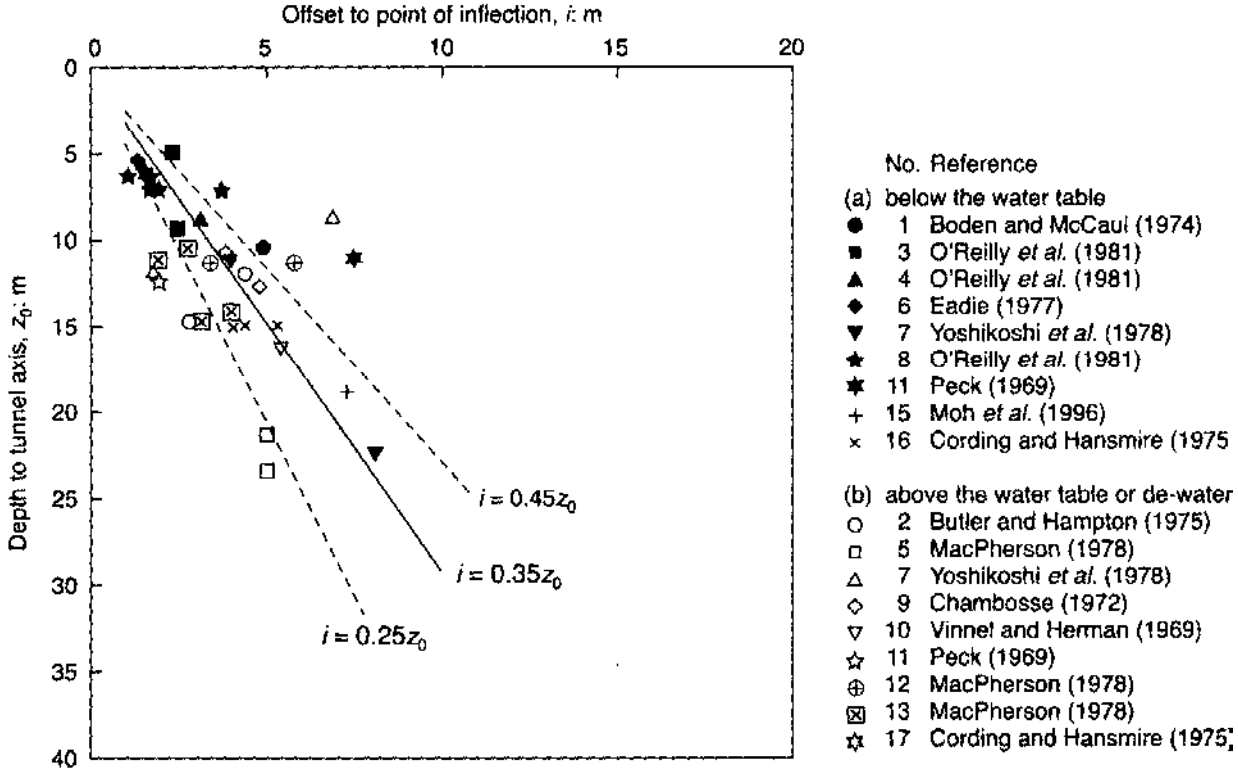
Mair & Taylor (1997)

Ground movements caused by tunnelling

- Settlement trough width

$$i = Kz_o$$





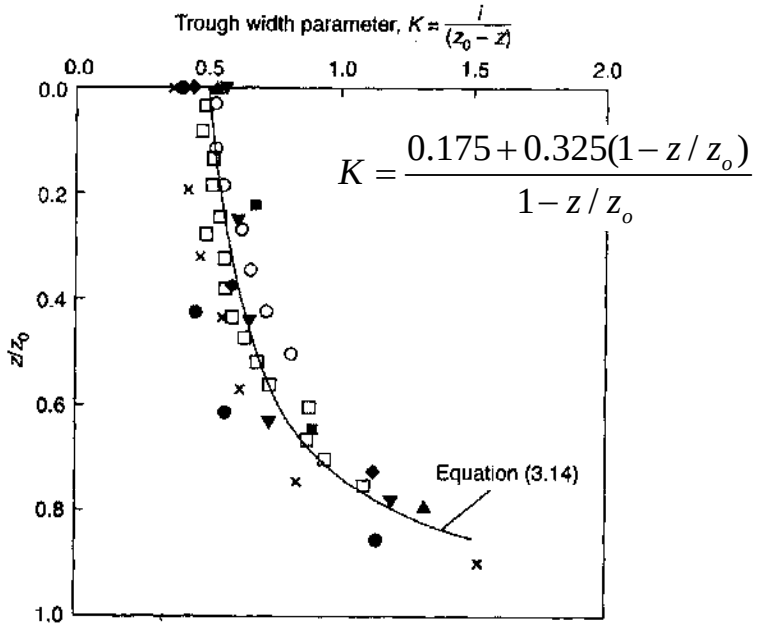
- K = 0.25 in sands

  O'Reilly & New (1982)

Mair & Taylor (1987)

Ground movements caused by tunnelling

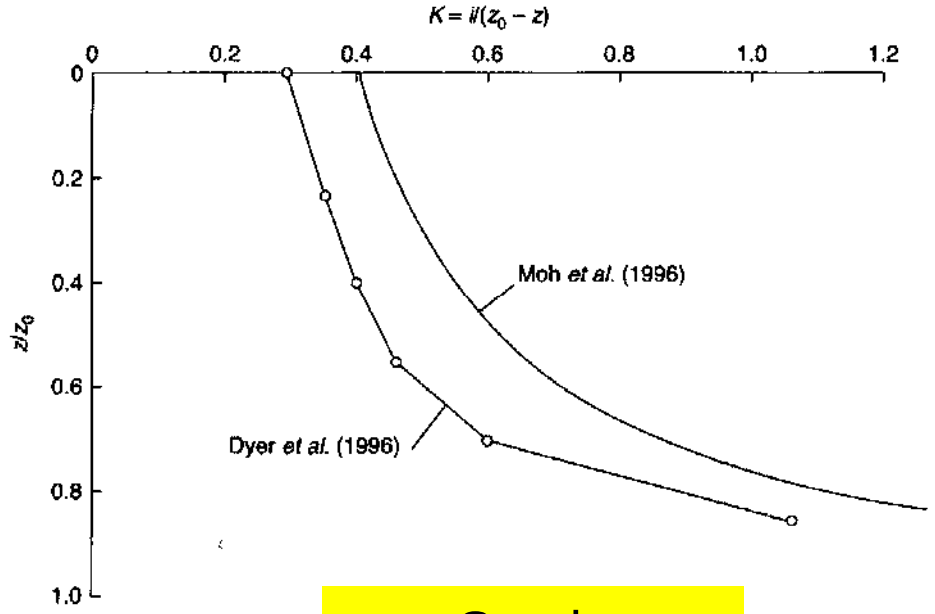
- Subsurface movements



Location	Soil type	D: m	z_0: m	Reference
● Green Park	London Clay	4.2	29	Attewell and Farmer (1974)
▲ Regents Park (northbound)	London Clay	4.2	20	Barrat and Tyler (1976)
▼ Regents Park (southbound)	London Clay	4.2	34	Barrat and Tyler (1976)
■ Willington Quay	Soft clay	4.3	13.5	Glossop (1978)
◆ Heathrow Express	London Clay	11.3	22	New and Bowers (1994)
× St. James's Park (westbound)	London Clay	4.85	31	Nyren (1998)
○ Centrifuge* model 2DP	Soft clay	0.06	0.13	Mair (1979)
□ Centrifuge* model 2DV	Soft clay	0.06	0.22	Mair (1979)

*Models tested at 75 g: equivalent full-scale D = 4.5 m, z_0 = 9.8 m (2DP), 16.5 m (2DV)

Clays

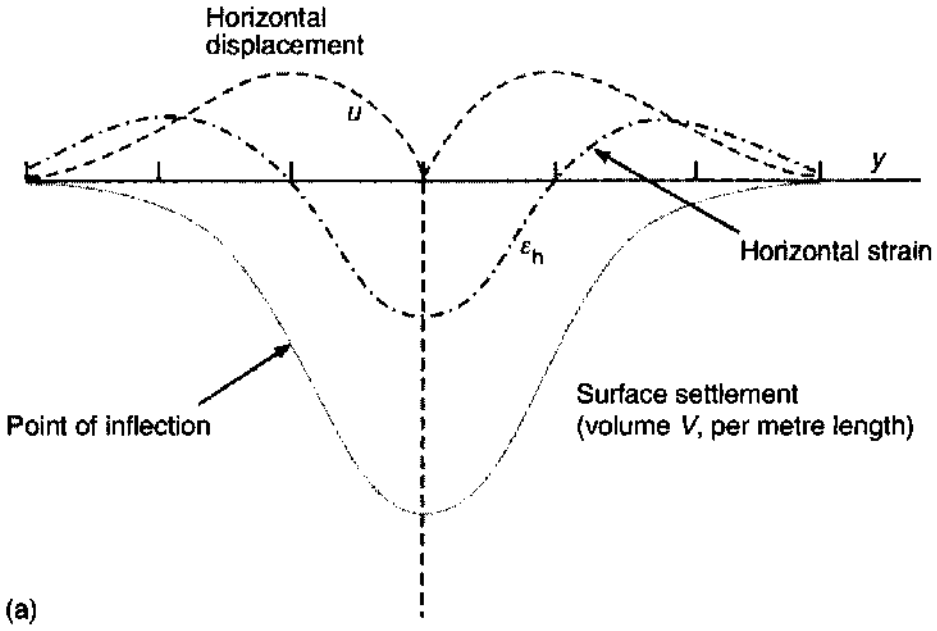


Sands

Mair et al. (1993)

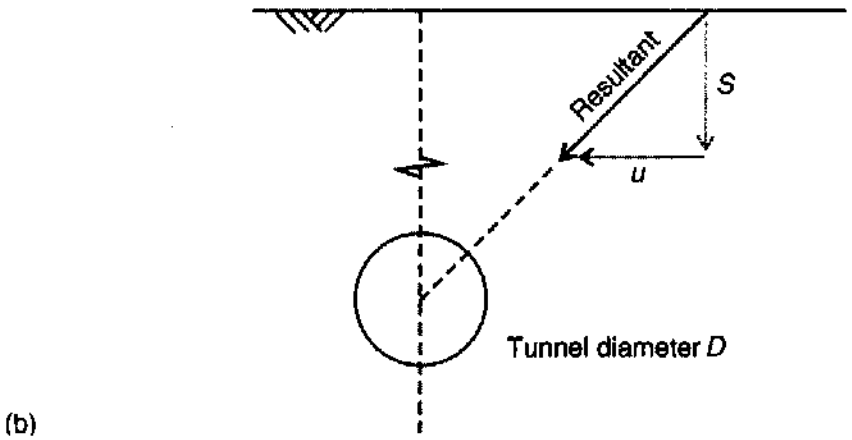
Ground movements caused by tunnelling

- Horizontal movements



$$s_h = \frac{y}{z_0} s_v$$

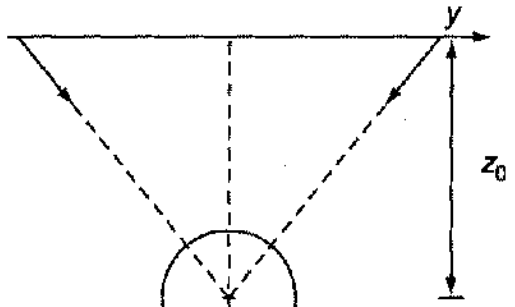
$$\frac{s_h}{s_{hmax}} = 1.65 \frac{y}{i} \exp\left(\frac{-y^2}{2i^2}\right)$$



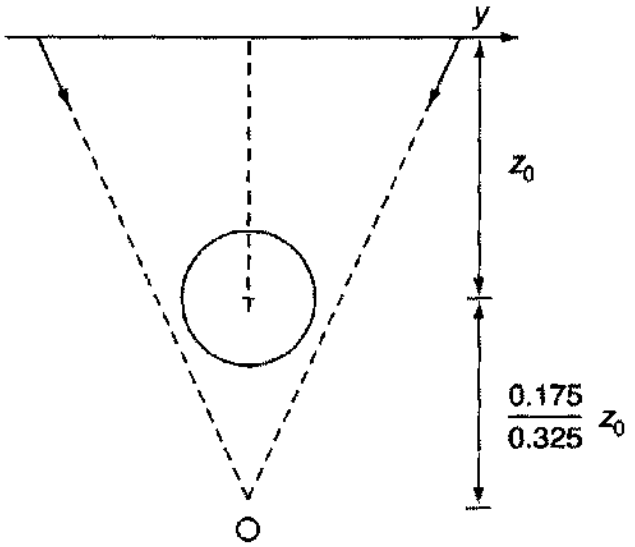
Attewell (1978)
O'Reilly & New (1982)

Ground movements caused by tunnelling

- Horizontal movements



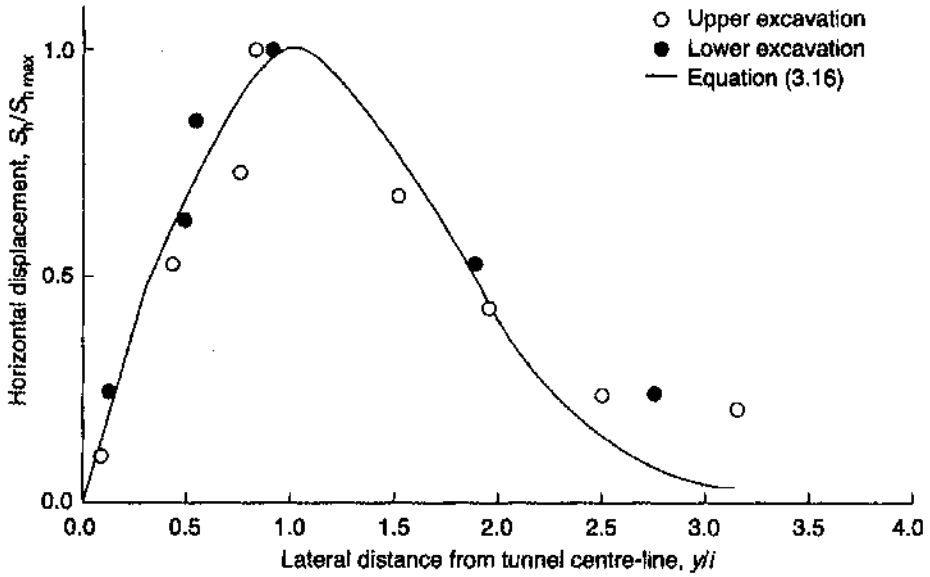
(a) Vectors directed towards axis
(Attewell, 1978; O'Reilly and New, 1982)



(b) Vectors directed towards point O
(Taylor, 1995)

Ground movements caused by tunnelling

- Horizontal movements



NATM in sands

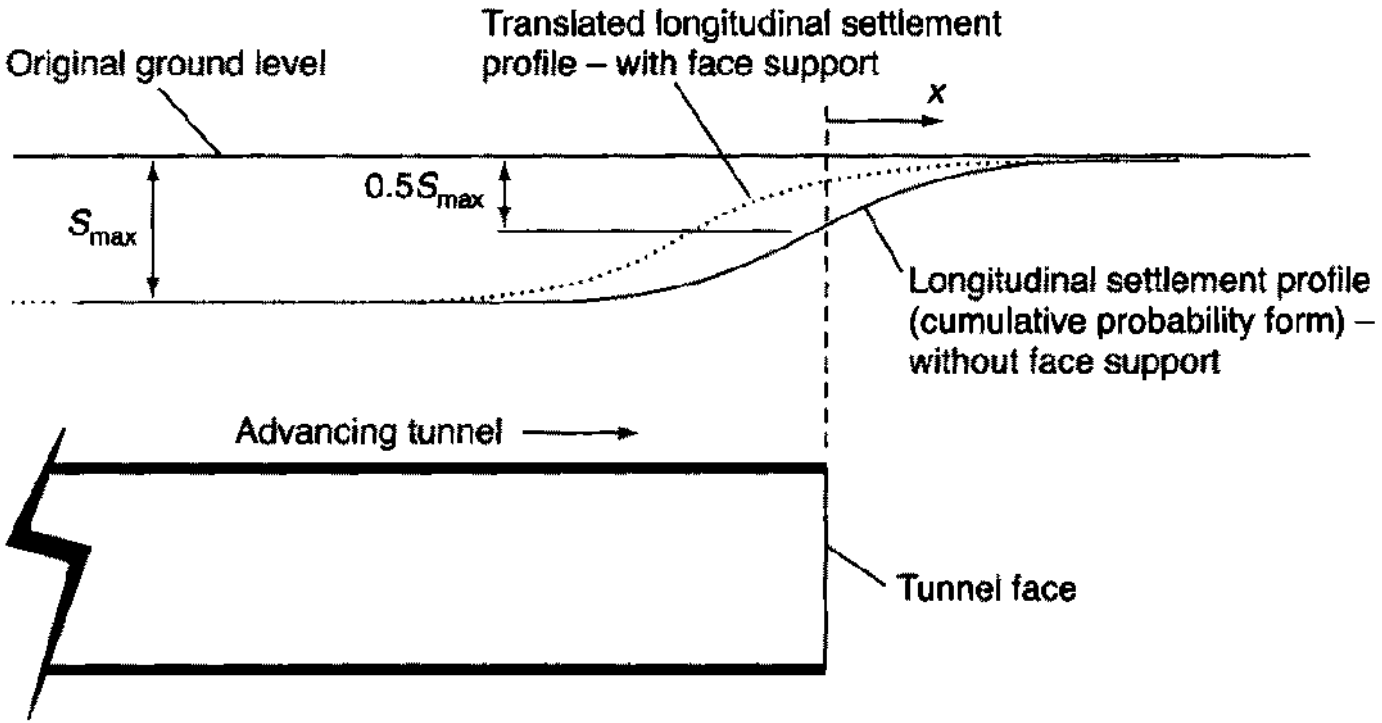
Hong & Bae (1995)

Ground movements caused by tunnelling

- Development of ground movements
  - Attewell & Woodman (1982) suggested using the cumulative probability curve

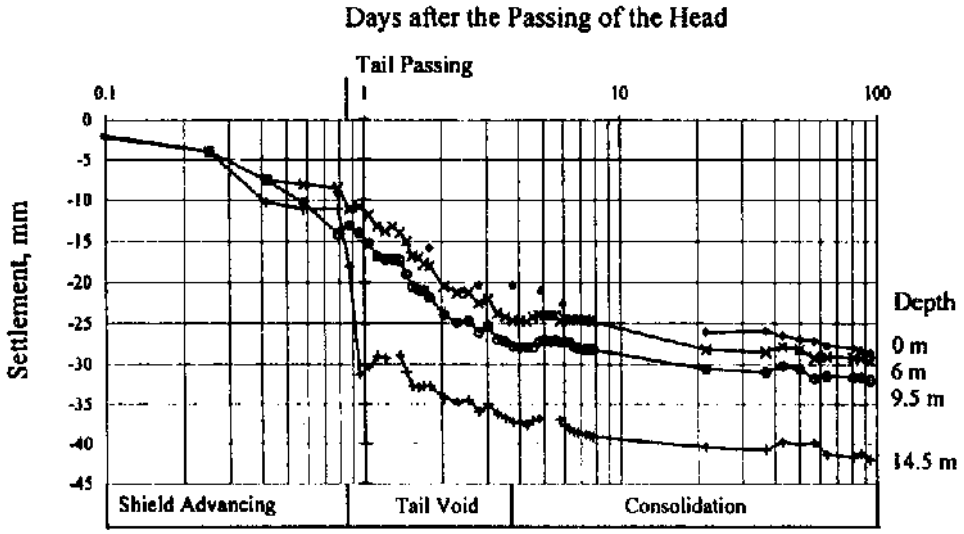
$$G(\alpha) = \frac{1}{\sqrt{2\pi}} \int_{-\alpha}^{\alpha} \exp(-\beta^2 / 2) d\beta$$

$$G(\alpha) = 1 - G(-\alpha)$$



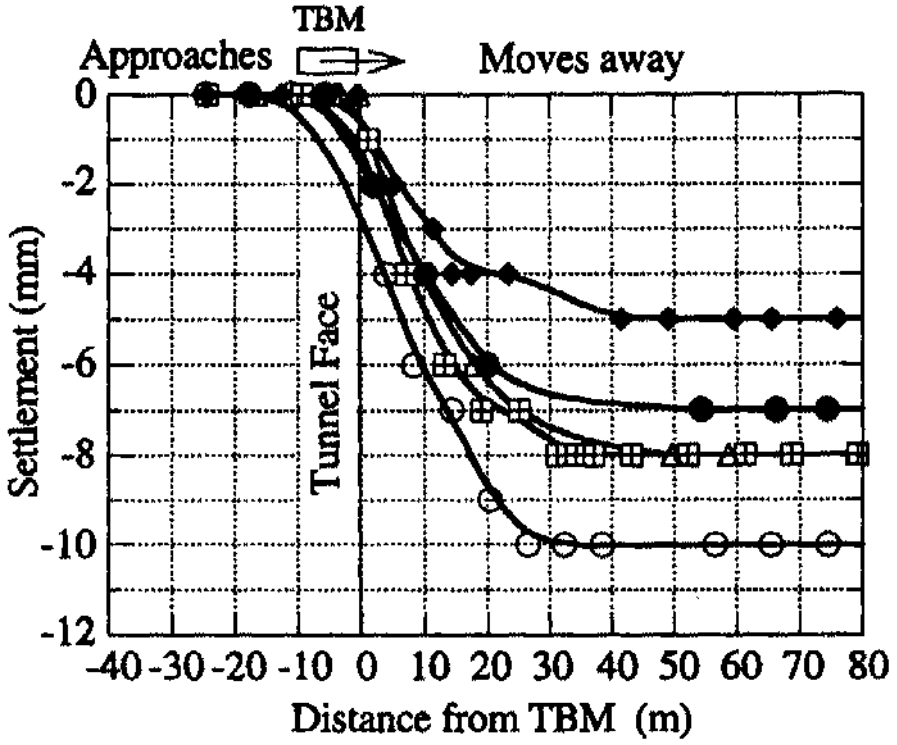
Ground movements caused by tunnelling

- Development of ground movements



EPB tunnelling in silty sands in Taipei

Moh et al. (1996)



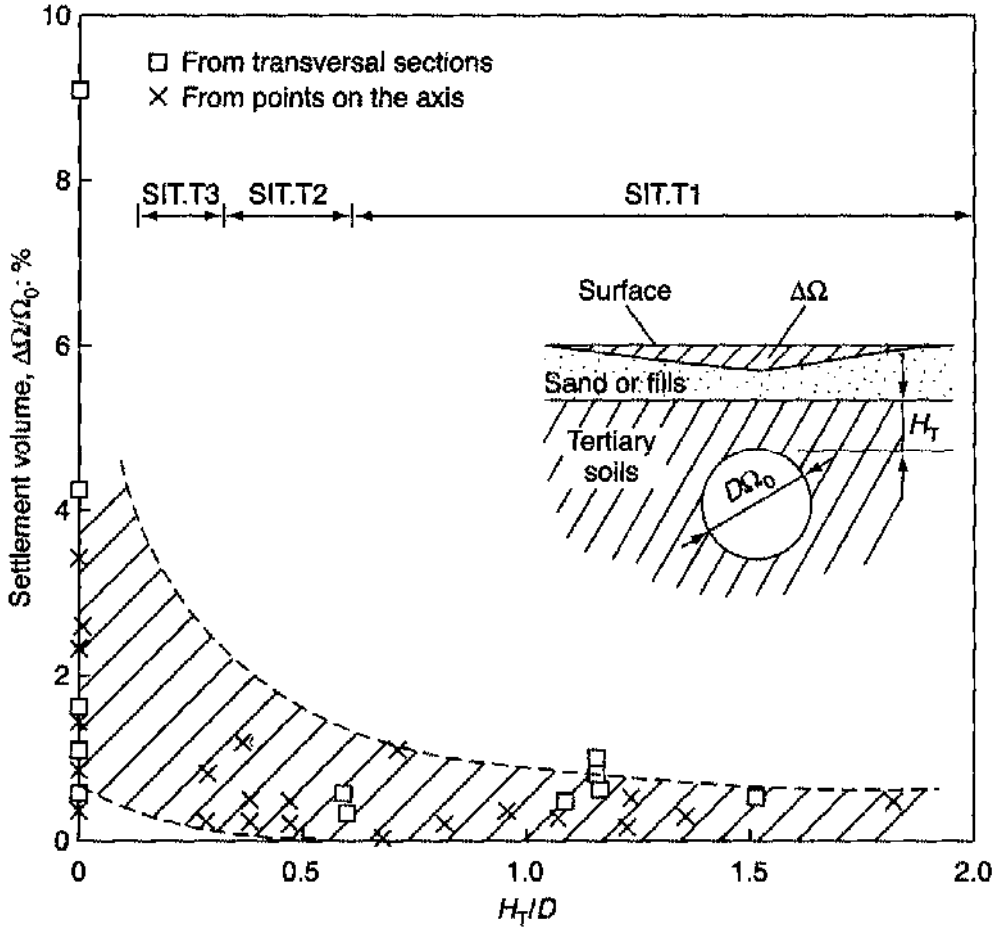
EPB tunnelling in sands in Cairo

Ata (1996)

Ground movements caused by tunnelling

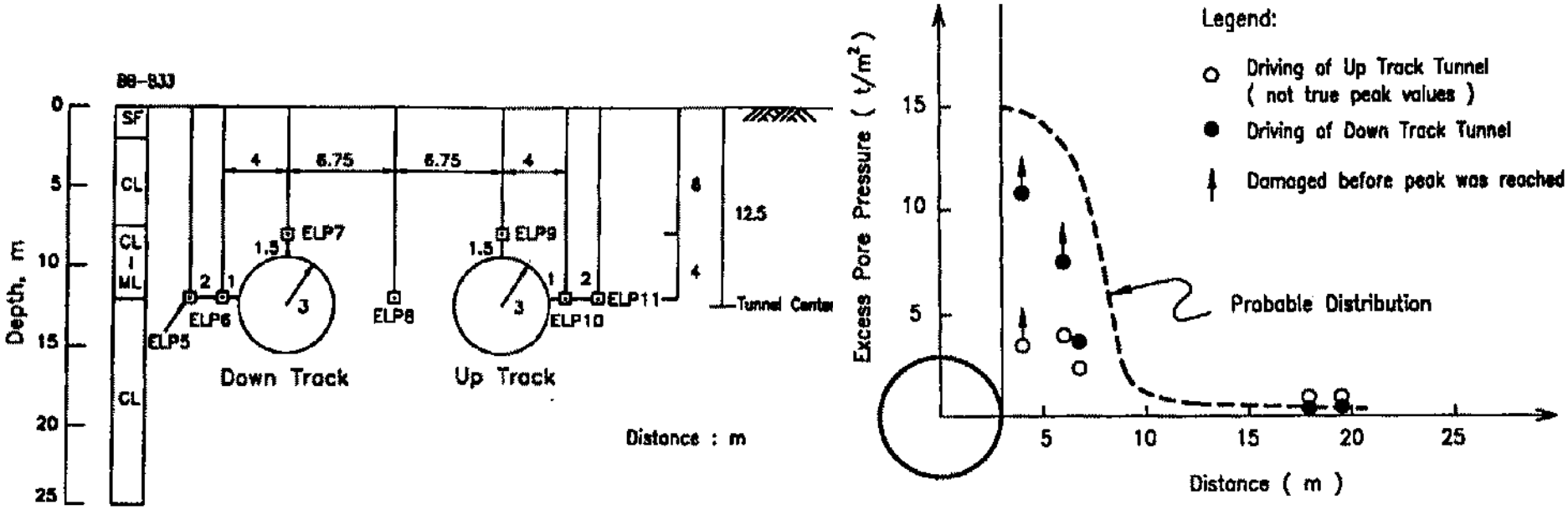
- Typical ground losses:
  - Open faced tunnelling: 1% - 2% in stiff clay (London clay). NATM in London clay: 0.5%-1.5%
  - Closed-face tunnelling around 0.5%. In soft clays 1% - 2%
  - Beware of mixed face situations or when granular/fill lies on top of the tunnel

Madrid Metro observations



Ground movements caused by tunnelling

- Consolidation movements
  - Generation of pore water pressures
    - Overpressurization of the face
    - High tail void grouting pressures

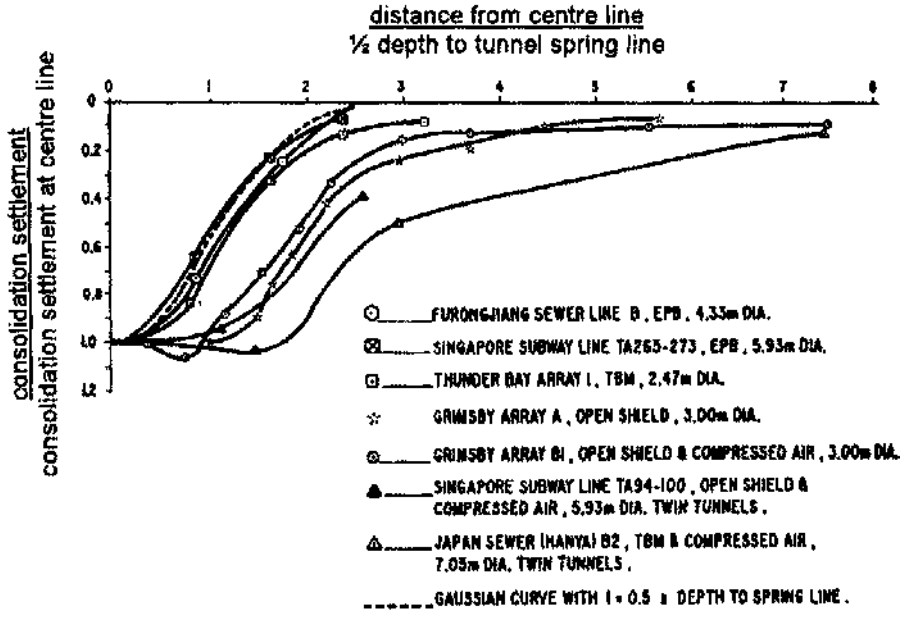


EPB tunnelling in soft silty clay in Taipei

Hwang et al. (1995)

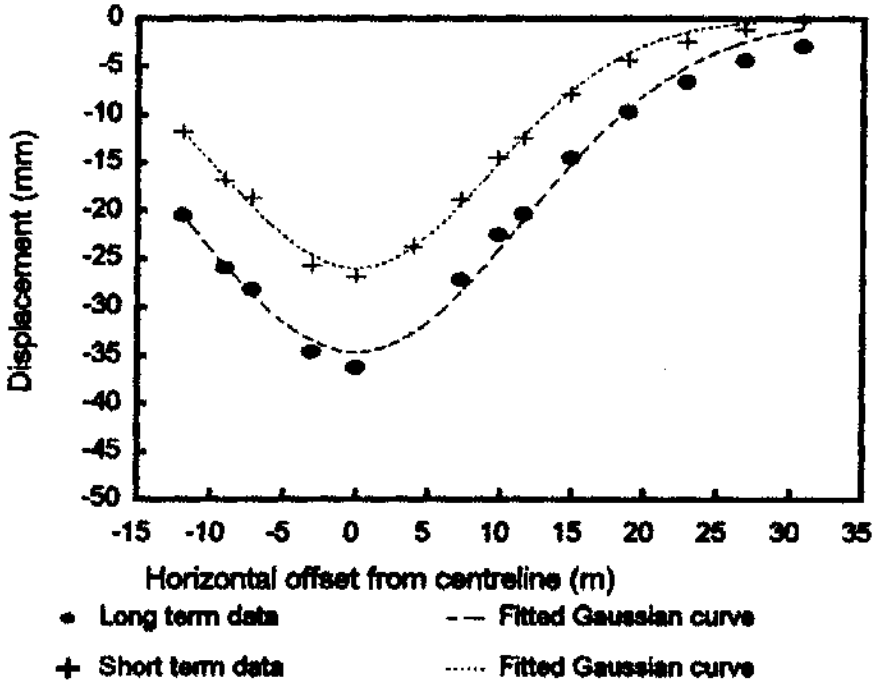
Ground movements caused by tunnelling

- Consolidation movements: two sources
  - Dissipation of pore water pressures generated: trough width similar to the short-term one
  - Tunnel lining acting as a drain: wide settlement trough



Long term settlement troughs for tunnels in soft clays

Shirlaw (1995)

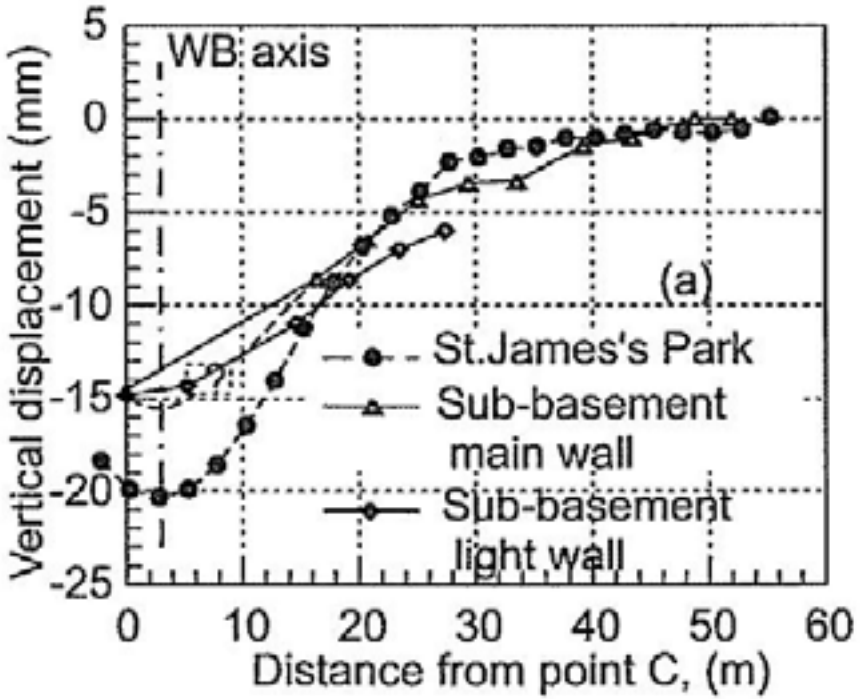


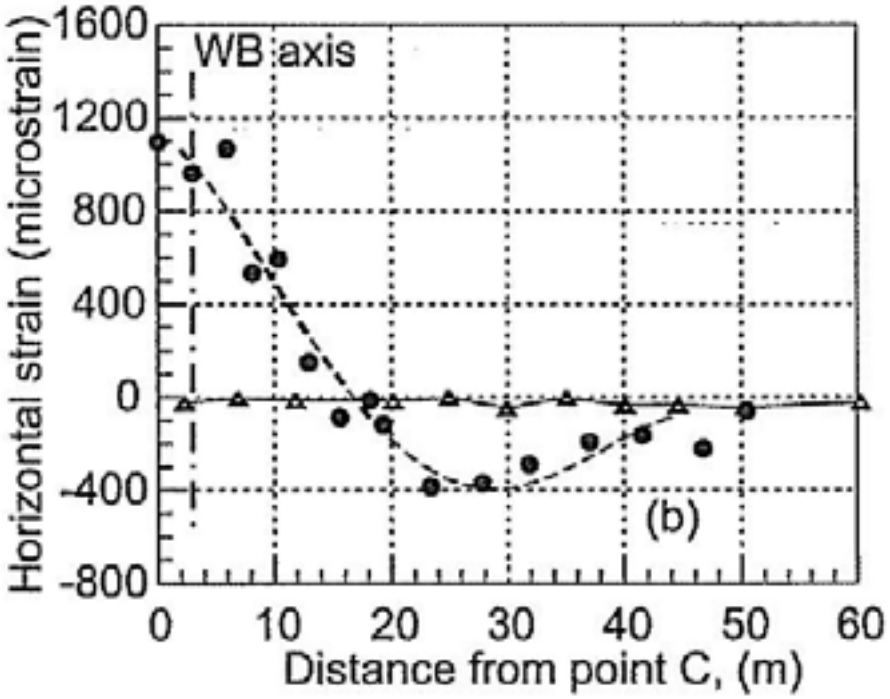
Immediate and post construction settlements in London clay

Bowers et al. (1996)

Ground movements caused by tunnelling

- Effect of the stiffness of the building
  - Treasury building and St. James greenfield site

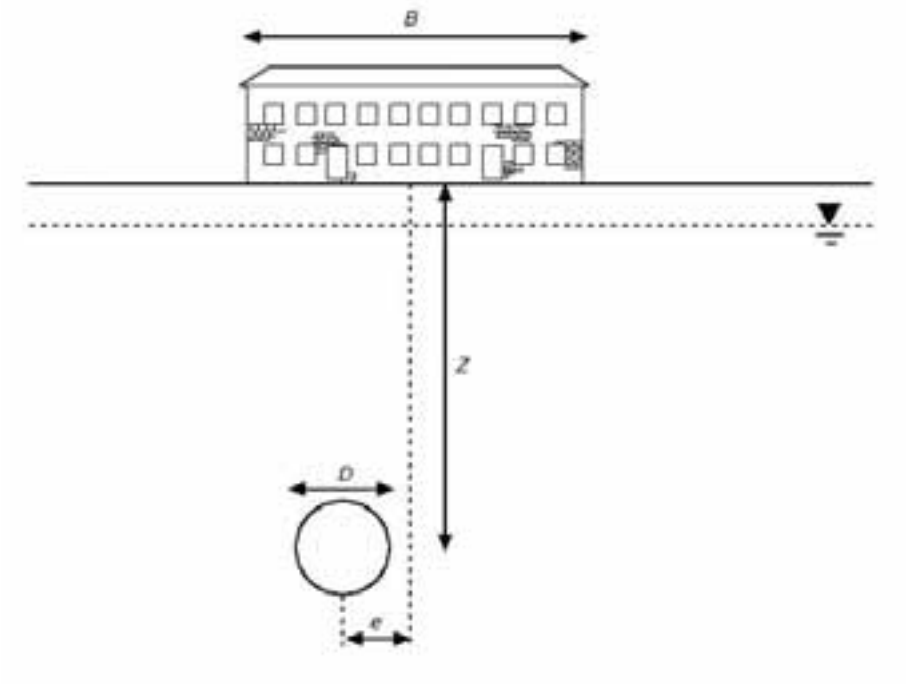


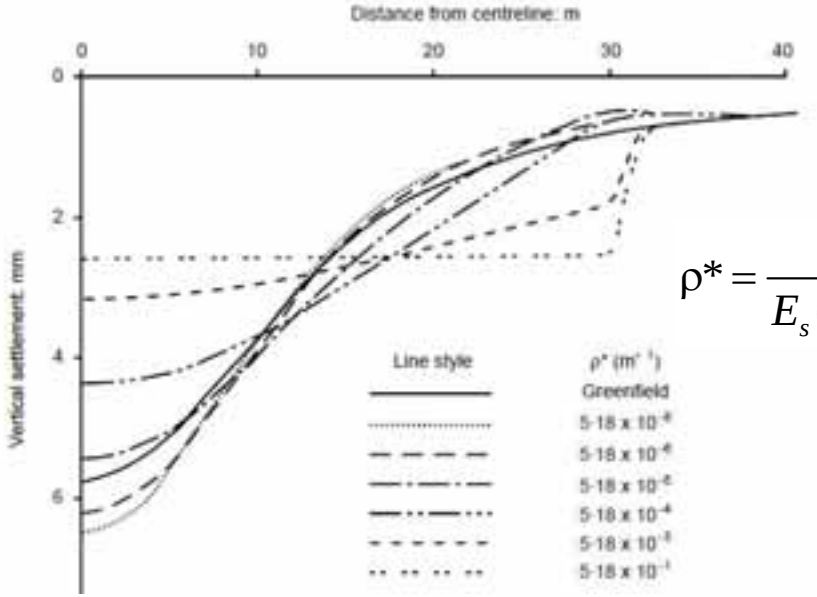


Viggiani and Standing (2001)

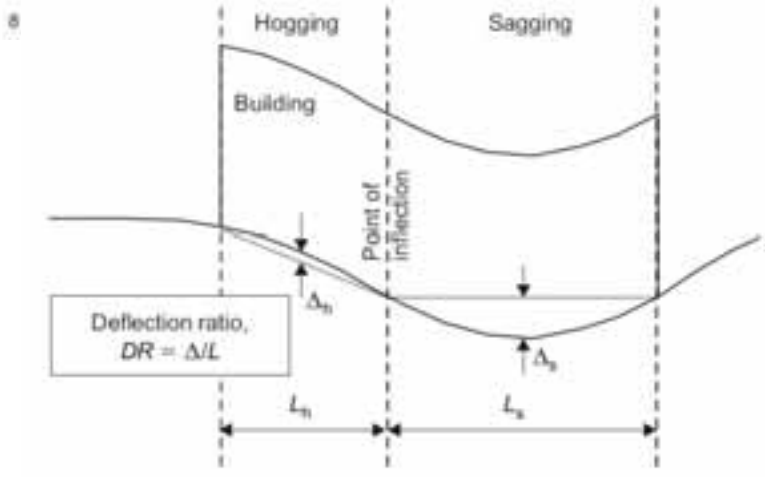
Ground movements caused by tunnelling

- Effect of the stiffness of the building
  - Based on (nonlinear) finite element analysis





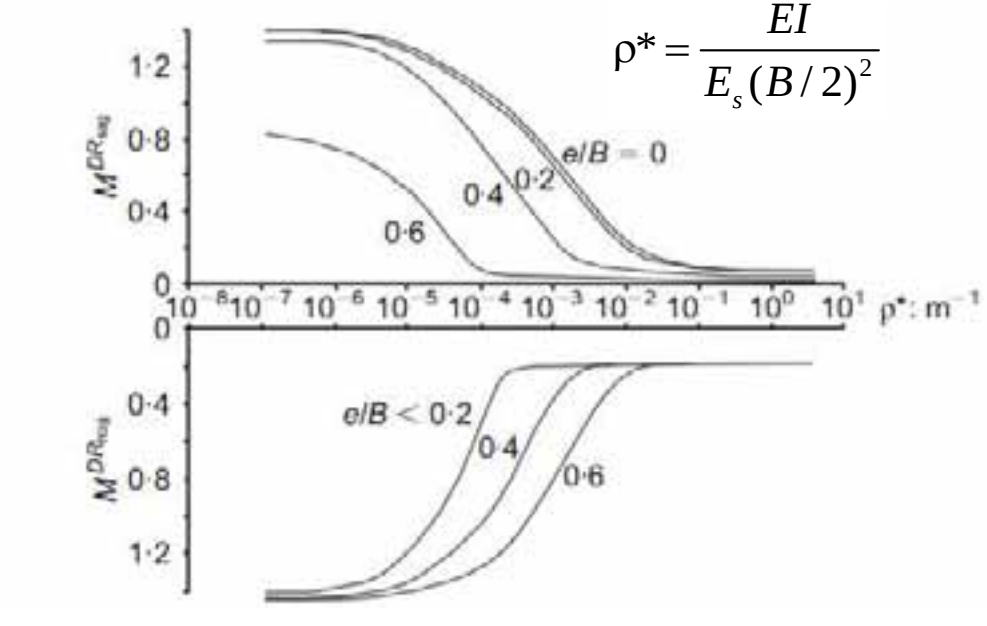
$$\rho^* = \frac{EI}{E_s (B/2)^2}$$



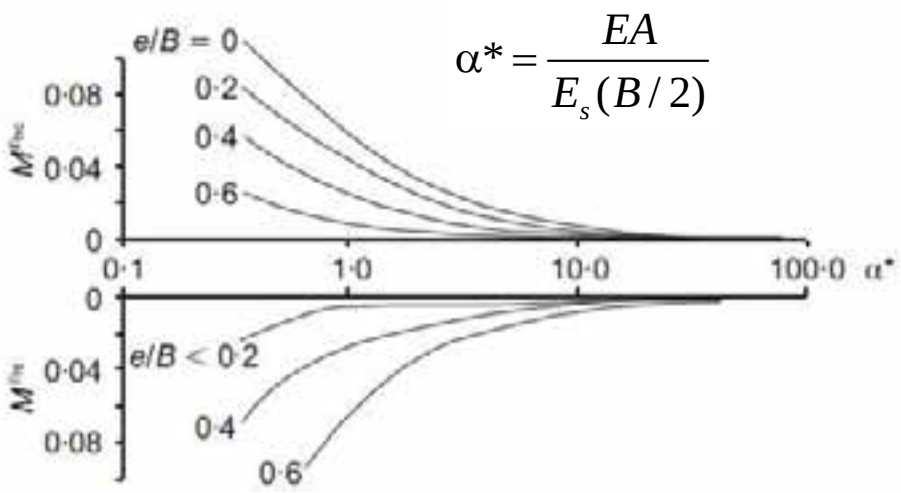
Addenbrooke and Potts (1997)

