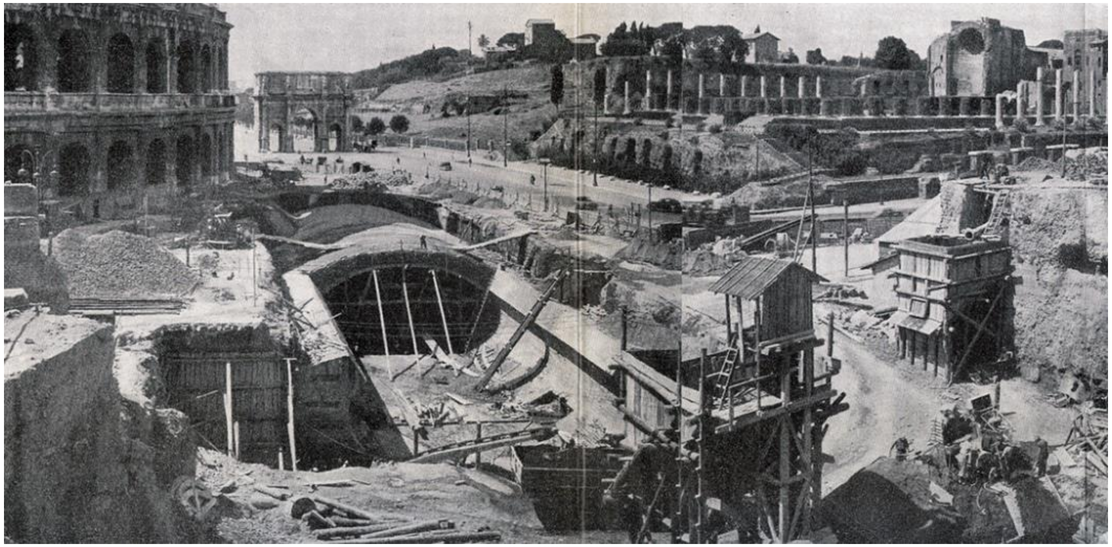
Ε.Ε.Σ.Υ.Ε.
Ελληνική Επιτροπή Σηράγγων και Υπογείων Έργων

Celebration of Saint Barbara
30 November 2015

Evaluating the effects of tunnelling on historical buildings: the example of Line C of Roma underground

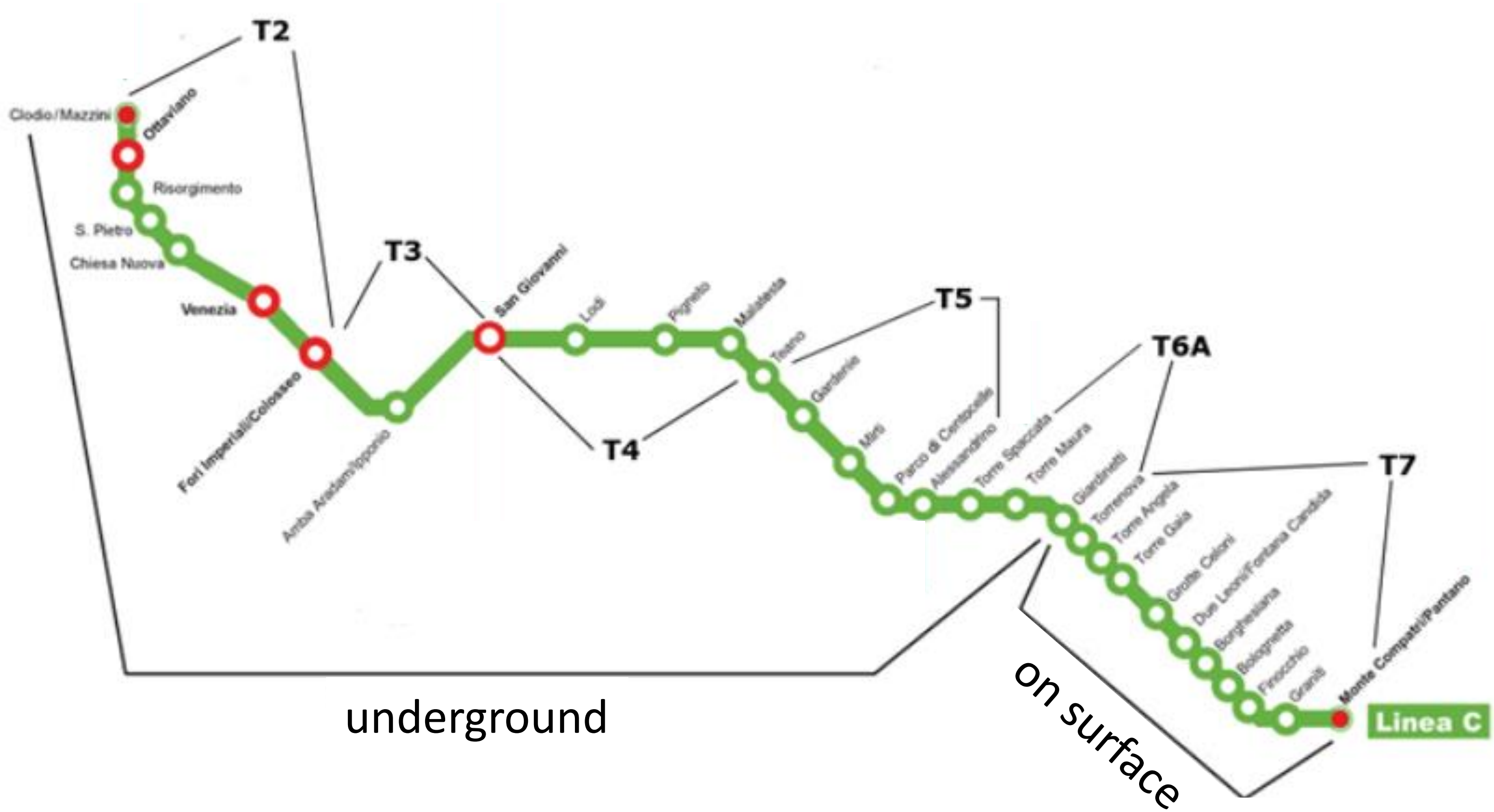


Giulia Viggiani Università di Roma Tor Vergata

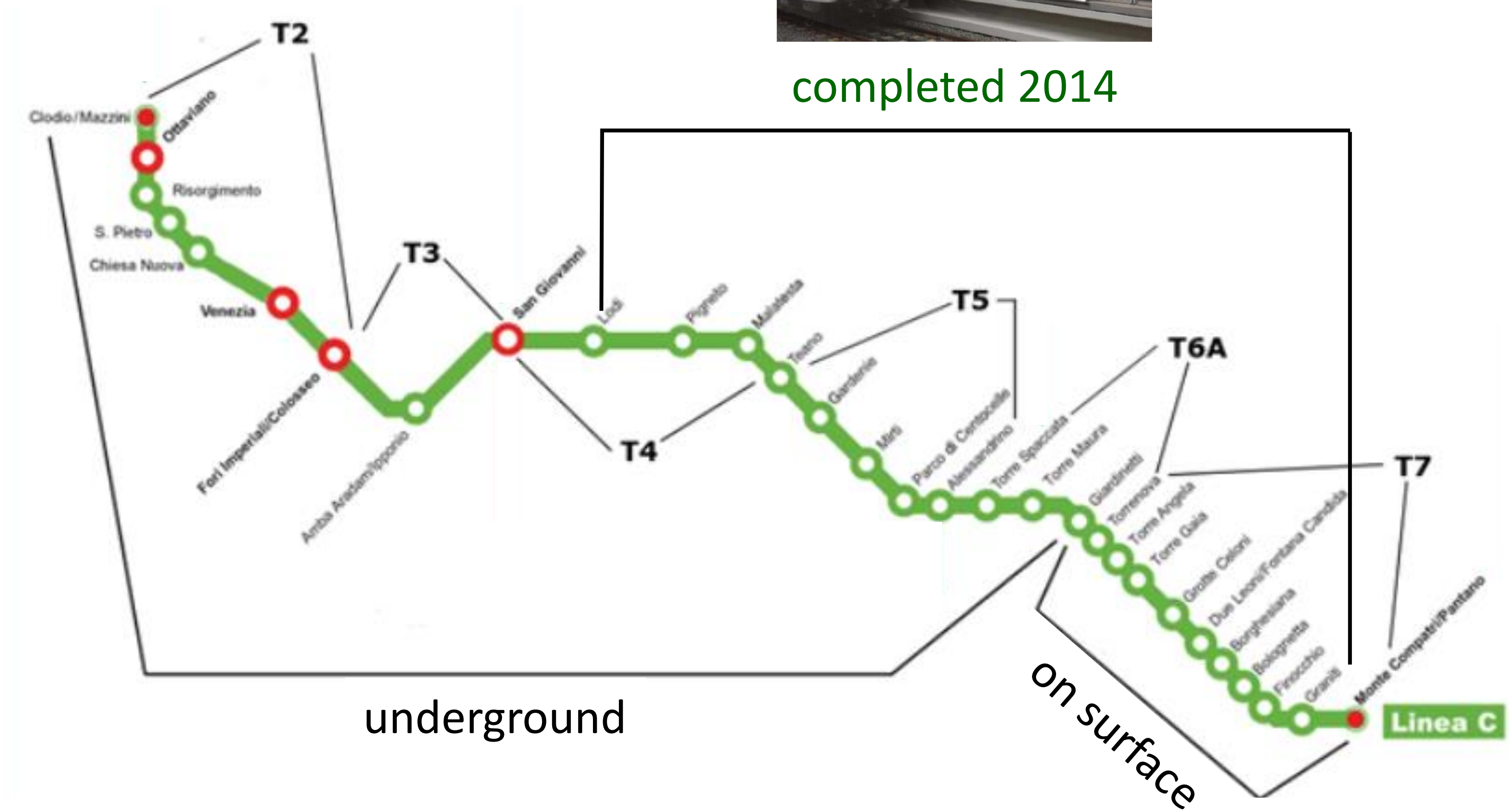
Sebastiano Rampello & Luigi Callisto
Sapienza Università di Roma

