PURDUE UNIVERSITY

Purdue Geotechnical Society

16th G.A. Leonards Lecture

Protecting Sensitive Structures from Tunnelling in Urban Environments

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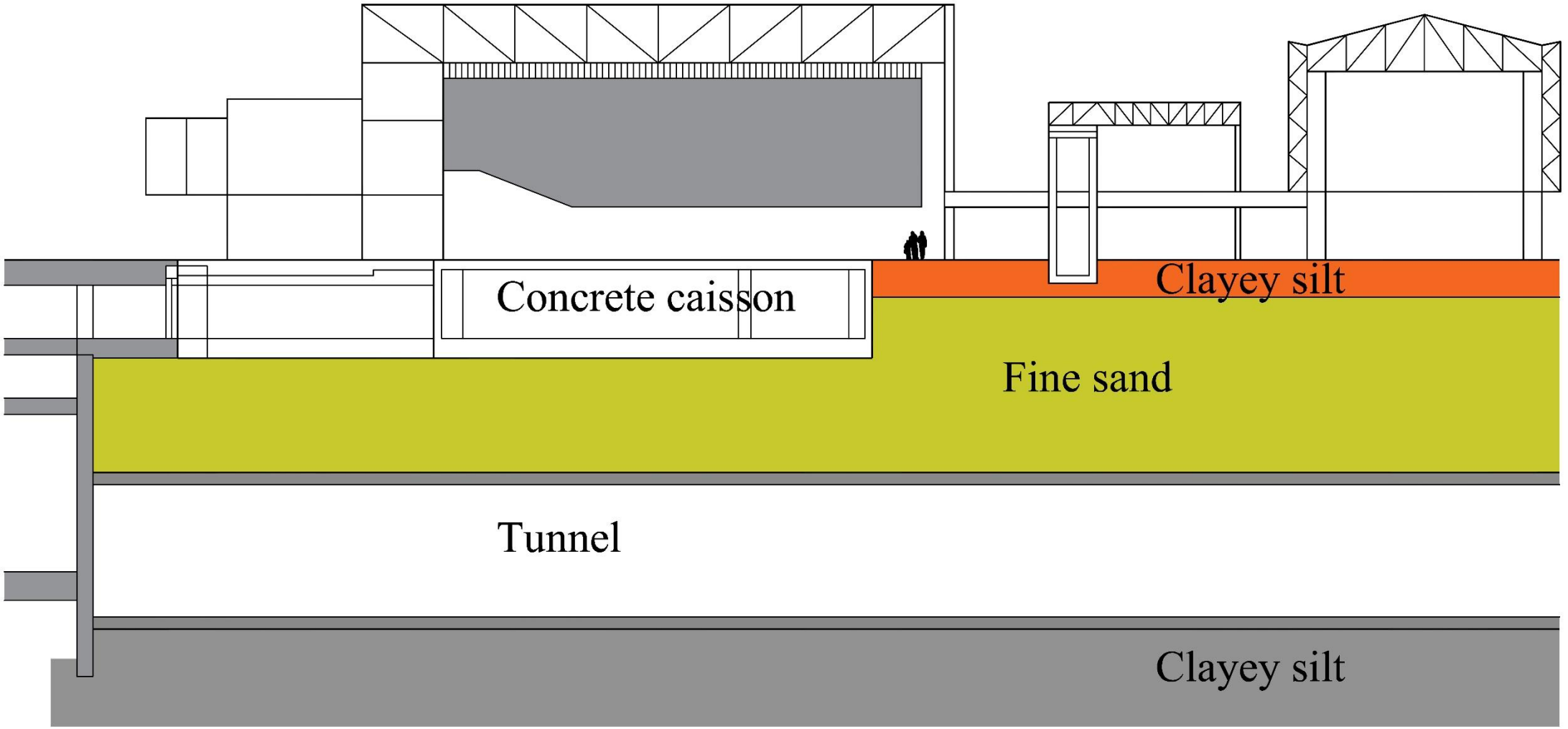
West Lafayette, April 27th, 2018

https://upload.wikimedia.org/wikipedia/commons/5/55/SF_-_lago1.jpg

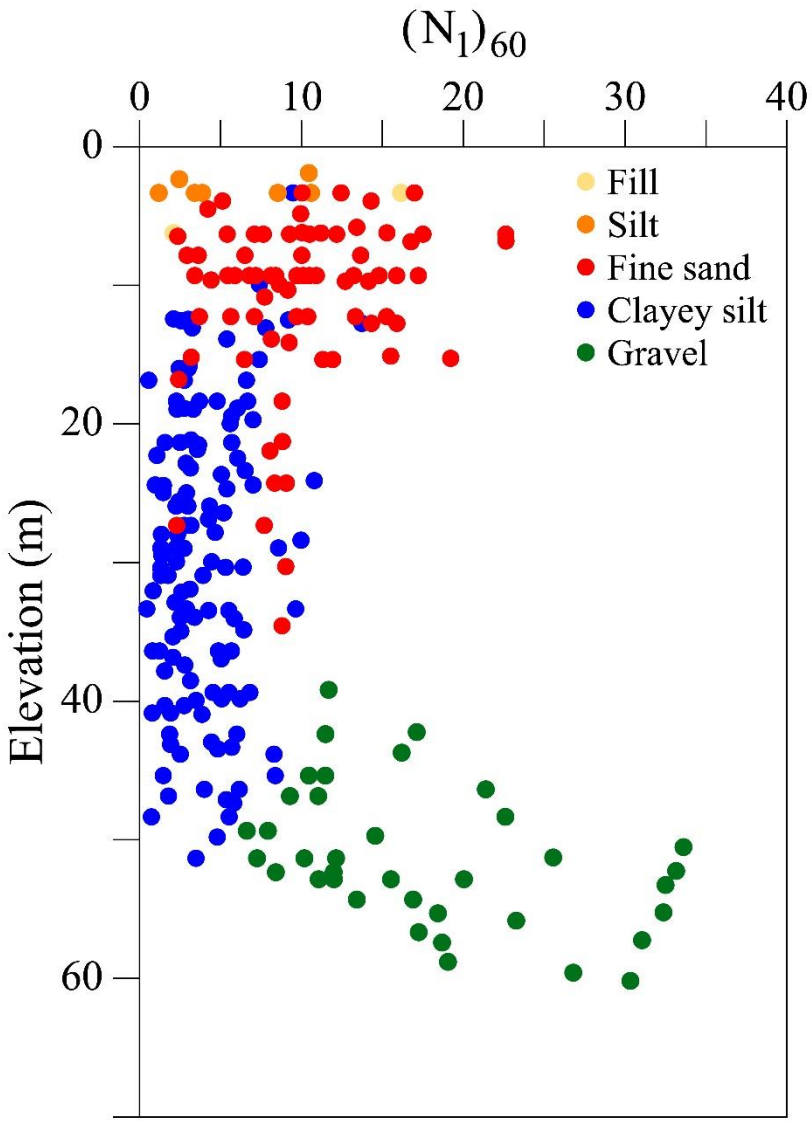
Barcelona high speed railway crossing

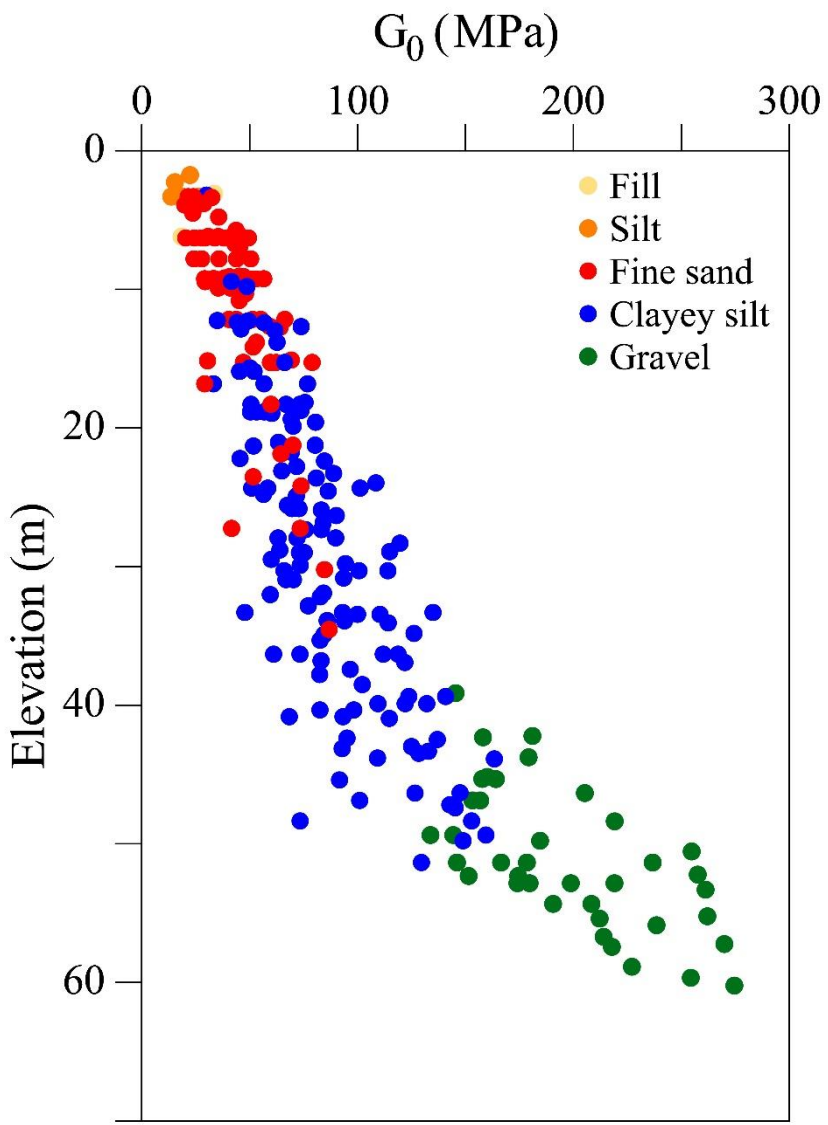
Terminal 2. Barcelona Airport

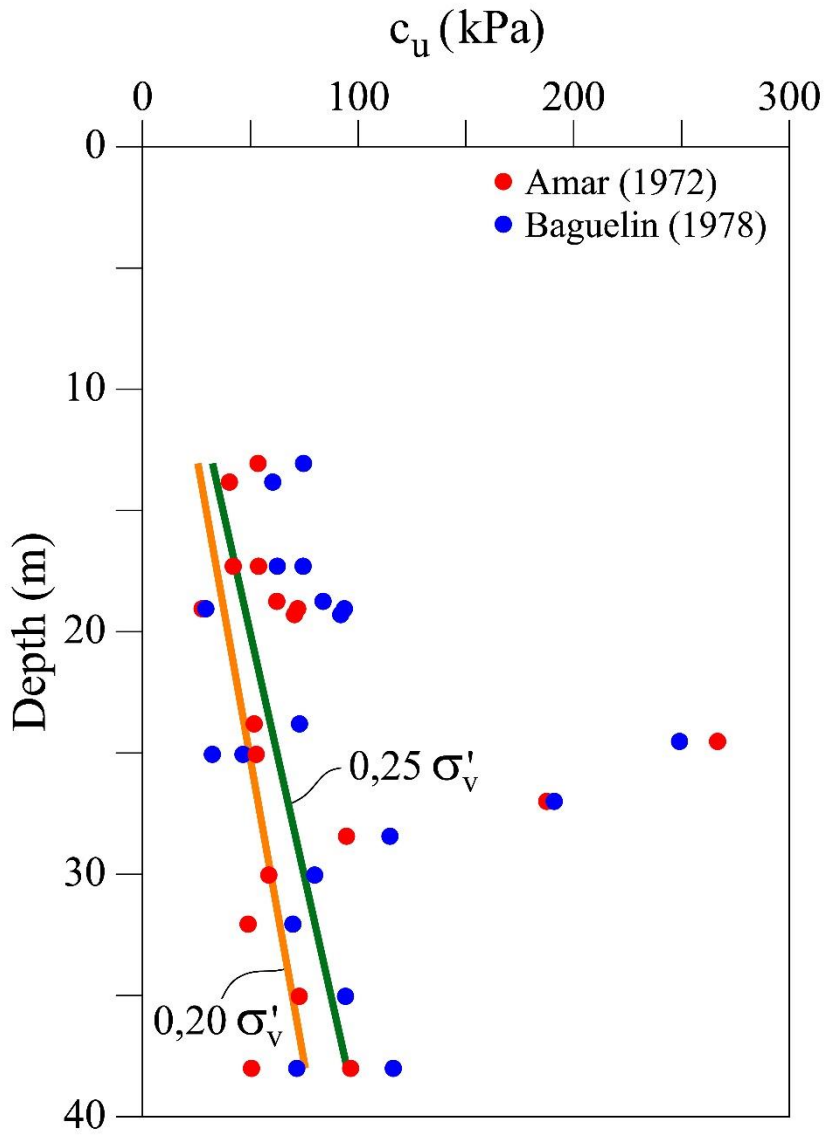
Railway tunnel under Terminal 2. Barcelona airport



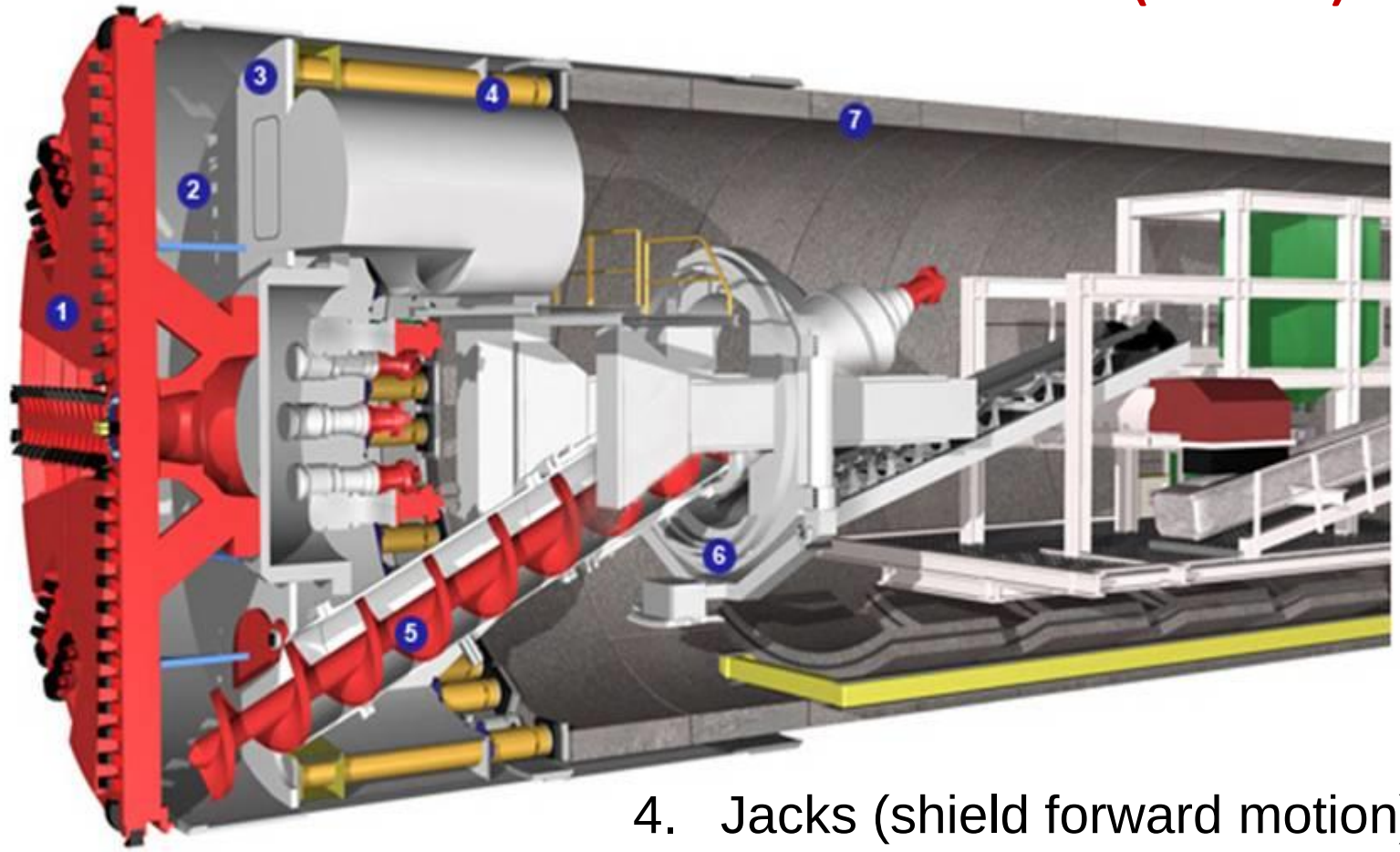
SPT, small strain stiffness and undrained strength. Barcelona airport







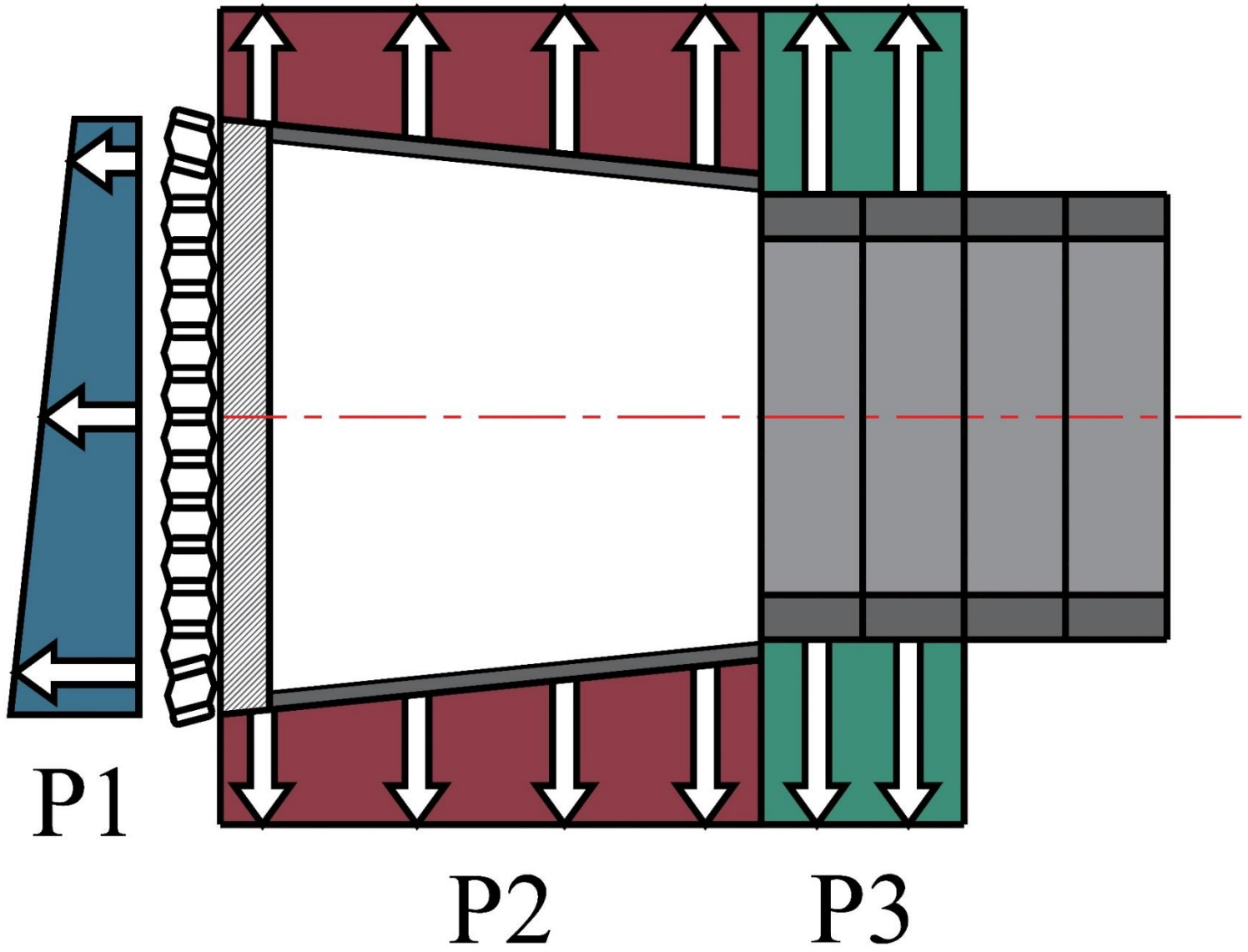
Earth Pressure Balance Shield (EPBS)



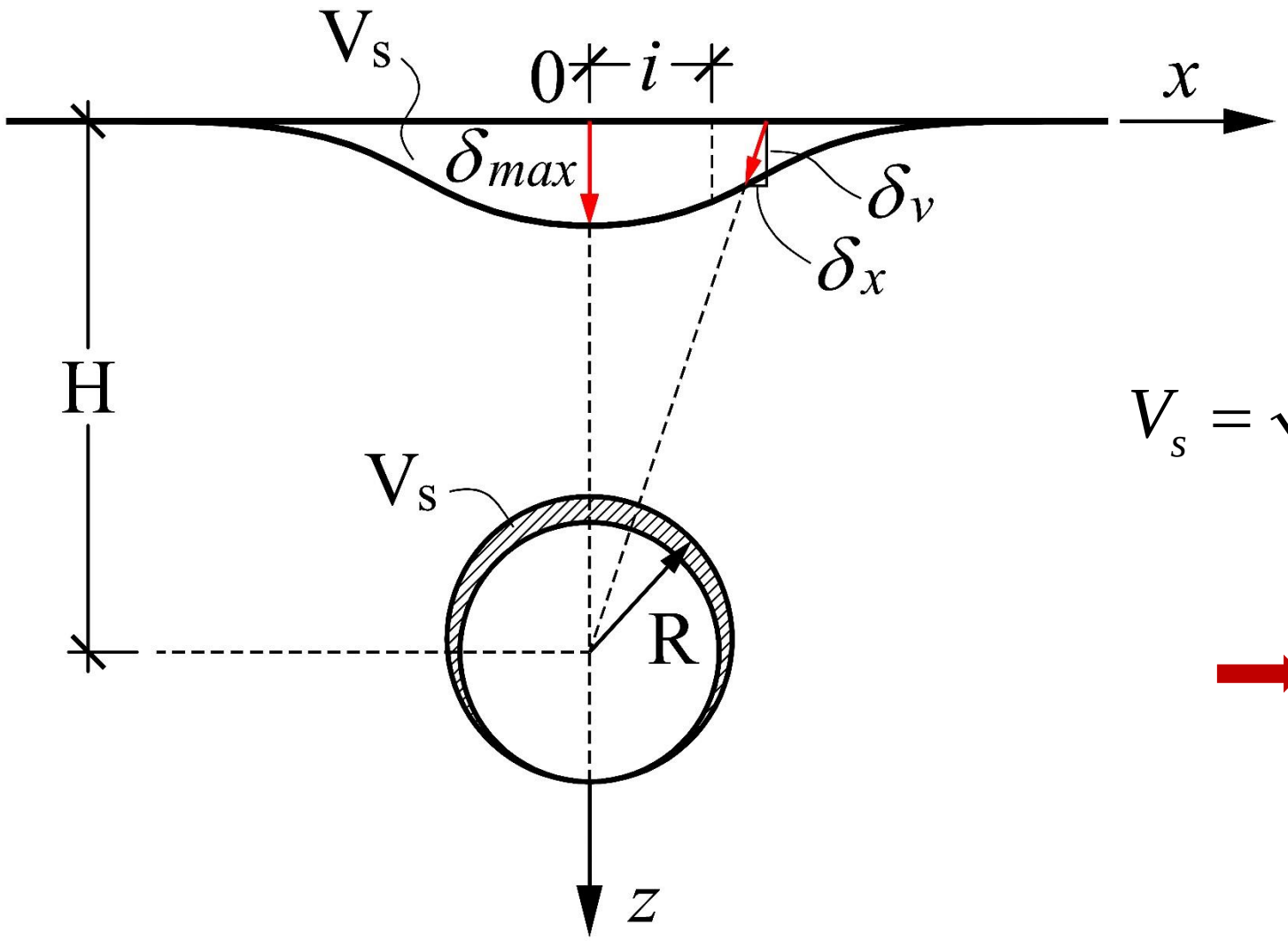
1. Excavation wheel
2. Pressure chamber (Front support)
3. Water tight bulkhead
4. Jacks (shield forward motion)
5. Screw conveyor (Debris removal and pressure chamber control)
6. Dowel erector
7. Tunnel liner

Building the tunnel under Terminal 2. Barcelona airport

Pressures against soil at excavation boundaries



Basics of soil deformation around tunnels



$$\delta_v(x) = \delta_{\max} e^{-\frac{x^2}{2i^2}}$$

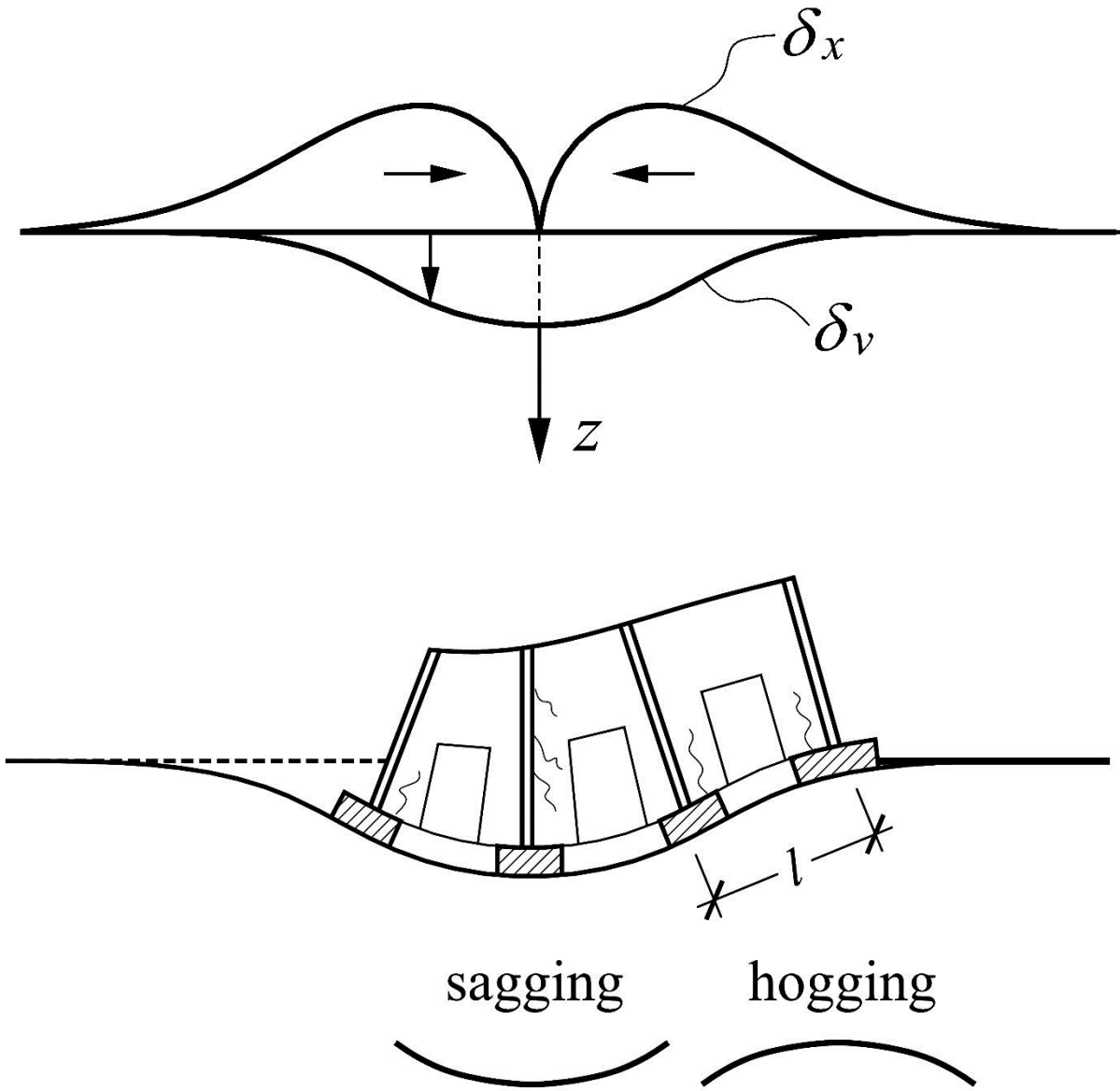
$$V_s = \sqrt{2\pi} i \delta_{\max} \qquad V_s^* = \frac{V_s}{\pi R^2} \qquad i = \frac{H}{2}$$

$$\rightarrow \quad \delta_v(x) = V_s^* \sqrt{2\pi} \frac{R^2}{H} e^{-\frac{x^2}{2i^2}}$$

0.1%; 0.5%; 1%....

$\rightarrow \delta_x(x)$? : Displacement vector goes through tunnel center

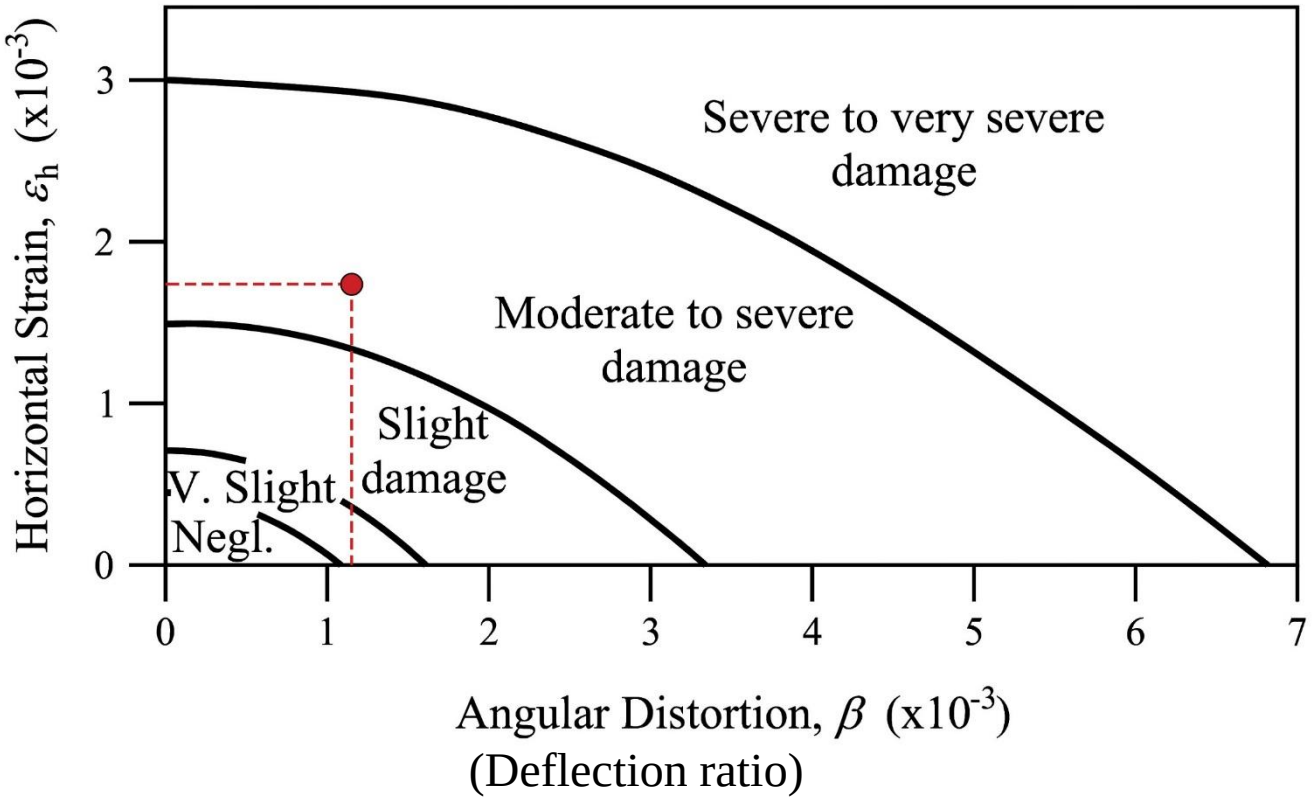
Damage induced by tunnelling



Deflection ratio

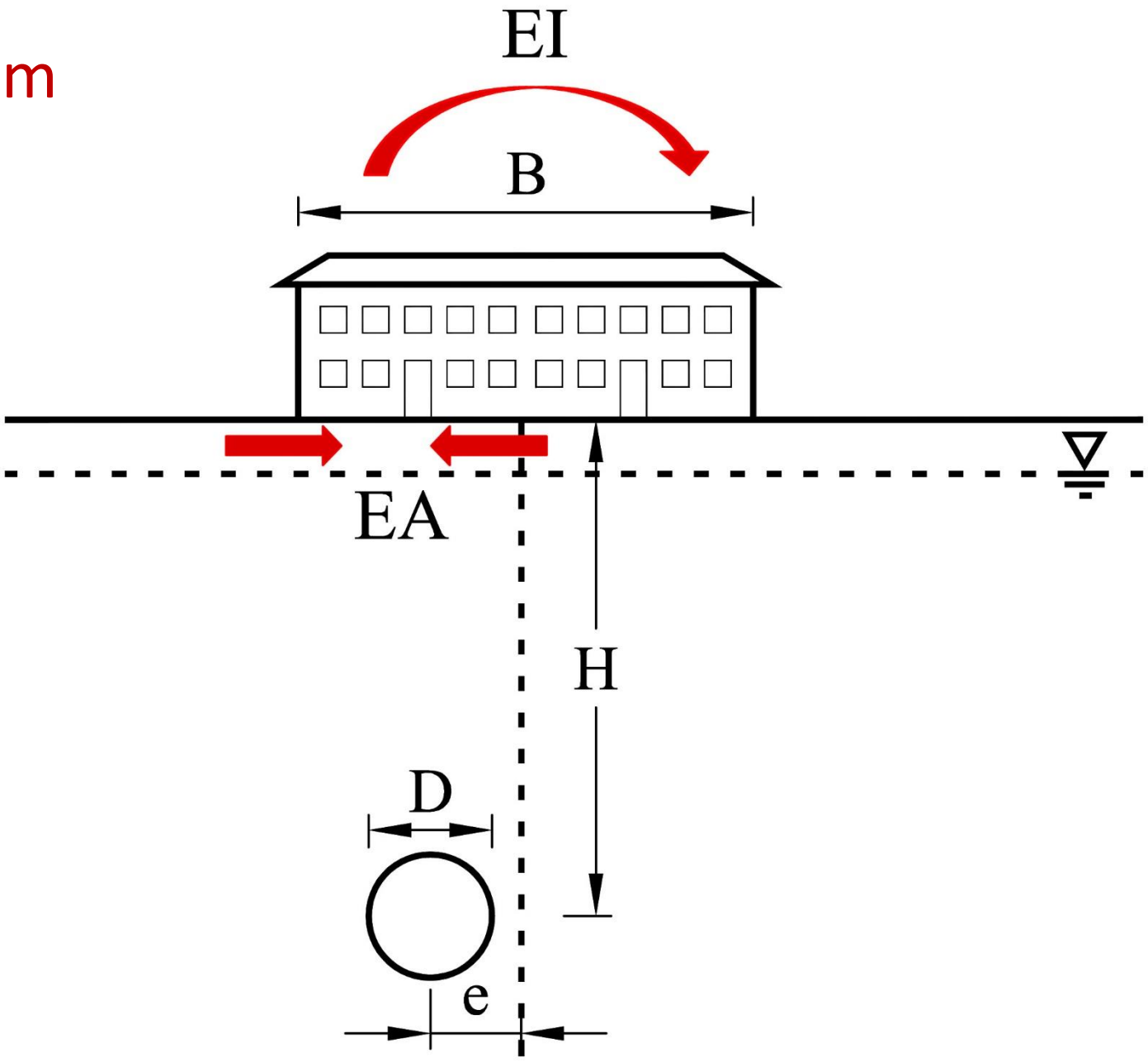
Horizontal strain

$$\text{Damage} = f\left(\frac{\Delta\delta_v}{l}, \frac{\Delta\delta_x}{l}\right)$$



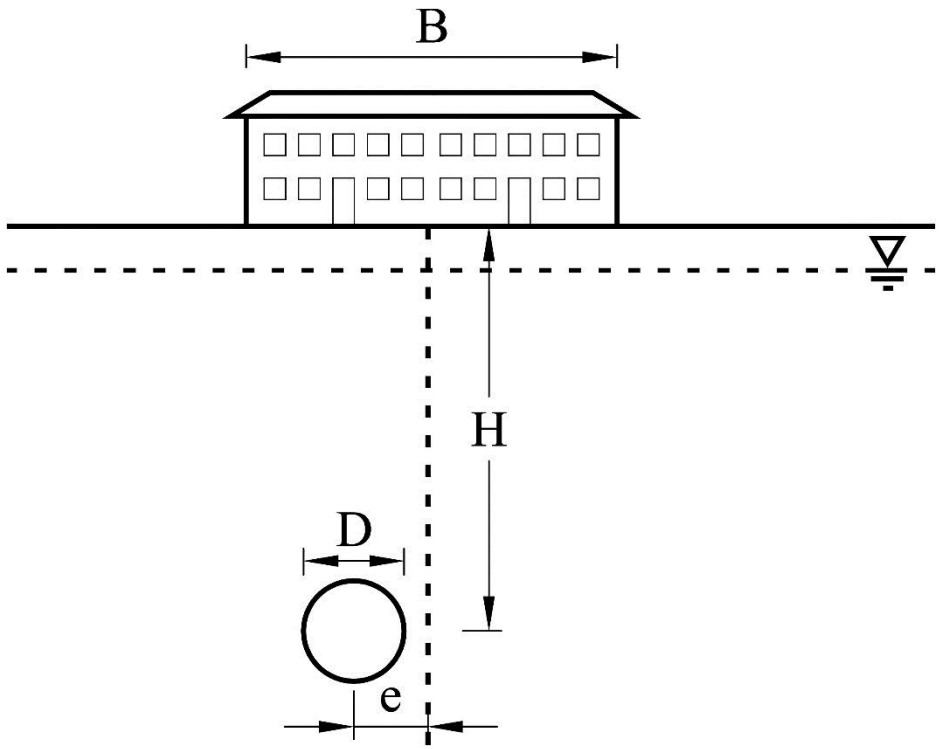
(Simplified from Boscardin & Cording, 1989)