Ground movements caused by tunnelling

- Effect of the stiffness of the building
  - Based on (nonlinear) finite element analysis



Modification factors for deflection ratio

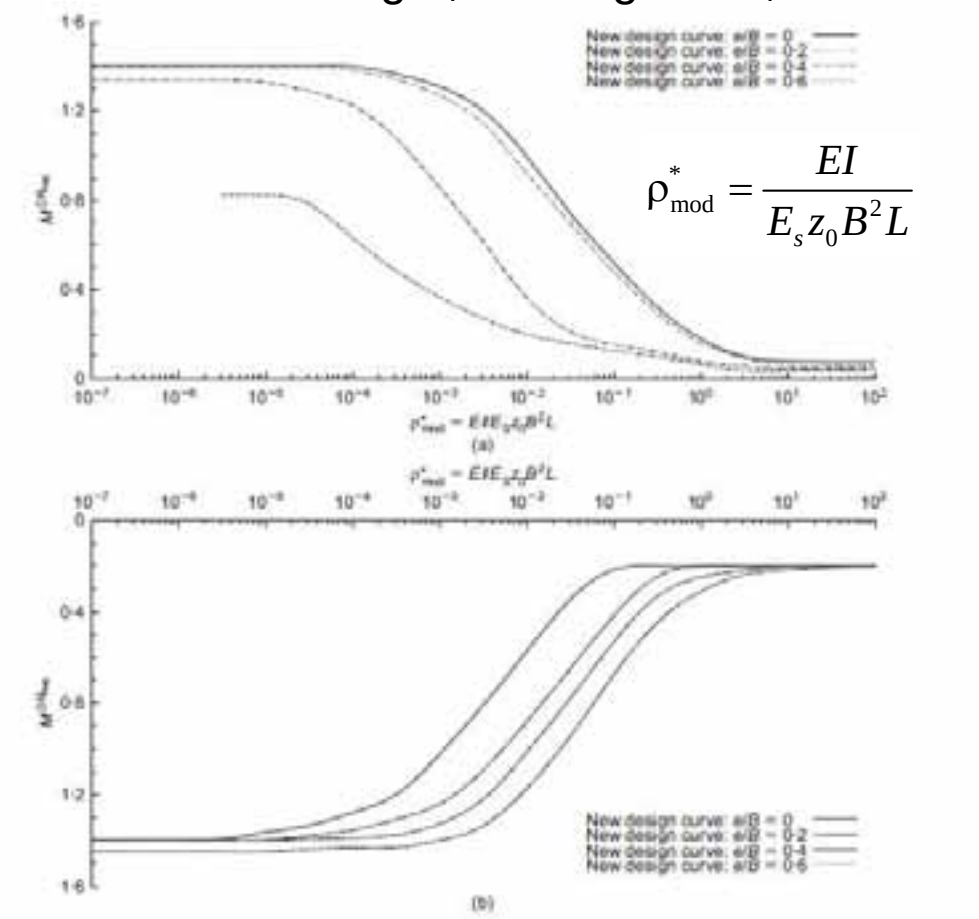


Modification factors for horizontal strain

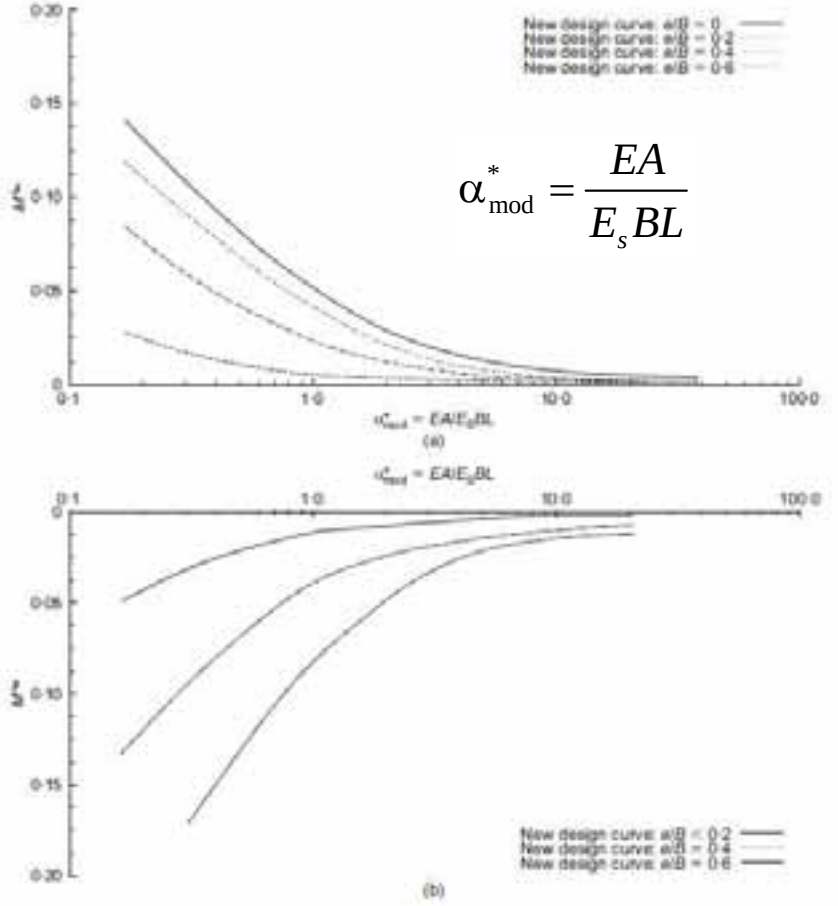
Addenbrooke and Potts (1997)

Ground movements caused by tunnelling

- Effect of the stiffness of the building
  - Based on more finite element analysis including 3-D analyses, building weight, building width, interfaces. (Franzius et al., 2006)



$$\rho^*_{mod} = \frac{EI}{E_s z_0 B^2 L}$$



$$\alpha^*_{mod} = \frac{EA}{E_s BL}$$

Modification factors for deflection ratio

Modification factors for horizontal strain

Ground movements caused by tunnelling

- Assessing the risk of building damage: The Jubilee line procedure (Burland et al., 2002)
  - Three stages of assessment:
    - Preliminary assessment: a simple and conservative approach, check settlement less than 10 mm and θ less the 1/500
    - Second stage assessment: make use of “greenfield” empirical predictions and damage criteria. The stiffness of the building may be taken into account but is it not often done
    - Detailed evaluation for those buildings classifies as being at risk of category 3 damage or greater. If confirmed, design remedial measures (MGT)
  - Jubilee line, accepted category damage: 2
  - There is a tendency to reduce the category of accepted damage
    - In Barcelona Metro and High speed train tunnelling, accepted damage category is 0!

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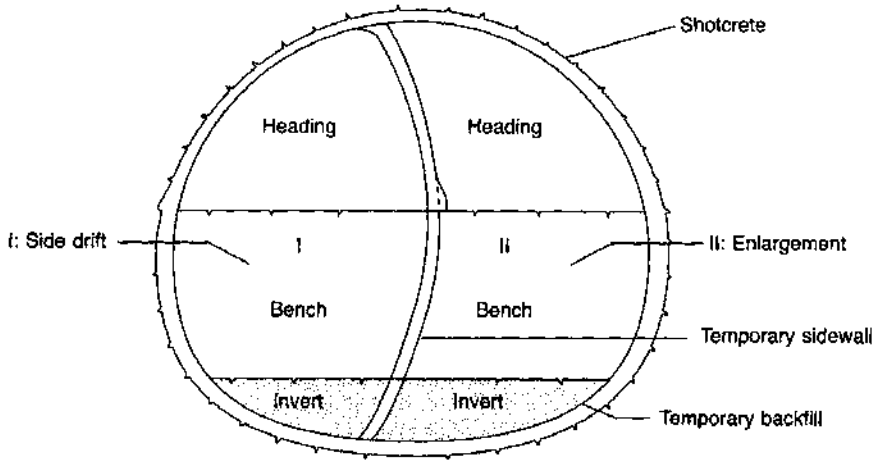
Procedures for ground movement control

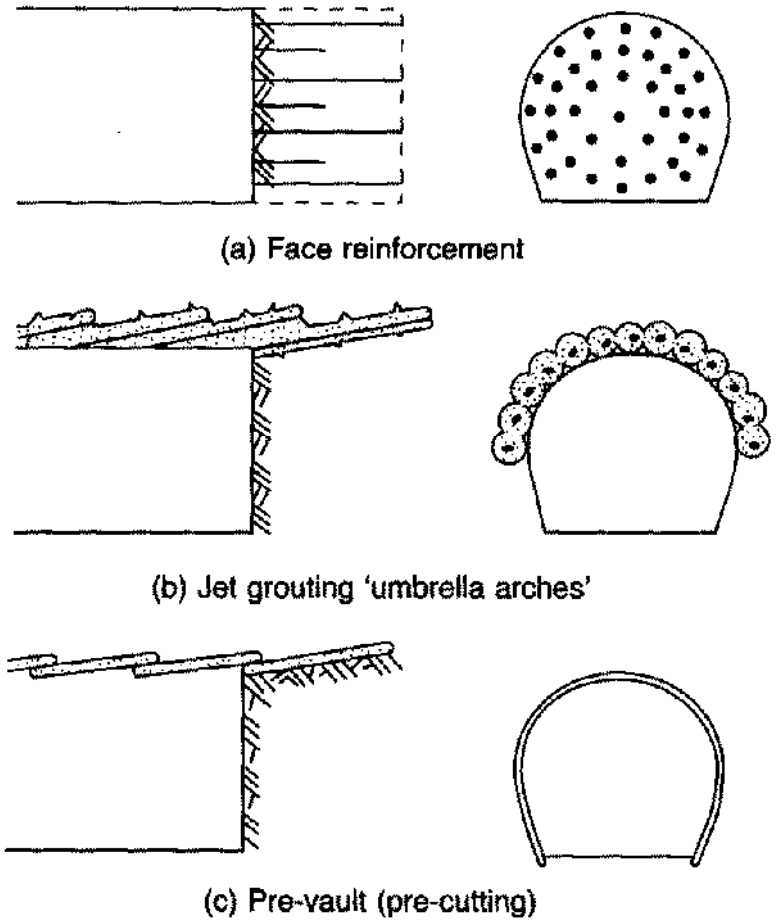
- In-tunnel measures
  - Tunnelling method / TBM design
  - Face support measures
  - Excavation in parts
  - Mechanical pre-cutting
  - Barrel (umbrella) vaulting
- Structural measures
  - Deep and shallow underpinning
  - Increase tensile capacity
  - Reducing sensitivity of the structure
  - Structure jacking
  - Barrel vaulting
- Ground treatment
  - Compensation grouting
  - Ground improvement: permeation grouting, jet grouting, compaction grouting, freezing
  - Inserting structural elements
    - screen or curtain walls
    - steel pipes
  - Drainage and control of ground water

(adapted from Harris, 2001)

Procedures for ground movement control

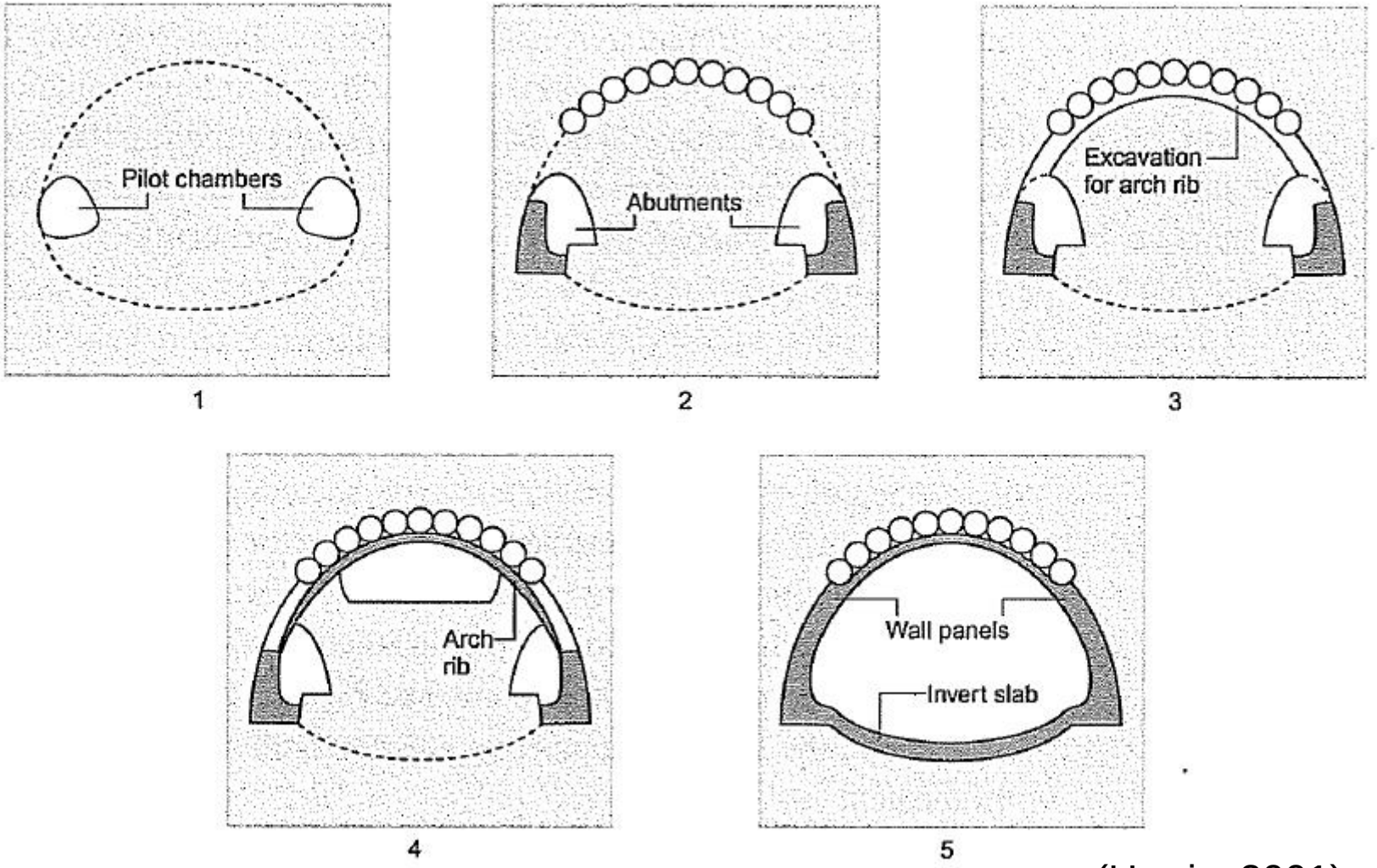
- In-tunnel measures





Procedures for ground movement control

- In-tunnel measures: barrel vaulting and excavation by parts



(Harris, 2001)

Procedures for ground movement control

- In-tunnel measures
  - Tunnelling method / TBM design
  - Face support measures
  - Excavation in parts
  - Mechanical pre-cutting
  - Barrel (umbrella) vaulting
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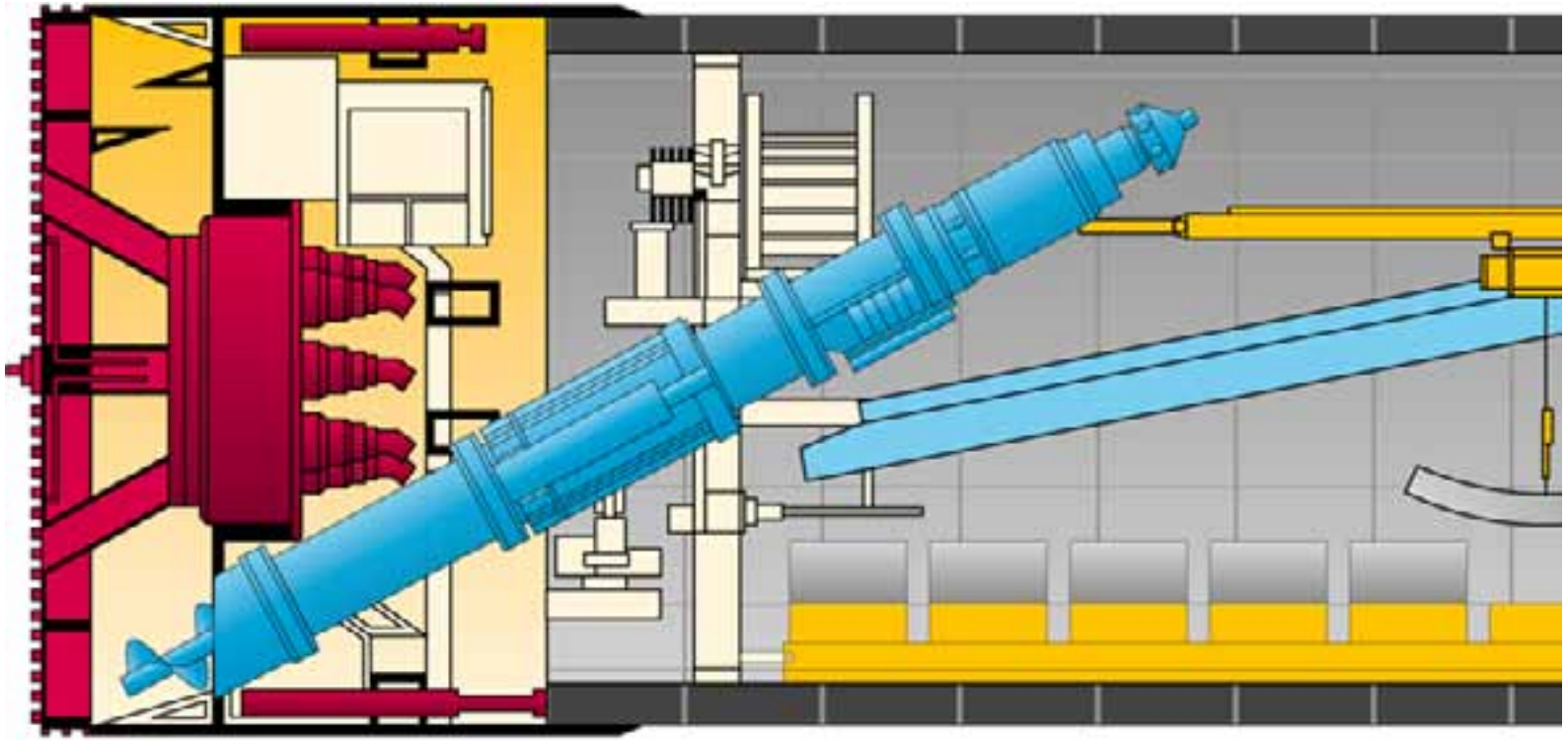
Tunnelling procedure

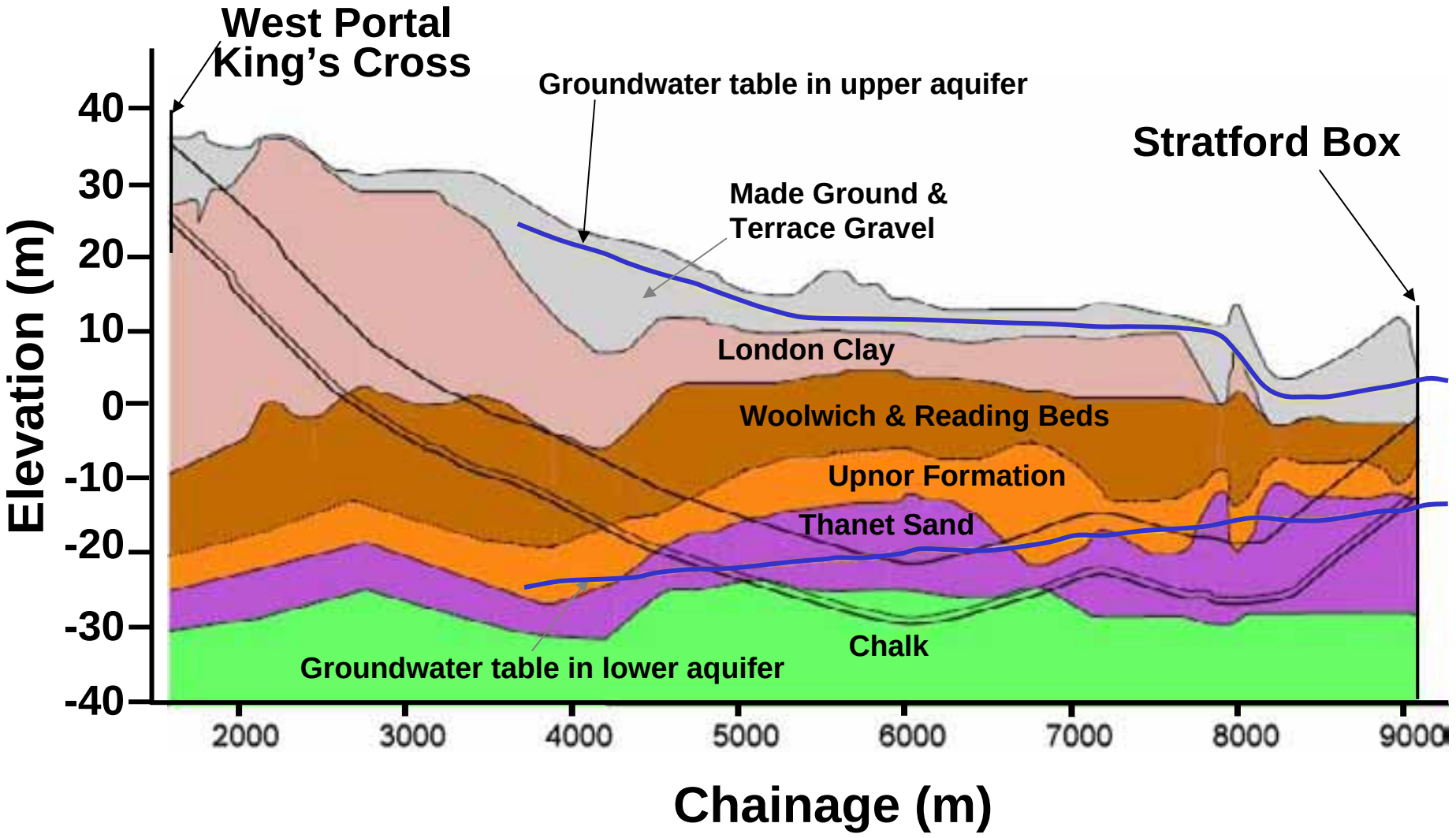
- TBM



Closed shield machine. Earth pressure balance TBM (EPB)

Tunnelling procedure

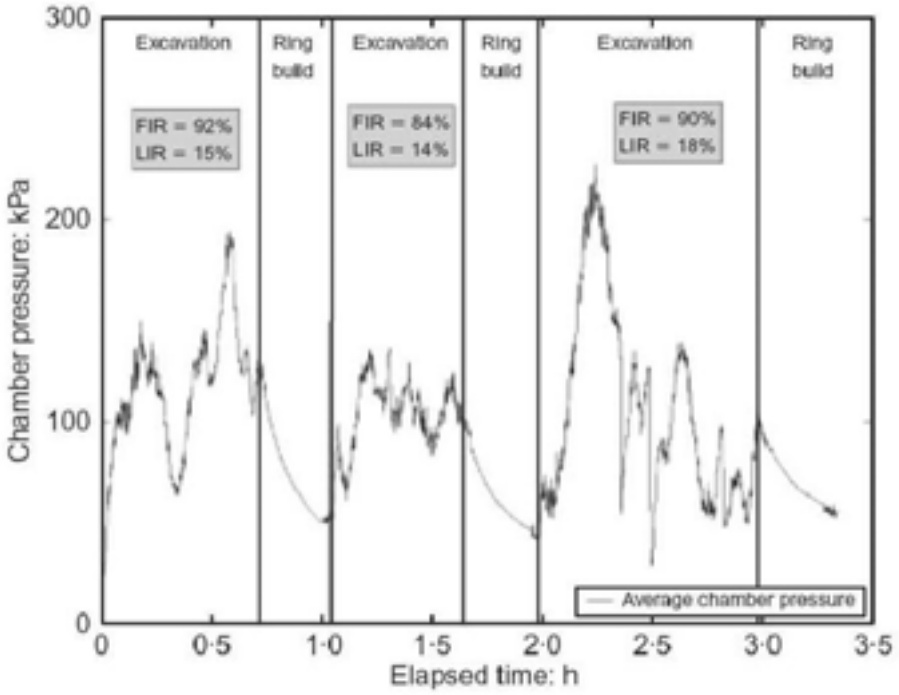
- Geology of Channel Tunnel Rail Link (C220)



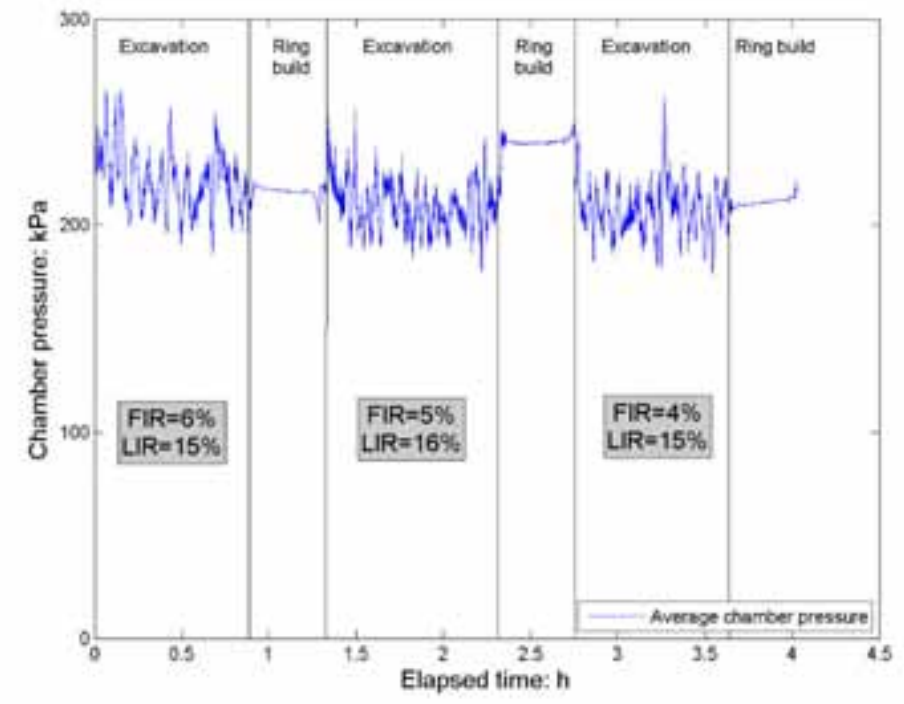
- 7.4 km of twin tunnels of 8.1 m diameter

Tunnelling procedure

- Face pressure control Channel Tunnel Rail Link (C220)



Lambeth group

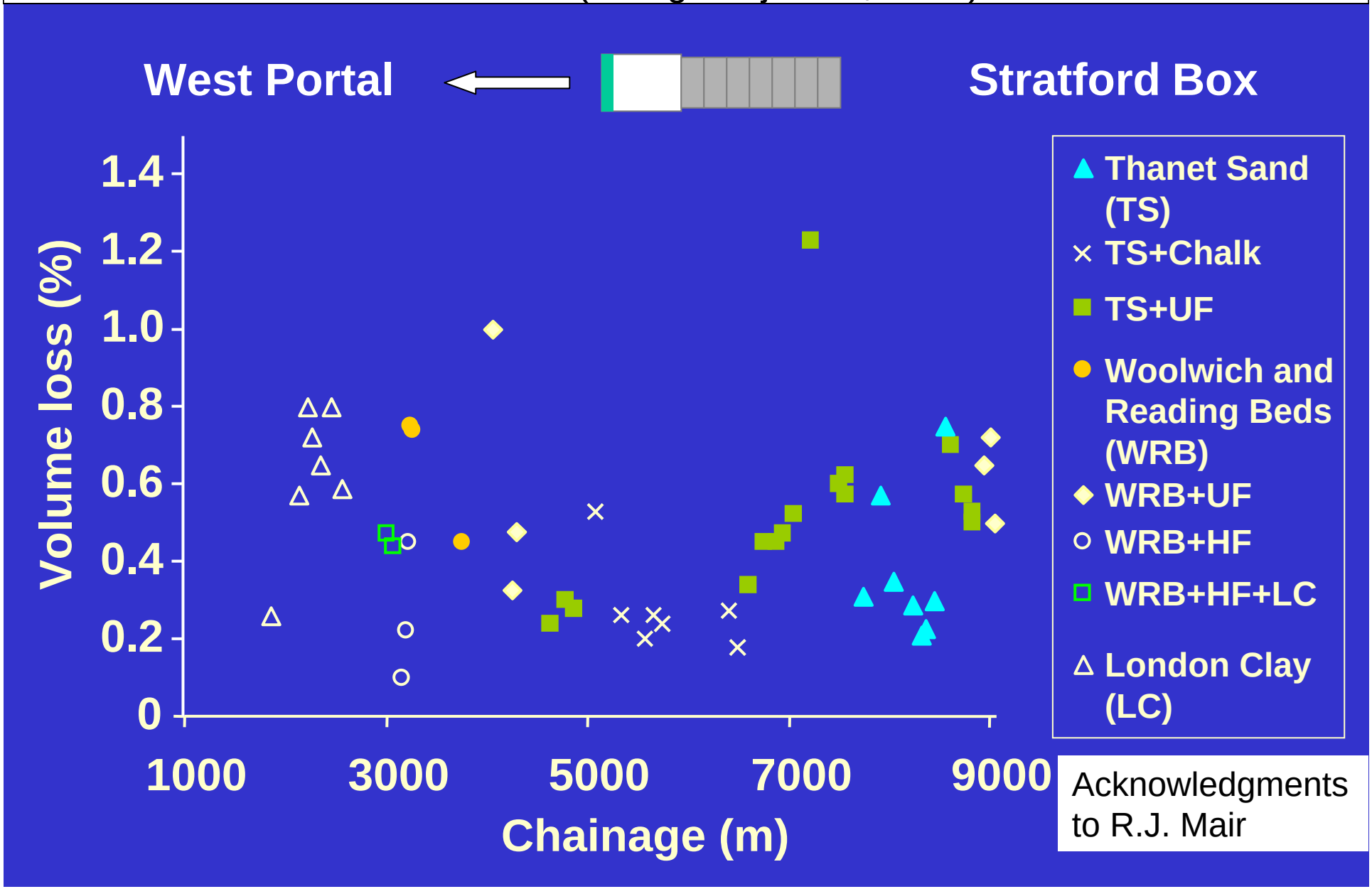


London clay

(Borghi & Mair, 2006)

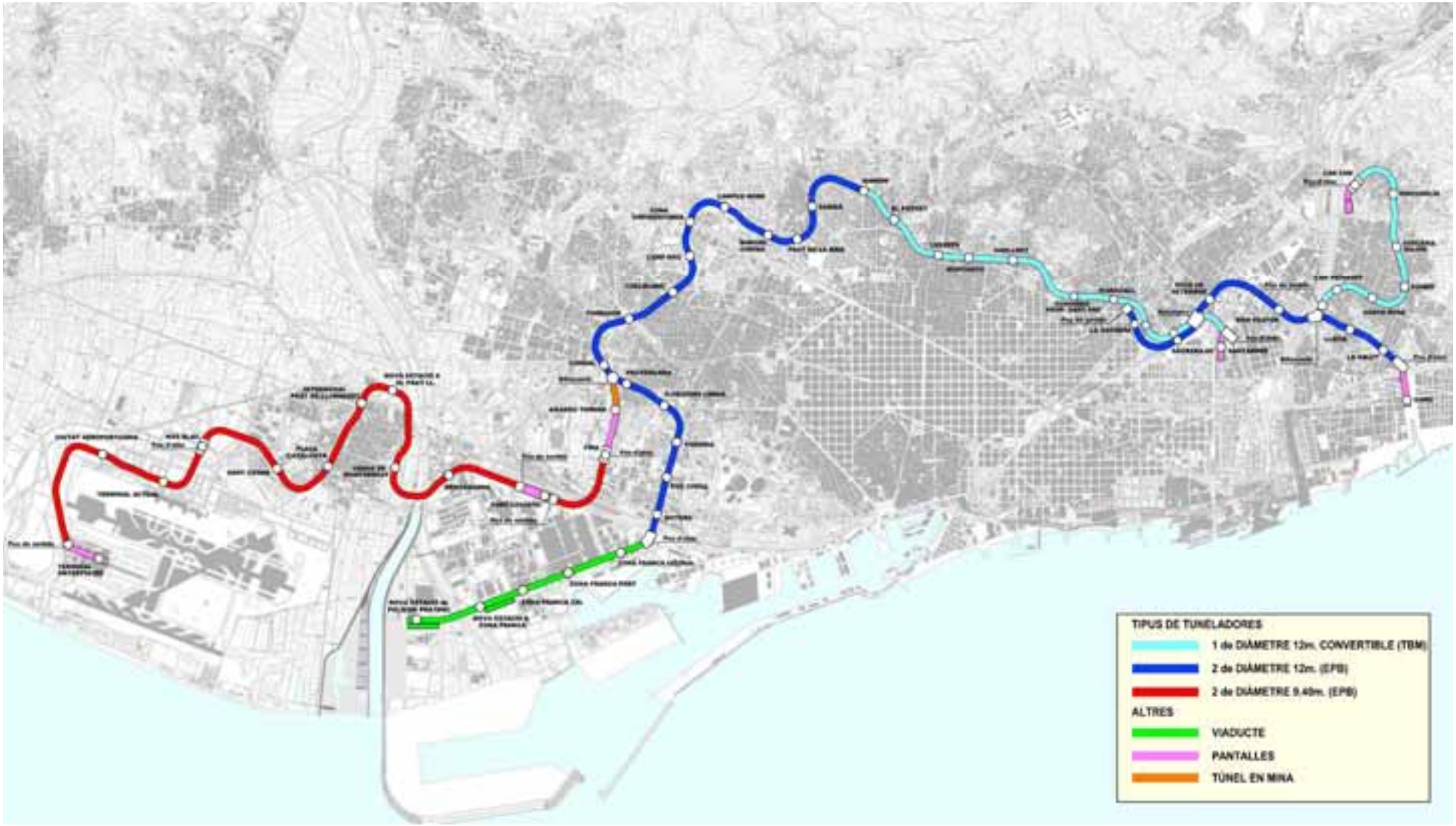
Control de movimientos causados por túneles

- Volume loss CTRL C220 (Wongsaroj et al., 2005)



Acknowledgments to R.J. Mair

Barcelona Metro: Line 9



- 27.2 km: 12.3 m diameter tunnel
- 11.9 km: 9.4 m diameter tunnel
- 5.0 km: cut and cover tunnel
- 0.9 km: mined tunnel
- 2.8 km: viaduct

TOTAL: 47.8 km (52 stations)

Barcelona Metro: Line 9

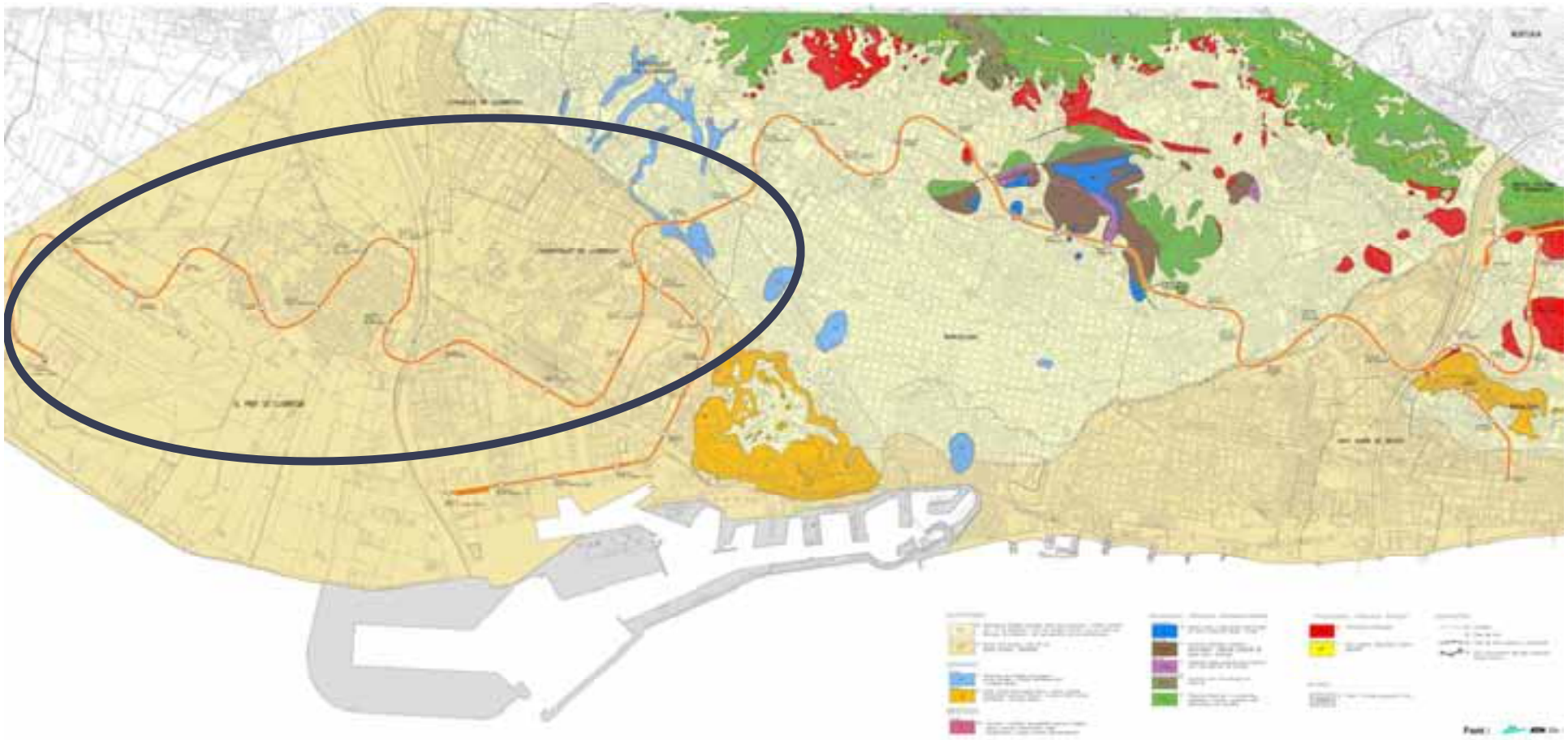
- TBMs used

Mixed mode TBM
11,95m dia.