Fabio Soccodato Università di Cagliari

LINE C ROMA UNDERGROUND OVERVIEW



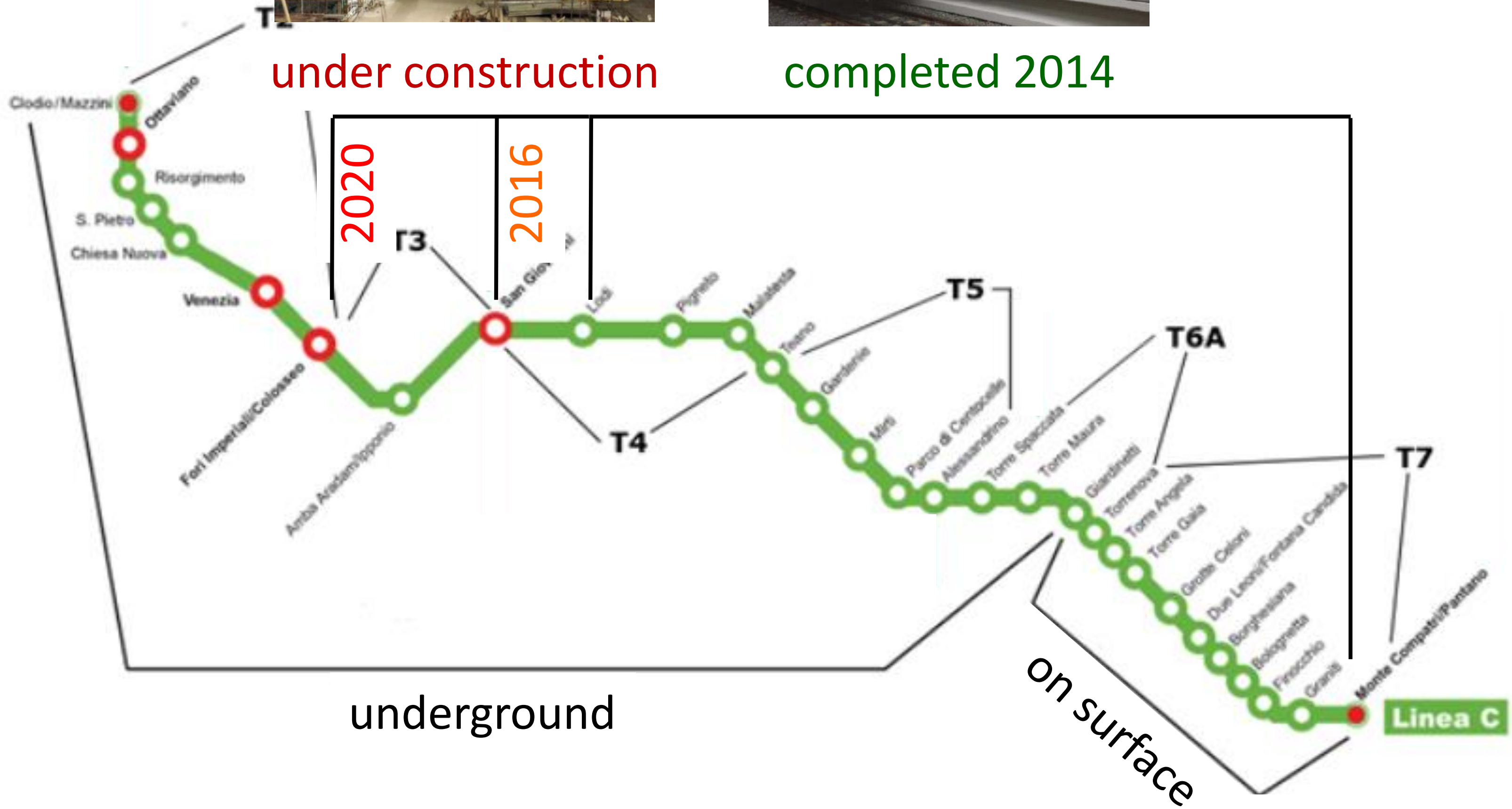
LINE C ROMA UNDERGROUND OVERVIEW



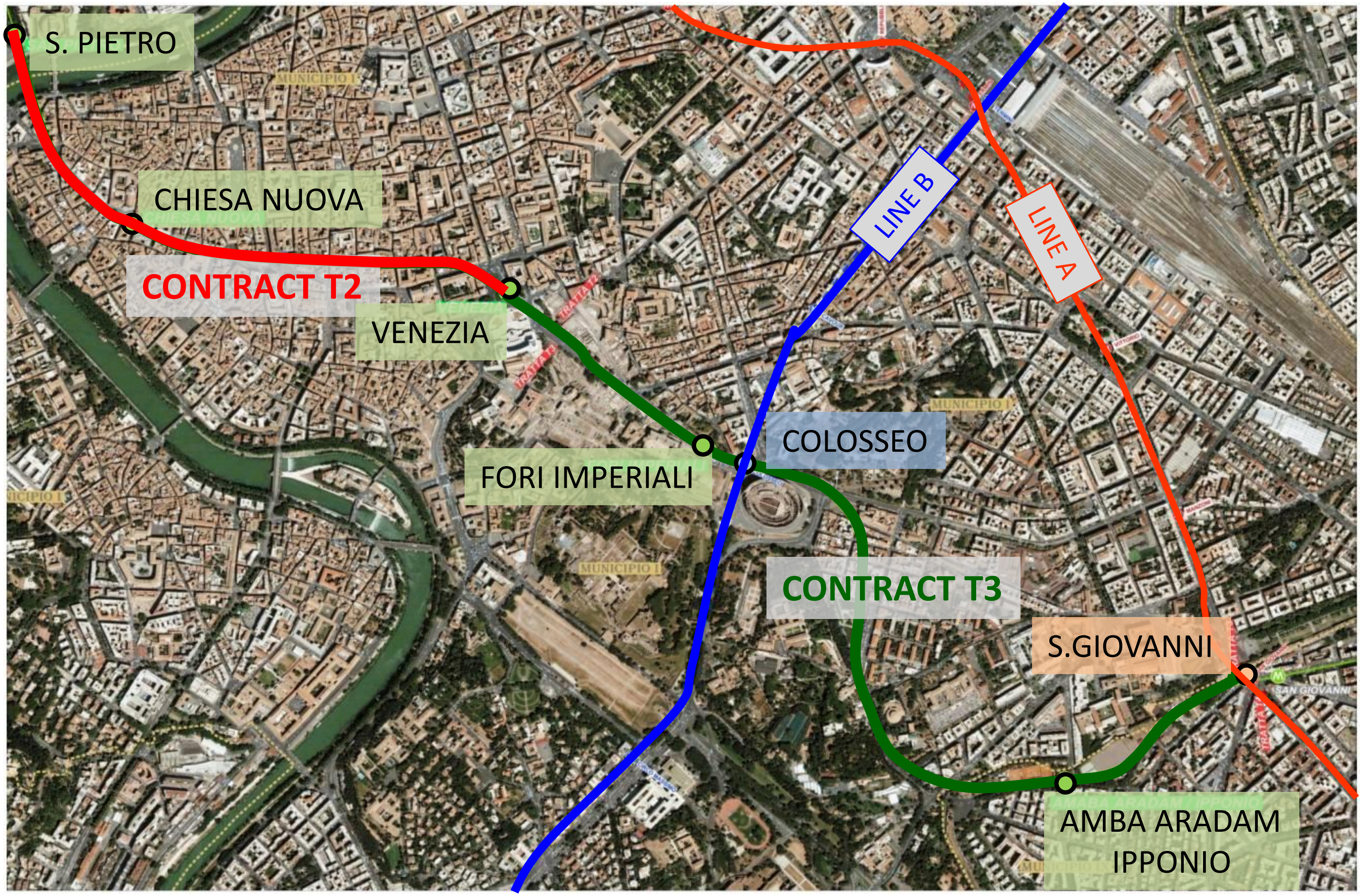
Dicii

under construction

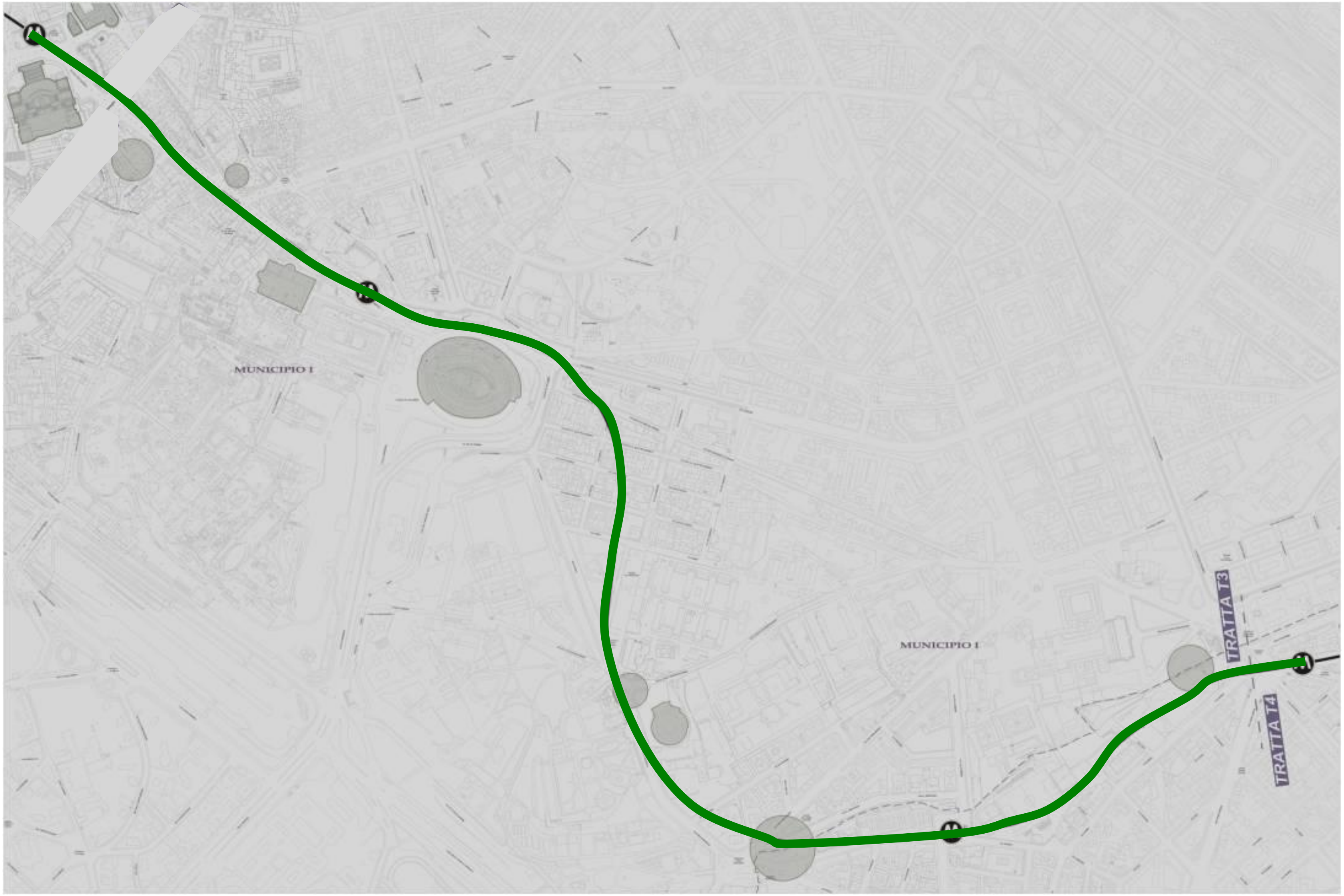
completed 2014



ROMA UNDERGROUND LINE C central stretch

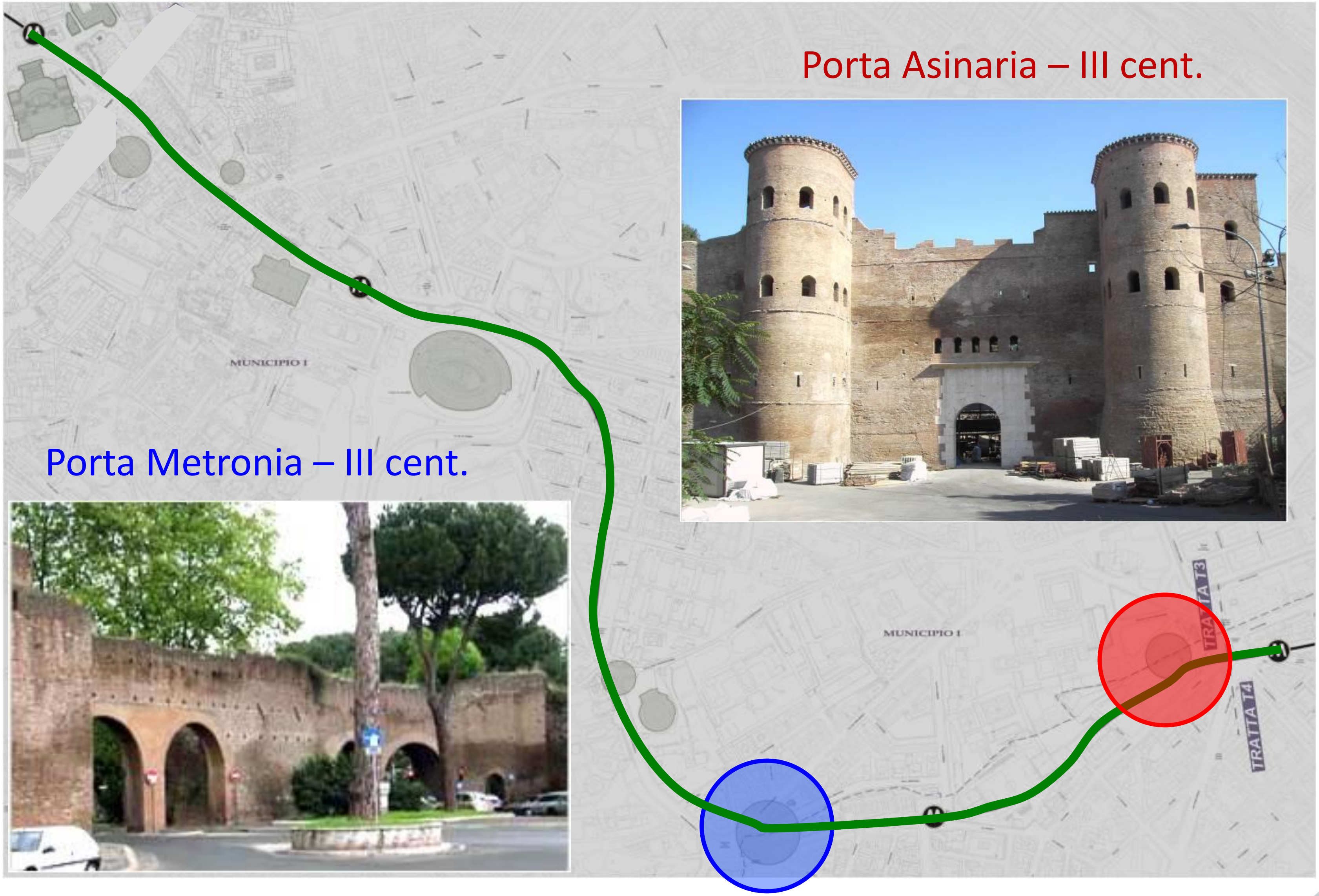


CONTRACT T3 BUILT ENVIRONMENT

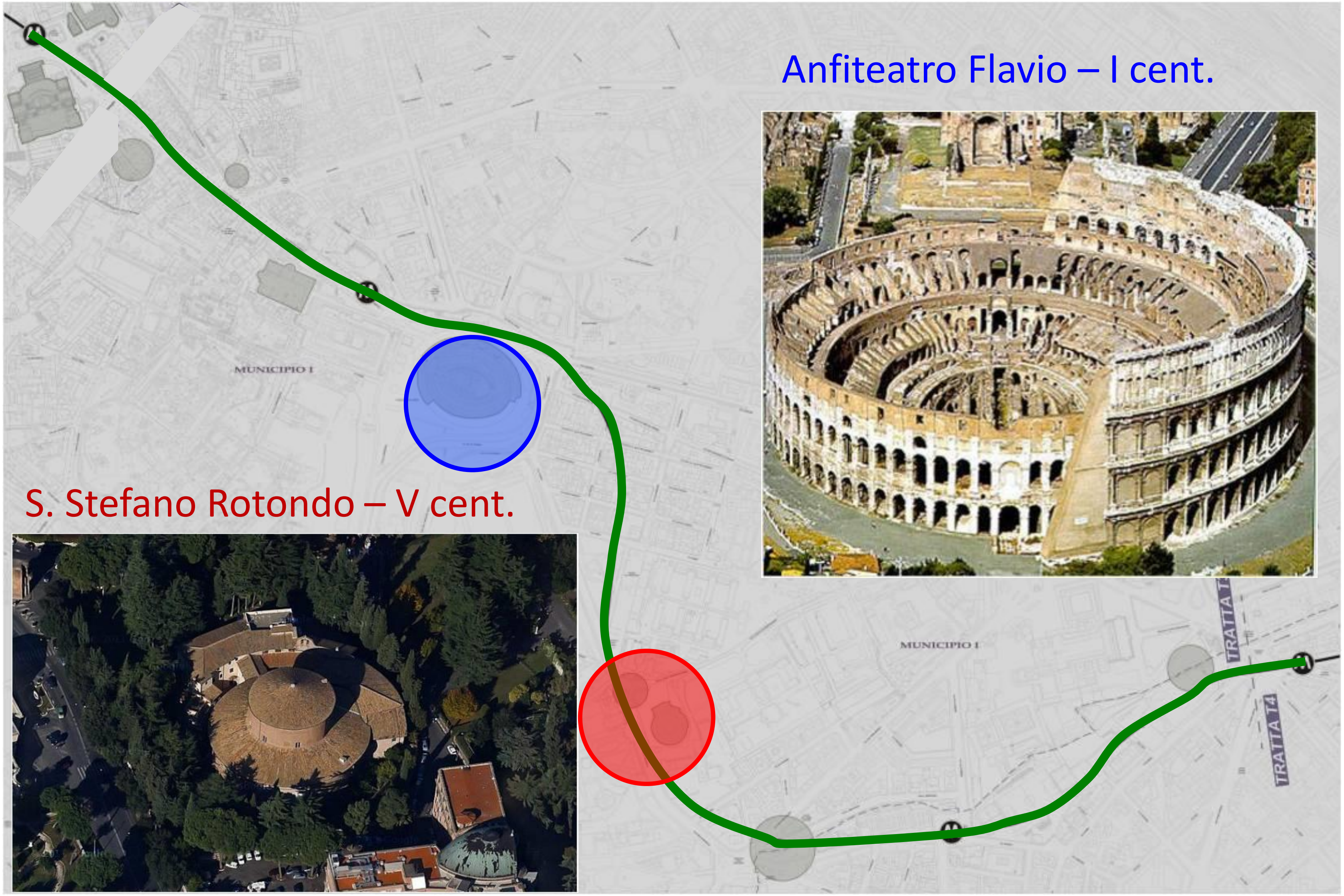


CONTRACT T3 BUILT ENVIRONMENT

Dicii

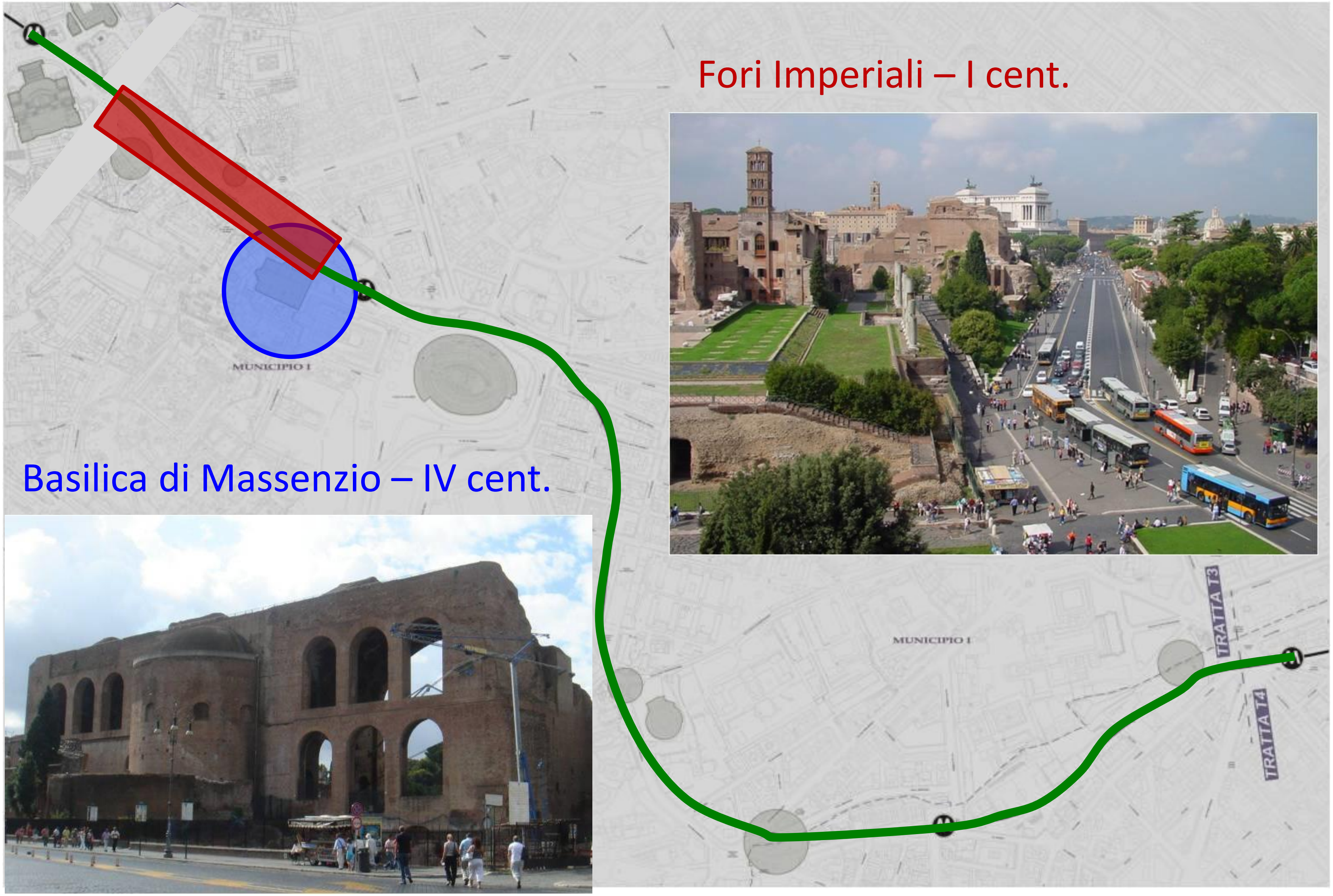


CONTRACT T3 BUILT ENVIRONMENT



CONTRACT T3 BUILT ENVIRONMENT

Dicii

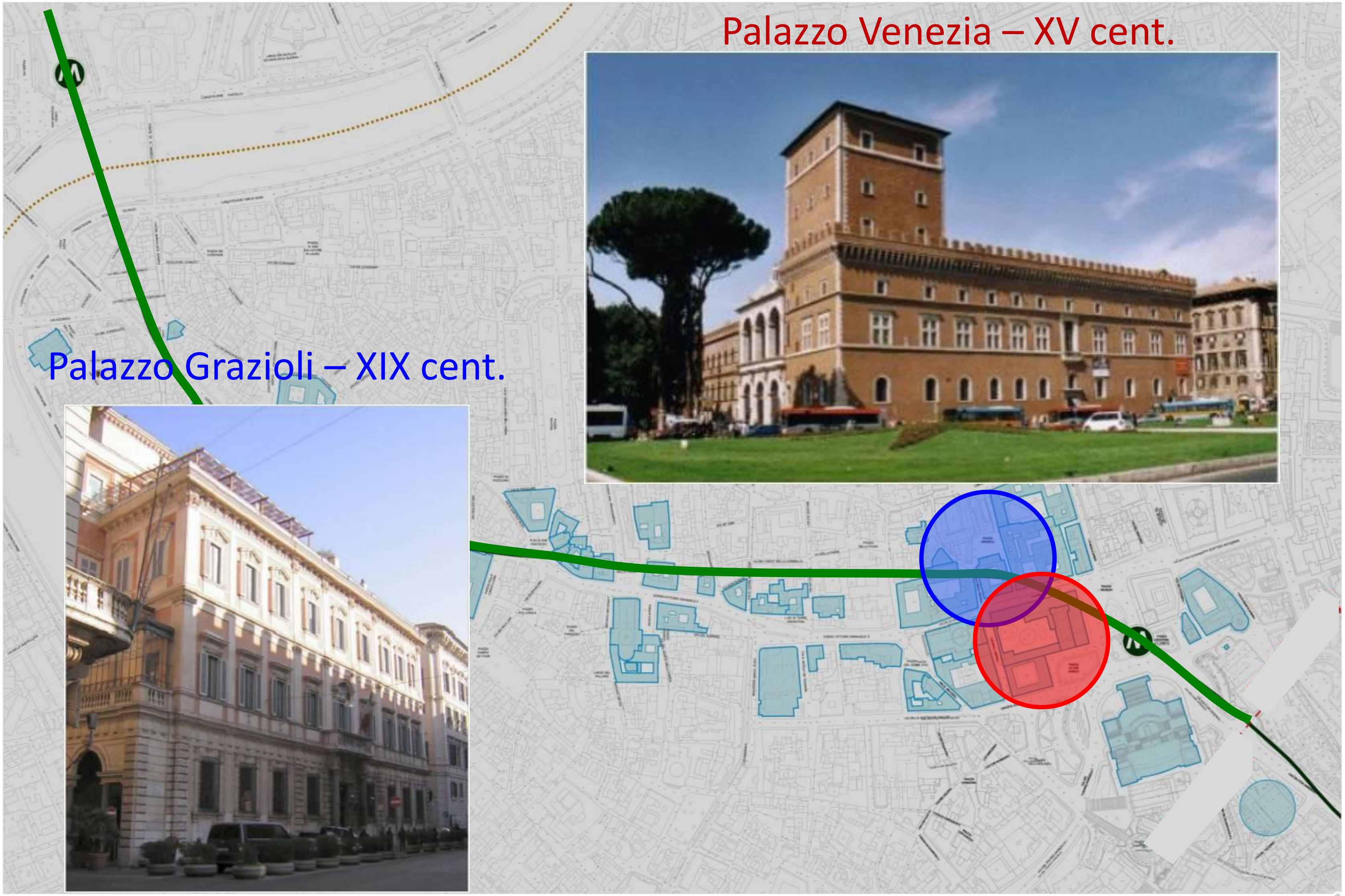


CONTRACT T2 BUILT ENVIRONMENT

CONTRACT T2 BUILT ENVIRONMENT

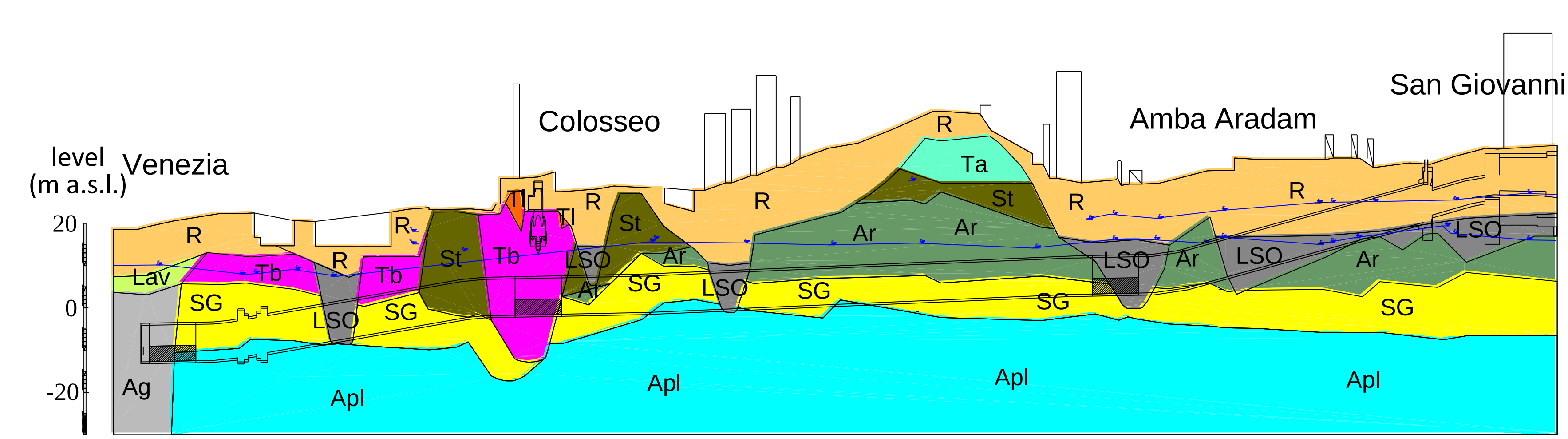
Dicii

CONTRACT T2 BUILT ENVIRONMENT



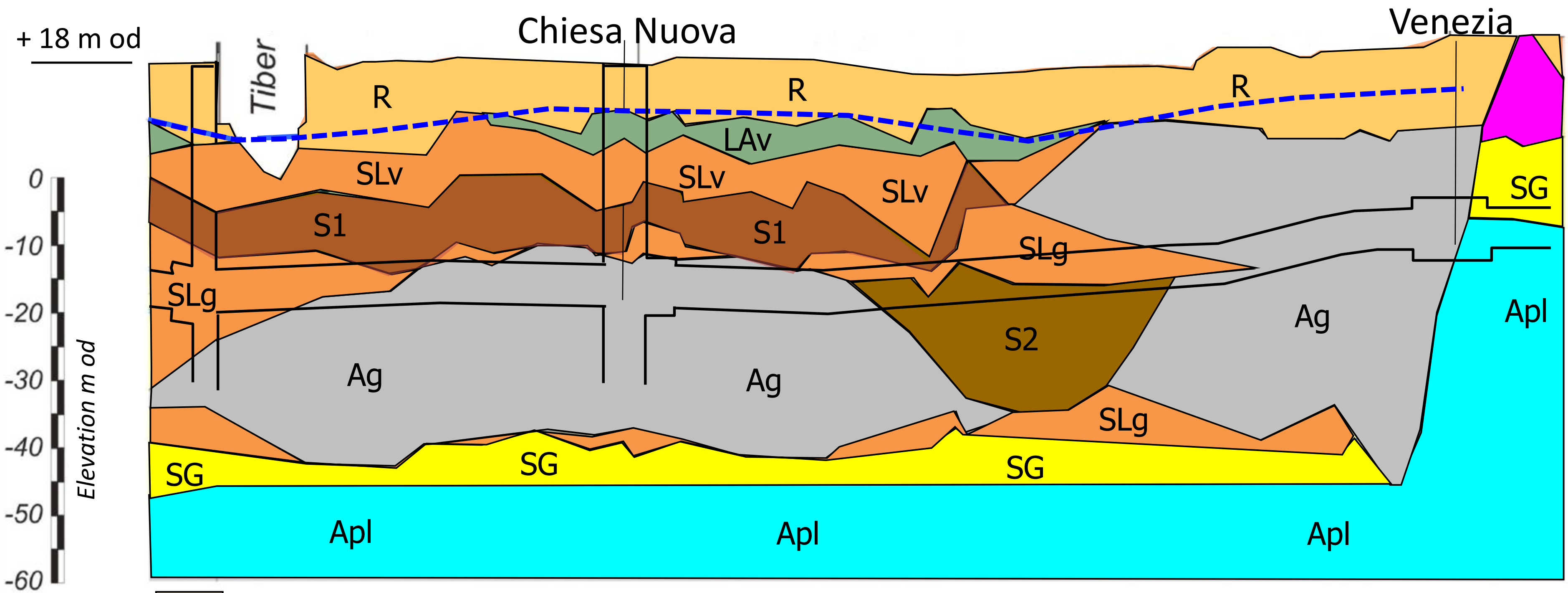

Palazzo del Banco di S. Spirito
(Antica Zecca) – XVI cent.
Palazzo Sforza Cesarini
XVIII cent.

CONTRACT T3 SOIL PROFILE



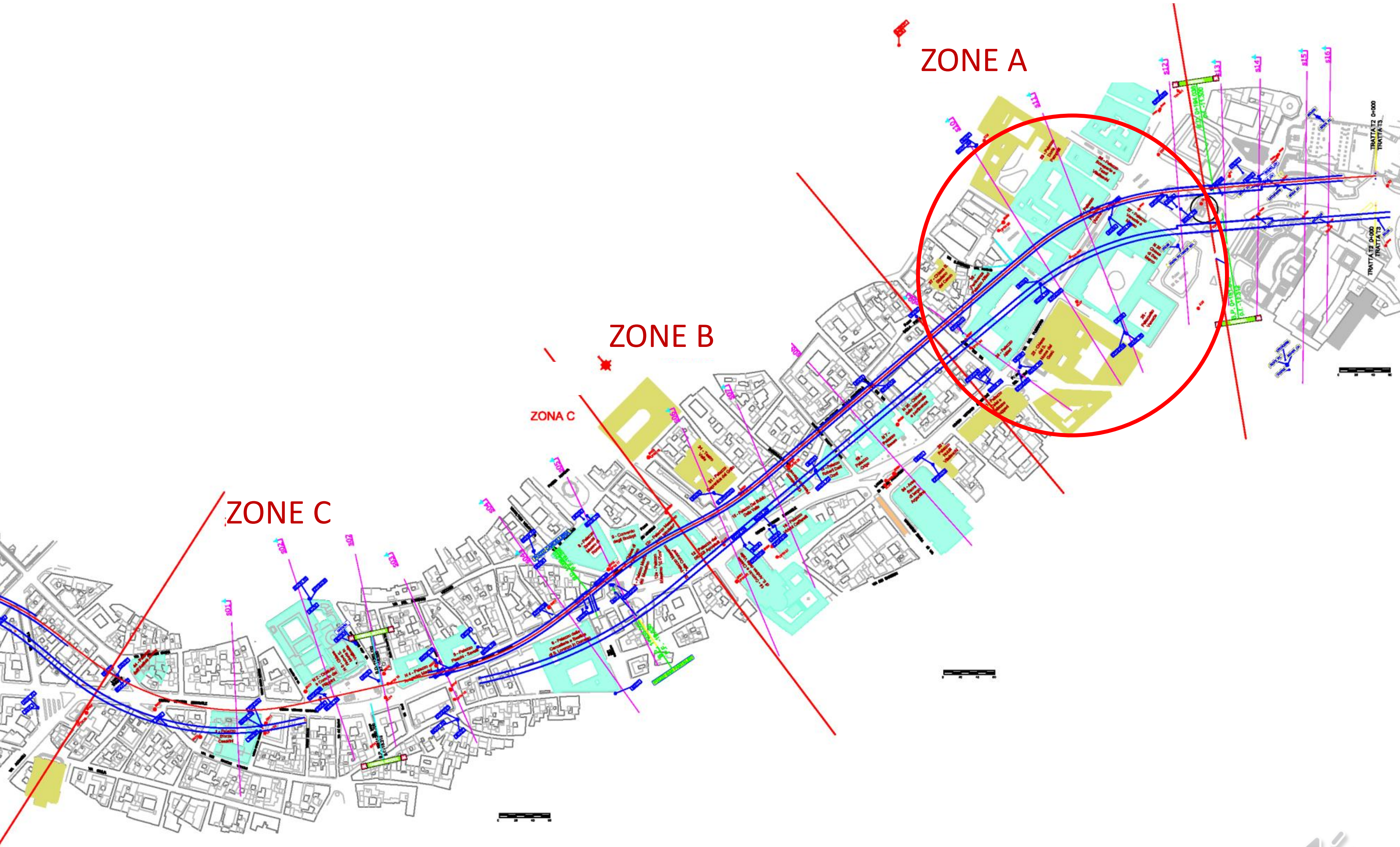
R	made ground		
Ta	pyroclastic deposits		
LSO, Ag	alluvial silty clay and silty sand		
Tb	sand	*Valle Giulia*	Pleistocene
St, Ar	sandy silt, clayey silt	*Paleotevere*	Pleistocene
SG	sand and gravel		
Apl	stiff silty clay	*Monte Vaticano*	Pliocene

CONTRACT T2 SOIL PROFILE

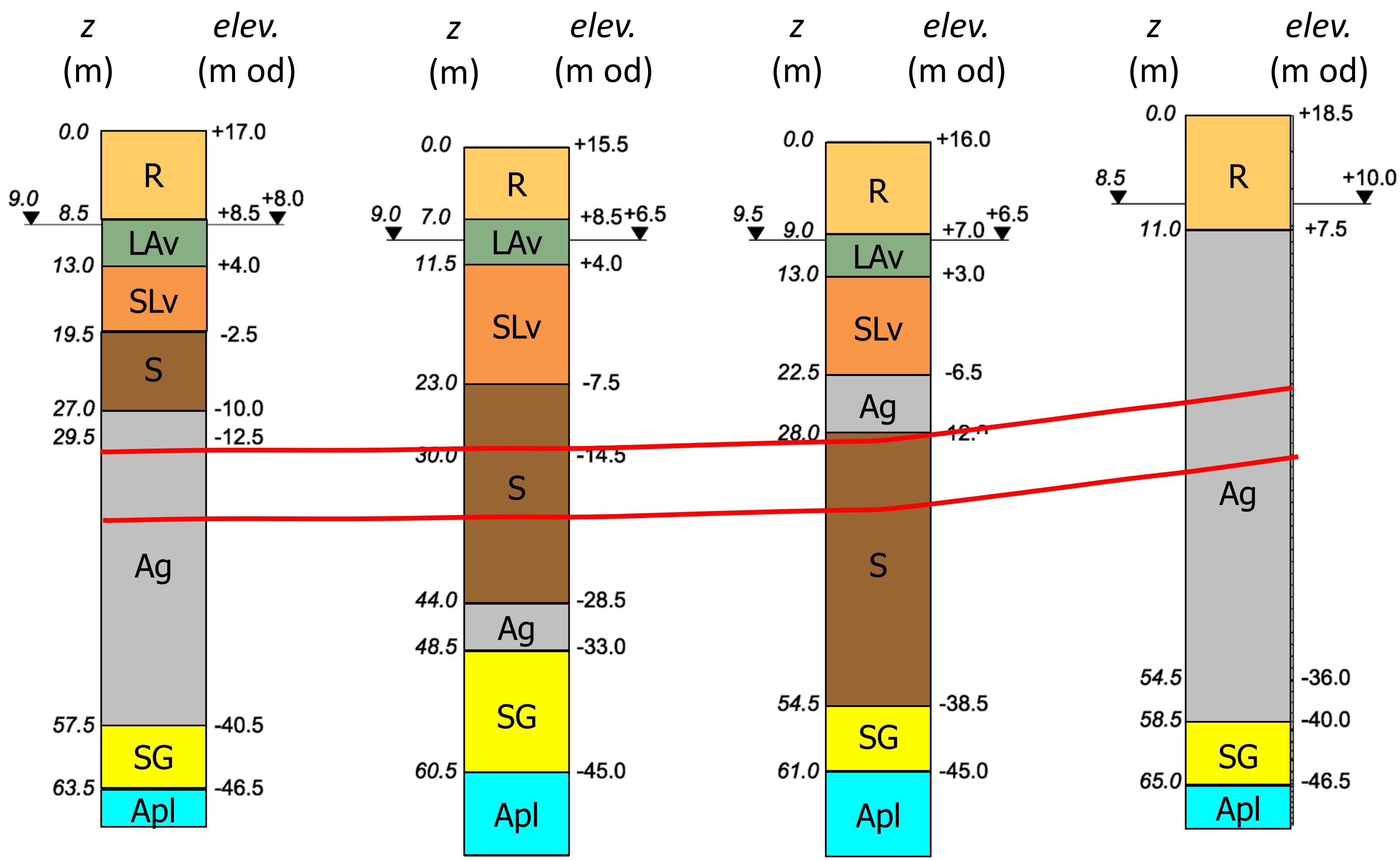


R	made ground		
LAv	clayey silts		
S1, S2	sand	*Alluvium*	Holocene
Ag	silty clay		
SLg, SLv	silty sand		
SG	sand and gravel		Pleistocene
Apl	stiff silty clay	*Monte Vaticano*	Pliocene

CONTRACT T2 - PLAN VIEW



CONTRACT T2 SOIL PROFILE / TUNNELS DEPTH

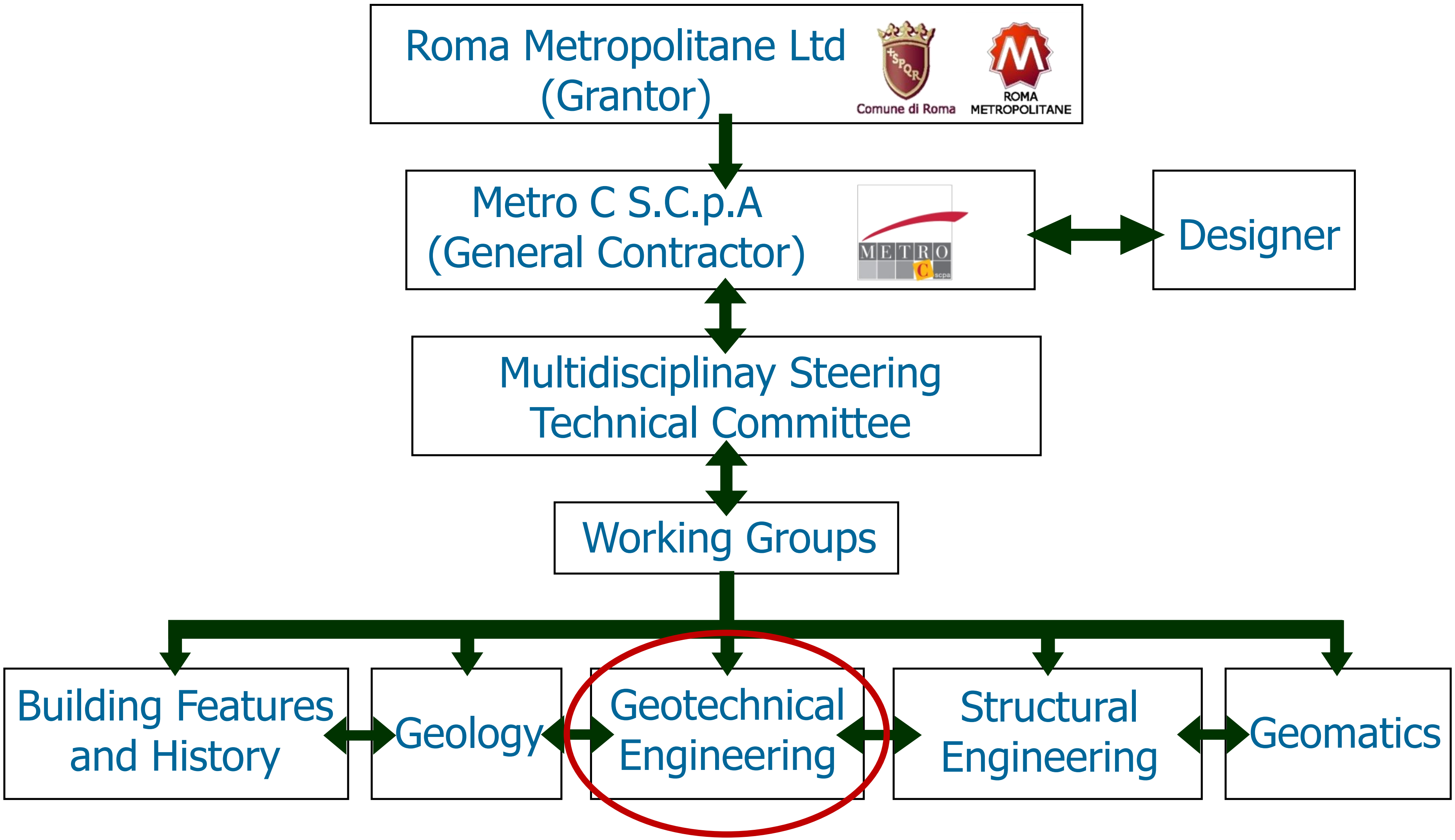


zone C (sects. 1–5)

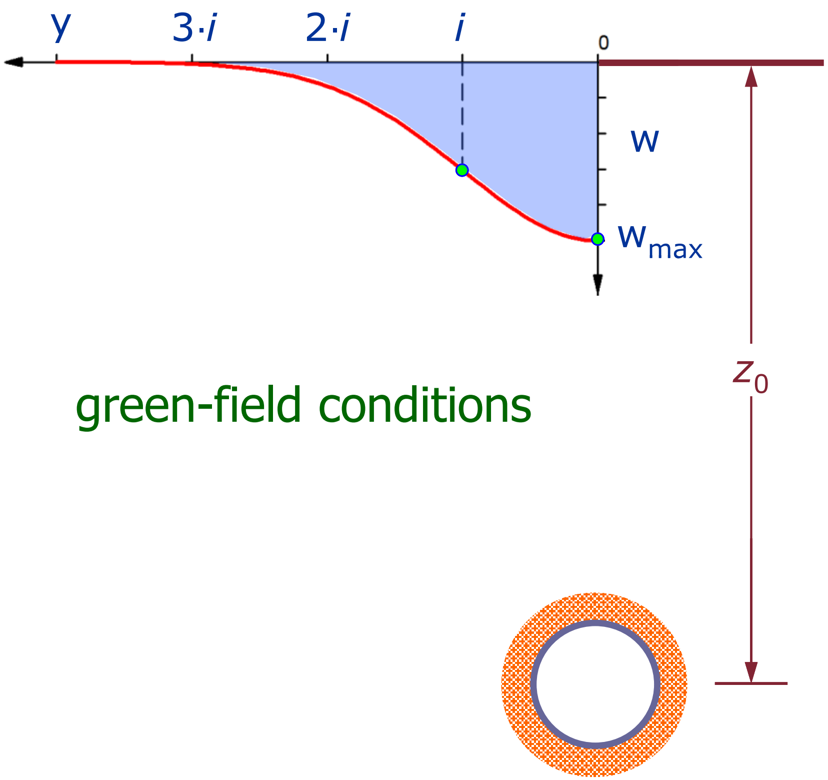
zone B (sects. 6–7)

zone B (sect. 8)

zone A (sects. 9–12)