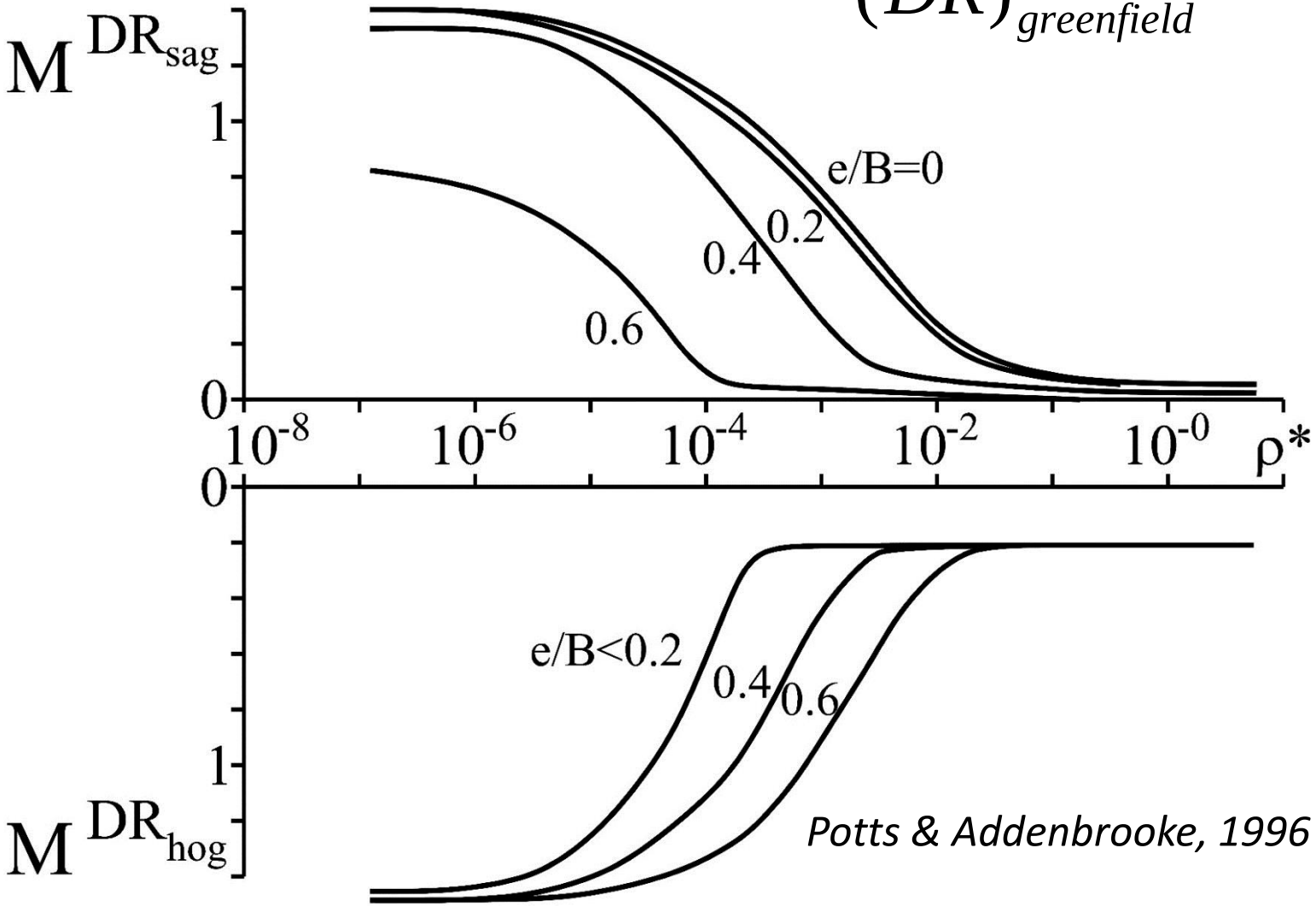
Tunnel-building interaction
The building as an elastic beam



Modification Factors for Deflection Ratios (DR)

$$M^{DR} = \frac{(DR)_{tunnel+building}}{(DR)_{greenfield}}$$

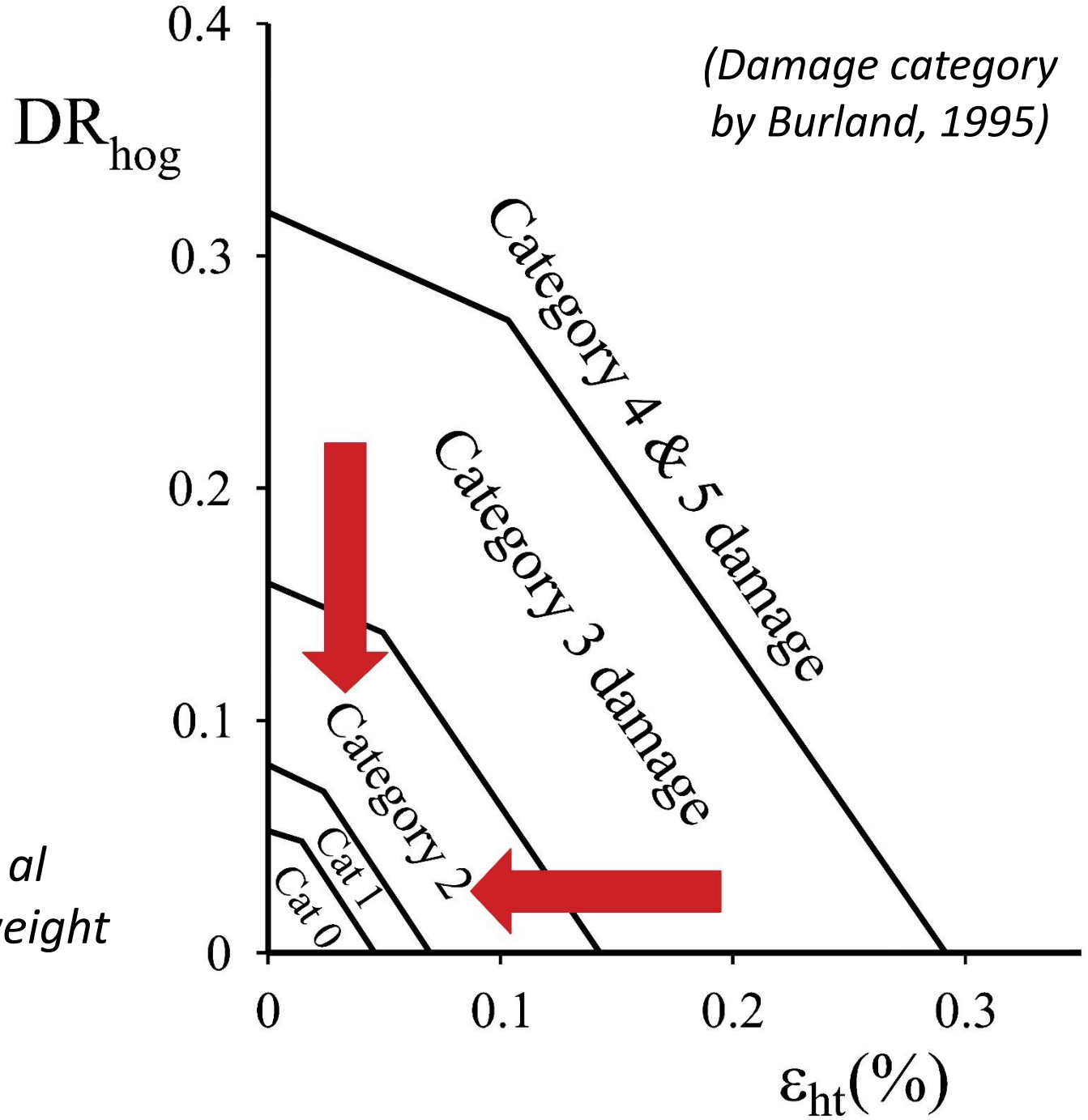




Potts & Addenbrooke, 1996

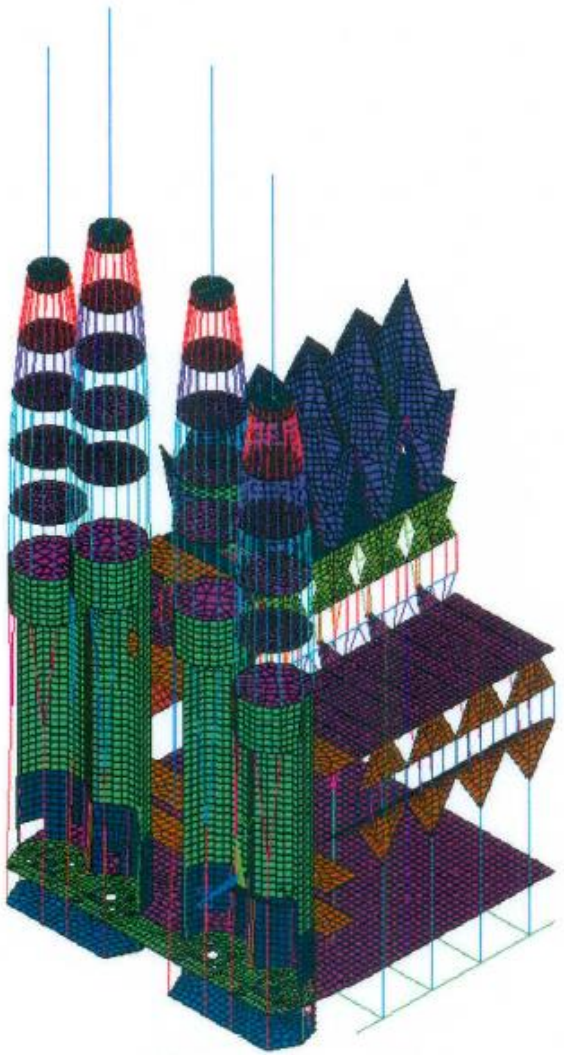
$$\rho^* = \frac{(EI)_{Building}}{E_{Soil\,(\gamma=10^{-4})}(B/2)^4}$$

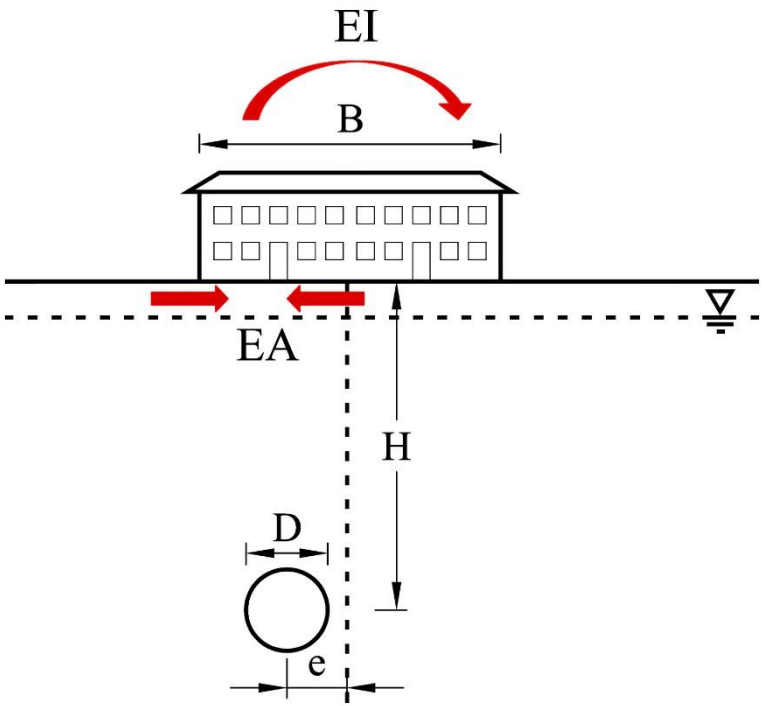
Effect of building flexural and horizontal stiffness

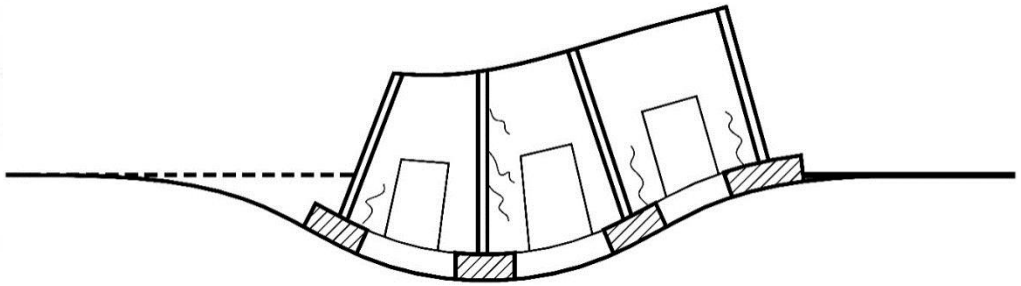


- *Additional contribution by Franzius et al (2005): 3D parametric study + building weight*

Structural model of Sagrada Familia modernist Basilica

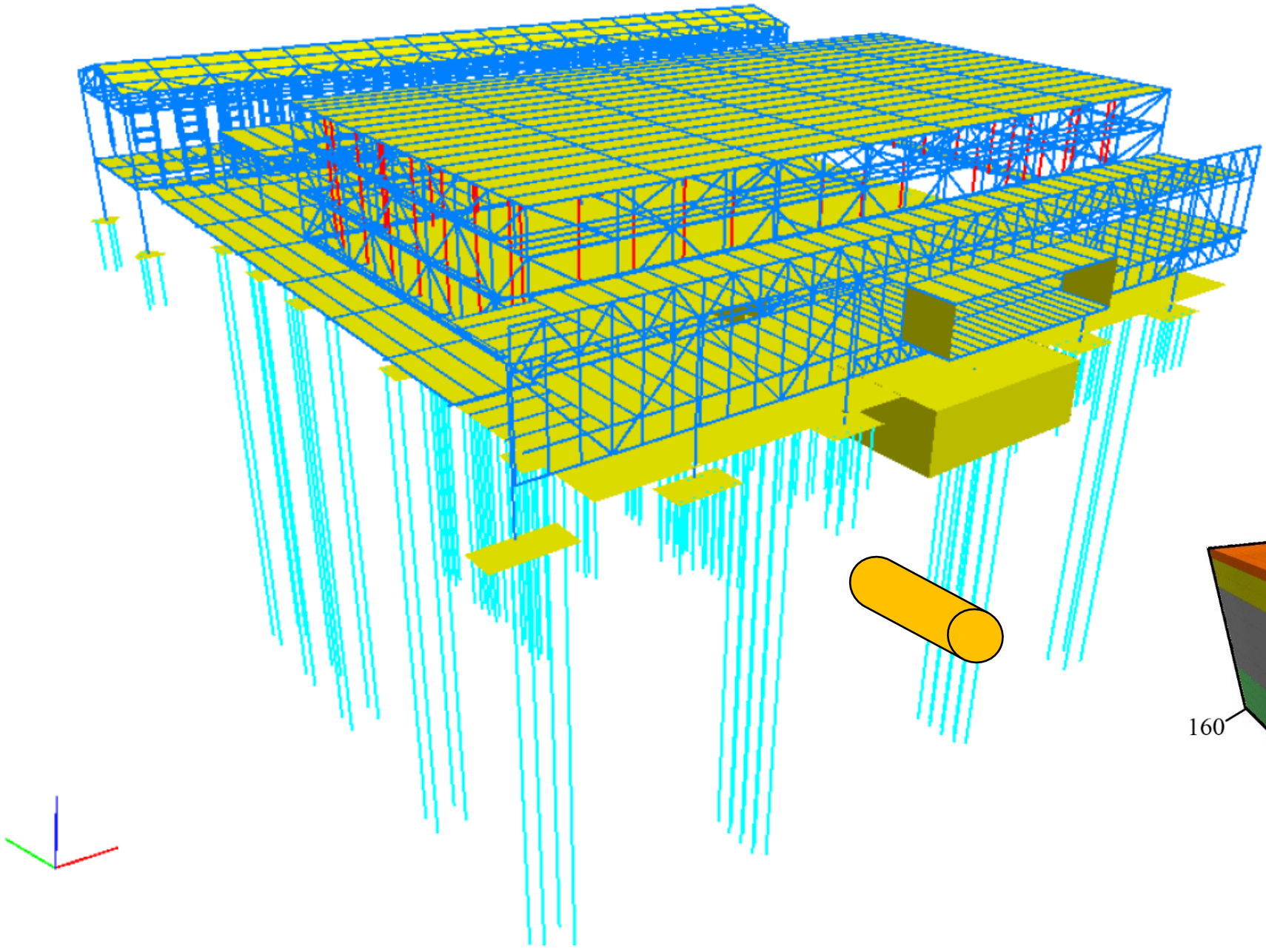


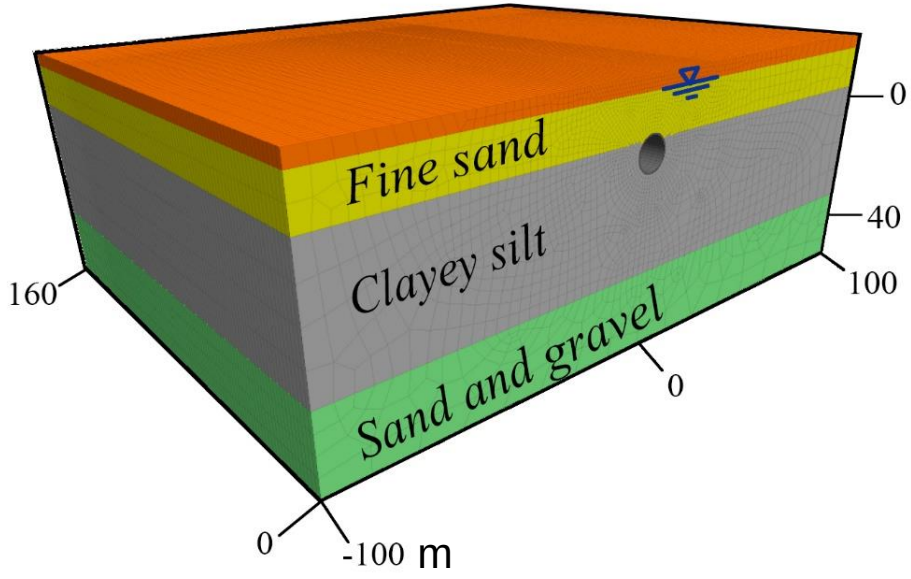




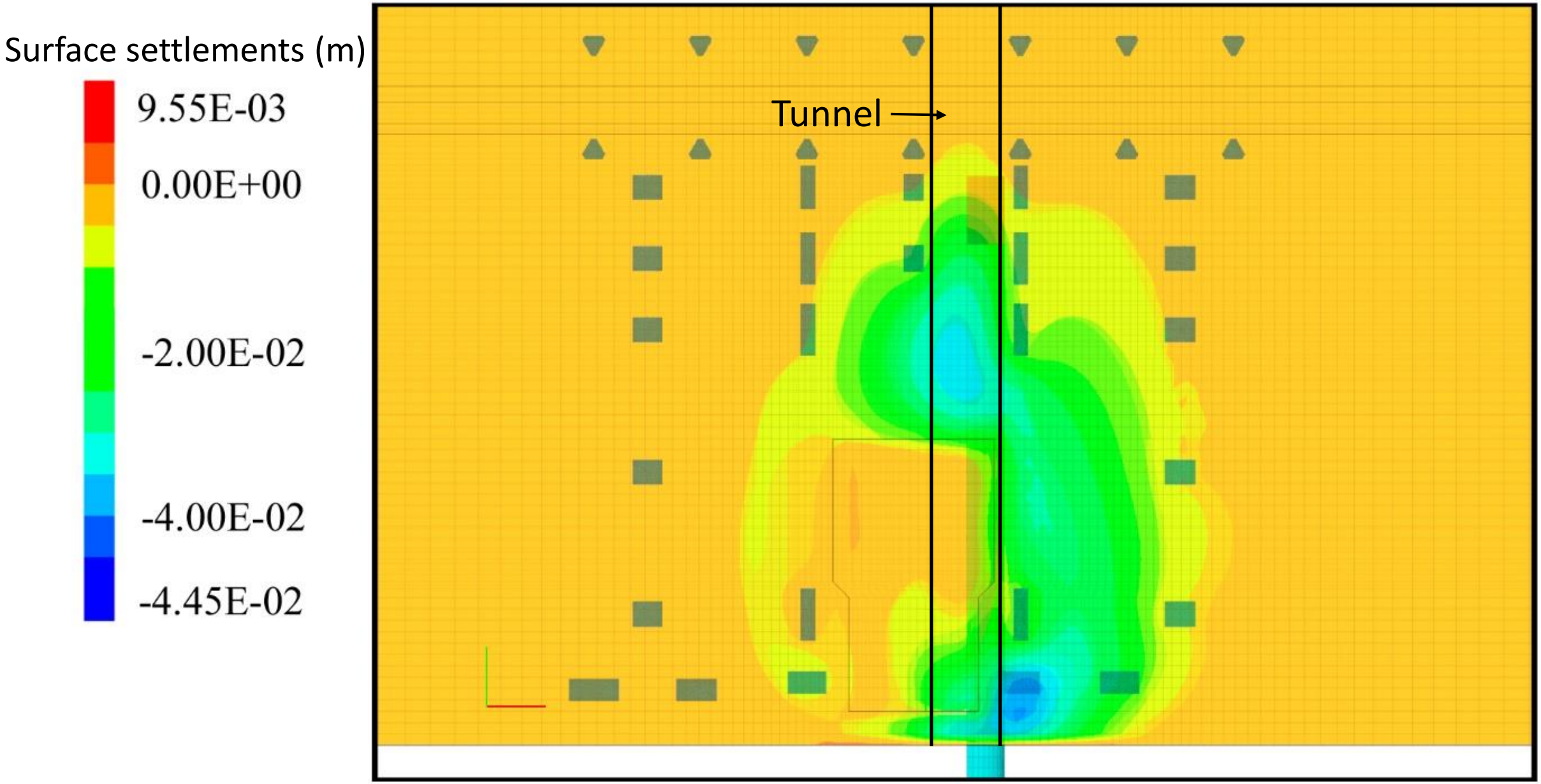
Structural model by INTEMAC, 2005

Model for the crossing of Terminal 2, Barcelona airport



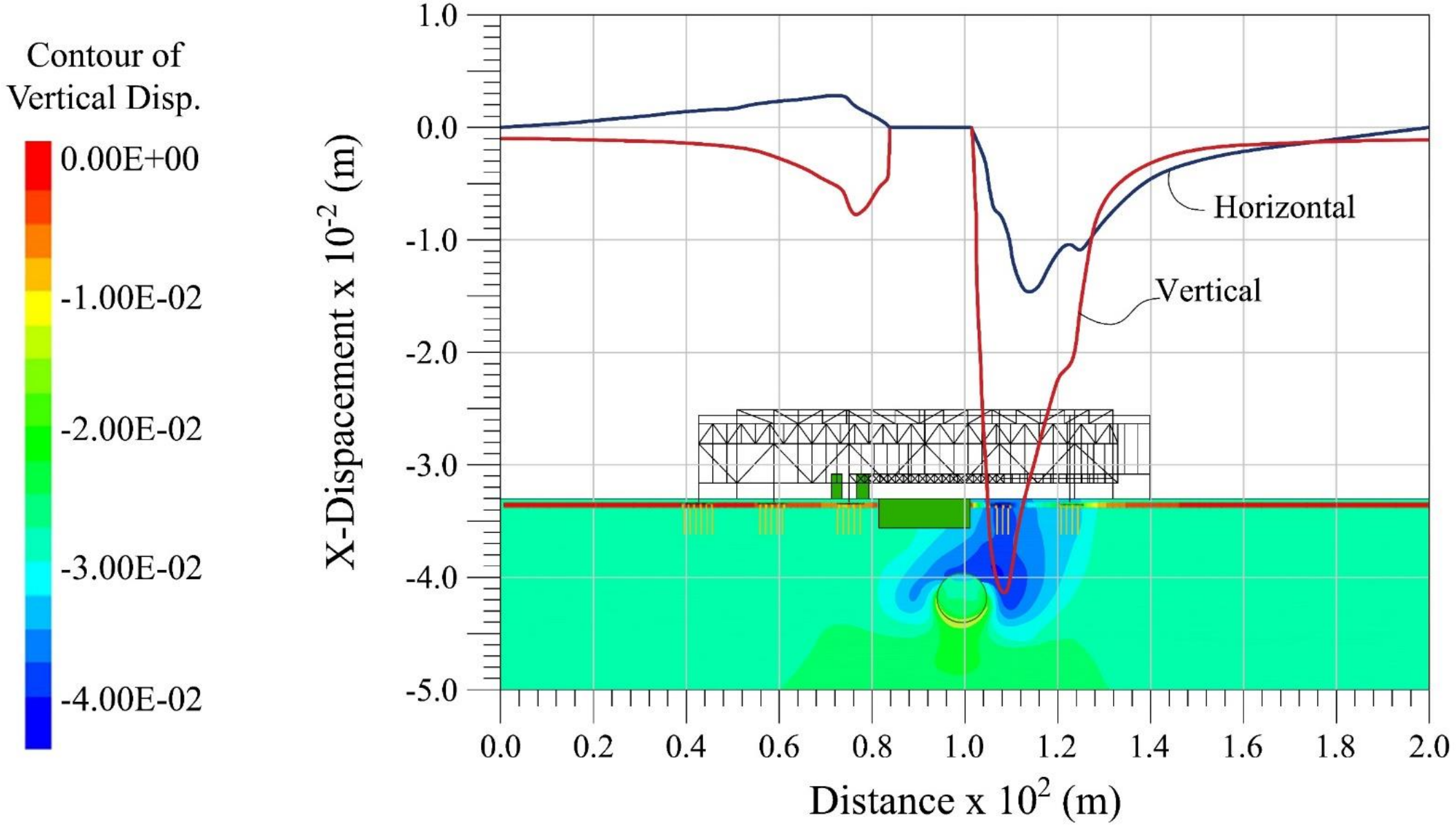


Simulation of Terminal 2 crossing. 3D Soil + Tunnel + Structure model



(Geoconsult, 2017)

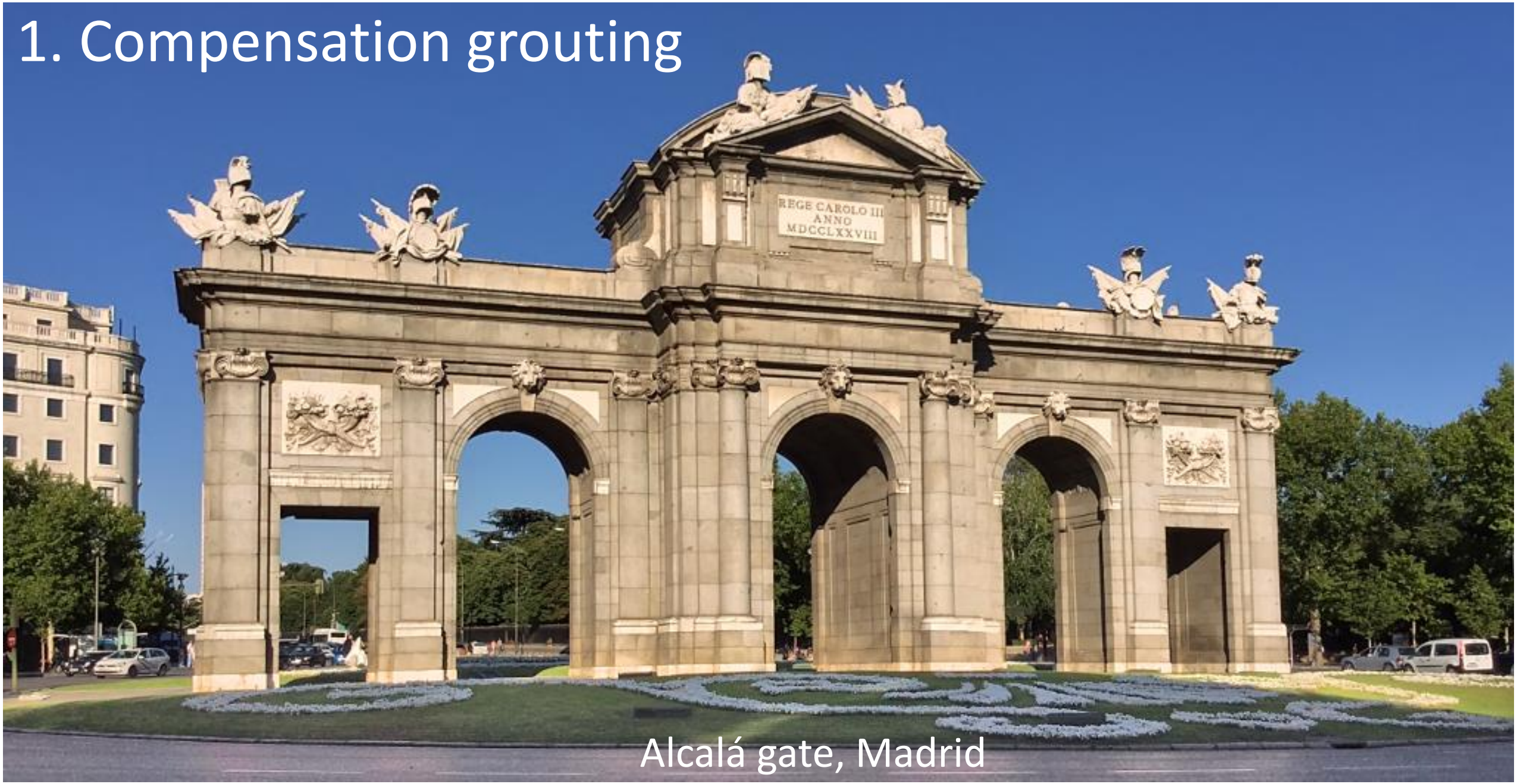
Simulation of Terminal crossing. 3D Soil + Tunnel + Structure model



Contents

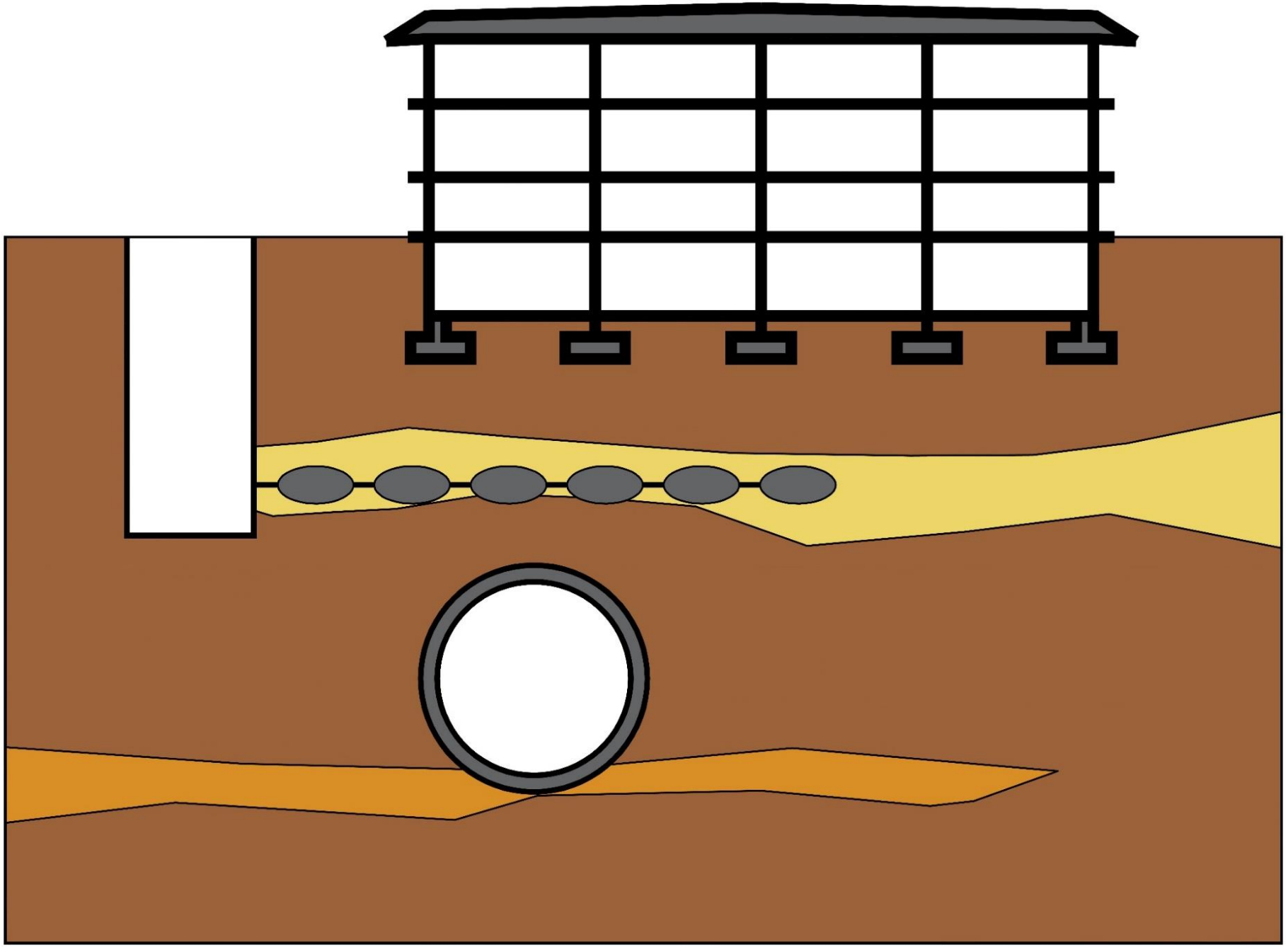
1. Compensation grouting
   - ➢ Semi-analytical solution
2. Protection walls
   - ➢ Semi-analytical solution
3. Other mitigation techniques