EPB
12,06m Ø dia. (2)

EPB
9,40m dia. (2)

Barcelona Metro: Line 9



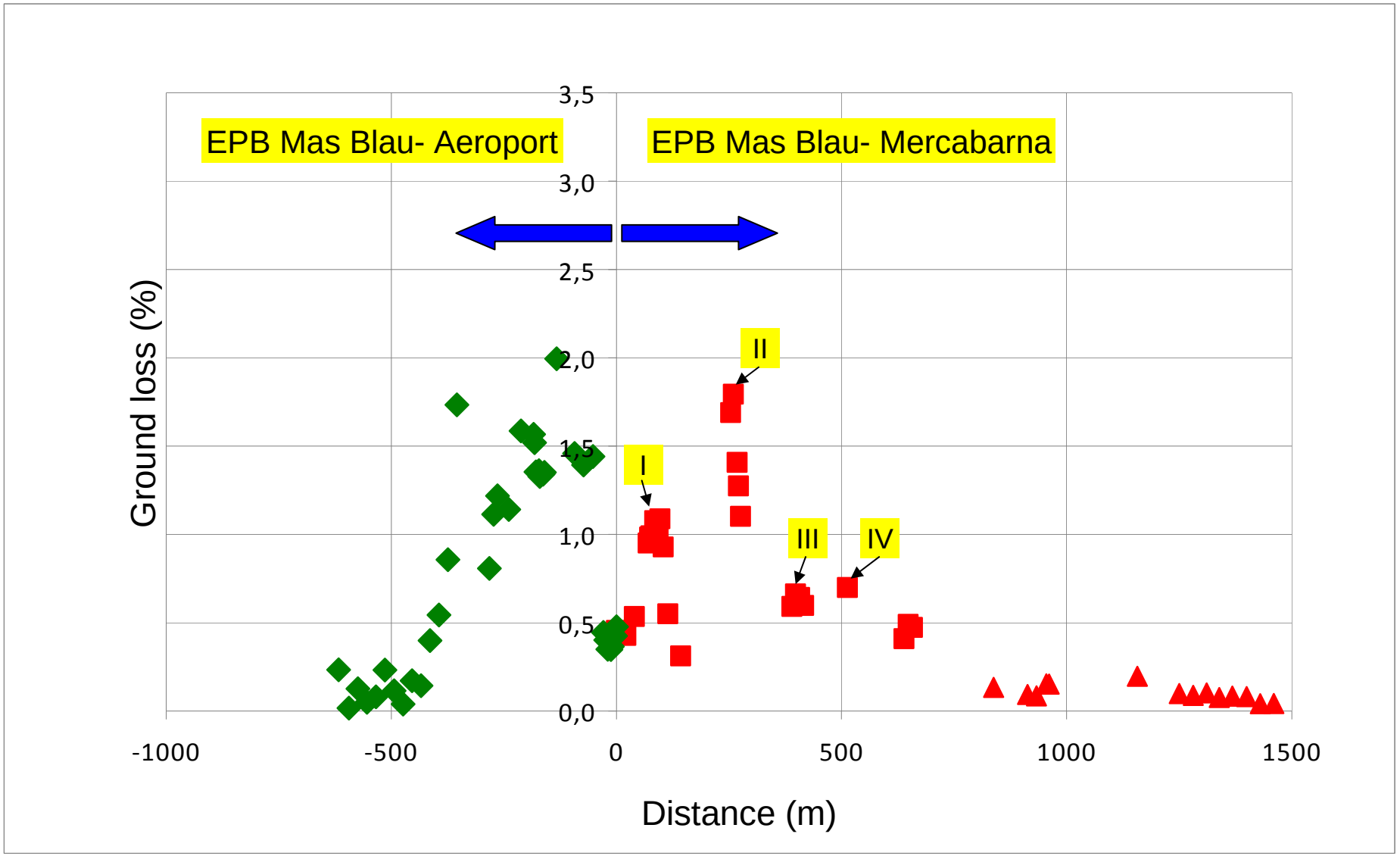
Soil profile in the Llobregat delta

Barcelona Metro: Line 9

EPB Mas Blau- Mercabarna
Diameter 9.4 m

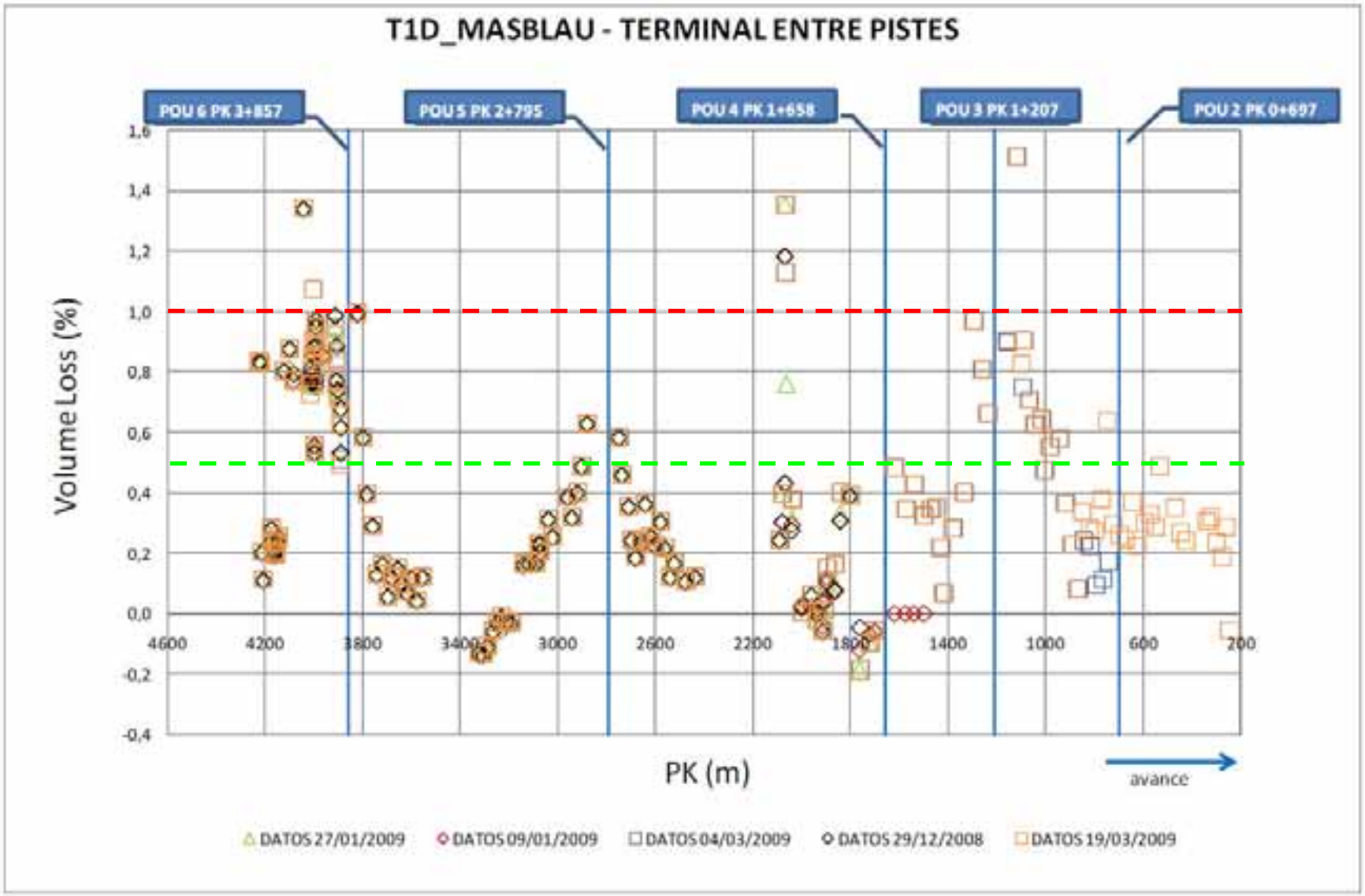
Barcelona Metro: Line 9

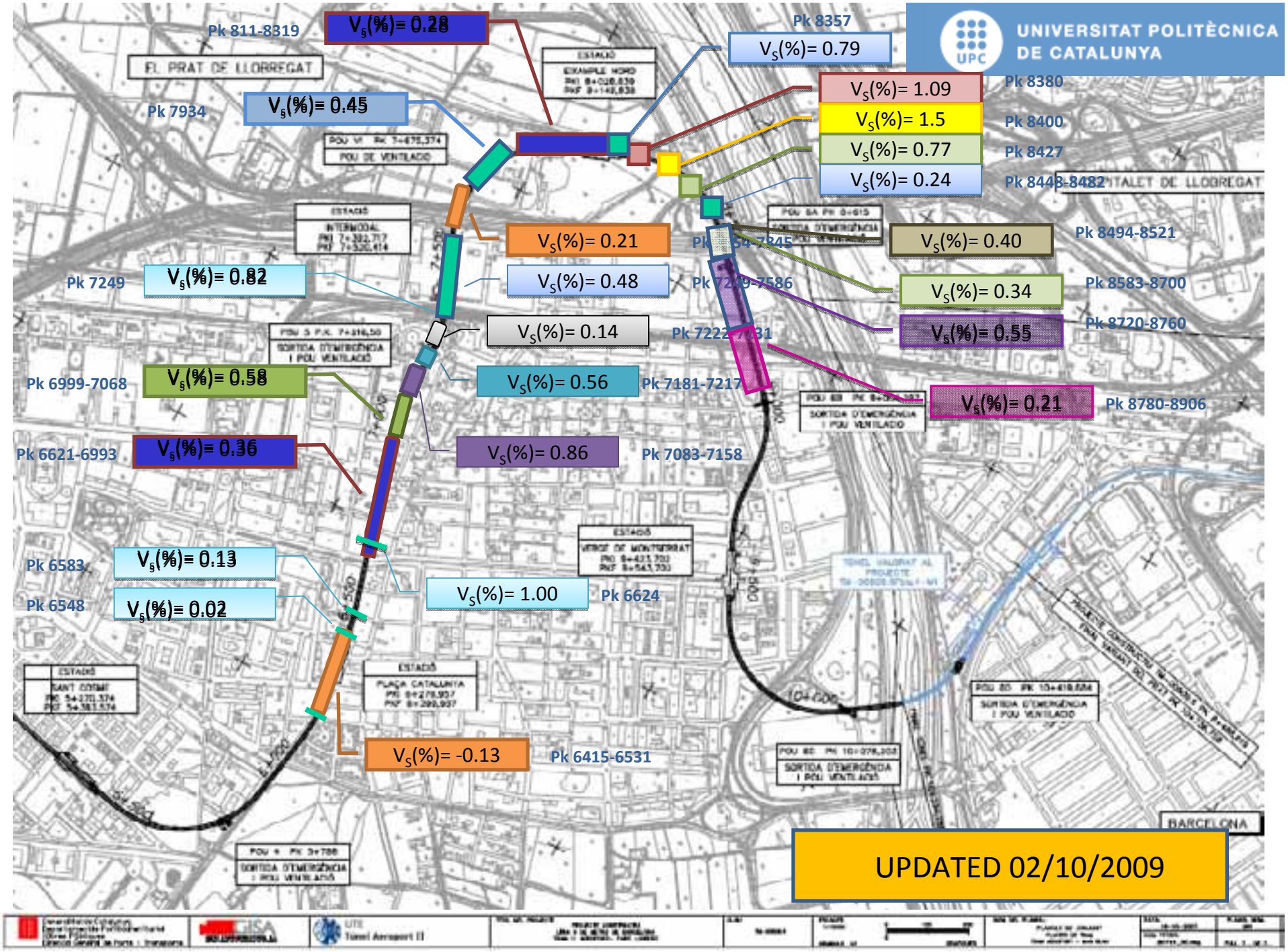
Volume loss



Barcelona Metro: Line 9

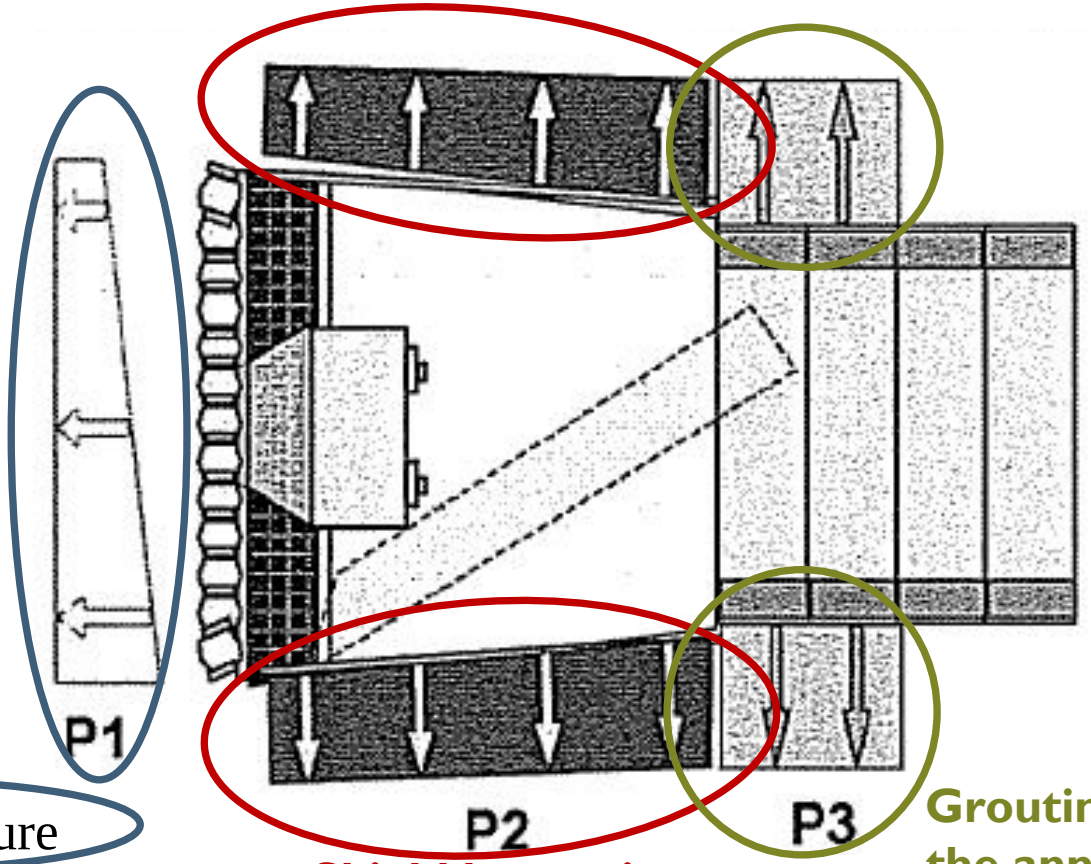
Volume loss




UNIVERSITAT POLITÈCNICA DE CATALUNYA
UPC
Pk 811-8319
V_s(%)= 0.28
EL PRAT DE LLOBREGAT
Pk 7934
V_s(%)= 0.45
Pk 8357
V_s(%)= 0.79
V_s(%)= 1.09
Pk 8380
V_s(%)= 1.5
Pk 8400
V_s(%)= 0.77
Pk 8427
V_s(%)= 0.24
Pk 8448-8482
V_s(%)= 0.21
V_s(%)= 0.40
Pk 8494-8521
Pk 7249
V_s(%)= 0.82
V_s(%)= 0.48
V_s(%)= 0.34
Pk 8583-8700
V_s(%)= 0.14
V_s(%)= 0.55
Pk 8720-8760
Pk 6999-7068
V_s(%)= 0.58
V_s(%)= 0.56
Pk 7181-7217
V_s(%)= 0.21
Pk 8780-8906
Pk 6621-6993
V_s(%)= 0.36
V_s(%)= 0.86
Pk 7083-7158
Pk 6583
V_s(%)= 0.13
Pk 6548
V_s(%)= 0.02
V_s(%)= 1.00
Pk 6624
V_s(%)= -0.13
Pk 6415-6531
BARCELONA
UPDATED 02/10/2009

EPB tunnelling

- Tunnelling pressures



Face pressure

P1 = Face pressure

P2 = Shield pressure

P3 = Grouting pressure

Shield bentonite pressure

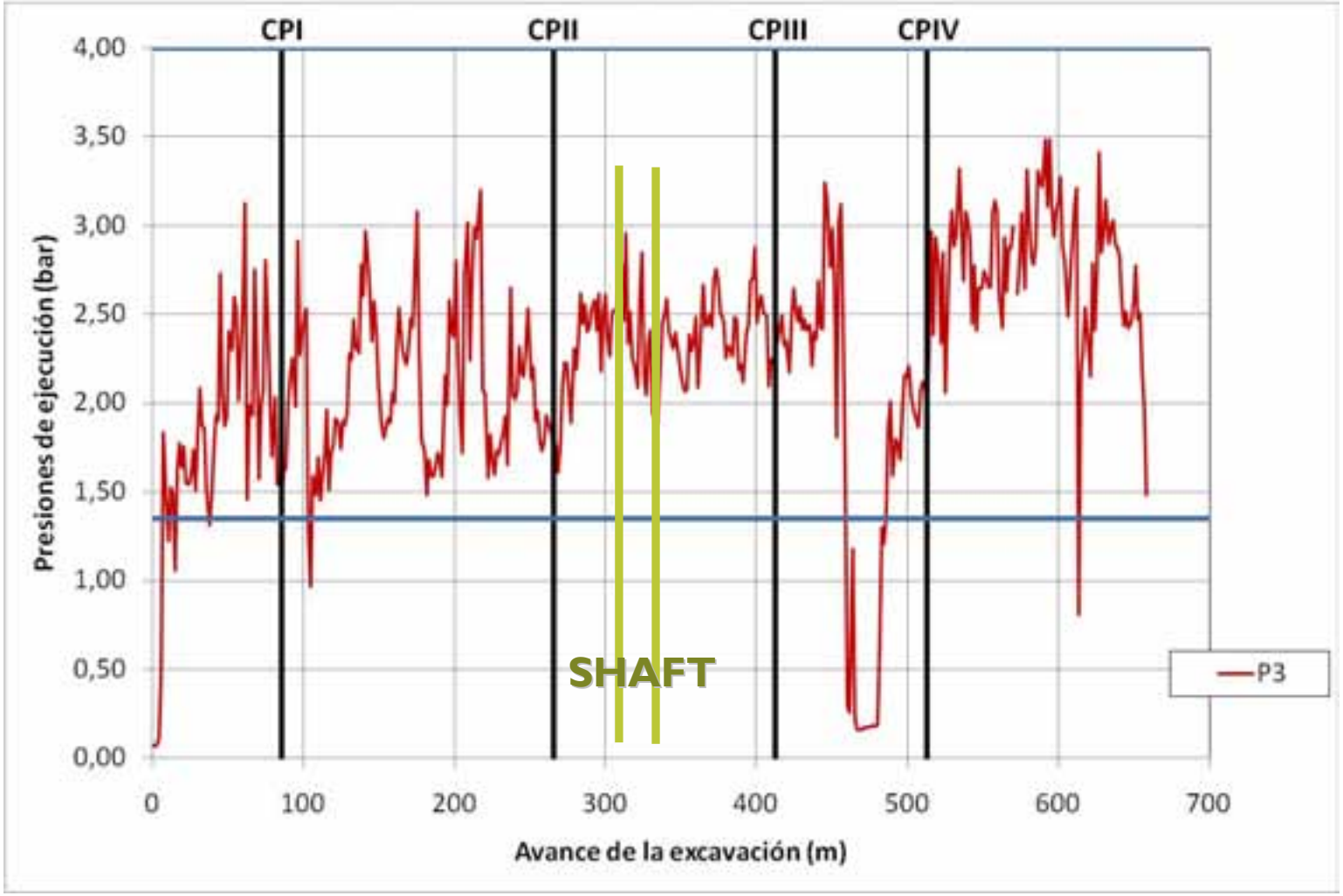
Grouting pressure in the annulus between soil and lining

EPB tunnelling

- Bentonite injection through the shield

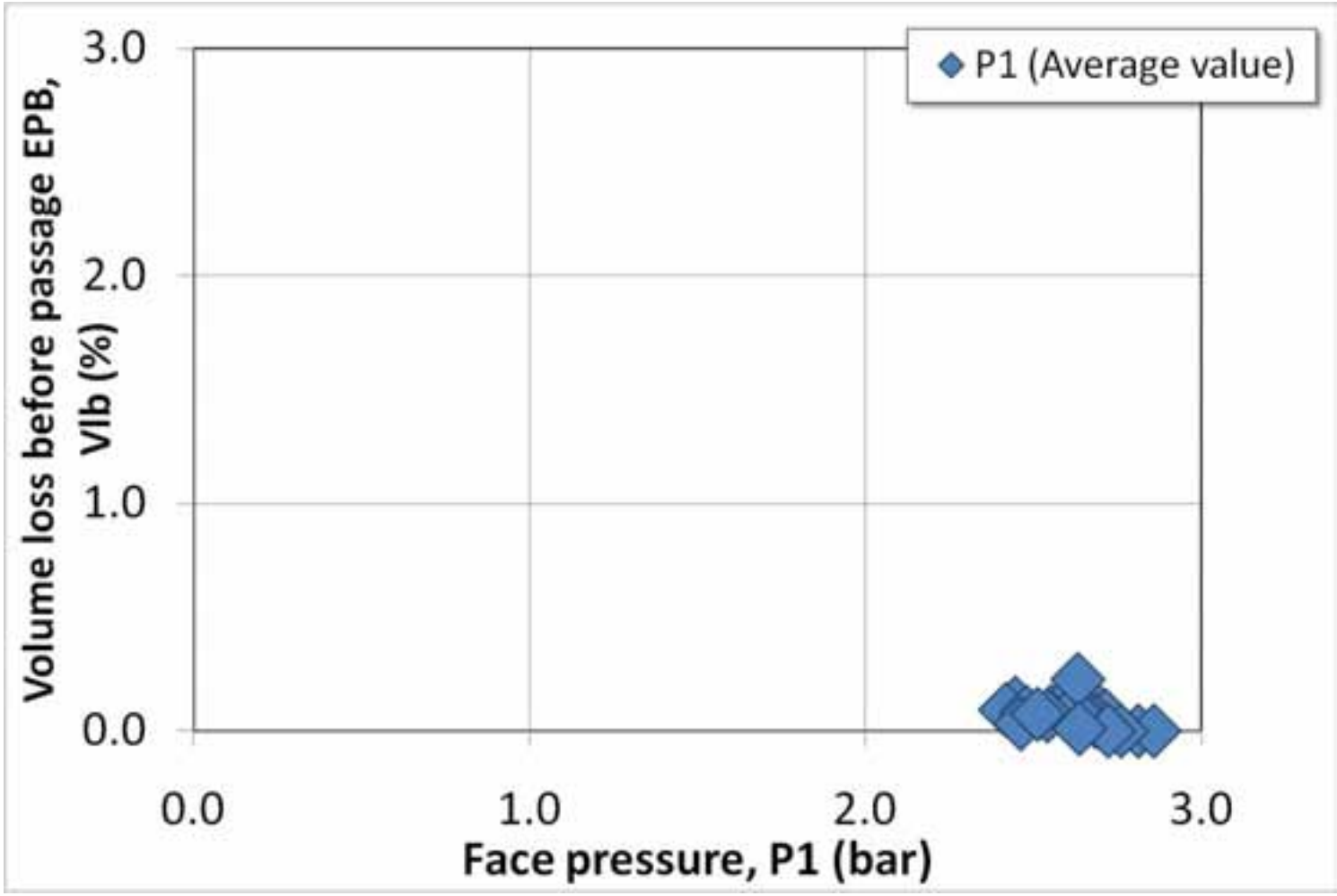
EPB tunnelling

- Recorded grouting pressure, P3



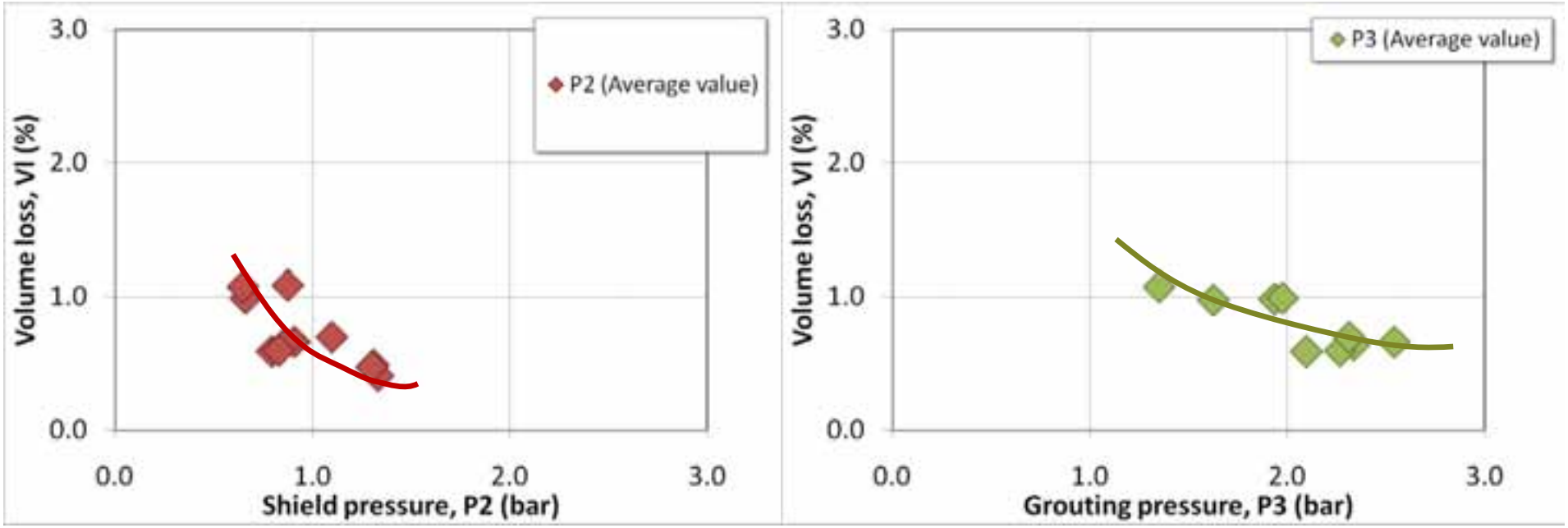
EPB tunnelling

- Volume loss before passage of EPB (ahead of face)



EPB tunnelling

- Effect of grouting pressures on total volume loss



Shield pressure, P2

Grouting pressure, P3

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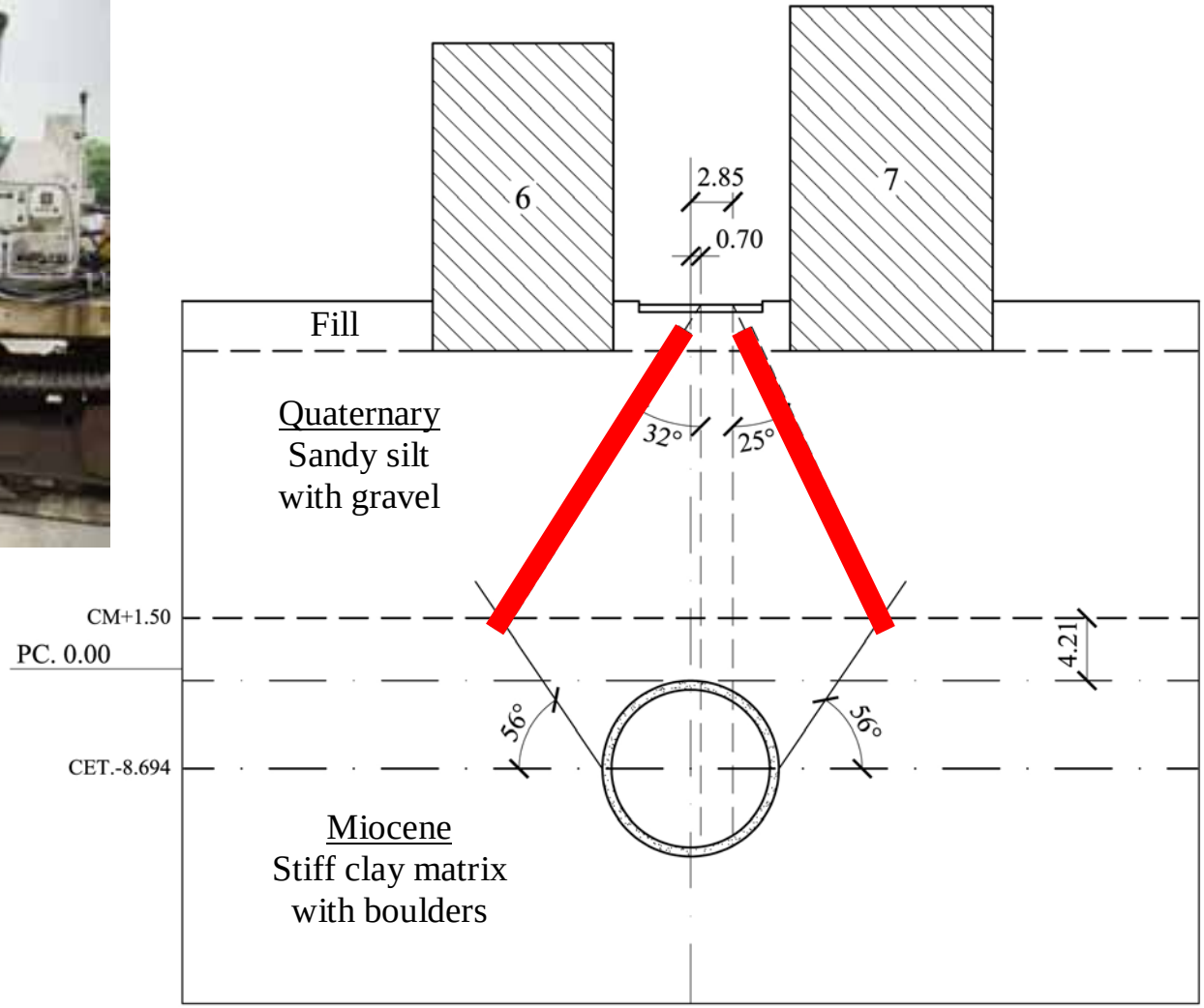
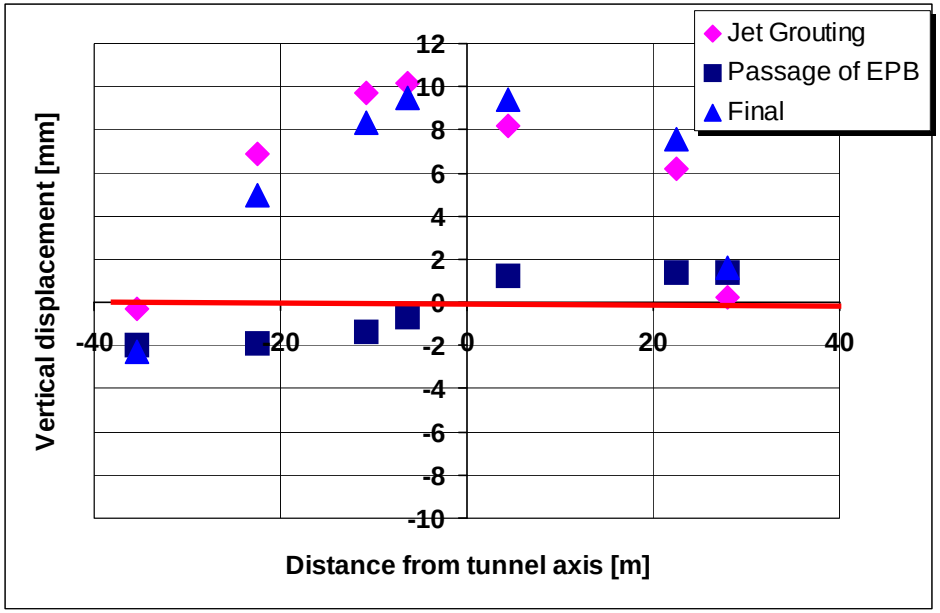
Screen (curtain) walls