Roma Metropolitane Ltd
(Grantor)
Comune di Roma
ROMA METROPOLITANE
Metro C S.C.p.A
(General Contractor)
METRO C scpa
Designer
Multidisciplinay Steering
Technical Committee
Working Groups
Building Features and History
Geology
Geotechnical Engineering
Structural Engineering
Geomatics

simplified analyses **LEVEL 1**

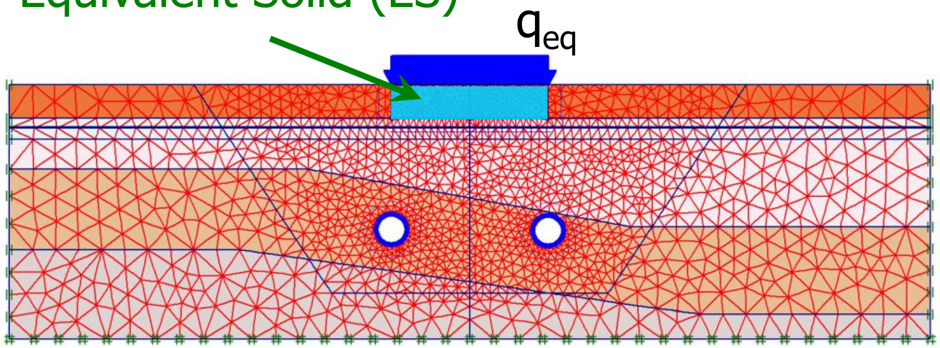


green-field conditions

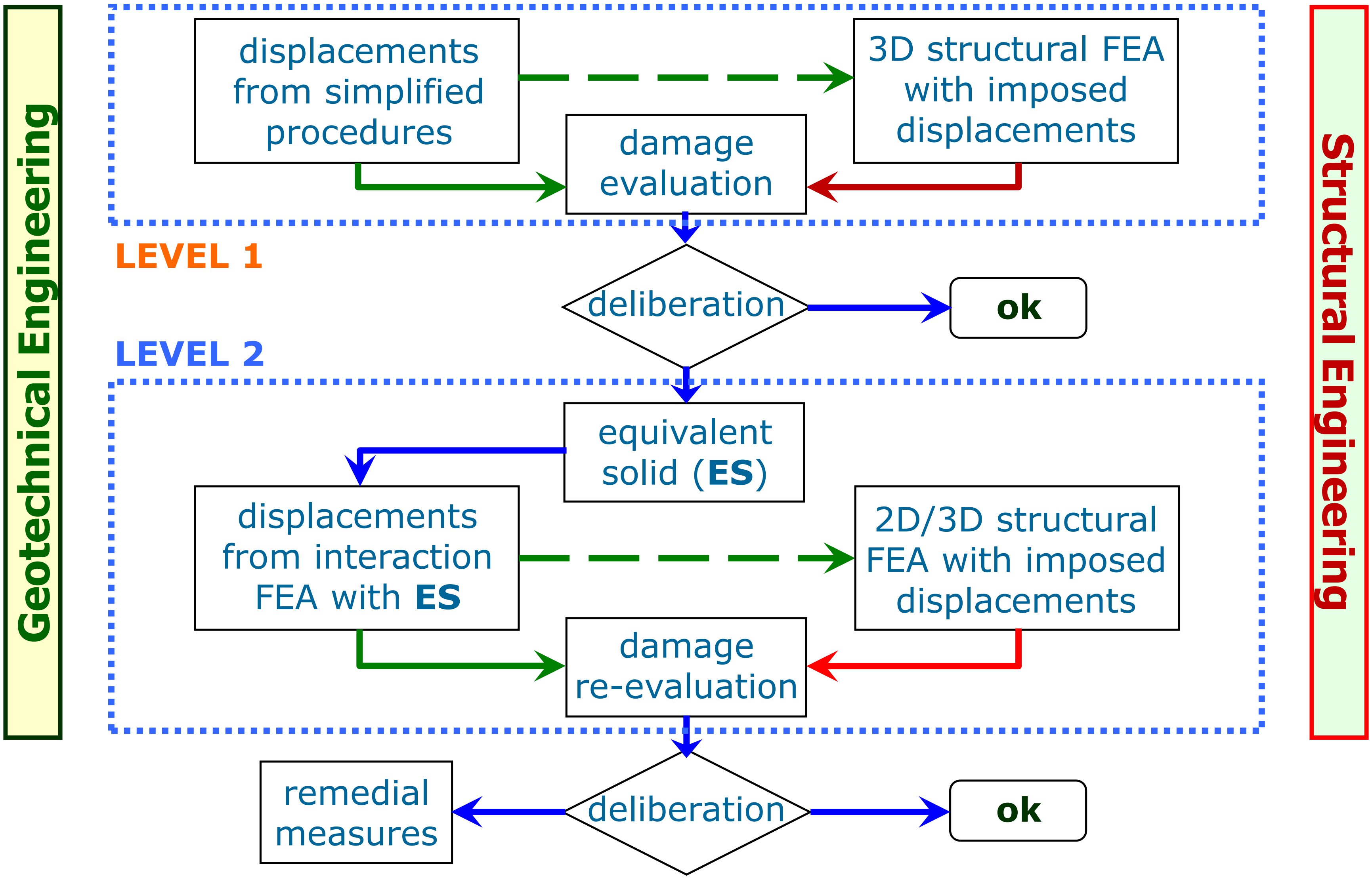
interaction analyses **LEVEL 2**

plane strain conditions (2D)
three-dimensional conditions (3D)

Equivalent Solid (ES)

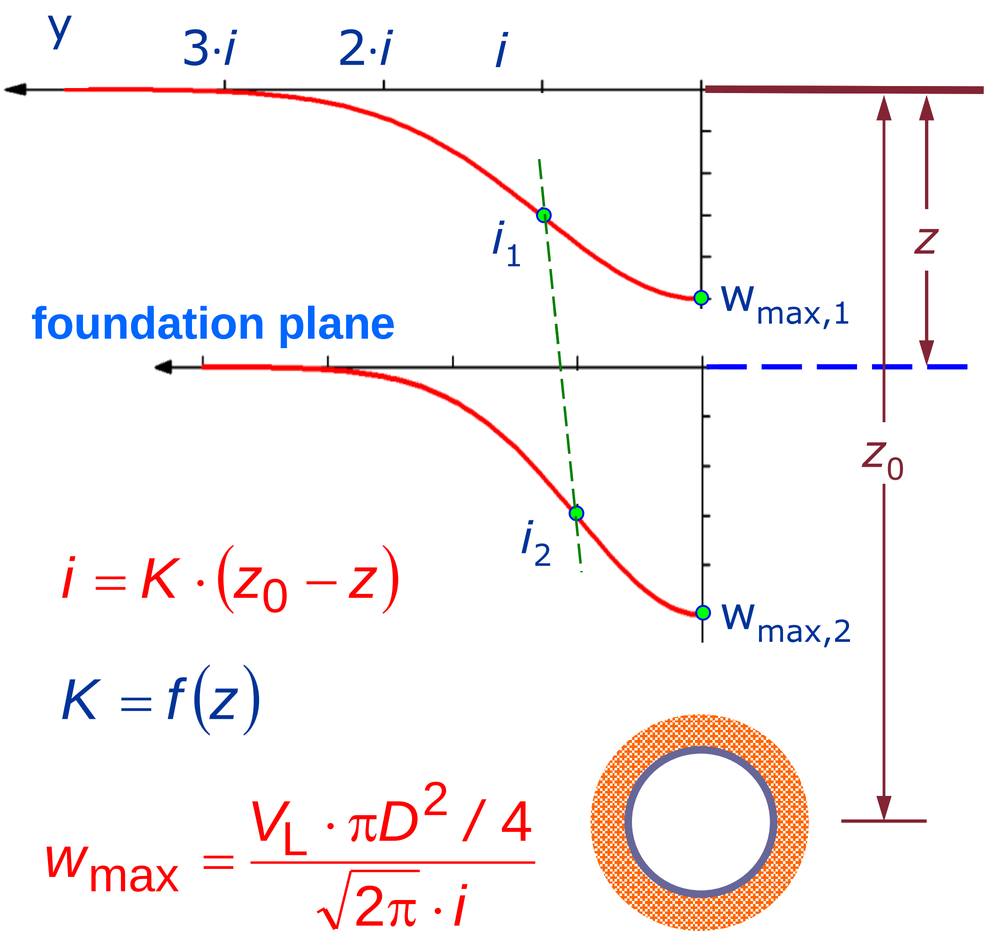


INTERACTION STUDIES ORGANISATION OF WORK



LEVEL 1 analyses

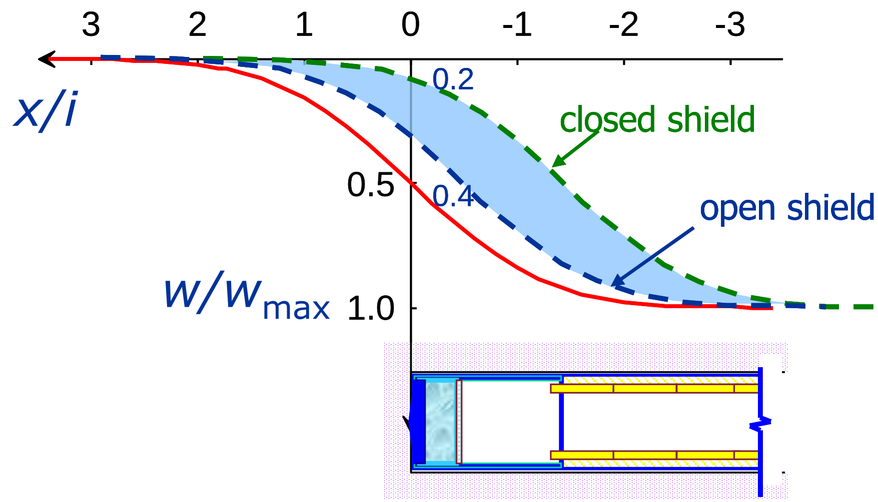
semi-empirical procedures



$$i = K \cdot (z_0 - z)$$

$$K = f(z)$$

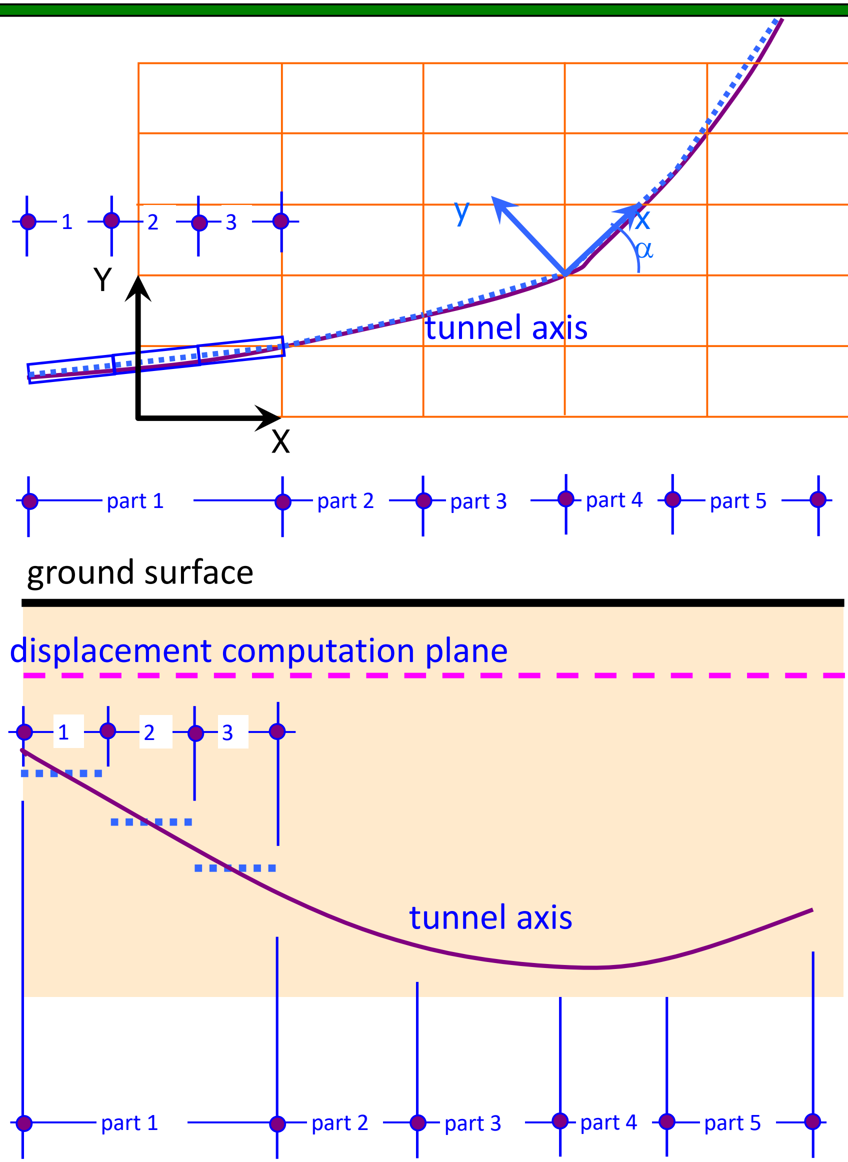
$$w_{max} = \frac{V_L \cdot \pi D^2 / 4}{\sqrt{2\pi} \cdot i}$$

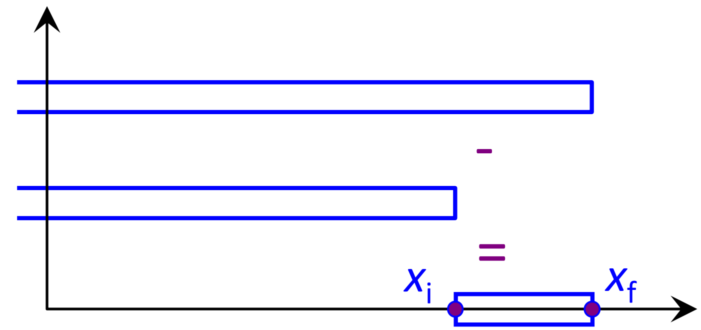


$V_L = 0.5 \div 1.0$ %

$K = 0.4 \div 0.5$

$D = 6.7$ m





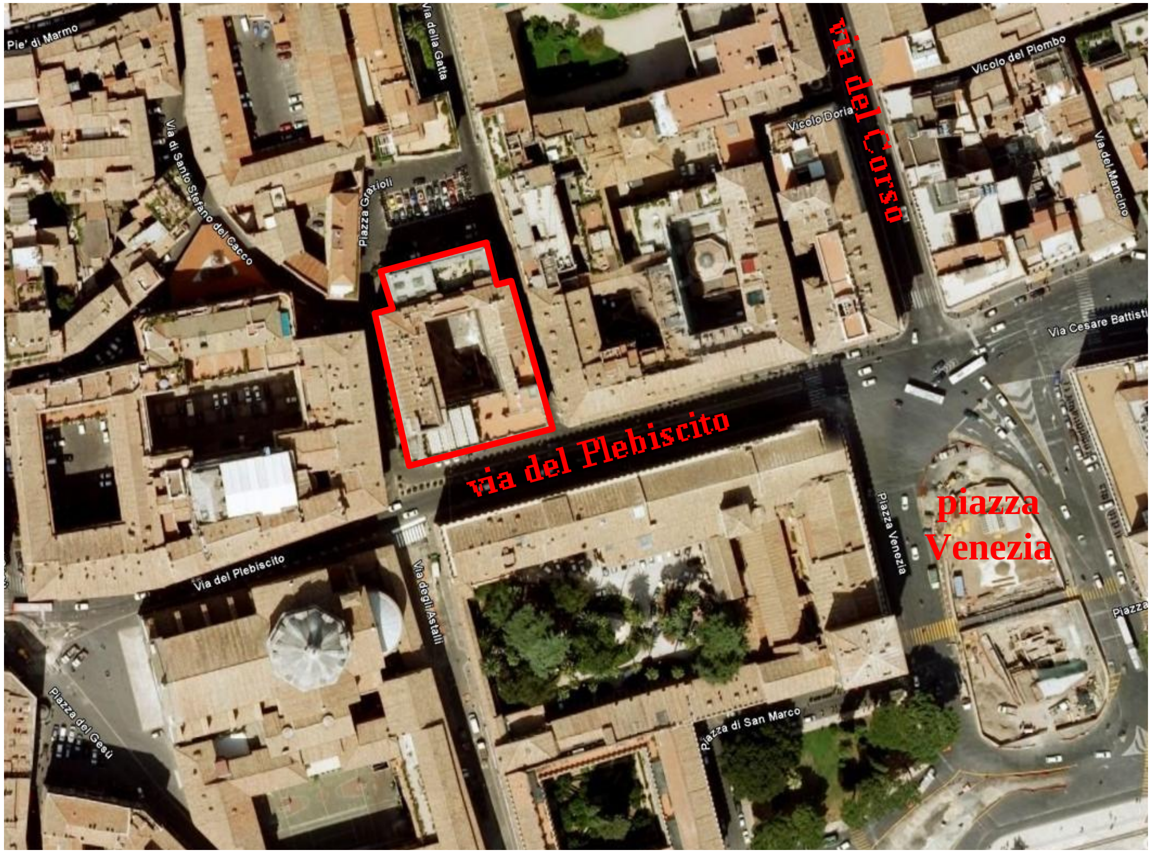
plan view

profile

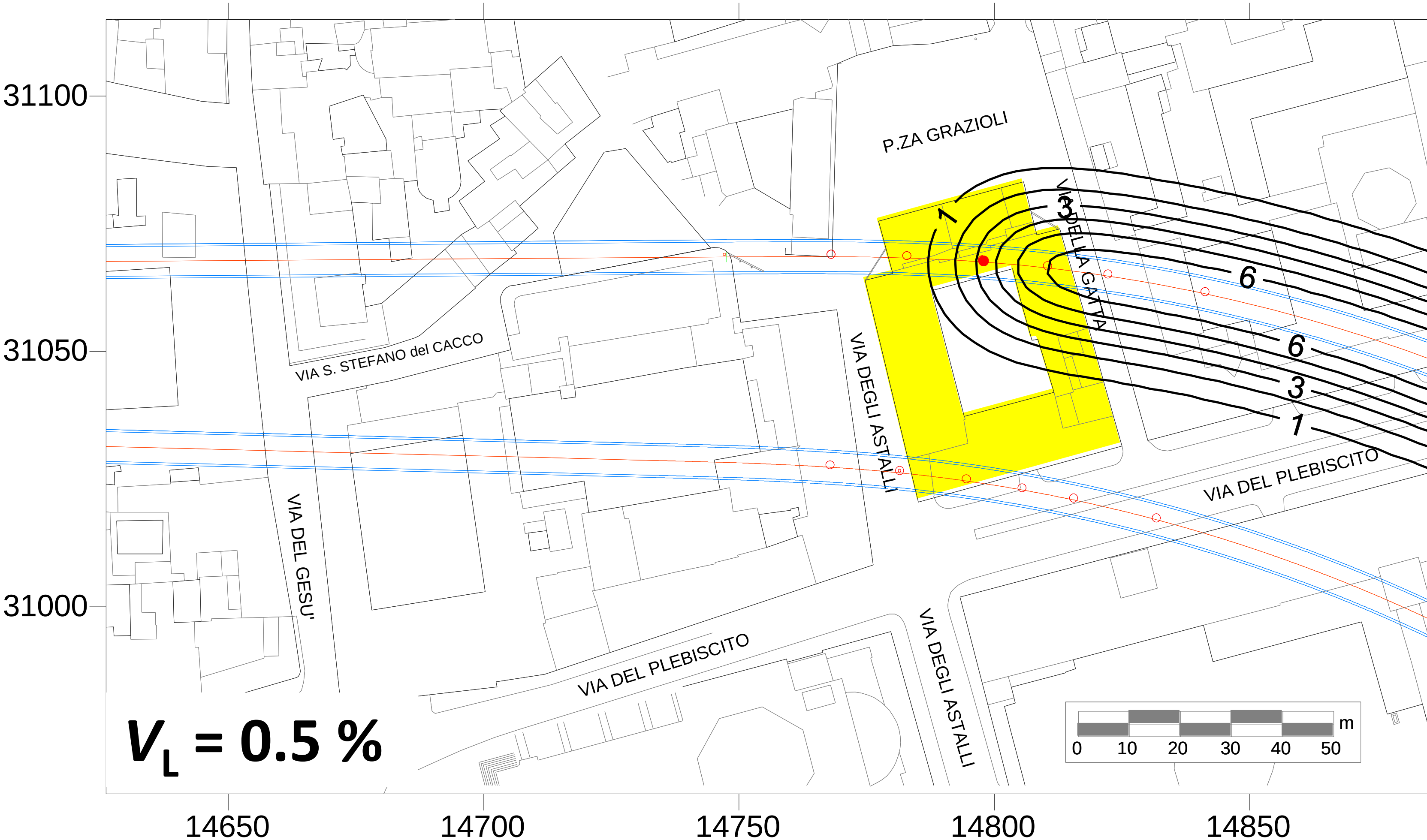
O'Reilly and New (1982)

- displacements of each segment as the difference of two tunnels of semi-infinite length
- total displacements computed by simple superposition
- horizontal strains along a given alignment obtained by rotating the strain tensor