1. Compensation grouting



Alcalá gate, Madrid

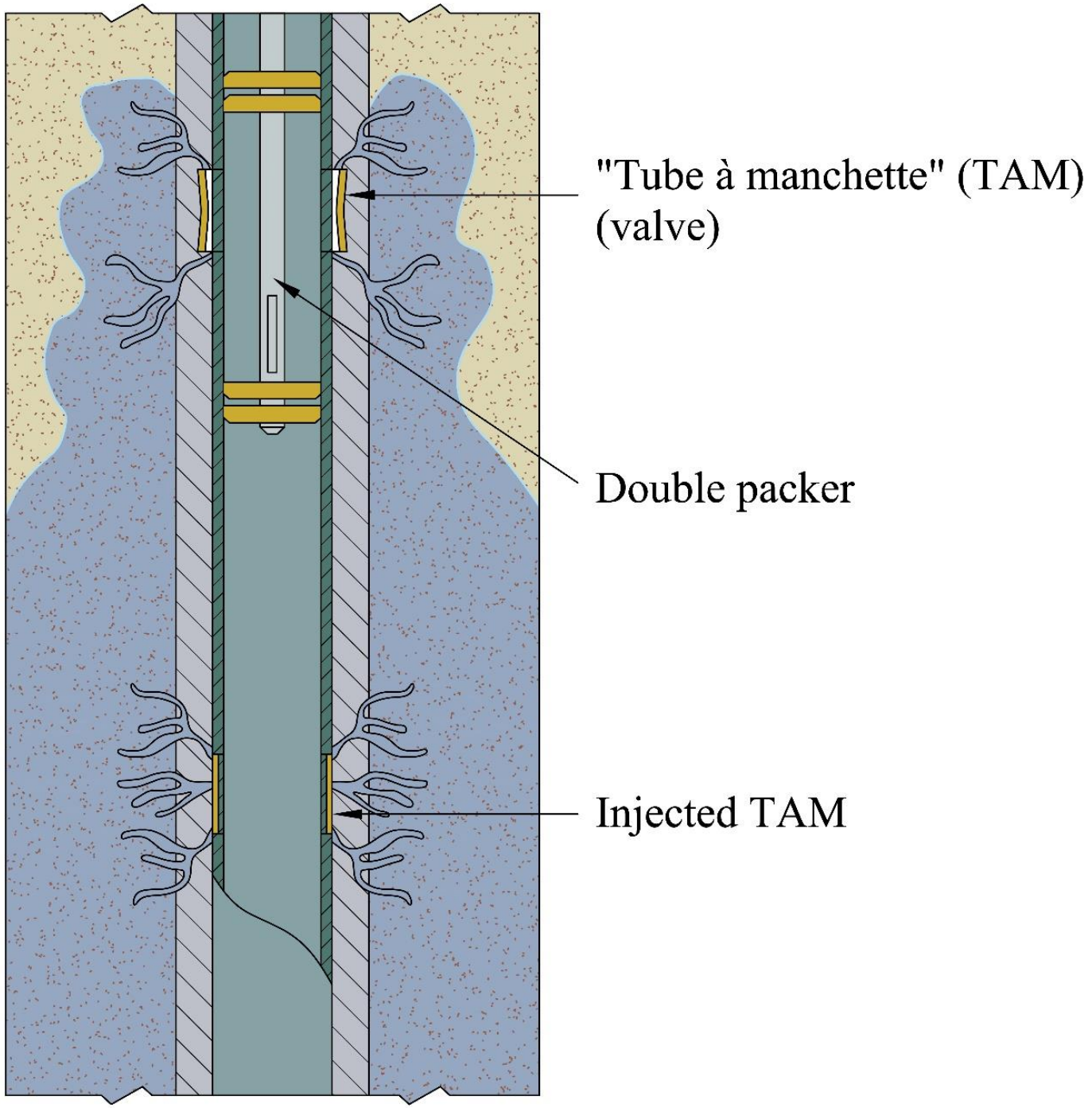
Compensation Grouting

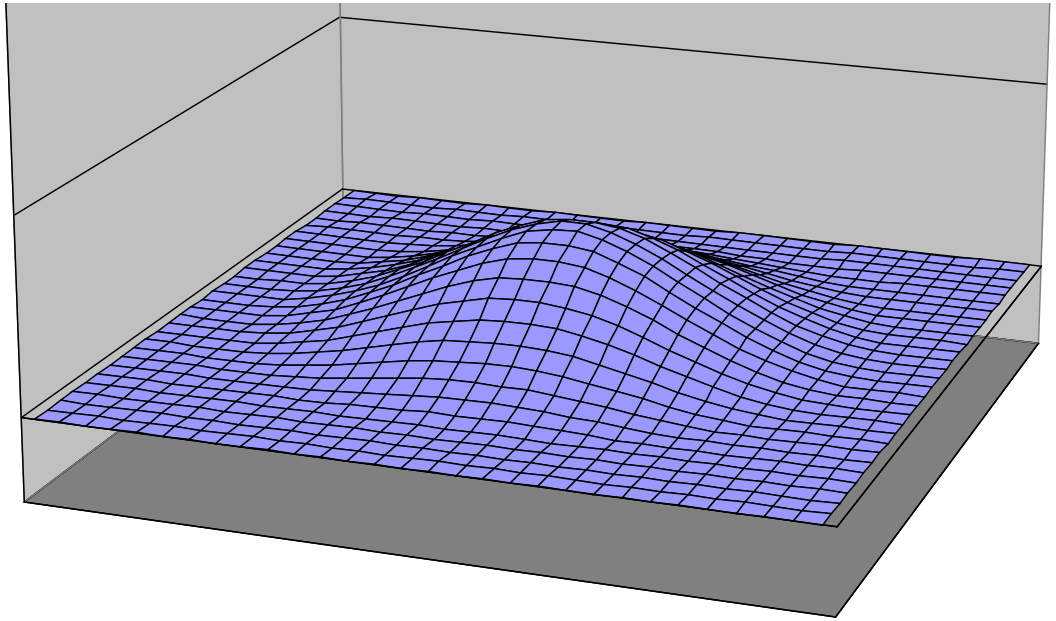


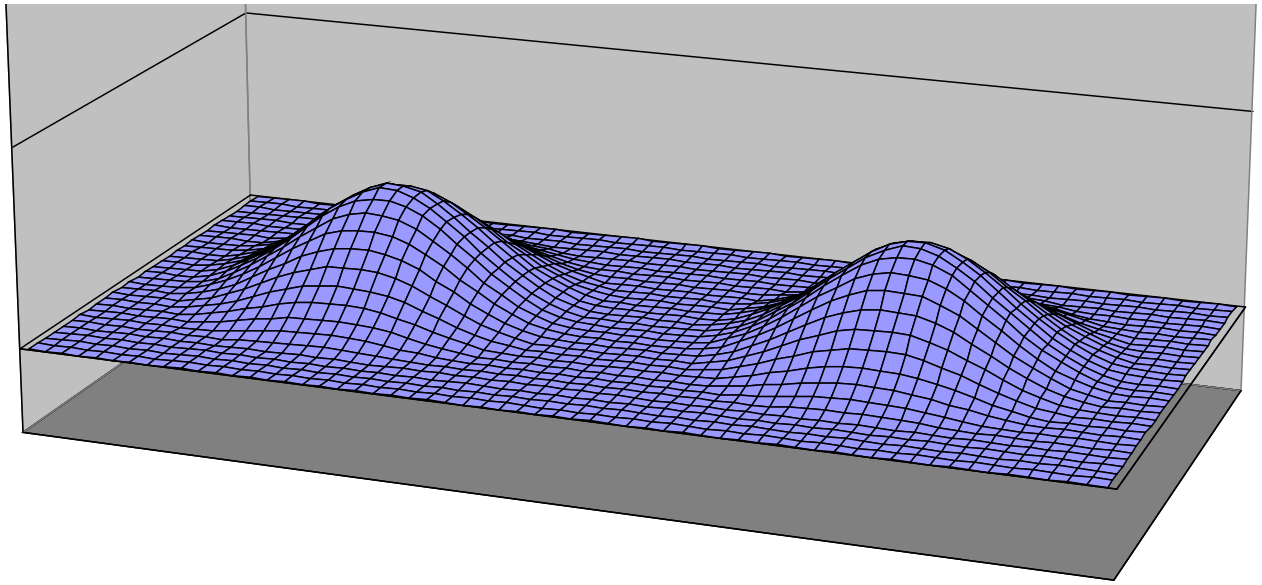
“TAM”

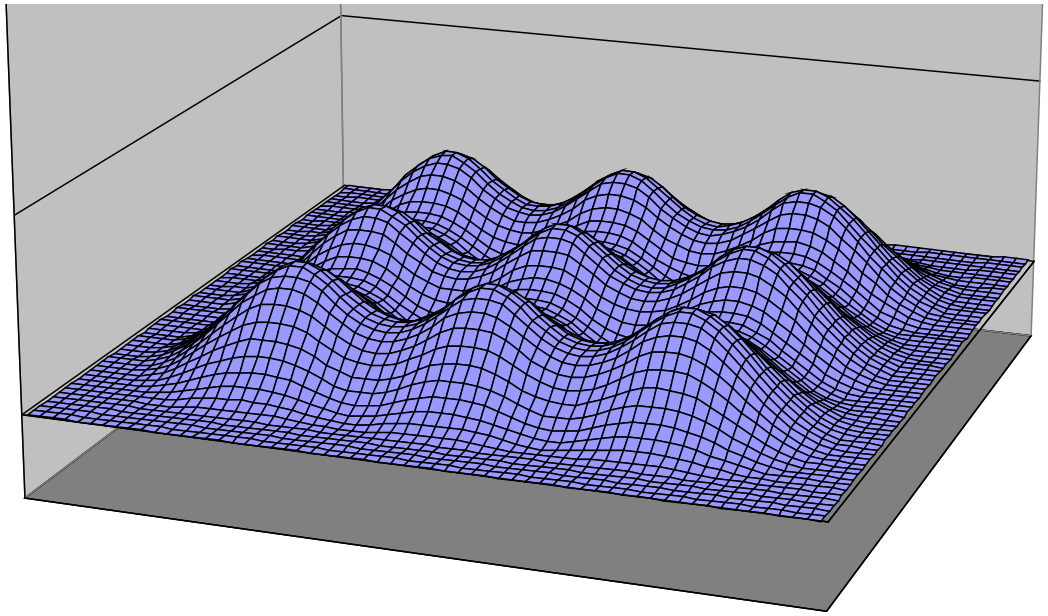
Tubes à Manchettes

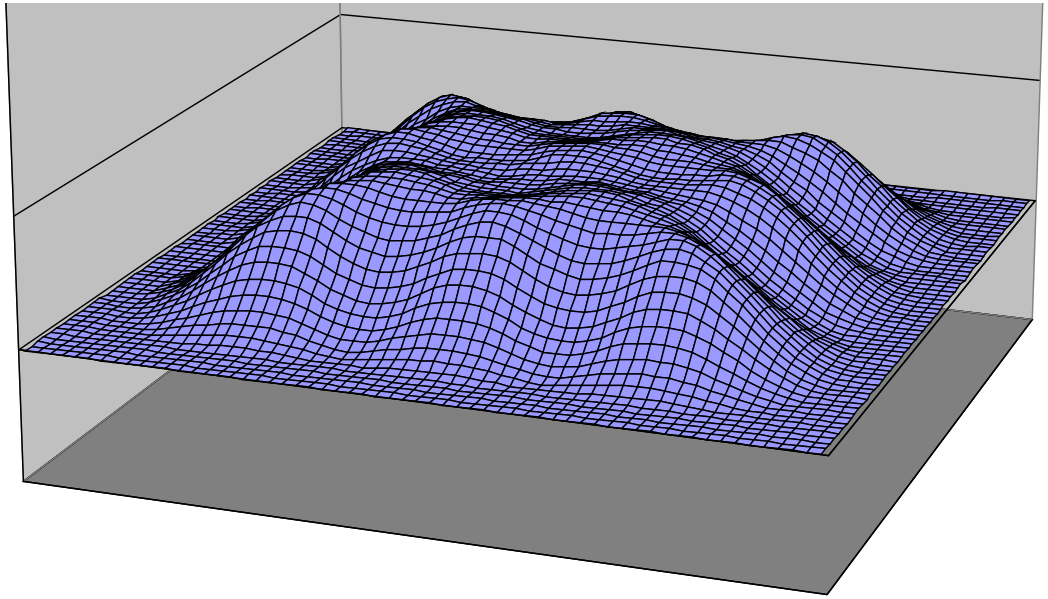
TAM + Double Packer injection technique







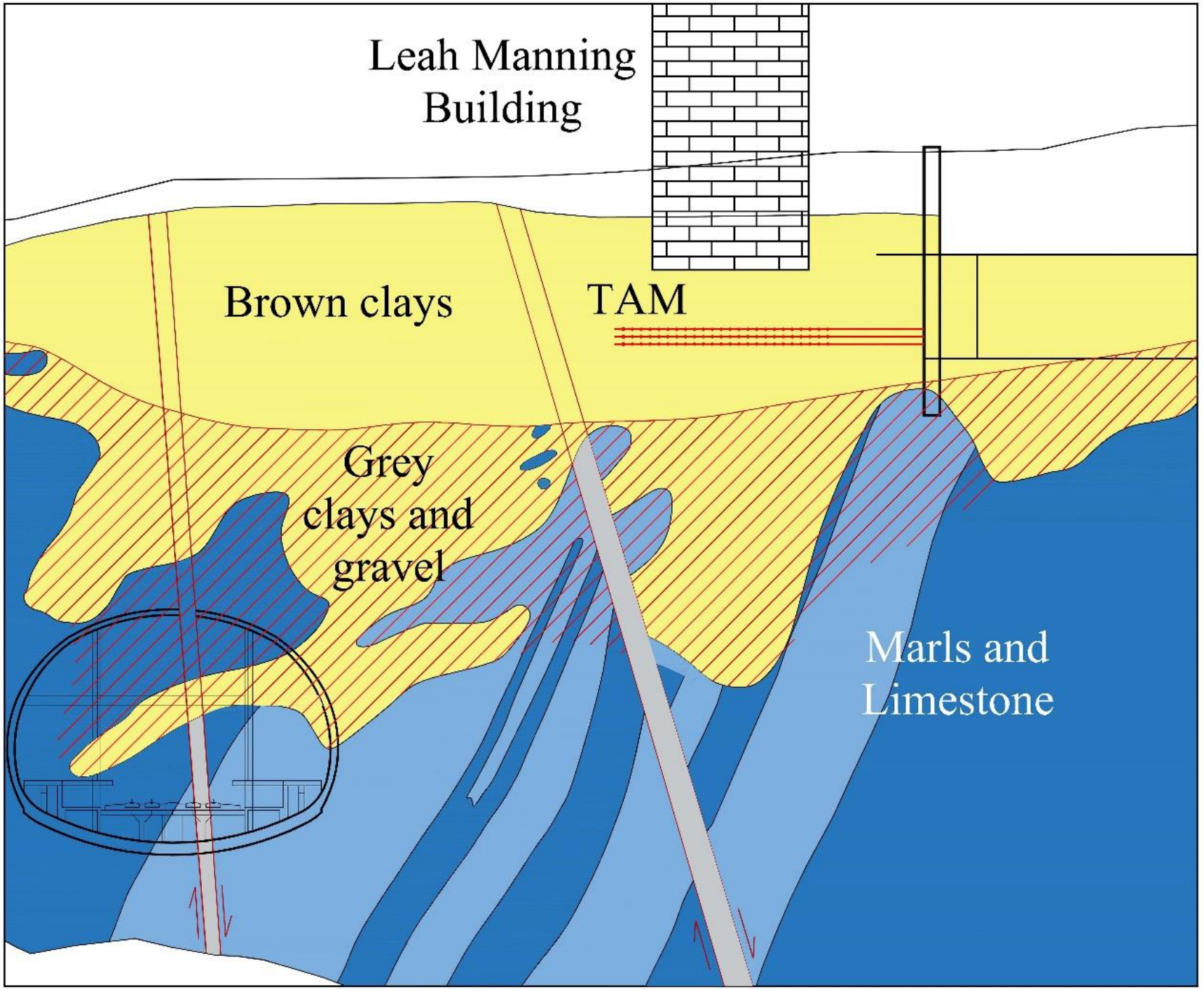




Bilbao metro

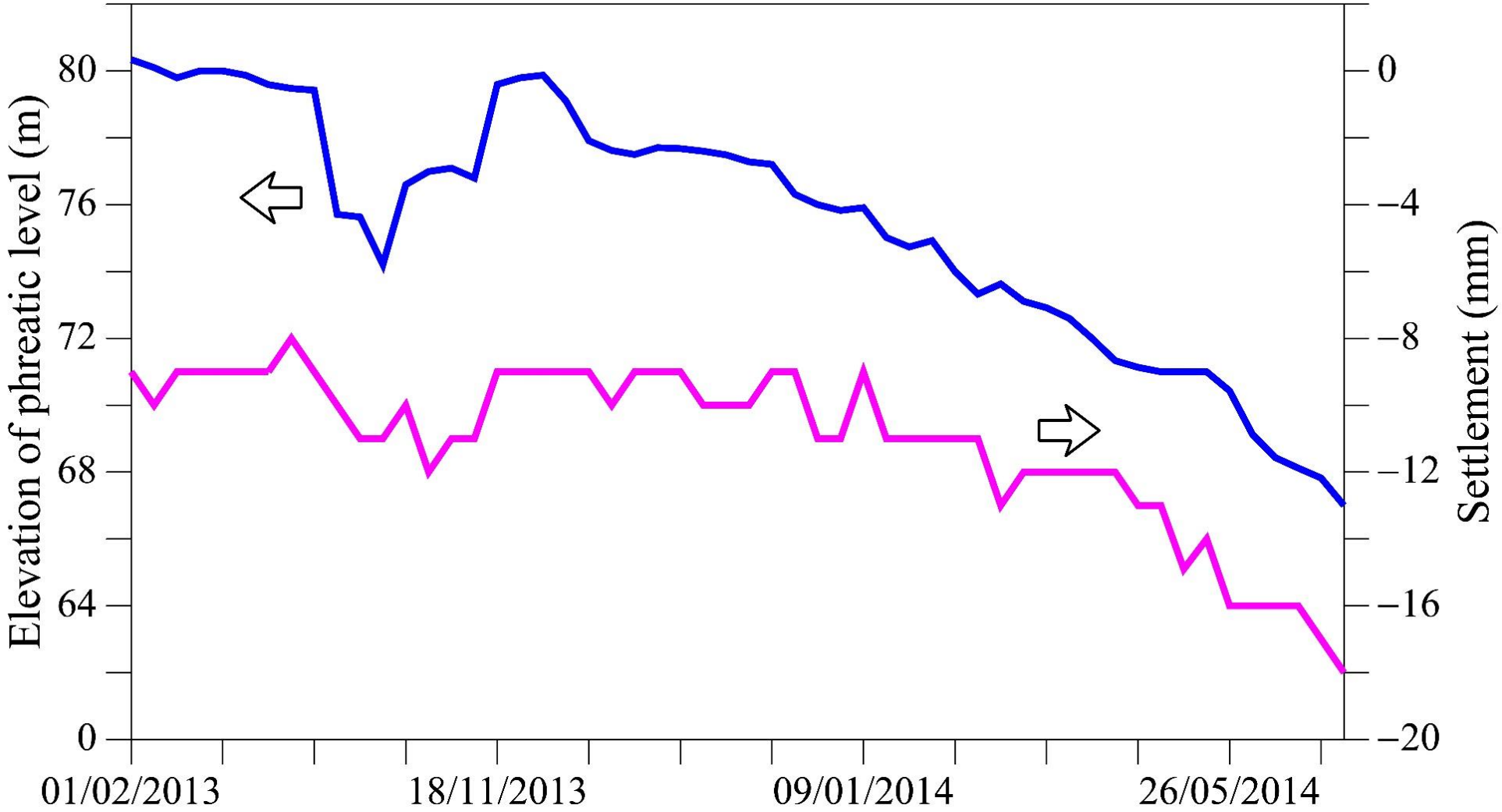
- Slender building
- Complex geology
- Tunnel parallel and close to building
- Small cover to diameter ratio
- Isolated footings
- Footings on rock at one end

Bilbao metro



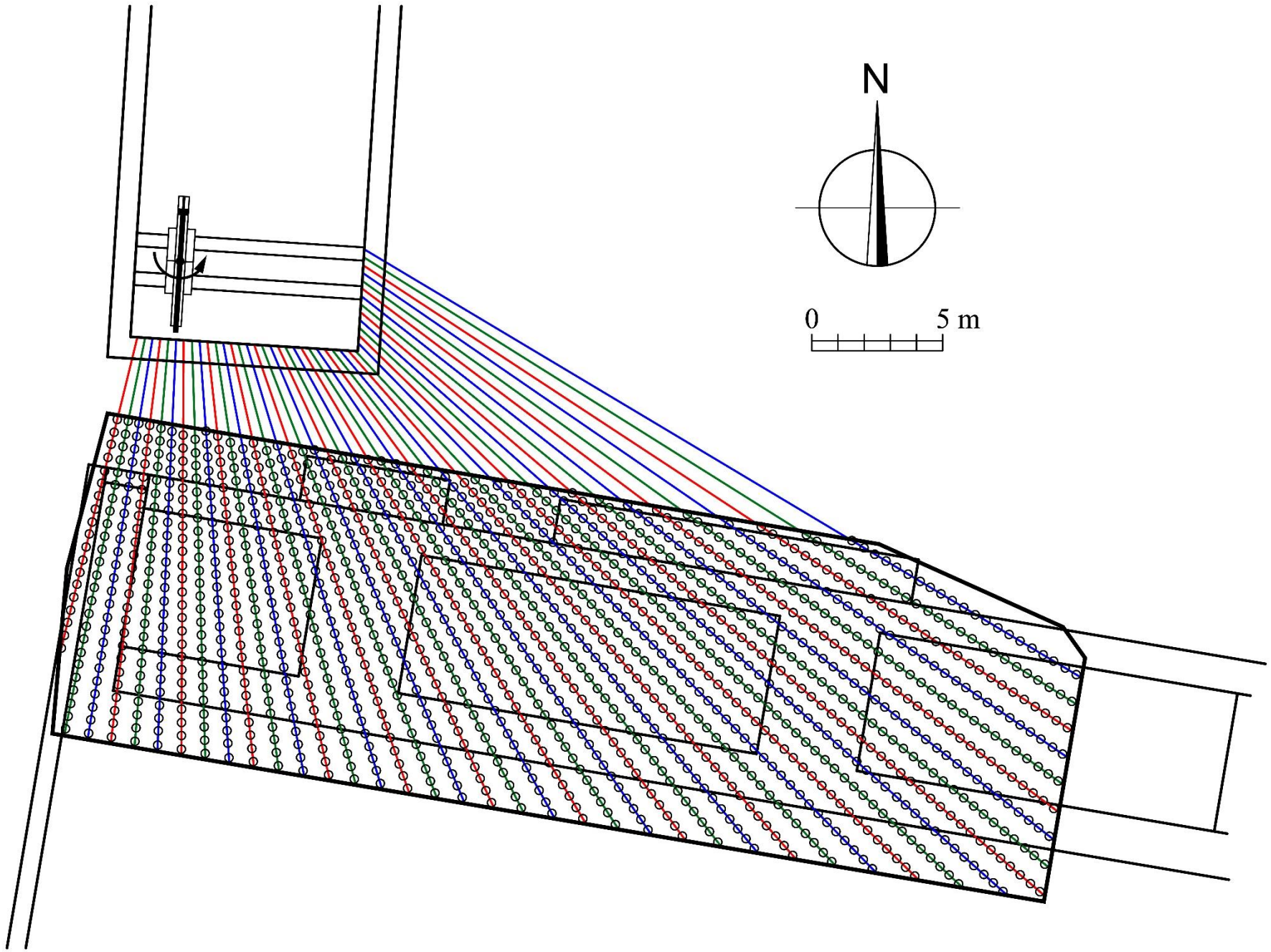
Bilbao metro

Ground water lowering induced by tunnel construction and building settlement



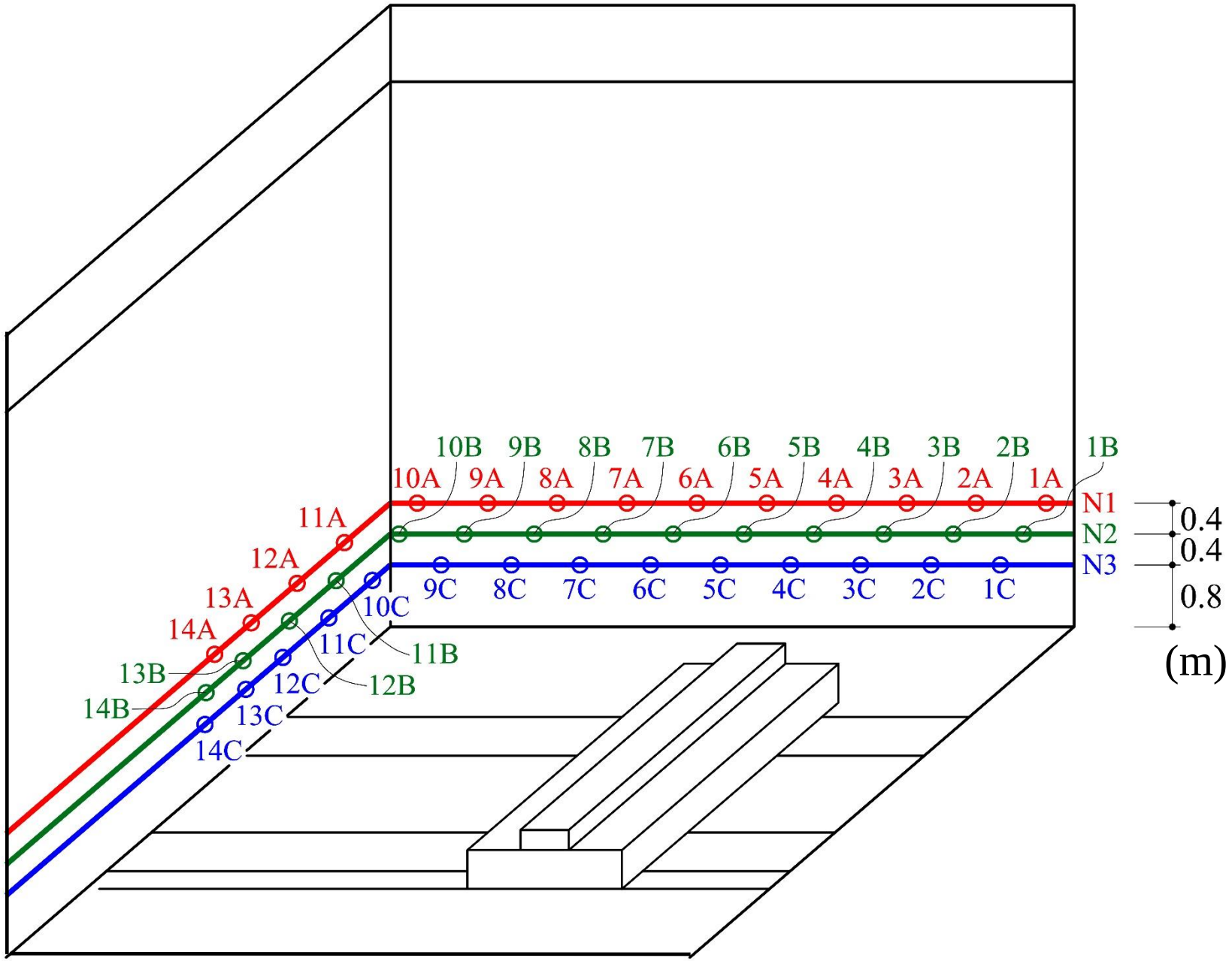
Bilbao metro

Plan view of compensation grouting boreholes



Bilbao metro

Three levels of compensation grouting boreholes

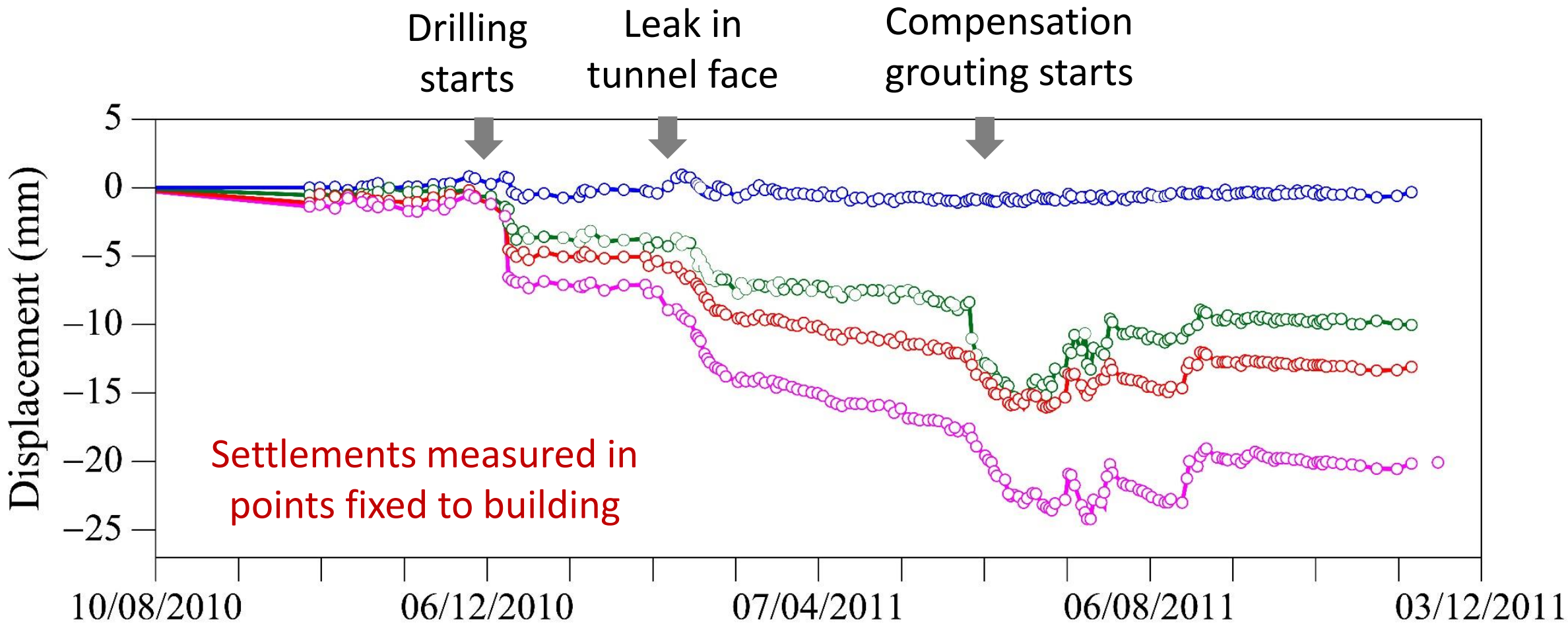



6A
5A
4A
3A

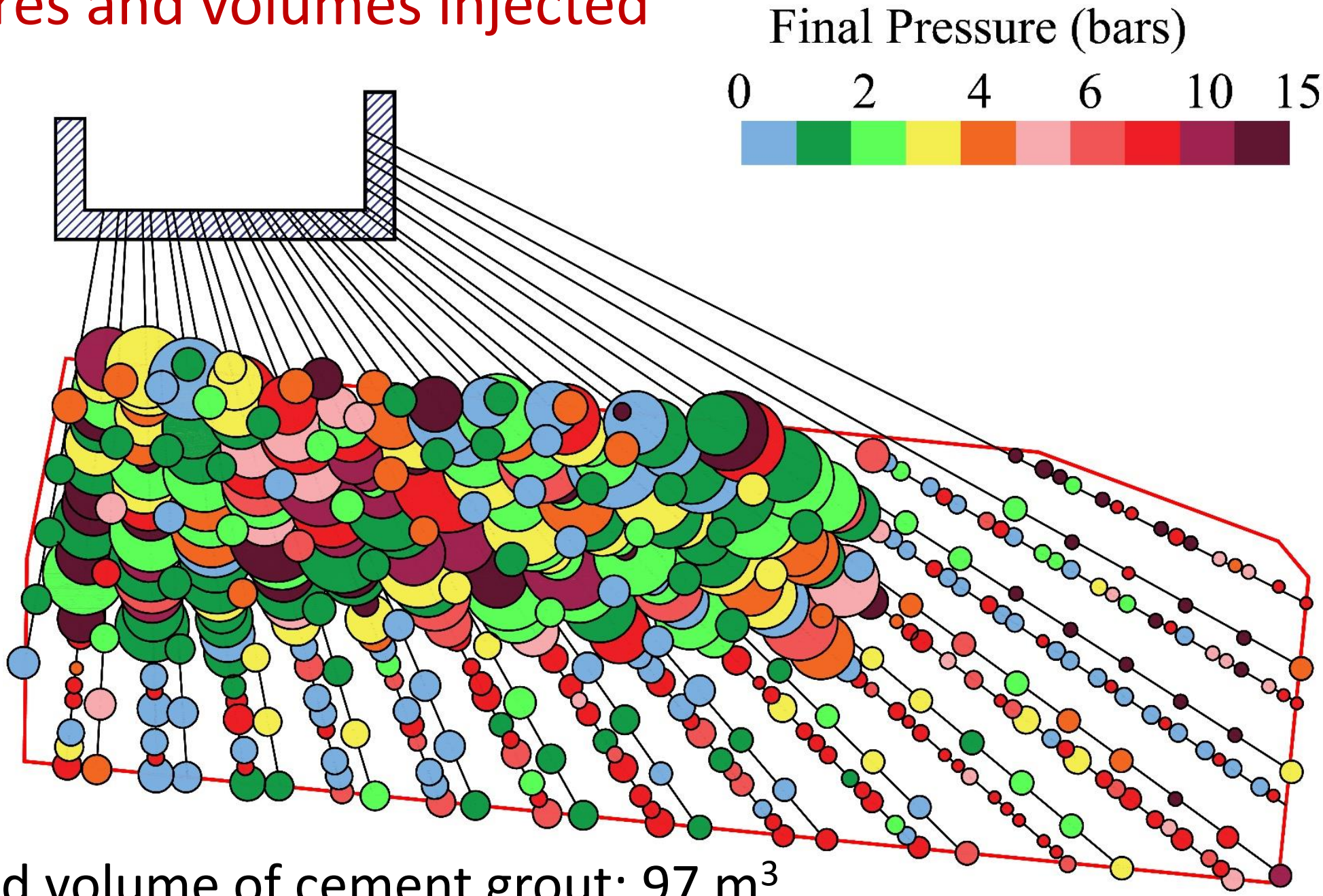
Bilbao metro

Monitoring

Bilbao metro



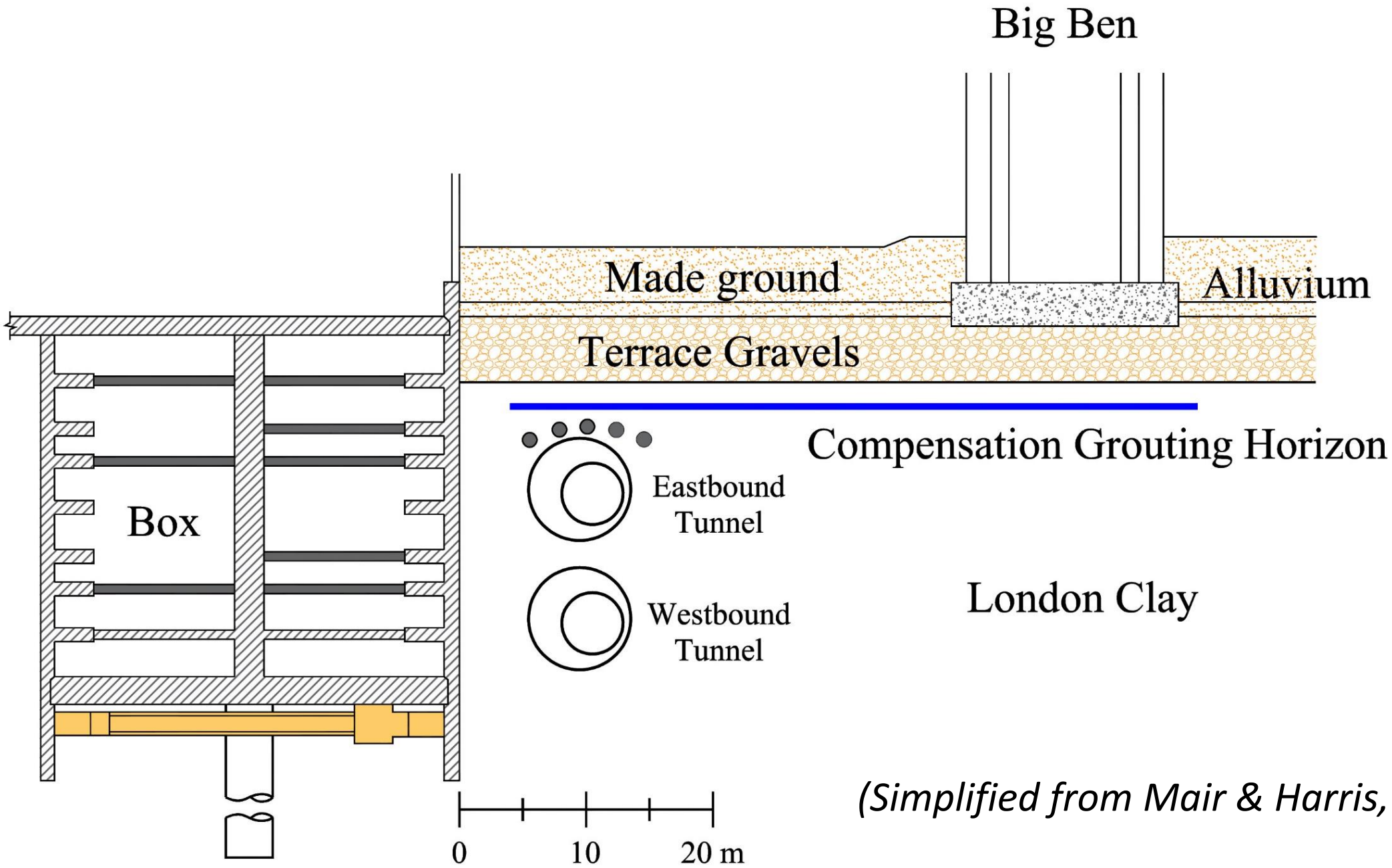
TAM. Pressures and volumes injected



- Total injected volume of cement grout: 97 m^3

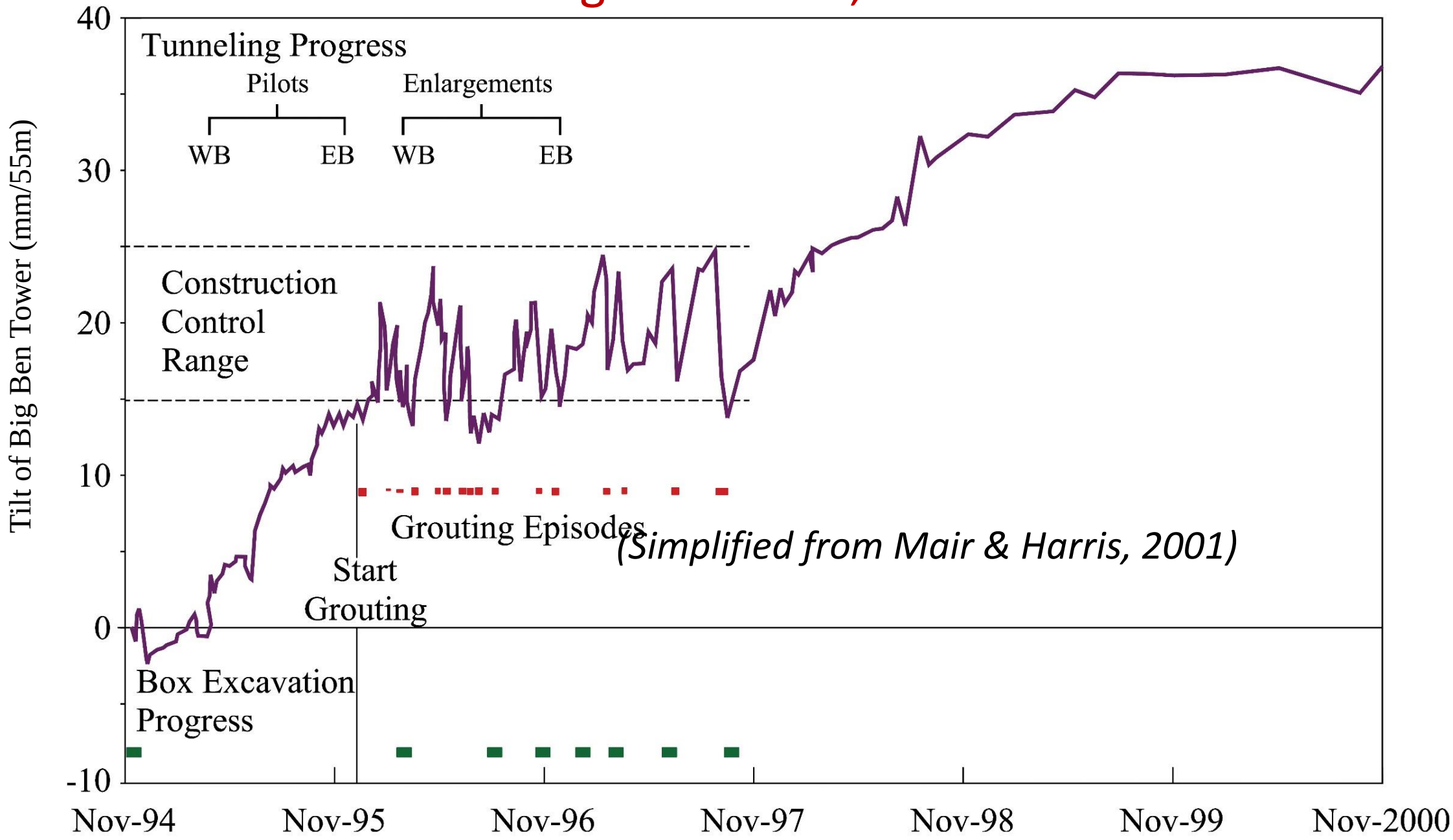

London
Big Ben

Tilt of Big Ben Tower



(Simplified from Mair & Harris, 2001)