- Jet-grouting screen



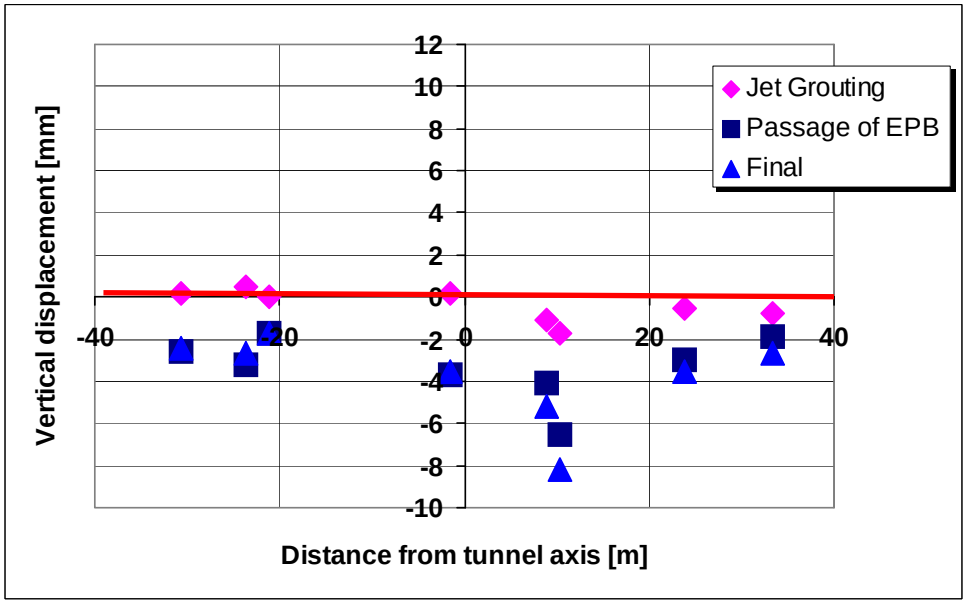
Salvador Seguí street

Jet grouting screen: ground movements



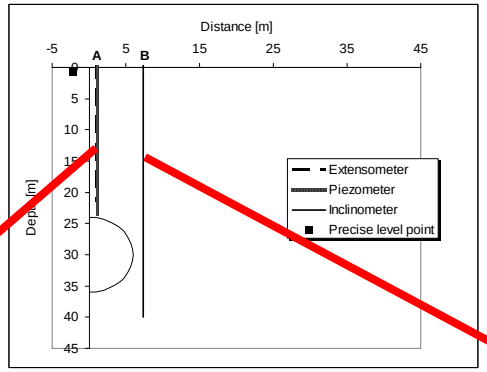
PK 4+800

Salvador Seguí street

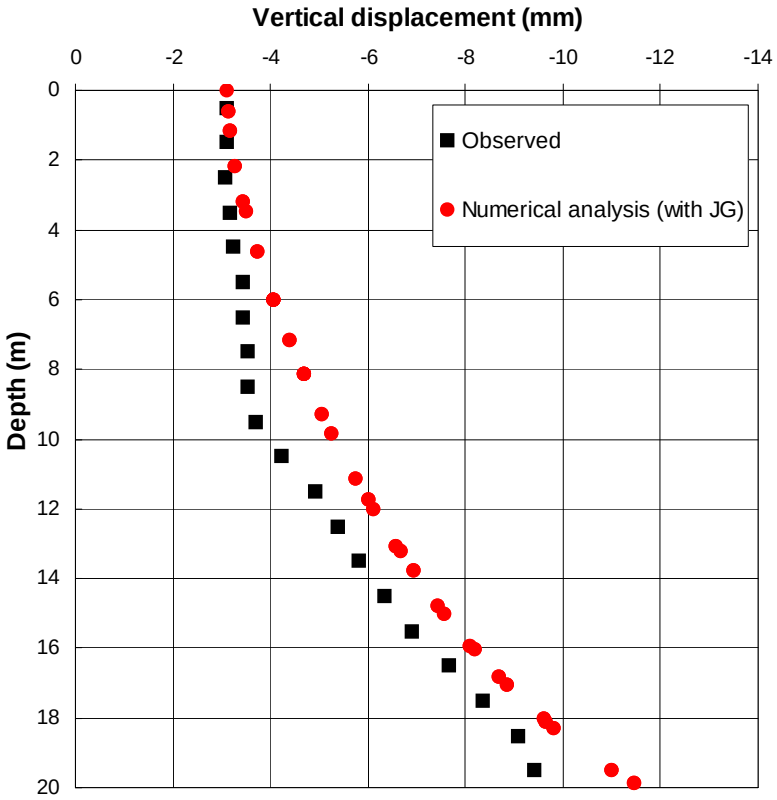


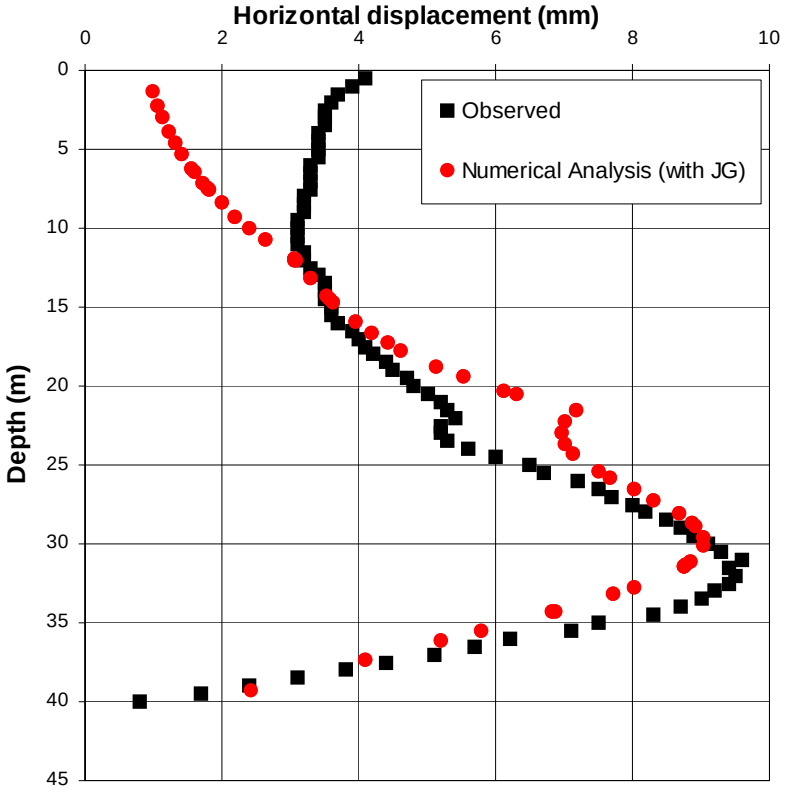
PK 4+770

Jet grouting screen: ground movements



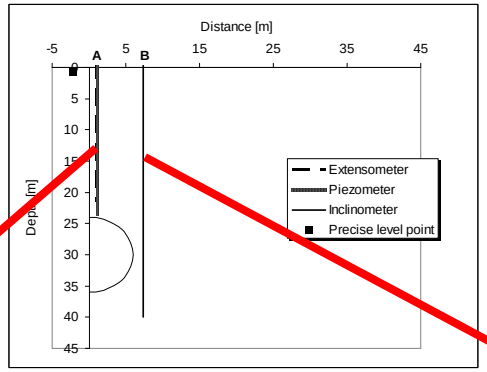
PK 4+775



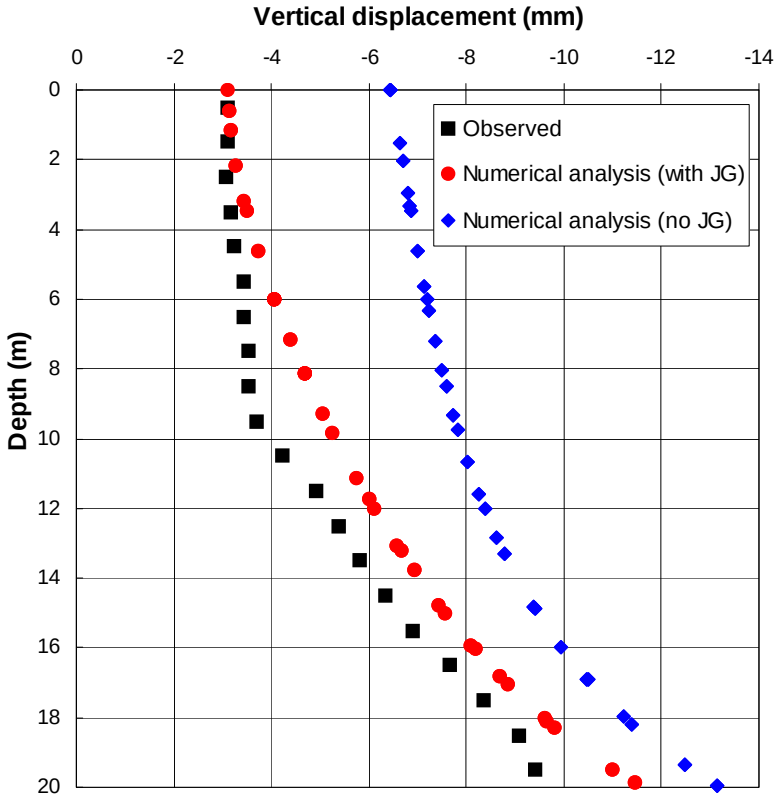


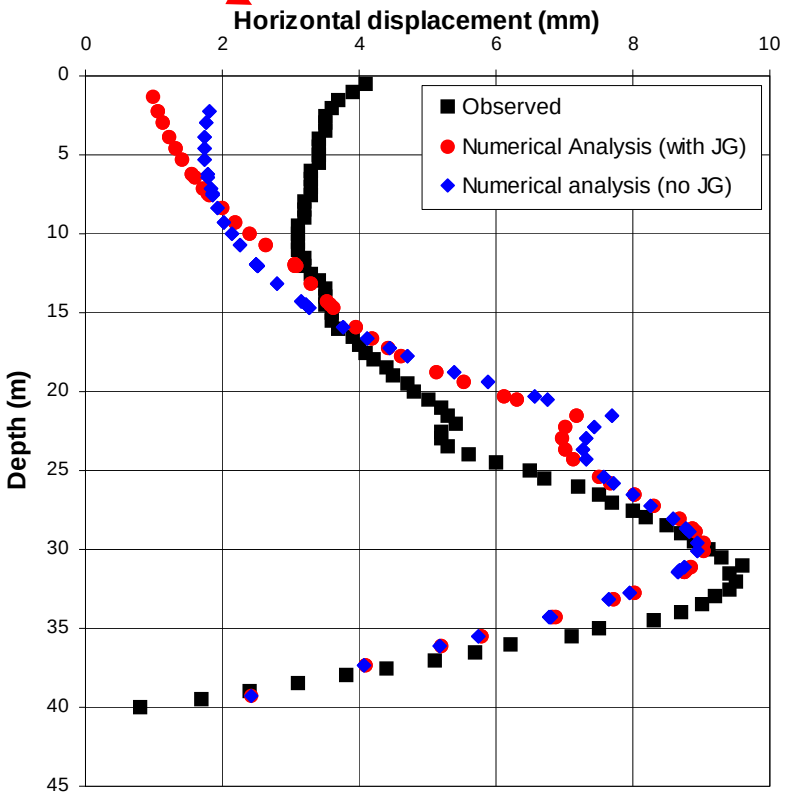
Salvador Seguí street

Jet grouting screen: ground movements



PK 4+775



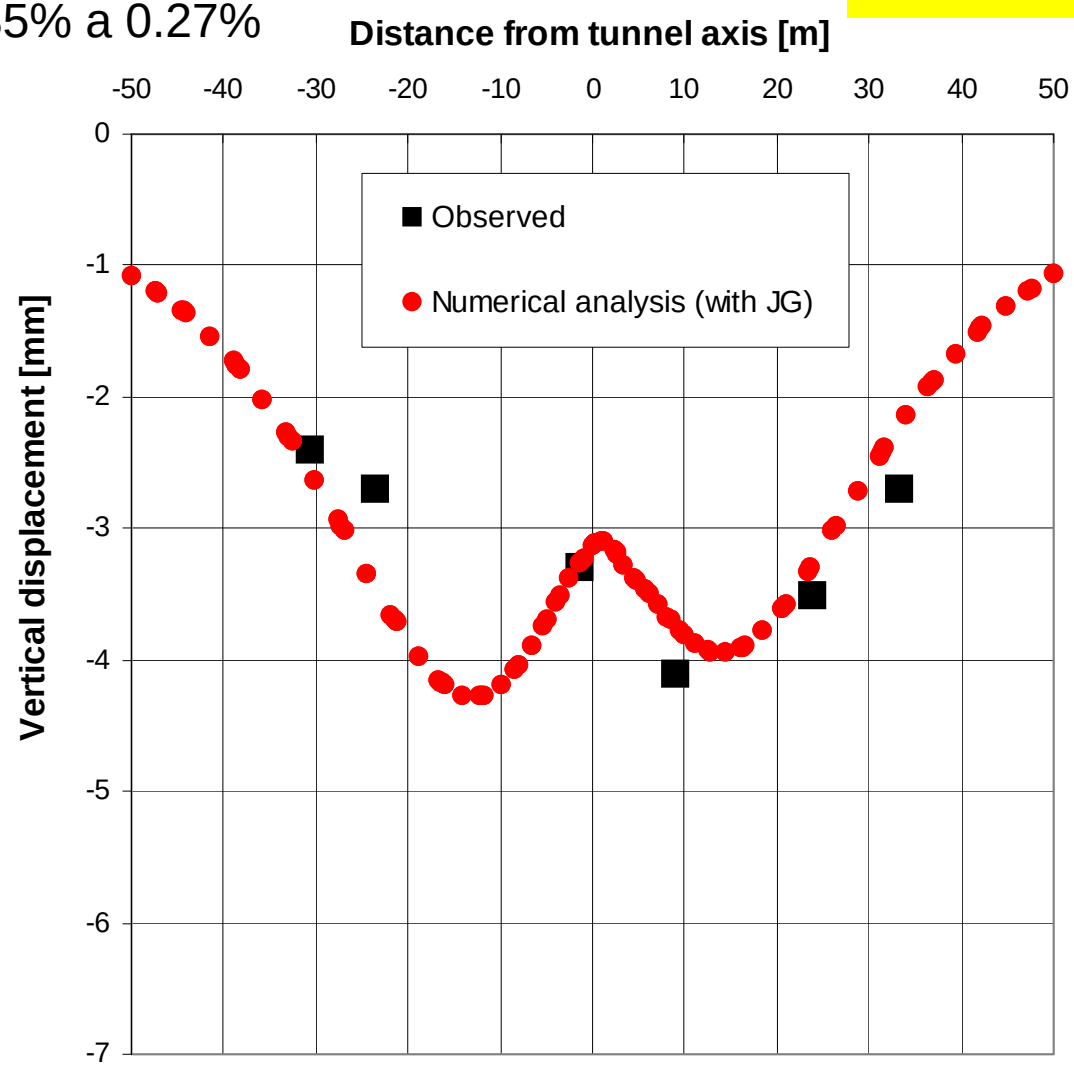


Salvador Seguí street

Jet grouting screen: ground movements

Pérdida de volumen, V_l,
reducida de 0.35% a 0.27%

Settlements

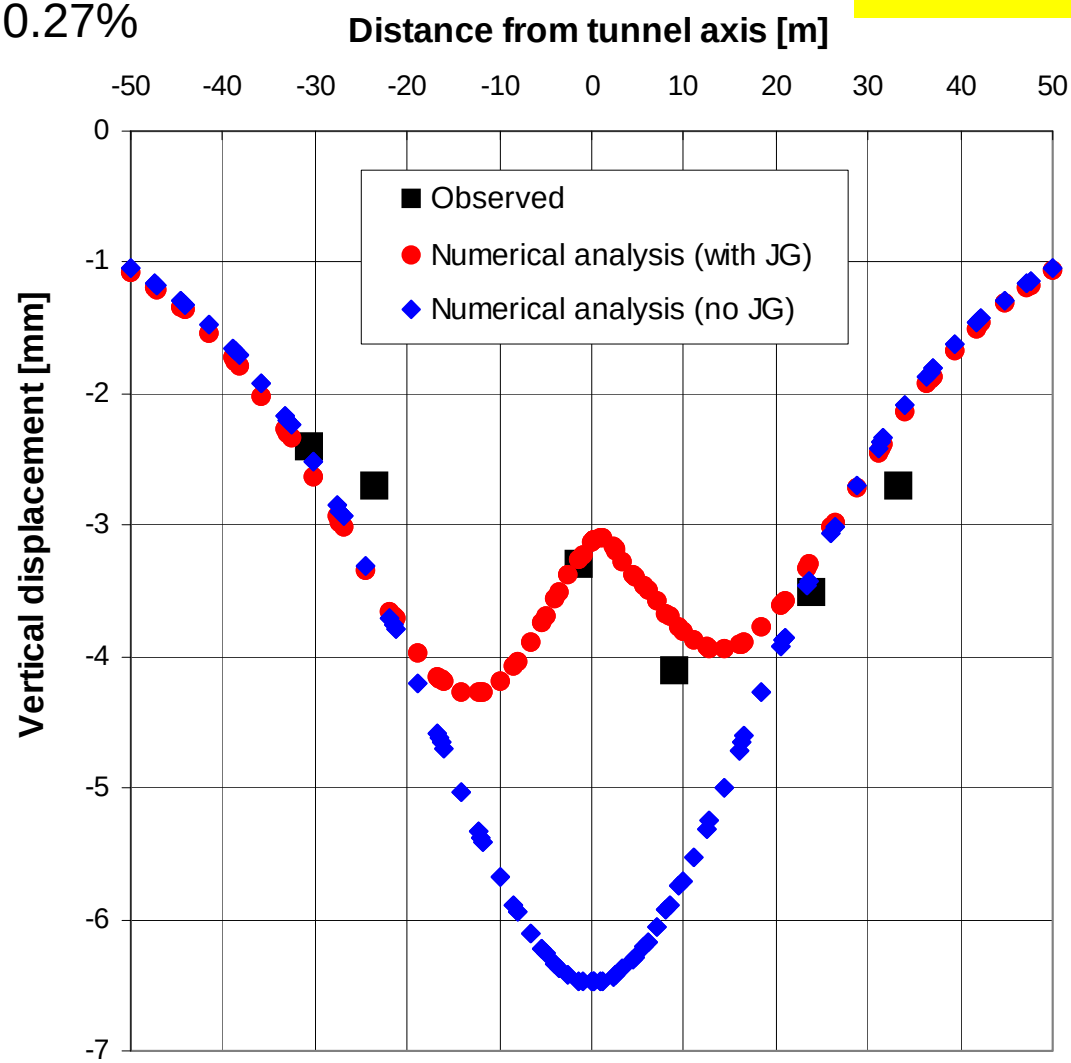


Salvador Seguí street

Jet grouting screen: ground movements

Volume loss reduced
from 0.35% to 0.27%

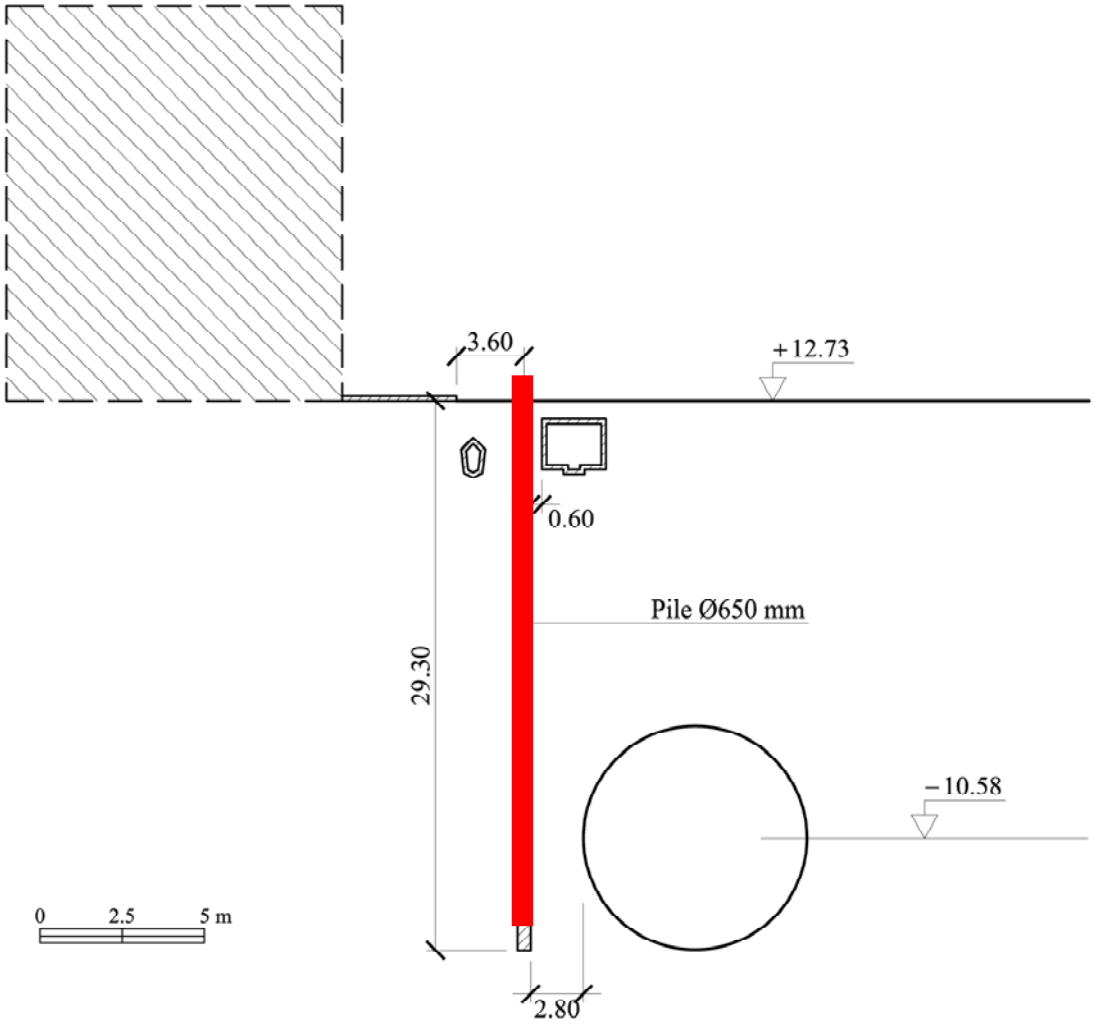
Settlements



Salvador Seguí street

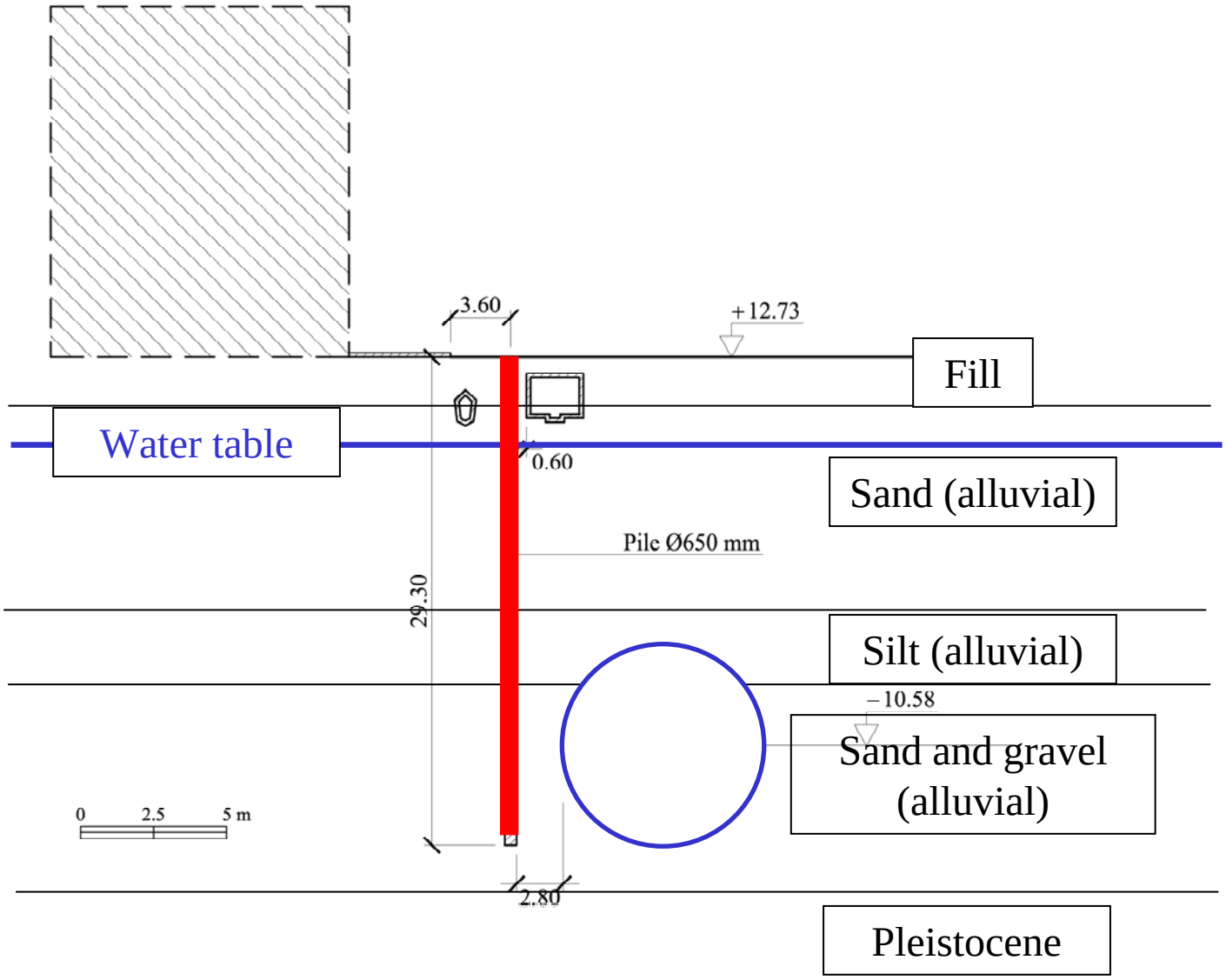
Screen (curtain) walls

- Pile screen wall



Sant Adrià street

Pile screen wall

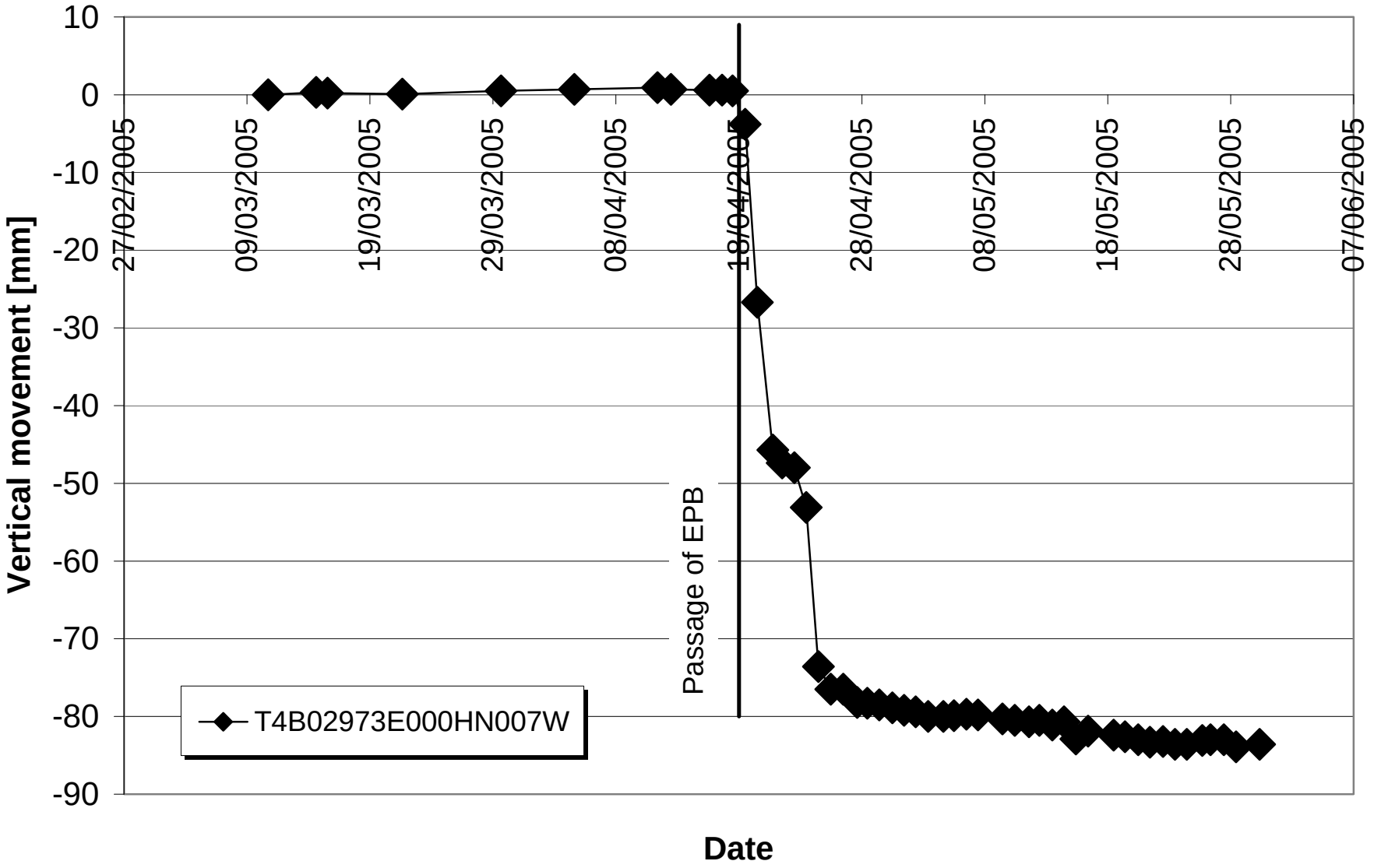


Sant Adrià street

Pile screen wall

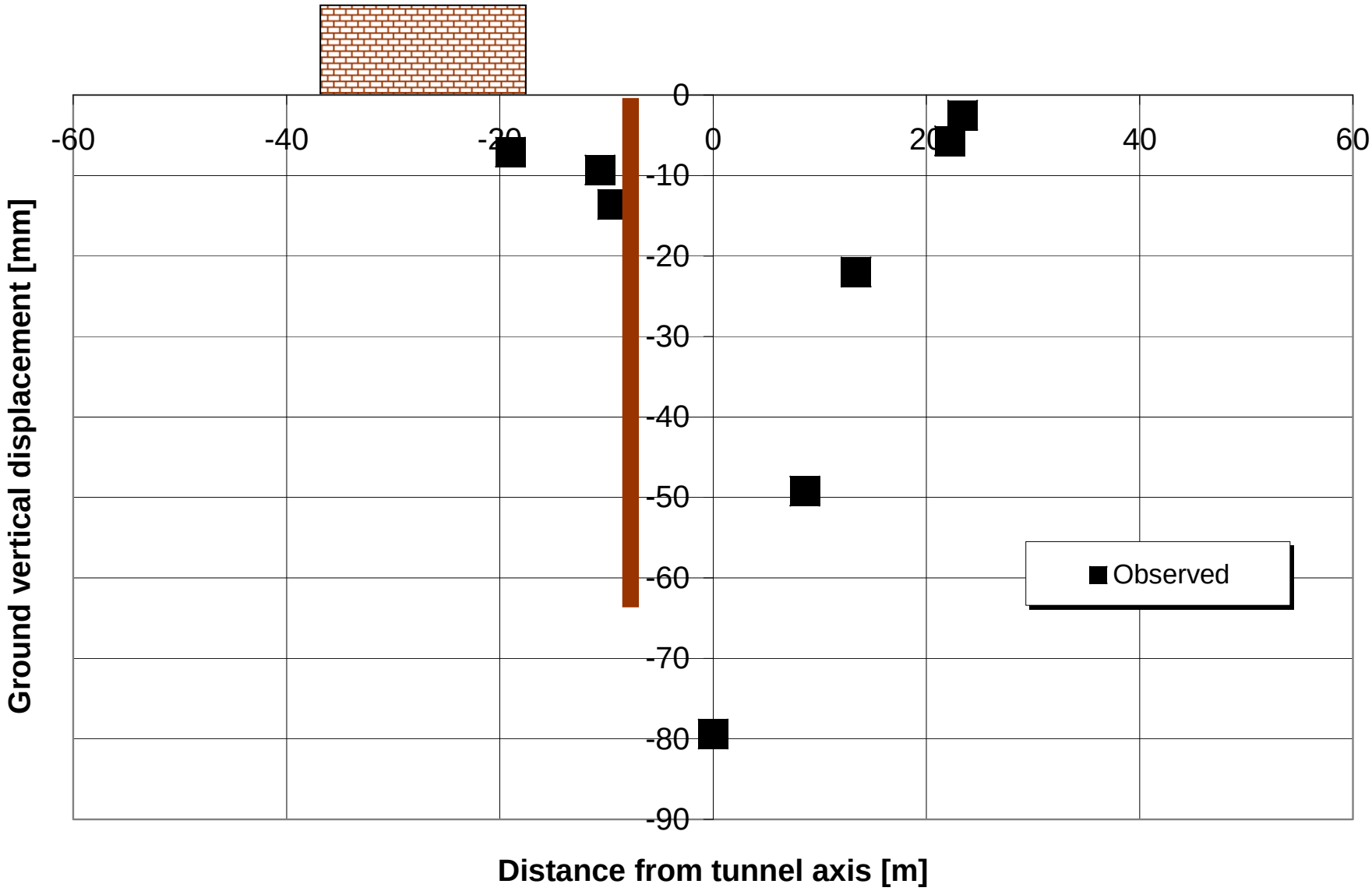
Sant Adrià street

Pile screen wall



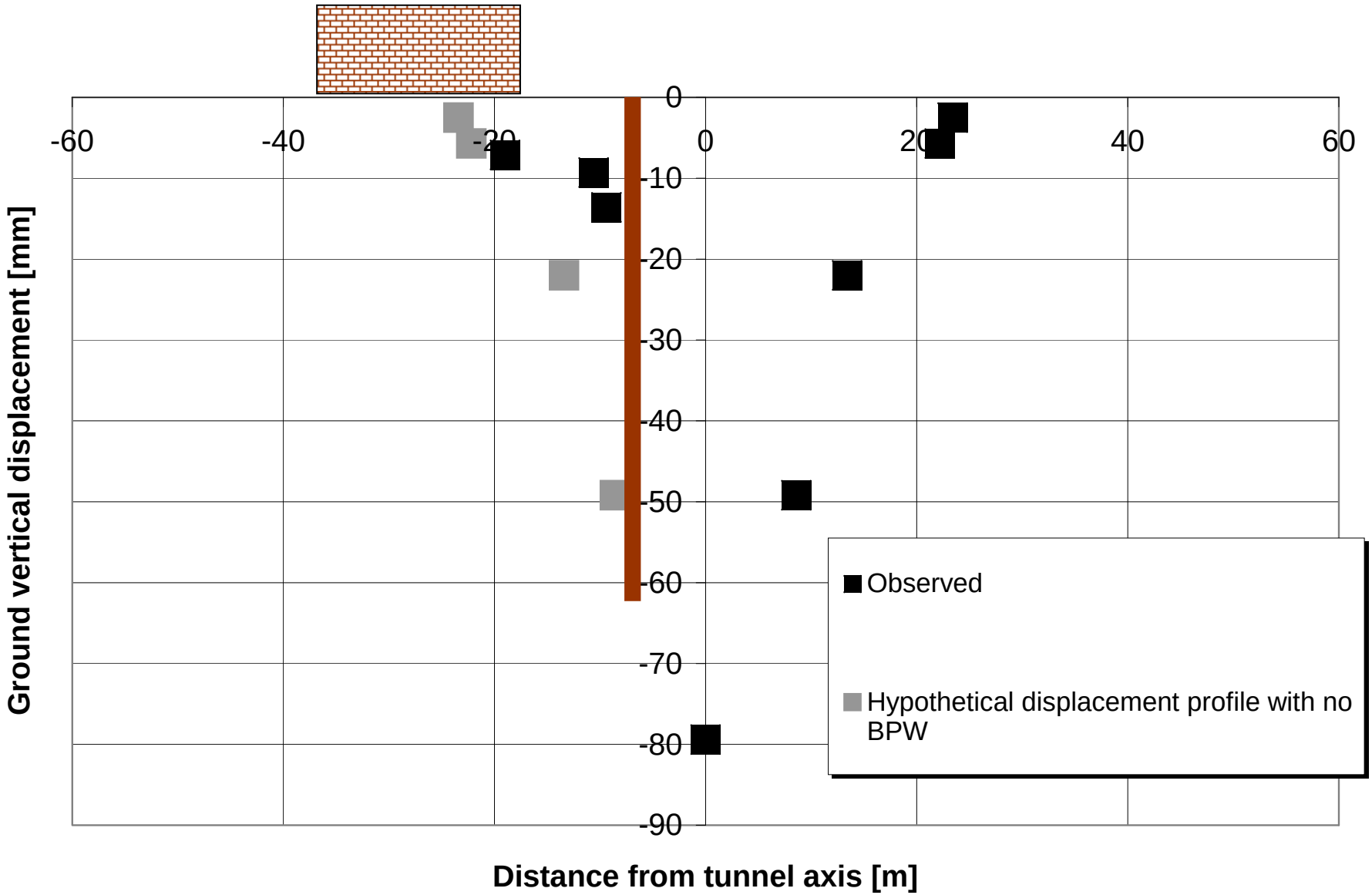
Surface settlement on tunnel axis

Pile screen wall



Surface settlements

Pile screen wall

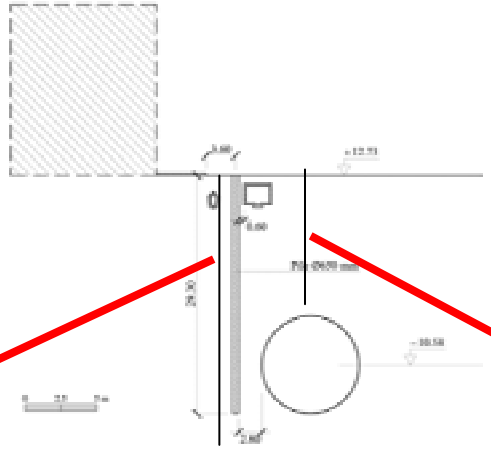


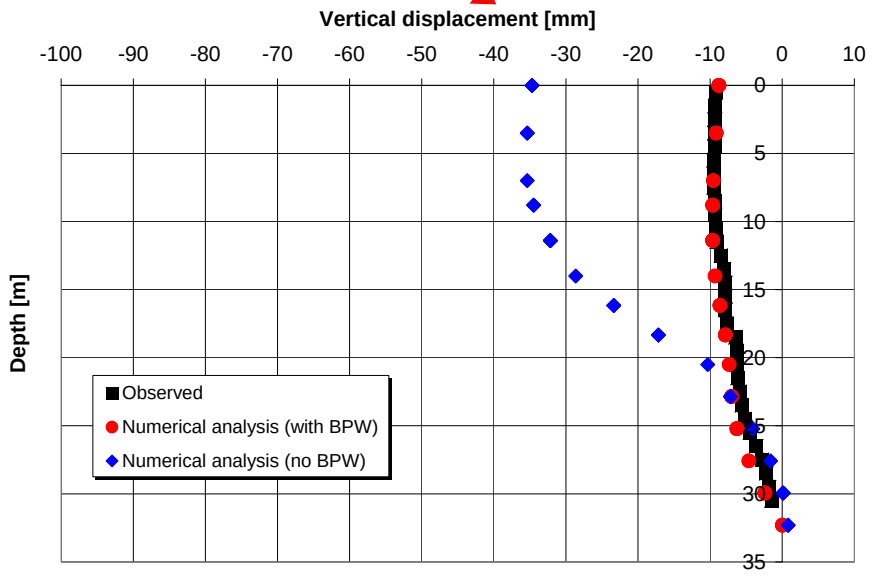
Surface settlements

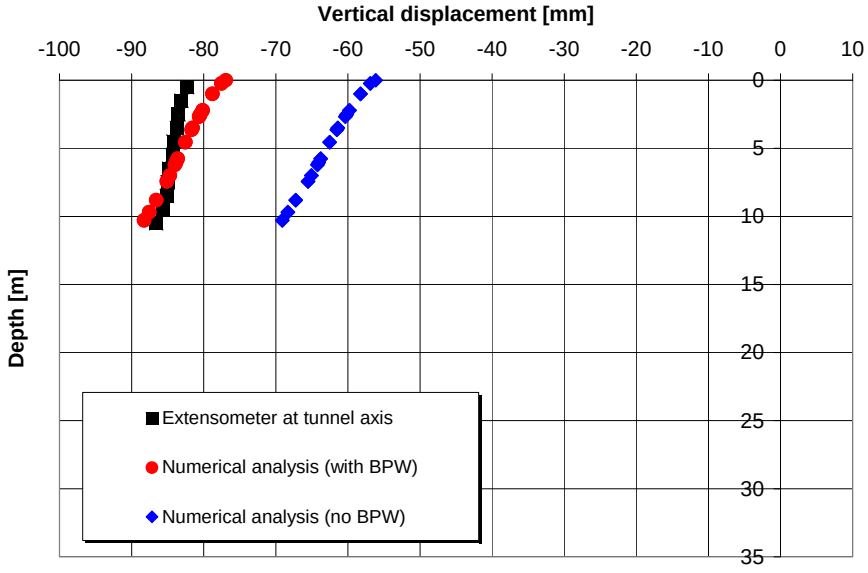
Pile screen wall

Sant Adrià street

PK 2+973





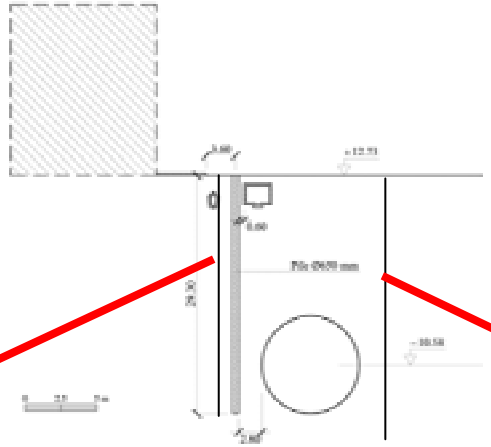


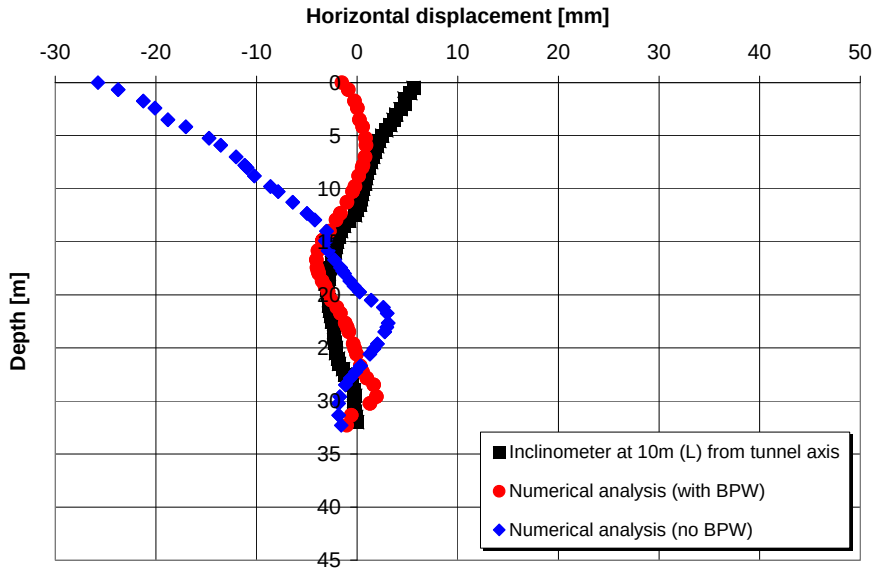
Vertical displacements

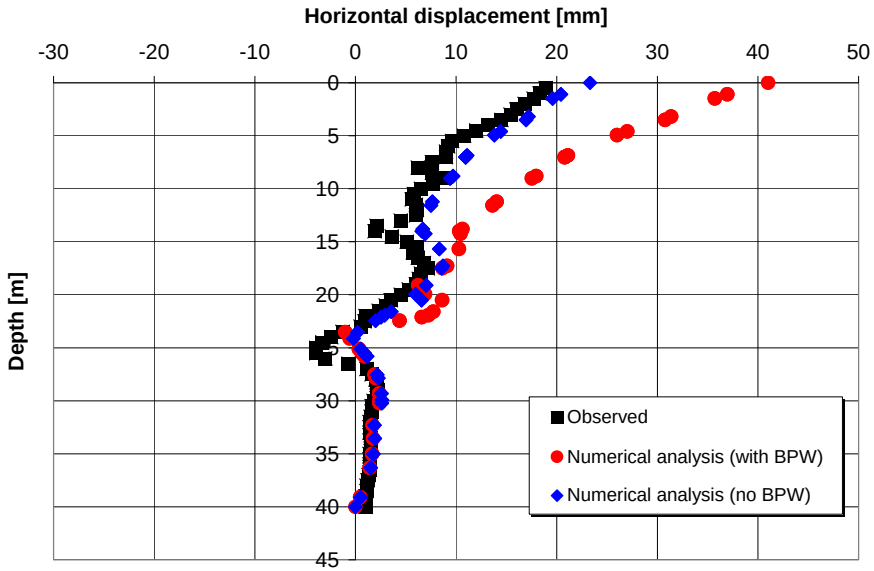
Pile screen wall

Sant Adrià street

PK 2+973

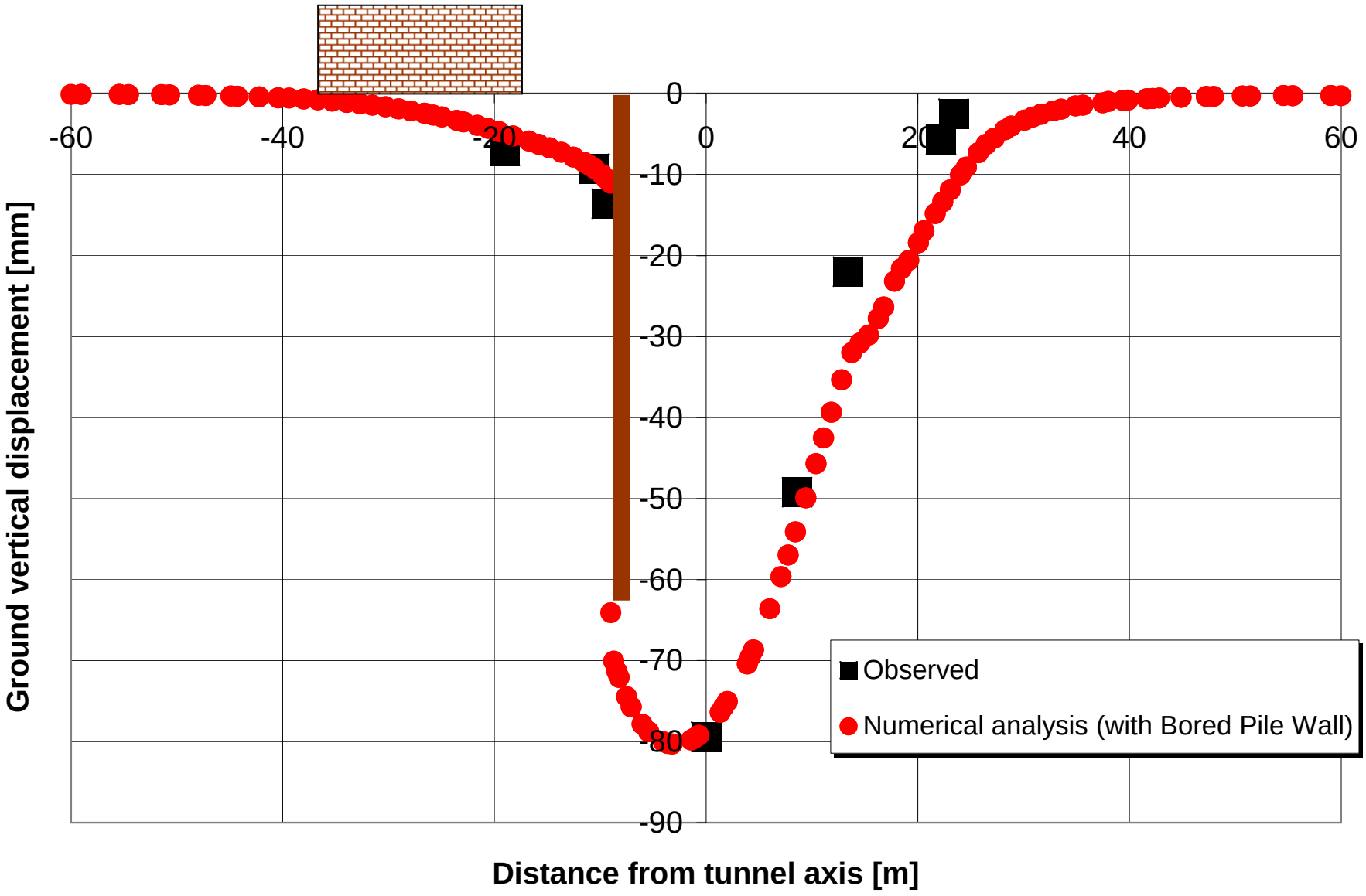






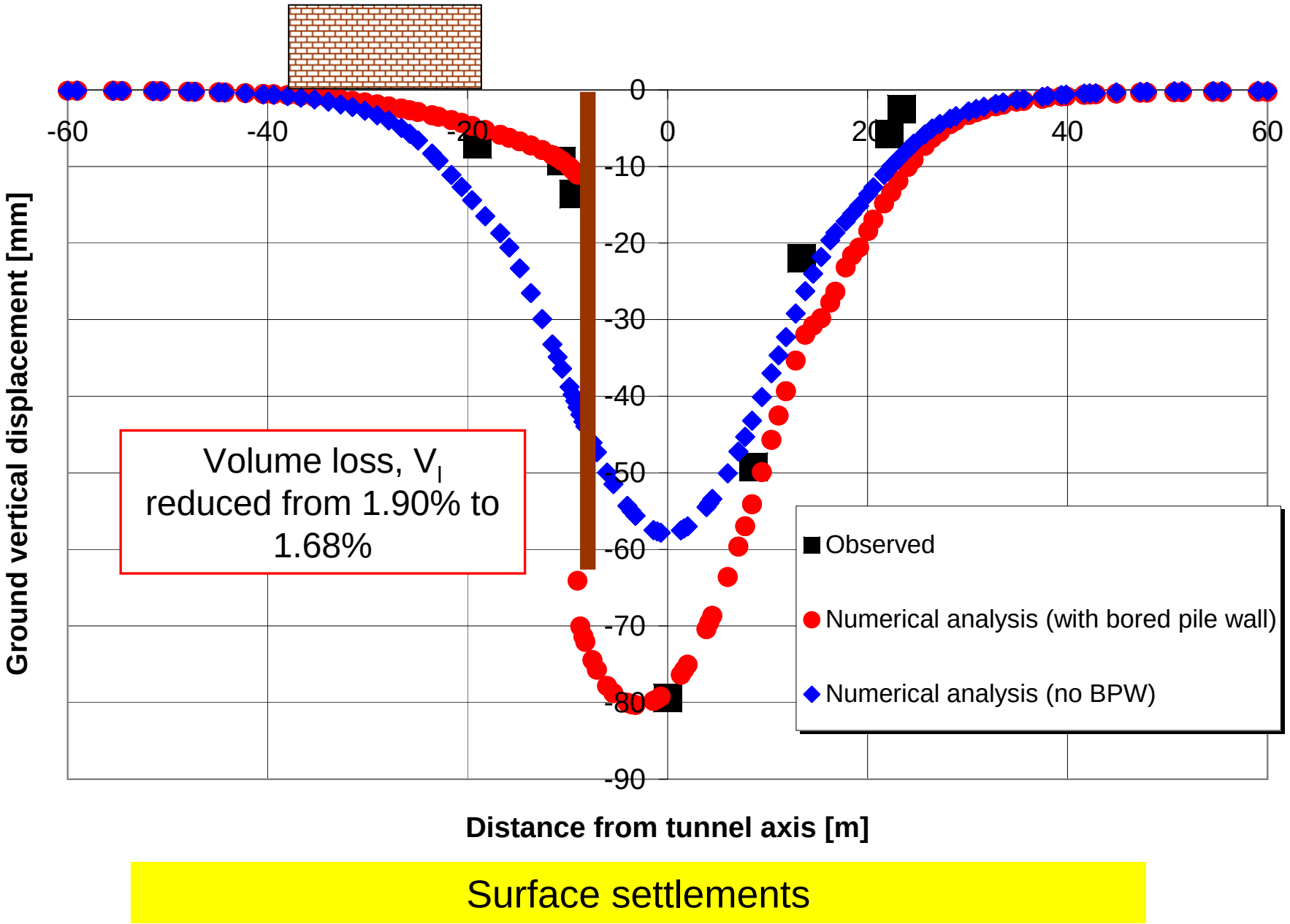
Horizontal displacements

Pile screen wall



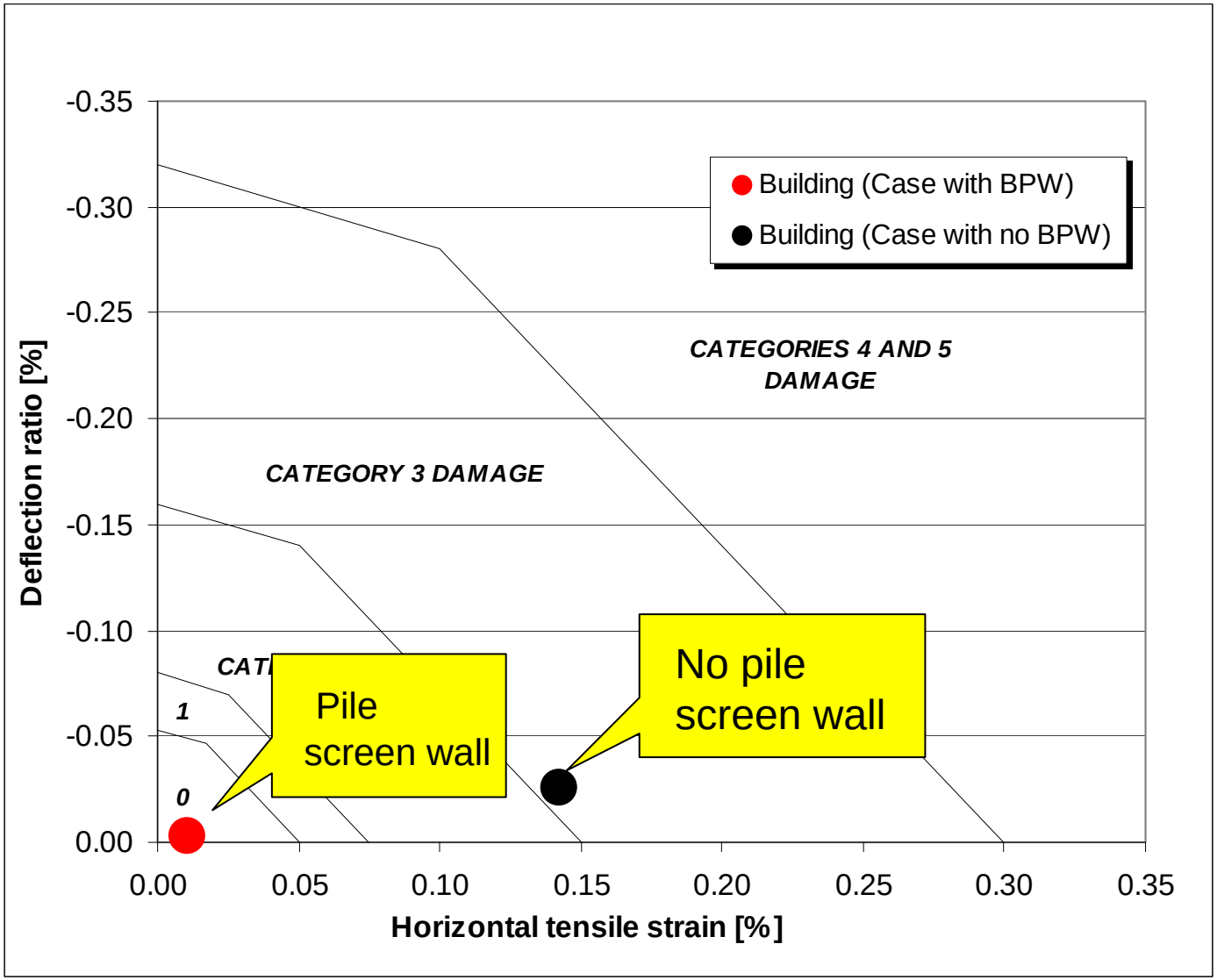
Surface settlements

Pile screen wall



Surface settlements

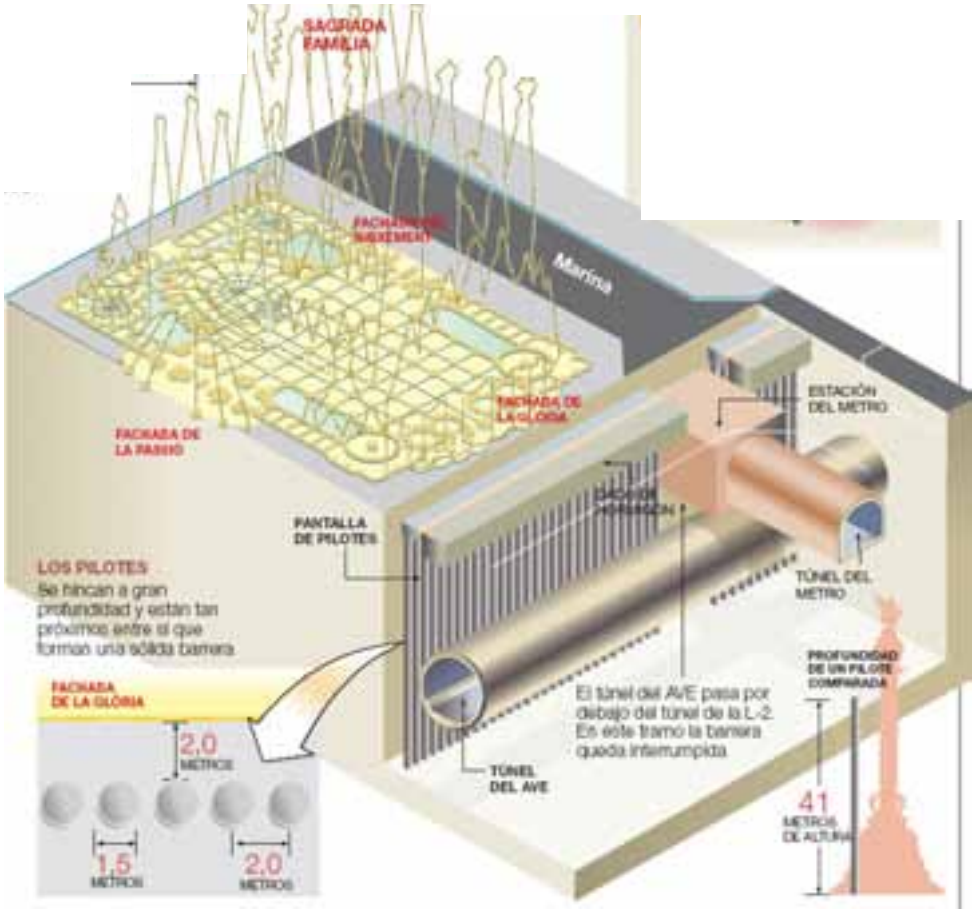
Pile screen wall

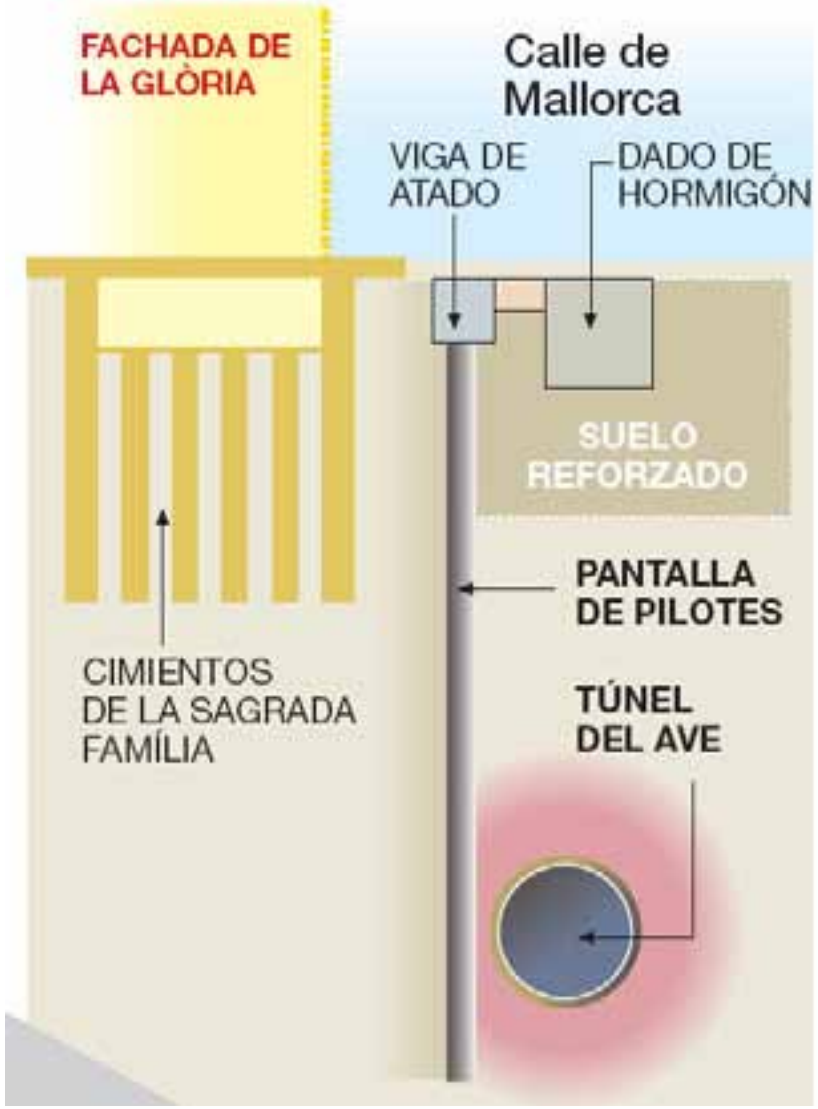


Sant Adrià street PK 2+973

A tunnel close to the Sagrada Familia church (Barcelona)