LEVEL 1 PALAZZO GRAZIOLI

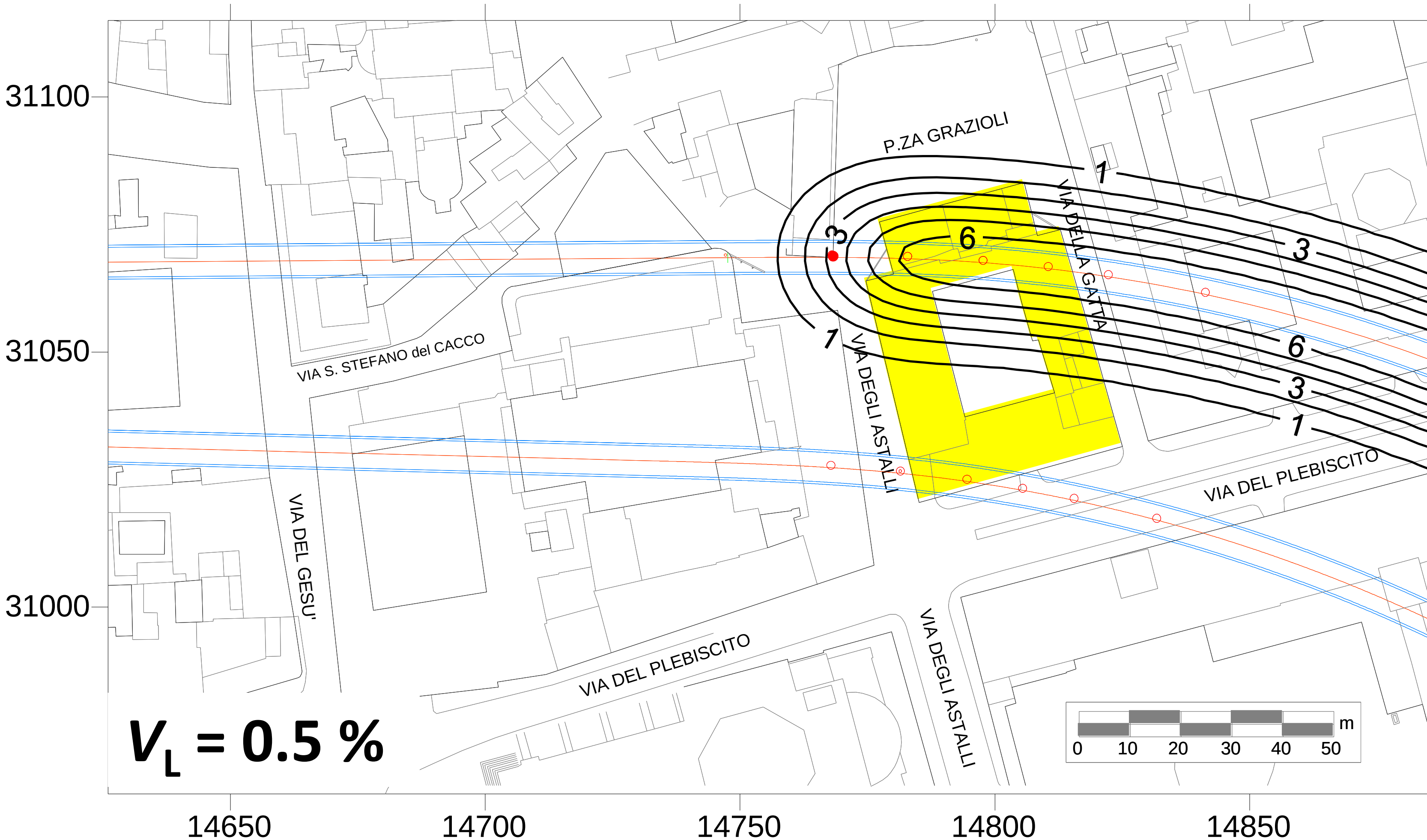


LEVEL 1 PALAZZO GRAZIOLI settlements at foundation level



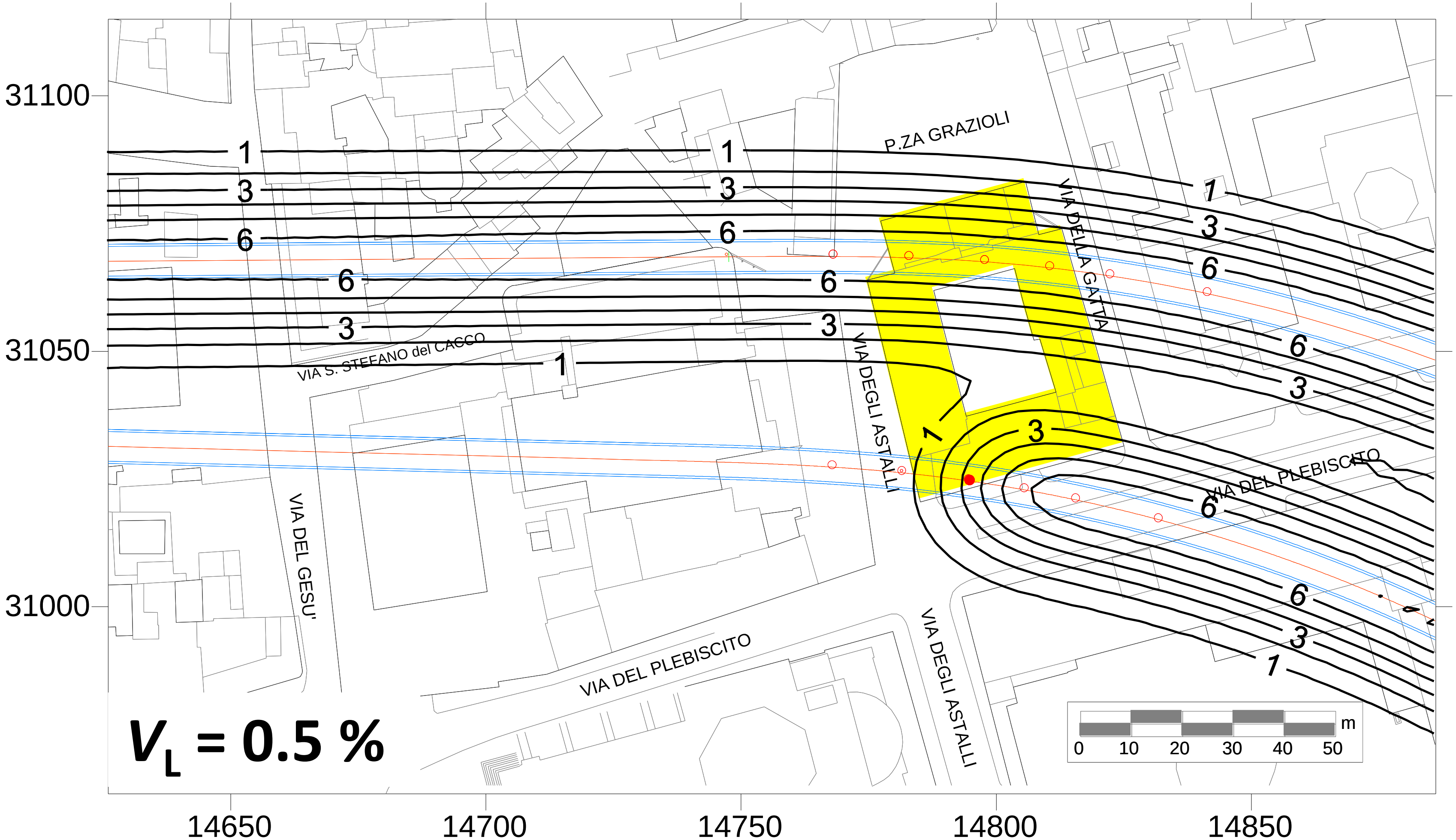
$V_L = 0.5\ \%$

LEVEL 1 PALAZZO GRAZIOLI settlements at foundation level



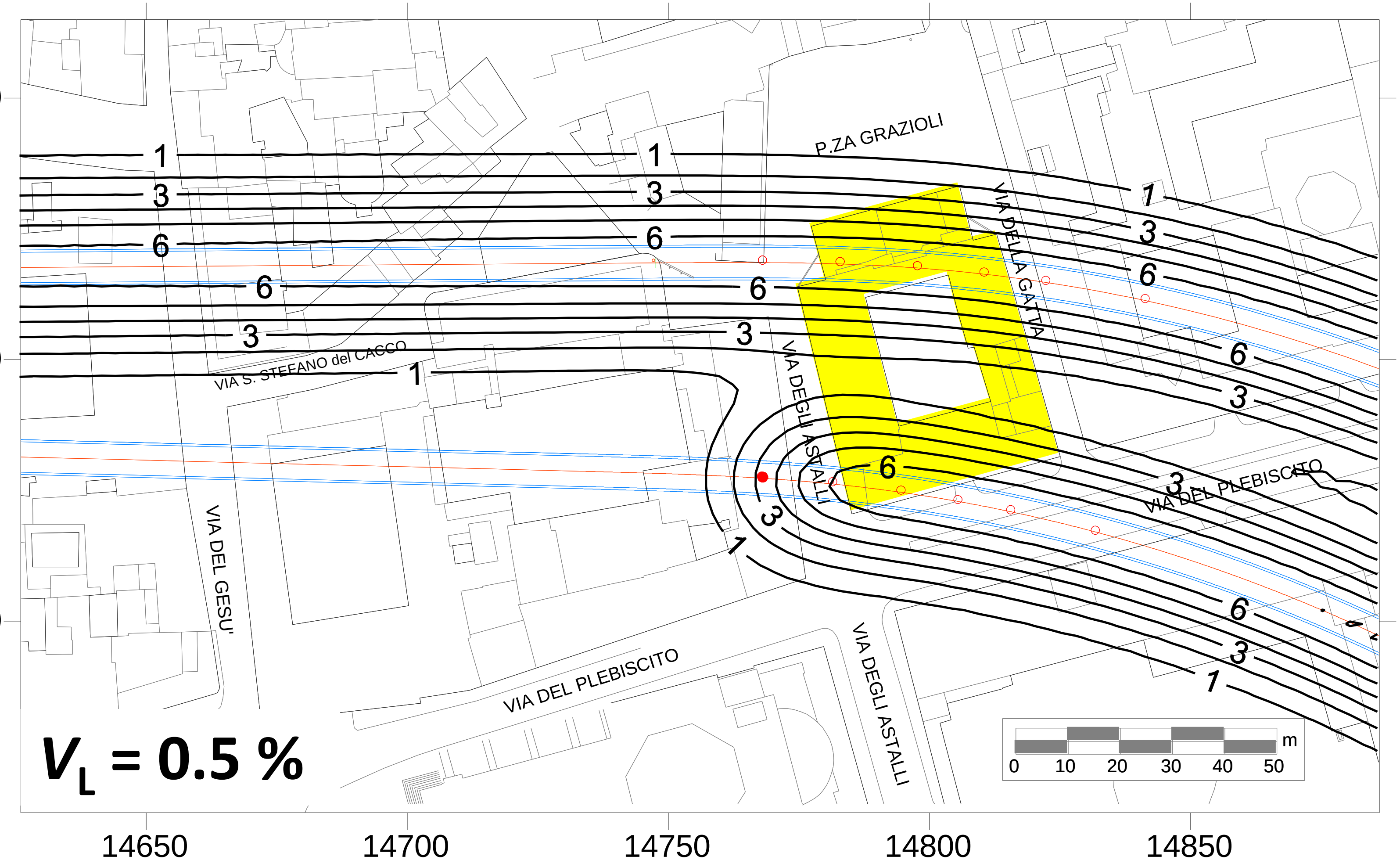
$V_L = 0.5\ \%$

LEVEL 1 PALAZZO GRAZIOLI settlements at foundation level



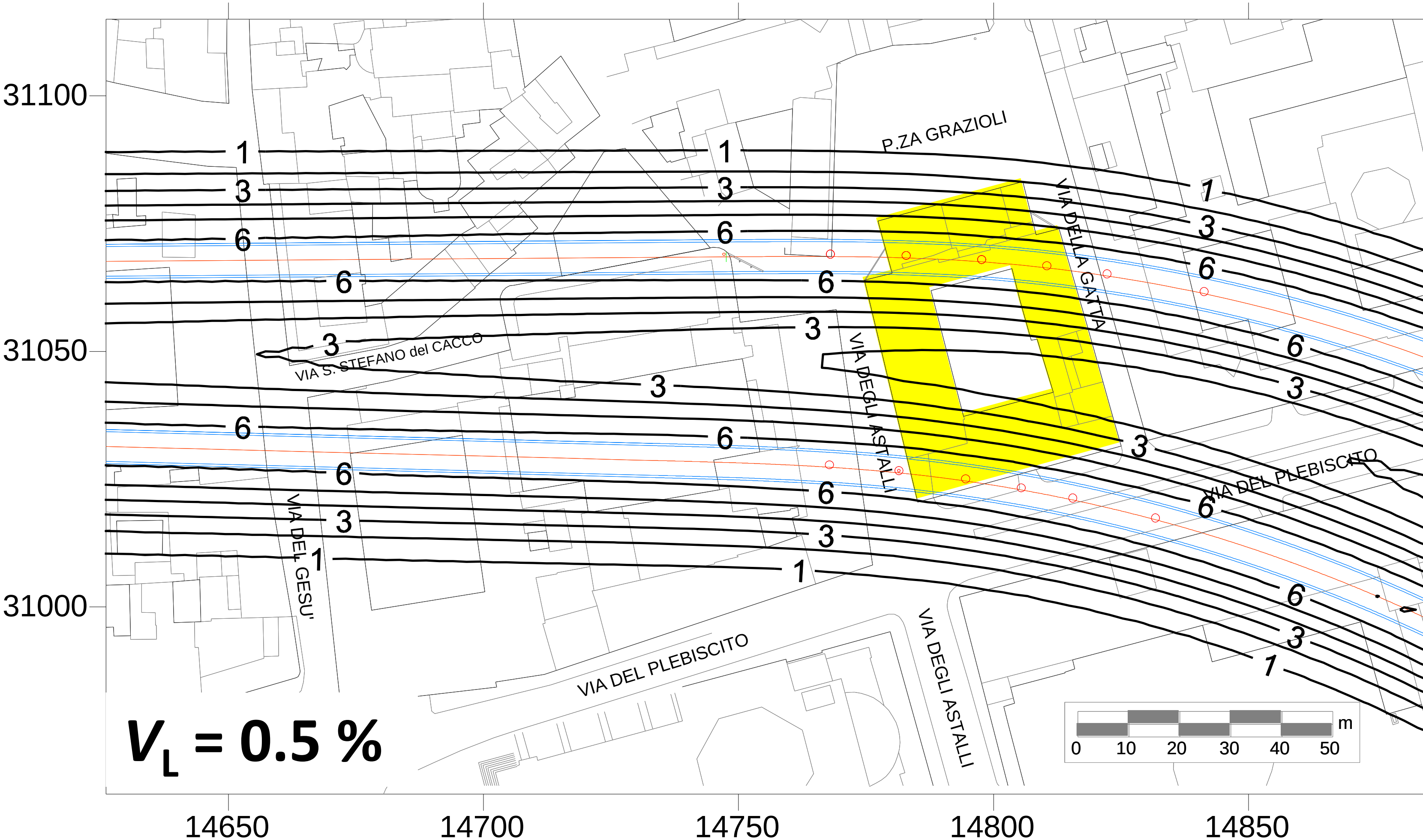
$V_L = 0.5\ \%$

LEVEL 1 PALAZZO GRAZIOLI settlements at foundation level



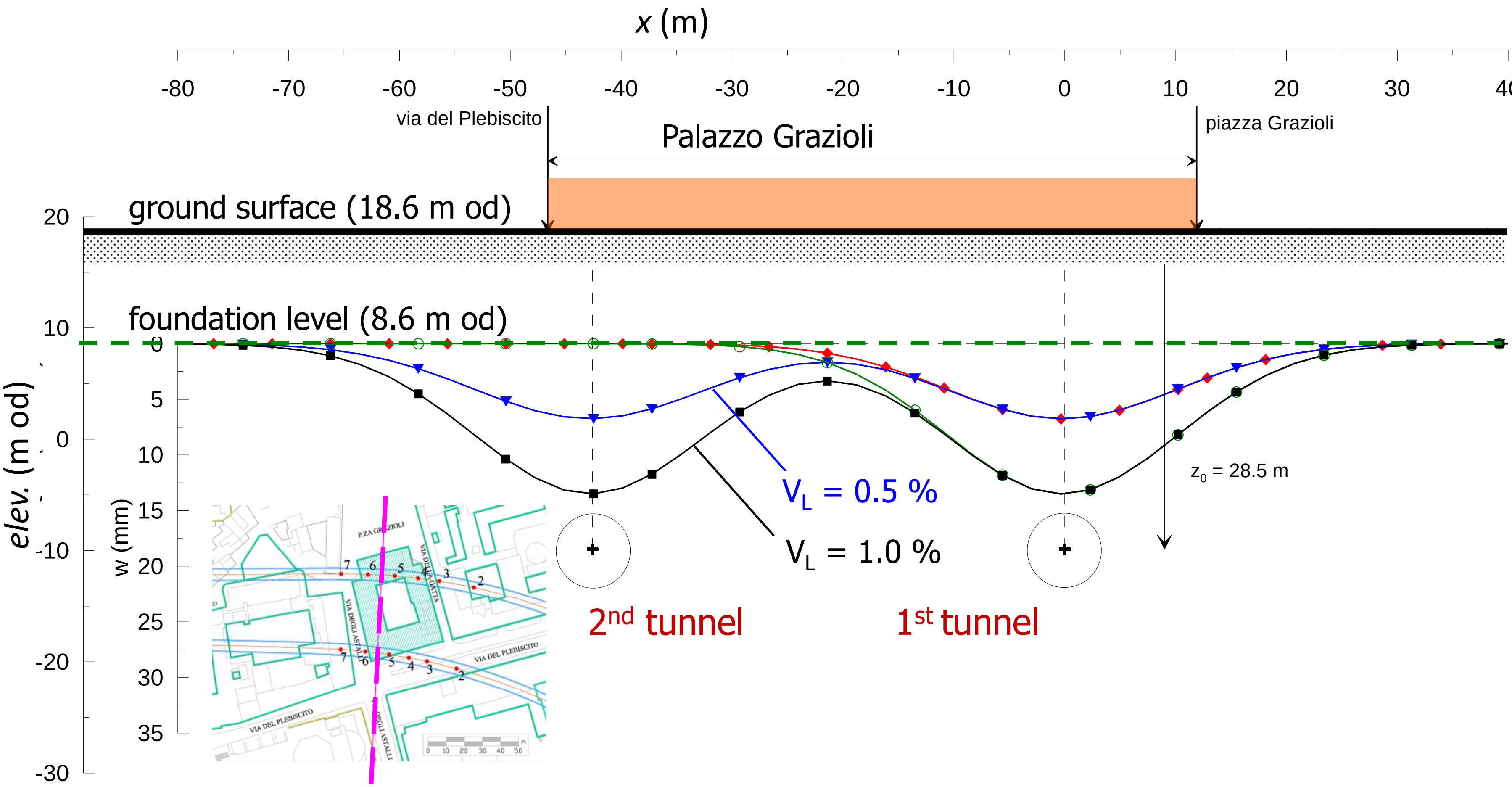
V_L = 0.5 %

LEVEL 1 PALAZZO GRAZIOLI settlements at foundation level



$V_L = 0.5\ \%$

LEVEL 1 PALAZZO GRAZIOLI settlements at foundation level



LEVEL 2 analyses

soil-structure interaction

soil

- actual soil profile and p.w.p. regime
- geotechnical characterisation and constitutive soil model

tunnels

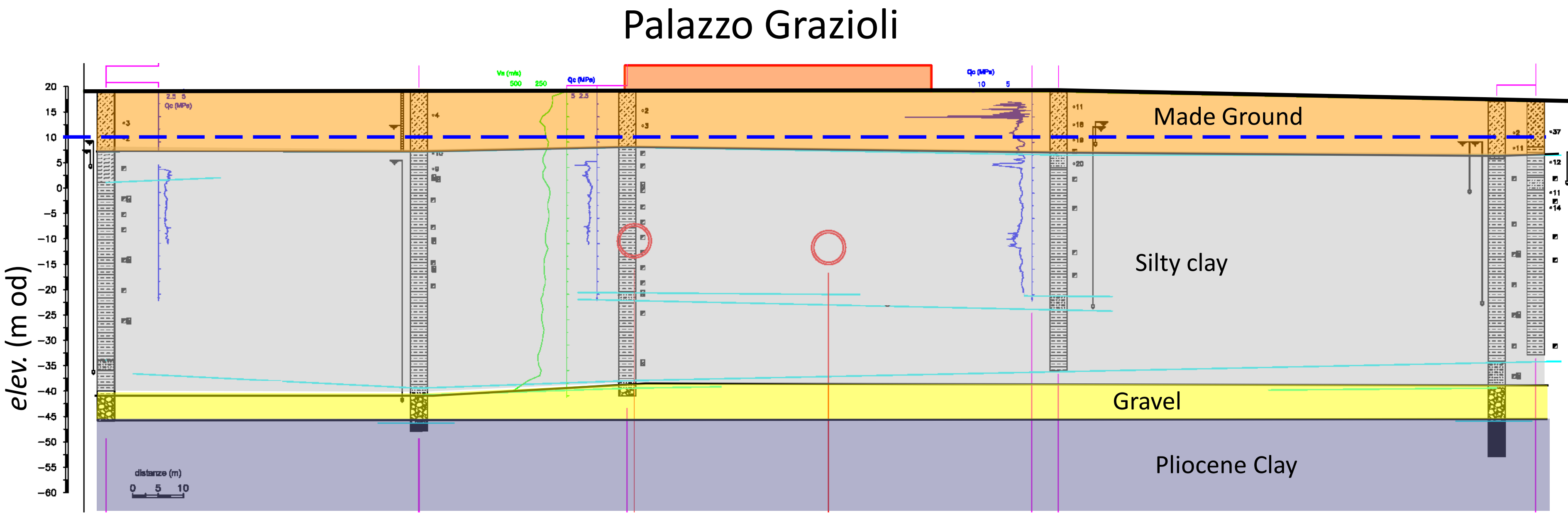
- 2D or 3D simulation of tunnel excavation
- long term effects

buildings

- stiffness
- weight
- embedded depth of foundations

} equivalent solid

LEVEL 2 PALAZZO GRAZIOLI soil profile and g.w. regime



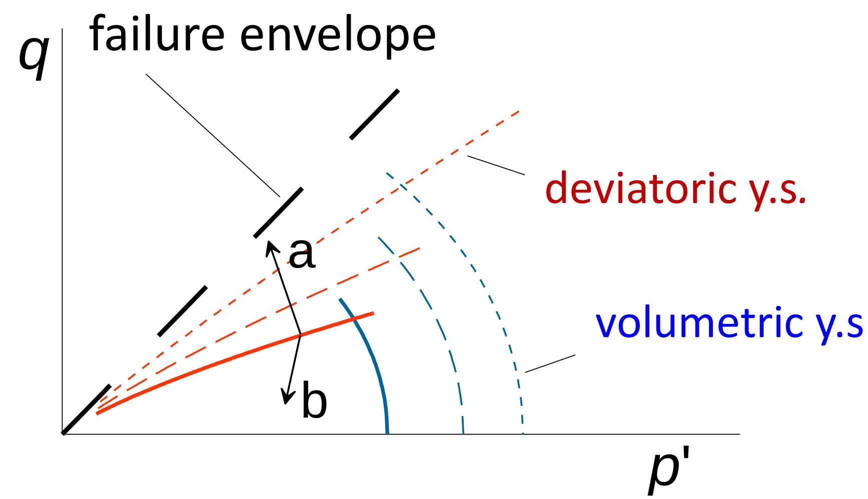
section 10

Hardening Soil (Shanz et al., 1999)
FE codes: Plaxis & Tochnog

- **(double) isotropic hardening**
- **Mohr Coulomb failure criterion**

- **deviatoric yield surface f_s**
  - function of γ^p
- **volumetric yield surface f_v**
  - function of ε_v^p

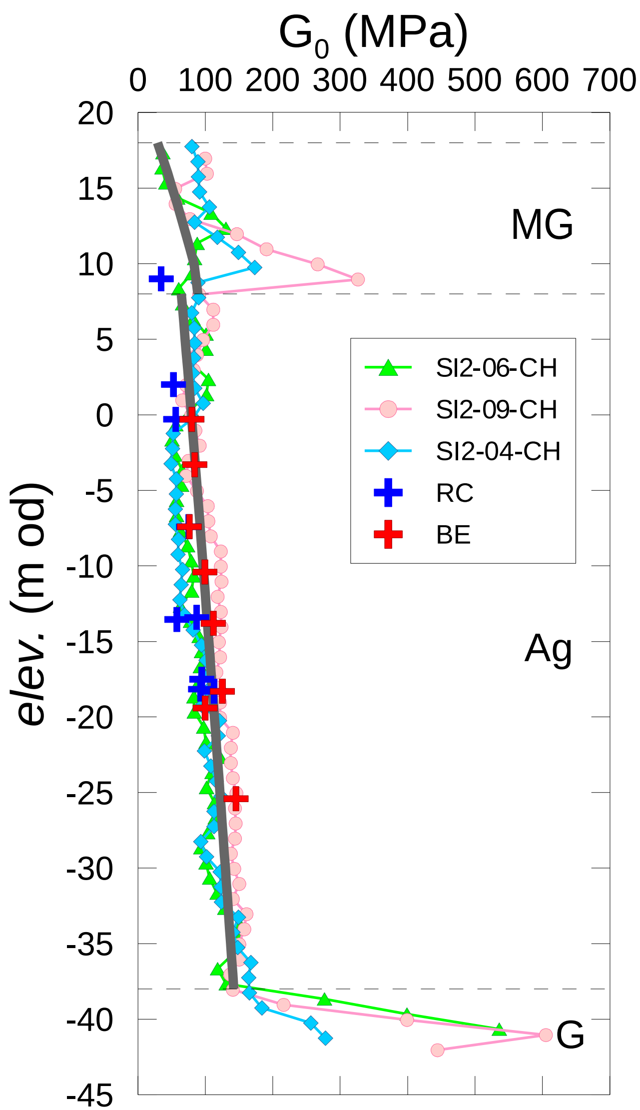
- **flow rule**
  - non associated for states on f_s
  - associated for states on f_v



- **elastic stiffness**
  - function of effective stress state

$$E' = E^{ref}\left(\frac{c'\cdot\cot\varphi' + \sigma_3'}{c'\cdot\cot\varphi' + p^{ref}}\right)^m$$

✓ non linear behaviour from small strain levels



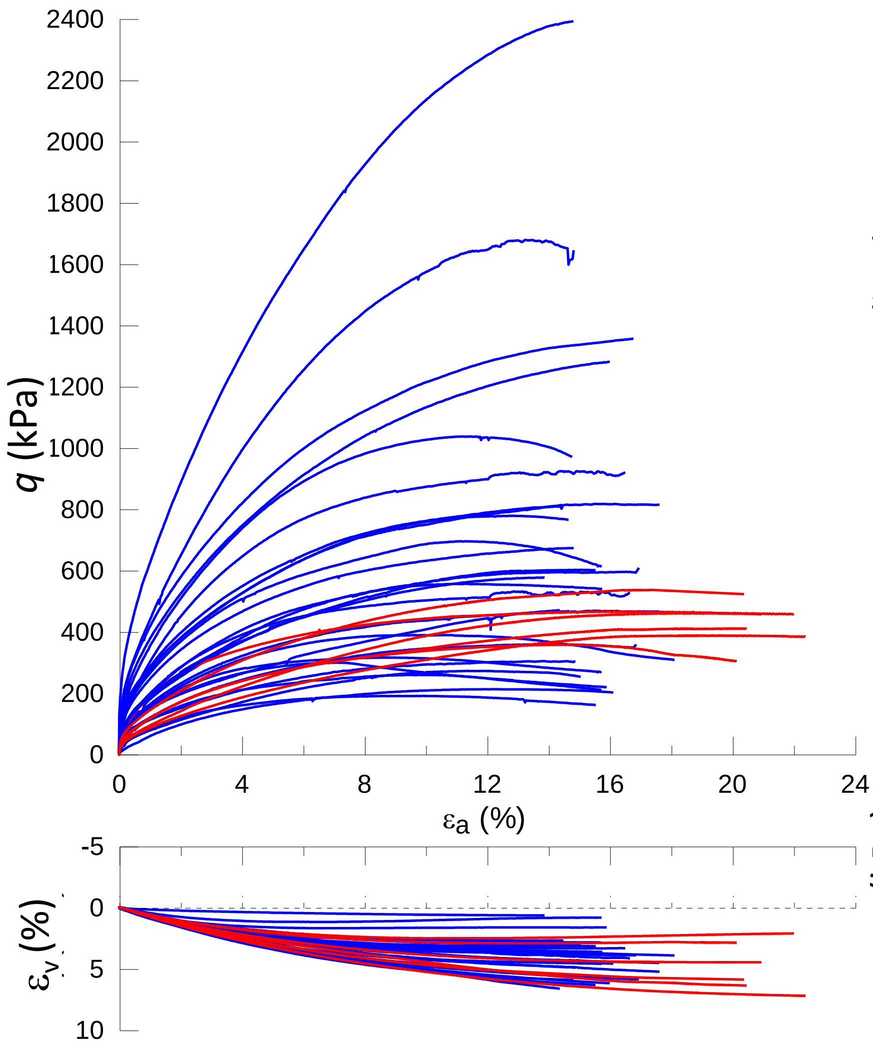
calibration of stiffness profile

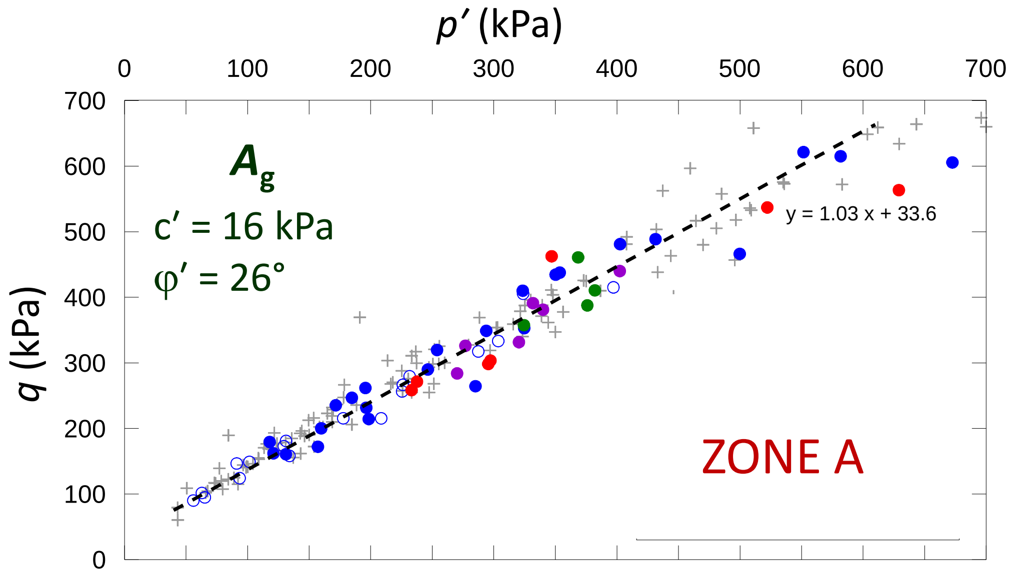
$$G = G^{ref}\left(\frac{c'\cdot\cot\varphi' + \sigma_3'}{c'\cdot\cot\varphi' + p^{ref}}\right)^m$$

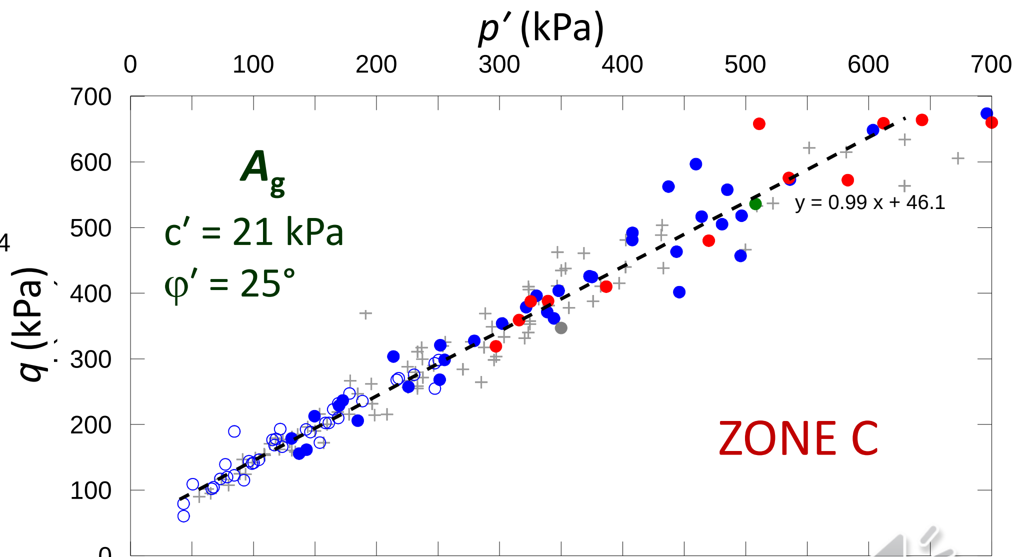
ZONE A

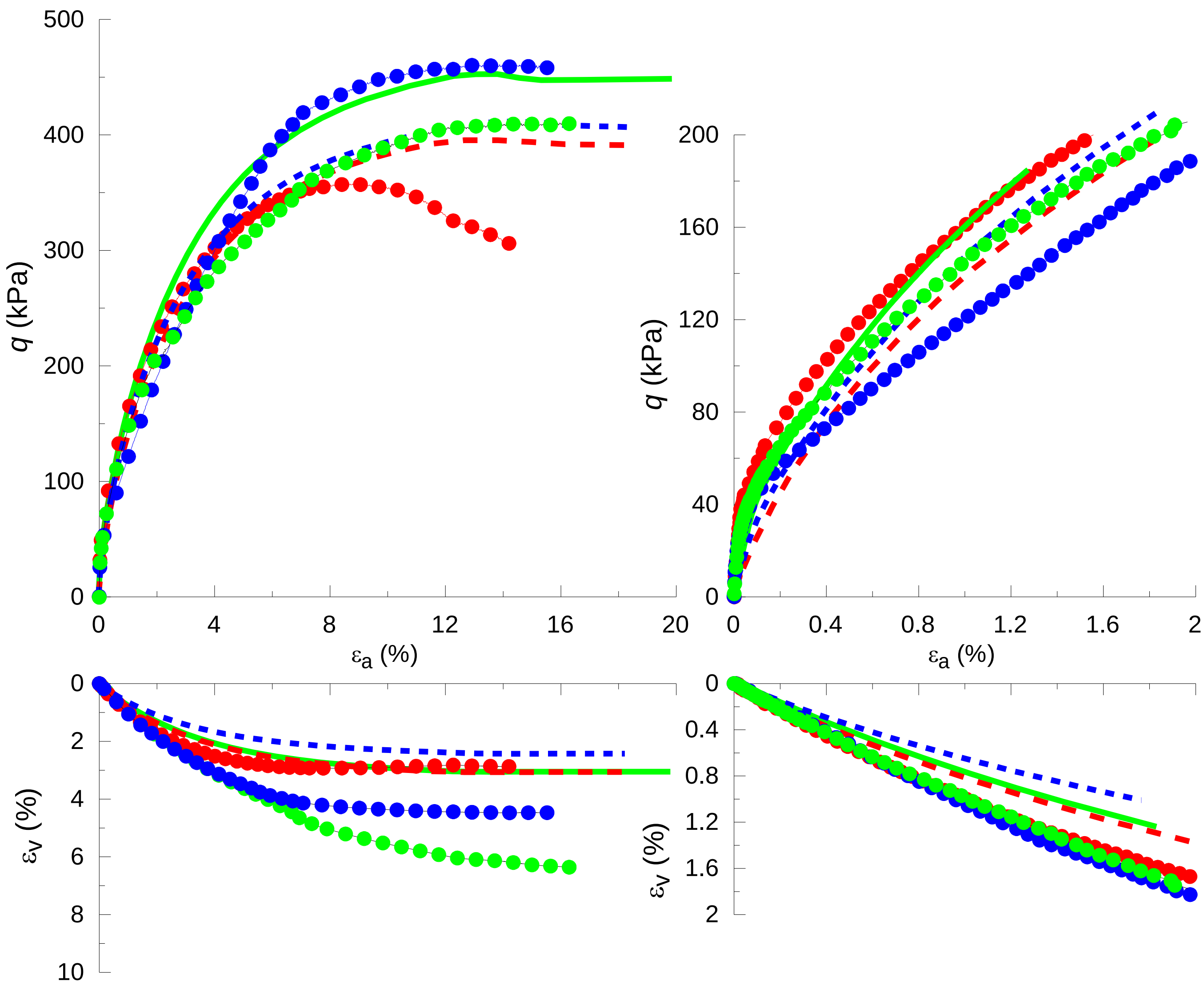
γ kN/m³	c' kPa	φ' °	*OCR*	K_0^{nc}	K_0^{oc}
18.4	20	25	1.35	0.577	0.655

E'^{ref}_{ur} (MPa)	*m*	ν
150	0.8	0.2


2400
2200
2000
1800
1600
1400
1200
1000
800
600
400
200
0
q (kPa)
0
4
8
12
16
20
24
εa (%)
-5
0
5
10
εv (%)


p′ (kPa)
0
100
200
300
400
500
600
700
q (kPa)
Ag
c′ = 16 kPa
φ′ = 26°
y = 1.03 x + 33.6
ZONE A


p′ (kPa)
0
100
200
300
400
500
600
700
q (kPa)
Ag
c′ = 21 kPa
φ′ = 25°
y = 0.99 x + 46.1
ZONE C



ZONE A

E'^{ref}_{50} MPa	E'^{ref}_{oed} MPa
7.5	**11.3**

soil

- actual soil profile and p.w.p. regime
- geotechnical characterisation and constitutive soil model

tunnels

- 2D or 3D simulation of tunnel excavation
- long term effects

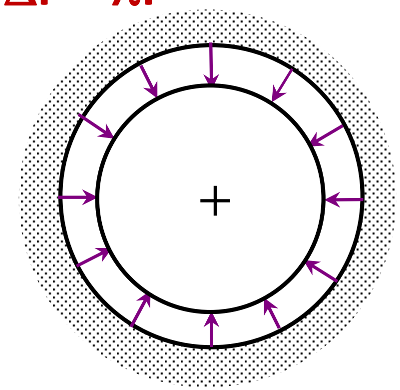
buildings

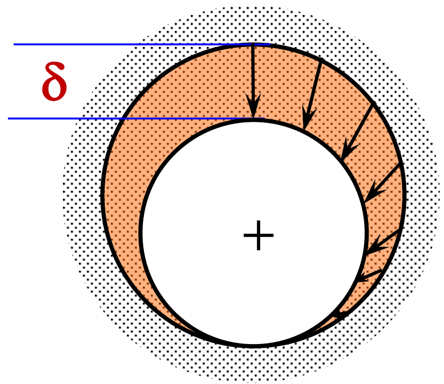
- stiffness
- weight
- embedded depth of foundations