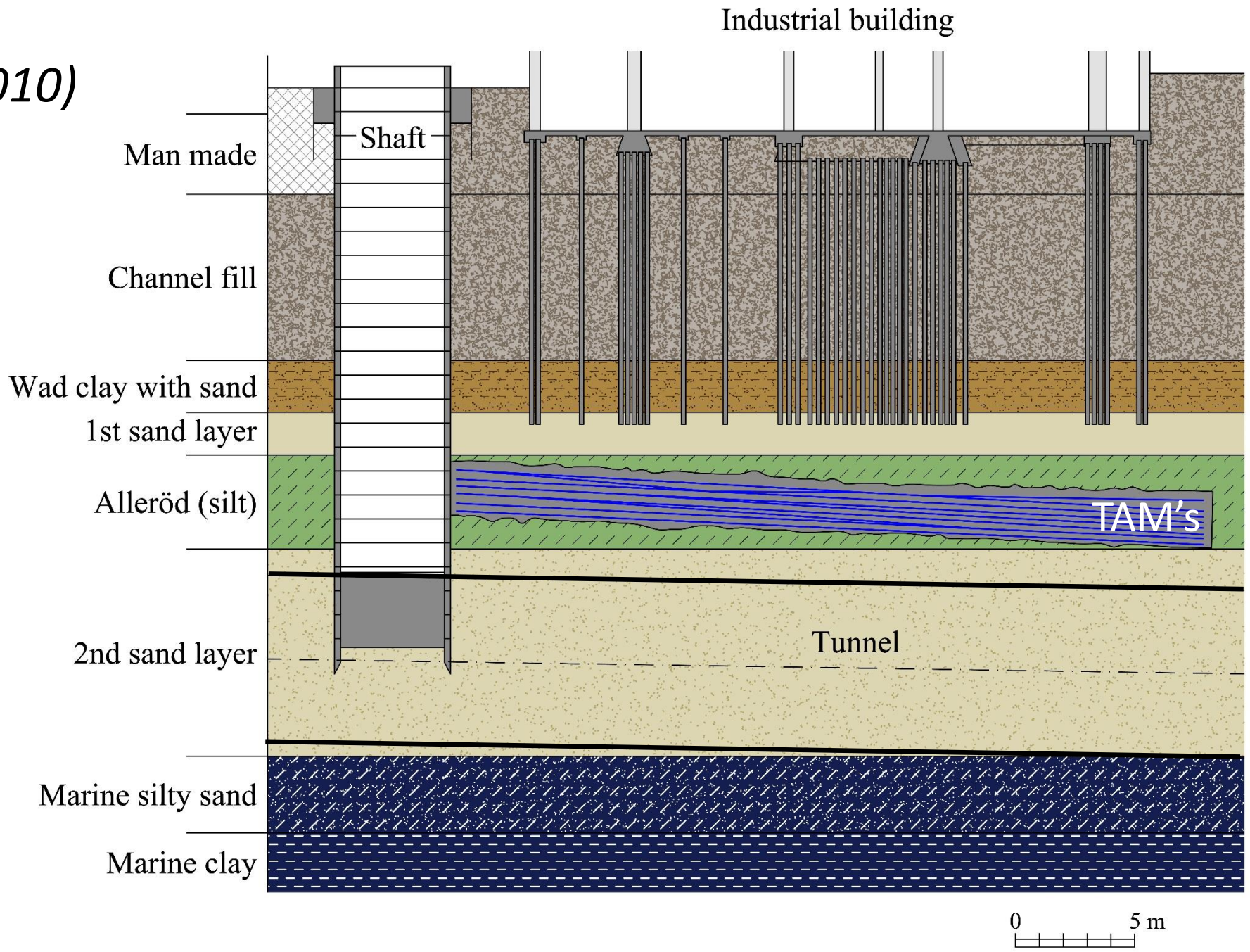
Tilt of Big Ben Tower, London



(Simplified from Mair & Harris, 2001)

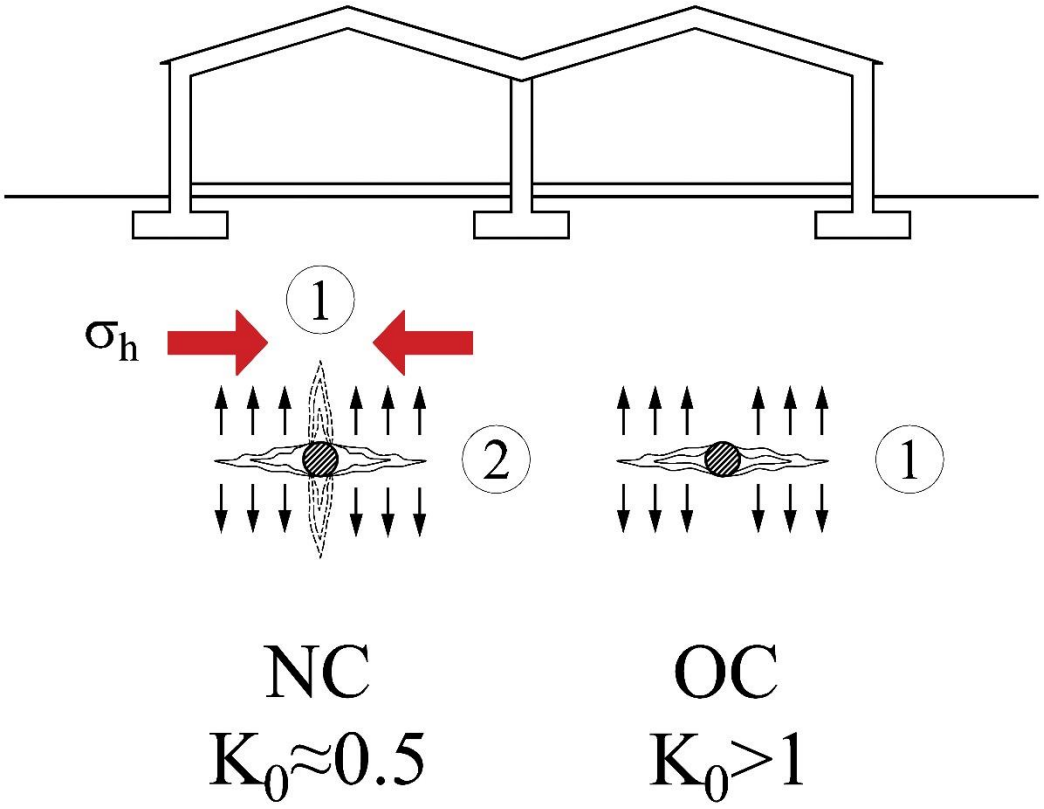
Amsterdam

(Bezuijen & Bosch, 2010)

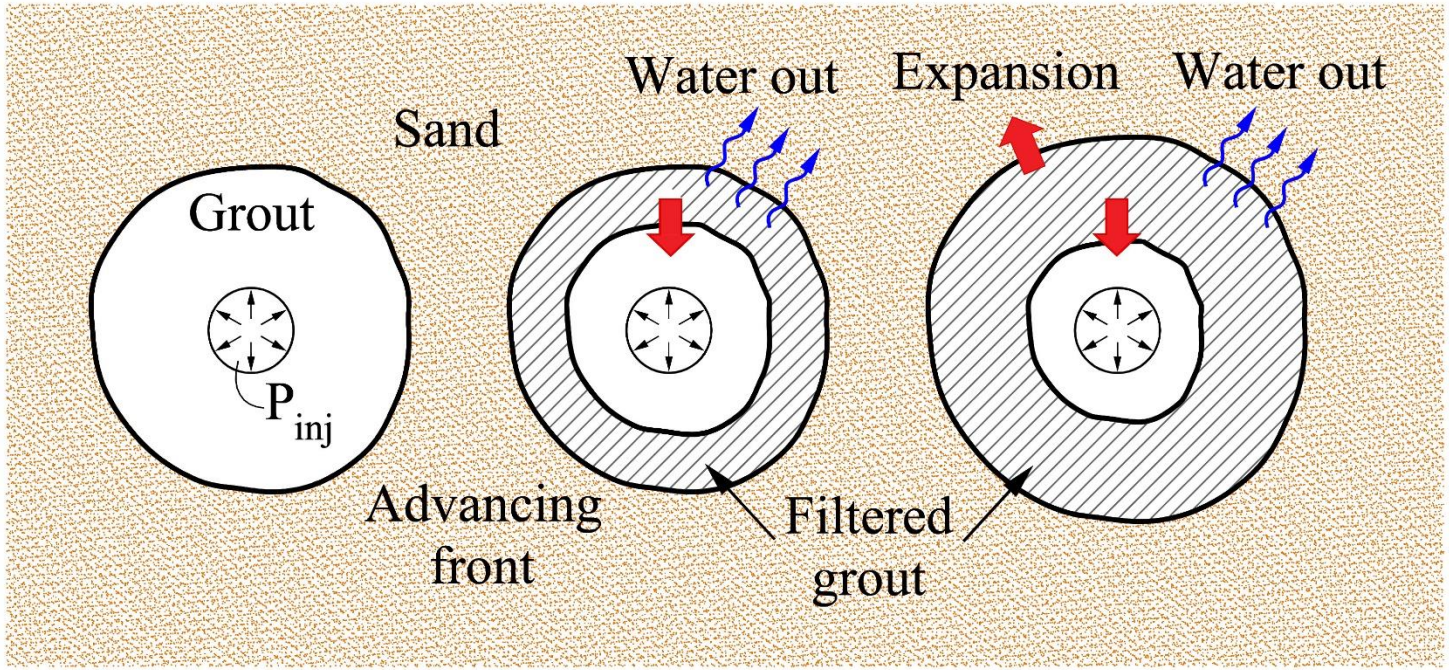


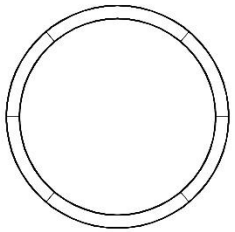
Deformation mechanisms

Fracture grouting (clays)



Compaction grouting (sands)



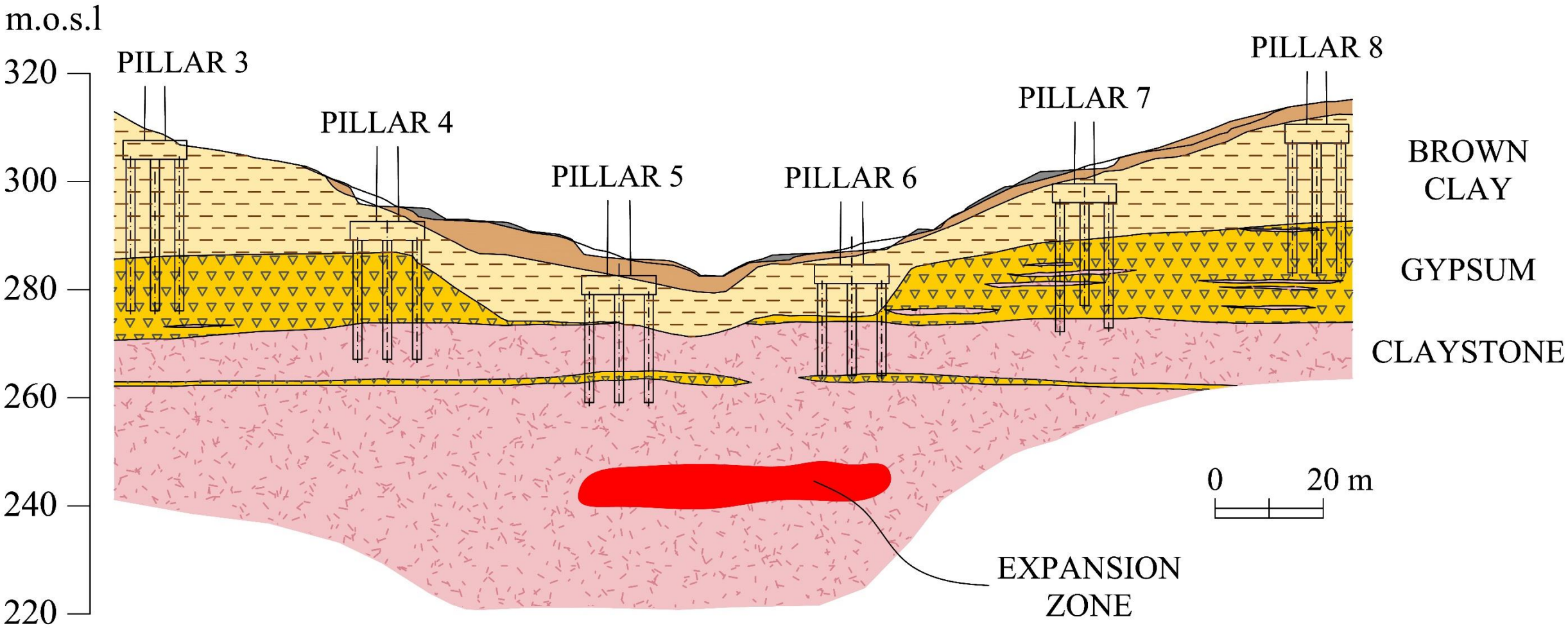


- For calculation purposes: A volume increase

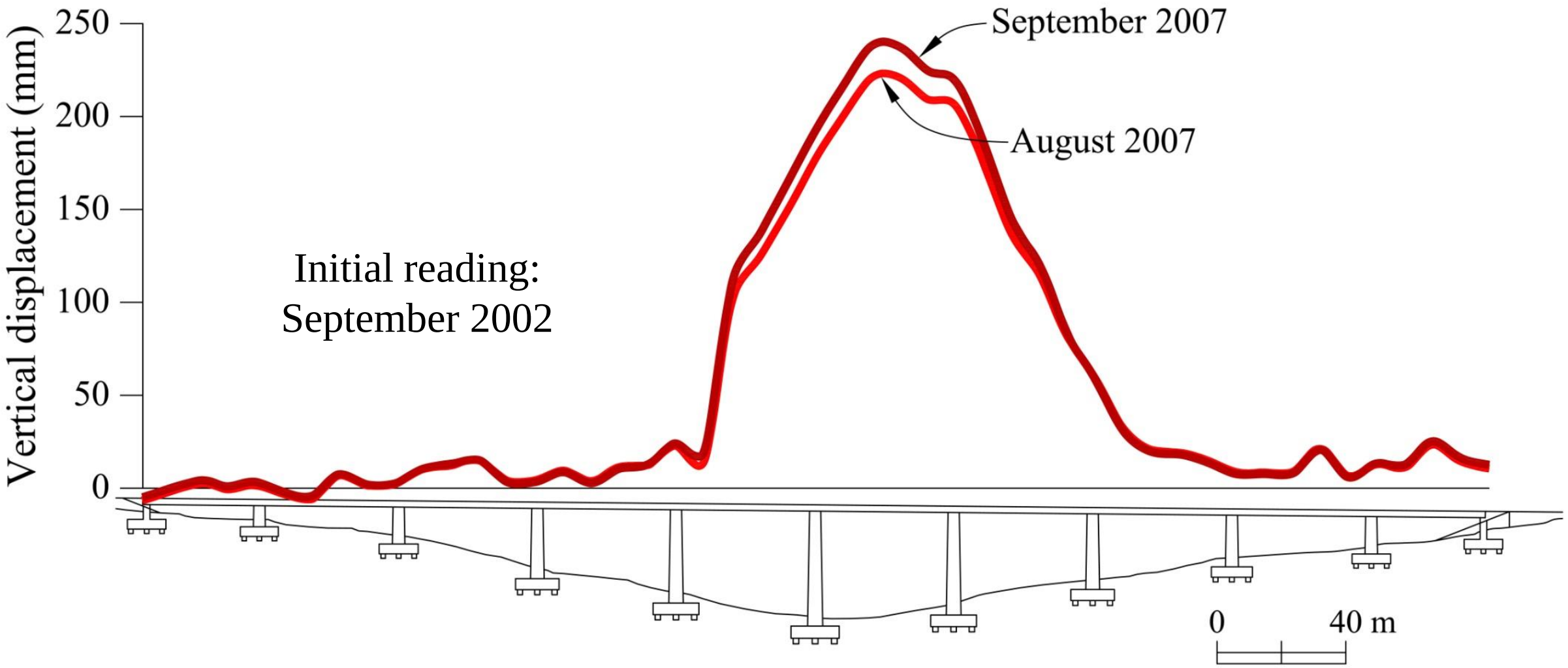
A semi-analytical solution for pile foundations subjected to soil volume change

(Alonso, Sauter & Ramon, 2015)

Pile foundations subjected to soil volume increase at depth

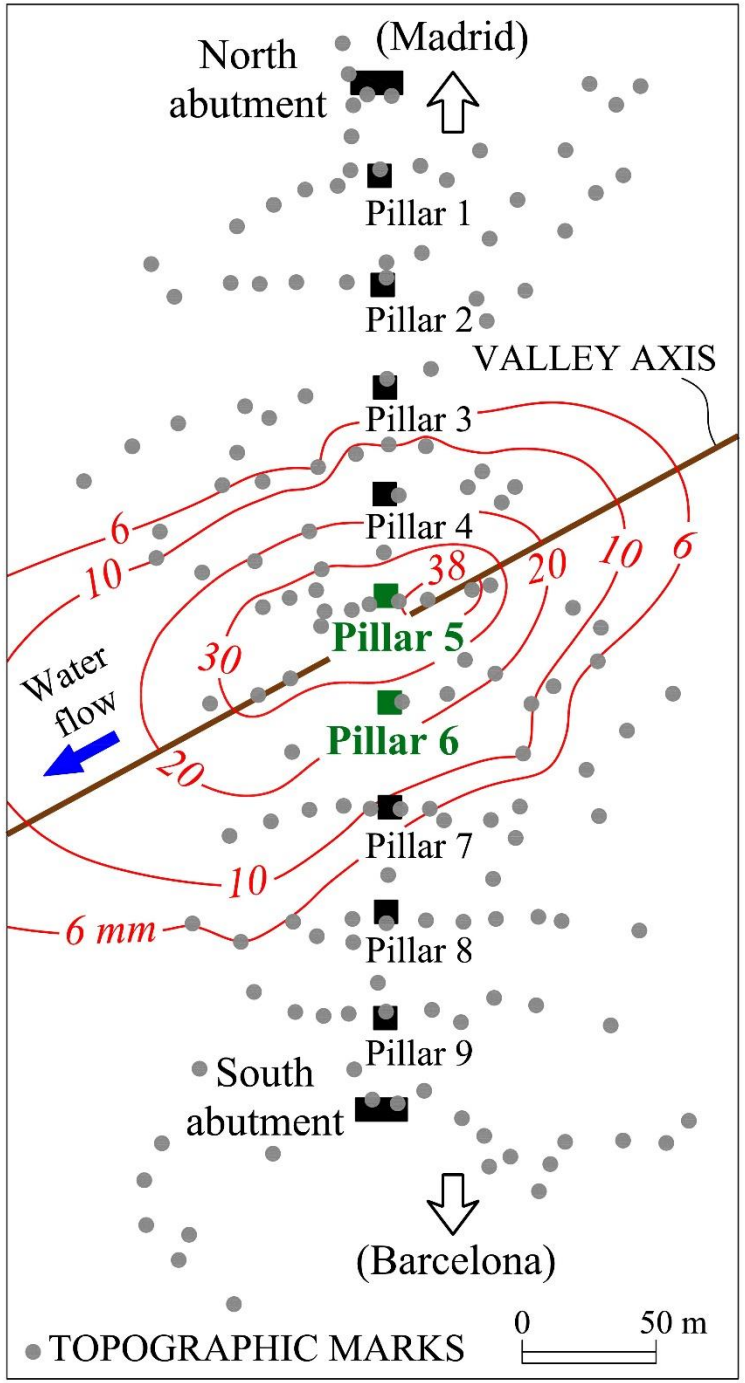


Heave profiles

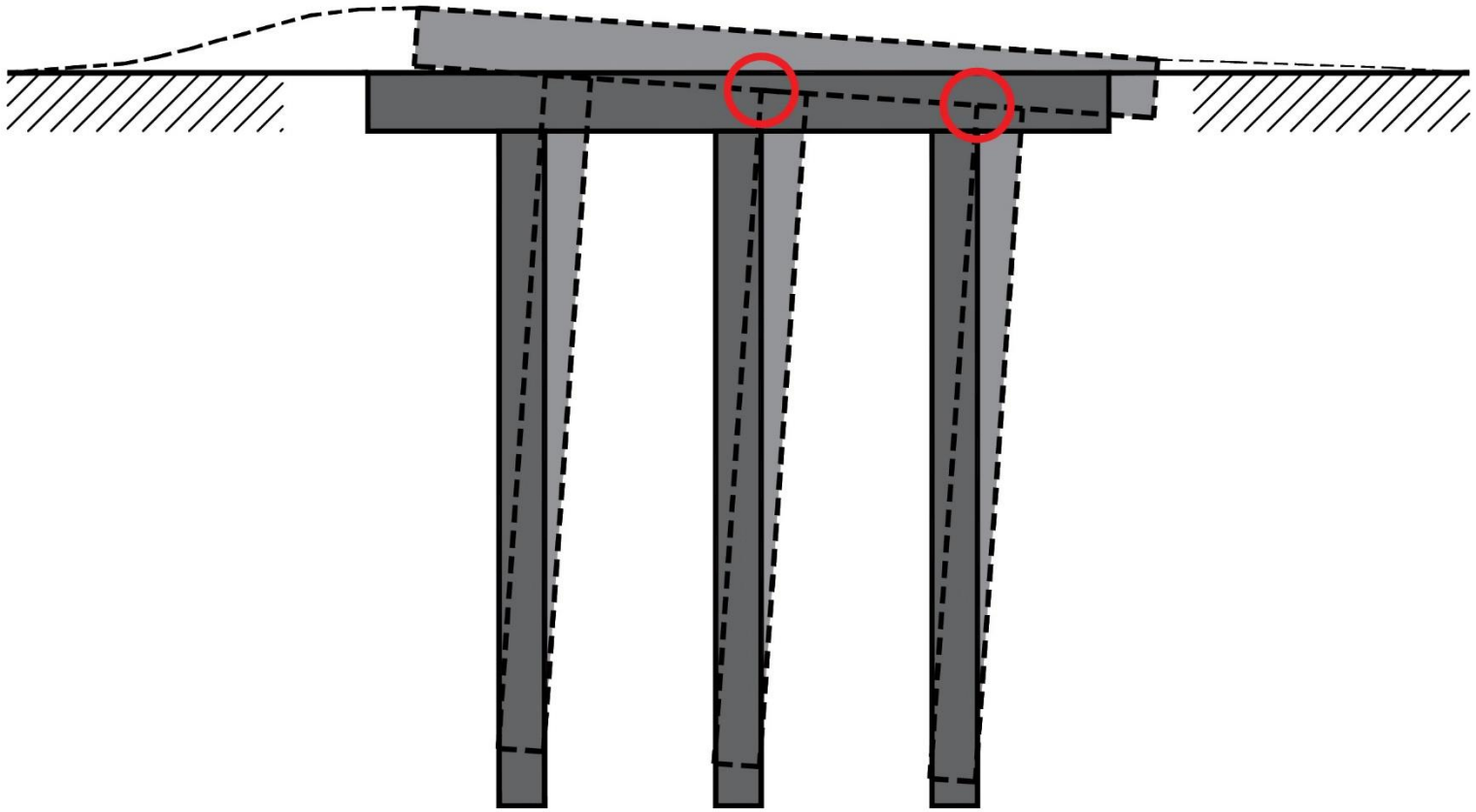


“Green Field” surface heave

Used for model validation

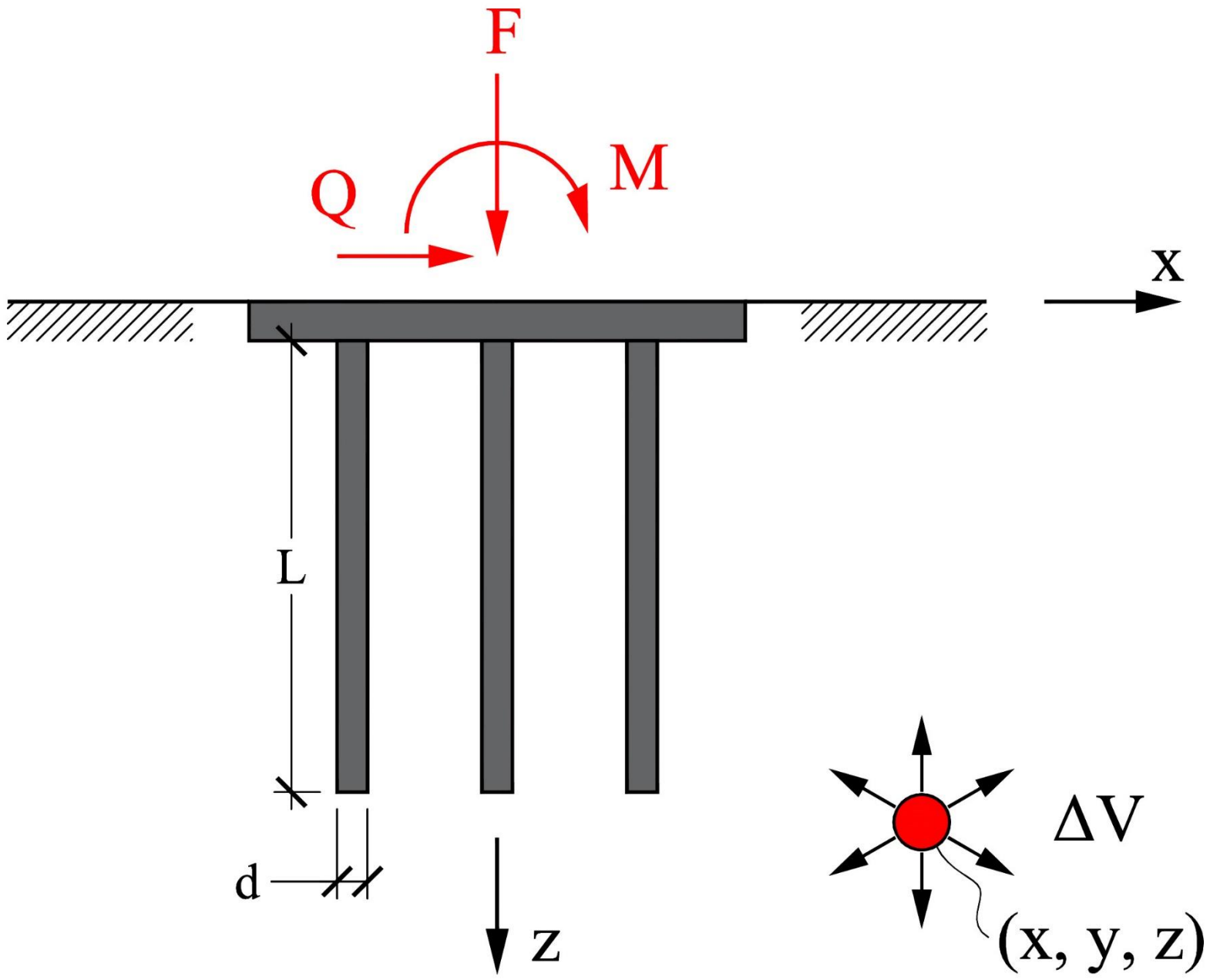


The problem



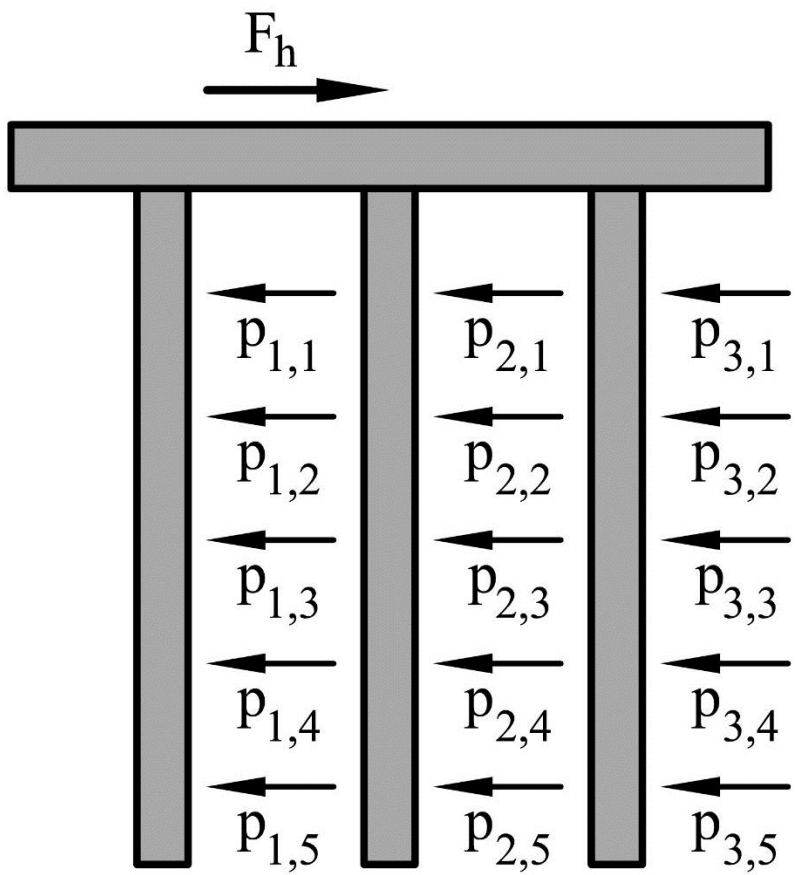
Expansion zone

The problem

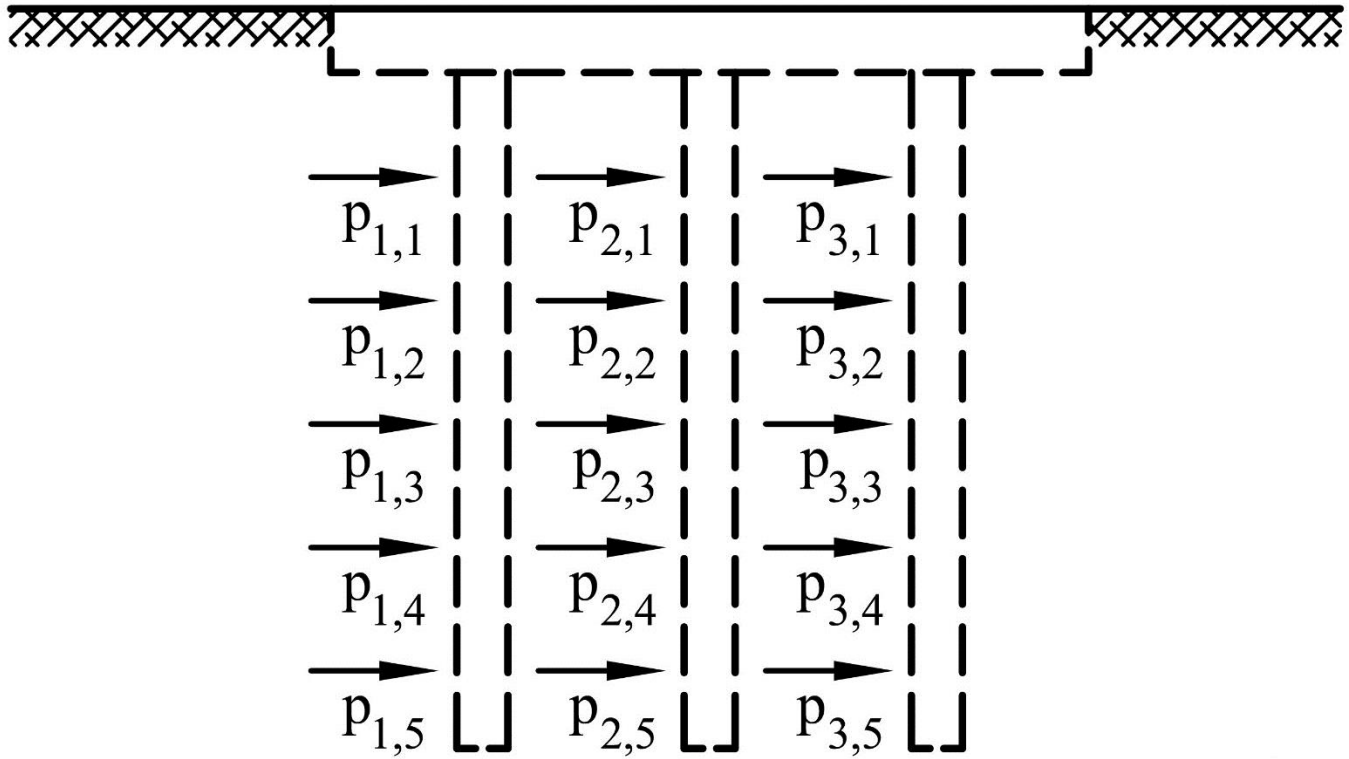


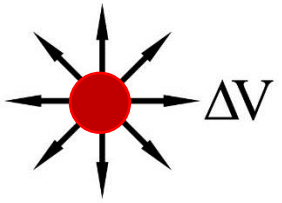
Solution scheme for horizontal displacements

Pile group structure



Soil





- Formulate compatibility of displacements + Equilibrium

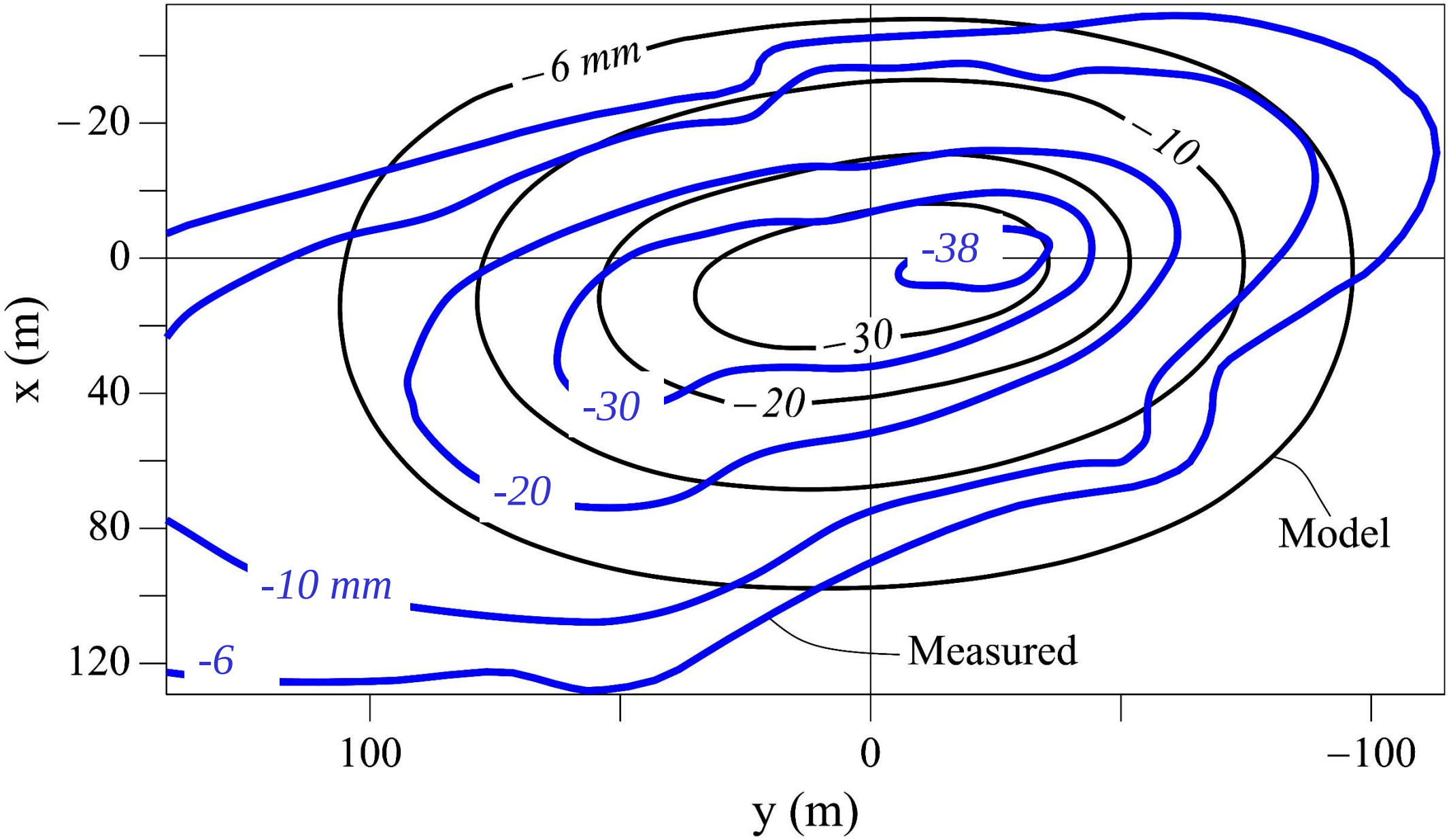
Model hypothesis

- Homogeneous and isotropic soil
- Linear elastic response of all materials involved
- Incompressible soil (kinematic conditions dominate)