- Building scheme

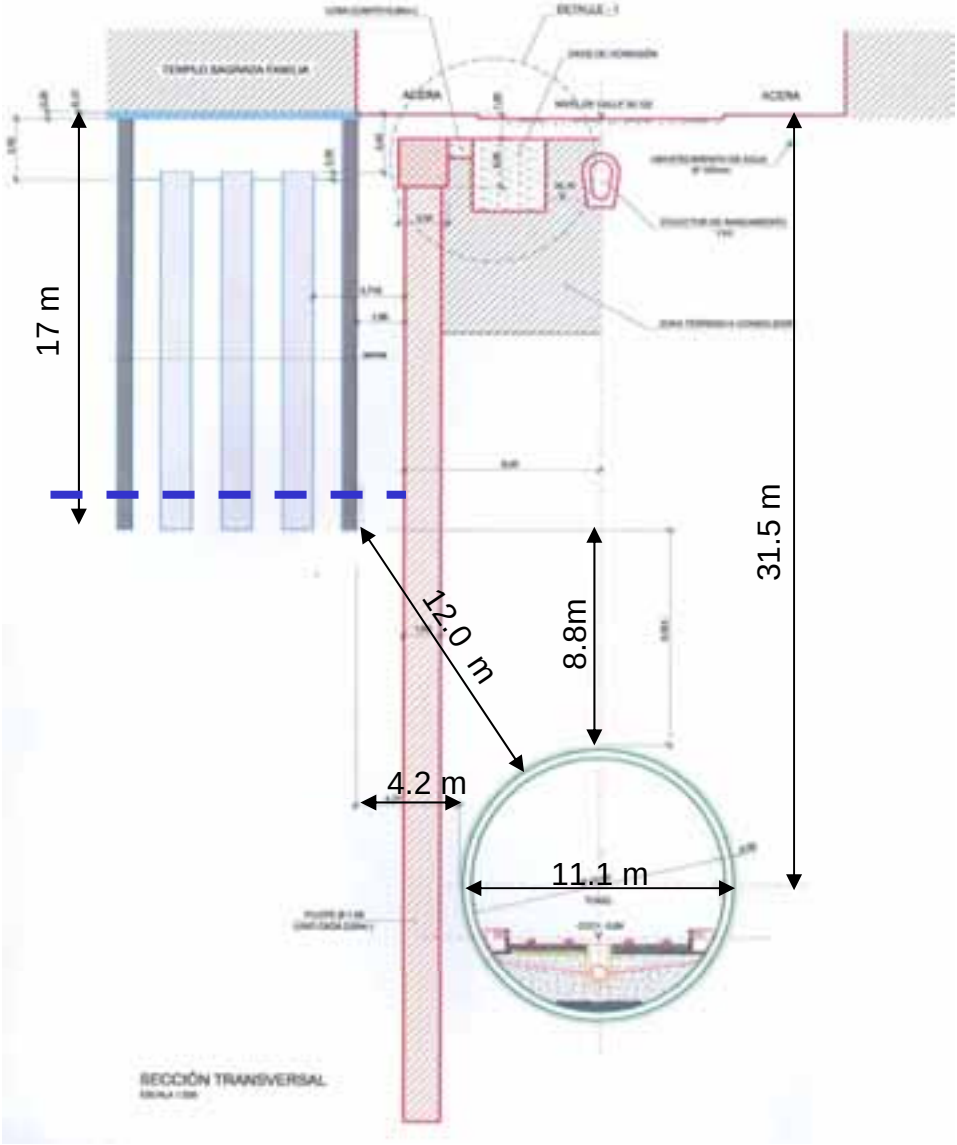




El Periódico

A tunnel close to the Sagrada Familia church (Barcelona)

- Building scheme: cross section

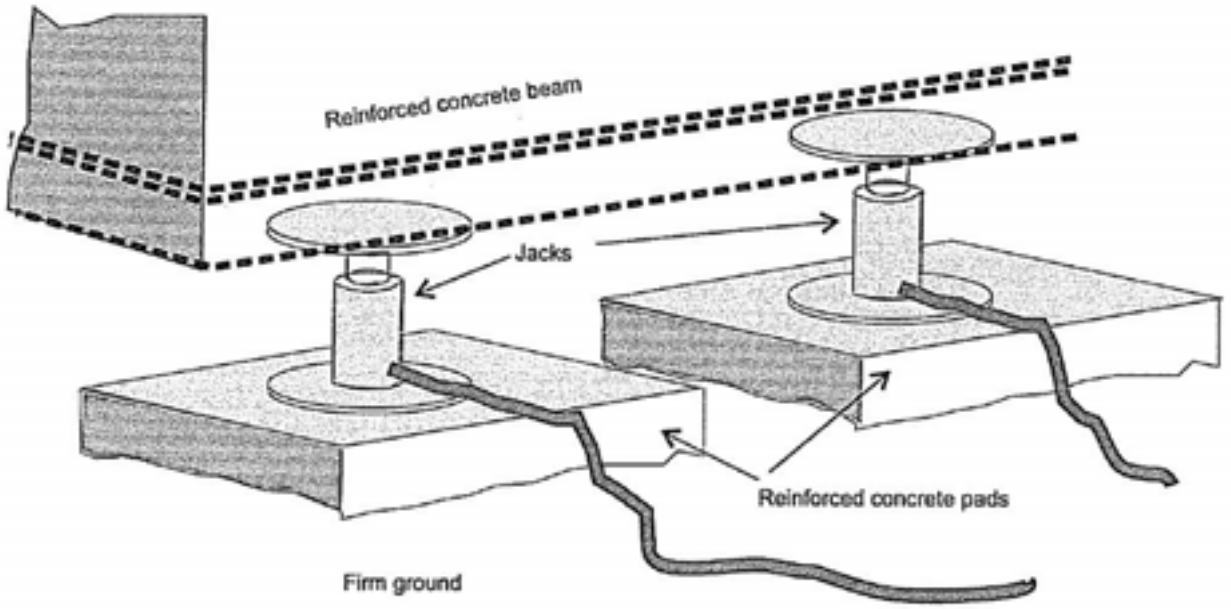


Outline

- Introduction
- Ground movements generated by tunnelling
- Procedures for ground movement control
  - General
  - Tunnelling procedure (TBMs)
  - Screen (curtain) walls
  - Structural movement compensation
  - Compensation grouting
- Final remarks

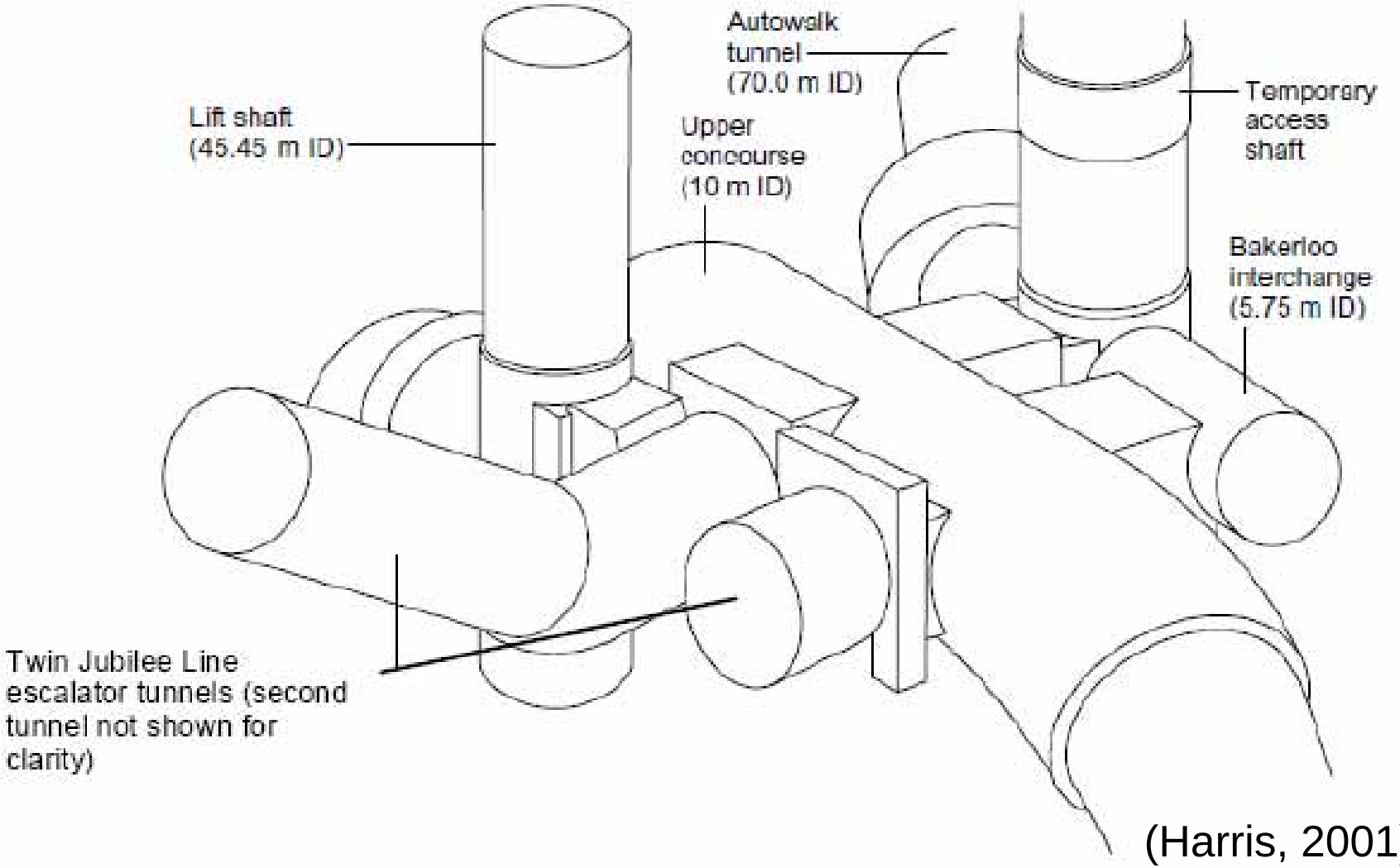
Structure jacking

- Advantages
  - Very precise control of settlement is possible
  - The system is useful in areas with potentially steep settlement gradients
  - The jacks can be use to produce settlements or heave
- Disadvantages
  - Complexity
  - Reaction time may be slow specially for heavy structures



Structural movement compensation

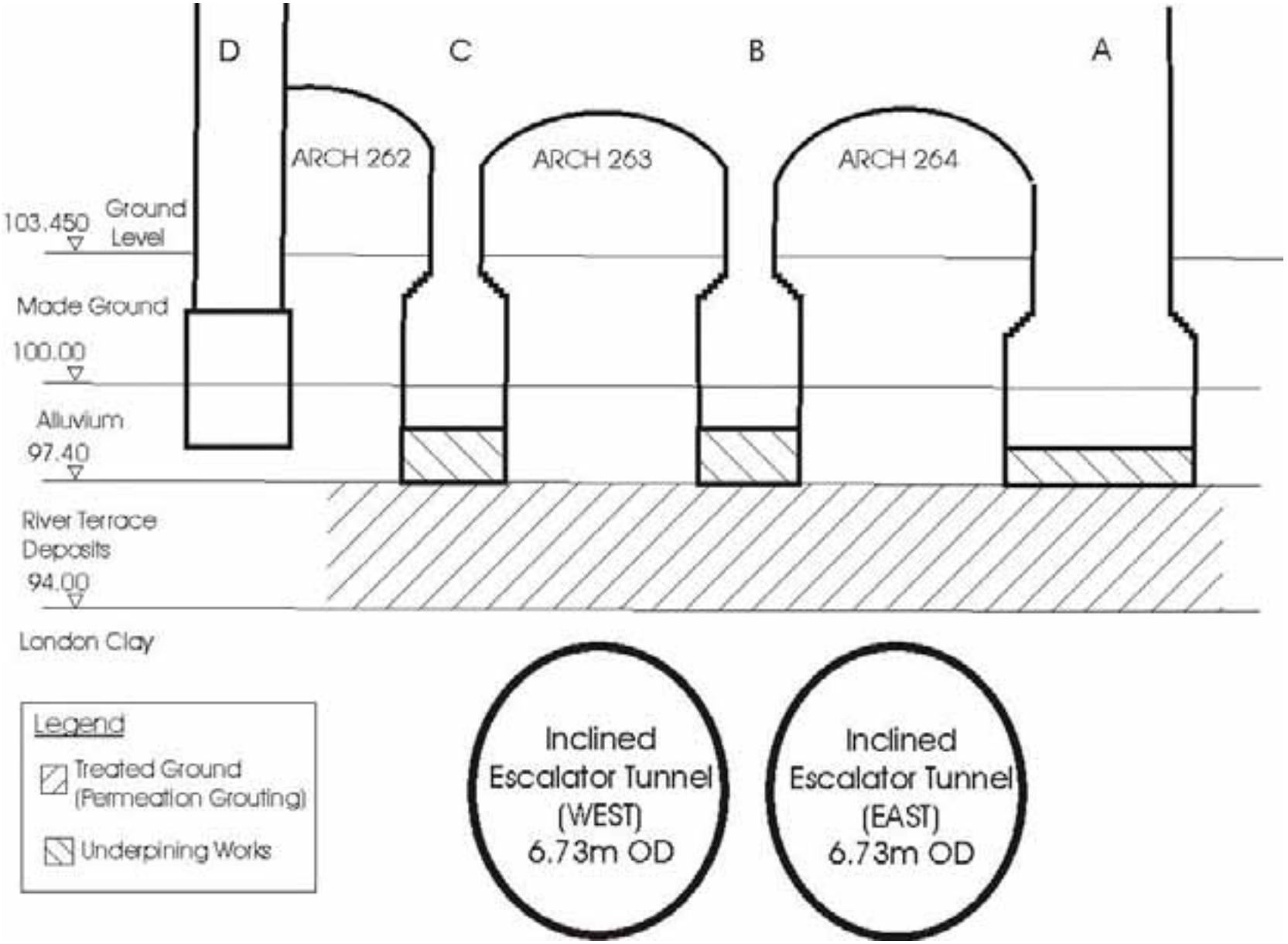
- Twin tunnels in Waterloo station (Jubilee Line Extension)



(Harris, 2001)

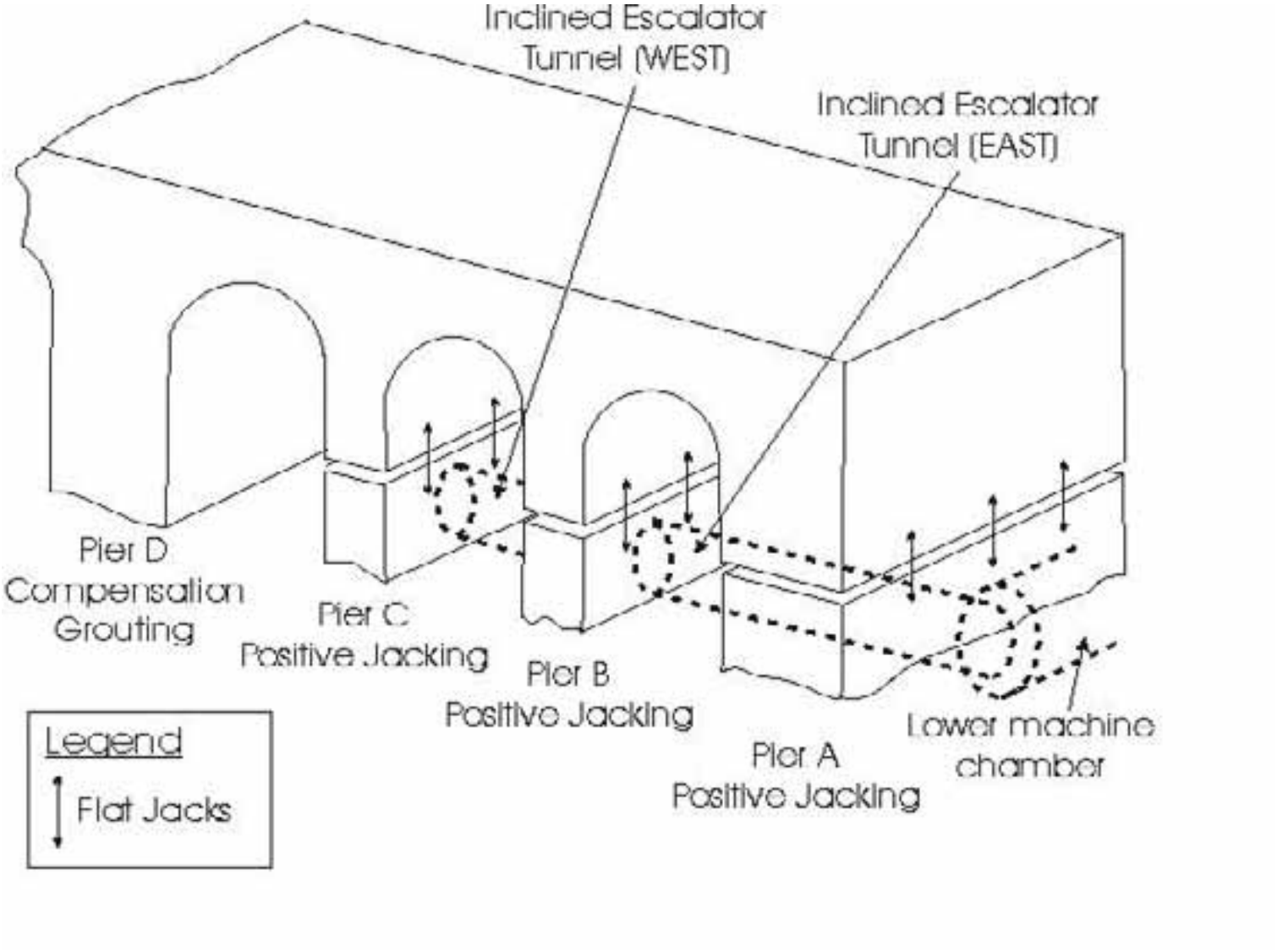
Structural movement compensation

- Cross section



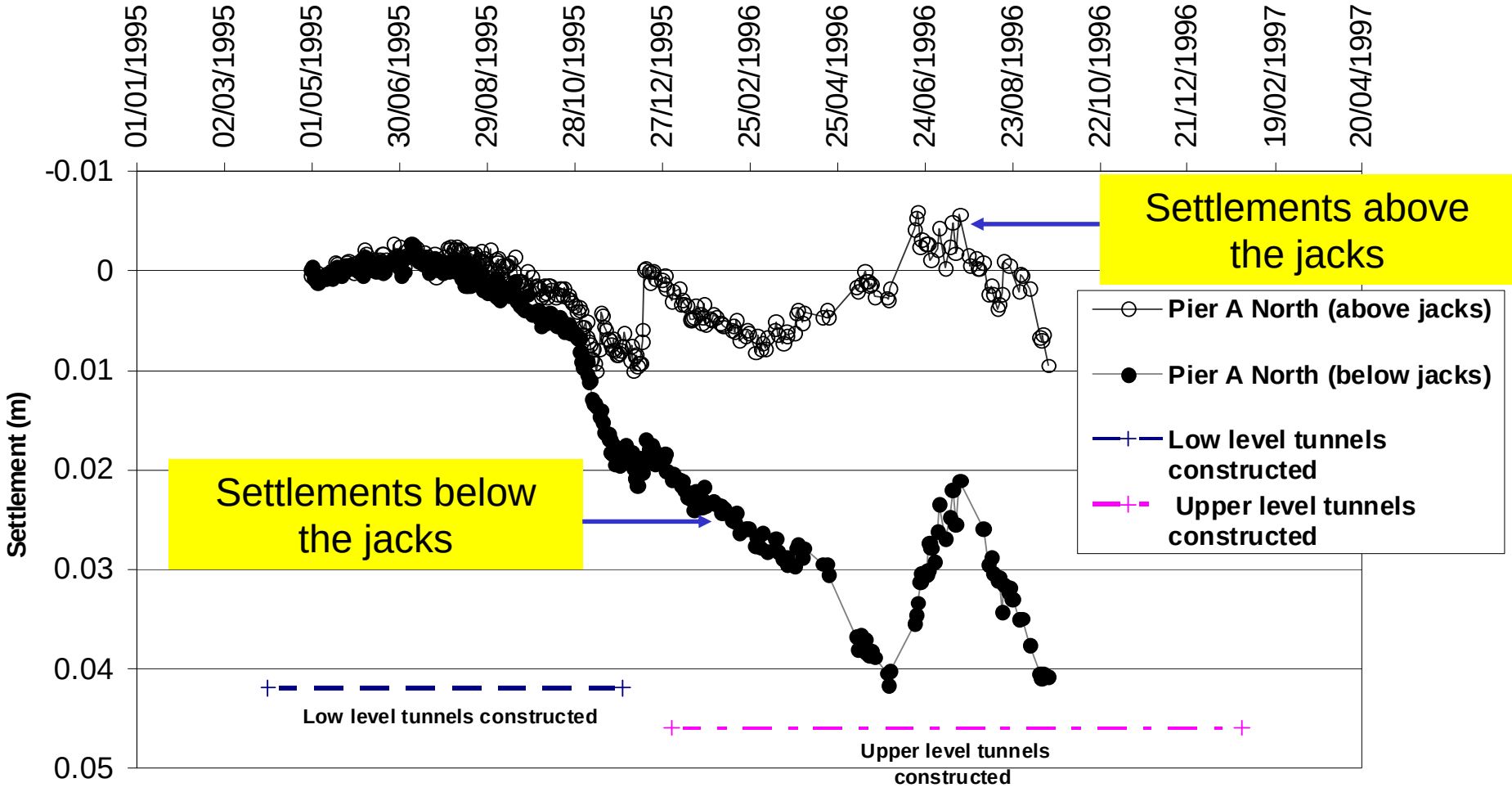
Structural movement compensation

- Lifting points in the structure (flat jacks)



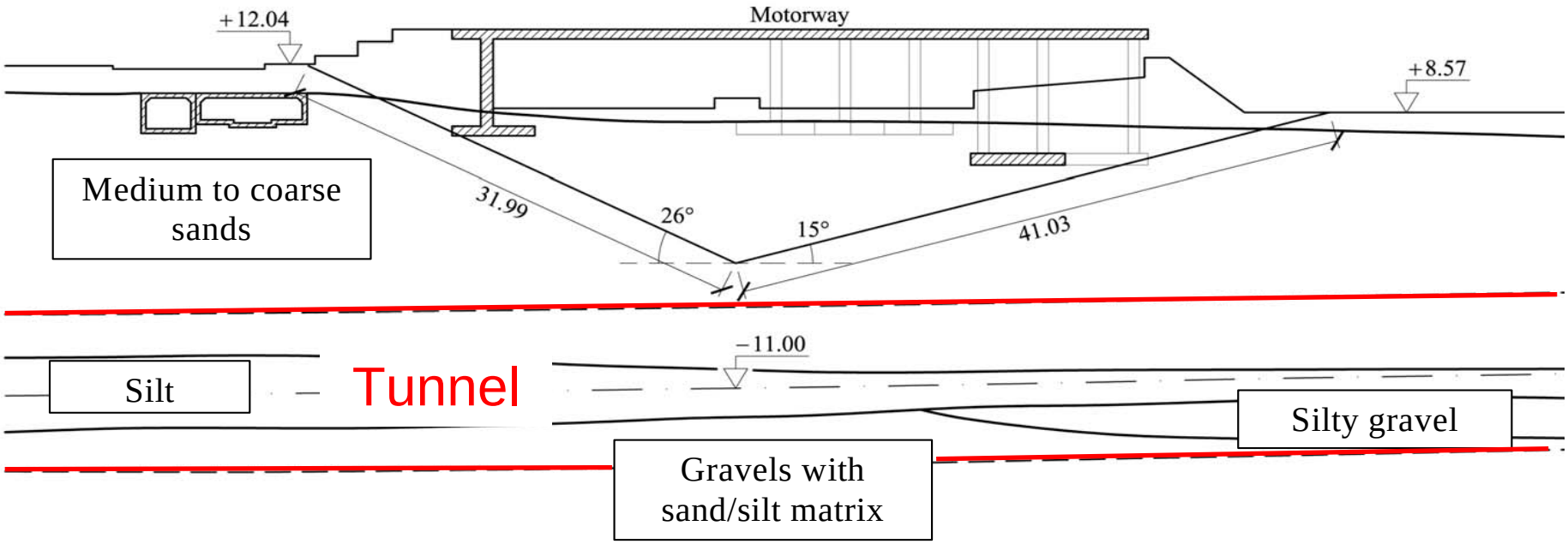
Structural movement compensation

- Twin tunnels in Waterloo station (Jubilee Line Extension)



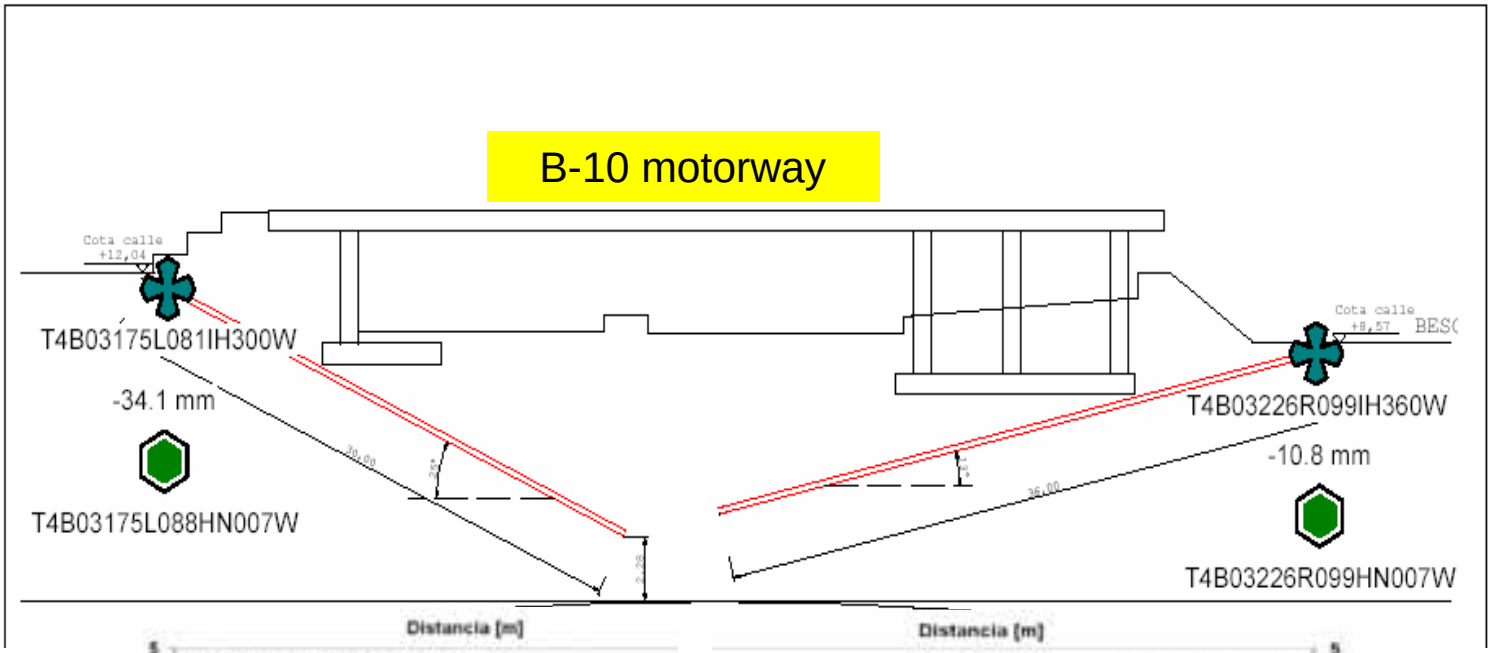
Structural movement compensation

- Passage of Line 9 below an urban motorway



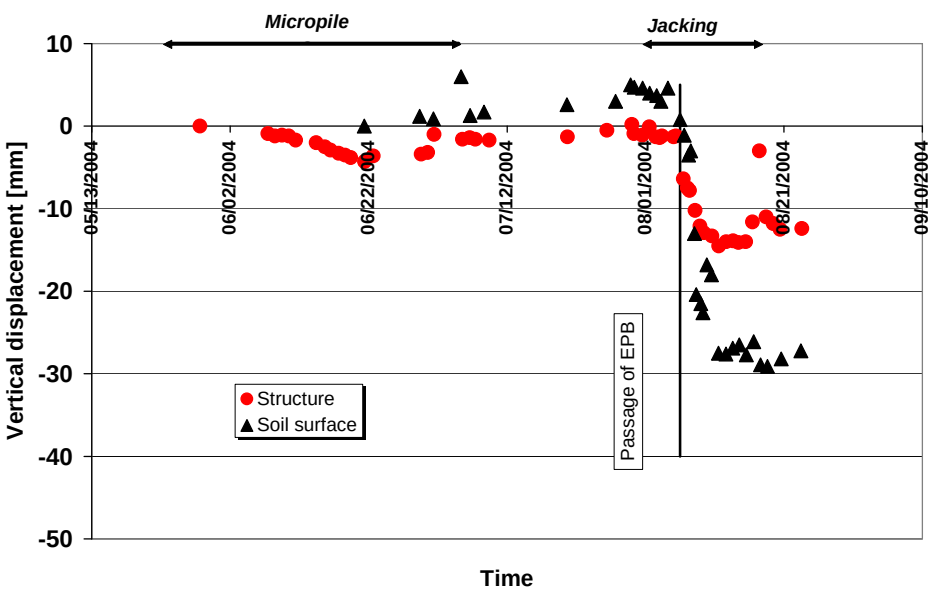
Structural movement compensation

Structural movement compensation

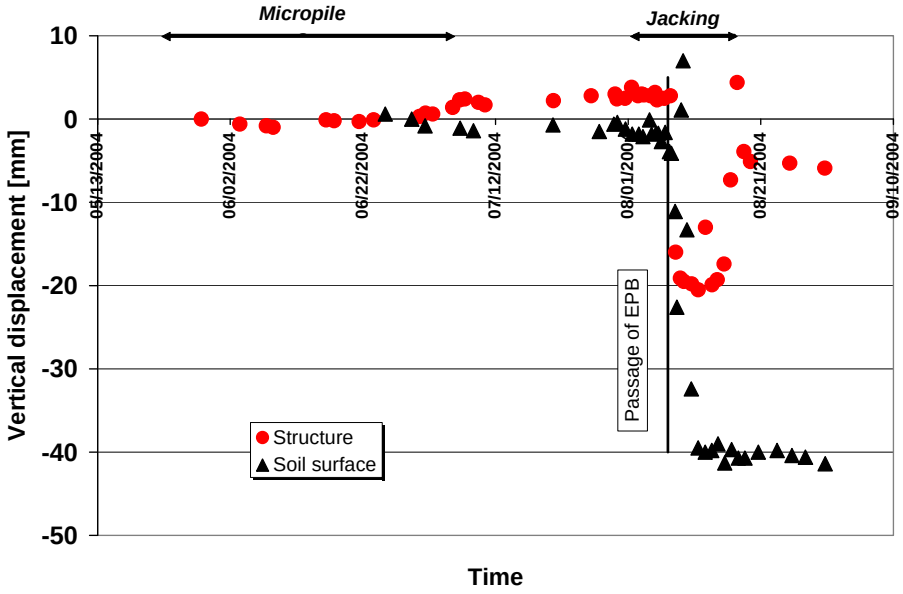


Distribution of vertical movements measured in subhorizontal inclinometers

Structural movement compensation



Abutment wall



Central pier

Surface and structure settlements

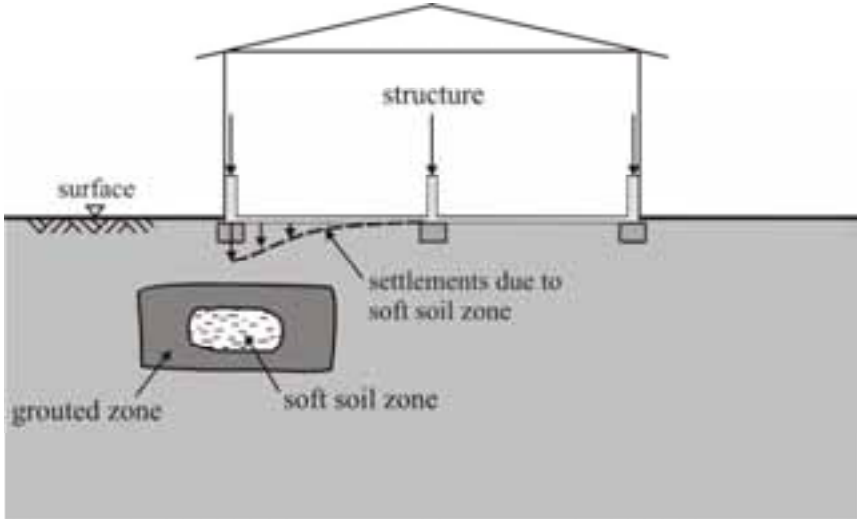
B-10 motorway

Outline

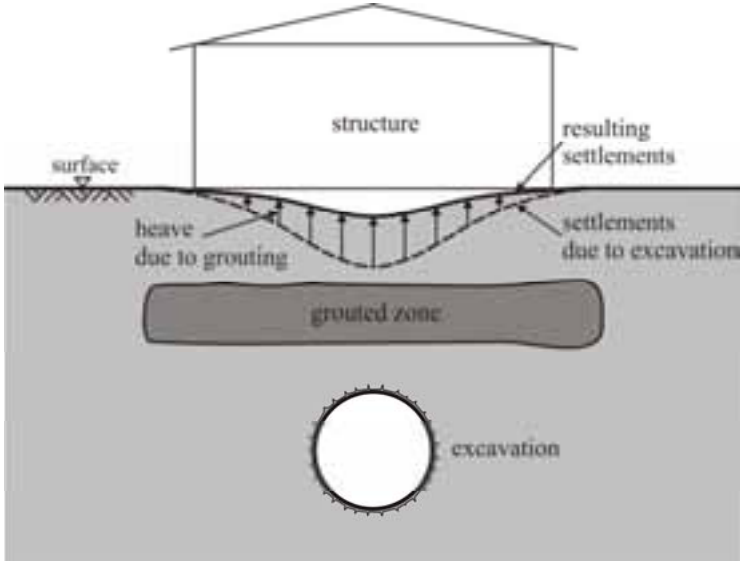
- Introduction
- Ground movements generated by tunnelling
- Procedures for ground movement control
  - General
  - Tunnelling procedure (TBMs)
  - Screen (curtain) walls
  - Structural movement compensation
  - Compensation grouting
- Final remarks

Settlement control by displacement grouting

- Corrective grouting (jacking)
  - Grouting is performed after settlement has occurred



- Compensation grouting
  - Grouting is performed simultaneously with settlement generation
  - Compensation grouting may be:
    - Concurrent
    - Observational

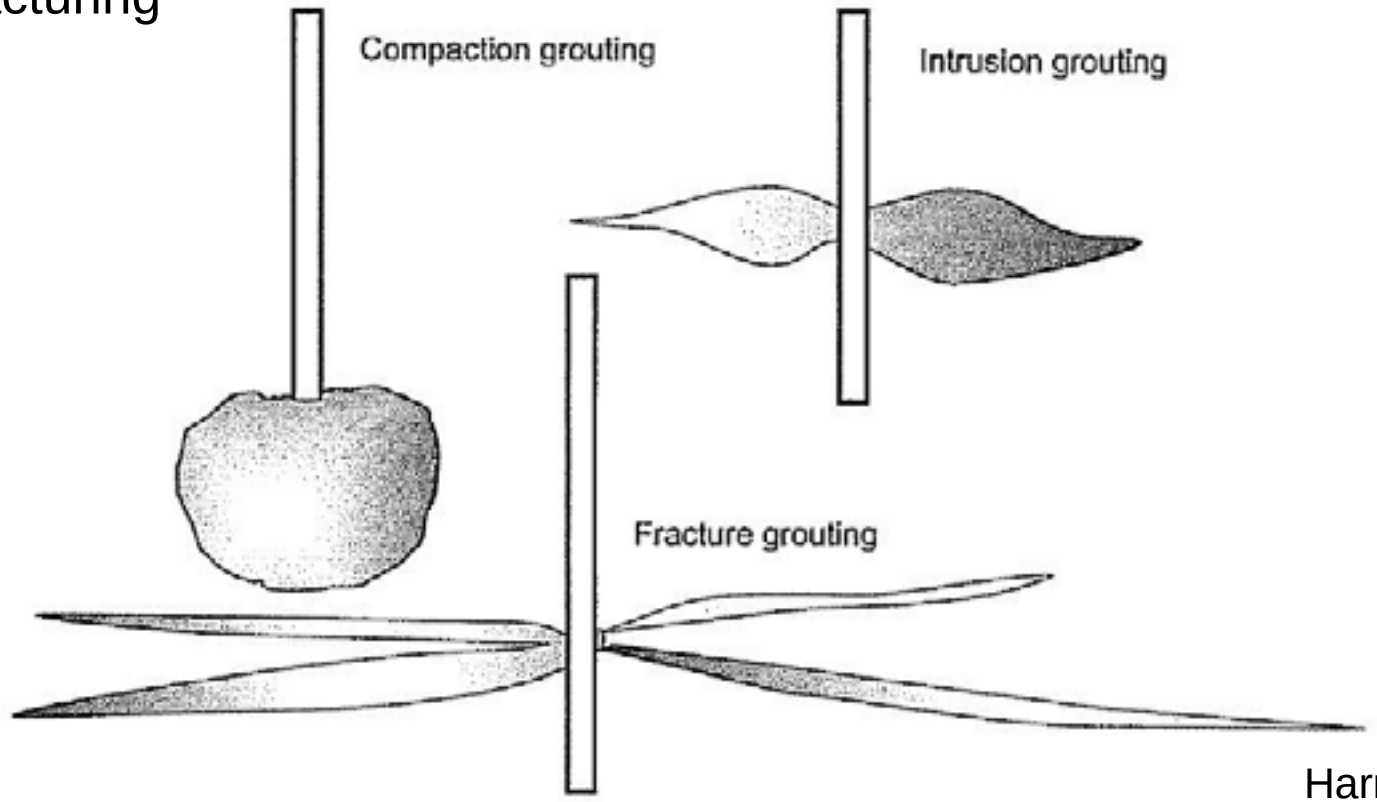


- *Monitoring is a key element of settlement control/compensation*

Kummerer (2003)

Types of grouting

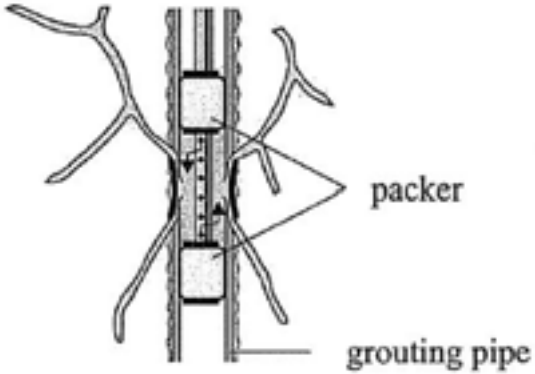
- Compaction grouting
  - Injection of stiff high viscosity grout
- Fracture grouting
  - Injection of low viscosity grout at pressures that cause fracturing
- Intrusion grouting
  - Injection of a fluid grout with a high solids content. Solids remain near point of injection but limited fracturing

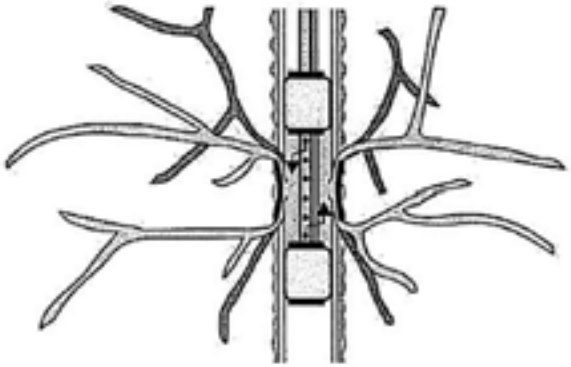


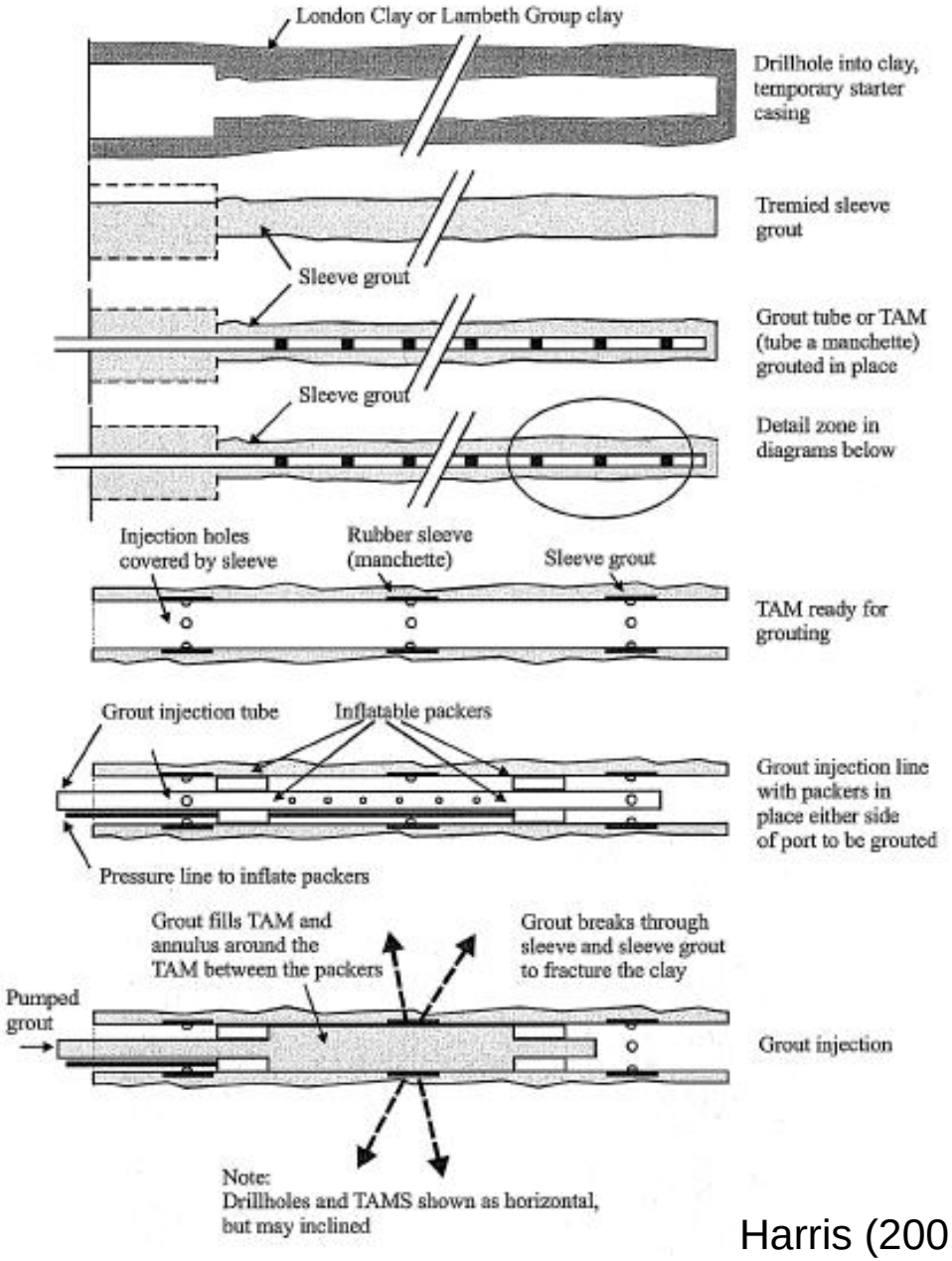
Harris (2001)