} equivalent solid

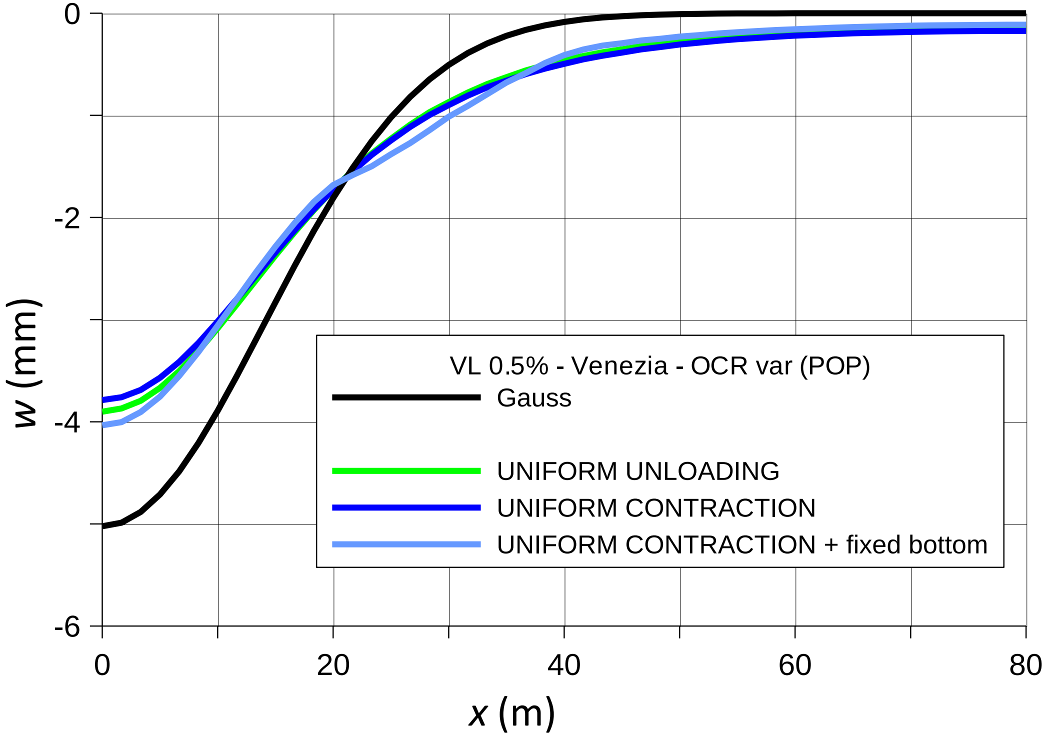
partial removal of nodal forces

$\Delta F = \lambda F$

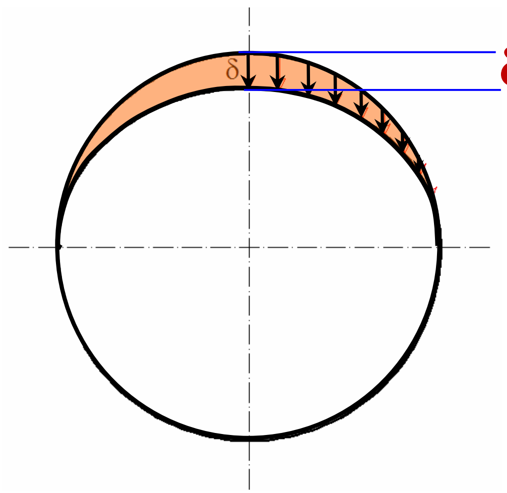




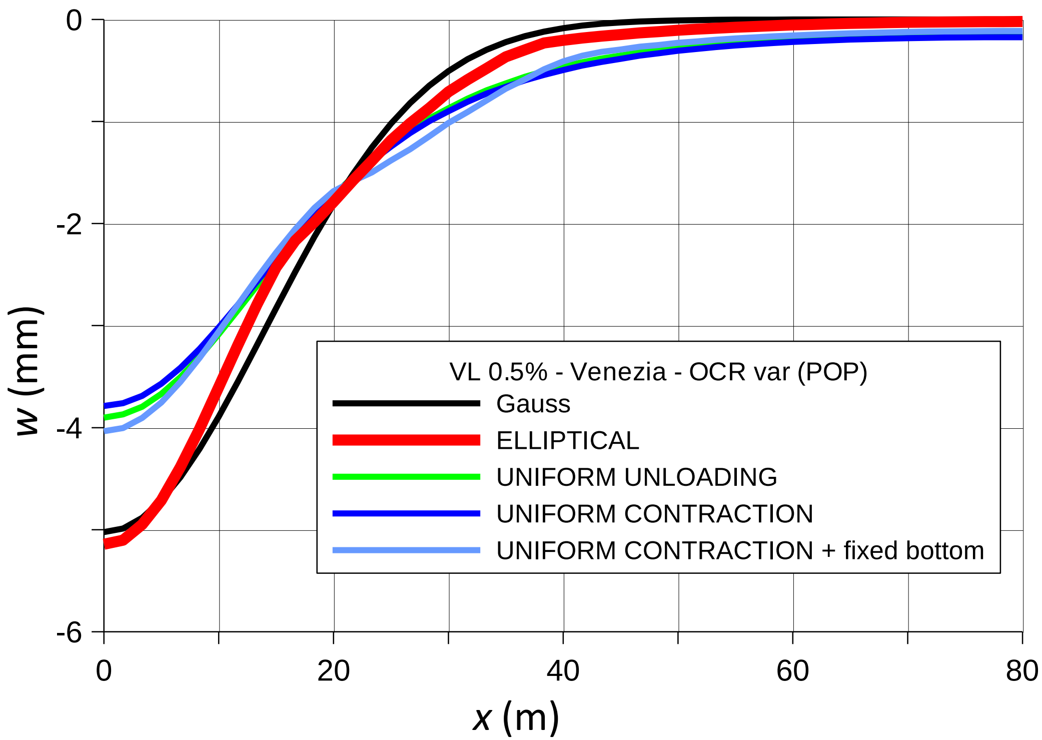
radial ground movement
(fixed invert)



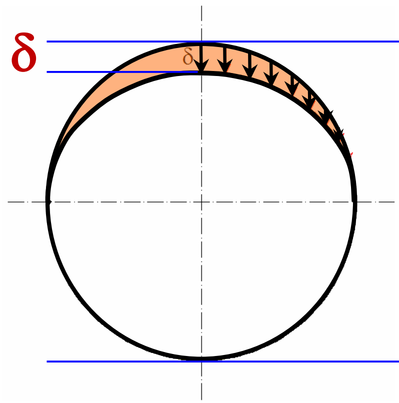
vertical elliptical ground movement



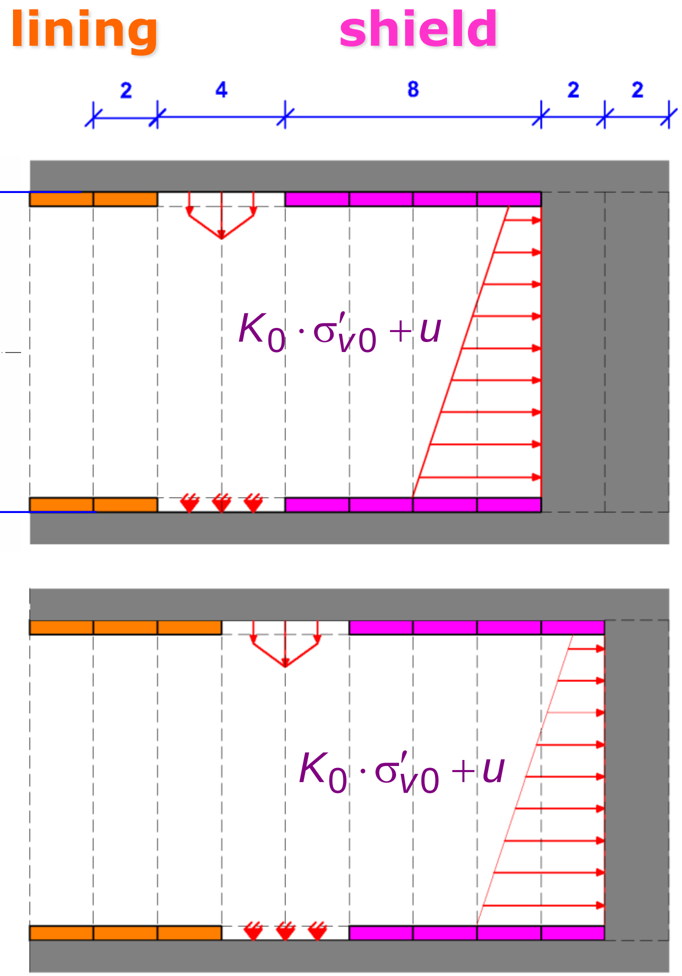
better prediction of w_{max} and width of settlement trough



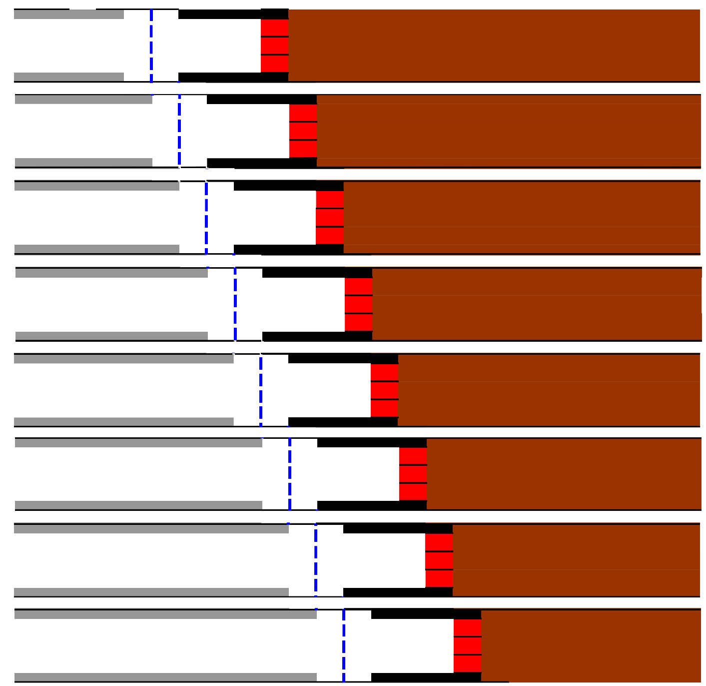
Dicii



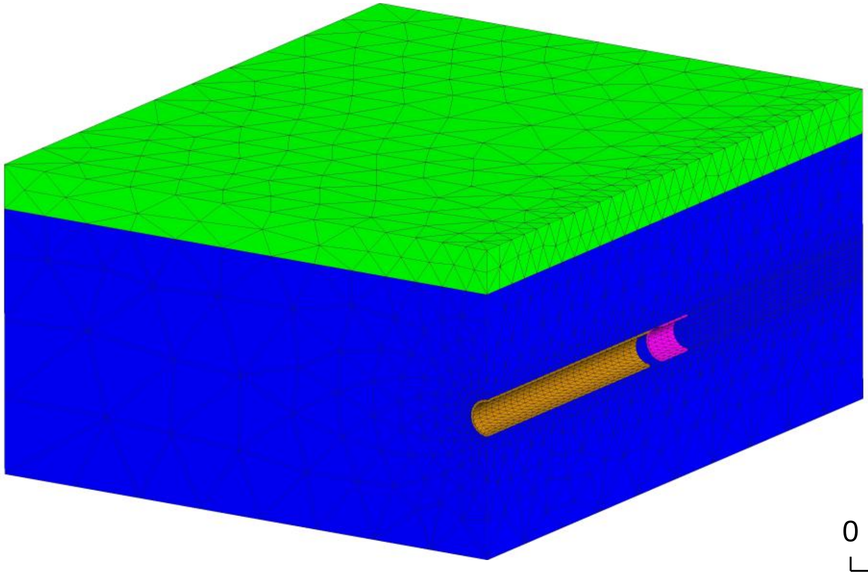
V_L = 0.5 % at ground surface



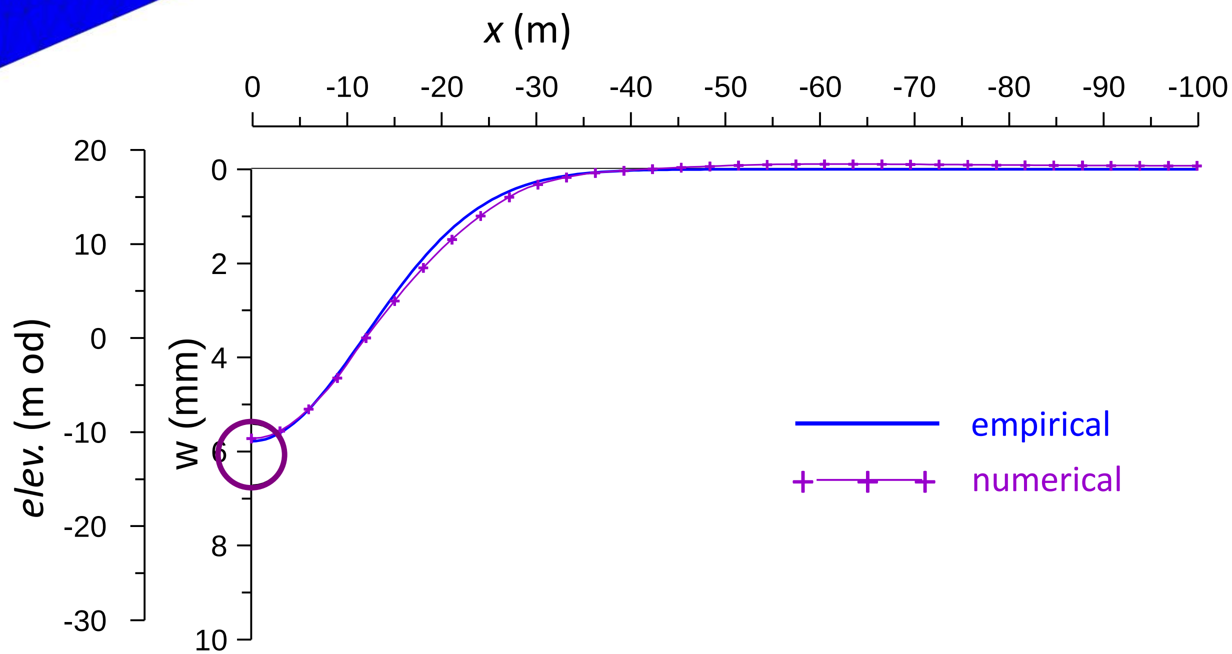
1. imposed displacement field
2. lining activation and release of displacements

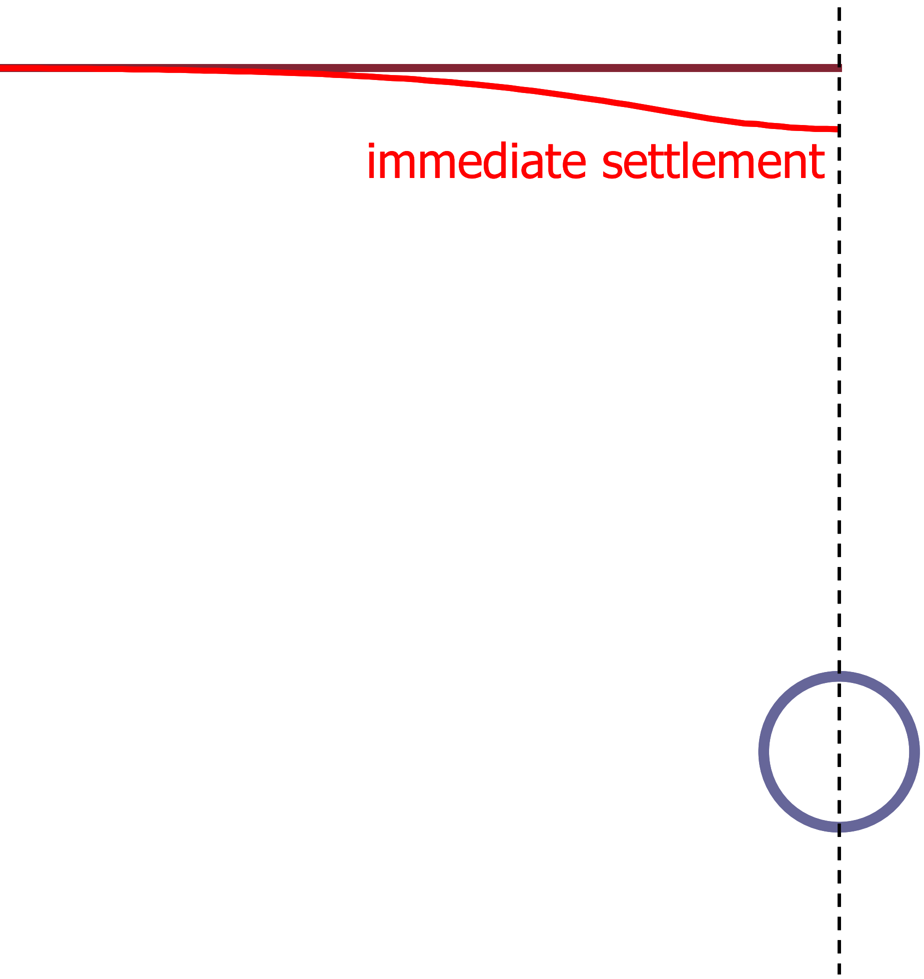


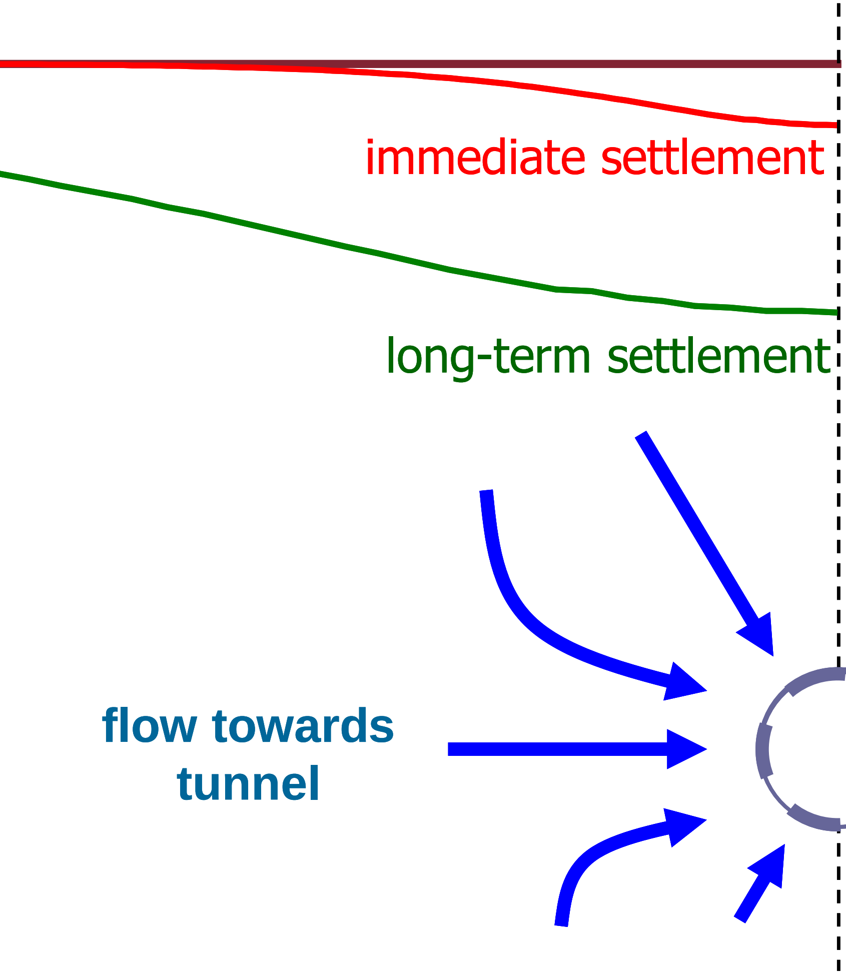
Dicii



1. V_L = 0.5 % at ground surface
2. comparison with Gaussian
3. same δ in interaction analyses




immediate settlement

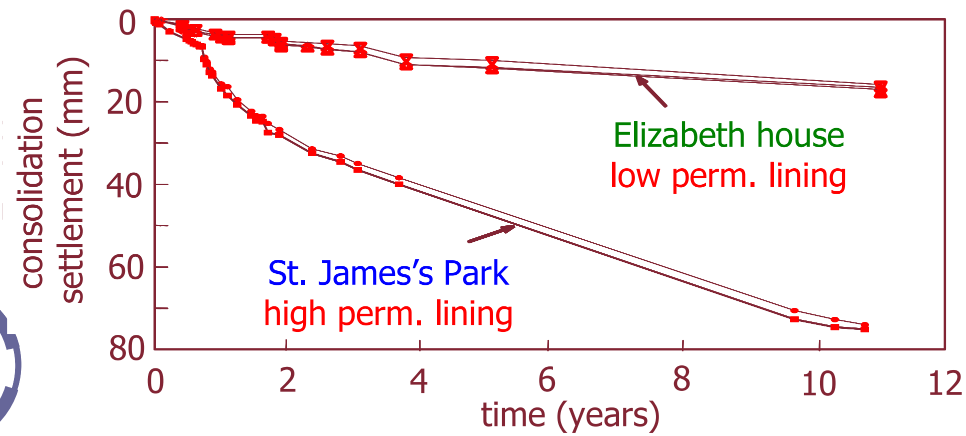


initial pwp distribution

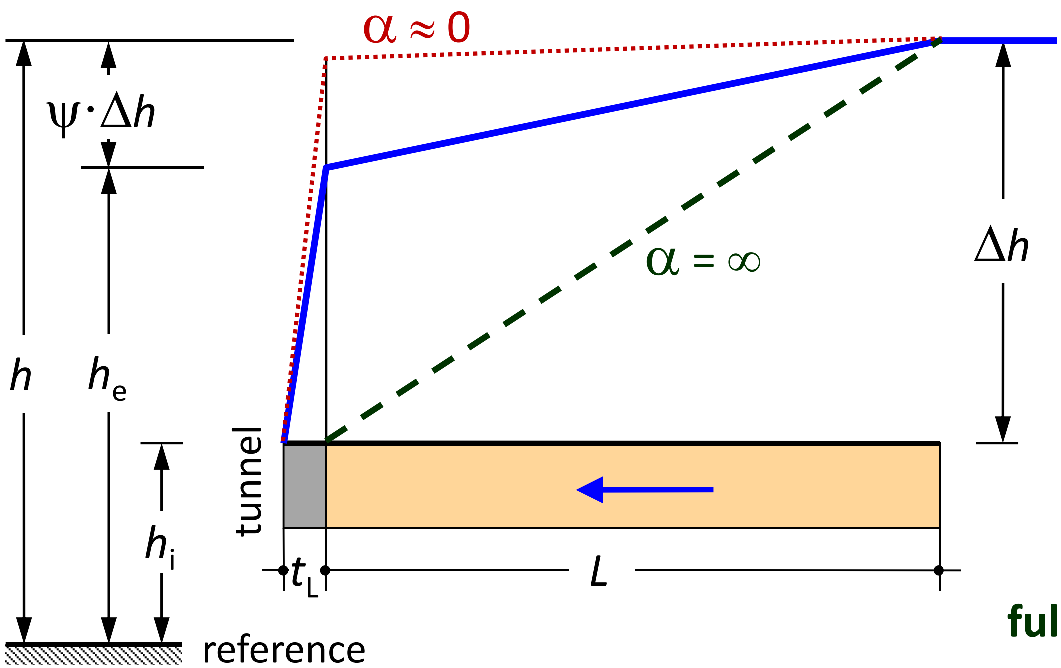
excess pwp generated by tunnelling

compressibility of the clay

lining permeability /soil permeability

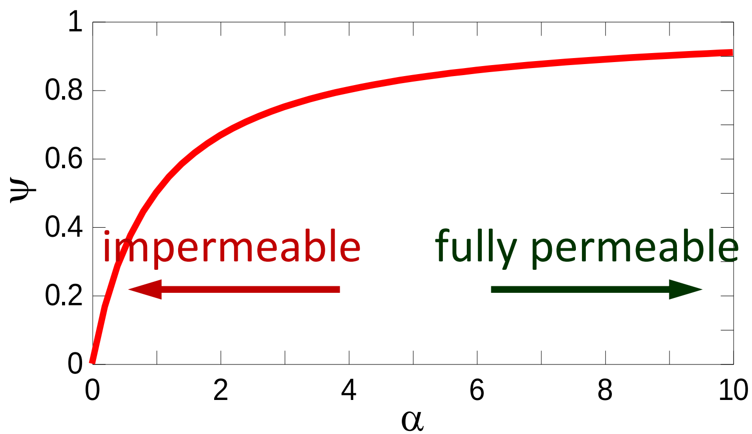


Mair (2008)



$$h_e = h - \frac{\alpha}{1+\alpha} \cdot \Delta h = h - \psi \cdot \Delta h$$

$$\alpha = \frac{k_{lining}}{k_{soil}} \cdot \frac{L}{t_L}$$



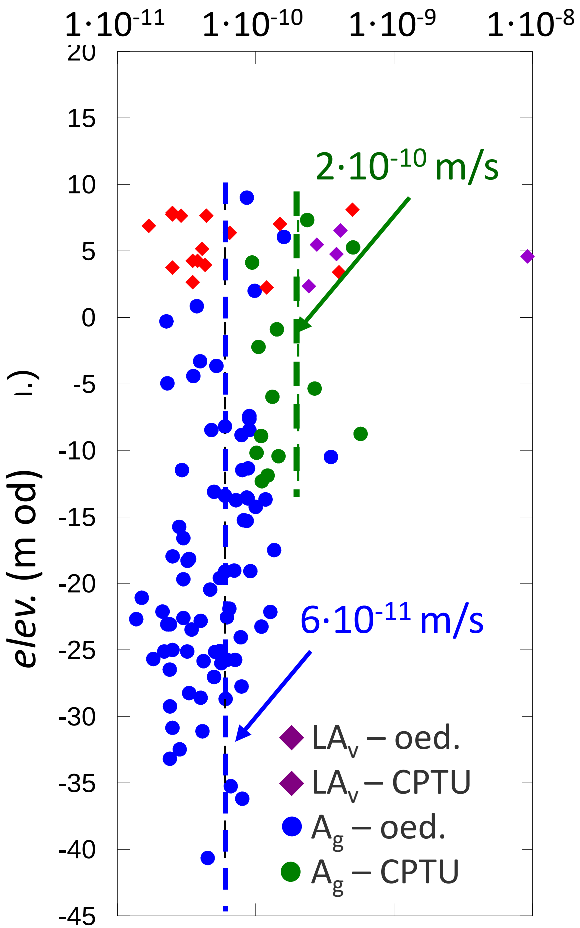
fully permeable lining

$\alpha = \infty$, $\psi = 1$ } $h_e = h_i$ ➡ max $\Delta\sigma'$

impermeable lining

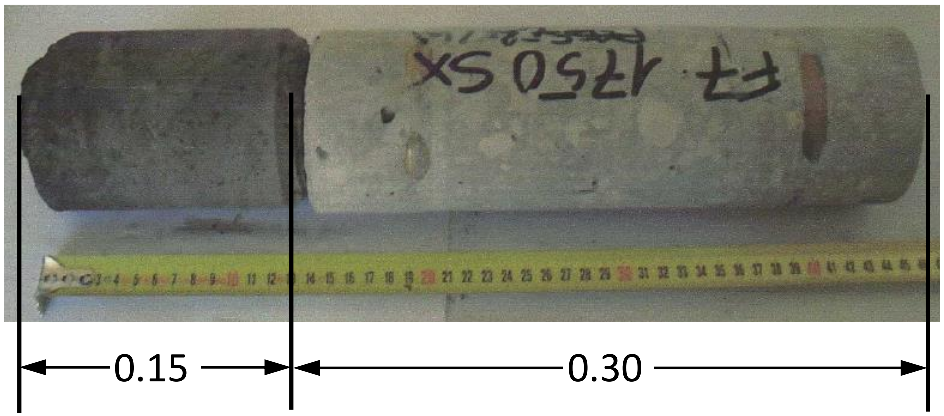
$\alpha = 0$, $\psi = 0$ } $h_e = h$ ➡ $\Delta\sigma' = 0$

soil



$$\overline{K}_{CPTU} \cong 3 \cdot \overline{K}_{oed}$$

tunnel lining

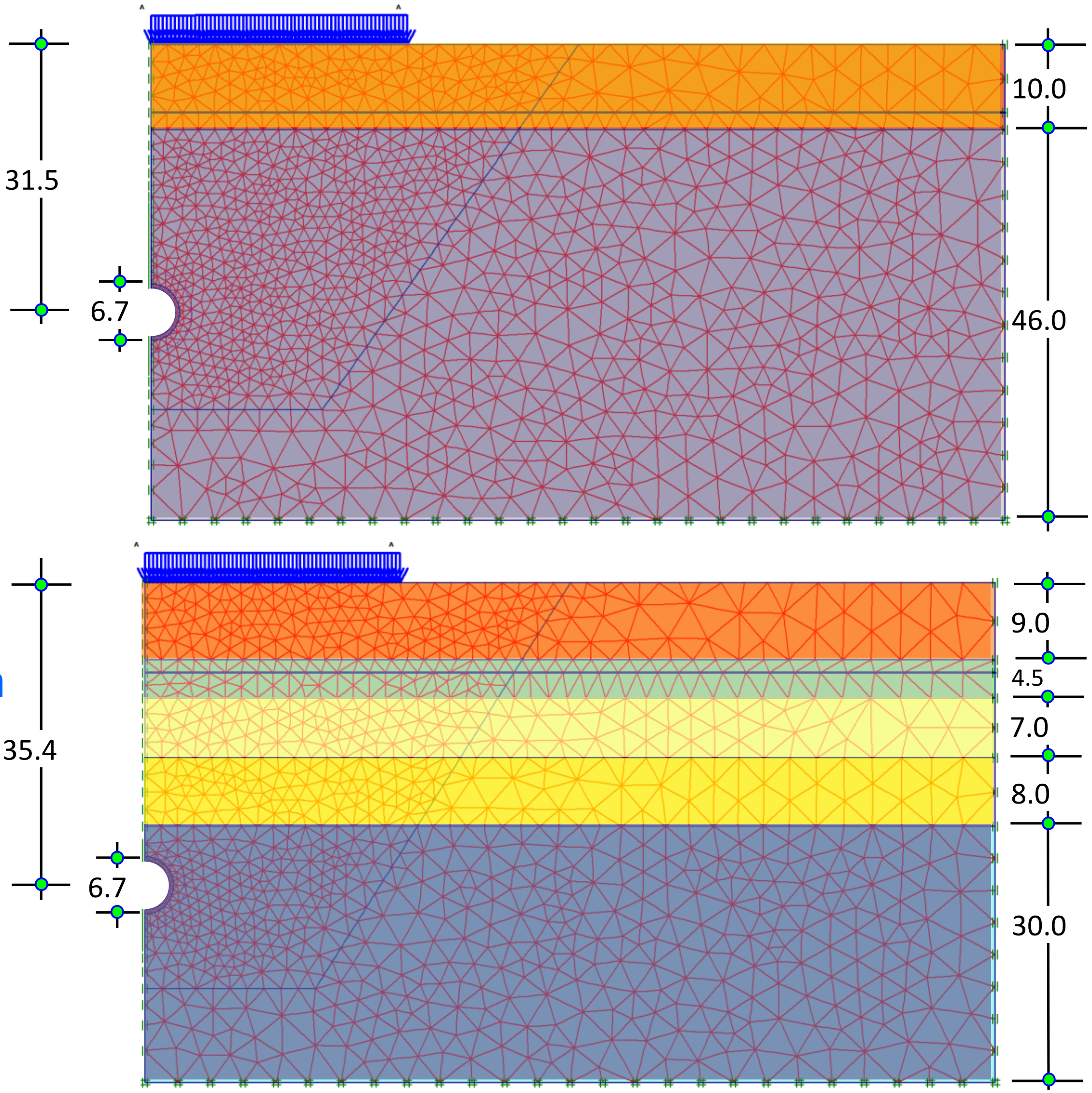


$$\left.\begin{array}{l}\overline{K}_{grout} = 2.5 \cdot 10^{-10}\ \text{m/s} \\ \overline{K}_{concr} \cong 10^{-11}\ \text{m/s}\end{array}\right\} \overline{K}_{lining} = 1.5 \cdot 10^{-11}\ \text{m/s}$$

$$\left.\begin{array}{l}\dfrac{K_{lining}}{K_{soil}} \cong 0.1 \\ L = 10 \div 20\ \text{m}\end{array}\right\} \Rightarrow \alpha = 2 \div 4$$