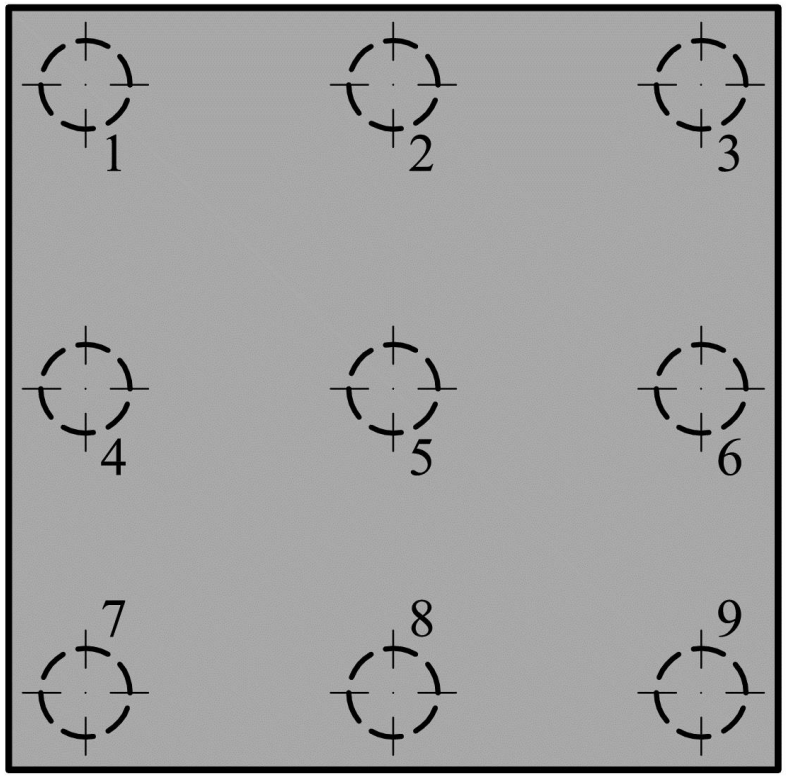
Fundamental solutions

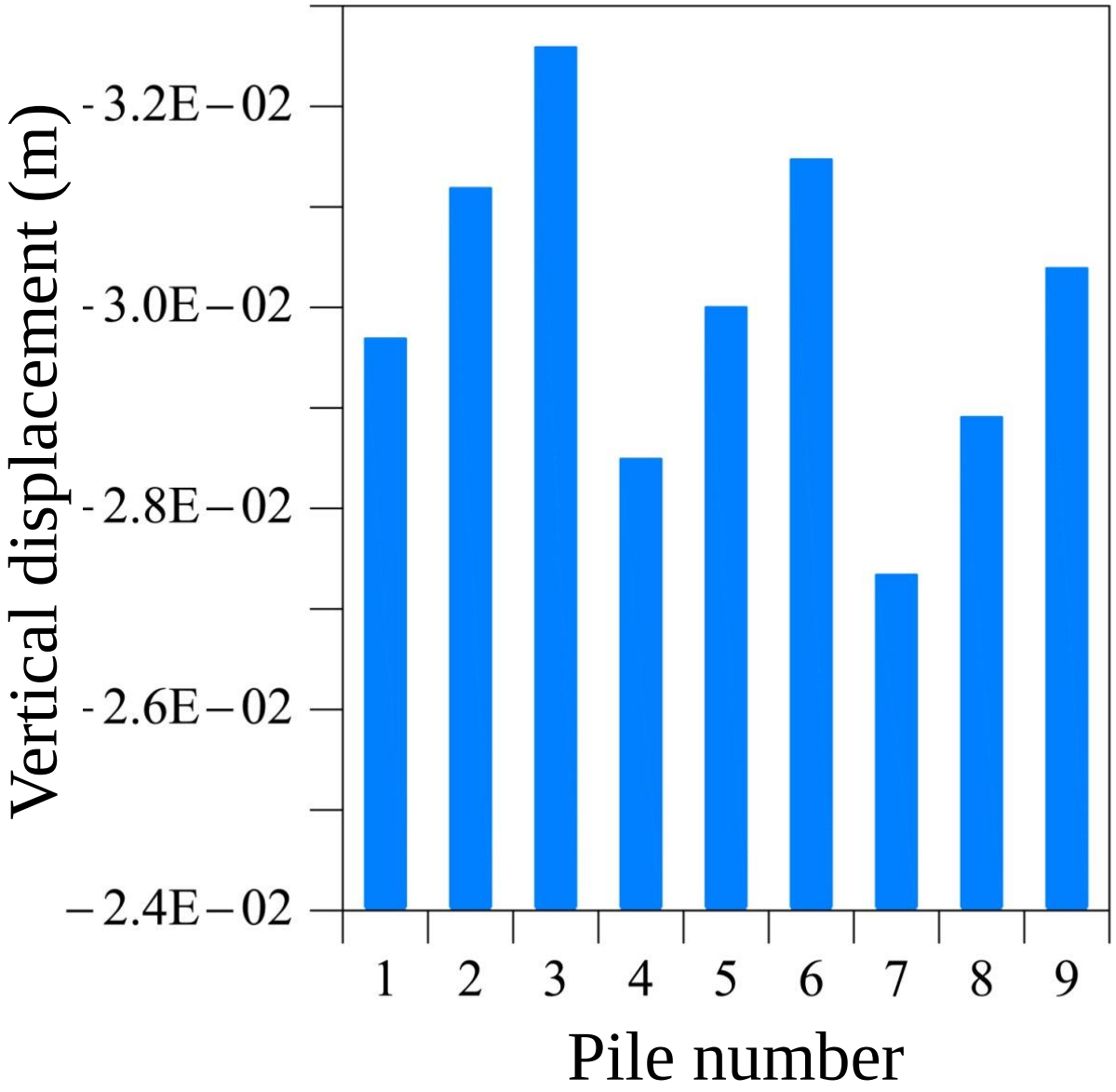
- Boussinesq, 1885
- Mindlin, 1936
- Sagaseta, 1987

Model validation against surface heave

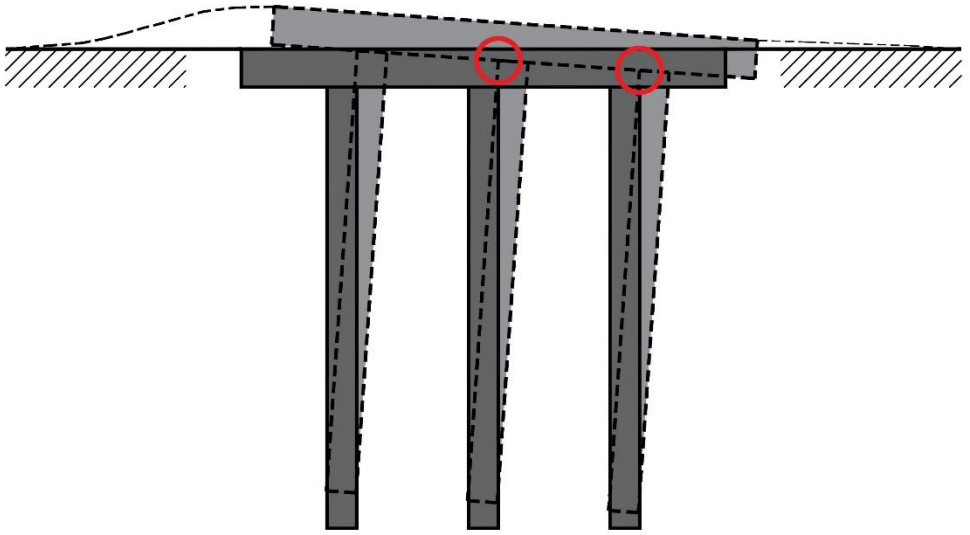


Calculated vertical displacements of pile heads





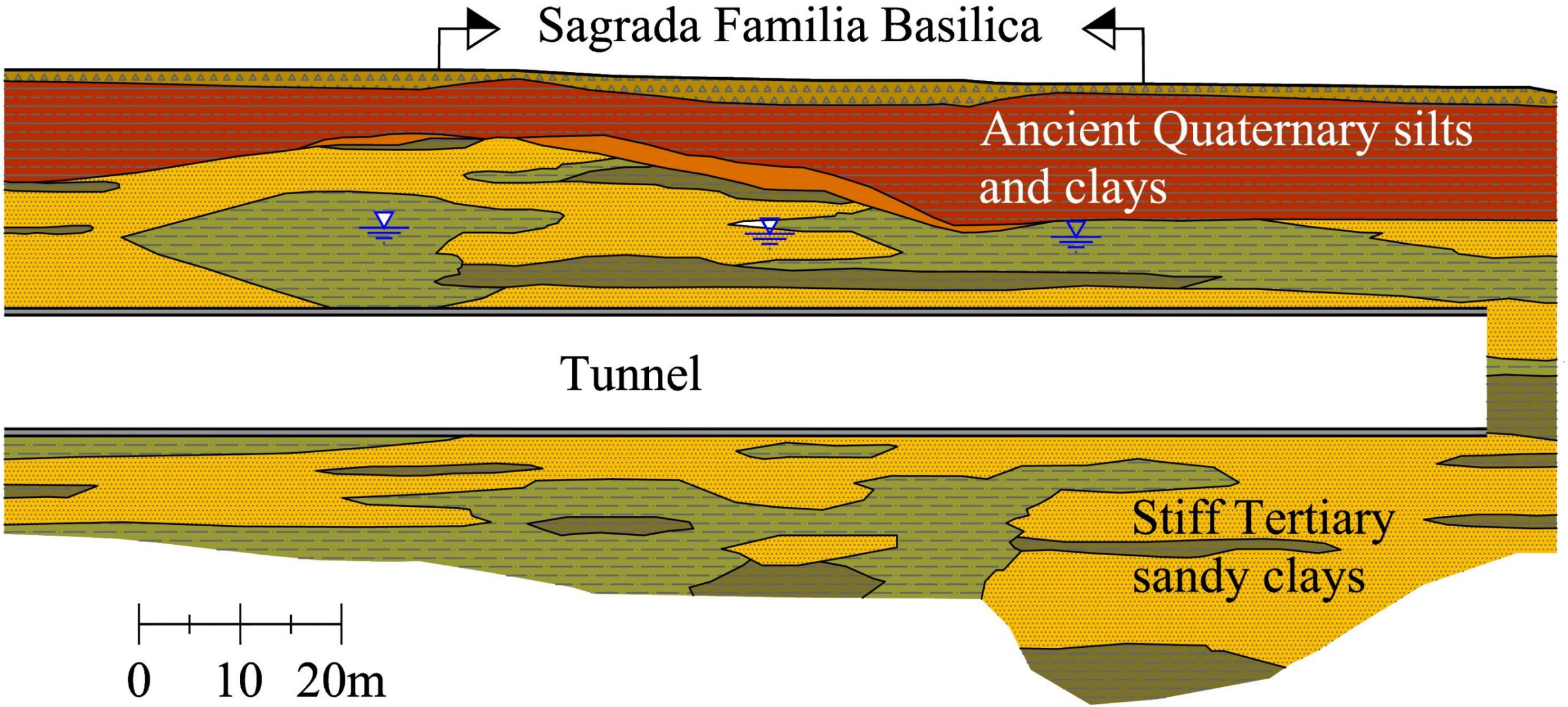
Calculated and measured inclination angles (°) of rigid pile group cap (3 x 3 piles) of Pillar 5 in five months



Direction of inclination	Calculated	Measured (21/Nov/07-25/Apr/08)
x	**0,0155**	**0,0176**
y	**0,0119**	**0,0191**

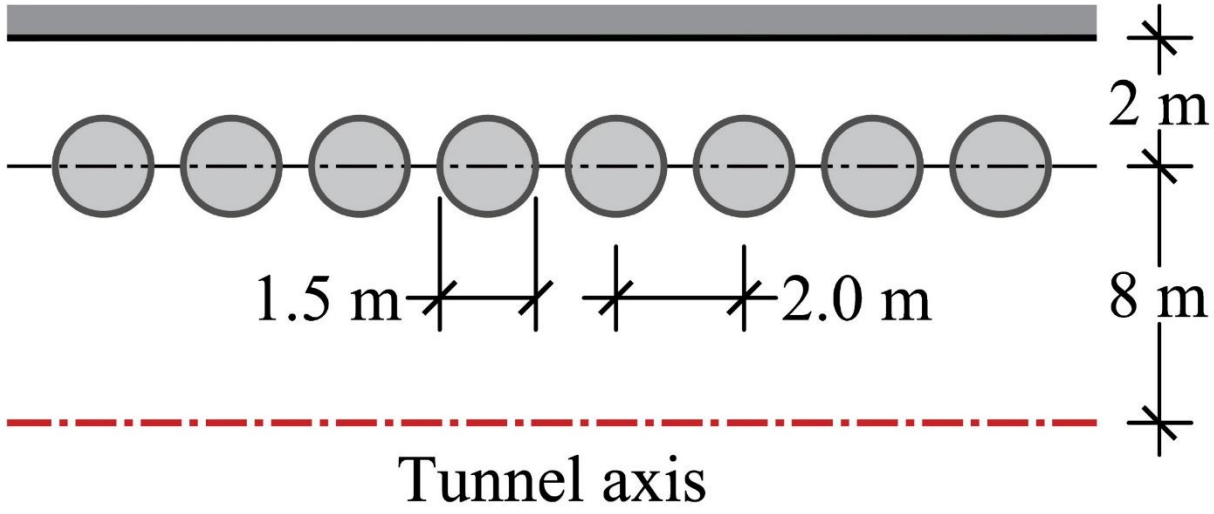
2. Protection walls

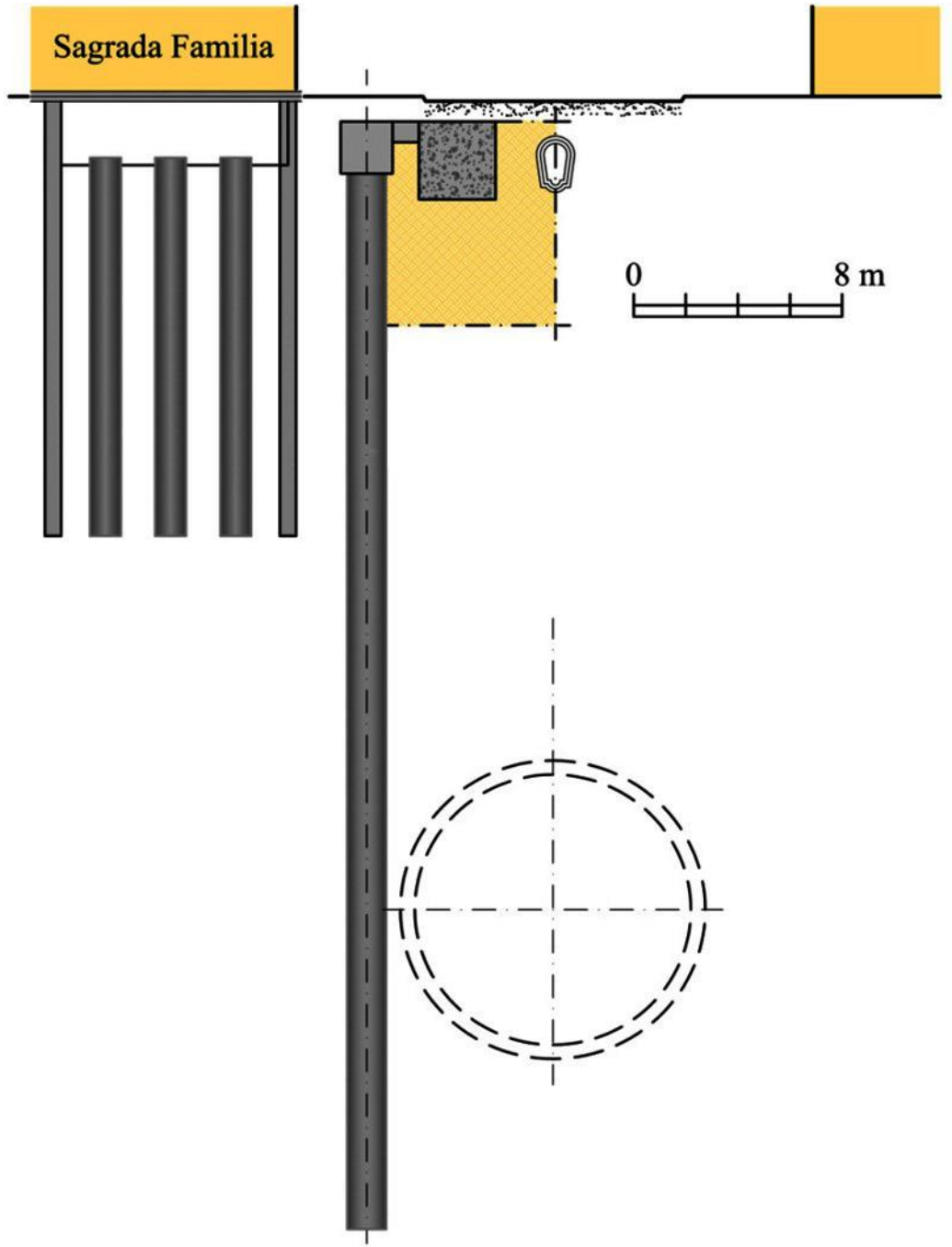
Lithological profile



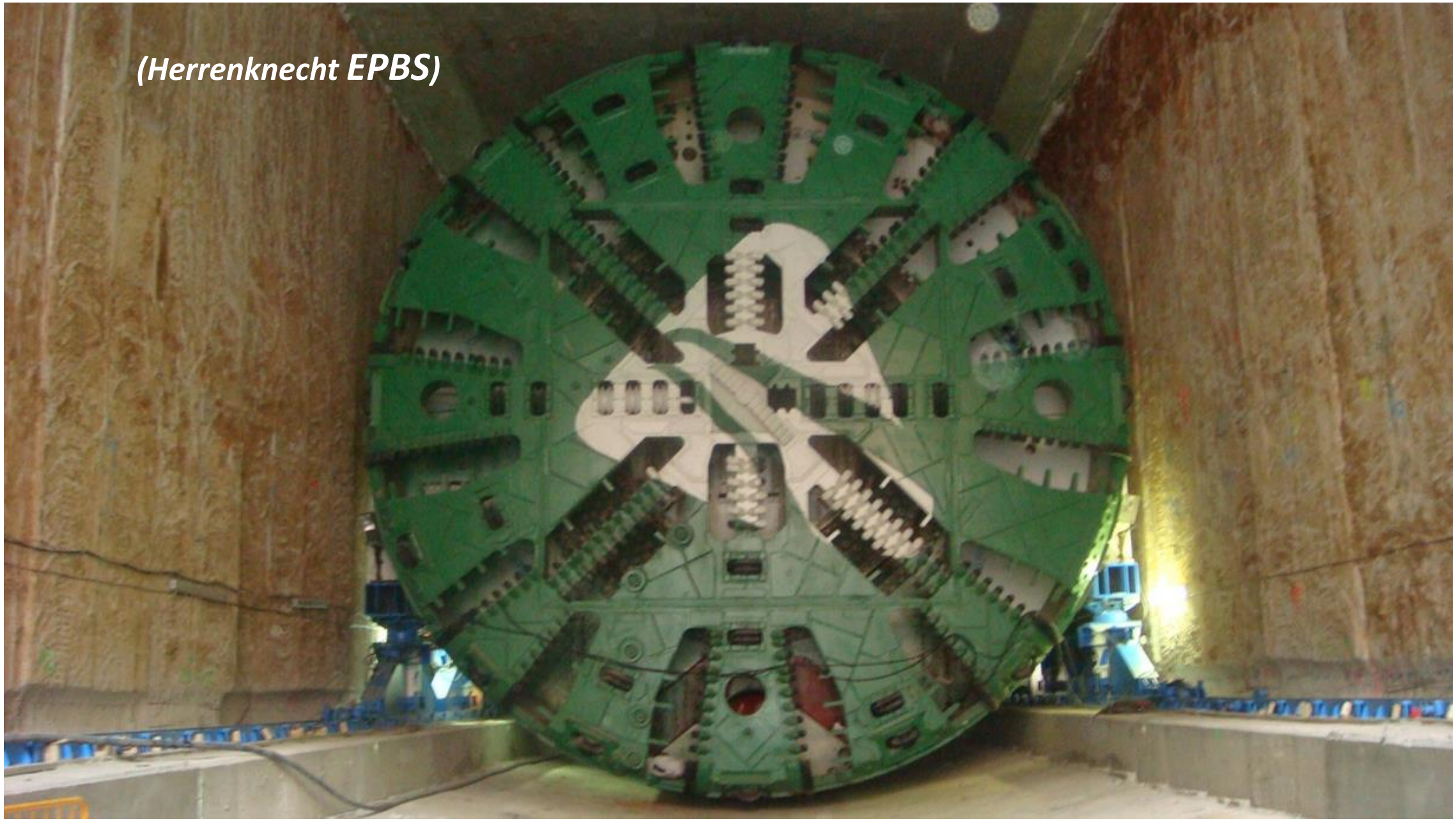
Adopted solution

- Pile wall: 1.5 m diameter piles every 2 m, 41 m long
- Reaction beam, 3x3 m cross section connected to pile wall capping beam
- Vertical gap between piles to avoid groundwater barrier effect

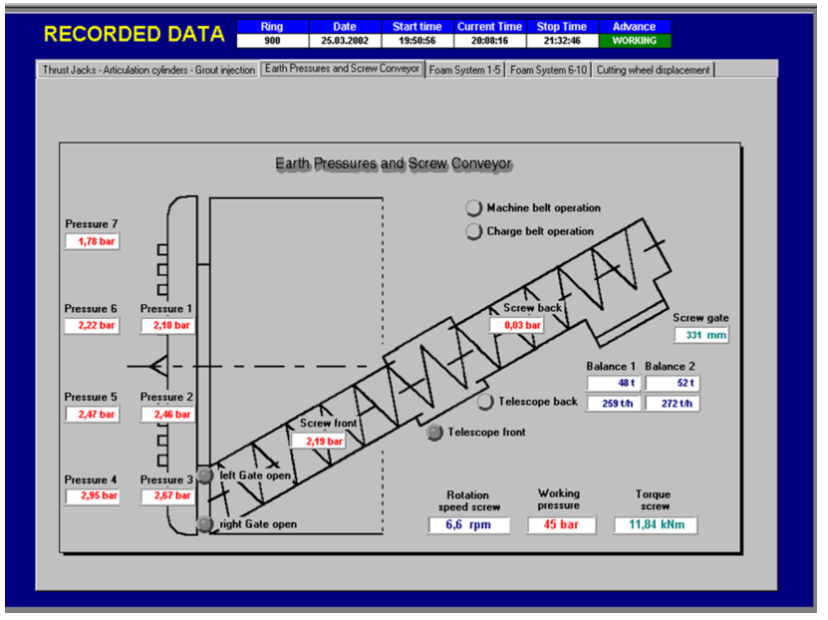


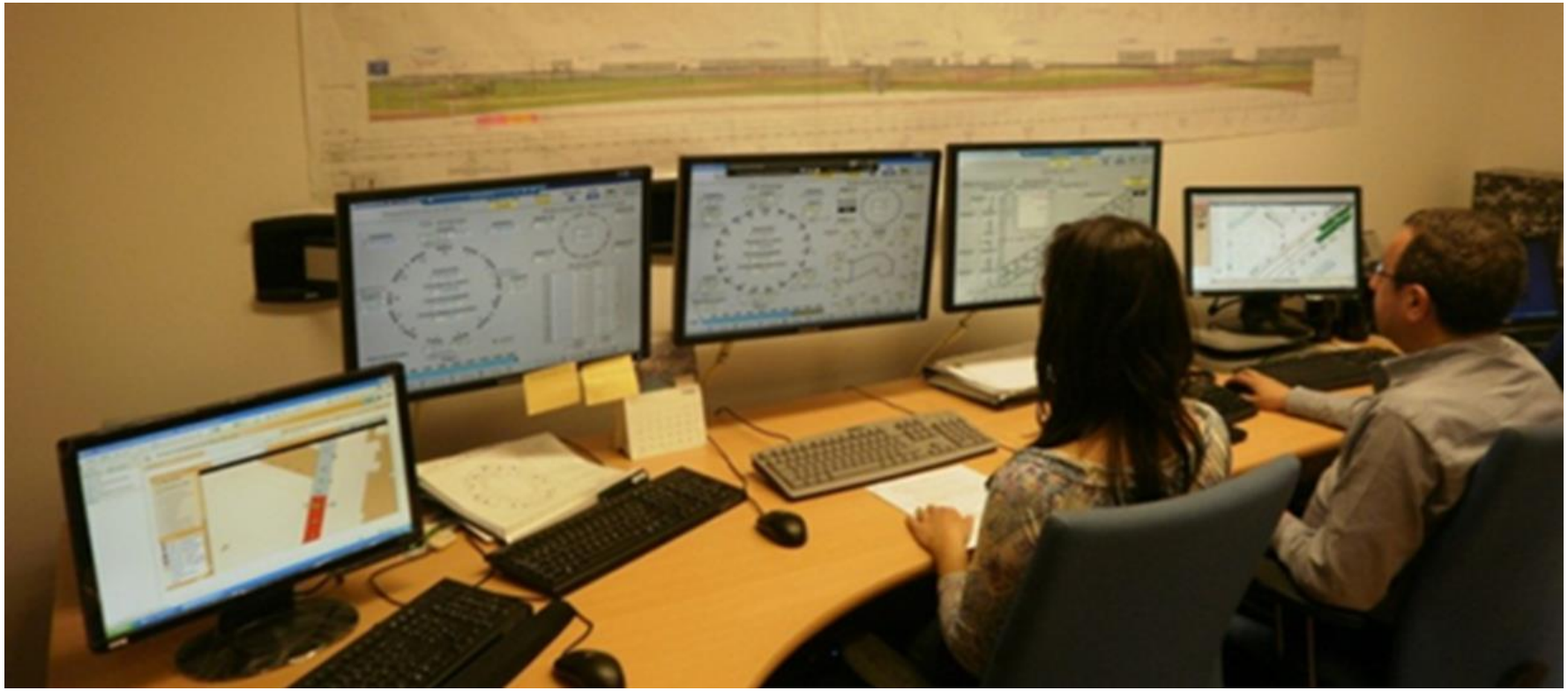


The technical challenge



EPBS control





A simplified calculation procedure for wall-tunnel interaction

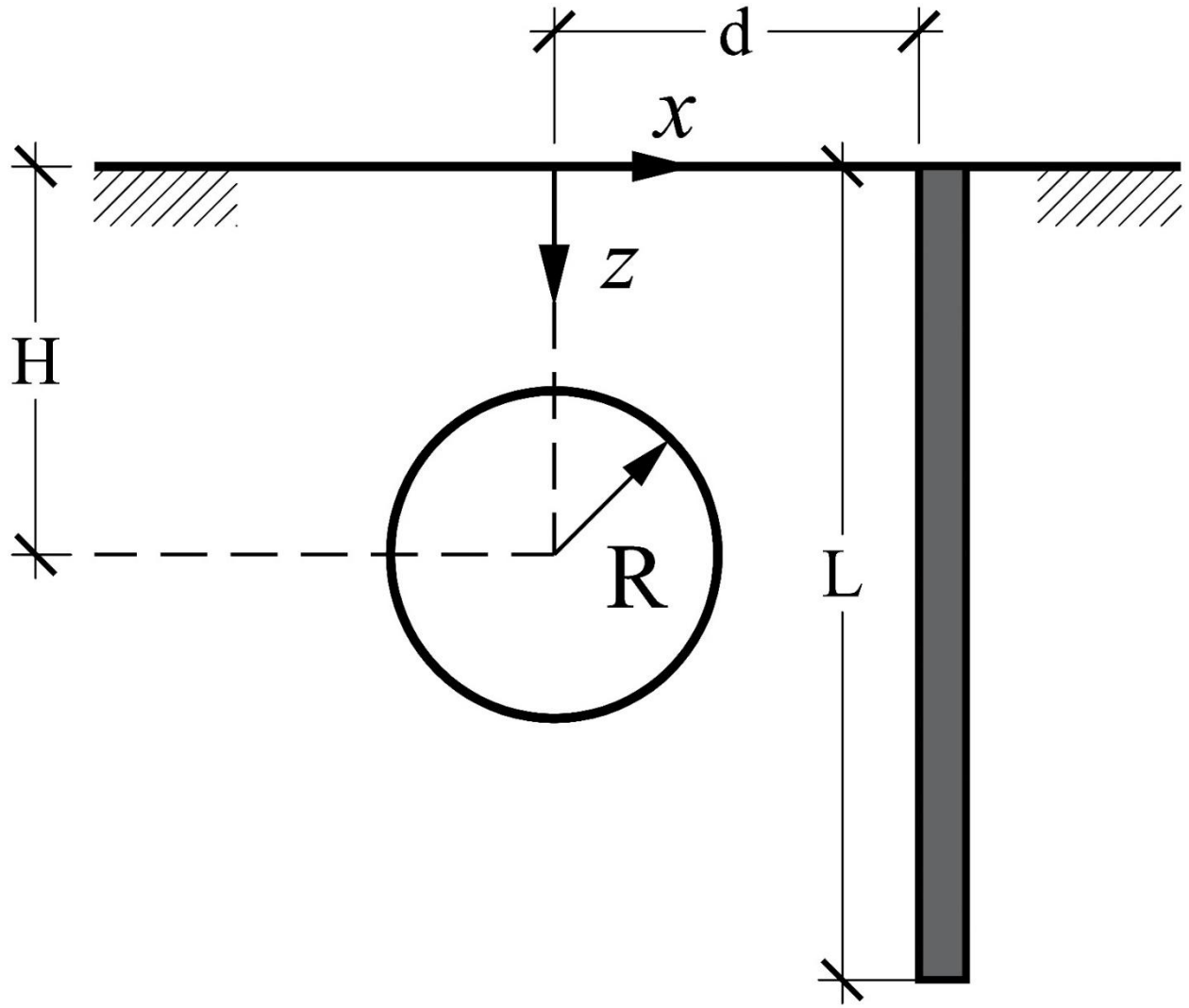
Hypothesis

- 2D Plane strain
- Soil: Linear elastic, Isotropic
- Undrained conditions ($\nu = 0.5$)

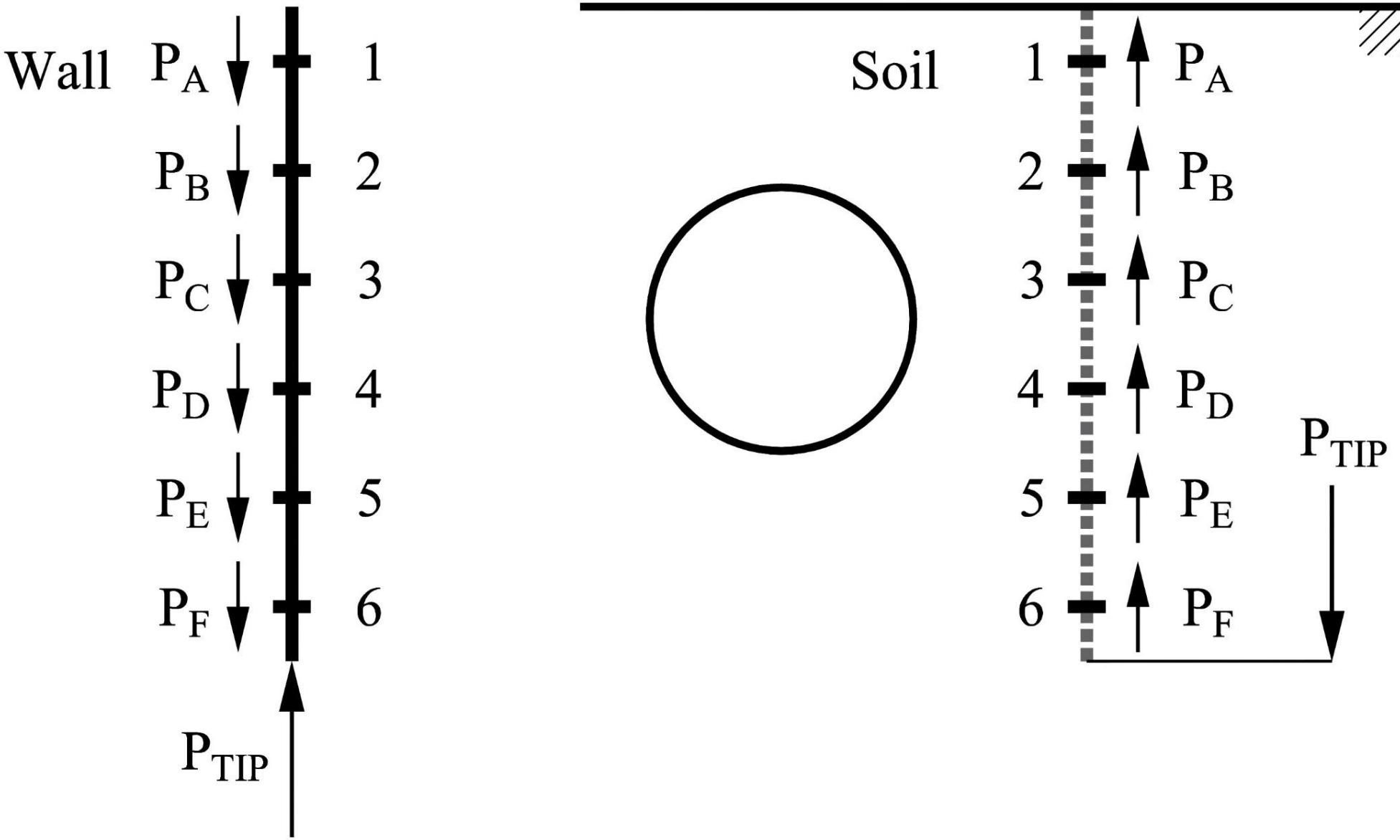
"Fundamental" solutions

- Melan (1932) for concentrated line load in half-space
- Longanathan and Poulos (1998) for soil deformations around tunnels

(Ledesma & Alonso, 2017)

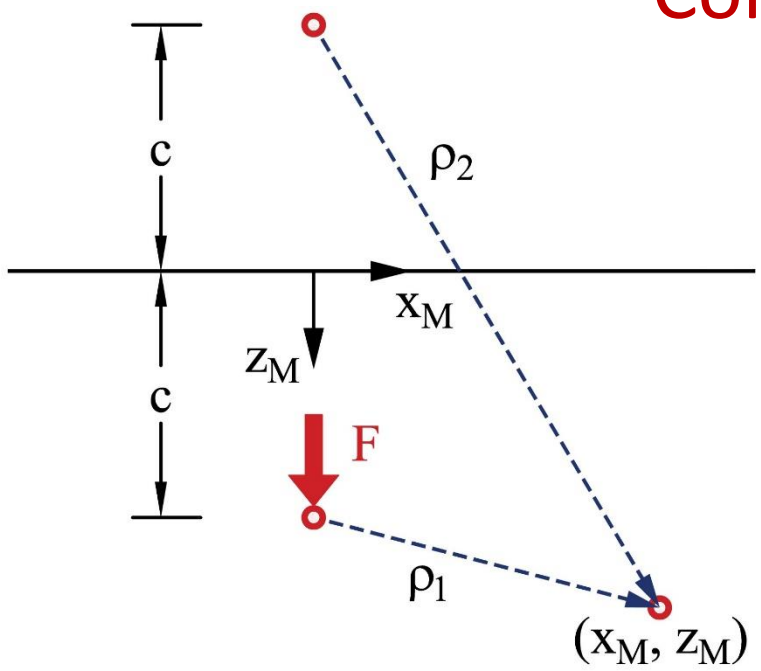


A simplified calculation procedure for wall-tunnel interaction



Compatibility of vertical displacements + Equilibrium

Melan's problem

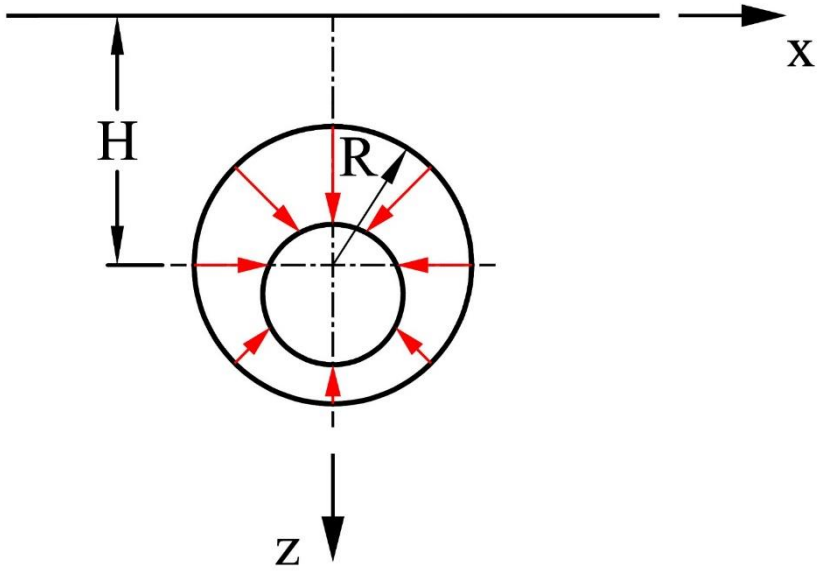


- Vertical displacements at wall axis ($x_M = 0$):

$$u_z = \frac{3F}{2\pi E_s}\left\{\ln\frac{\sqrt{c^2+w^2}}{c+z_M} - \frac{1}{2}\ln\frac{|z_M-c|}{(z_M+c)} + 1 - \frac{c^2}{c^2+w^2} + cz_M\left[\frac{1}{(c+z_M)^2}\right]\right\}$$