Fracture grouting

- TAM (sleeve) grouting

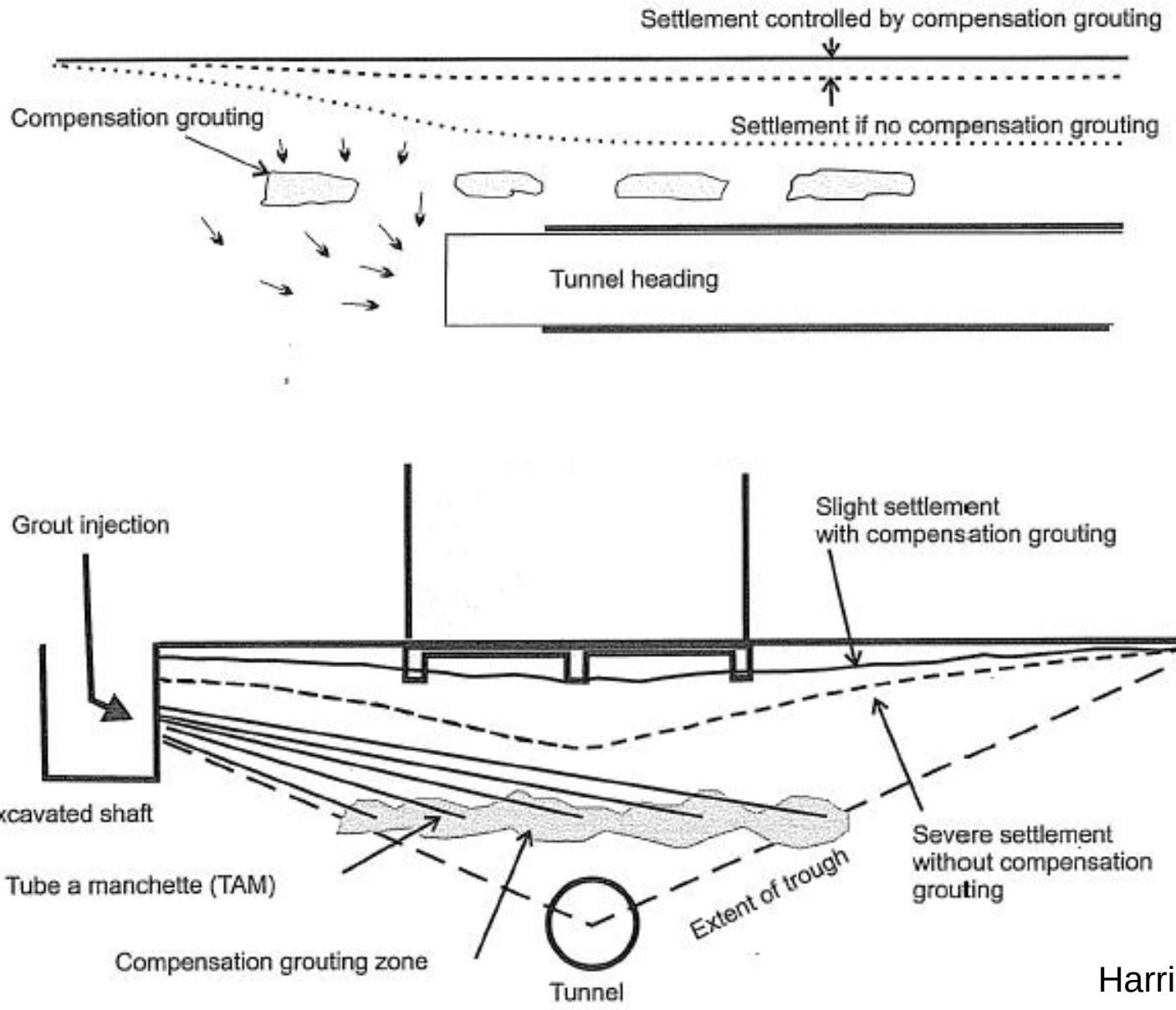






Harris (2001)

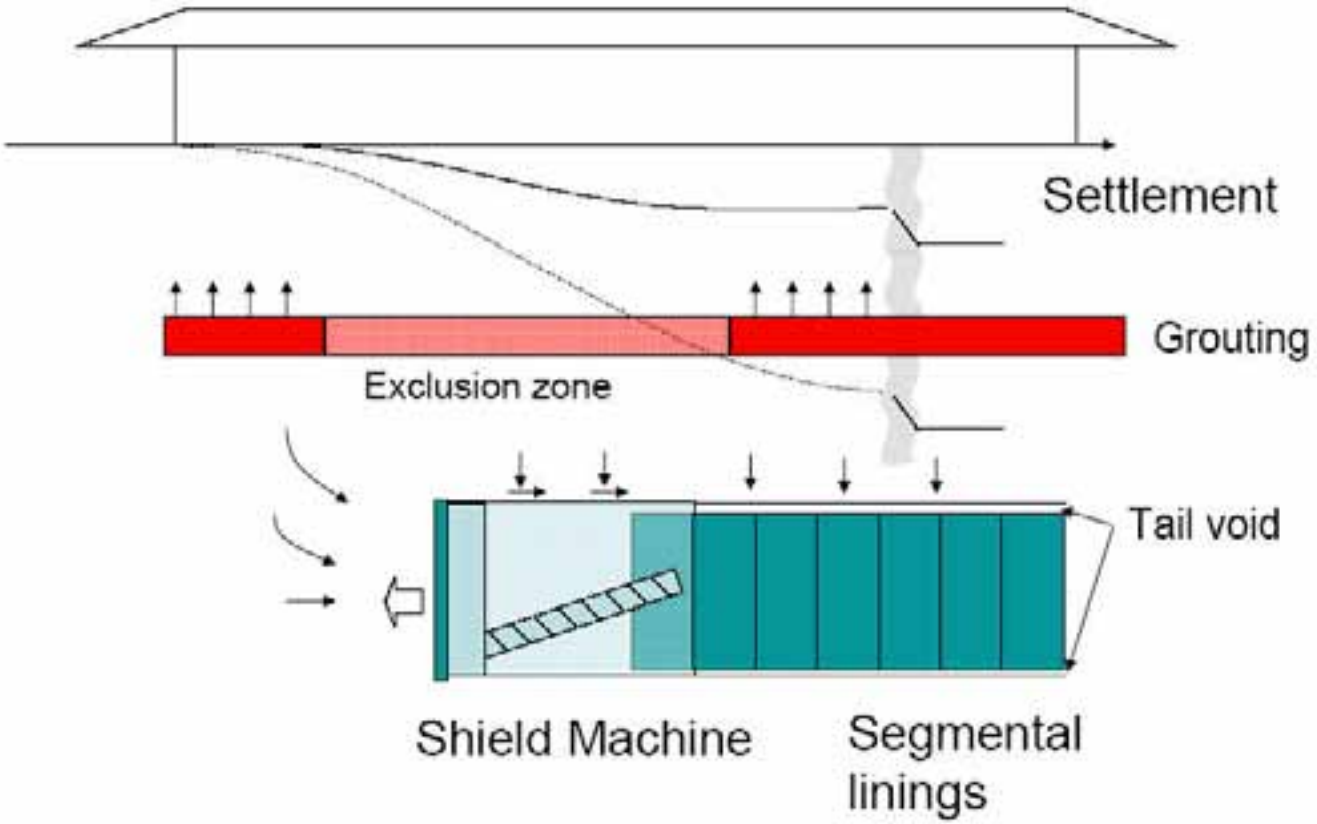
Compensation grouting



Harris (2001)

Compensation grouting

- The conceptual aim is to compensate the ground movements in the same zones where subsidence is generated
- This principle is not consistent with the need to leave anexclusion zone near the tunnel face
- There are practical difficulties to perform true compensation grouting when THM excavation advances rapidly



Compensation grouting: a bit of history

- Compaction grouting
  - Bolton Hill Tunnels, Baltimore (Baker et al, 1983)
  - Minneapolis tunnel (Cording et al., 1989)
  - By the 1990's compensation using compaction grouting well established in the US (Littlejohn, 2003)
- Fracture grouting
  - Essen in 1986 (Chambosse & Osterbein, 2001)
  - Vienna metro (Pototschnik, 1992)
  - Other tunnels in Germany & Austria (e.g. Raabe, 1989)
  - First used in UK in Waterloo station, 1992 (Mair & Hight, 1994)
  - Extensive use in Jubilee extension line, London (well documented; Burland, Standing & Jardine eds.)
  - Used extensively: Lisbon, Porto, Madrid, Barcelona, Antwerp and many others (also sometimes used in the US)
- The term ***compensation grouting***
  - Apparently coined by D.W. Hight (GCG) (Mair, 1994)

Compensation grouting

Compaction grouting vs. Fracture grouting

Compaction grouting

- Better control of grout extension
- More robust with respect to implementation parameters
- Repeat grouting requires redrilling
- Higher injection pressures
- Creates a smaller region of pore pressure increase
- Dominant in the US

Fracture grouting

- Little control of fracture extension and direction
- Multiple injection is straightforward (TAM grouting)
- Lower efficiency?
- Lower injection pressures
- Creates a larger region of pore pressure increase
- Dominant in the Europe

Compensation grouting

- Execution phases
  - Drilling and installation of TAMs
  - Preliminaty grouting
    - Pre-treatment grouting (immediately after installing TAMs)
    - Conditioning grouting (compress the ground, restore decompression caused by drilling and installation, leave the ground ready for lifting)
  - Concurrent grouting (during tunnel drilling/excavation)
  - Corrective grouting. After tunnel drilling/excavation

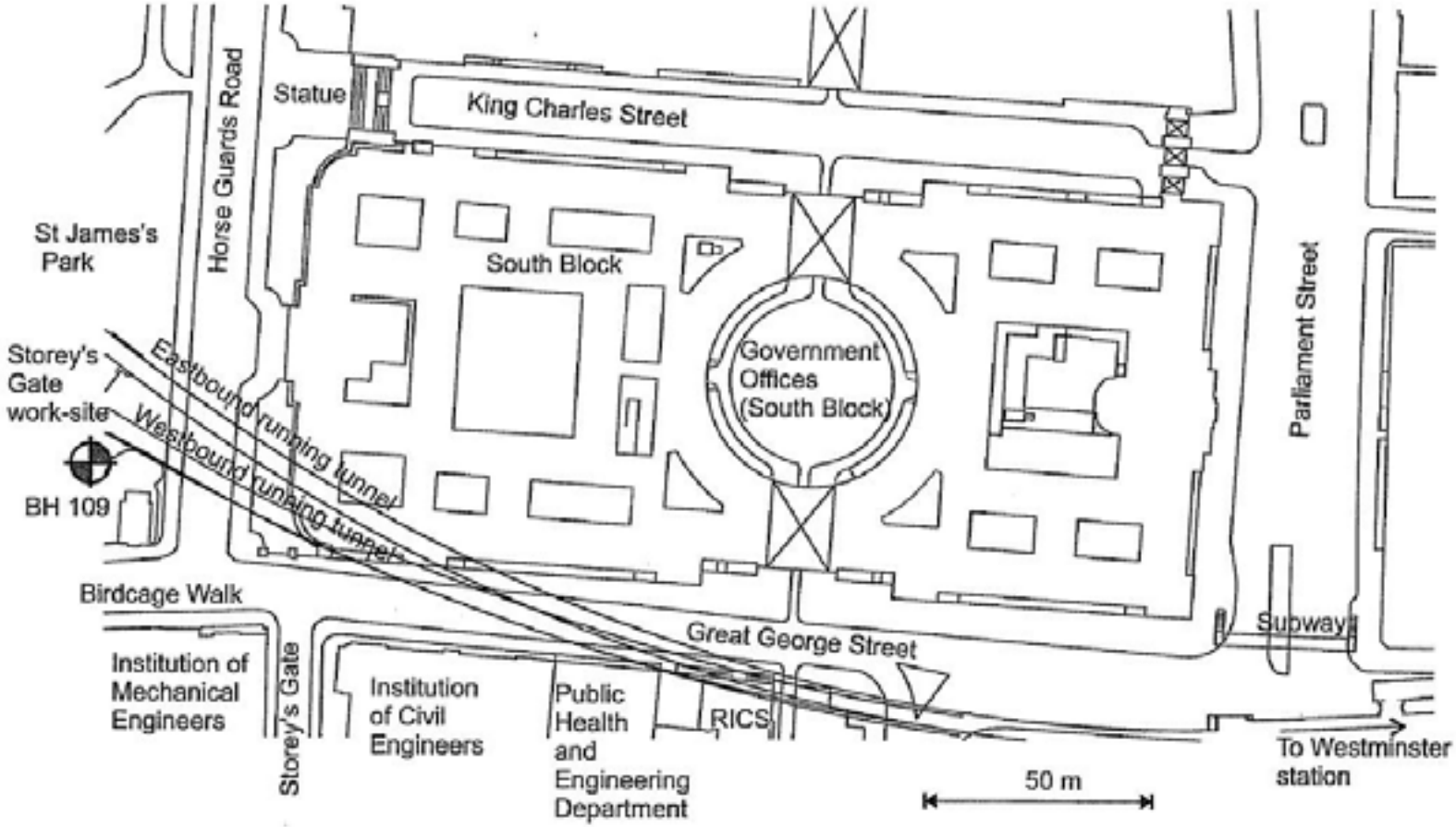
Compensation grouting

- Treasury Building (Jubilee Line Extension)

Viggiani and Standing (2001)

Compensation grouting

- Treasury Building (Jubilee Line Extension)



Plan view

Viggiani and Standing (2001)

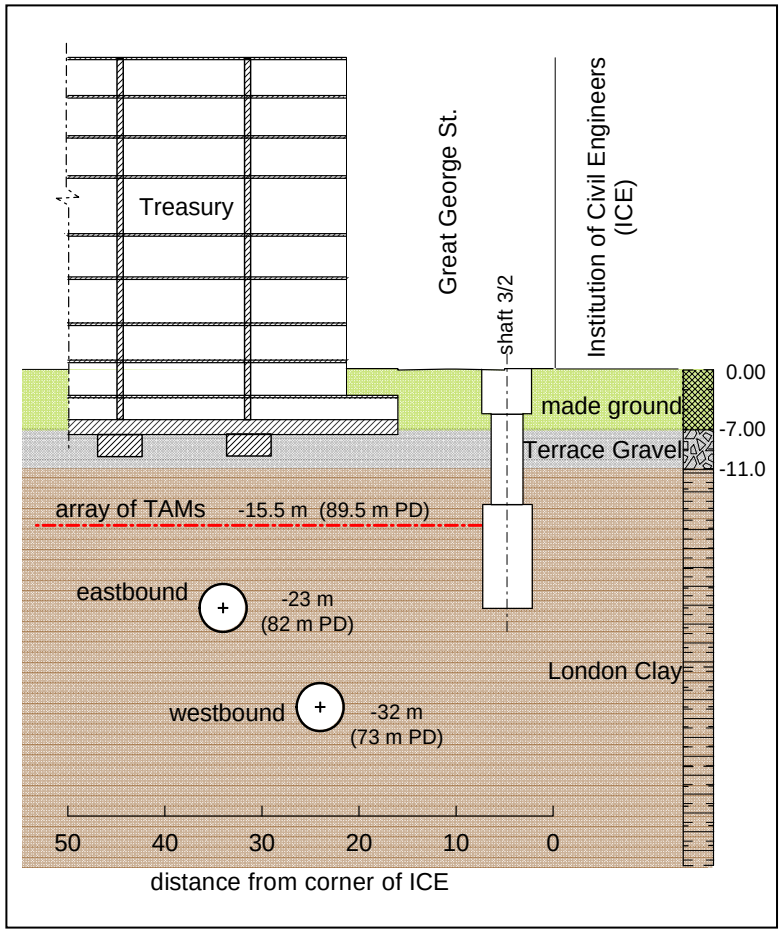
Compensation grouting

- Treasury Building (Jubilee Line Extension)

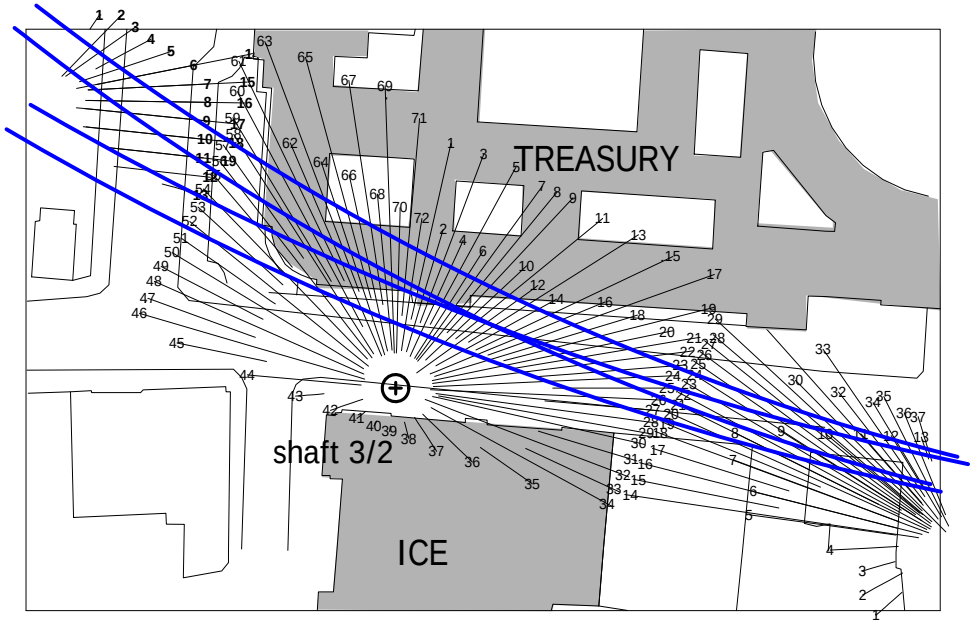
Viggiani and Standing (2001)

Compensation grouting

- Treasury Building (Jubilee Line Extension)



Cross section



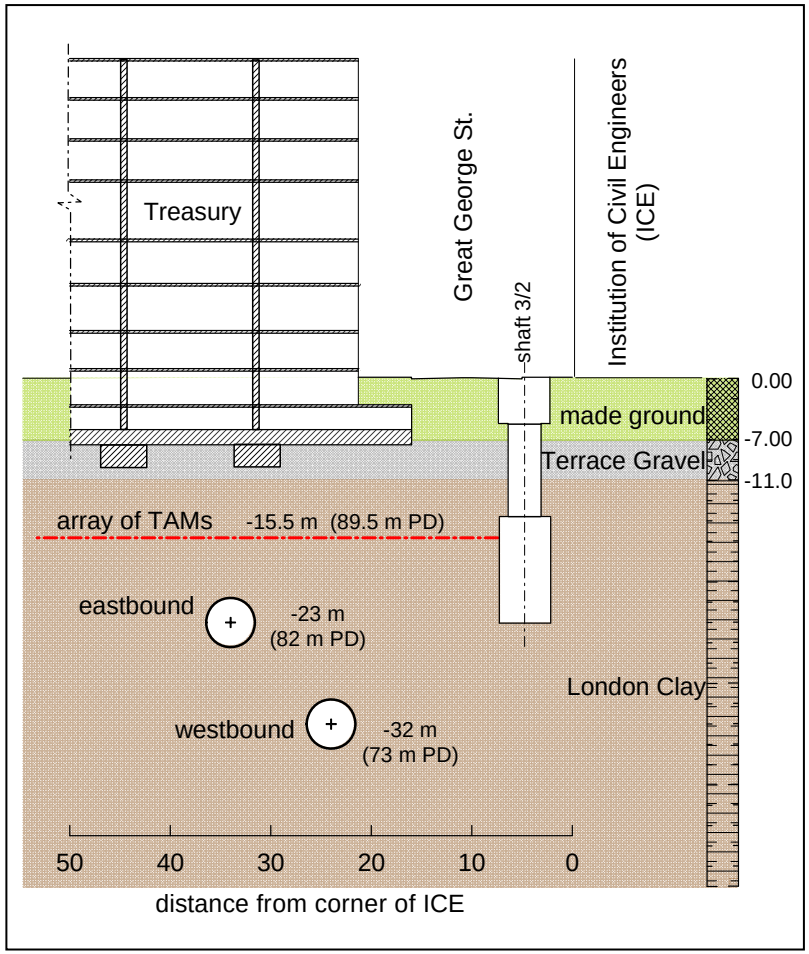
TAM array

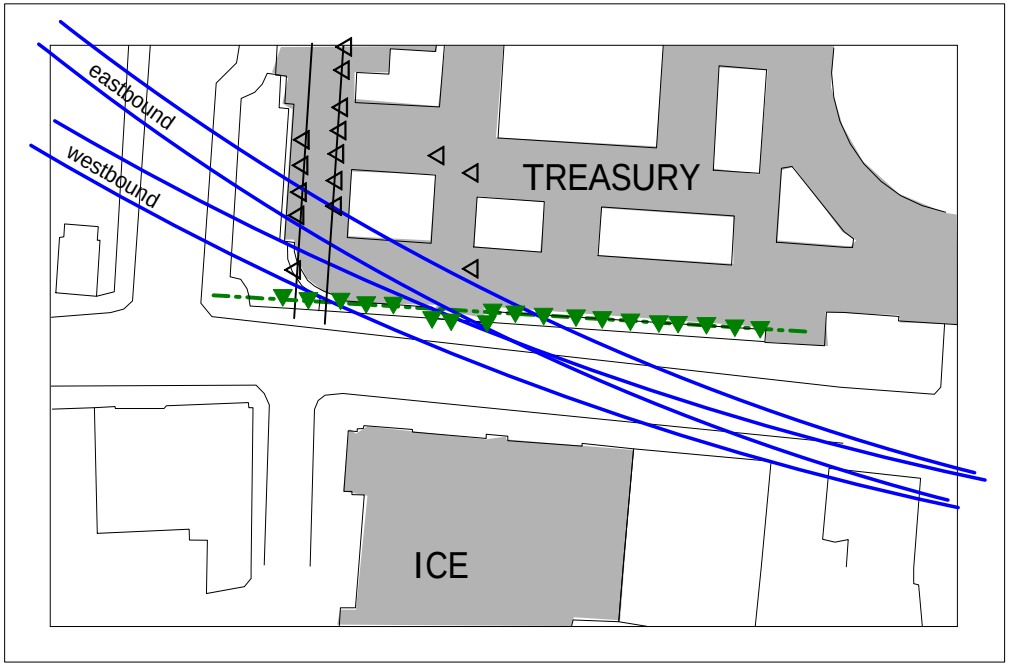
- 2 x 5m dia. Tunnels excavated with open-face shield

Viggiani and Standing (2001)

Compensation grouting

- Treasury Building (Jubilee Line Extension)

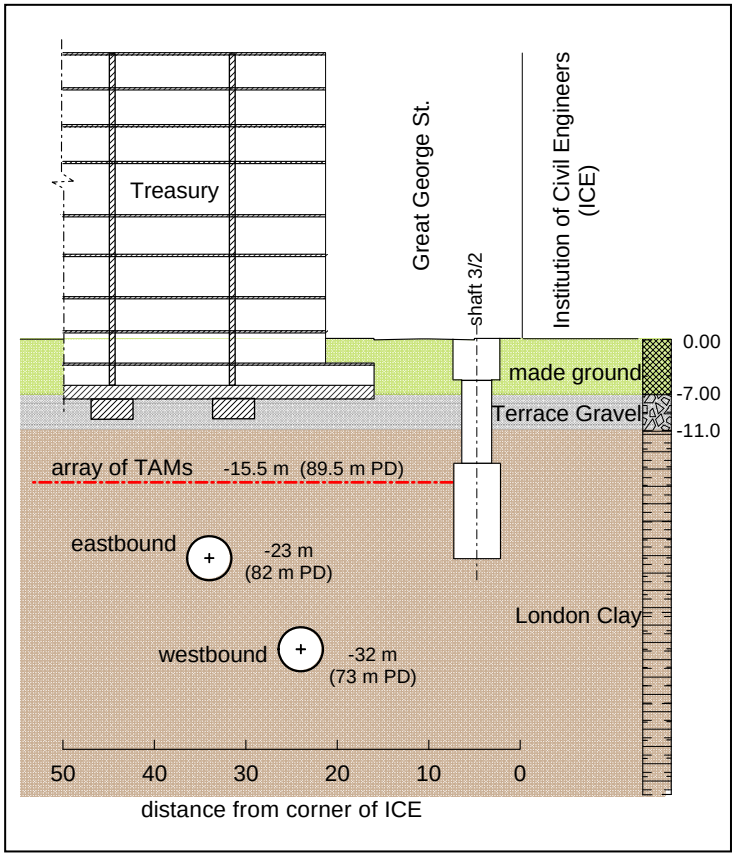


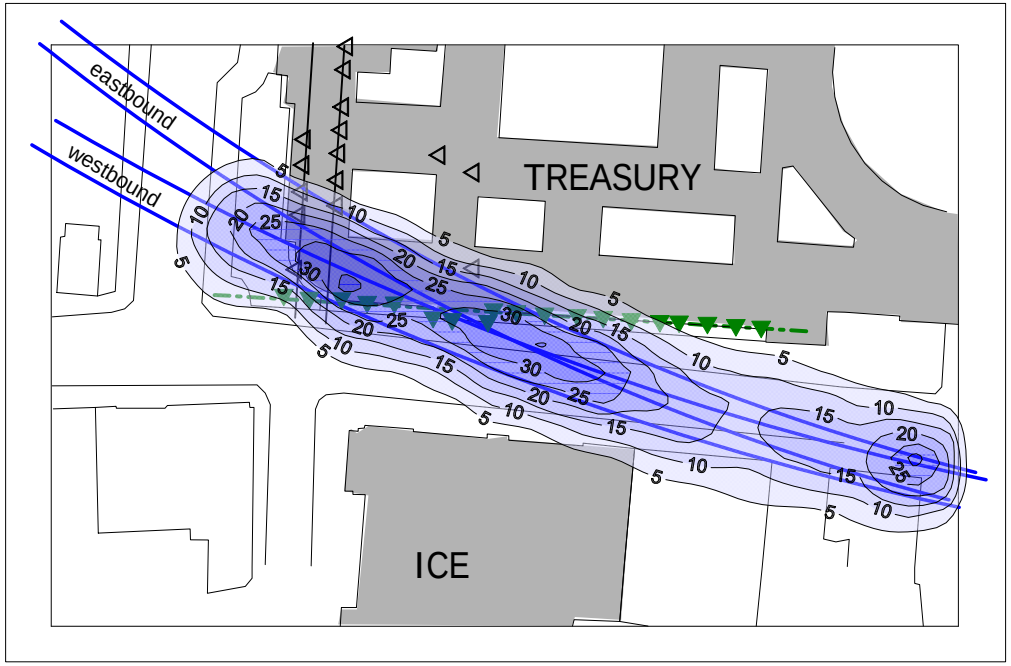


Location of levelling points

Compensation grouting

- Treasury Building (Jubilee Line Extension)





Contours of grouting intensity (l/m^2)

Observational grouting performed after drilling West tunnel

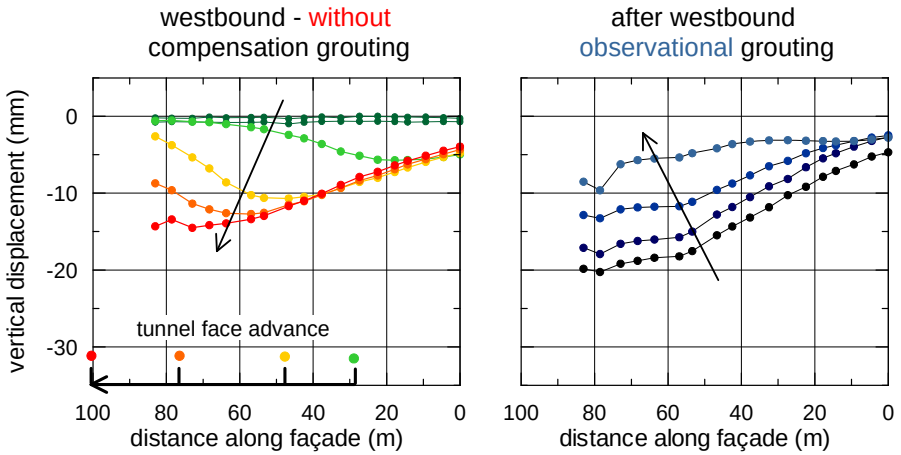
- GEF = 0.3-0.5 (0.7 in the final stage)

Viggiani, 2001

Compensation grouting

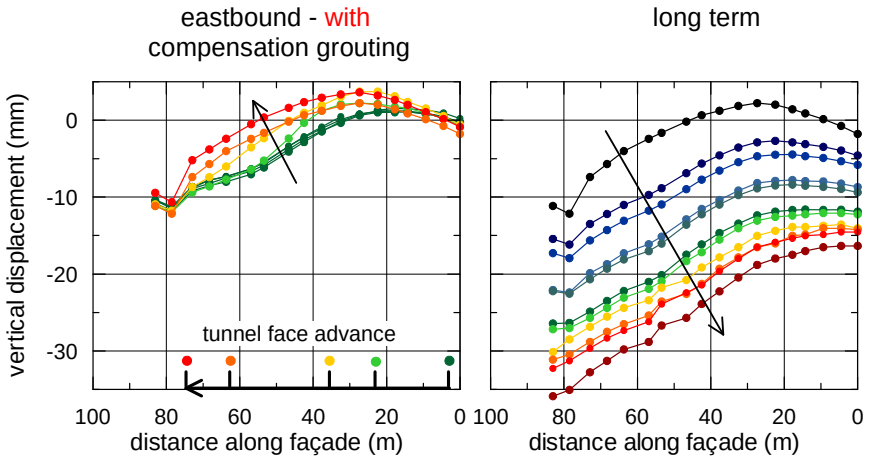
- Treasury Building (Jubilee Line Extension)

West tunnel
No compensation grouting



West tunnel
Corrective grouting

East tunnel
With compensation grouting



Long term settlements

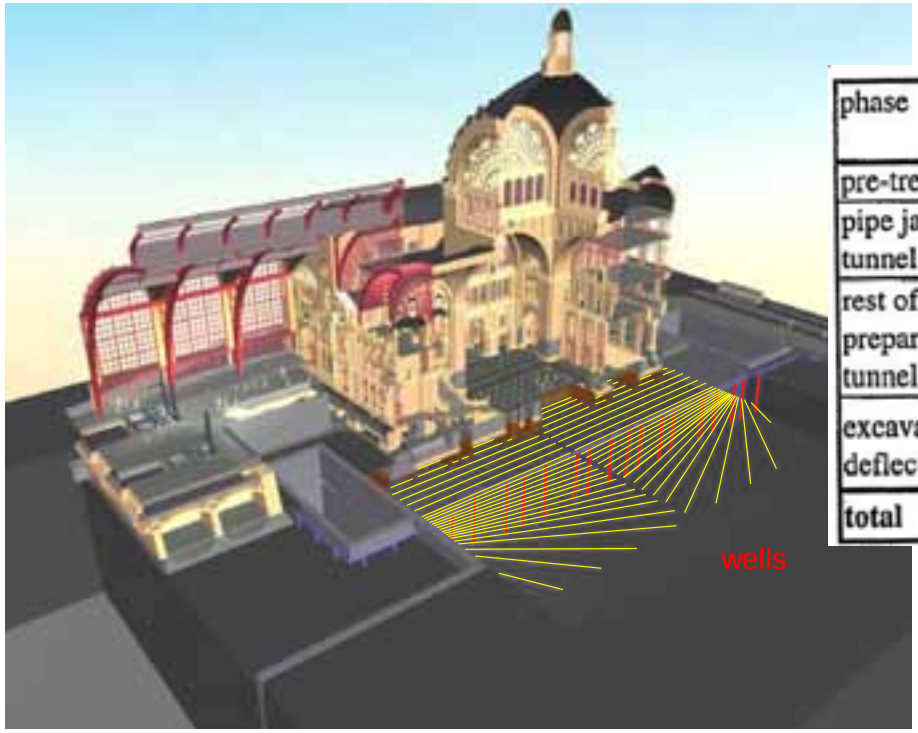
Settlements

- Transitory movements more severe

Viggiani and Standing (2001)

Compensation grouting

- GEF = Grout Efficiency Factor
  - GEF = Volume of ground heave/ volume of grout injected
    - Typical values for fracture grouting in stiff clays: 0,3 – 0,5; in granular soils can be as low as 0.05 - 0,1
    - In soft clays with low OCRs, GEF can be negative
  - GEF usually increases as grouting progresses



phase	grout volume (litres)	average per injection (litres)	efficiency (%)
pre-treatment	330,000	50	10
pipe jacking and part of tunnel walls	200,000	25	20
rest of tunnel walls and the preparatory work for the tunnel excavation	50,000	15	30
excavation of the tunnel and deflection of the roof slab	170,000	15	35
total	**750,000**	**33**	**20**

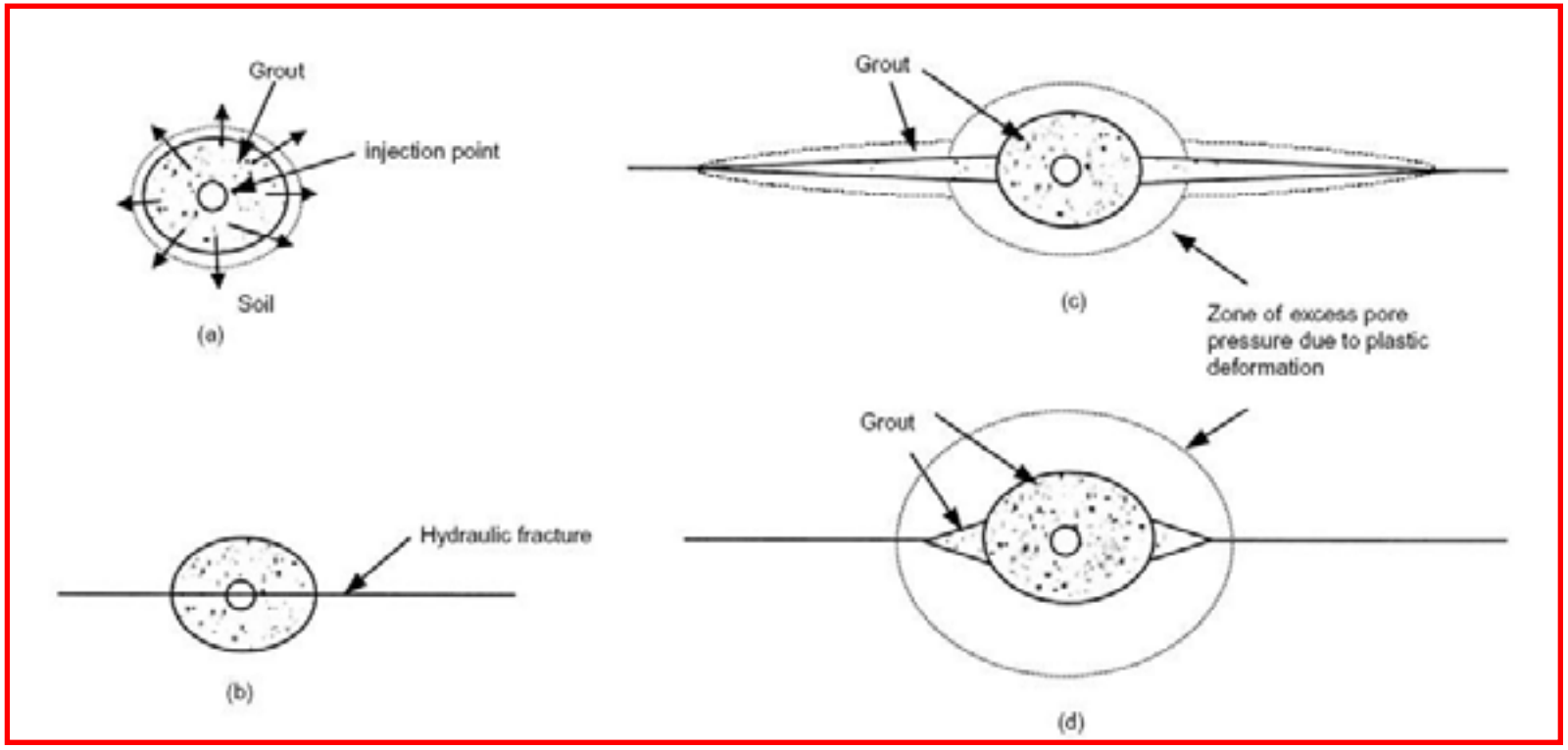
Antwerp Central Station

Kummerer at al. (2003)

Compensation grouting

❑ Use of compensation grouting in soft clays

- Grouting generates pore pressures especially in soft clays
- Dissipation of pore pressures will cause settlement and counteract compensation grouting heave

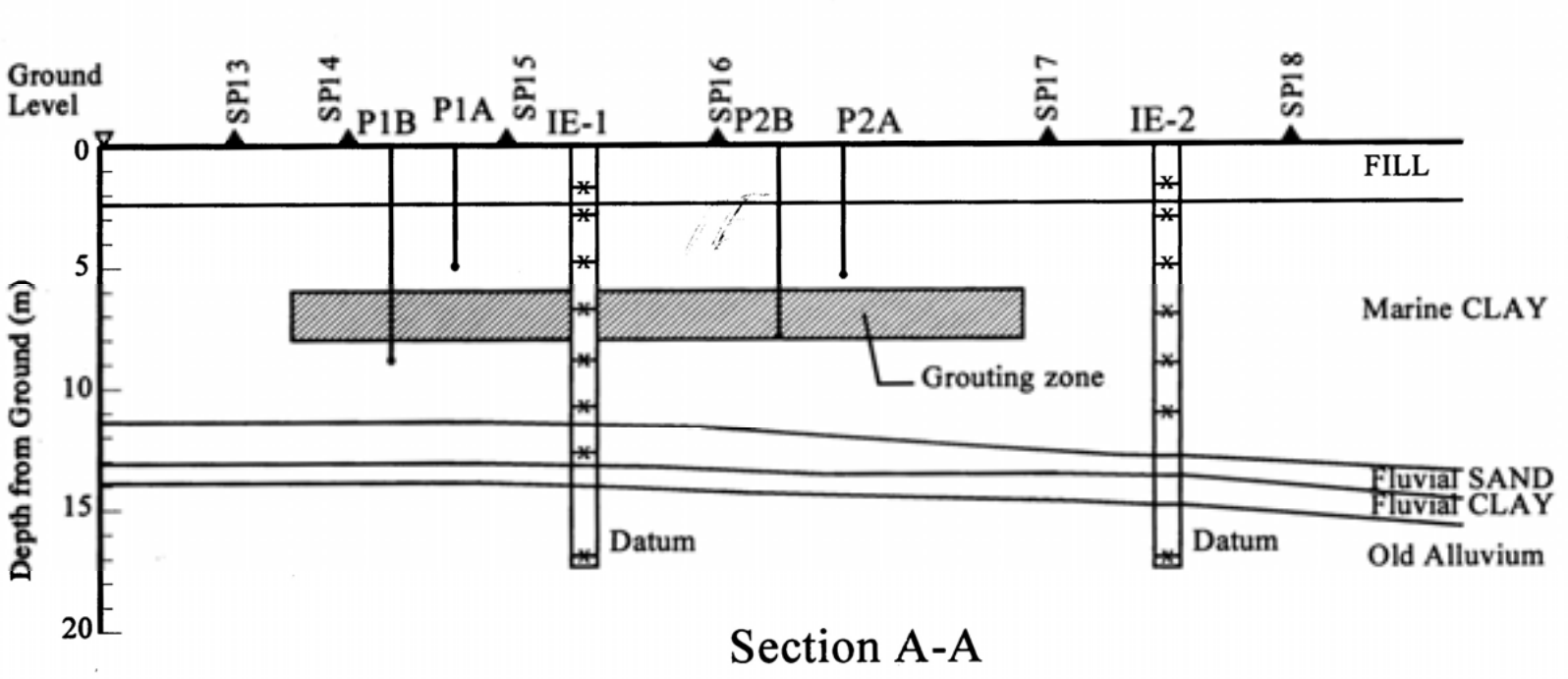


Komiya et al. (2001)

Compensation grouting

❑ Use of compensation grouting in soft clays

- Compensation grouting trial in Singapore marine clay (Shirlaw et al., 1999)