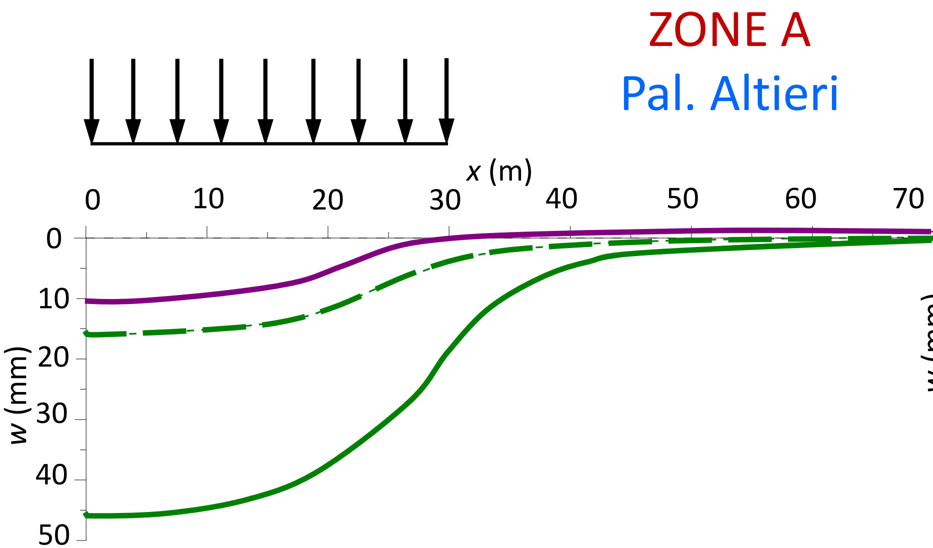
ZONE A
Pal. Altieri

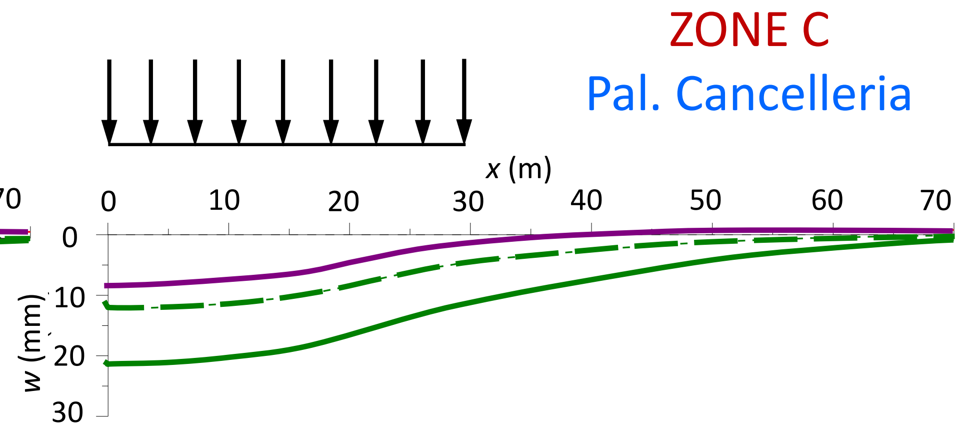
ZONE C
Pal. Cancelleria



made ground
silty clay

made ground
clayey silt
silty sand
sand
silty clay





end of tunnel construction

long term $k_{lining}/k_{soil} = 0.1$

long term $k_{lining}/k_{soil} = 0.01$

Dicii

soil

- actual soil profile and p.w.p. regime
- geotechnical characterisation and constitutive soil model

tunnels

- 2D or 3D simulation of tunnel excavation
- long term effects

buildings

- stiffness
- weight
- embedded depth of foundations

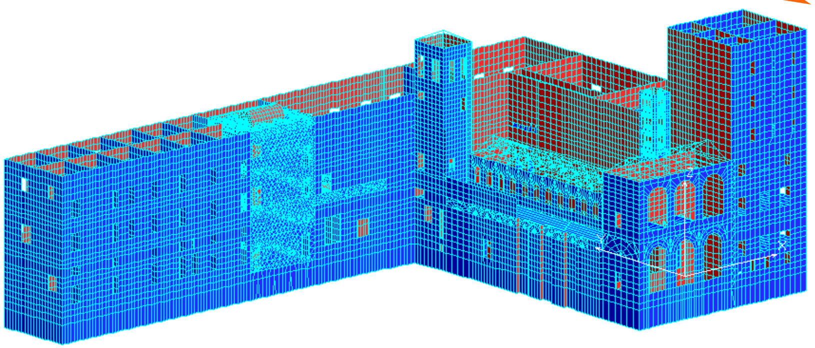
} equivalent solid

Equivalent Solid (ES)

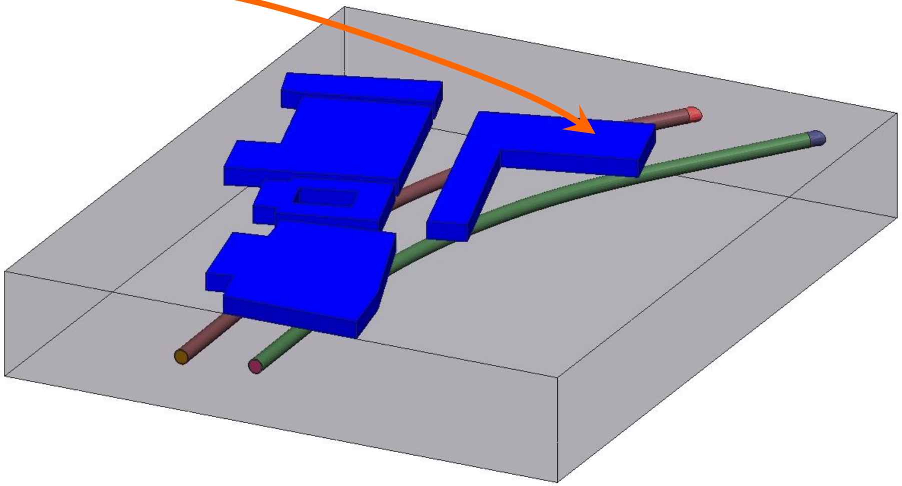
- given geometry
- embedded into the soil
- assumed elastic

1. green field displacements applied to complete model and simplified ES

E_{ES} varied to minimise differences between node reactions



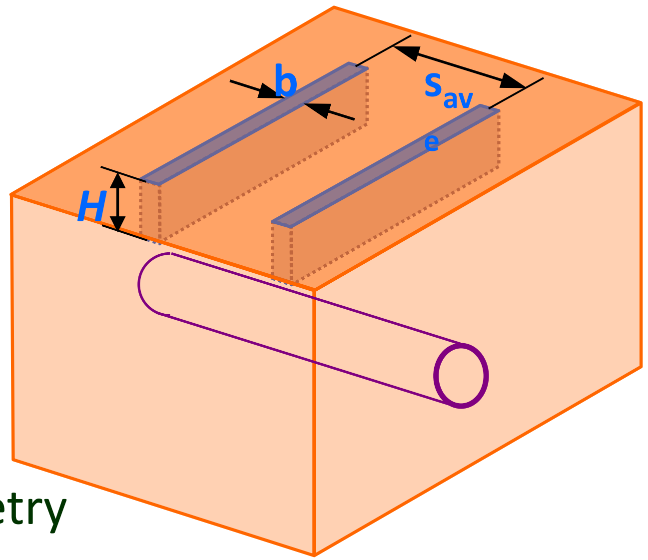
Palazzo Venezia

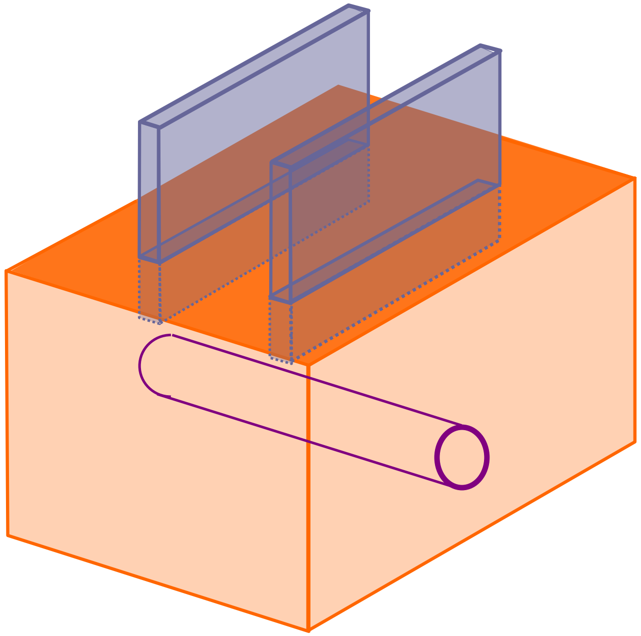


2. ES introduced in FE analyses and displacement field re-computed

3. new displacement field applied to the complete model

- section orthogonal to tunnel axis
- transverse bearing walls only

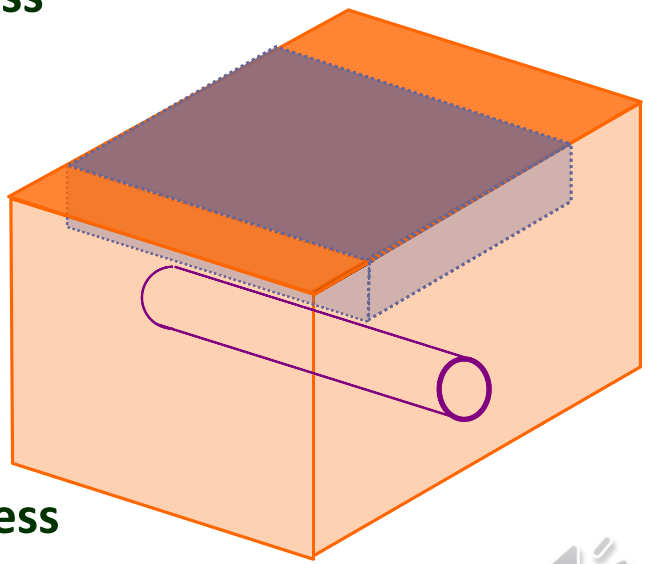




structural ES:

wall of given geometry

1st scaling of stiffness



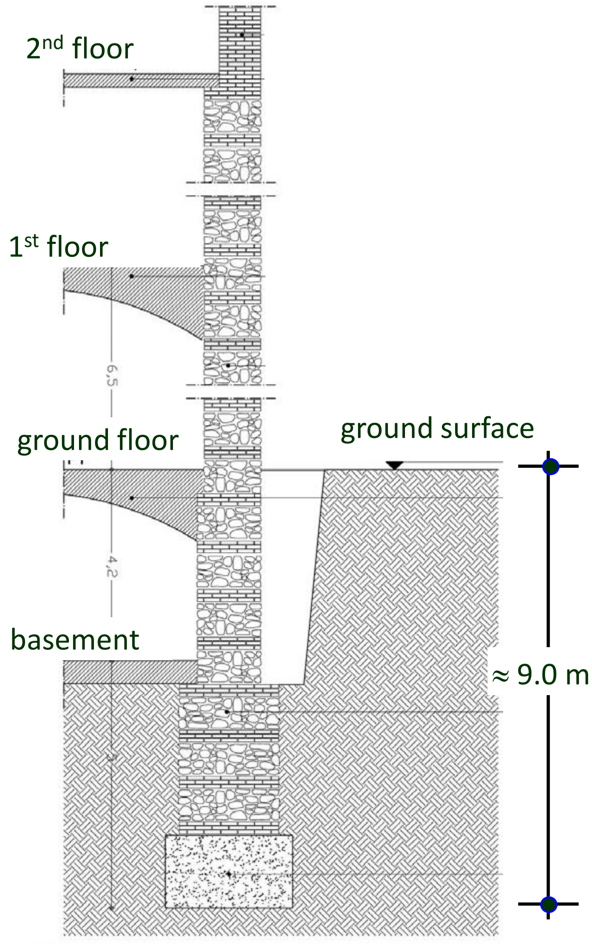
geotechnical ES:

infinite thickness

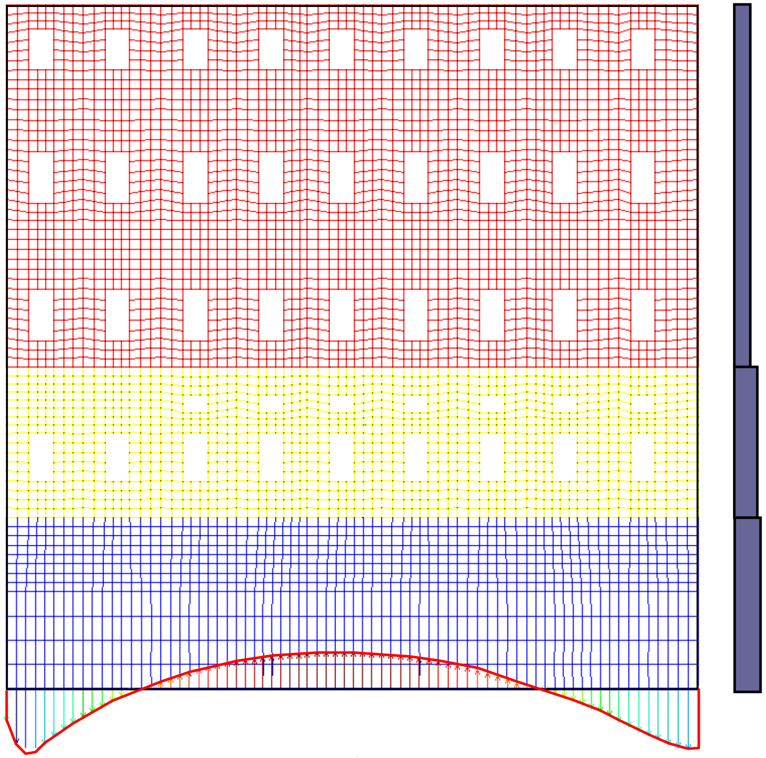
2nd scaling of stiffness

LEVEL 2 PALAZZO GRAZIOLI

PLAN

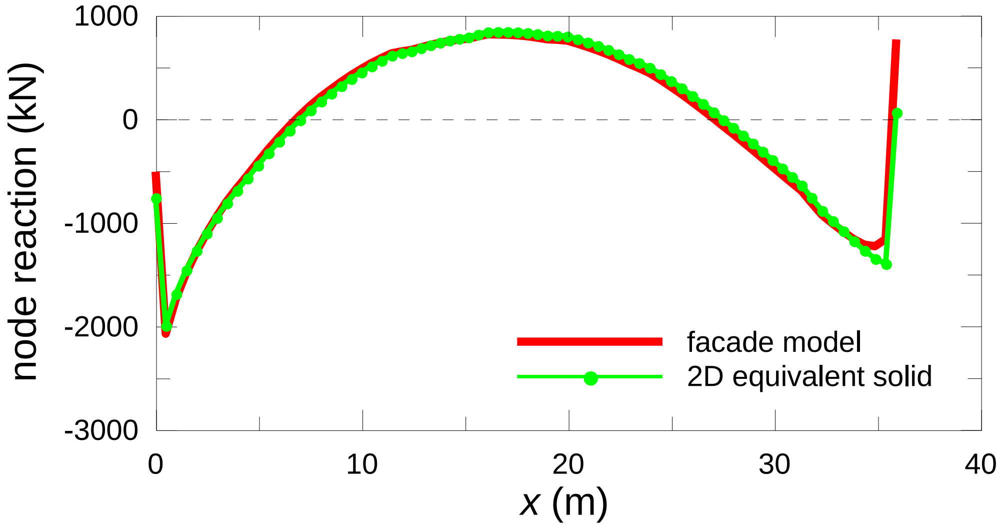


SECTION

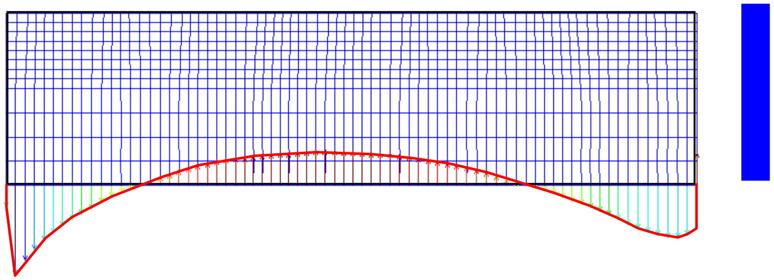


facade structural model

E = 2.5 GPa

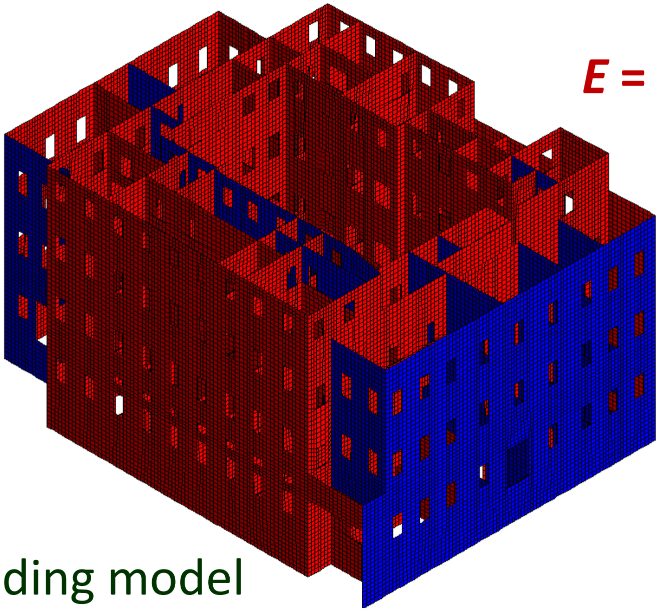


node reactions to given displacements



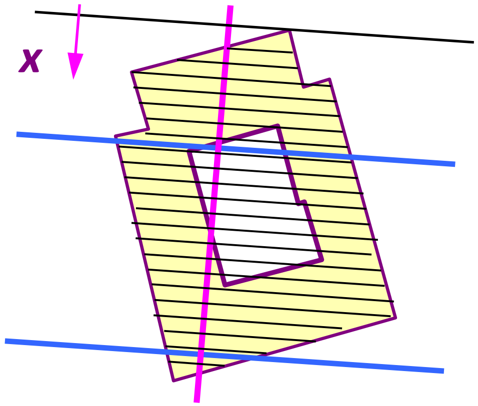
structural equivalent solid

$(E_{ES})_{str}$ = 3.9 GPa ⟹ $(E_{ES})_{mod}$ = 1.2 GPa

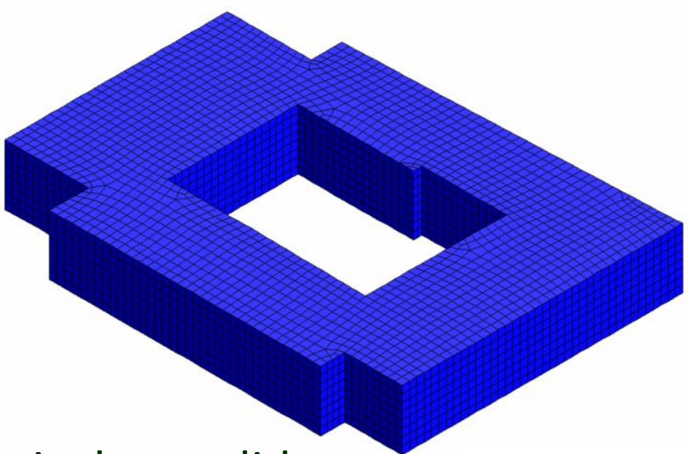


E = 2.5 GPa

building model

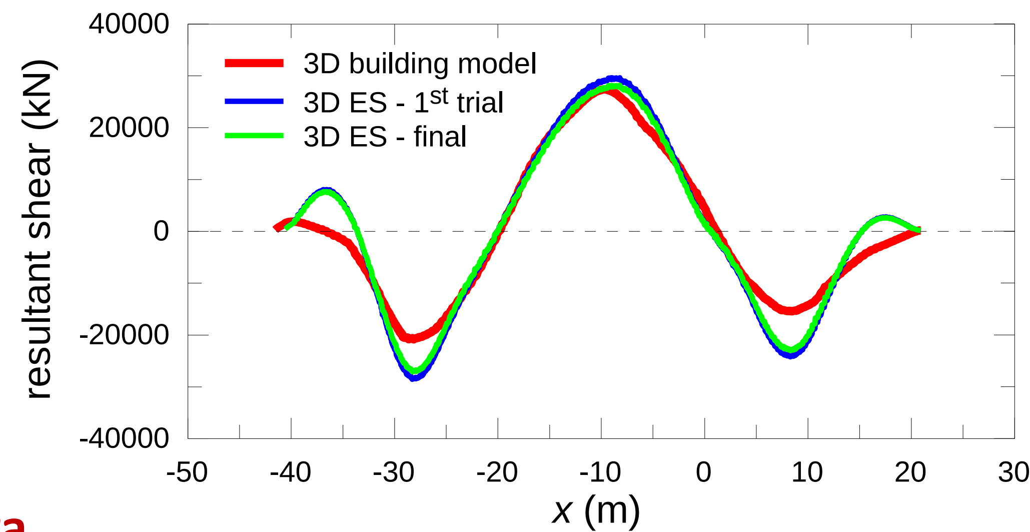


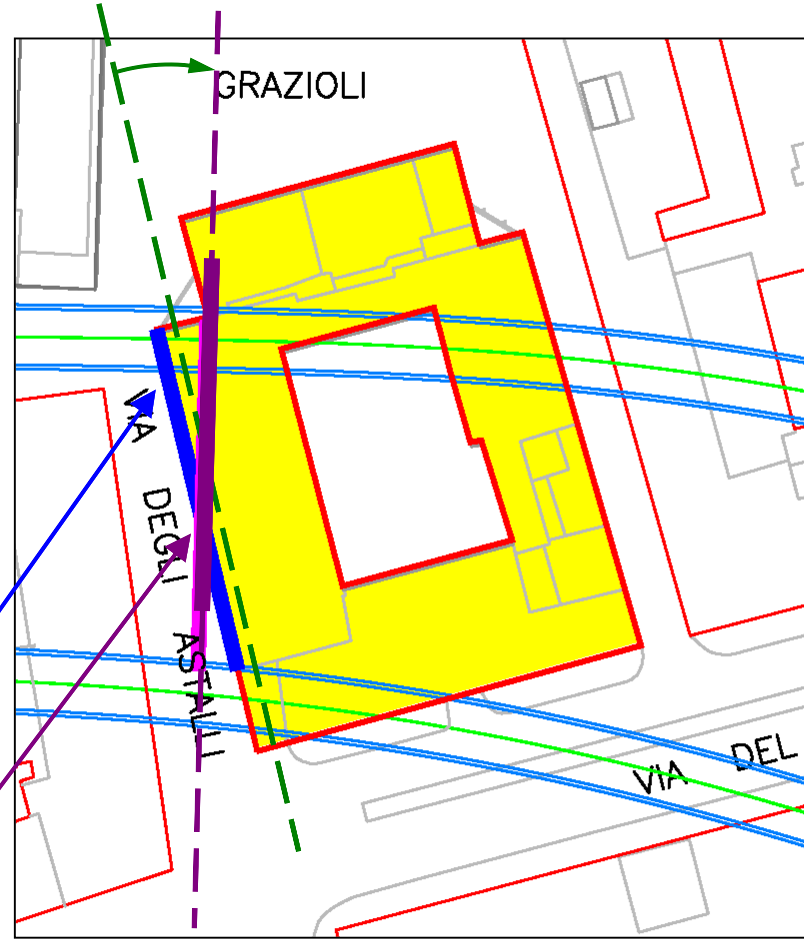
shear forces on transversal section



equivalent solid

$(E_{ES})_{str}$ = 2.38 GPa

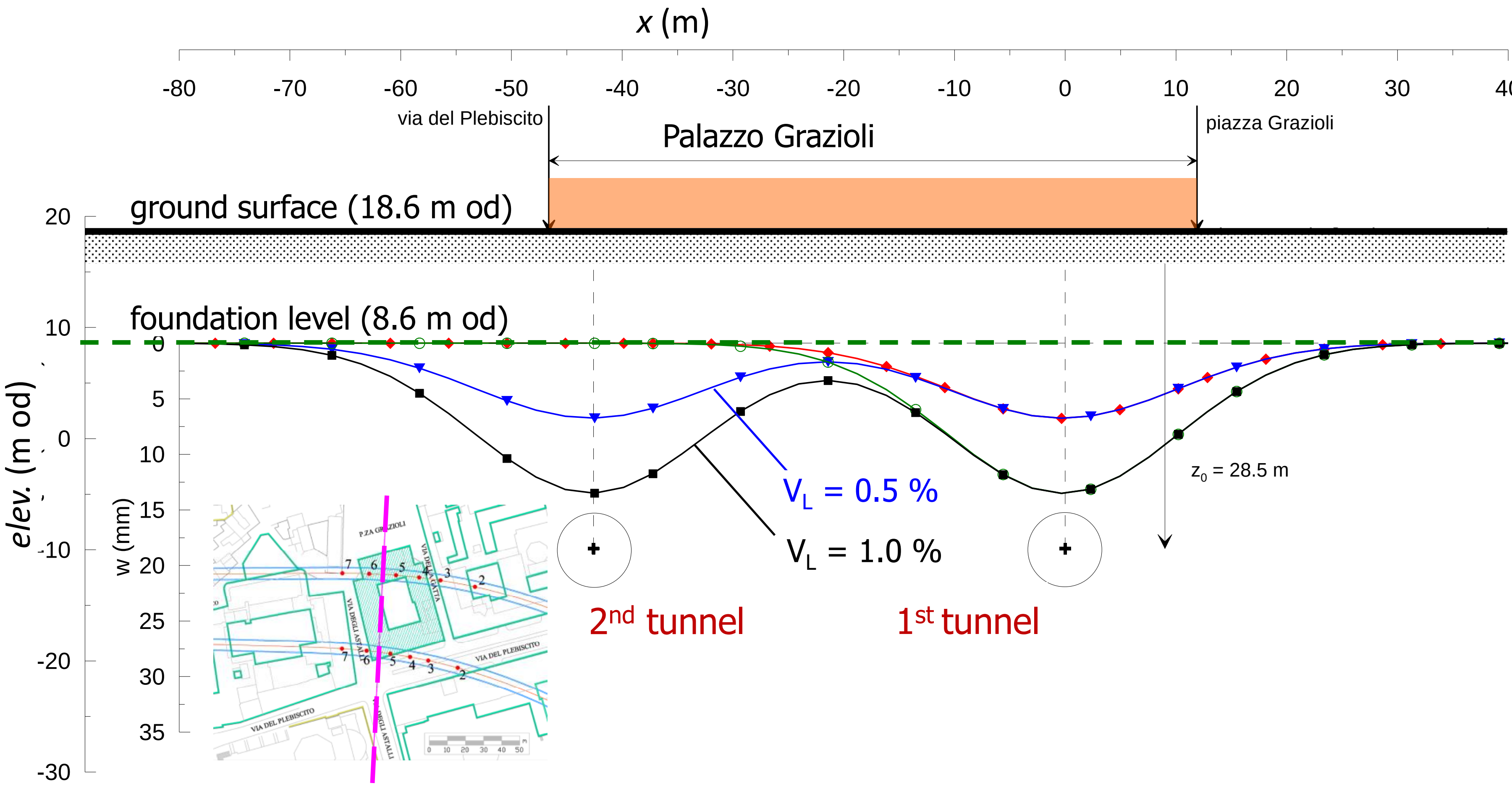


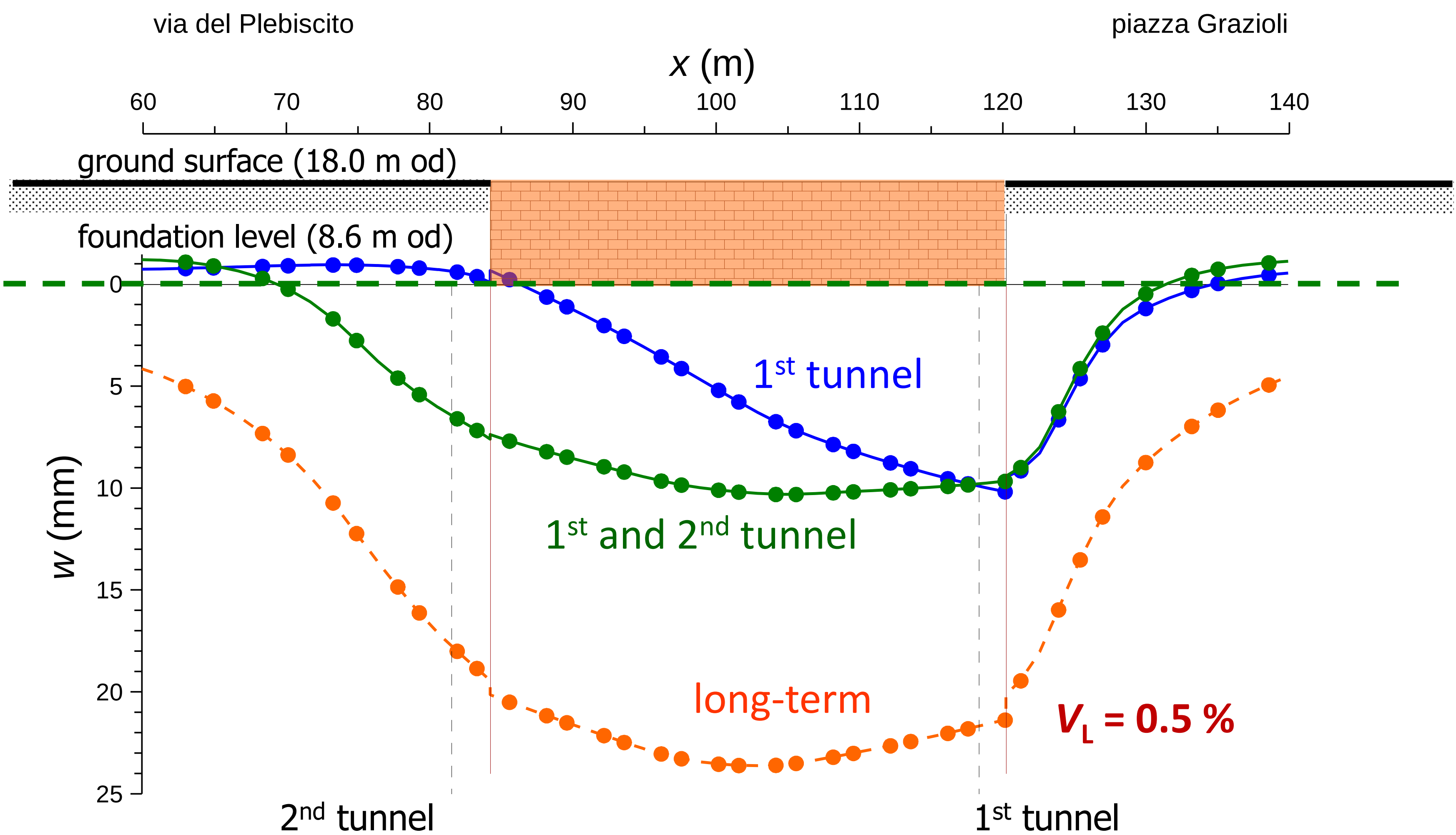


3D analysis
actual facade

2D analysis
assumed section

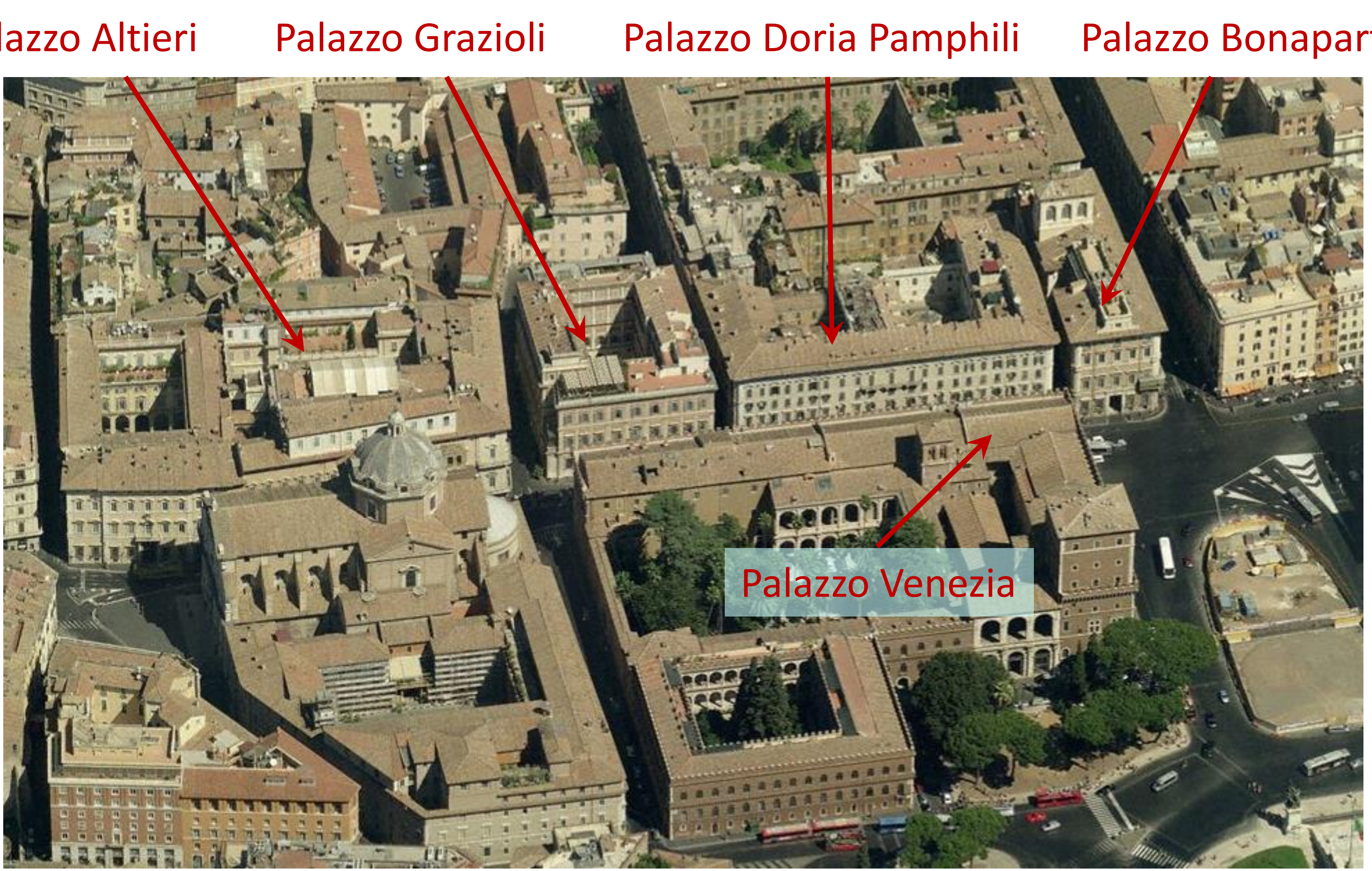
LEVEL 1 PALAZZO GRAZIOLI settlements at foundation level



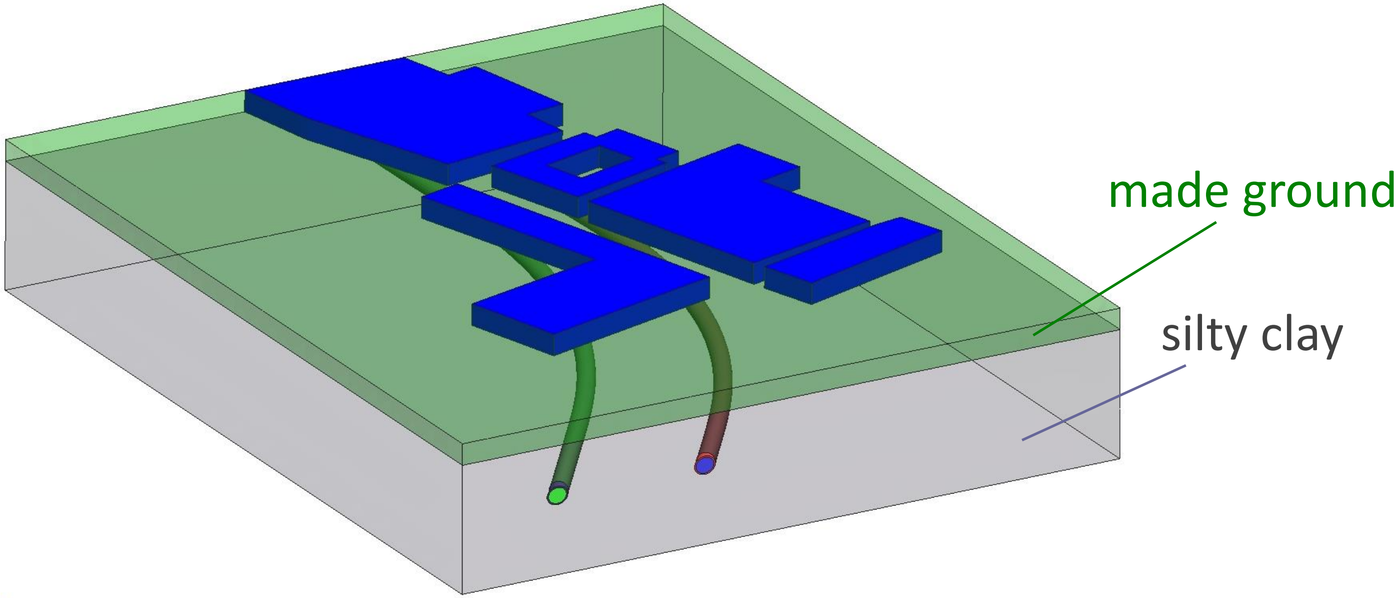


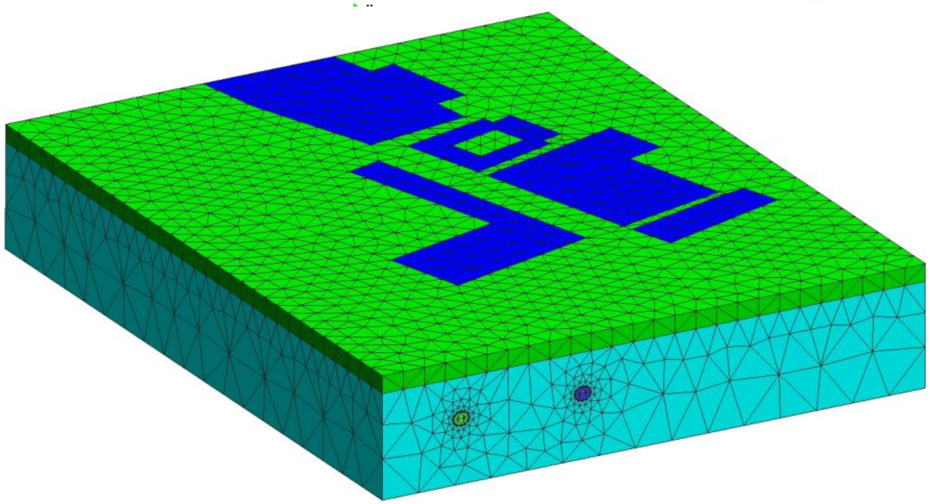
via del Plebiscito
piazza Grazioli
x (m)
60
70
80
90
100
110
120
130
140
ground surface (18.0 m od)
foundation level (8.6 m od)
0
5
10
15
20
25
w (mm)
1st tunnel
1st and 2nd tunnel
long-term
VL = 0.5 %
2nd tunnel
1st tunnel

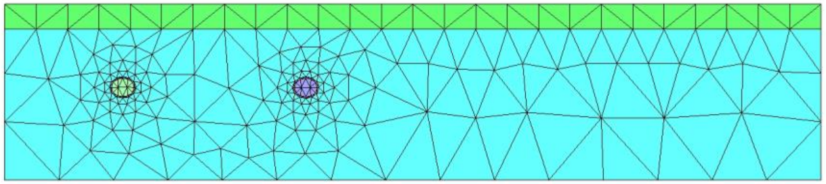
LEVEL 2 PALAZZO GRAZIOLI 3D FE interaction analyses



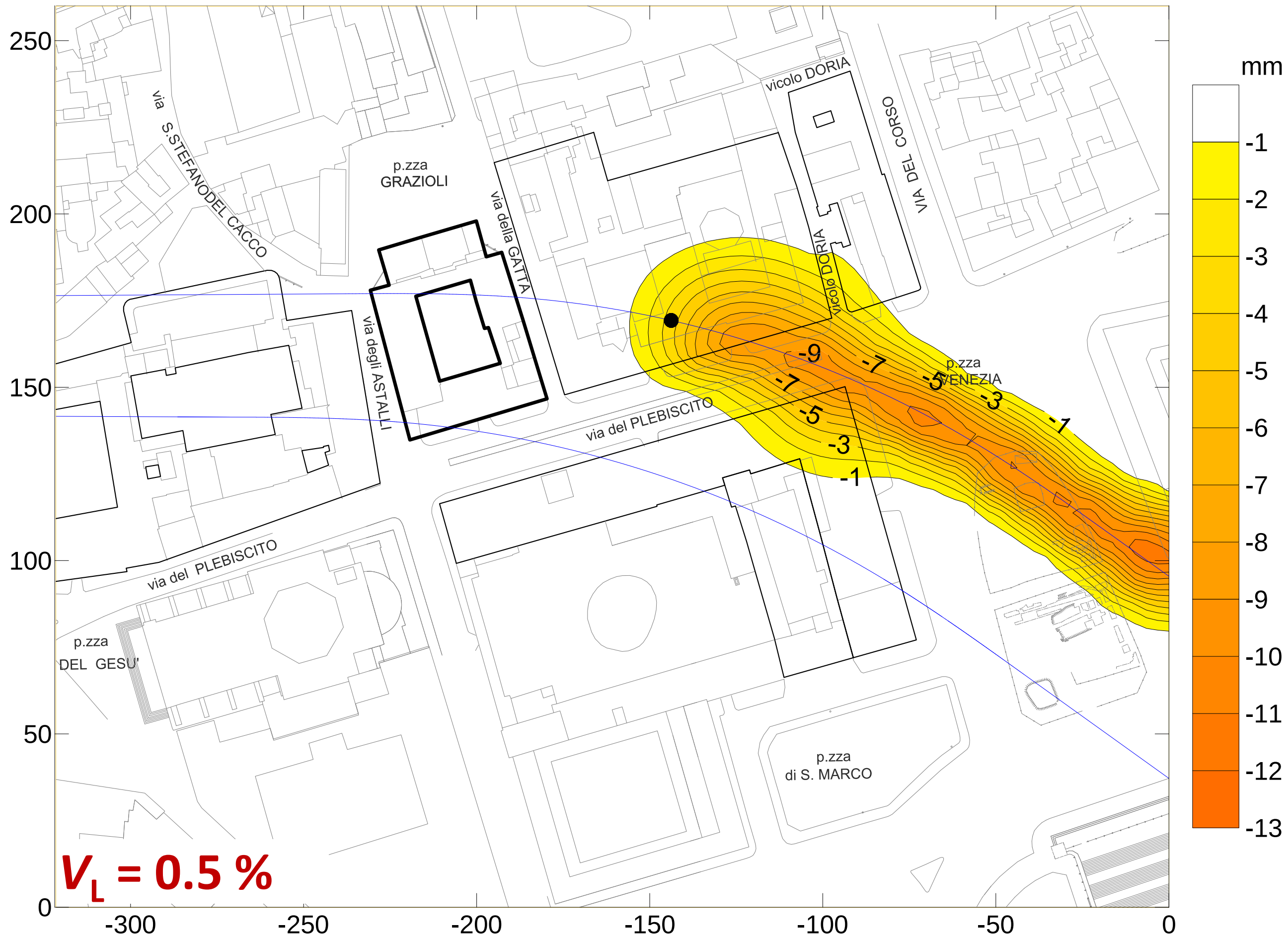
LEVEL 2 PALAZZO GRAZIOLI 3D FE interaction analyses



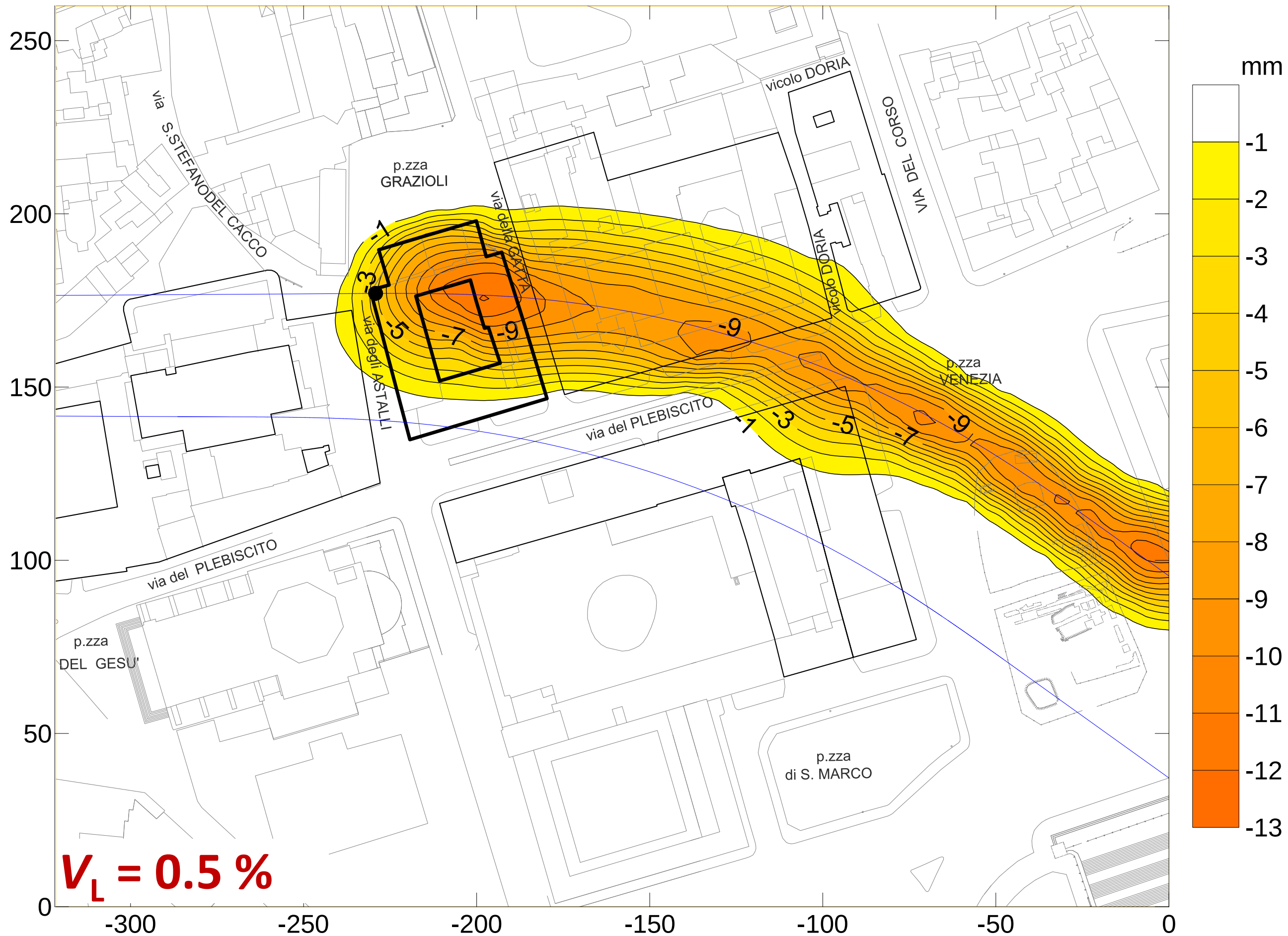




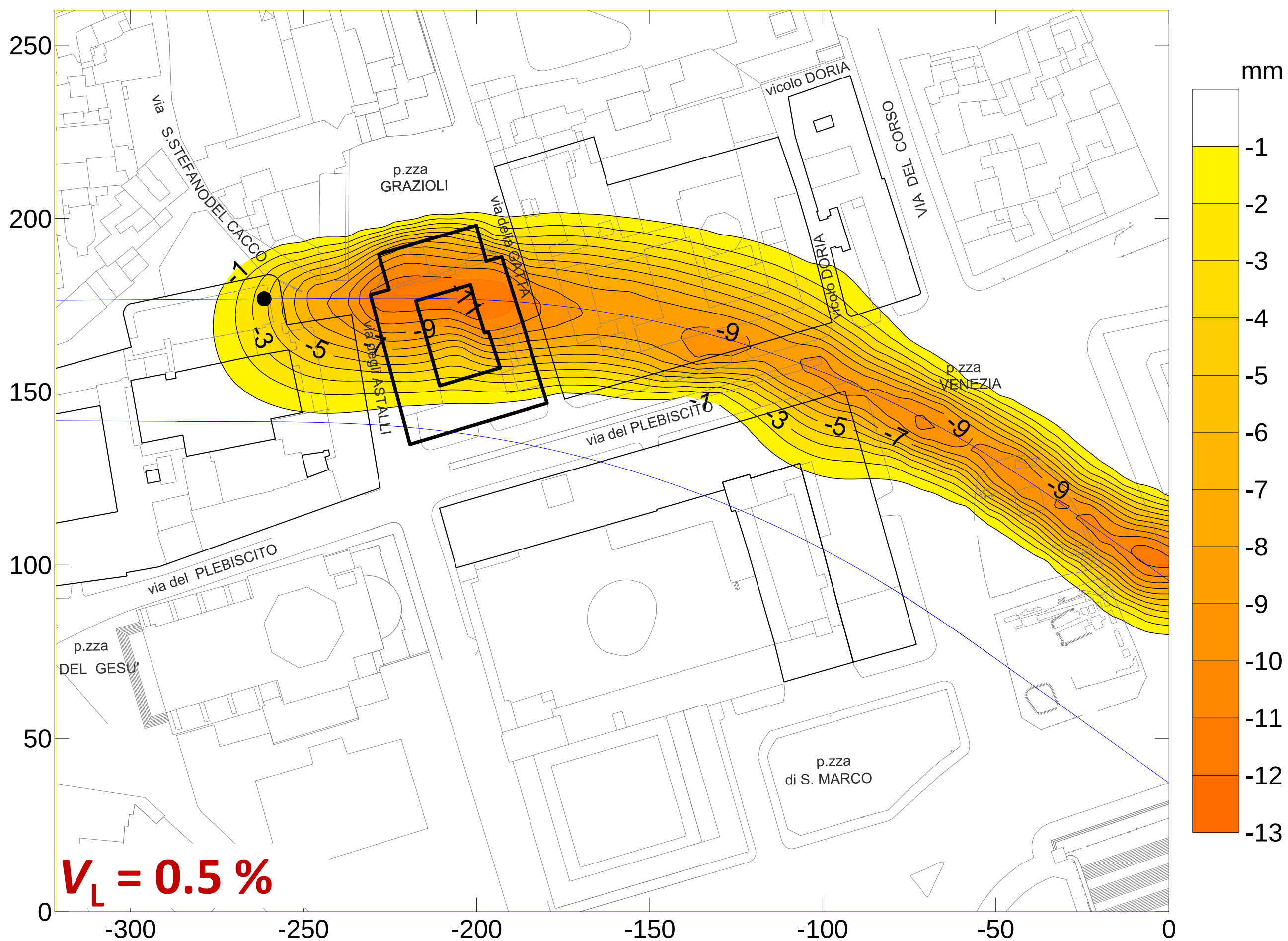
LEVEL 2 PALAZZO GRAZIOLI 3D FE analyses: settlements



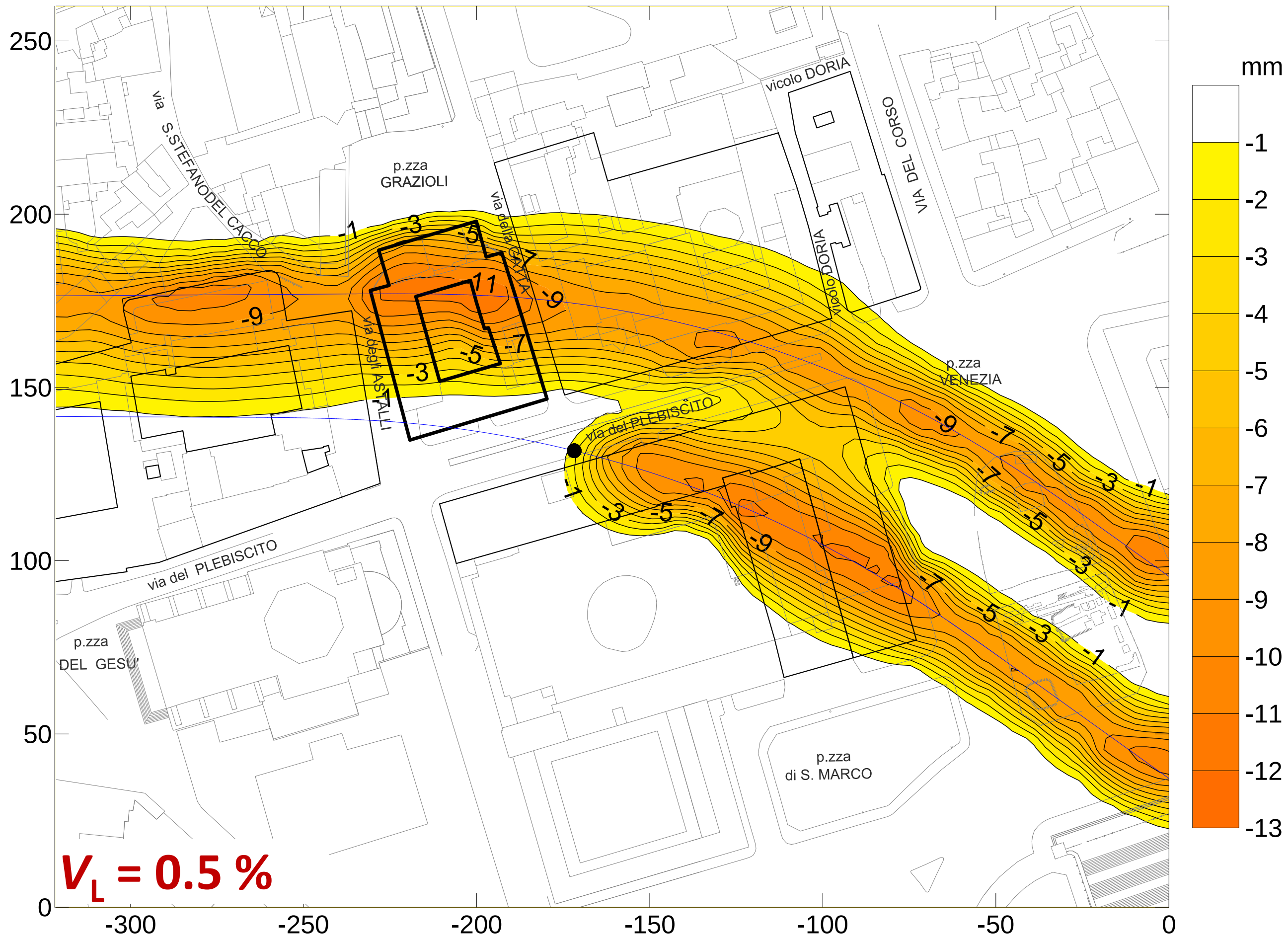
LEVEL 2 PALAZZO GRAZIOLI 3D FE analyses: settlements