(Melan, 1932)

L & P geometry



- Vertical displacements in half space:

$$u_z = R^2\left\{-\frac{z-H}{x^2+(z-H)^2} + \frac{z+H}{x^2+(z+H)^2} - \frac{2z[x^2-(z+H)^2]}{[x^2+(z+H)^2]^2}\right\}\epsilon$$

$$\epsilon = \epsilon_0 exp\left\{-\left[\frac{1.38x^2}{(H+R)^2} + \frac{0.69z^2}{H^2}\right]\right\}$$

Ground loss (V_s^*)

(Longanathan & Poulos, 1998)

Compatibility of vertical displacements + Equilibrium

- Soil displacements
  - Induced by tunnel excavation (L & P)
  - Wall-soil interface forces (Melan)
- Wall (elastic column)

$$(u_z)_i = u_n + \sum_{j=i+1}^{j=n} \left[\frac{N_j}{E_w A_w} \frac{L}{n} \right]$$

- Equilibrium

$$P_{tip} = \sum P_j$$

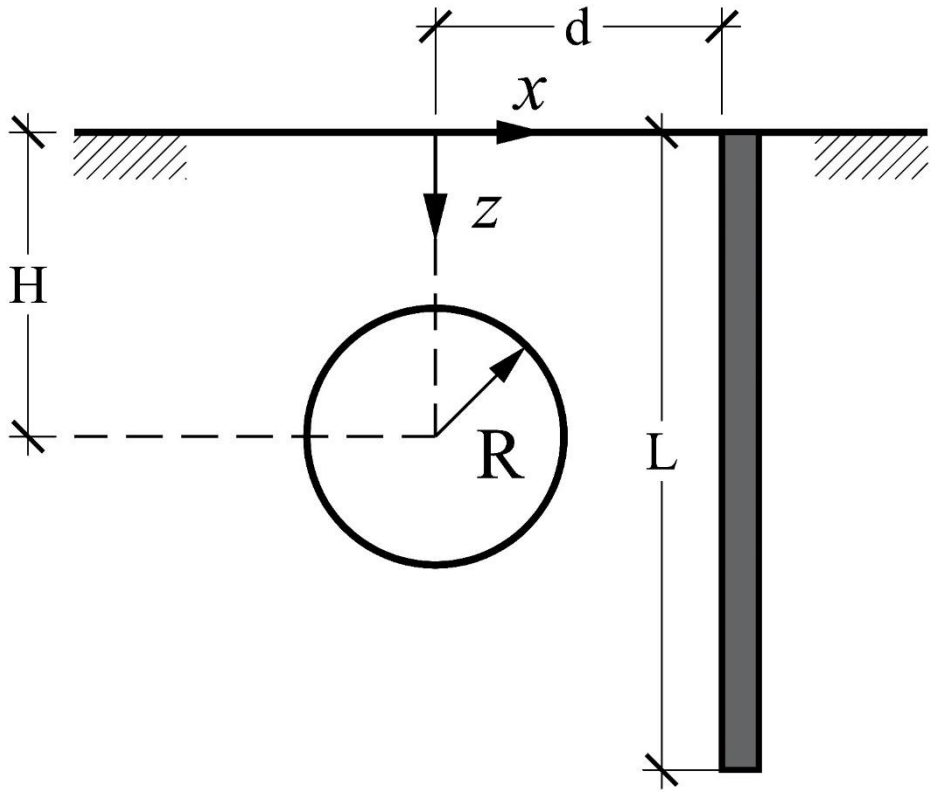
Dimensionless coefficients controlling the solution

$$\Pi_1 = \frac{H}{R}$$ Tunnel cover ratio (2 to 5)

$$\Pi_2 = \frac{d}{R}$$ Wall distance to tunnel (1 to 3)

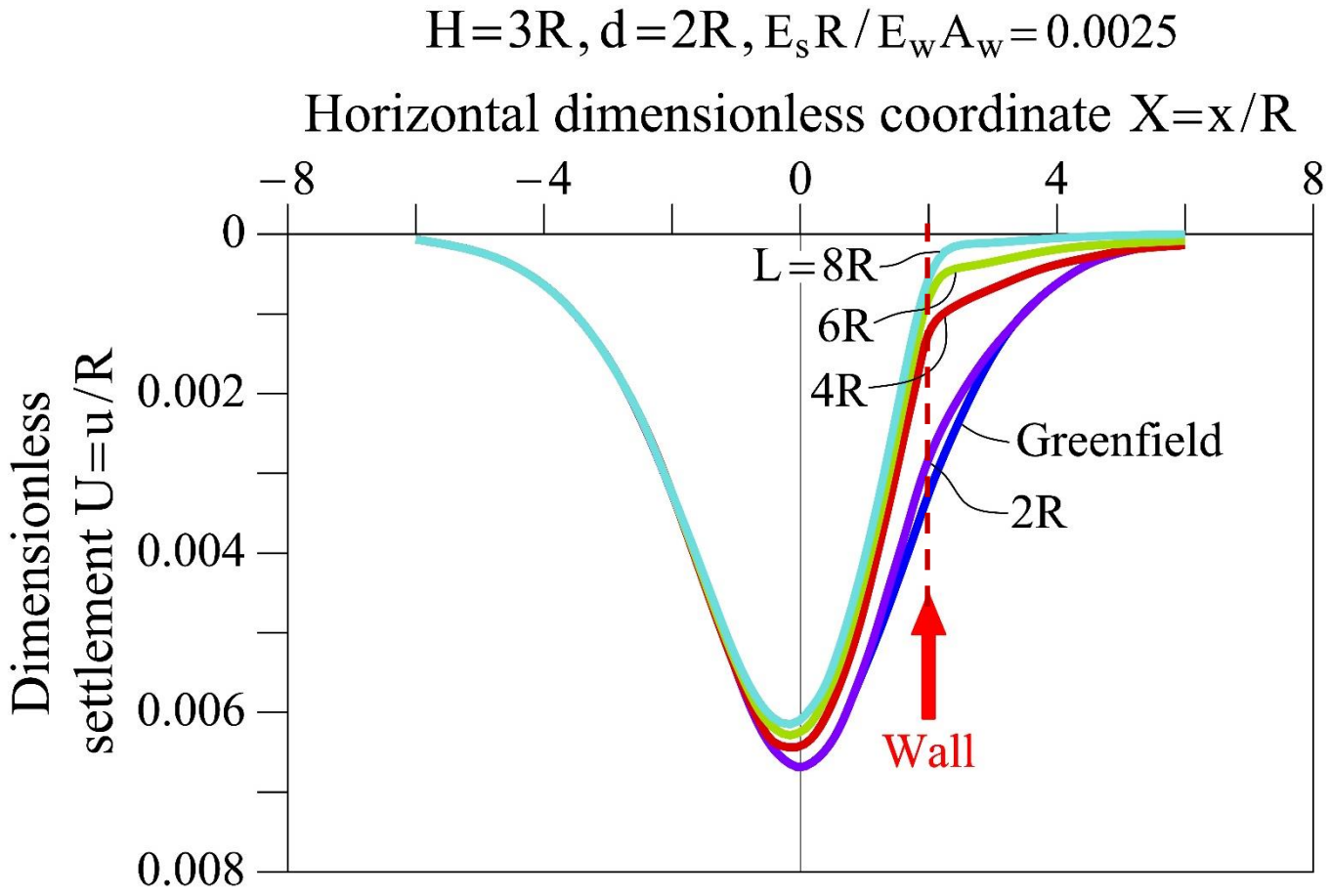
$$\Pi_3 = \frac{L}{R}$$ Wall length (1 to 10)

$$\Pi_4 = \frac{E_s R}{E_w A_w}$$ Stiffness ratio (2.5 E-5 to 2.5 E-1)



A base case

- Effect of wall length

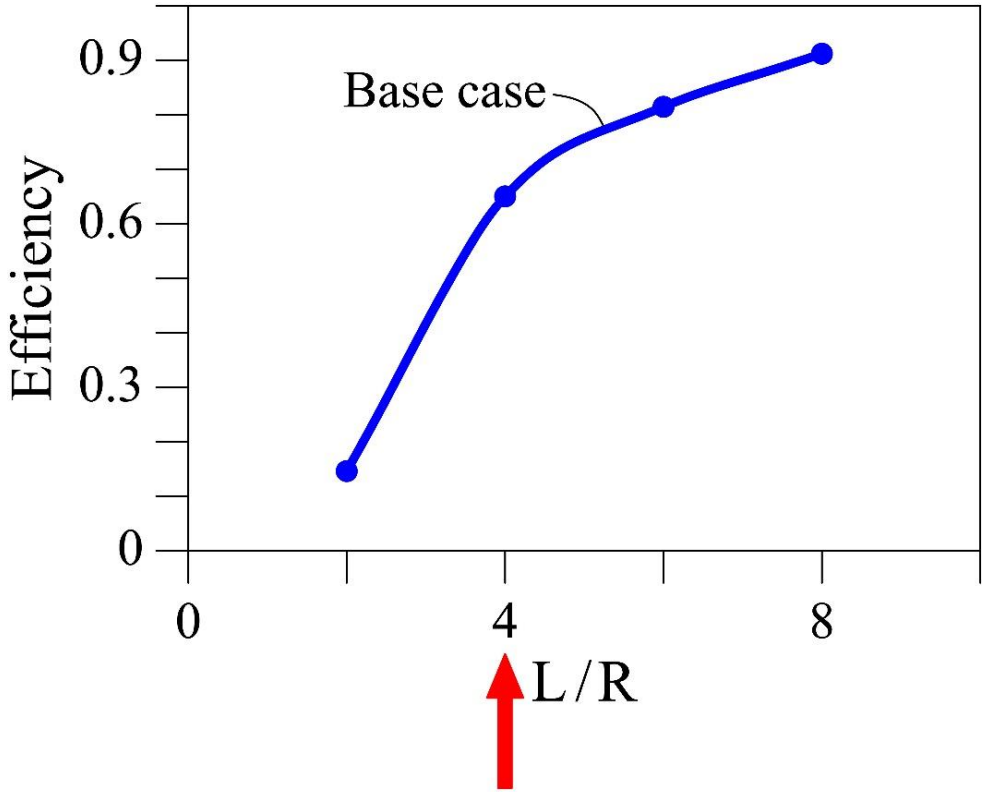


- Efficiency

$$\eta = \frac{s_{greenfield} - s_{behind\ wall}}{s_{greenfield}}$$

0: no effect

1: full effect

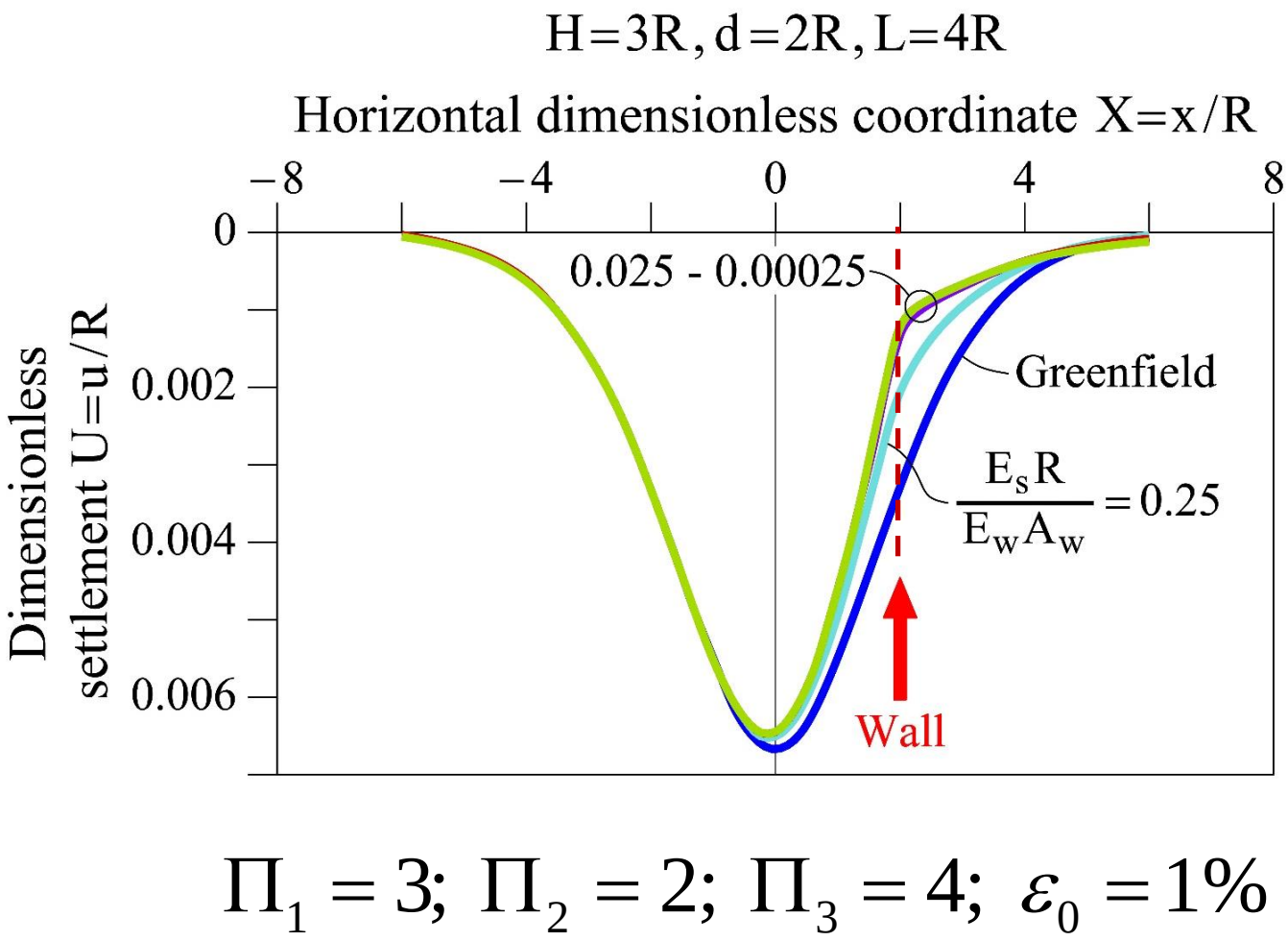


Pile tip at level of invert

$$\Pi_1 = 3;\ \Pi_2 = 2;\ \Pi_4 = 0.0025;\ \varepsilon_0 = 1\%$$

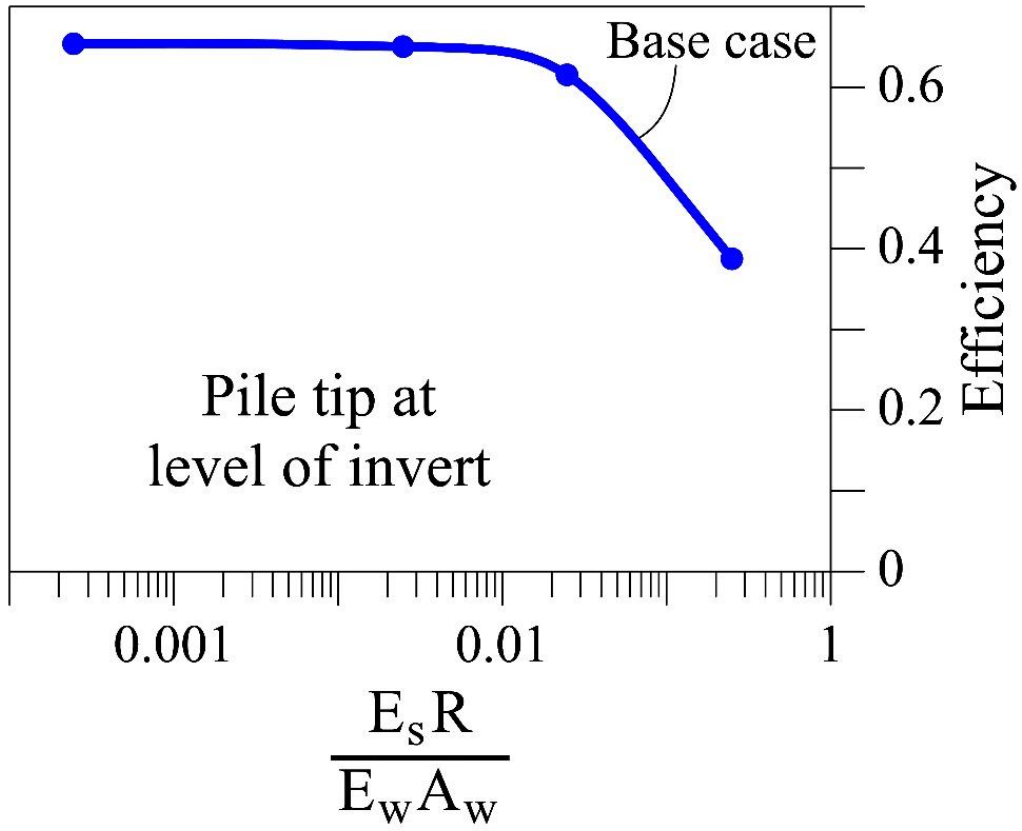
A base case

Effect of wall stiffness



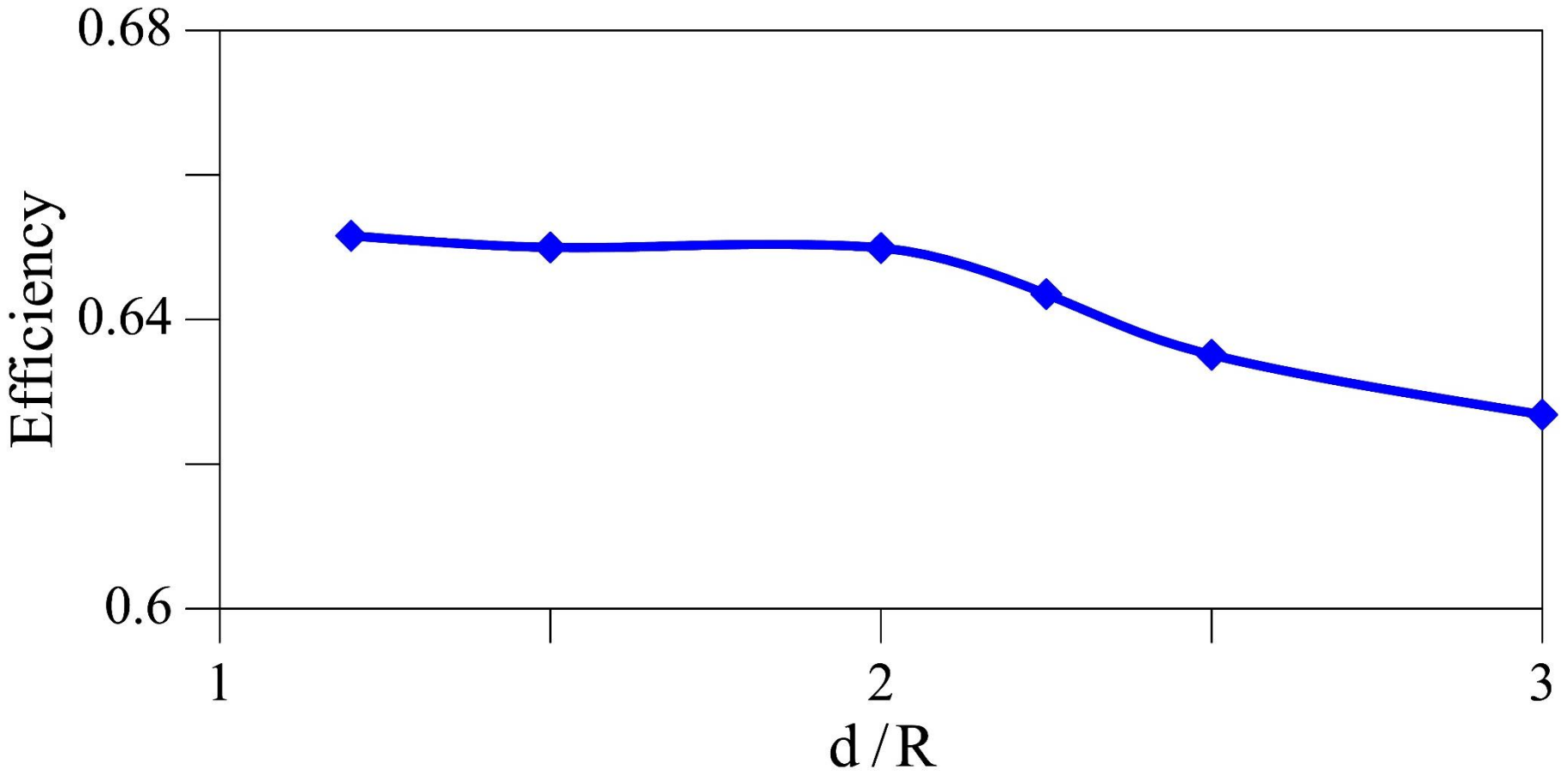
$$\Pi_1 = 3;\ \Pi_2 = 2;\ \Pi_3 = 4;\ \varepsilon_0 = 1\%$$

Efficiency



A base case

Effect of distance of pile wall to tunnel (d/R)

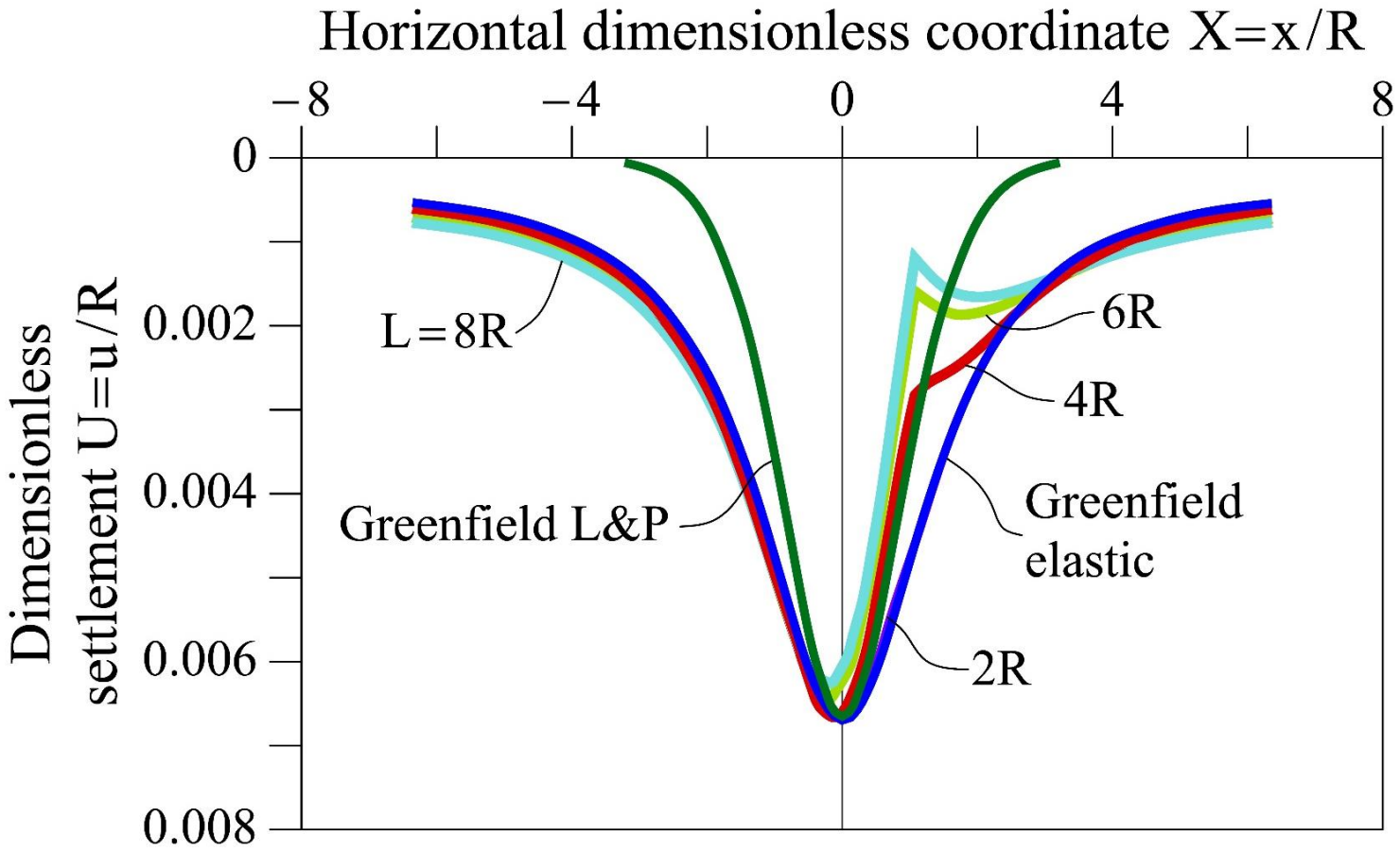


$\Pi_1 = 3;\ \Pi_2 = \text{variable};\ \Pi_3 = 4;\ \Pi_4 = 0.0025;\ \varepsilon_0 = 1\%$

An elastic FE analysis reproducing the base case

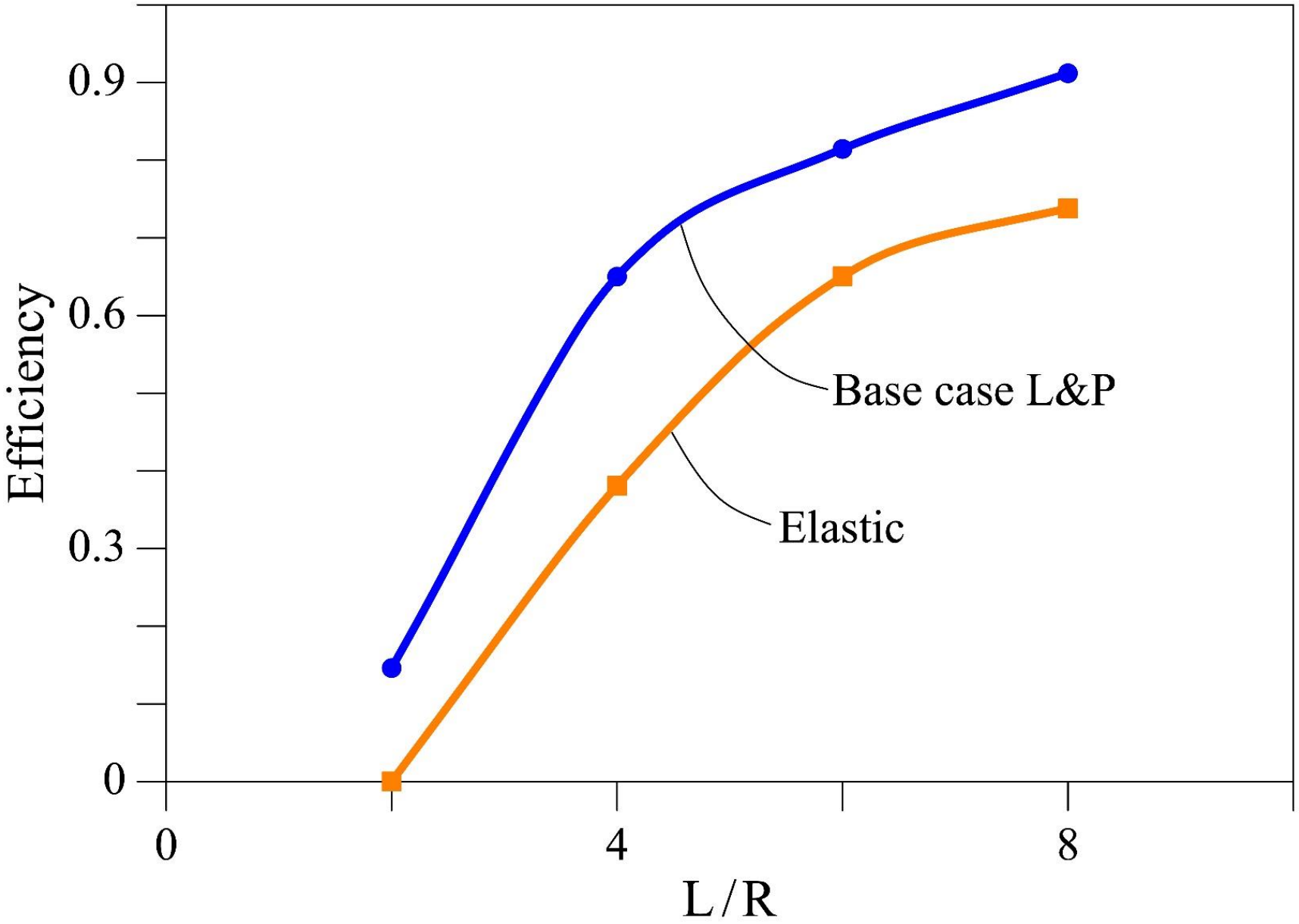
- Discretization boundaries: Rectangle 160 m wide x 100 m deep
- Volume loss: Adjusted to reproduce same maximum settlement of the base case, simplified procedure
- Effect of wall length (L/R: 2 to 8)

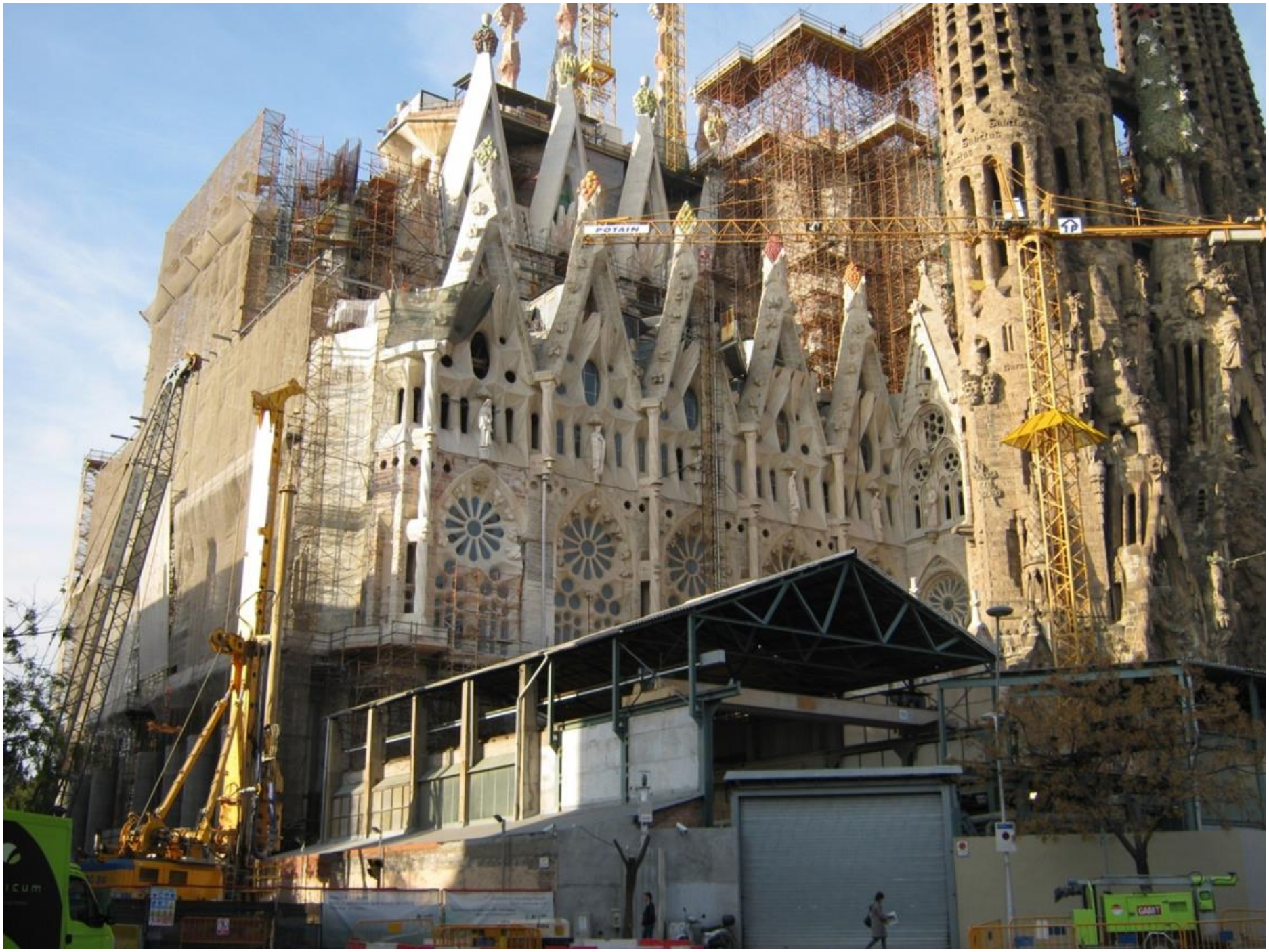
Effect of pile length



$$\Pi_1 = 3;\ \Pi_2 = 2;\ \Pi_3 = \text{variable};\ \Pi_4 = 0.0025$$

Efficiency: Simplified analytic vs FE analysis




POTAIN

Adopted solution

Pile wall: 1.5 diameter piles every 2 m,
41 m long

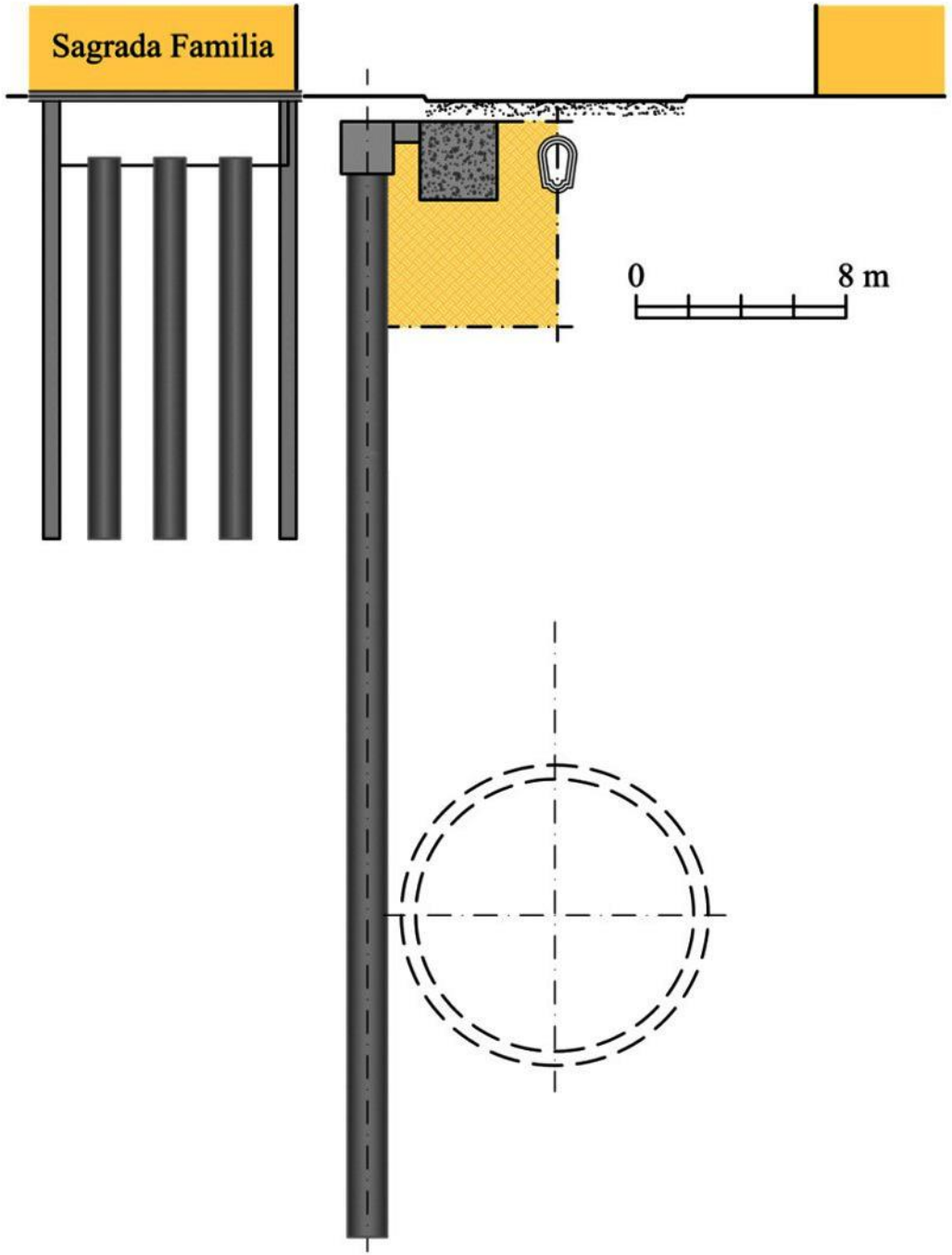
- Dimensionless coefficients:

$$\Pi_1 = \frac{H}{R} = 5.4$$

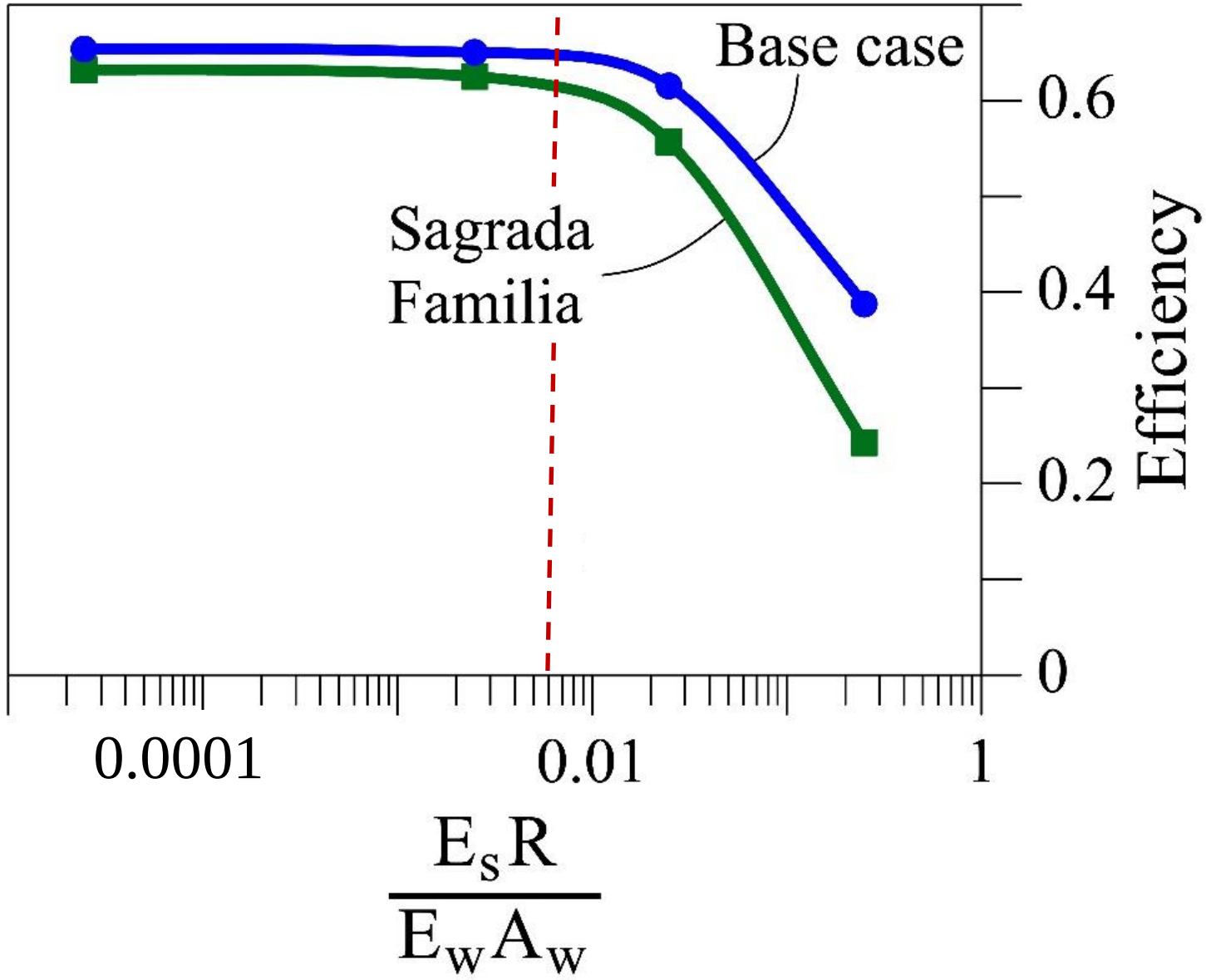
$$\Pi_2 = \frac{d}{R} = 1.4$$

$$\Pi_3 = \frac{L}{R} = 8$$

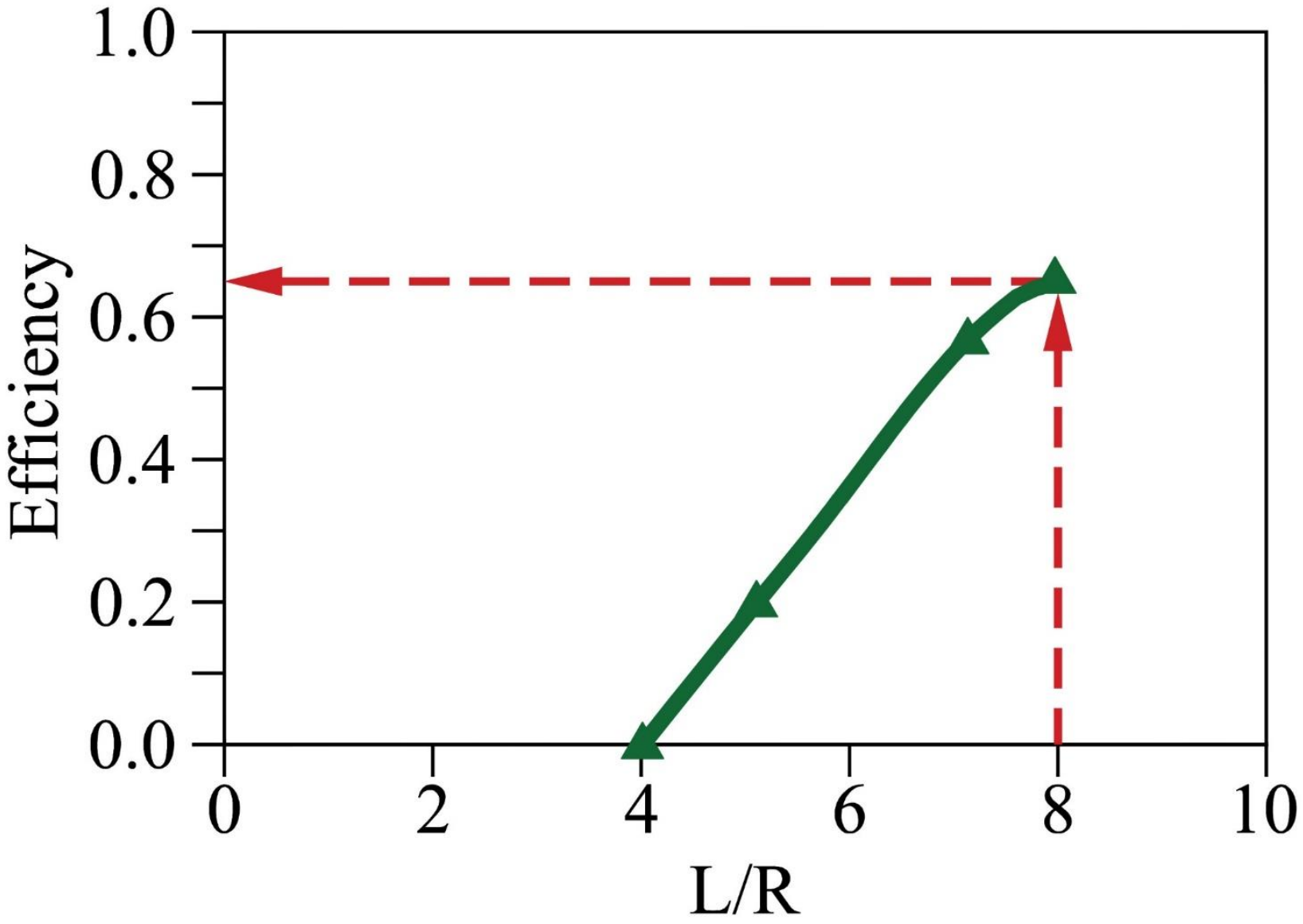
$$\Pi_4 = 0.006 \Rightarrow \begin{cases} E_s = 30MPa \\ E_w = 30000MPa \\ A_w = 1m^2 / m \end{cases}$$

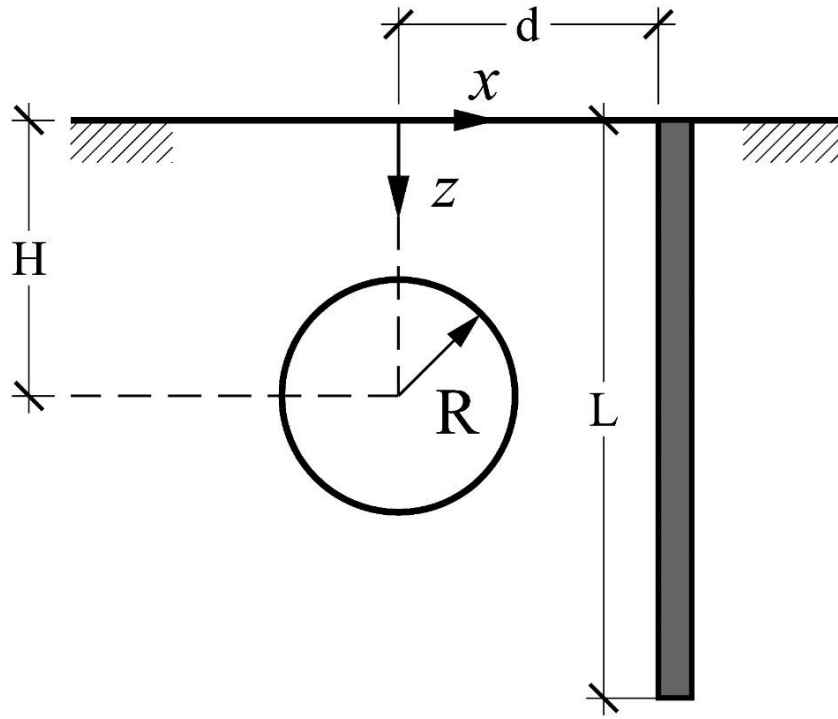


Effect of soil/wall stiffness on efficiency

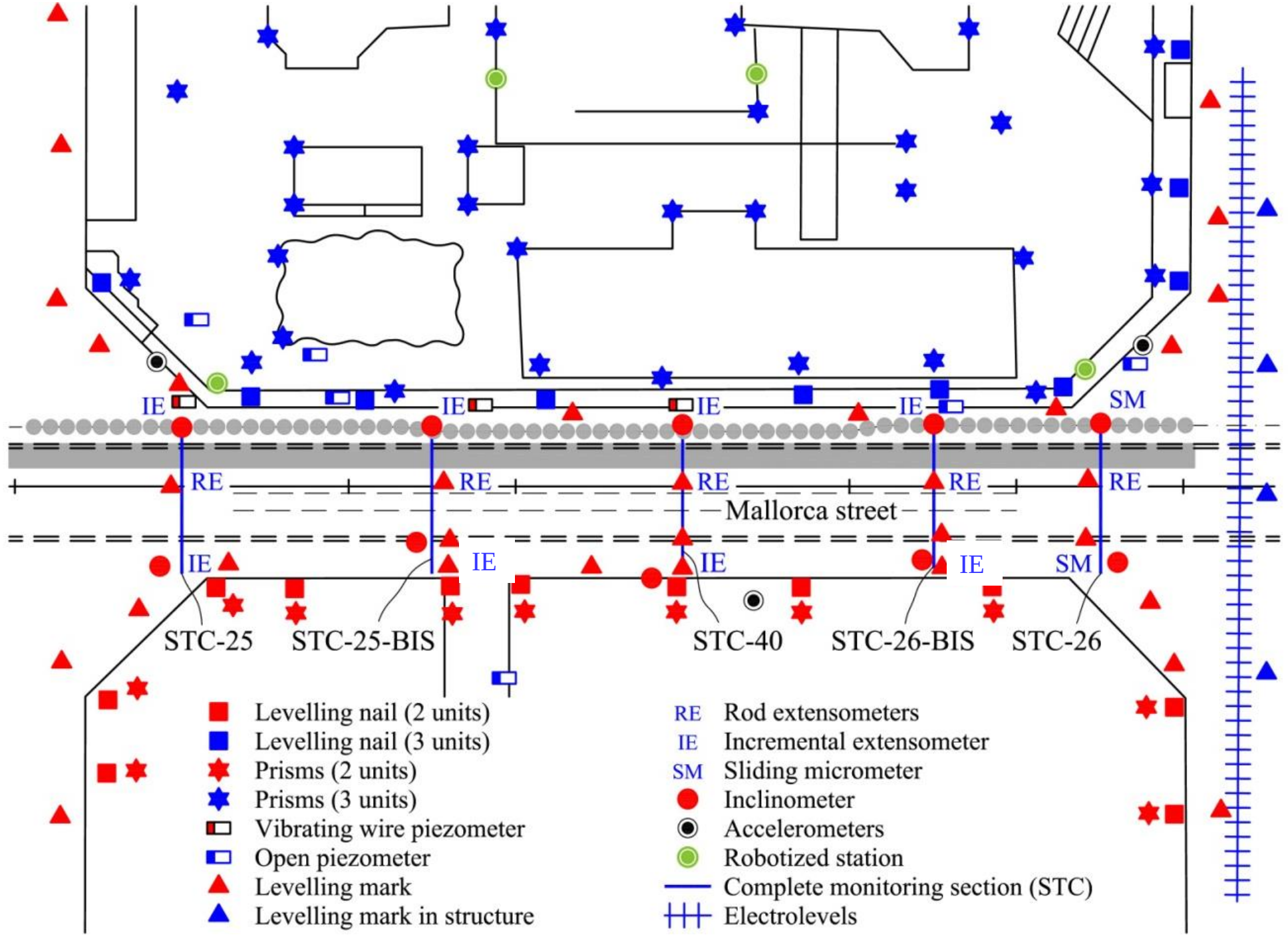


Effect of pile wall length on efficiency. Sagrada Familia (L/R = 8)



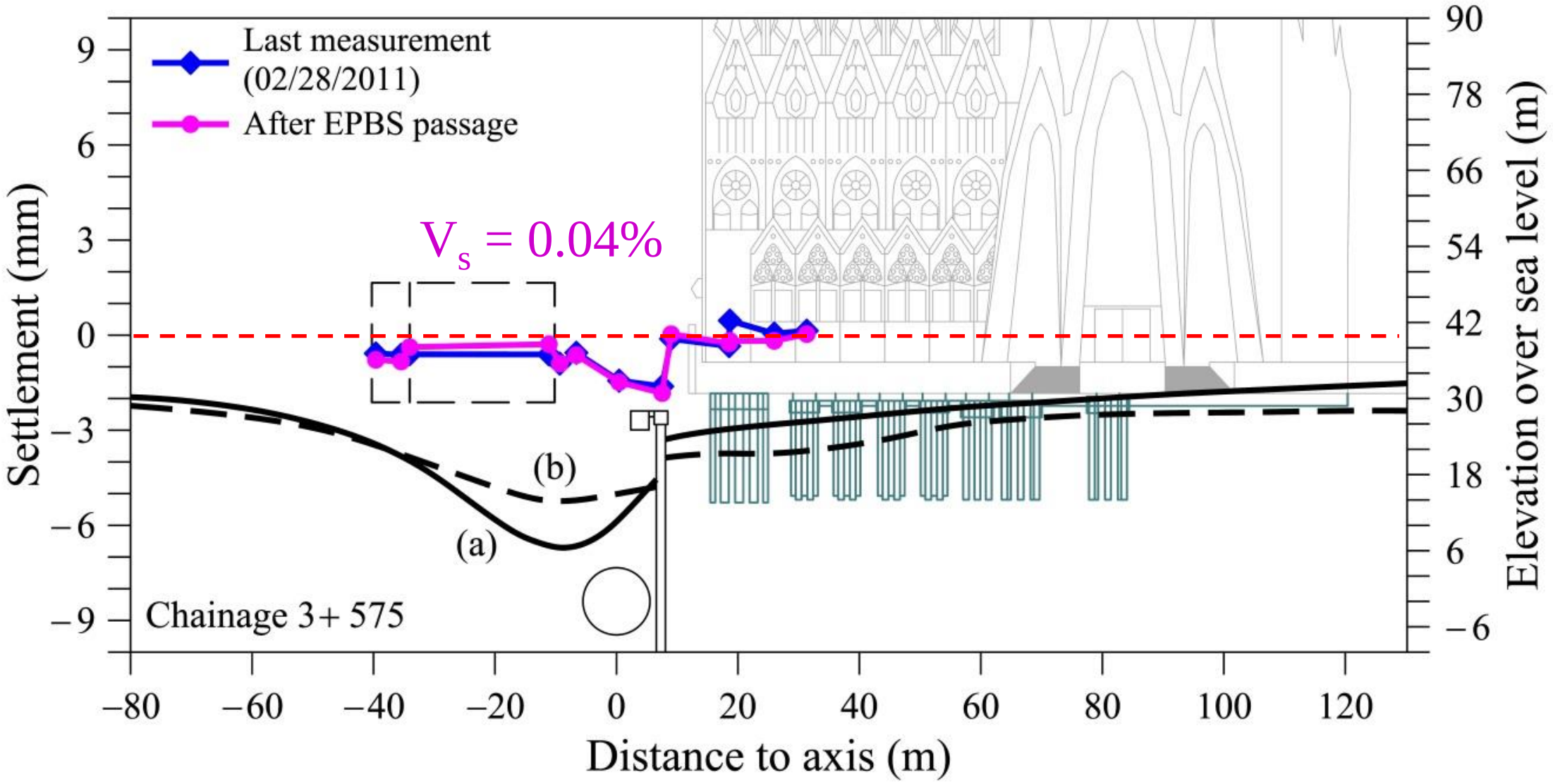


Plan view of monitoring devices



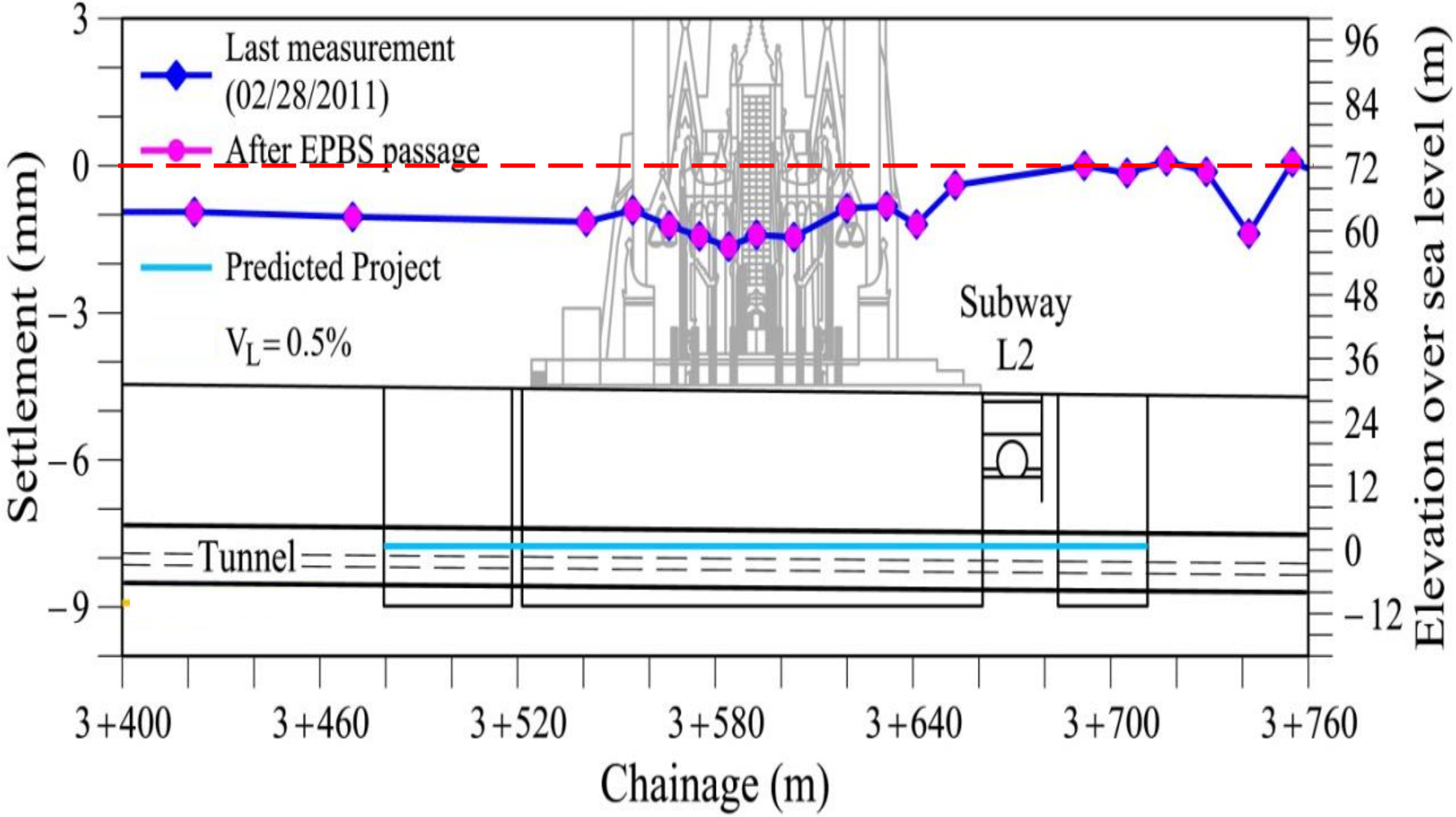
Automatic surveying

Small strain analysis. Volume loss in computations: 0.5%



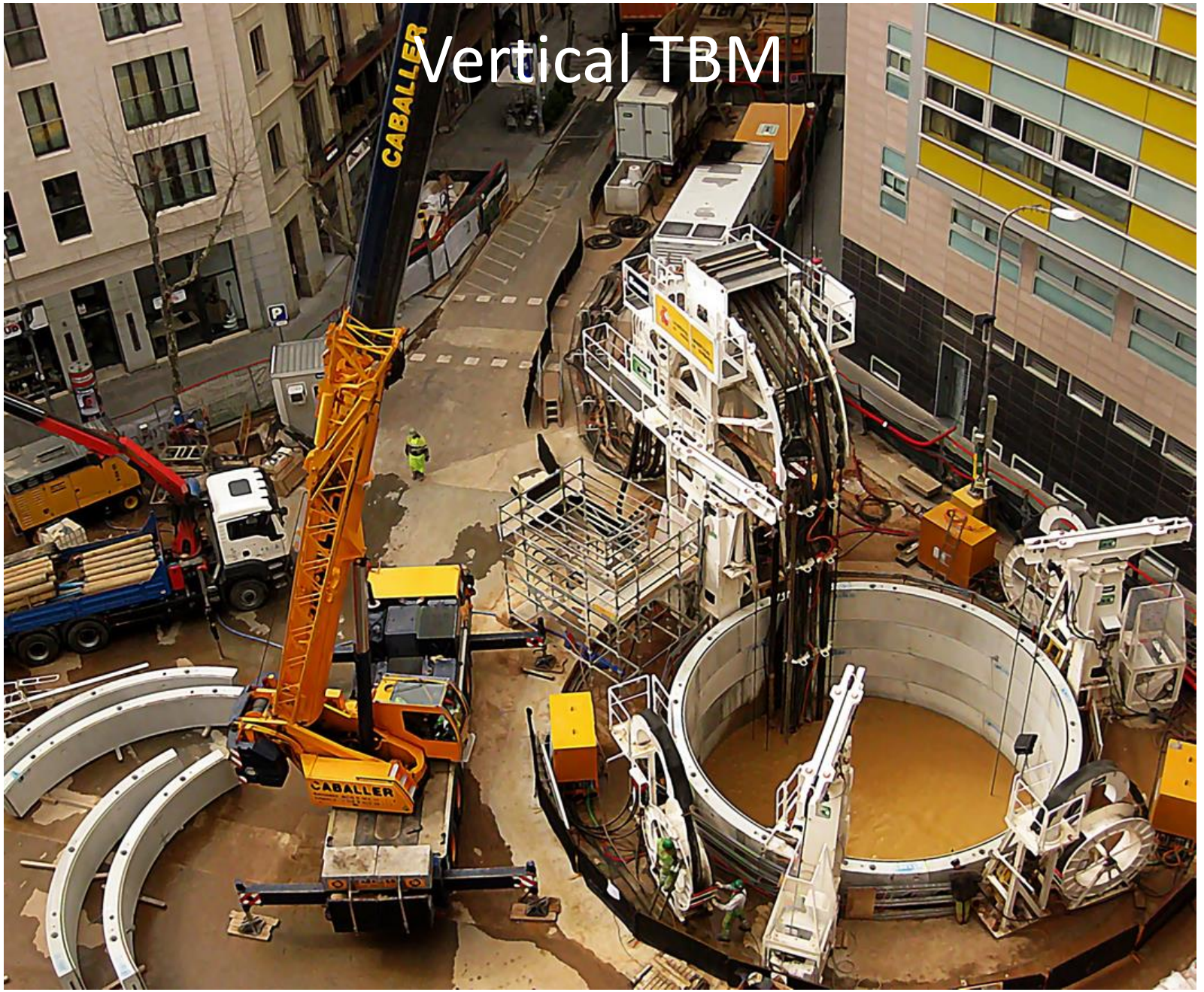
(a): No loads from monument and buildings. (b): Loads applied

Measured vertical displacements. Mallorca street



Vertical shafts for TBM inspection at atmospheric conditions


Hydromills
CABALLER
CABALLER
CABALLER


Vertical TBM
CABALLER
CABALLER

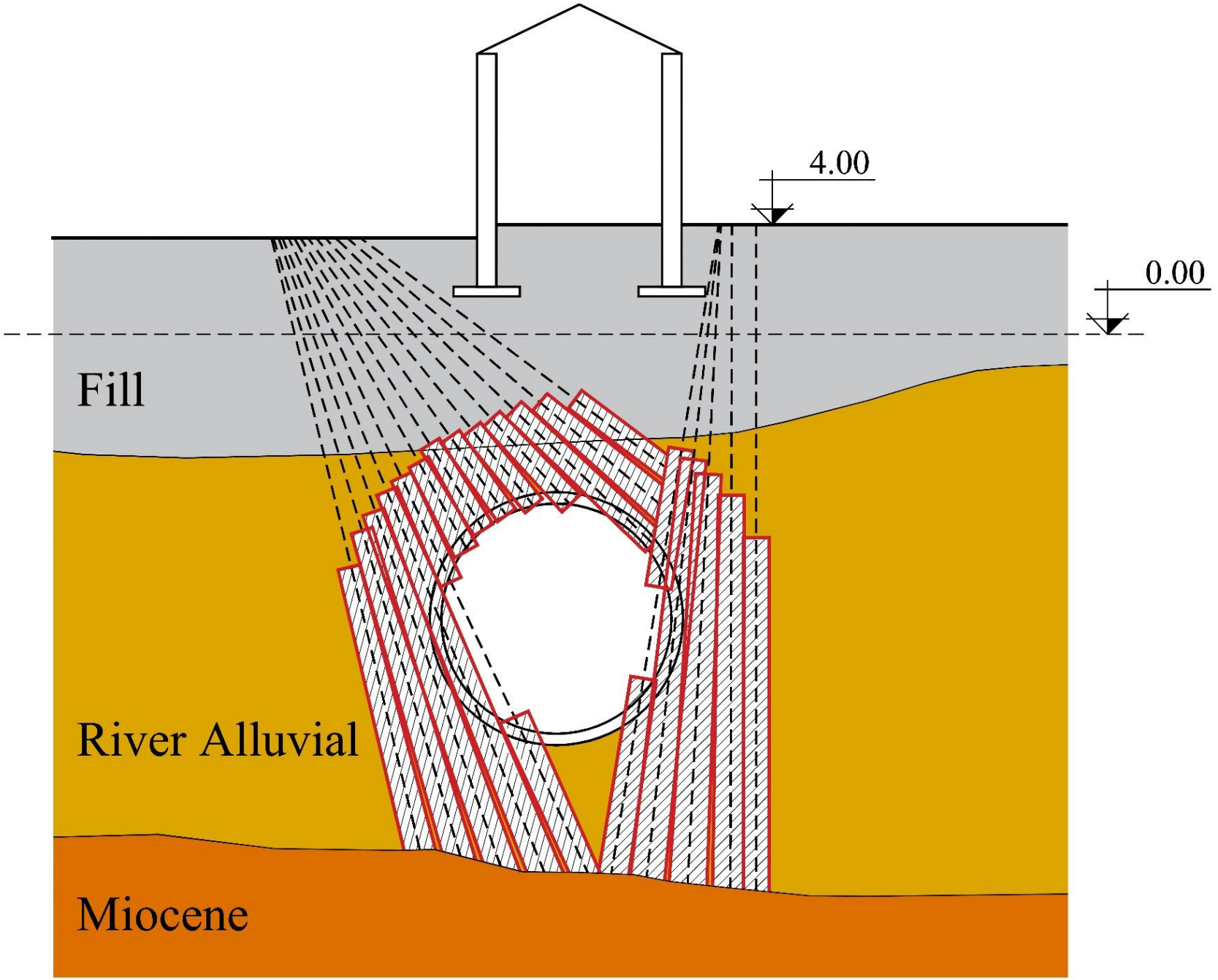
Pile excavation

3. Other mitigation techniques

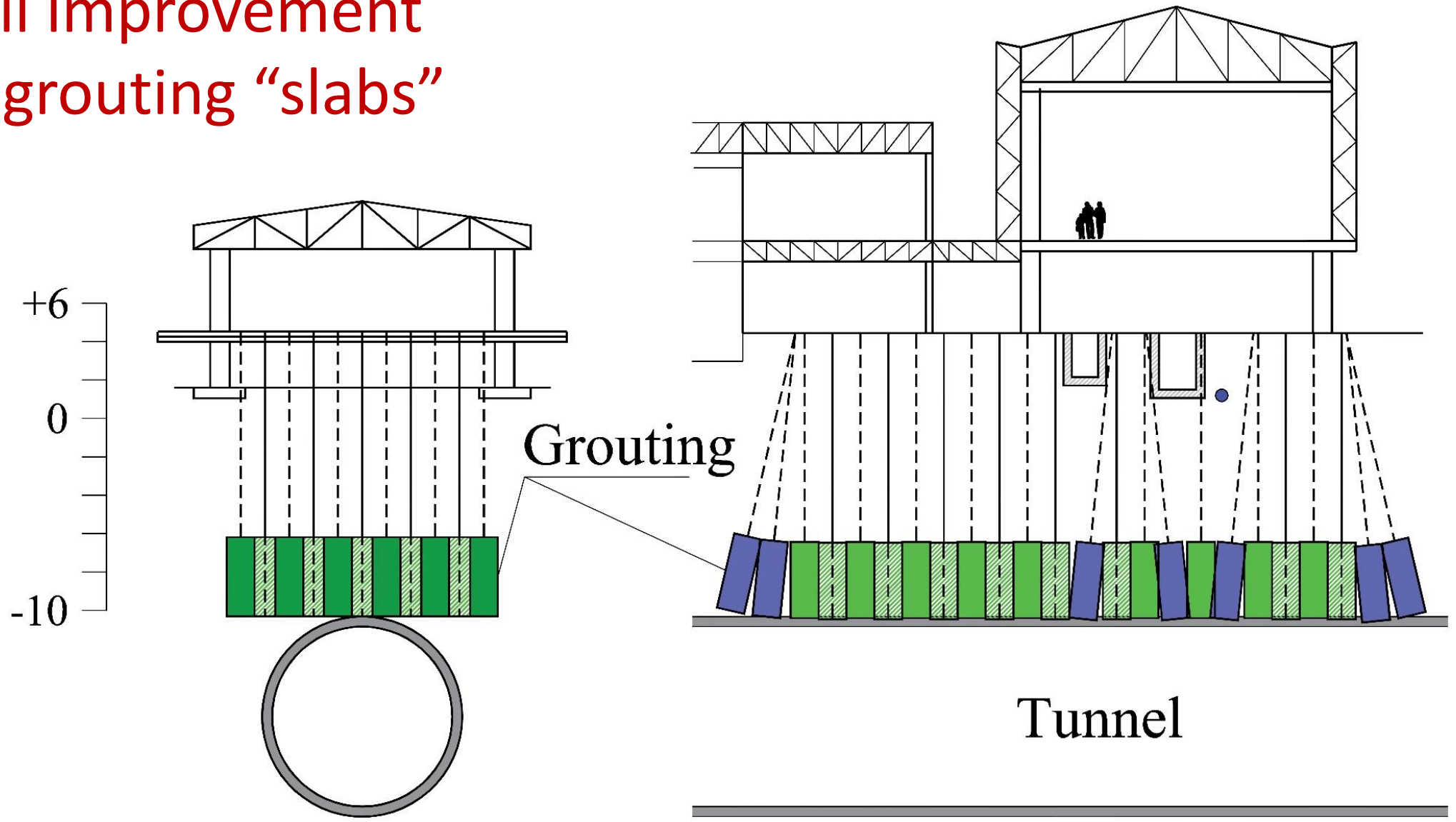
Convento do Carmo after 1755 Lisbon earthquake

Soil improvement. Jet grouting enclosures

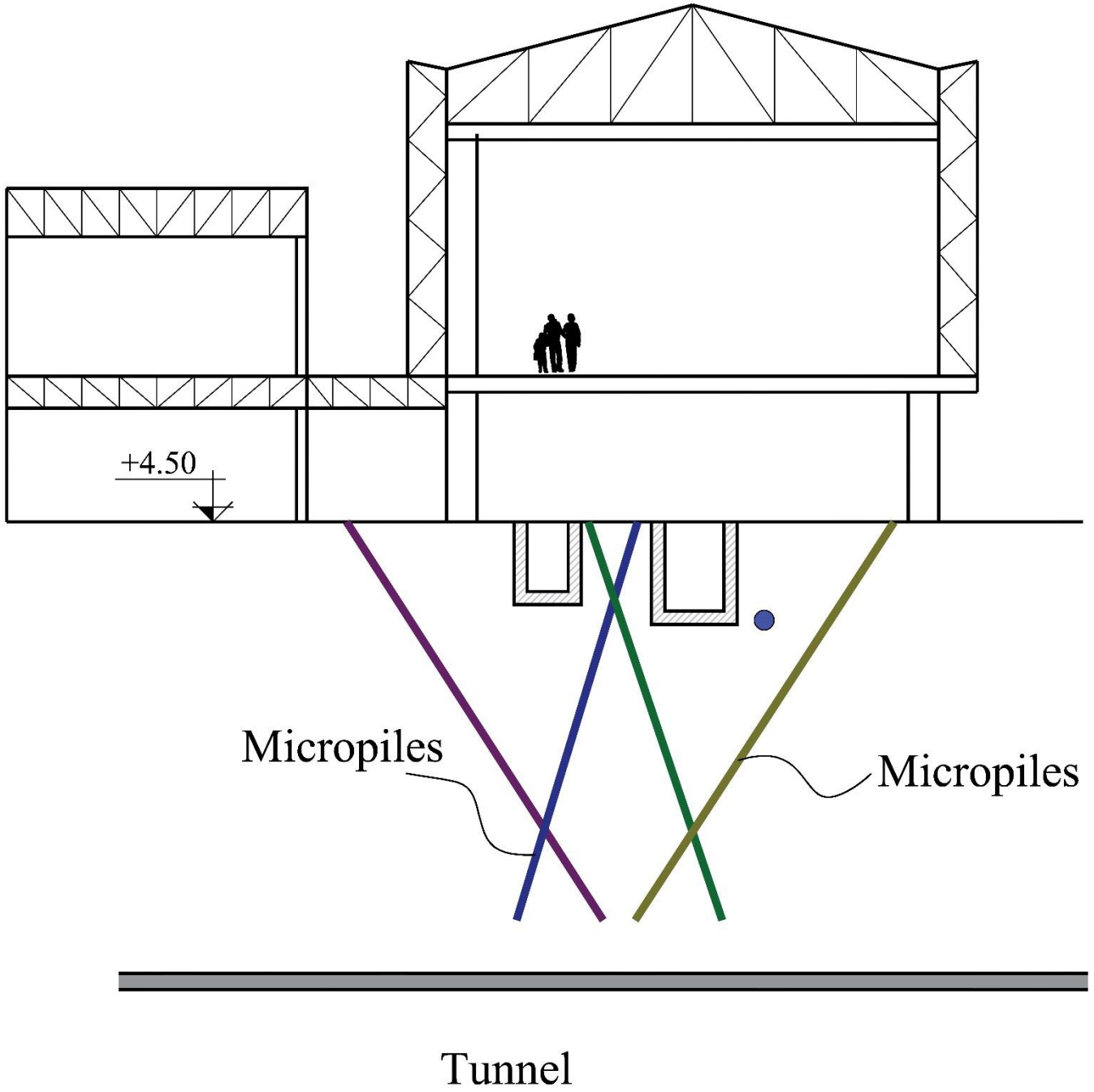
Lisboa underground. Sodré Station



Soil improvement
Jet grouting “slabs”