Section A-A

P1A,P1B,P2A,P2B- Vibrating wire piezometers

IE1 & IE2- Inclinometers with magnet extensometers

X- Magnets

Compensation grouting

❑ Use of compensation grouting in soft clays

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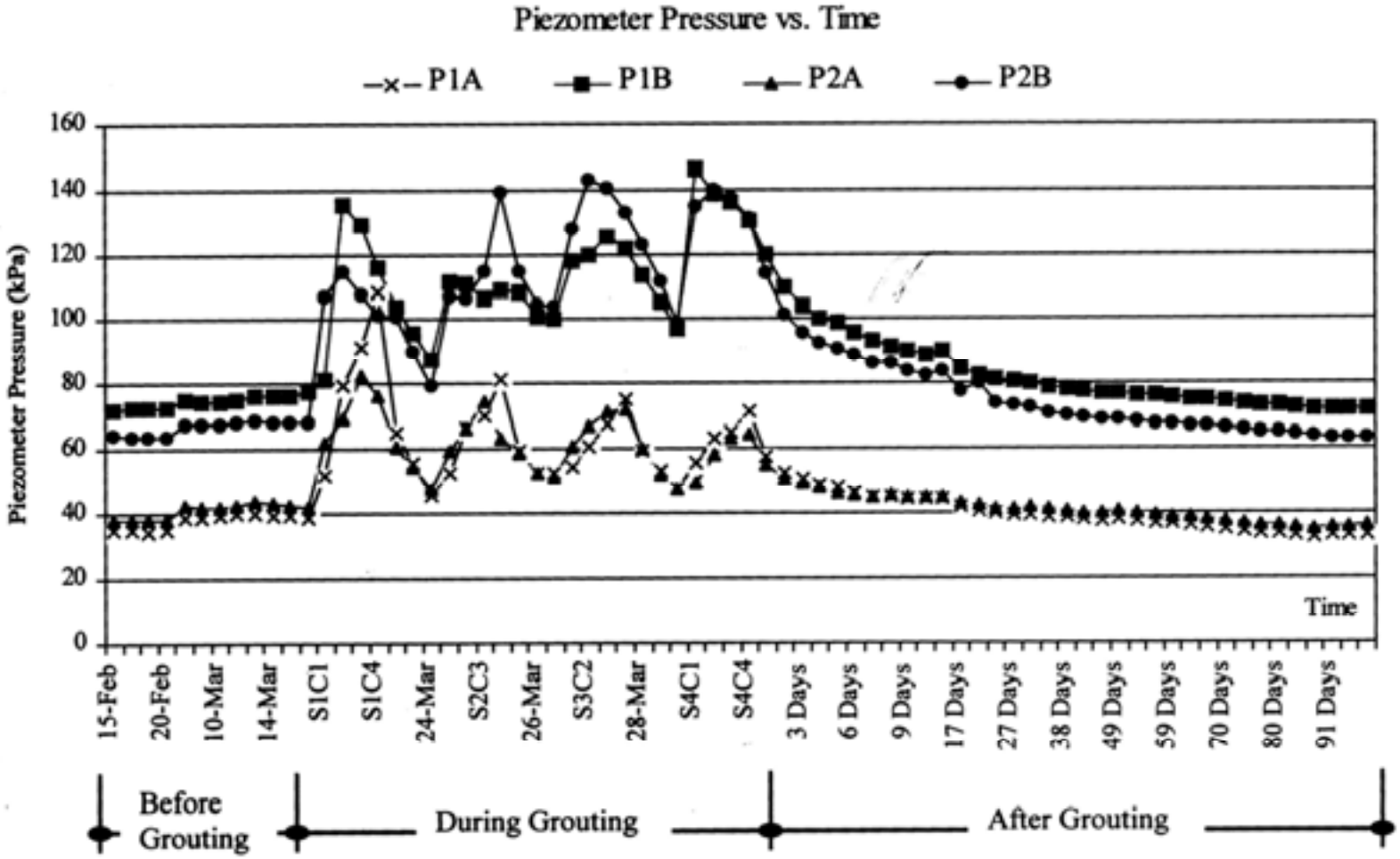

Compensation grouting

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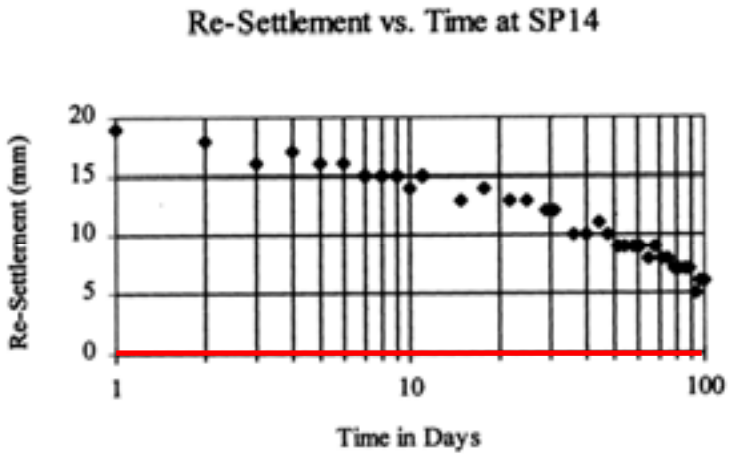
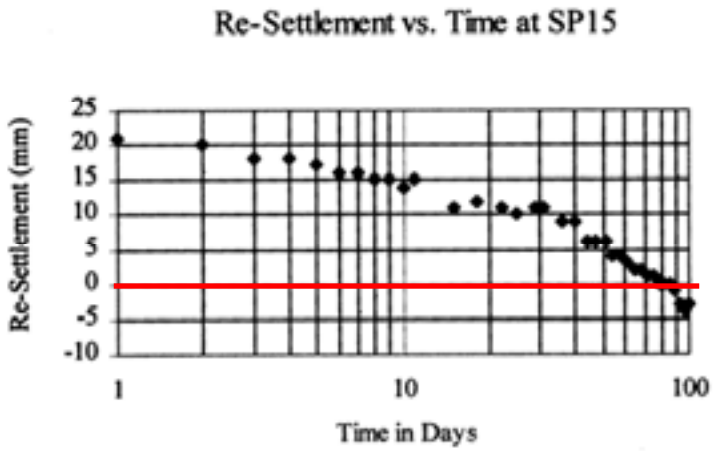
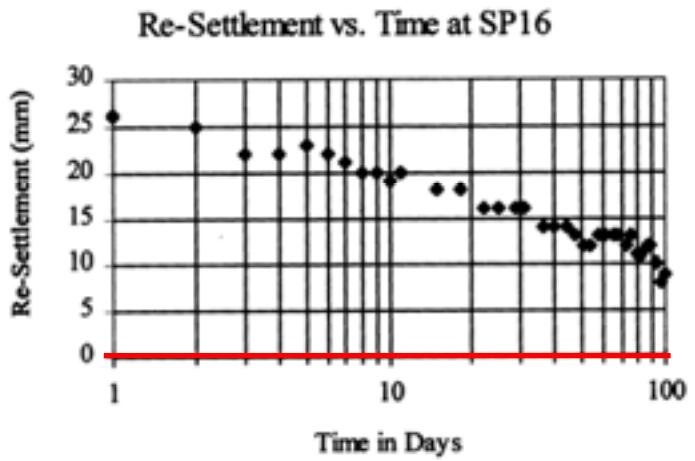
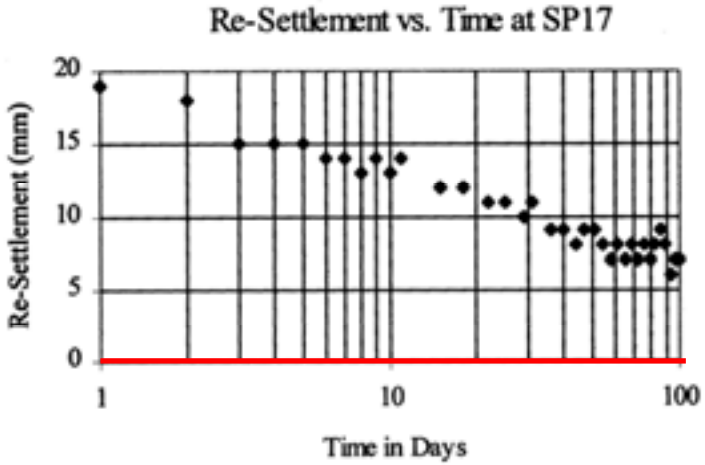
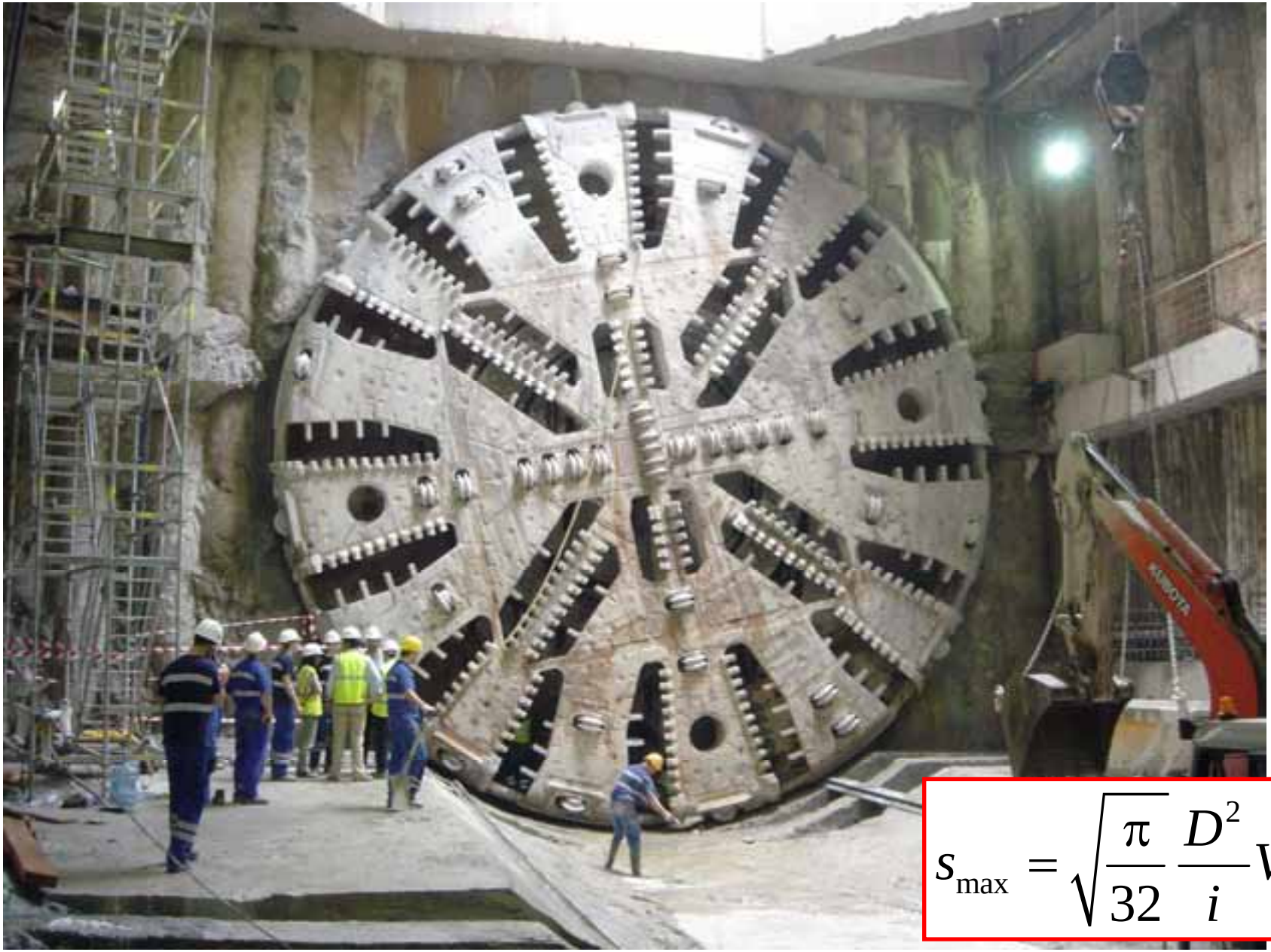






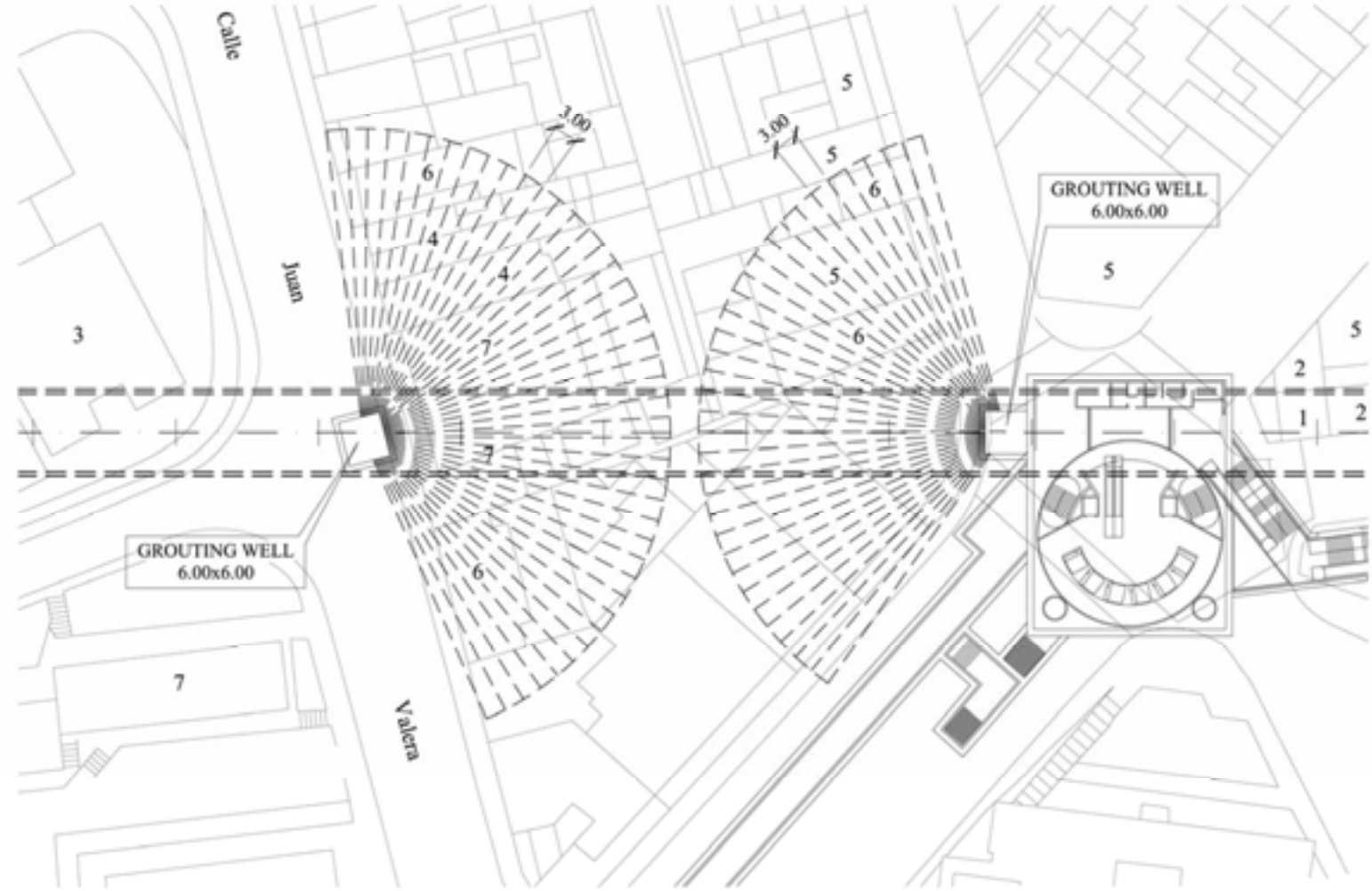


Compensation grouting



$$s_{\max} = \sqrt{\frac{\pi}{32}} \frac{D^2}{i} V_l$$

Compensation grouting

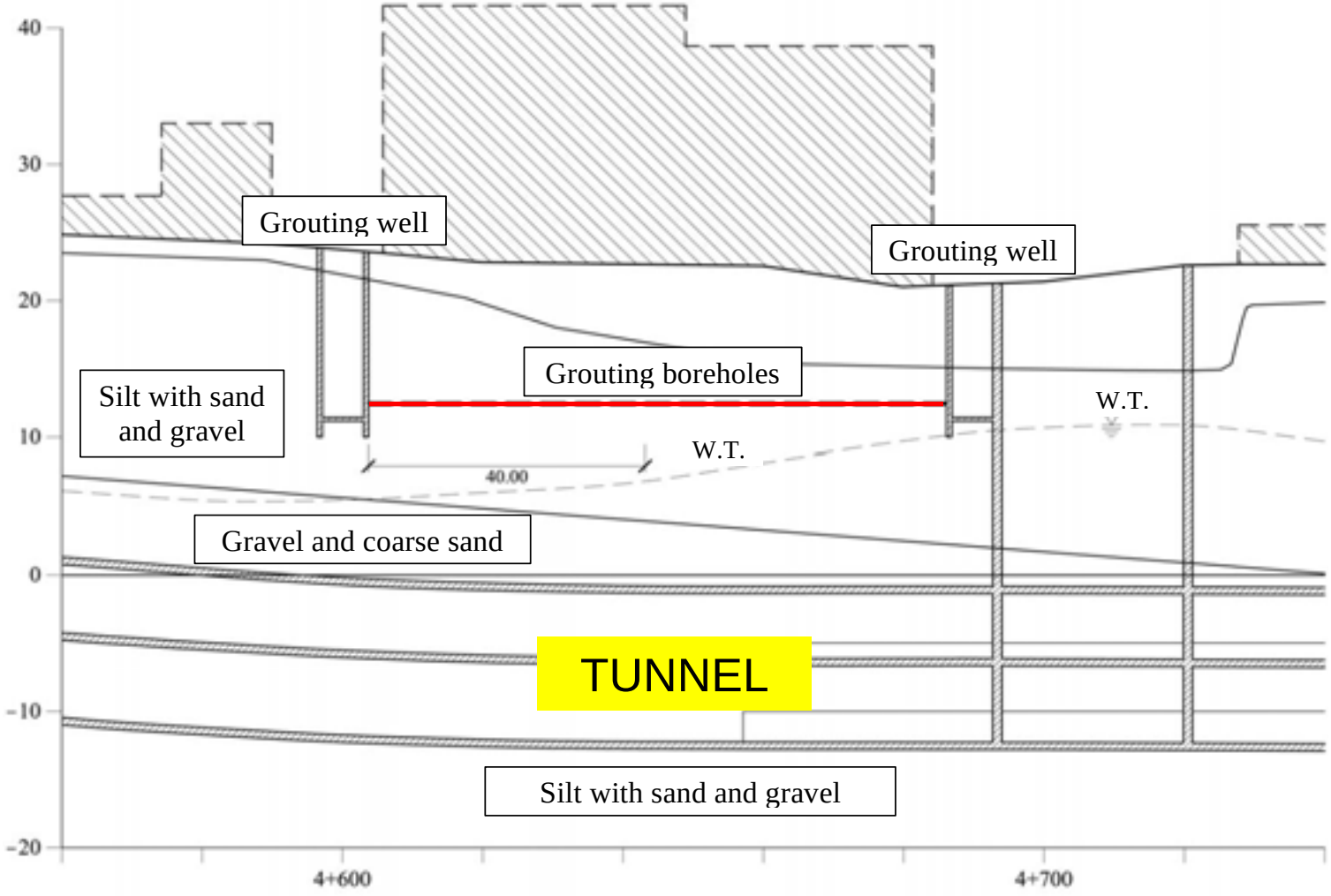


Juan Valera road

Compensation grouting

Juan Valera road

Compensation grouting



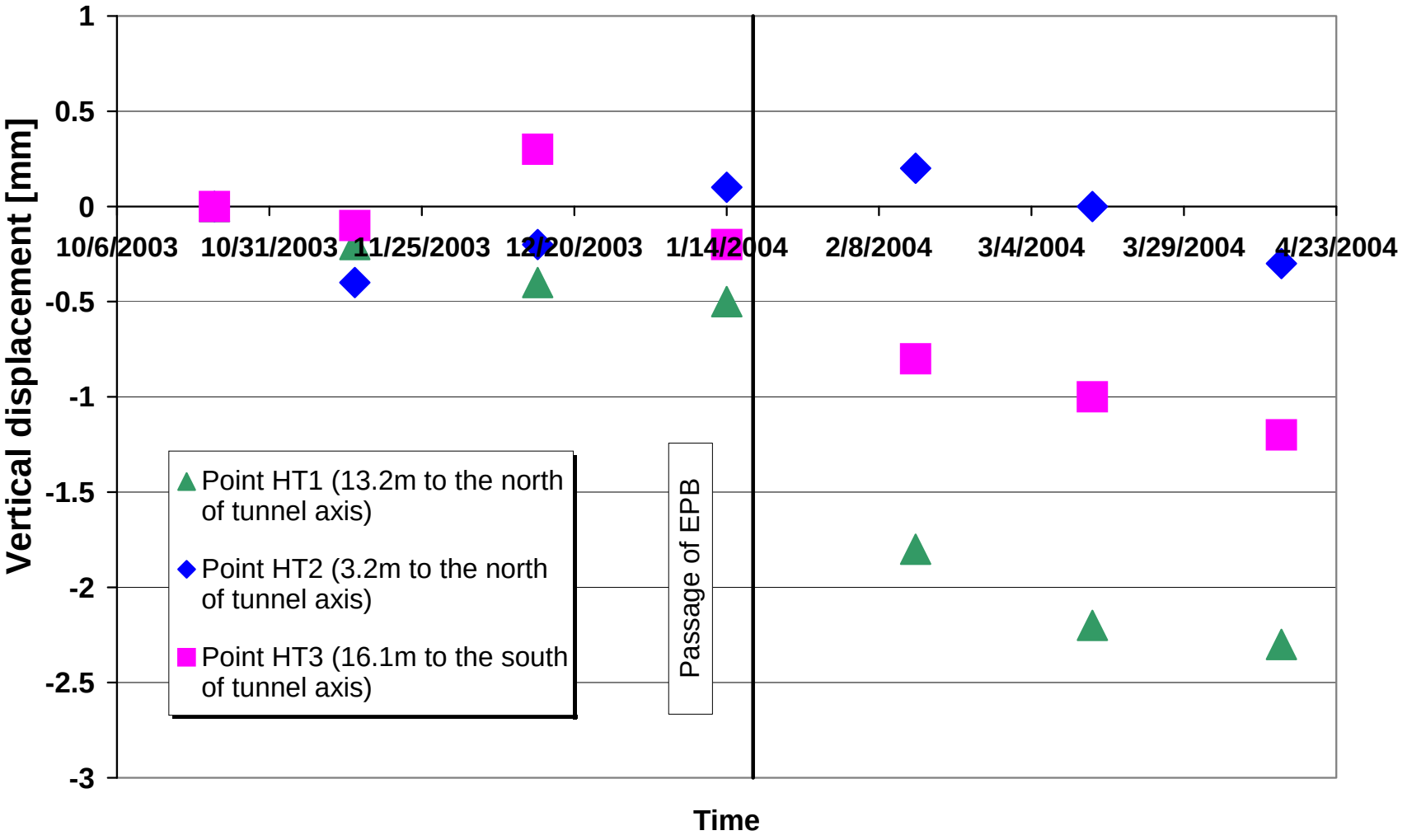
Juan Valera road

Compensation grouting

Rodio (2005)

Compensation grouting

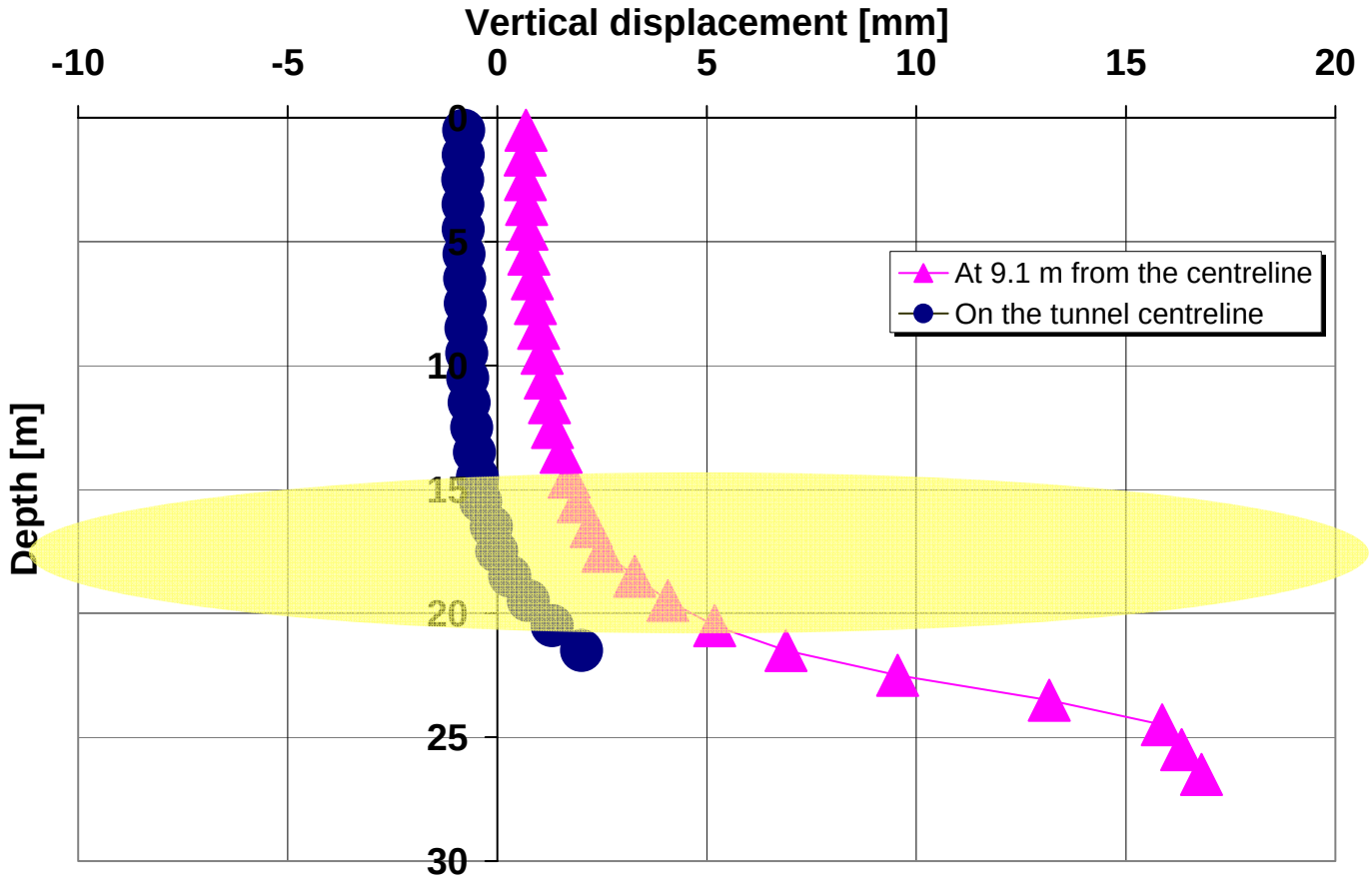
Compensation grouting



Juan Valera road

Compensation grouting

- Settlements

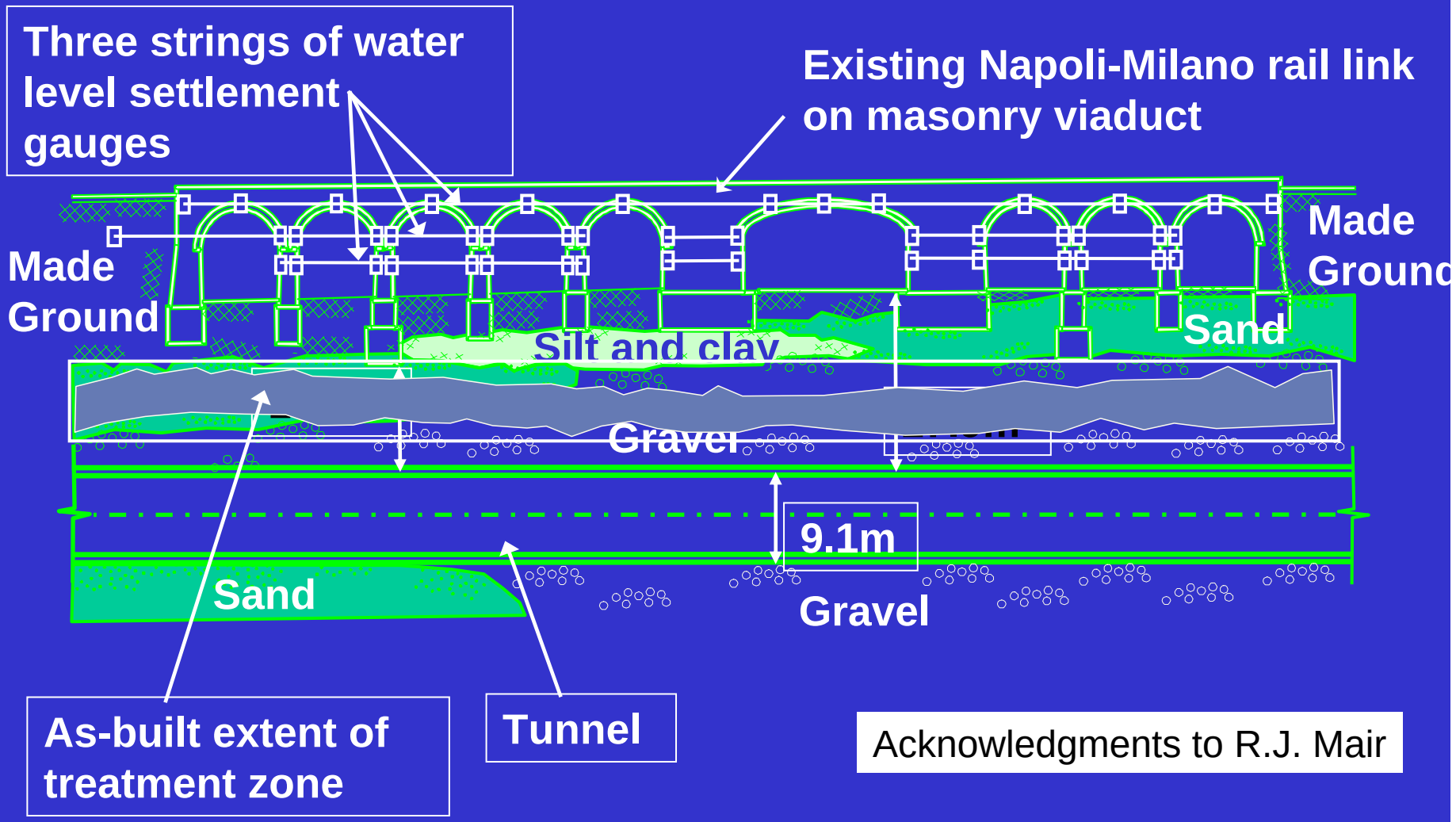


Juan Valera street

Compensation grouting

- Bologna viaduct and soil profile

Viaduct 112 m long, 11m wide



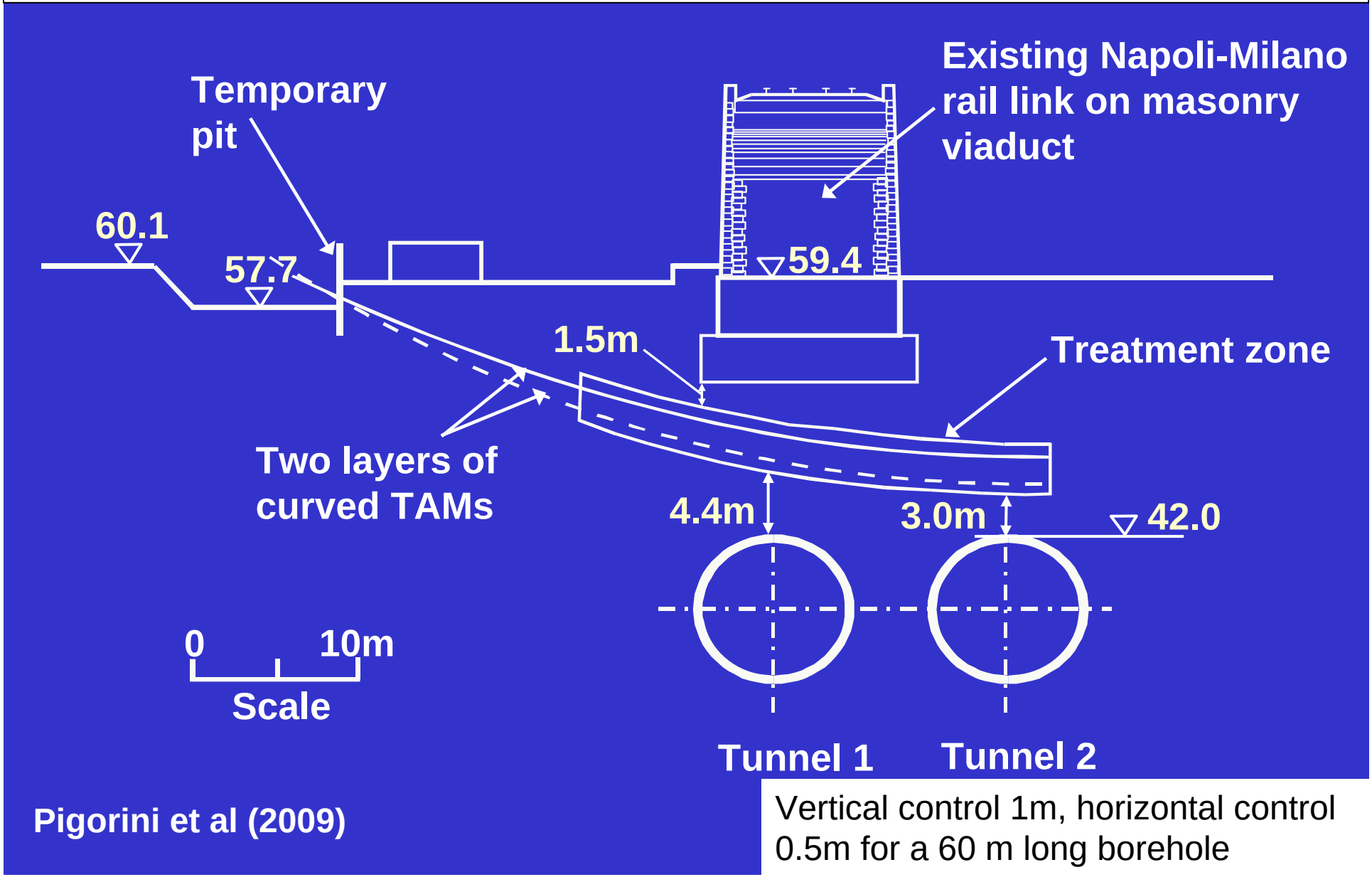
Acknowledgments to R.J. Mair

Compensation grouting

- Bologna viaduct

Compensation grouting

- Cross section

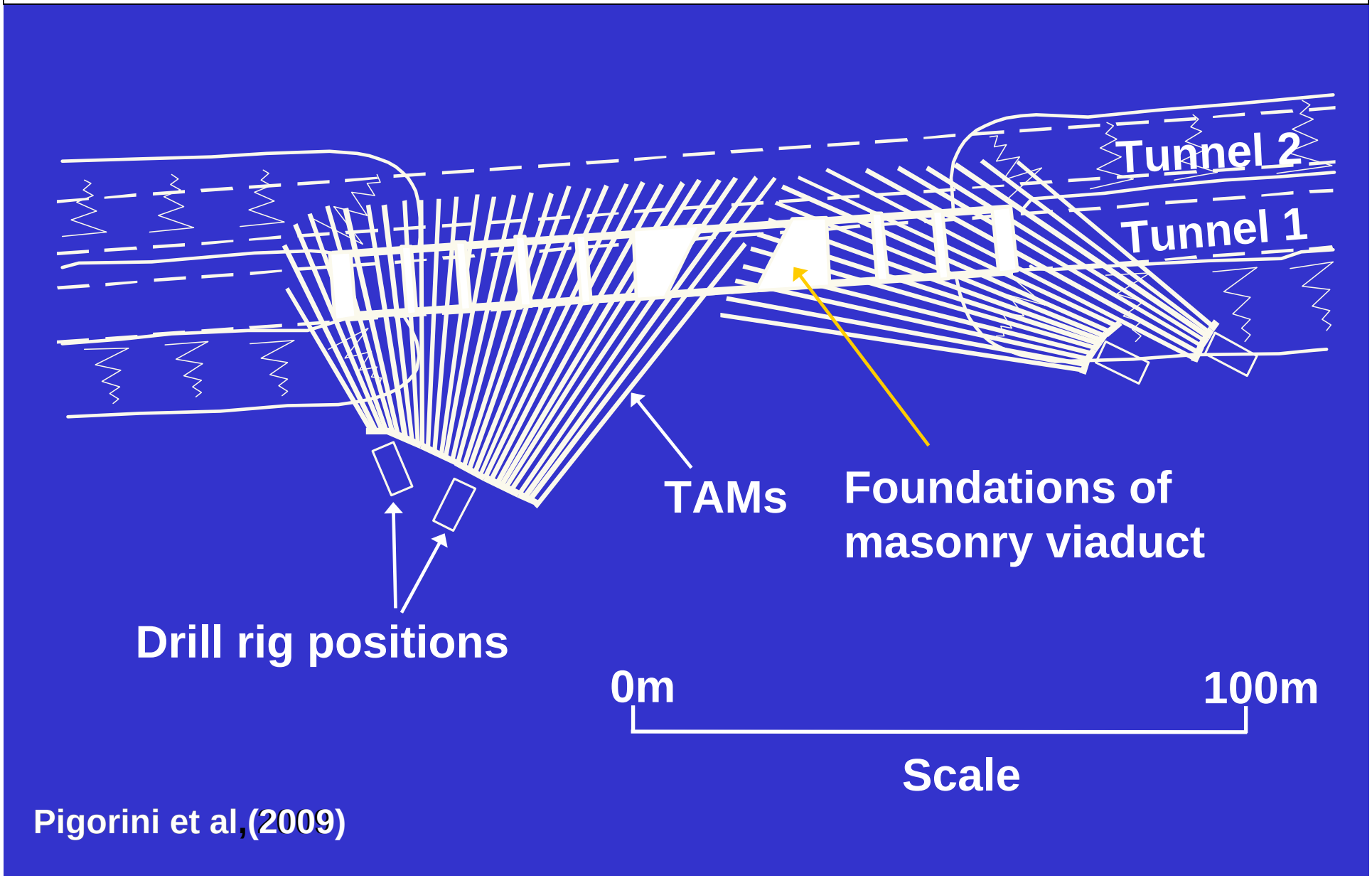


Pigorini et al (2009)

Vertical control 1m, horizontal control 0.5m for a 60 m long borehole

Compensation grouting

- TAMs array



Pigorini et al,(2009)

Compensation grouting

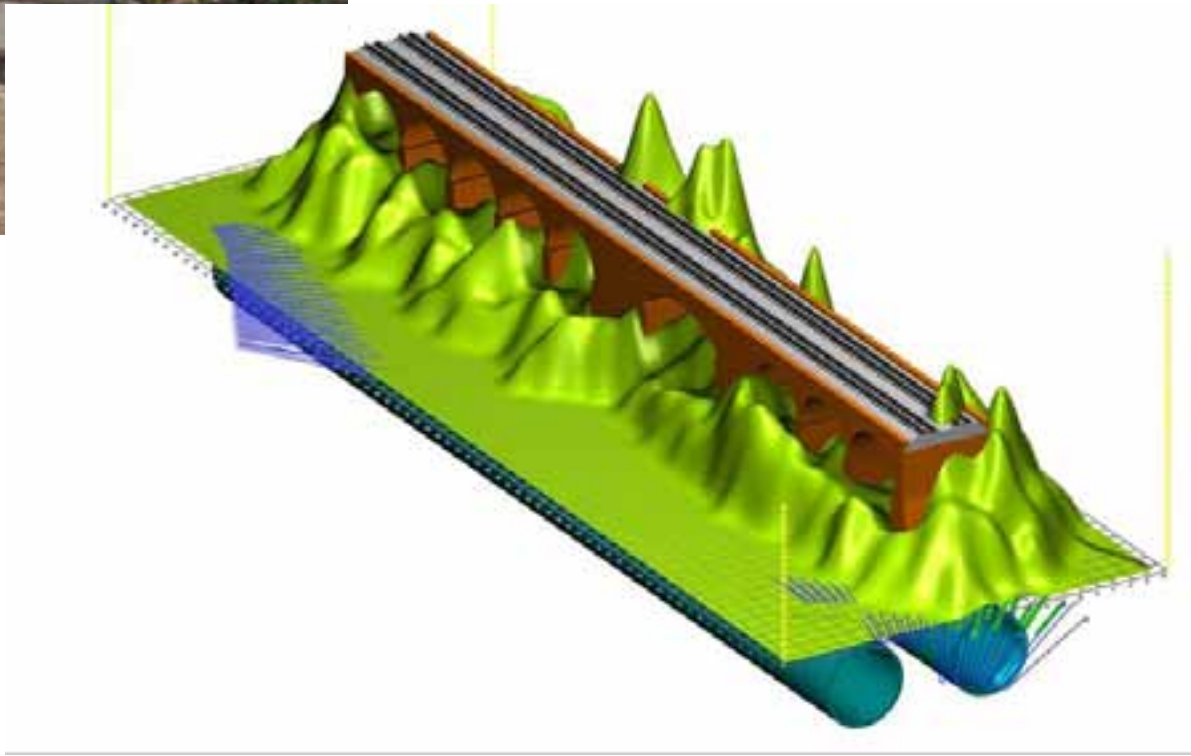
- Directional drilling

Compensation grouting

- Grouting

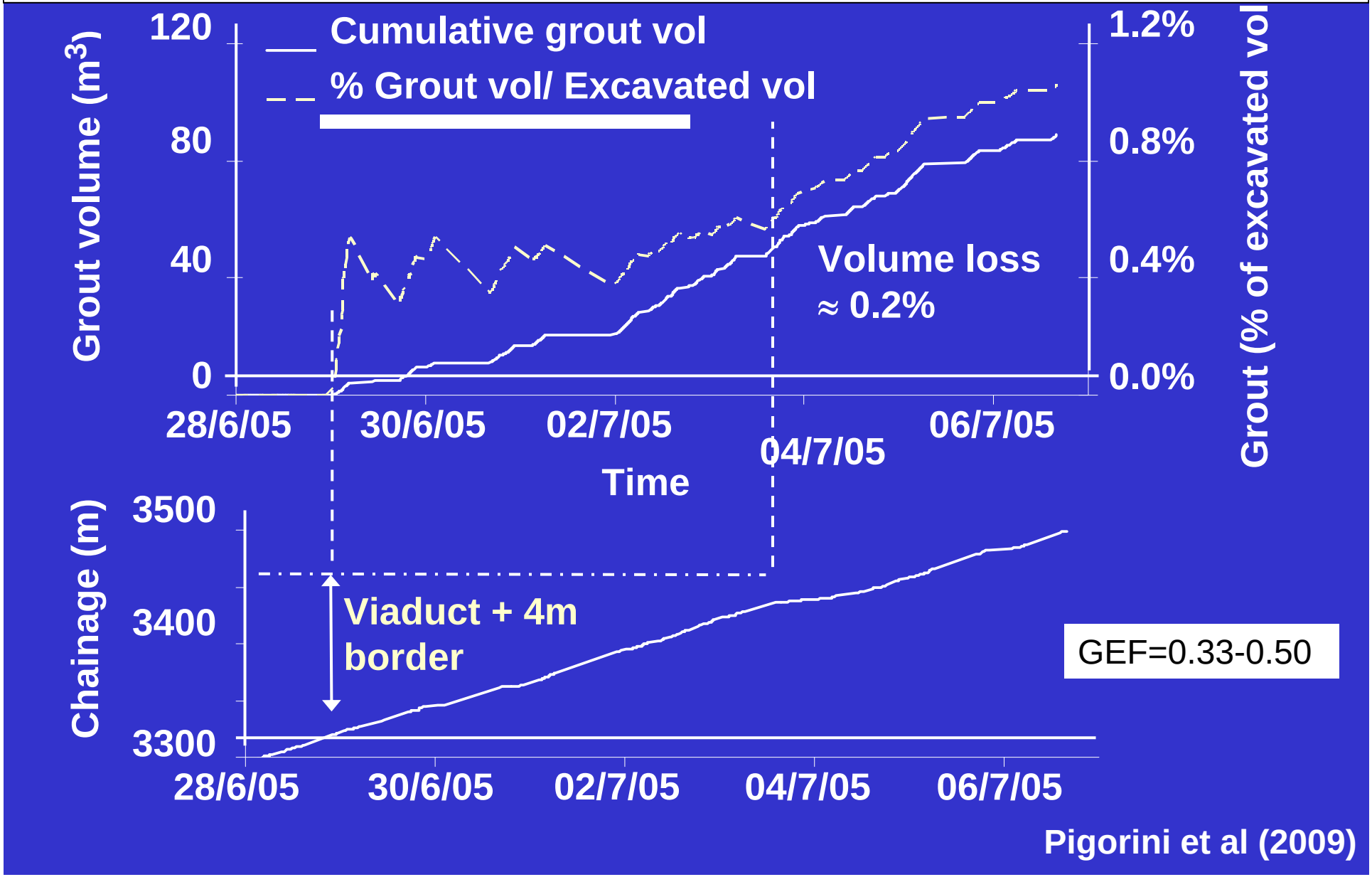
Compensation grouting

- Distribution of grouting volumes



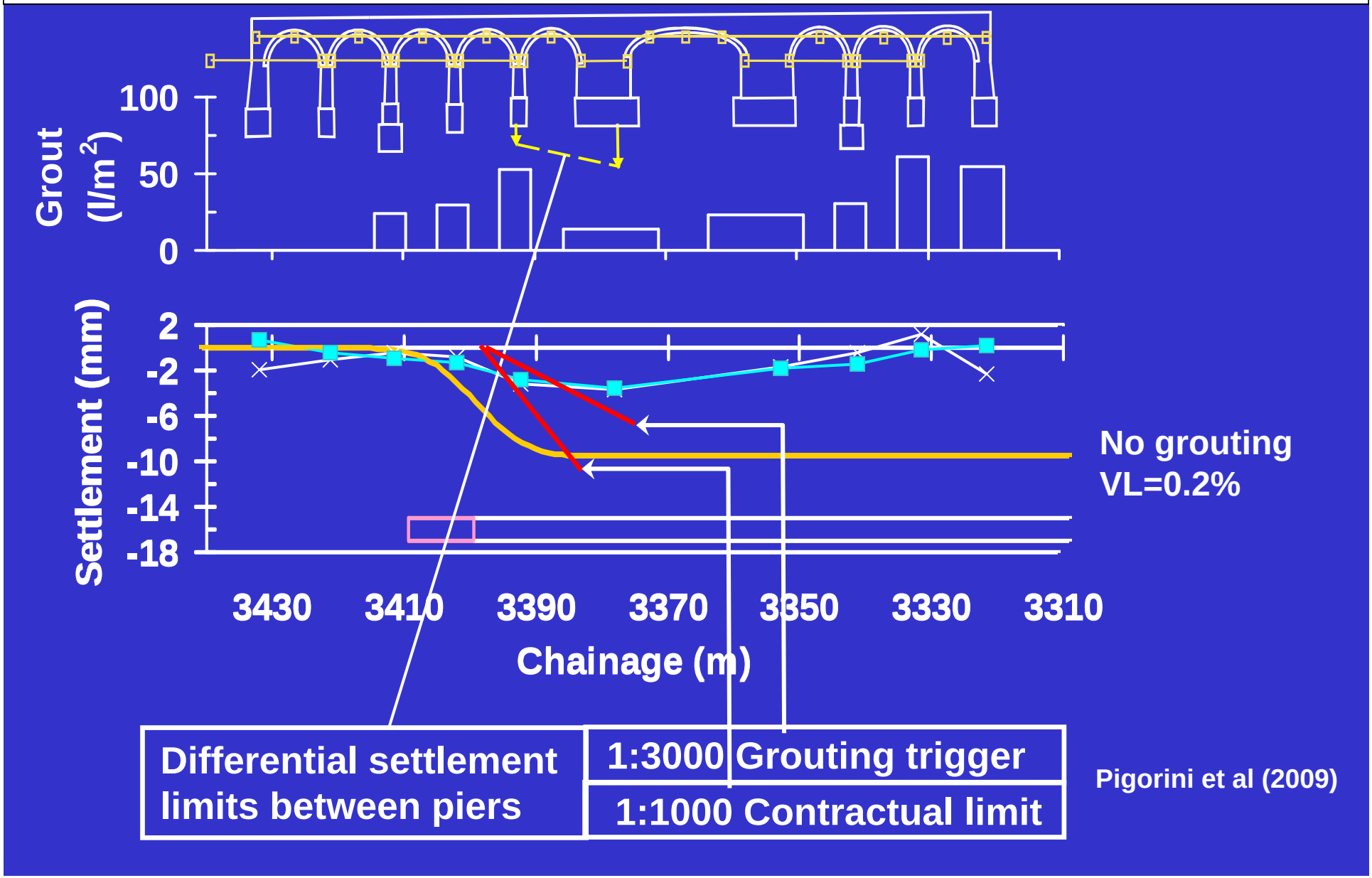
Compensation grouting

- Grout volume and progress of TBM1



Compensation grouting

- Evolución de asientos



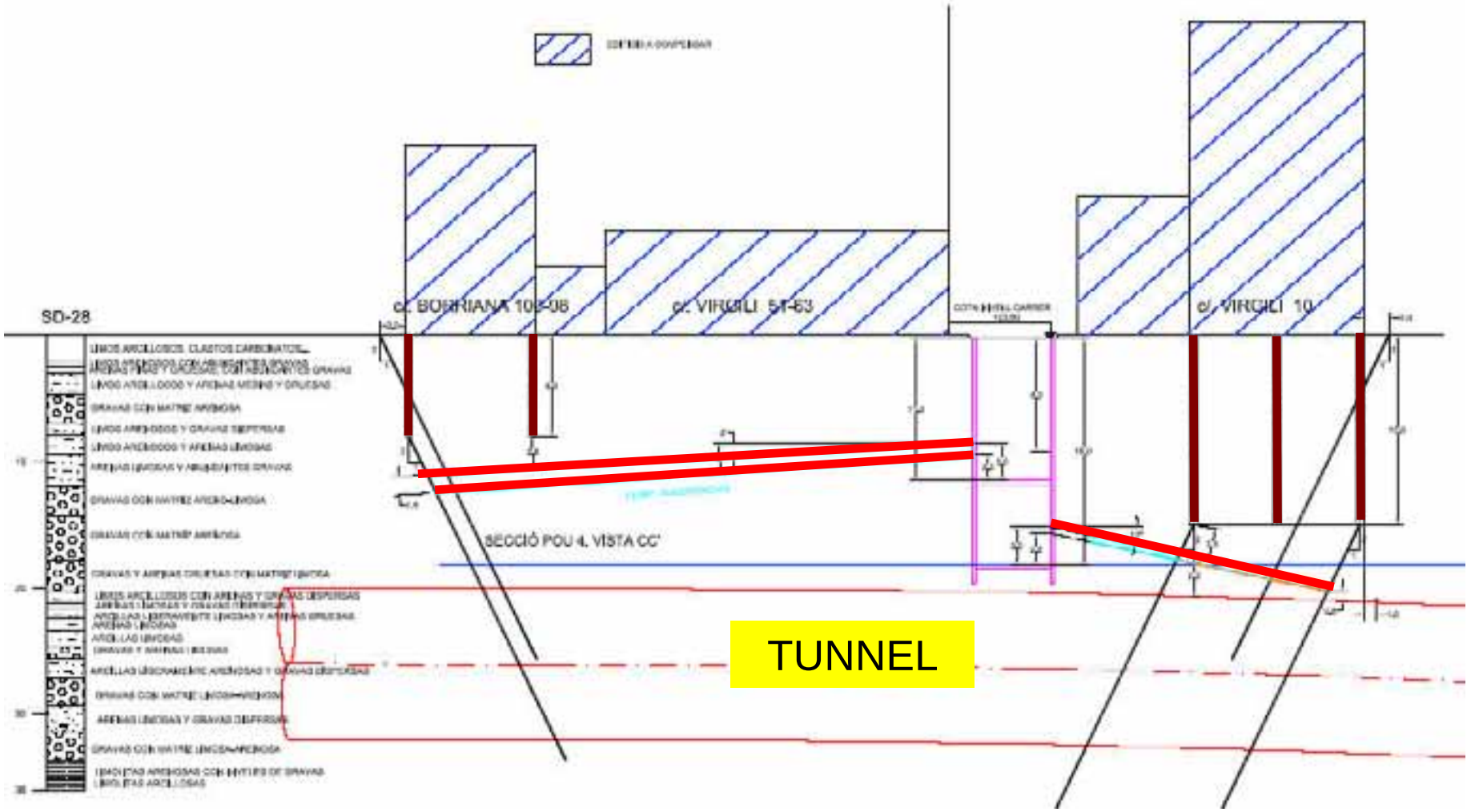
Compensation grouting

- Barcelona Metro: Line 9
  - Piled buildings

Ferran Soldevila street

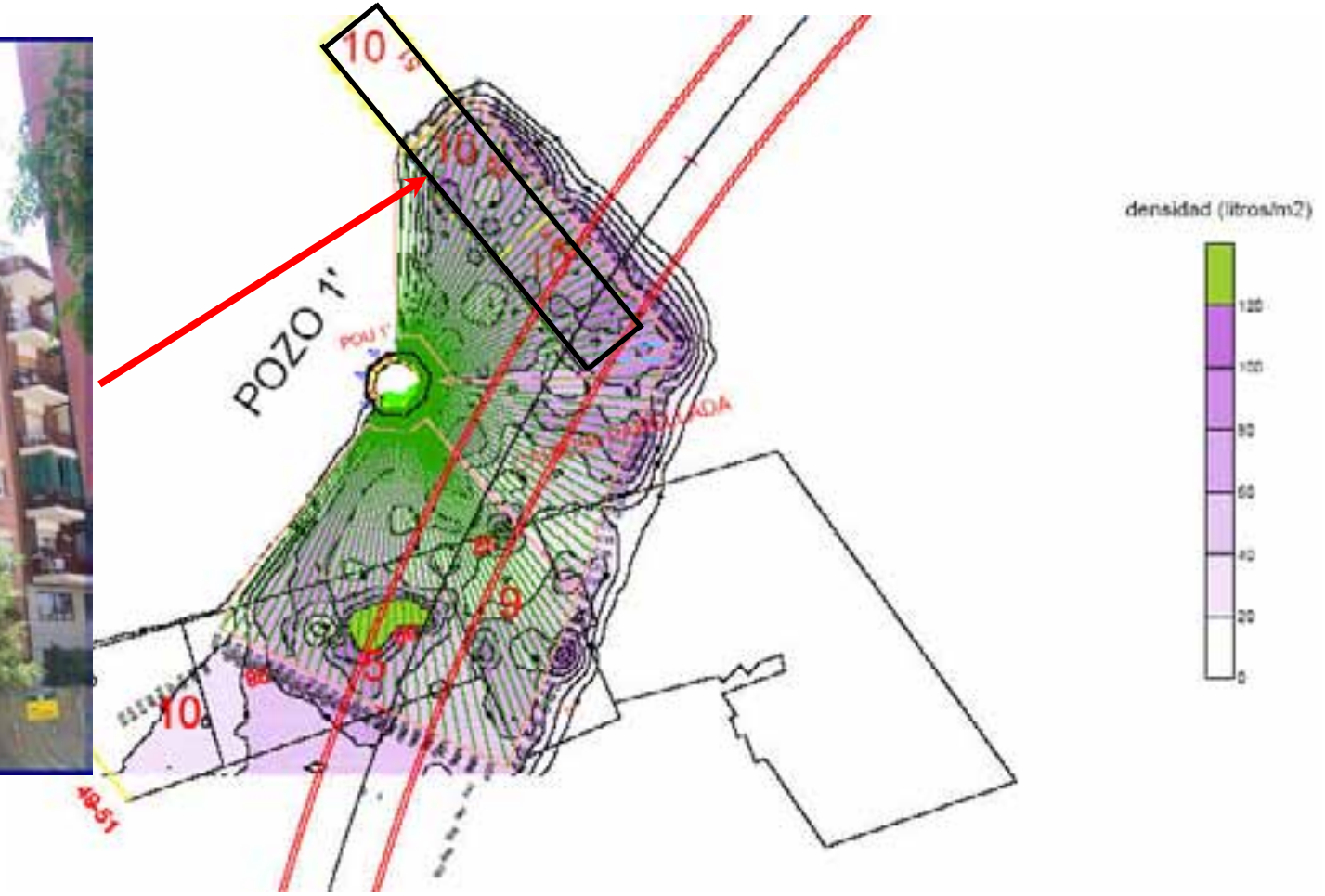
Compensation grouting

- Barcelona Metro: Line 9
  - Piled buildings



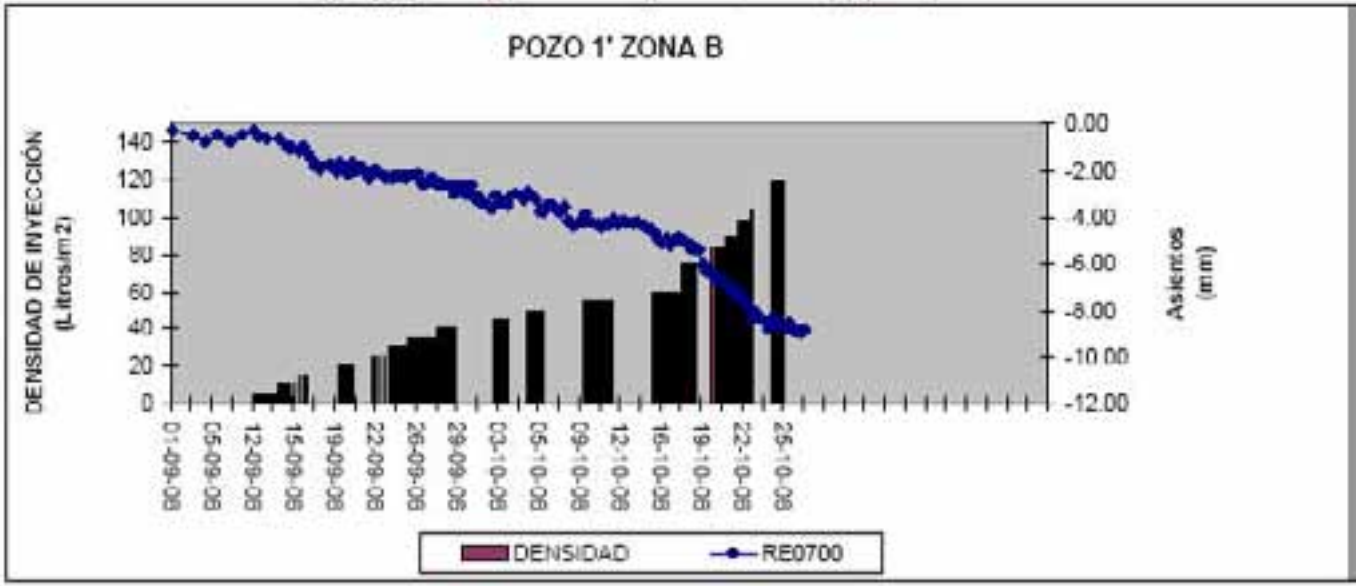
Compensation grouting

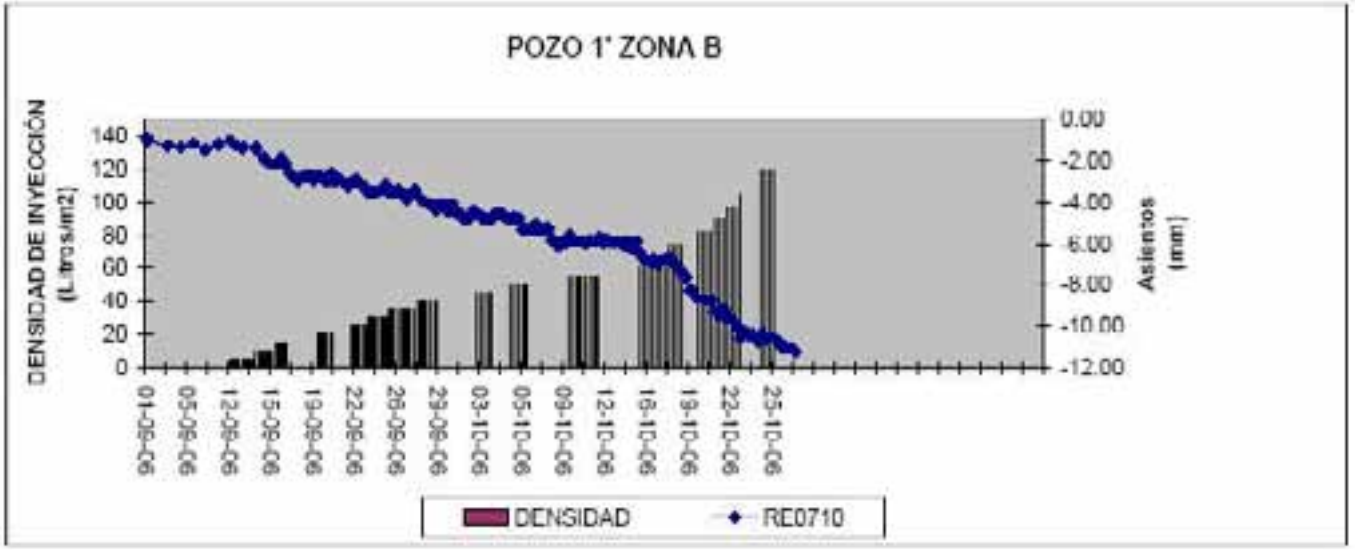
- Conditioning grouting



Compensation grouting

- Conditioning grouting



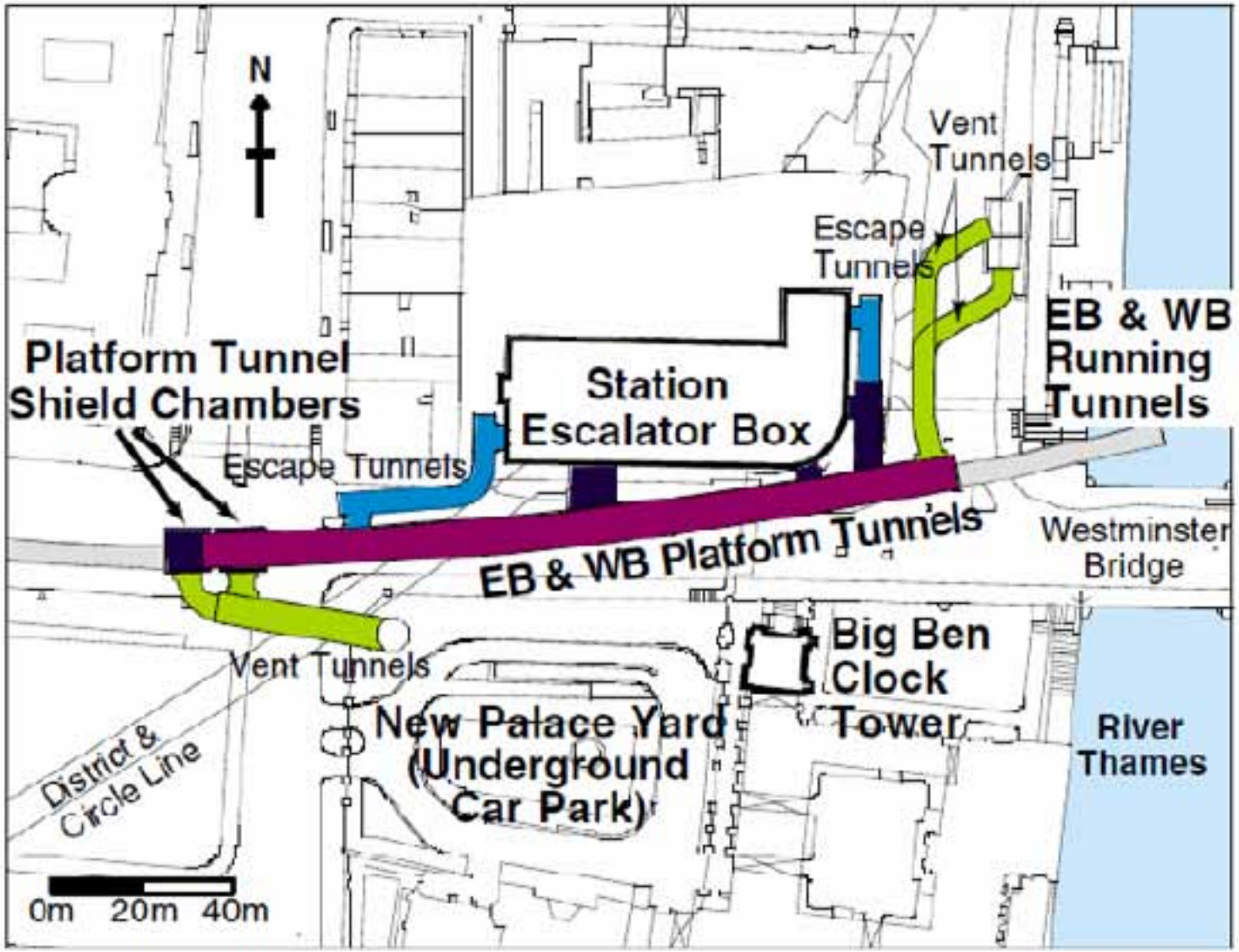


Compensation grouting

- Westminster station

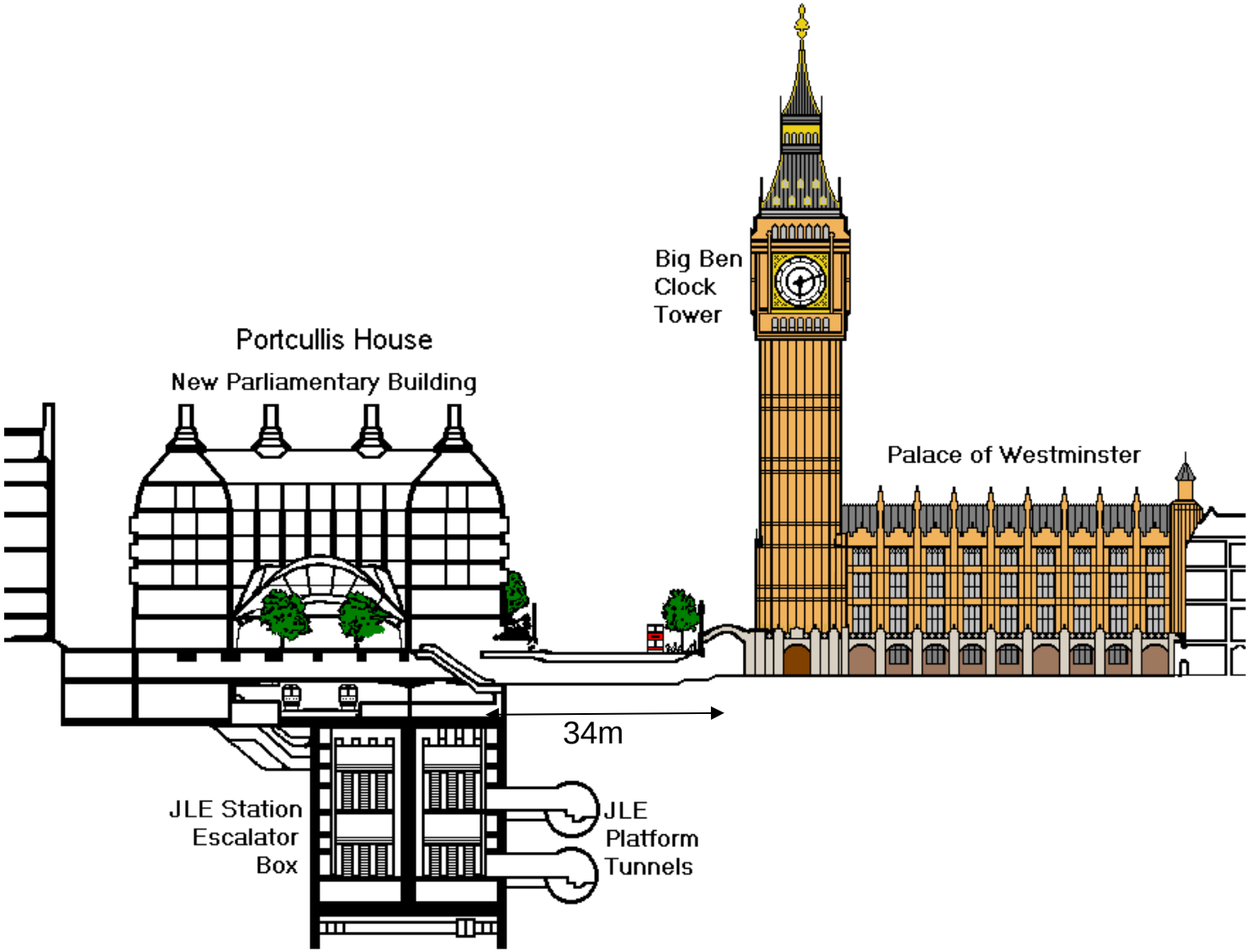
Compensation grouting

- Westminster station



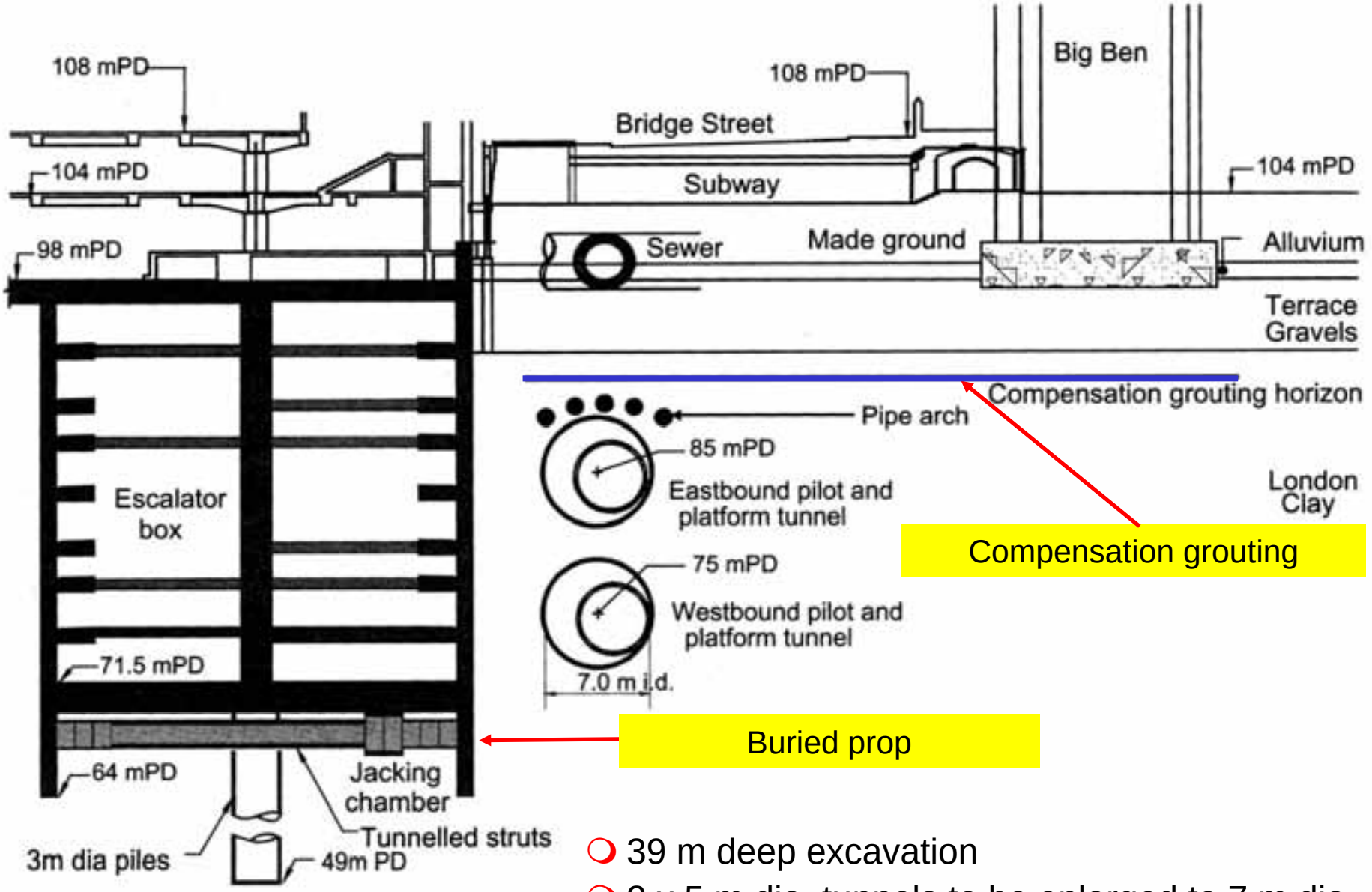
Inyecciones de compensación

- Westminster station



Compensation grouting

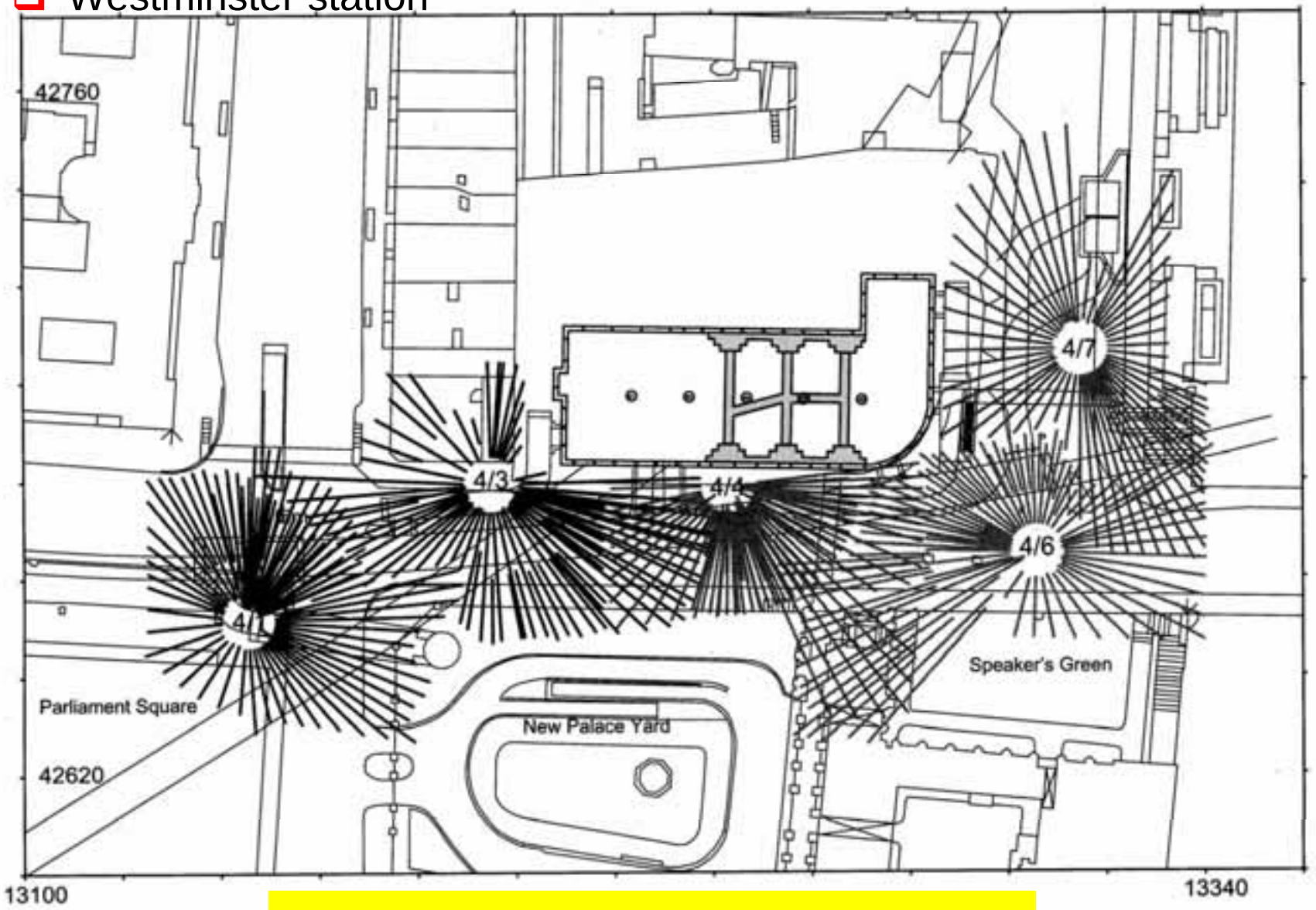
- Westminster station



- 39 m deep excavation
- 2 x 5 m dia. tunnels to be enlarged to 7 m dia.

Compensation grouting

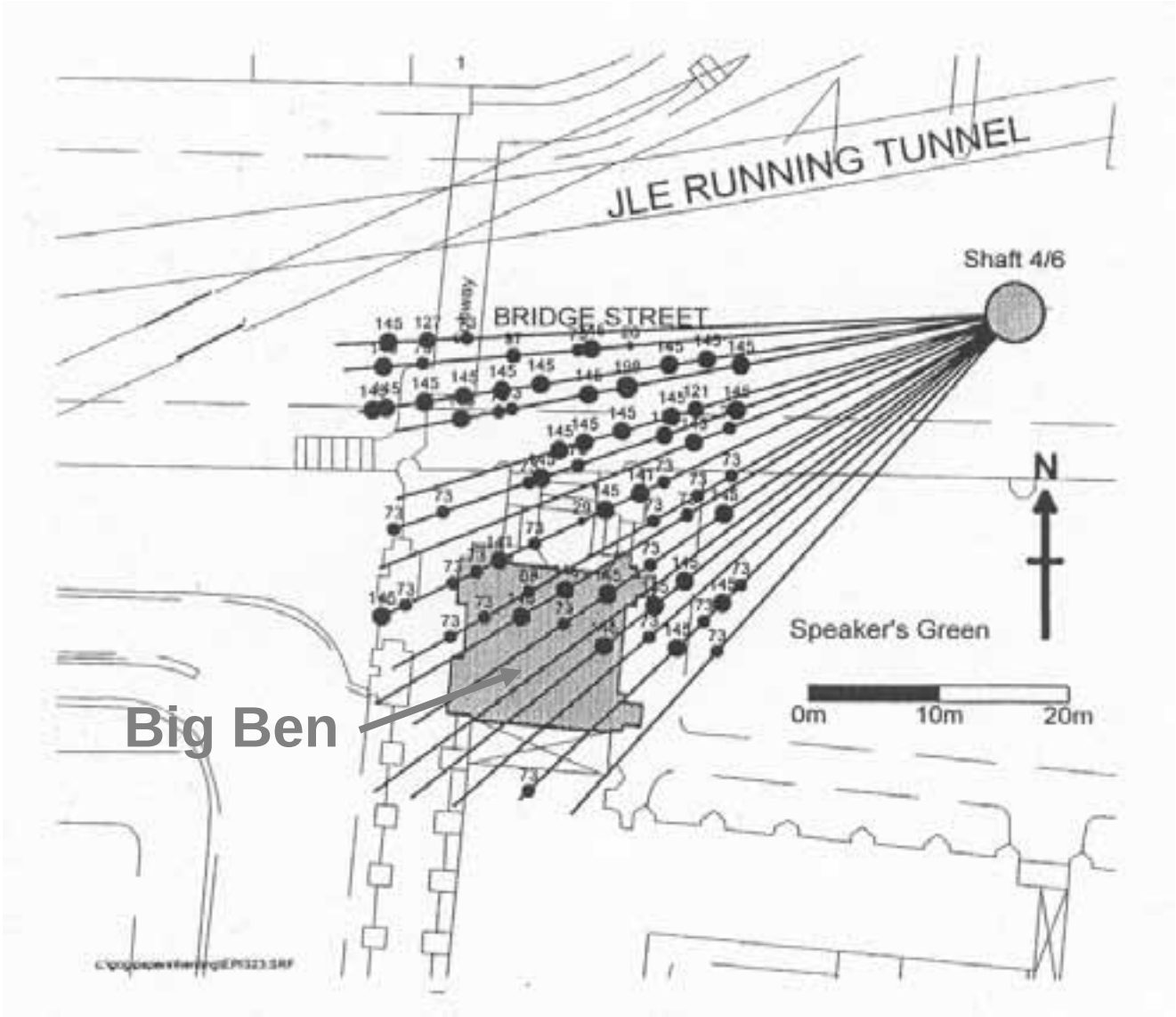
- Westminster station



TAMs array

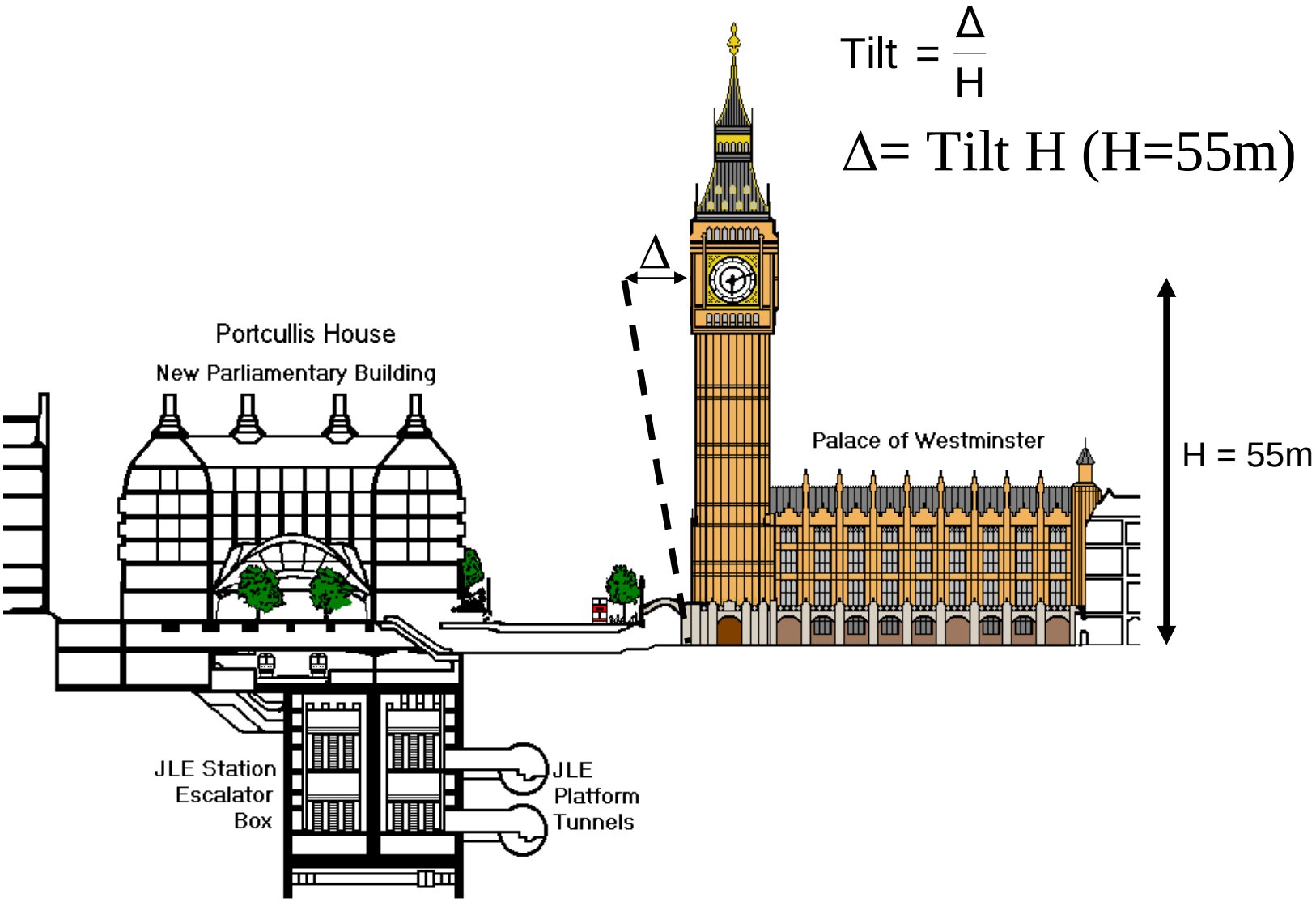
Compensation grouting

- Westminster station



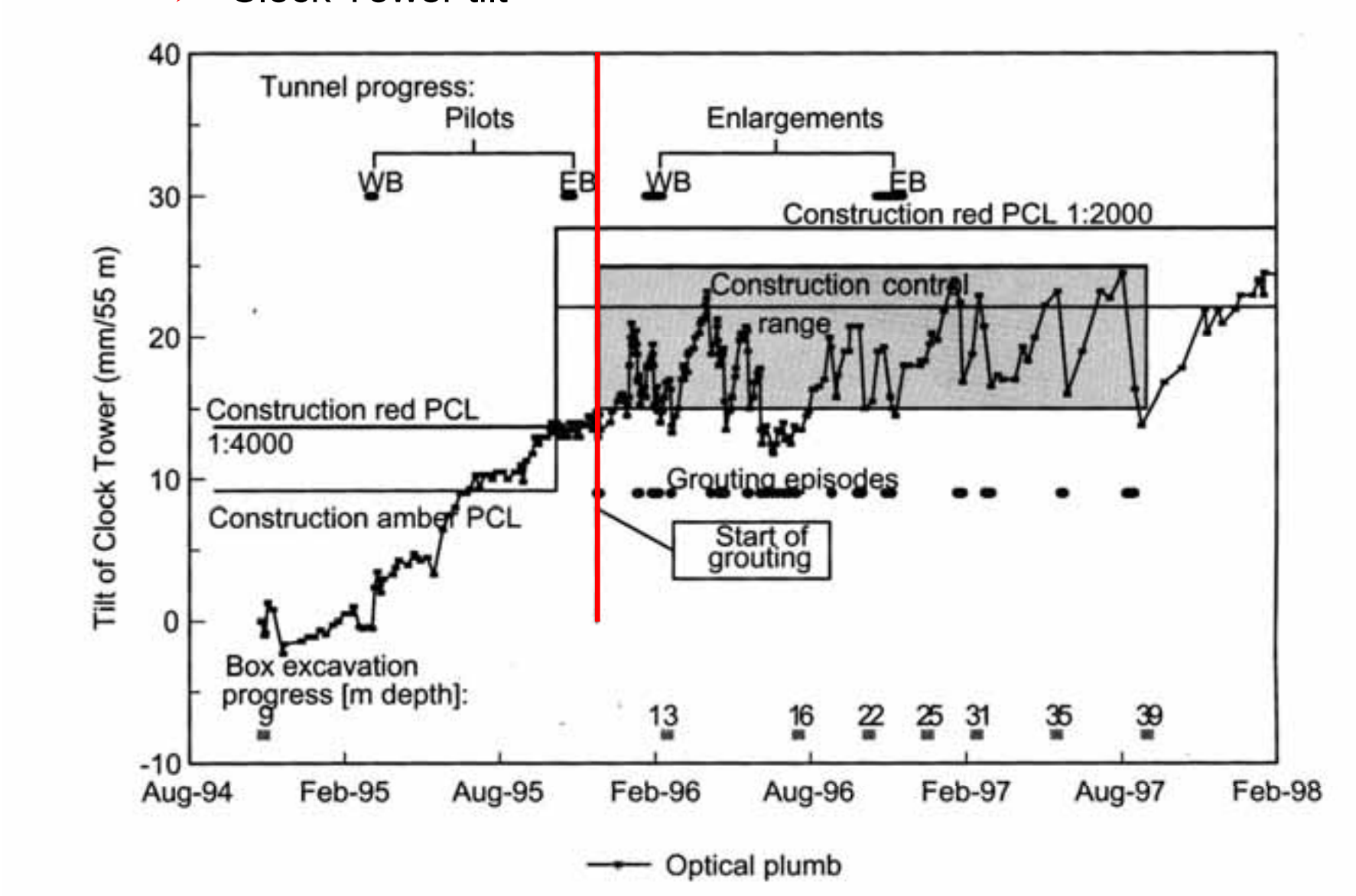
Inyecciones de compensación

- Westminster station
  - Clock Tower tilt



Compensation grouting

- Westminster station
  - Clock Tower tilt



Final remarks

- Control of ground movements is an absolute requirement when tunnelling in urban areas
  - There is an enhanced sensibility of public opinion concerning these issues
- The most effective measure for the control of ground movements is the selection of an adequate construction procedure and a good control of the works
- Screen (curtain) walls are an efficient way of ground movement control when the tunnels are not excavated below buildings
- Compensation grouting is an efficient way of ground movement control when the tunnels are excavated below buildings
  - There are however uncertainties over the behaviour mechanisms and control methods
- Whenever possible, acting directly on the structure leads to a better control when correcting the effect of ground movements
- Often the control measured also generate additional ground movements
  - It is not recommended, therefore, to try to reduce ground movements to negligible values