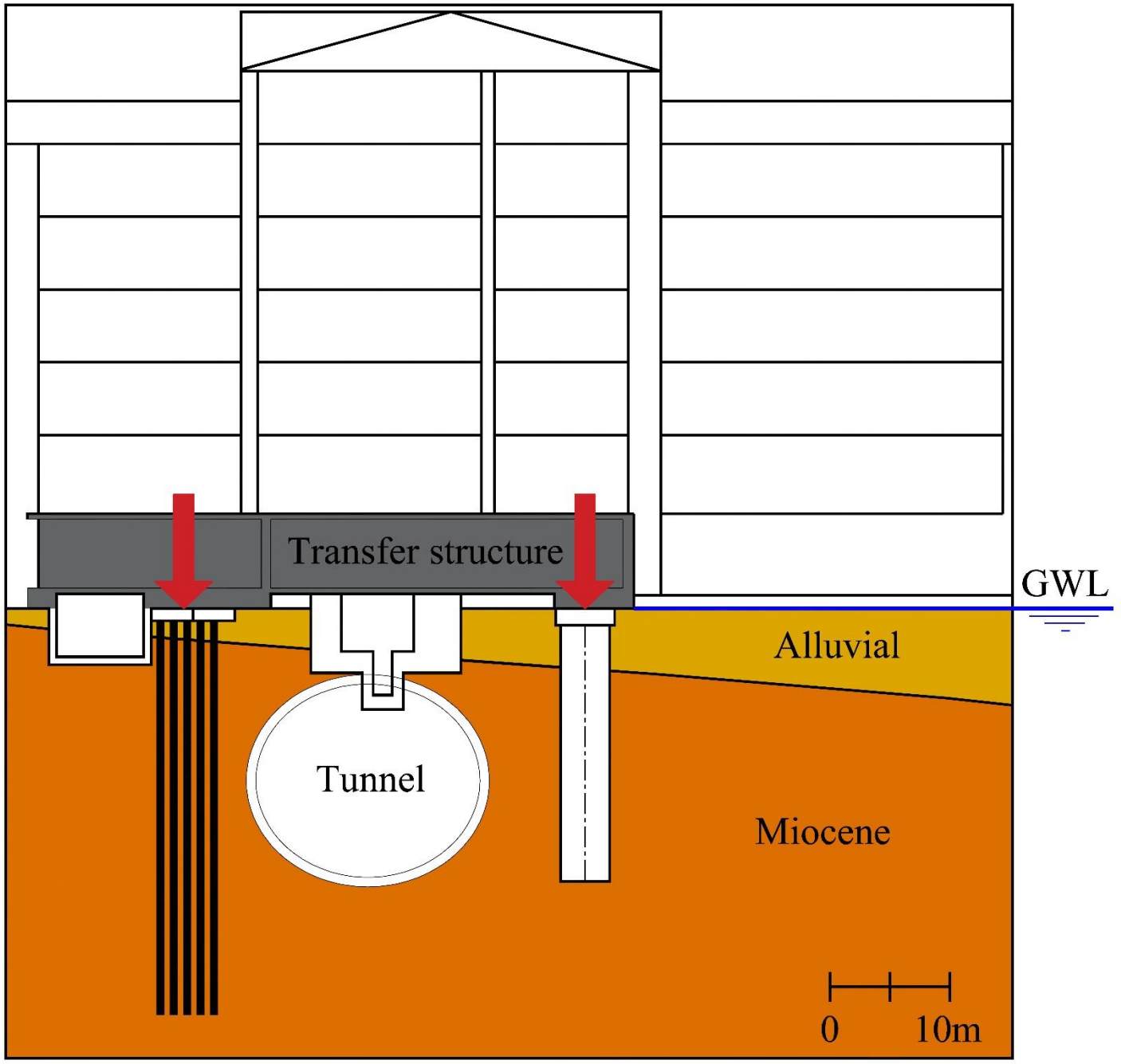


Micropile
“inverted tent”

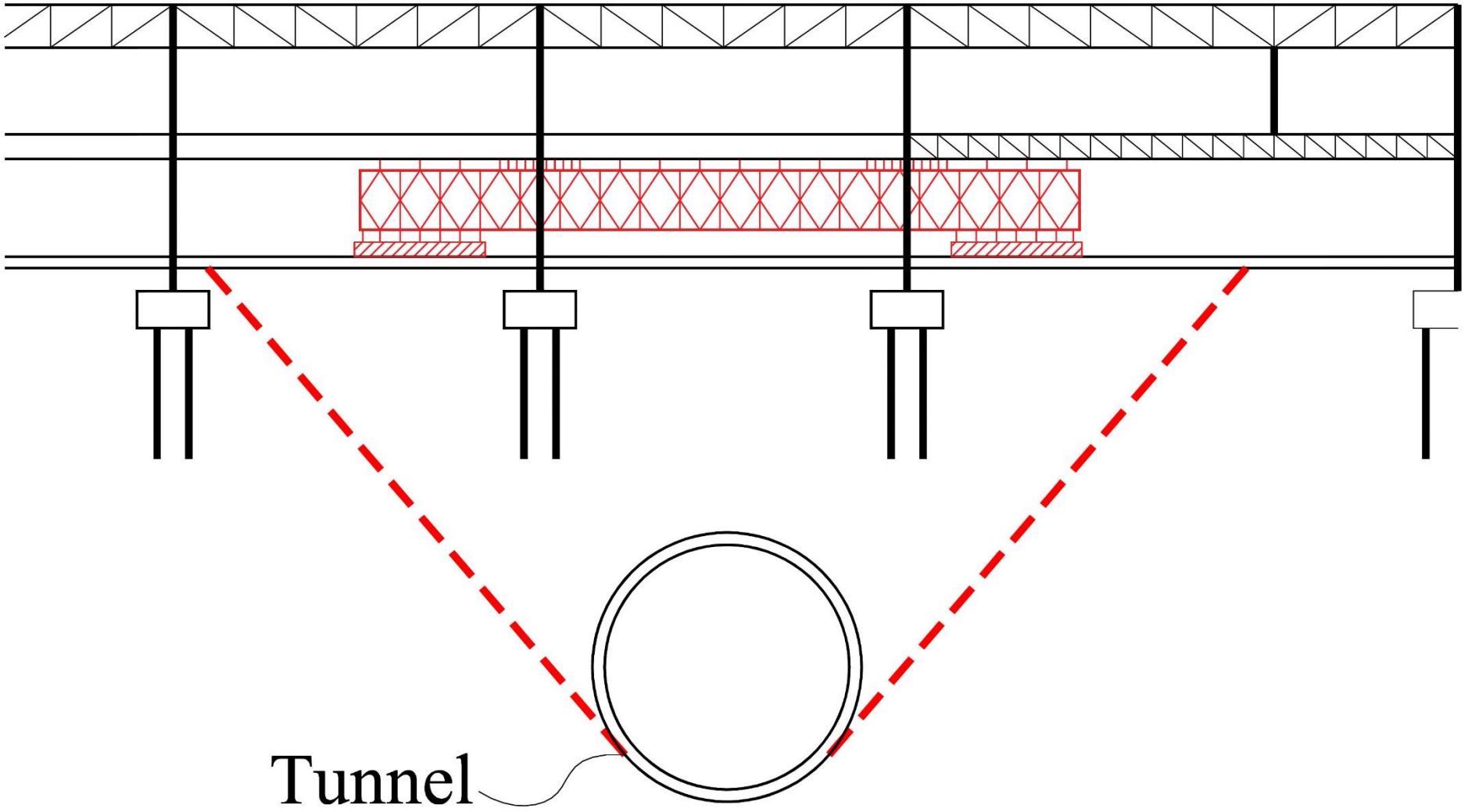


Underpinning

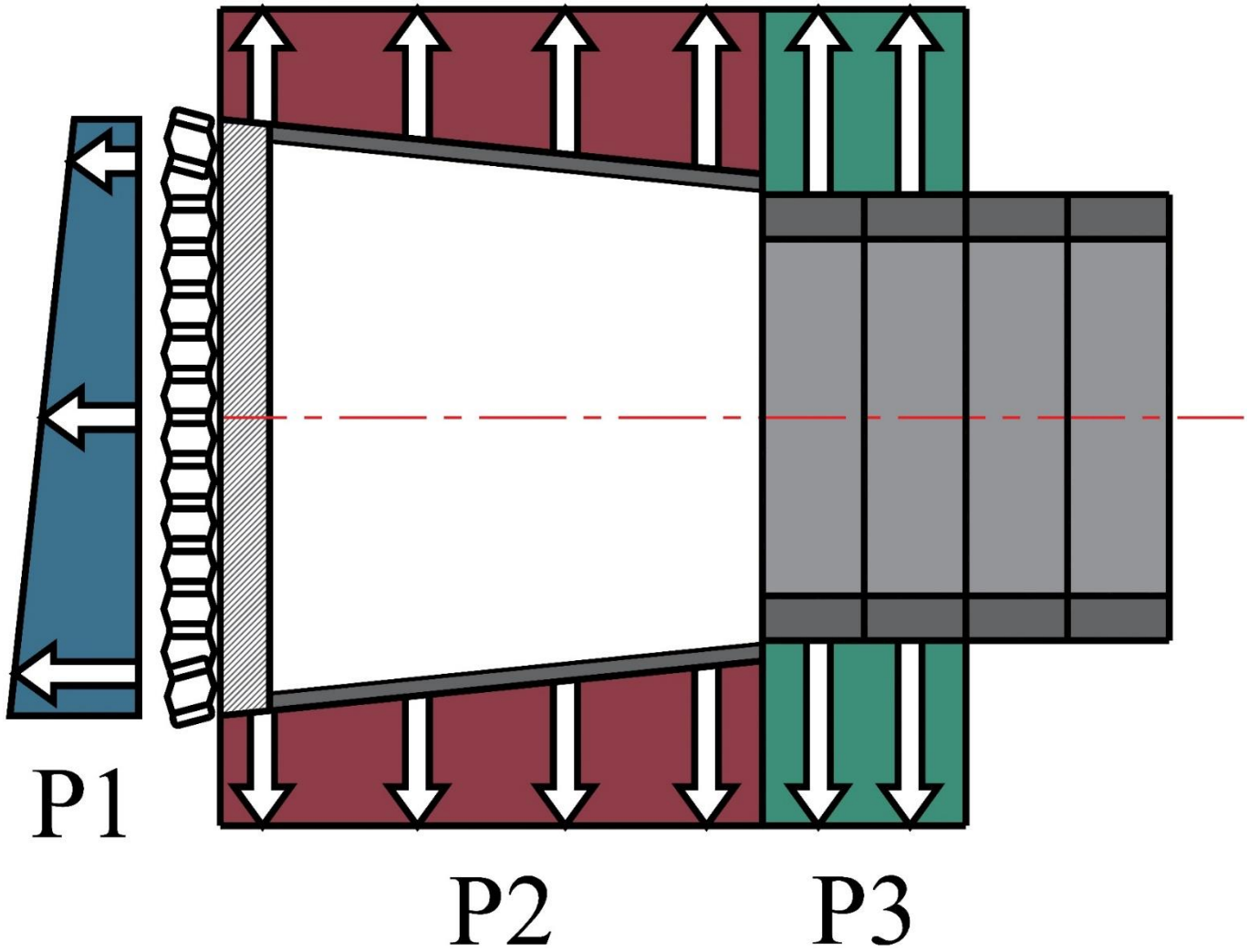
Lisboa underground Metropole Hotel



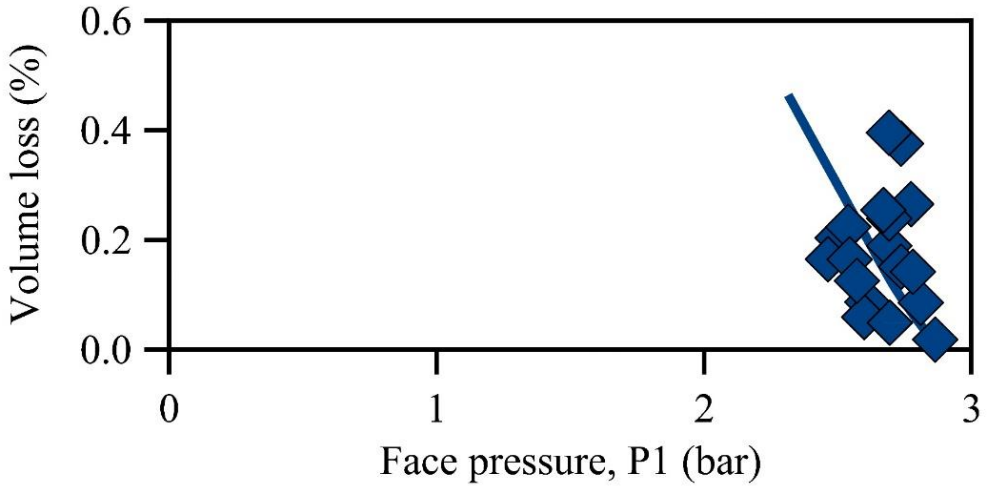
Structural reinforcement

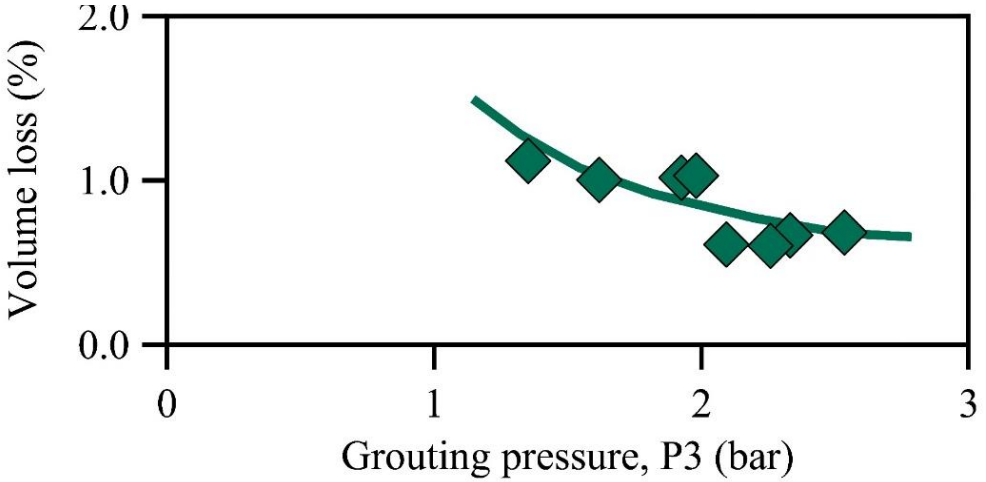


Controlling Volume Loss



Effect of EPBS pressures on Volume loss

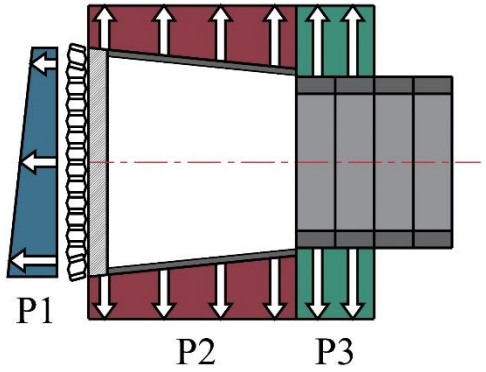




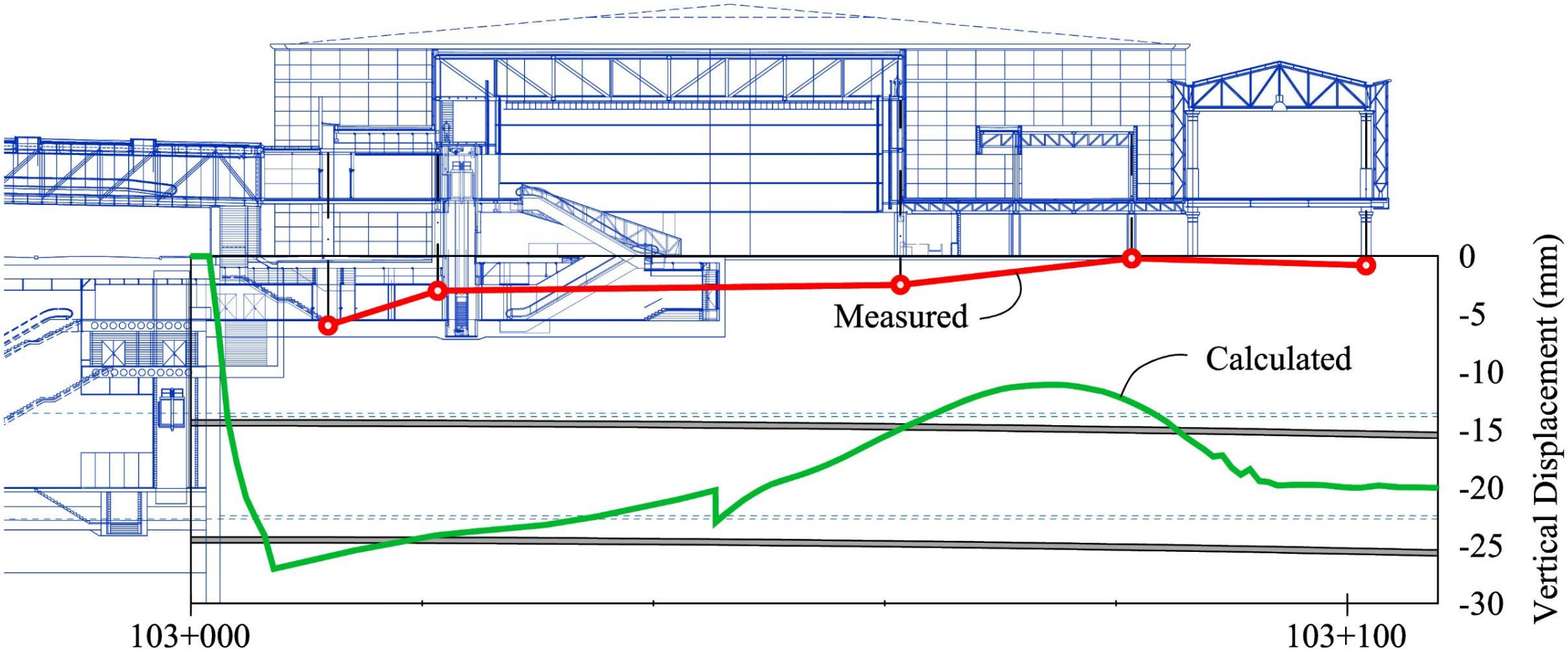
Field data from Line 9
Barcelona underground

DiMariano et al, (2016)

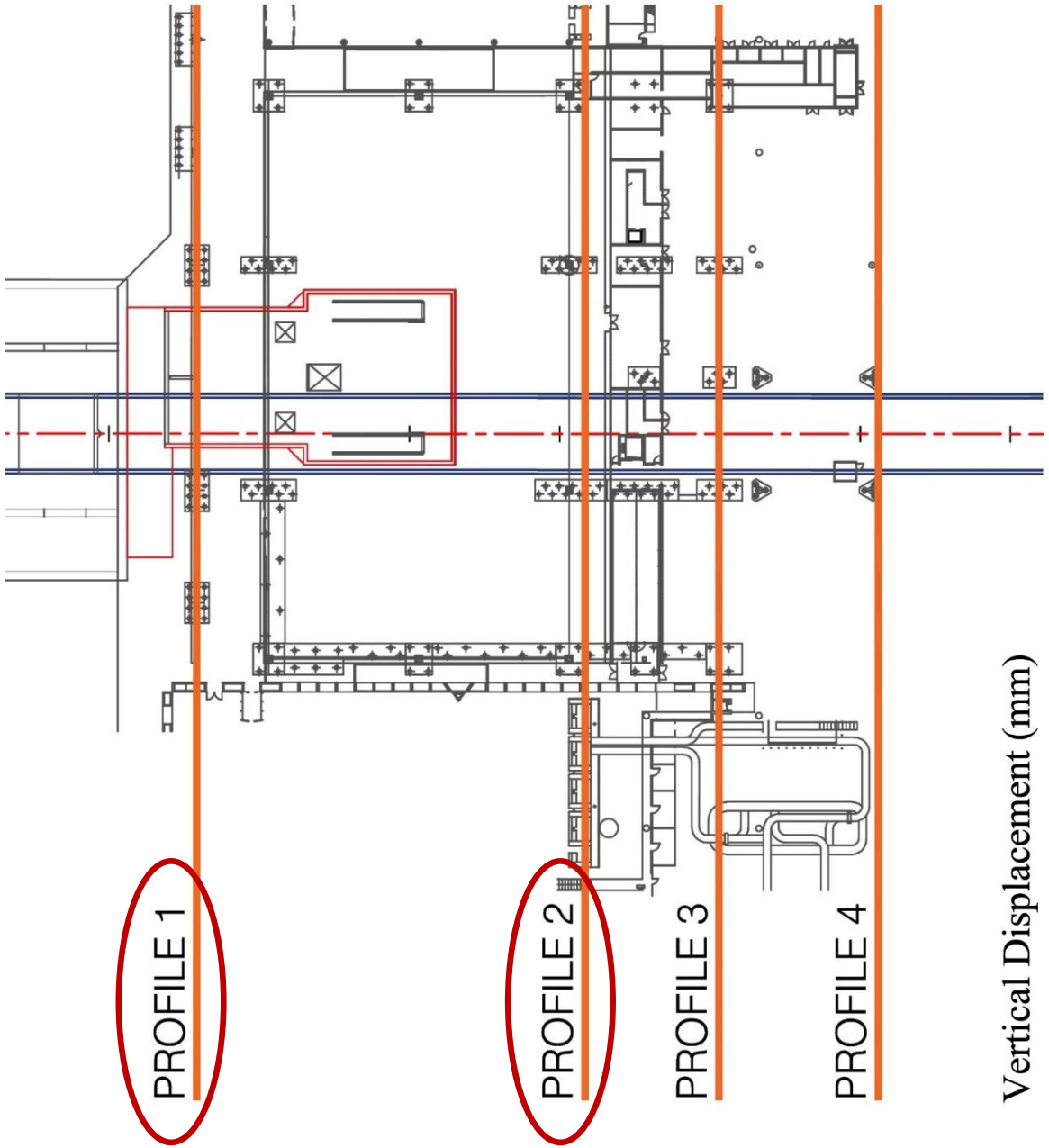
Pressures for the Crossing of Barcelona Airport Terminal 2

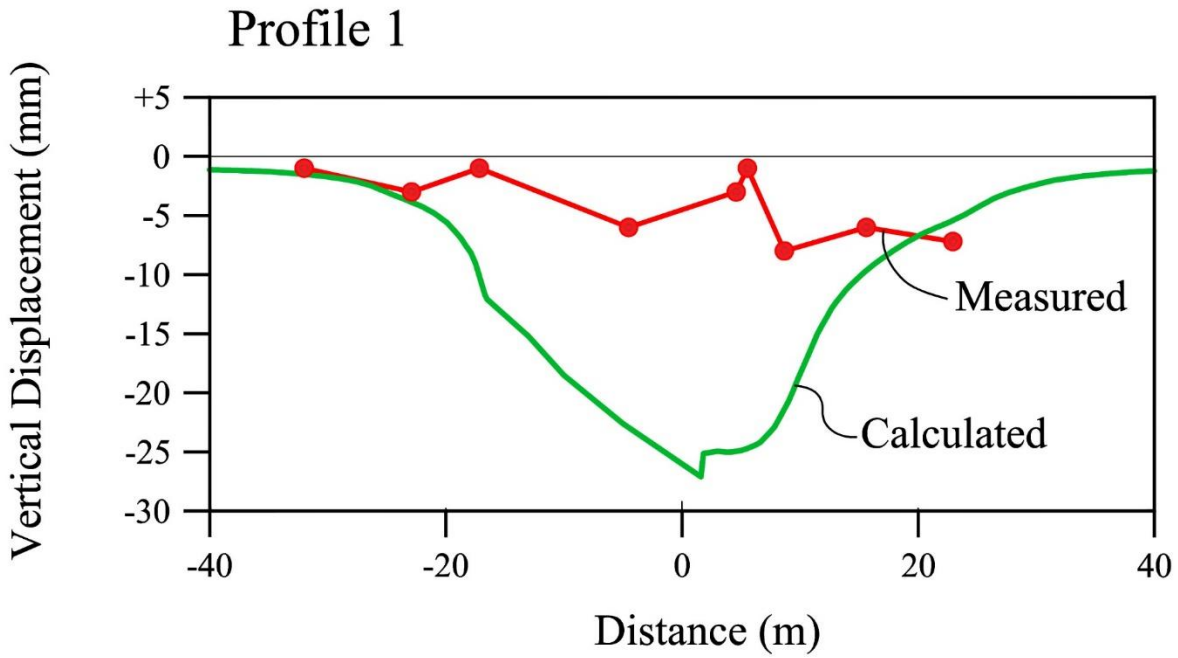


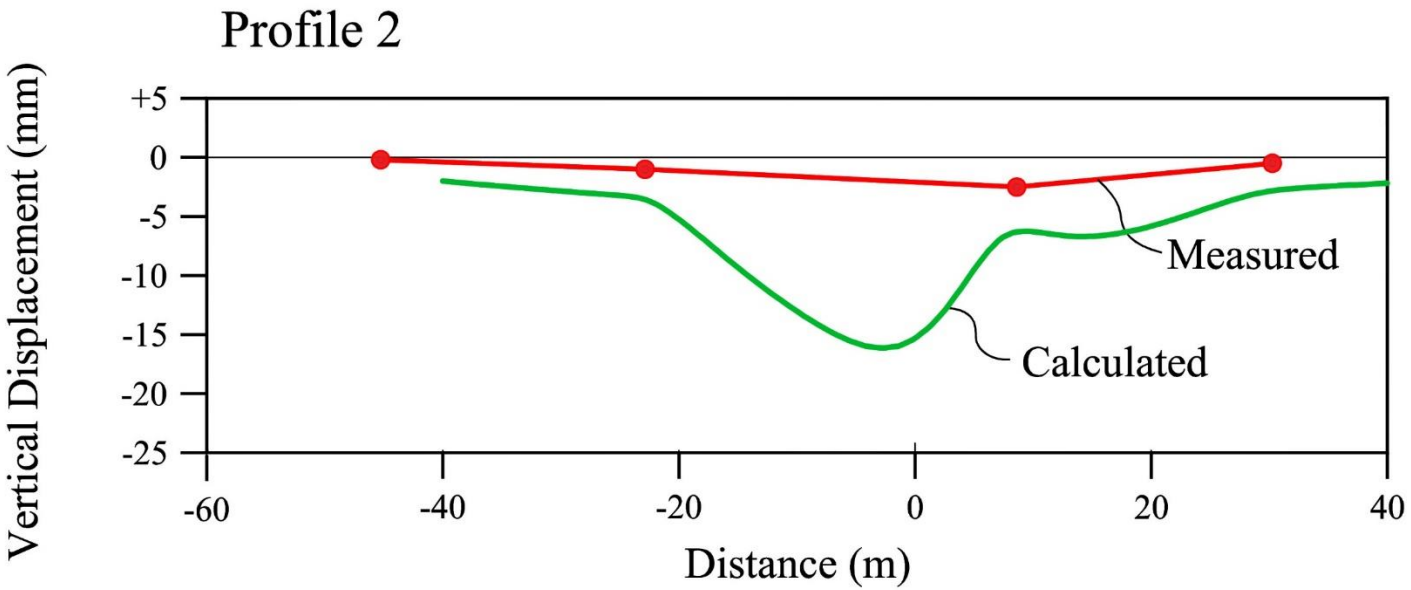
- P1 = 2,4 bars = 1,15 x Total horizontal stress. (Greenfield validation)
- P2 = 0 (Shield design does not allow it)
- ➢ P3 = P3 (Greenfield) + 0,8 bar



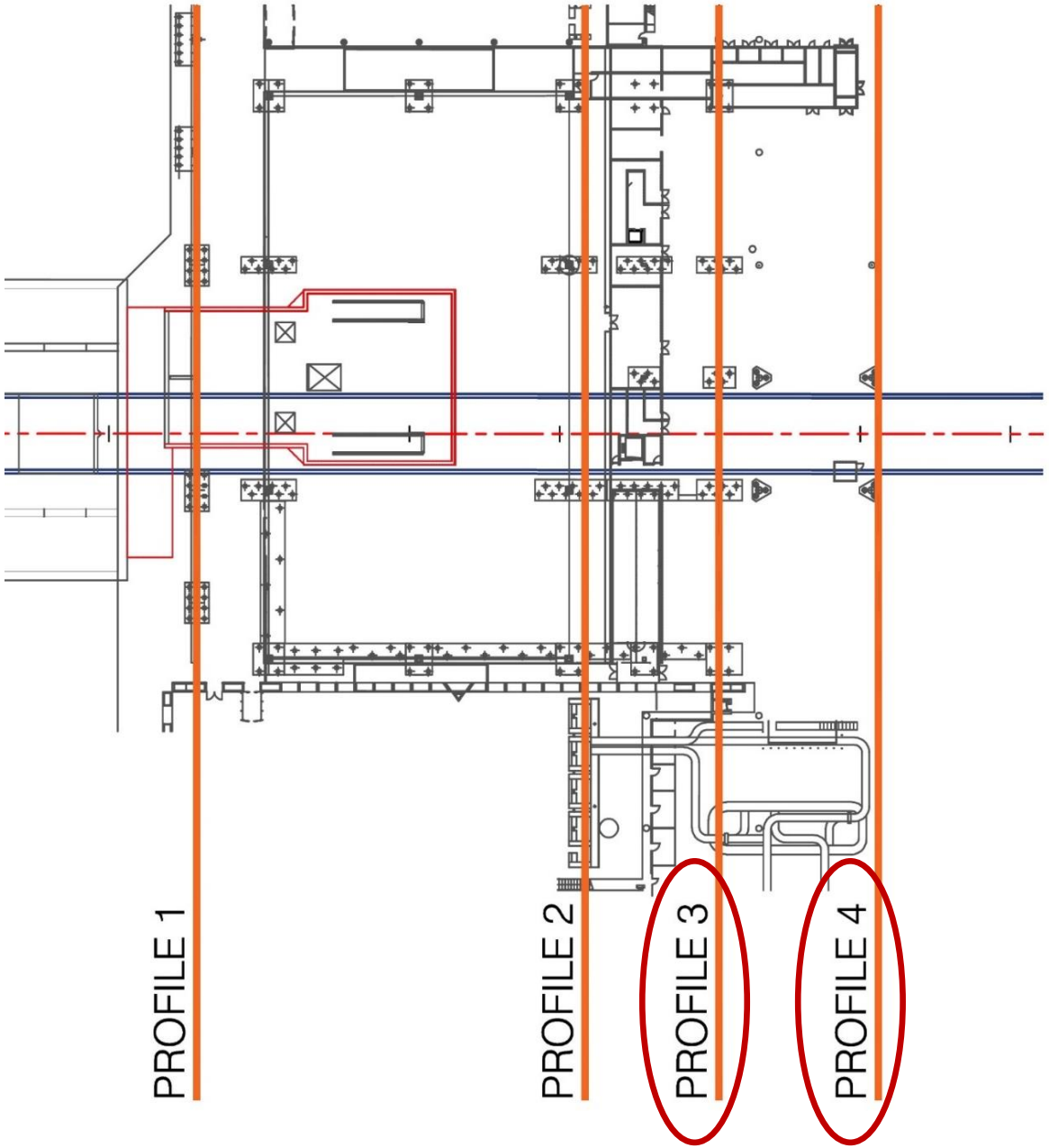
Settlement troughs. Barcelona Airport Terminal 2

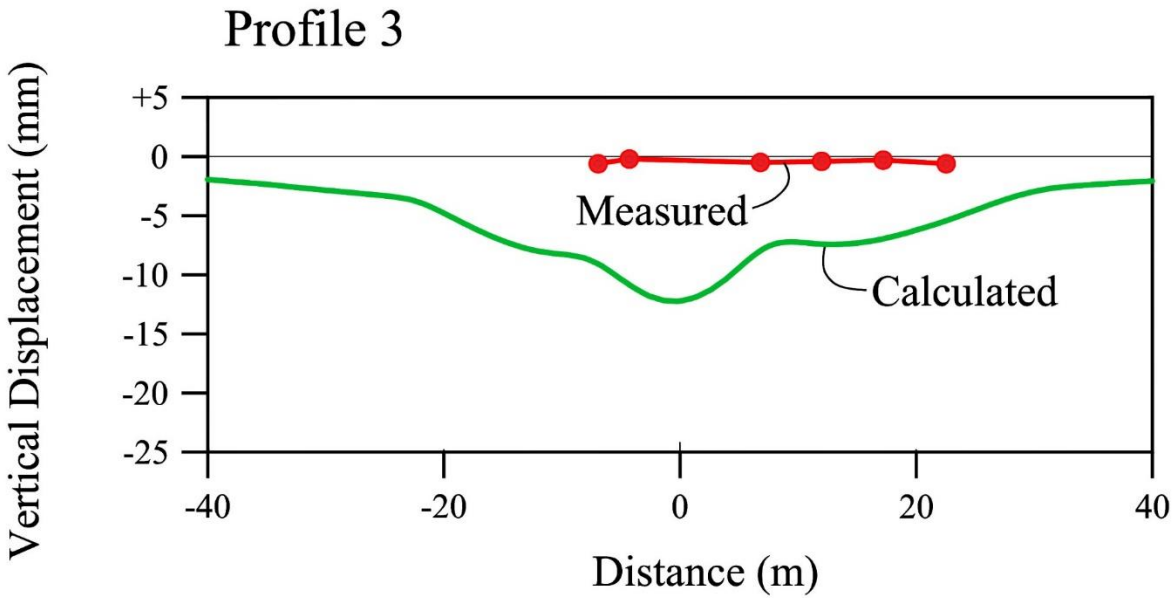


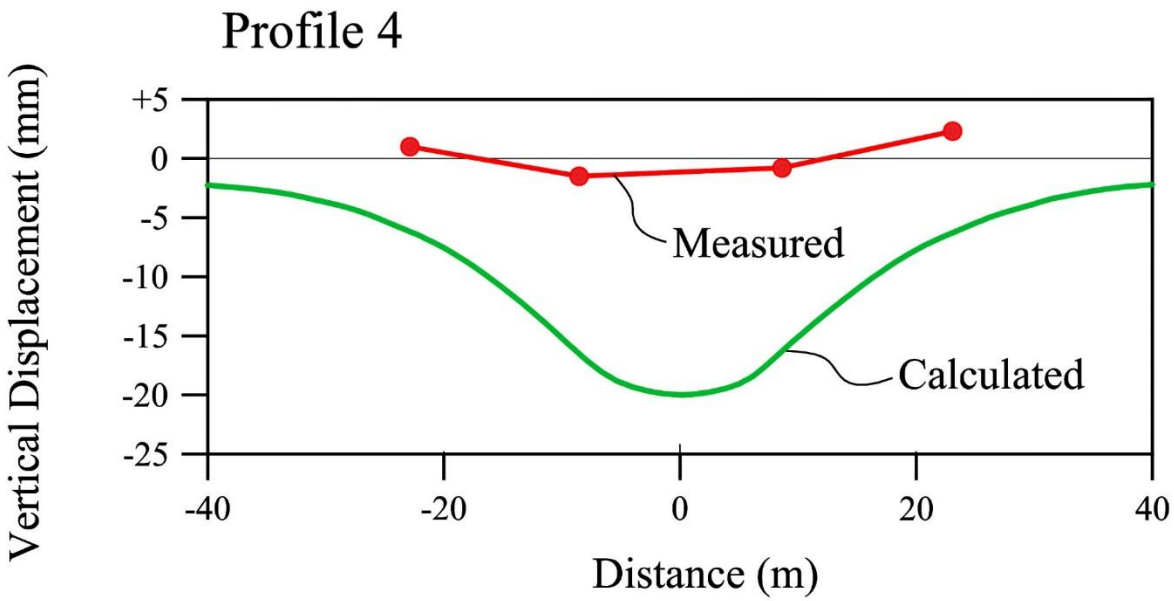




Settlement troughs. Barcelona Airport Terminal 2







Protecting Sensitive Structures from Tunnelling in Urban Environments

- Simplified procedures (building interpreted as a “thick beam” + critical tensile strains) are of limited application in singular buildings
- Compensation grouting
  - Success is not always guaranteed
  - Better results in clayey soils
- Protection walls
  - A reliable procedure

Protecting Sensitive Structures from Tunnelling in Urban Environments

- Semi-analytical procedures:
  - Good insight into the mechanics of the problem
  - Help designing engineering solutions at a reduced effort
- High efficiency of modern EPBS machines
  - Strict control of machine operations
  - Feedback from monitoring in real time
  - The best protection!

Acknowledgements

- Dr. D. Simic, *Ferrovial*
- Eng. S. Sánchez, *Geoconsult*
- Eng. L. Prieto, *Rodio Kronsa*
- Eng. E.V.S. Espiña, *Geoconsult*
- Prof. A. Ledesma, *UPC*
- Dr. A. di Mariano, *UPC*
- Prof. P. Roca, *UPC*
- Prof. A. Gens, *UPC*
- Eng. M. Sondon, *UPC*
- ADIF: Spanish Railway Administration

Thank you very much!