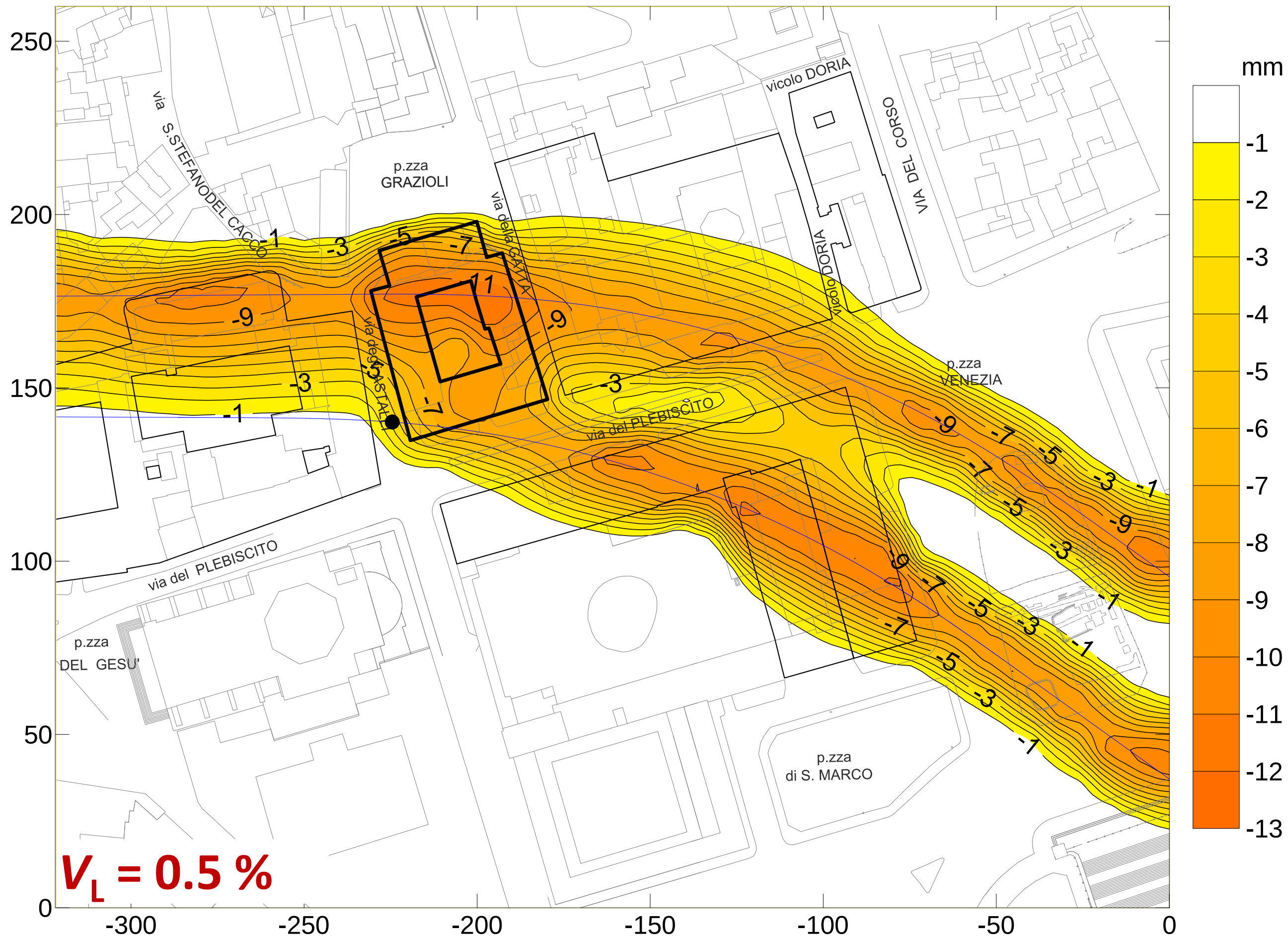
LEVEL 2 PALAZZO GRAZIOLI 3D FE analyses: settlements



LEVEL 2 PALAZZO GRAZIOLI 3D FE analyses: settlements

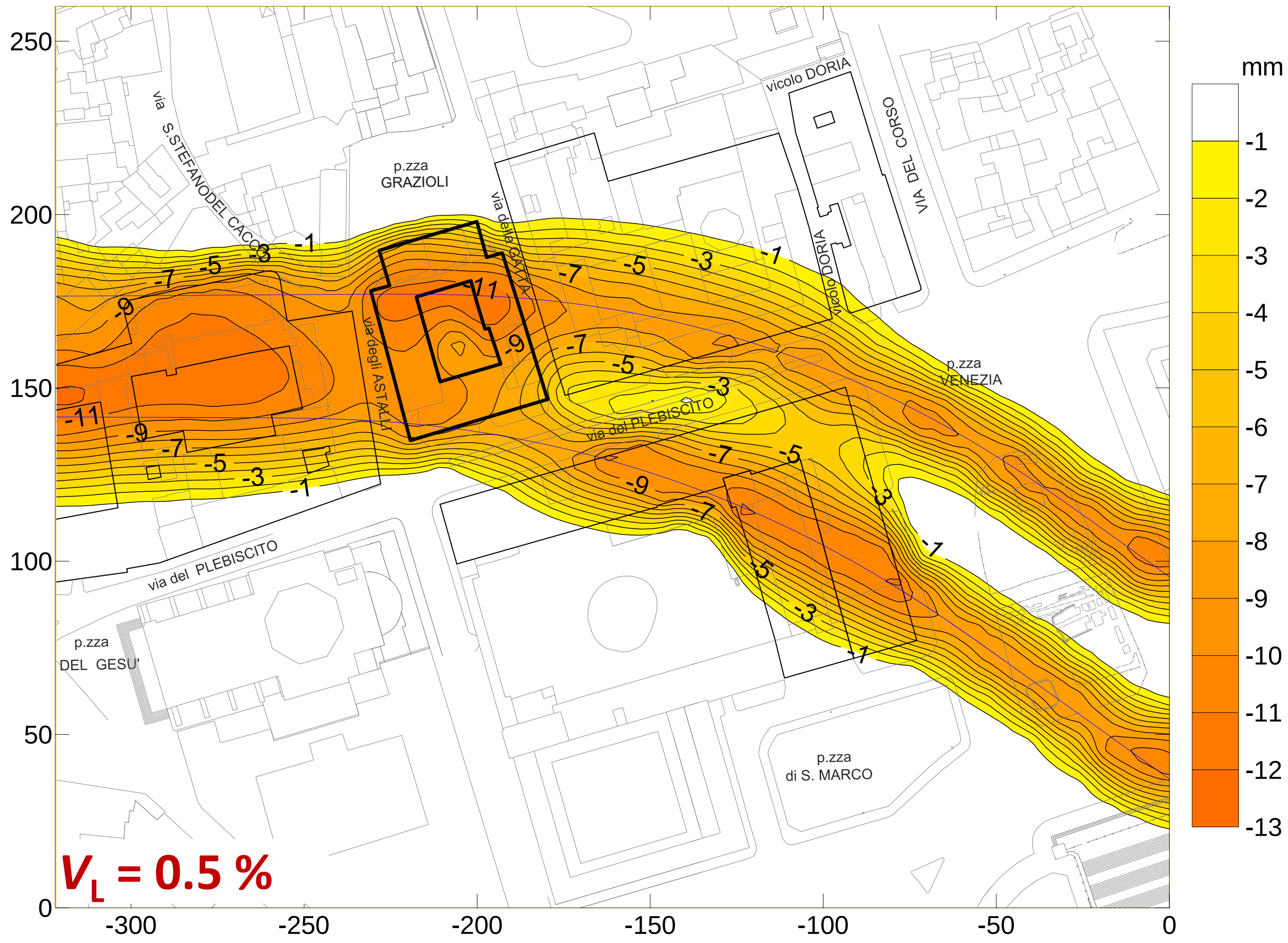


LEVEL 2 PALAZZO GRAZIOLI 3D FE analyses: settlements



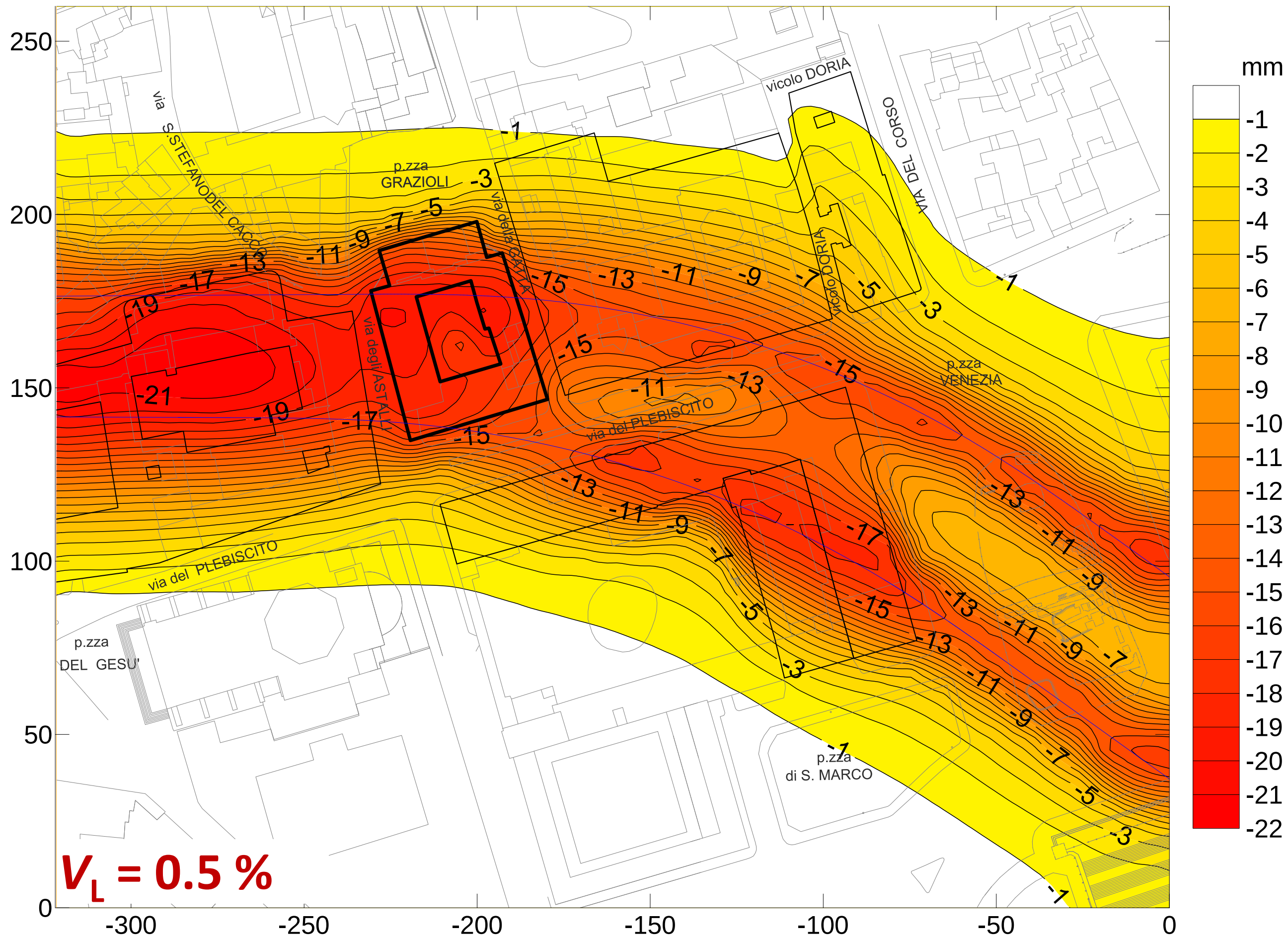
LEVEL 2 PALAZZO GRAZIOLI 3D FE analyses: settlements

end of construction

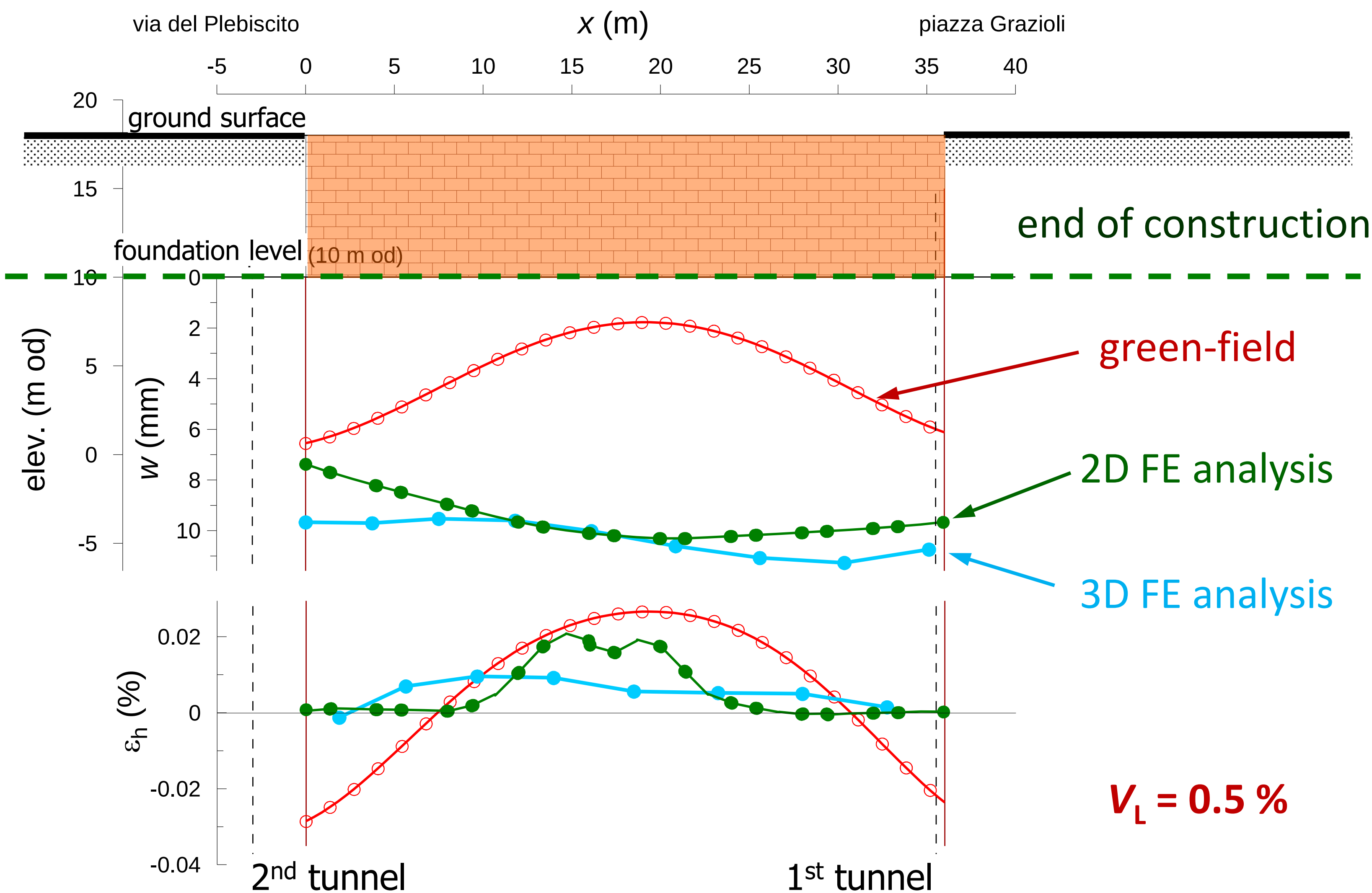


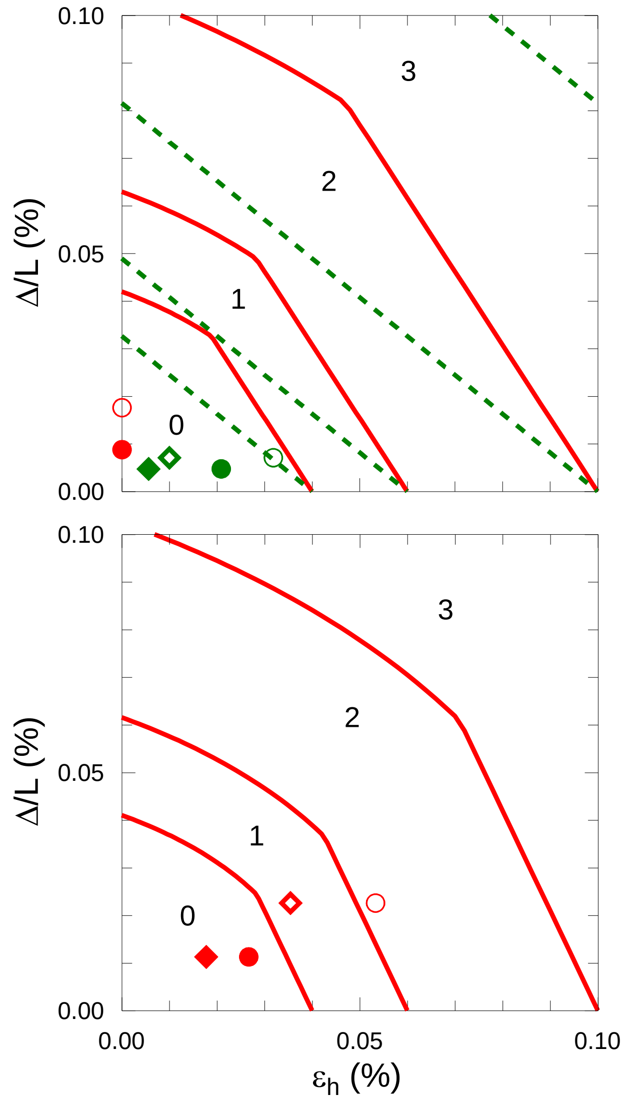
LEVEL 2 PALAZZO GRAZIOLI 3D FE analyses: settlements

long term



PALAZZO GRAZIOLI COMPARISON OF RESULTS





SAGGING

V_L = 0.5 %
- ● green field
- ◆ 2D-FE – $\varepsilon_{h,ave}$
- ● 2D-FE – $\varepsilon_{h,max}$

V_L = 1.0 %
- ○ green field
- ◇ 2D-FE – $\varepsilon_{h,ave}$
- ○ 2D-FE – $\varepsilon_{h,max}$

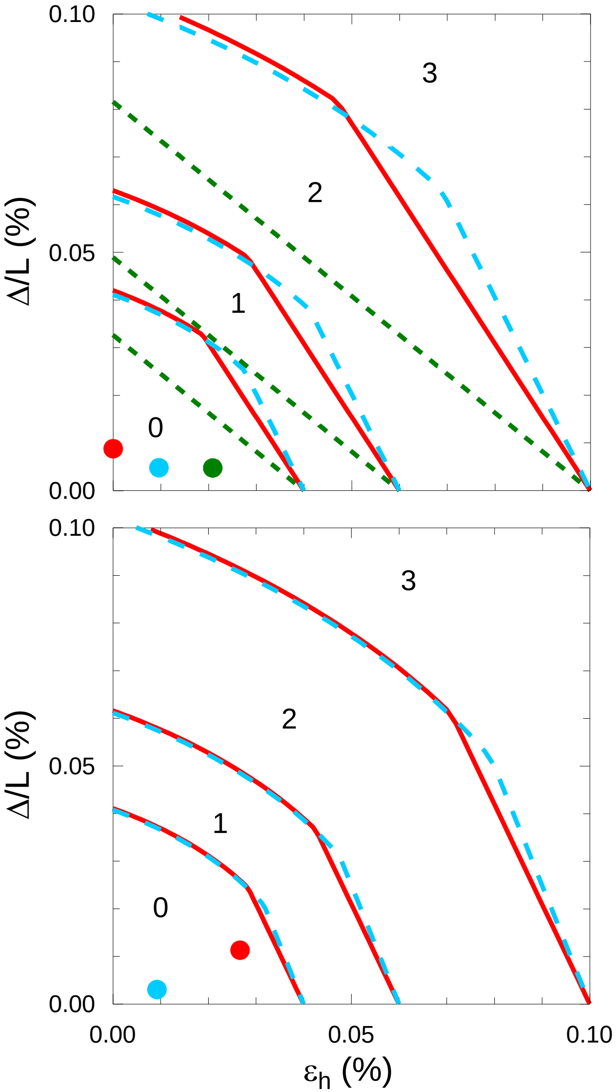
green field vs **2D FE**

HOGGING

V_L = 0.5 %
- ◆ green field – $\varepsilon_{h,ave}$
- ● green field – $\varepsilon_{h,max}$

V_L = 1.0 %
- ◇ green field – $\varepsilon_{h,ave}$
- ○ green field – $\varepsilon_{h,max}$

PALAZZO GRAZIOLI DAMAGE ASSESSMENT GE group



SAGGING

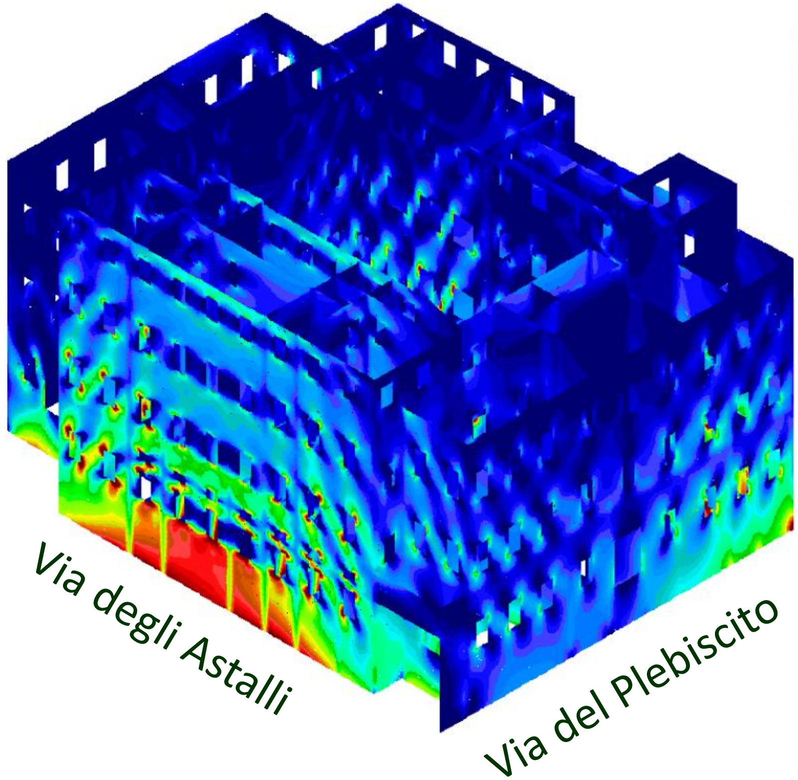
V_L = 0.5 %
- green field
- 2D-FE an.
- 3D-FE an.

green field vs **2D** & **3D** FE

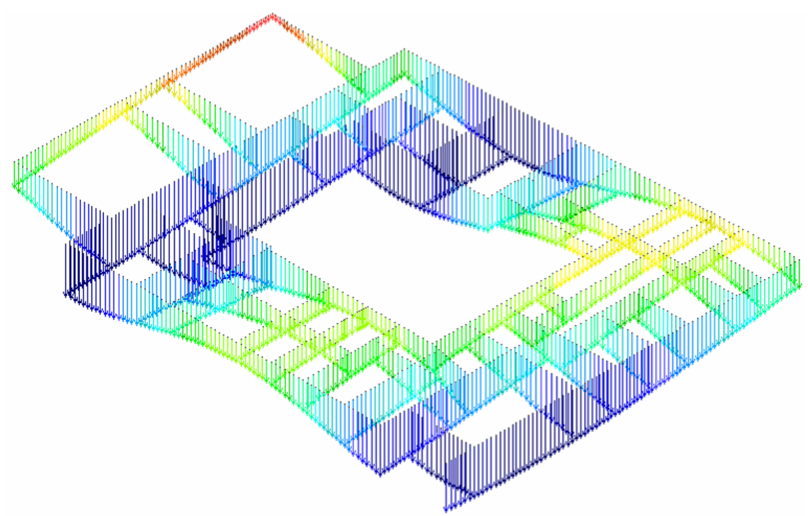
HOGGING

V_L = 0.5 %
- green field
- 3D FE an.

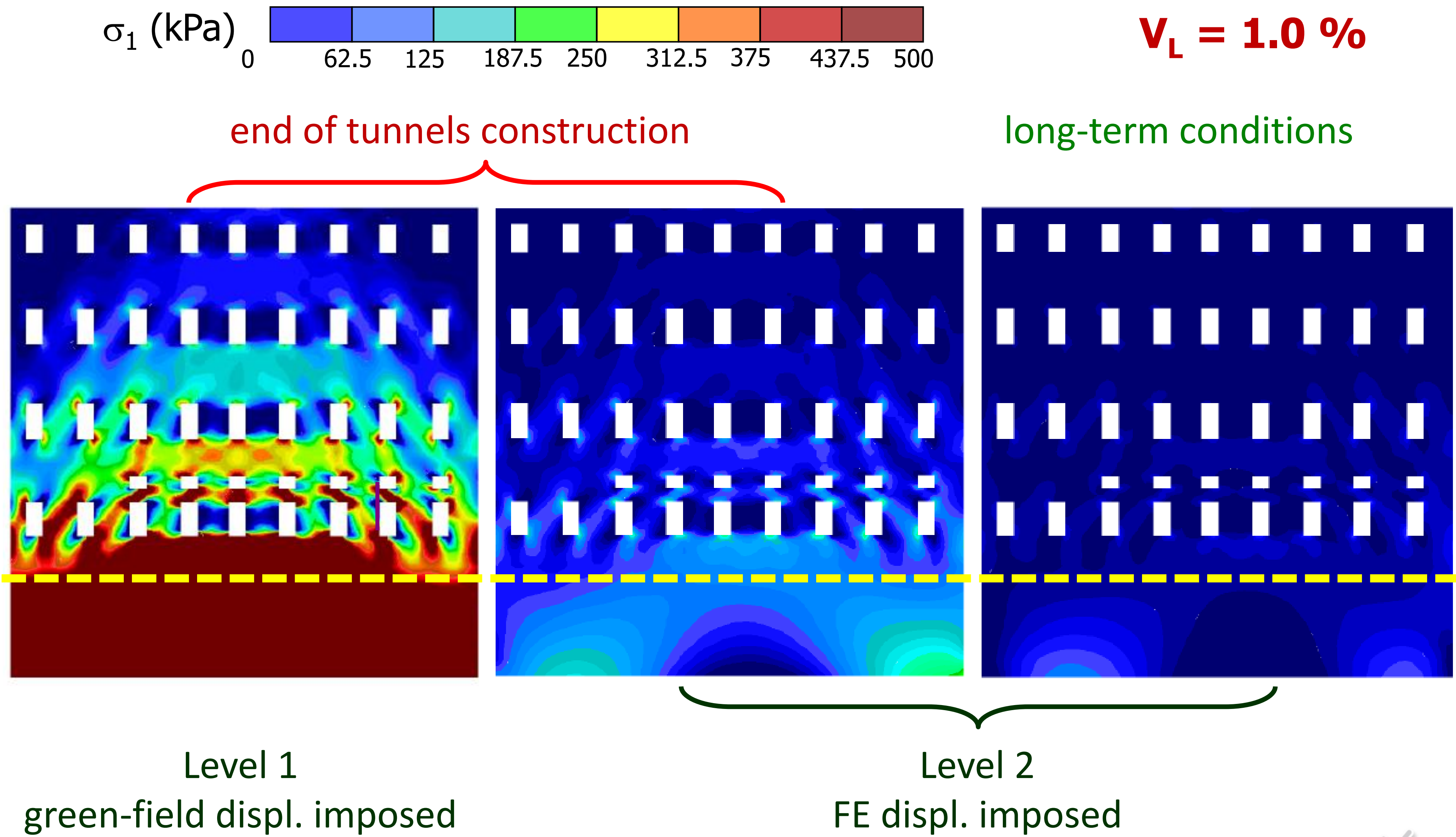
Ε.Ε.Σ.Υ.Ε.
Ελληνική Επιτροπή Σηράγγων και Υπογείων Έργων



contours of maximum principal stress



green-field displacement field


σ_1 (kPa)
0 62.5 125 187.5 250 312.5 375 437.5 500
V_L = 1.0 %
end of tunnels construction
long-term conditions
Level 1
green-field displ. imposed
Level 2
FE displ. imposed

what is it?

Large Collaborative Project funded by the EC through FP7

21 partners (I, R&D and SME)

9 European Countries

to address a set of research themes and objectives related to the construction, management , and maintenance of tunnels

NeTTUN

Università di Roma Tor Vergata LEADER
(Italy)

Ecole Nationale des Travaux Publics de l'Etat
(France)

National Technical University Athens
(Greece)

Metro C S.C.p.A.
(Italy)

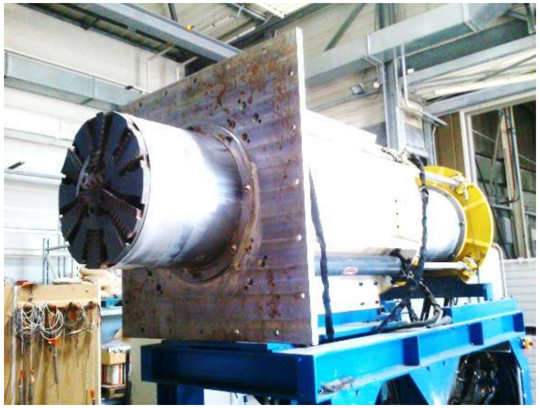
advisor Richard Kastner (INSA-Lyon)

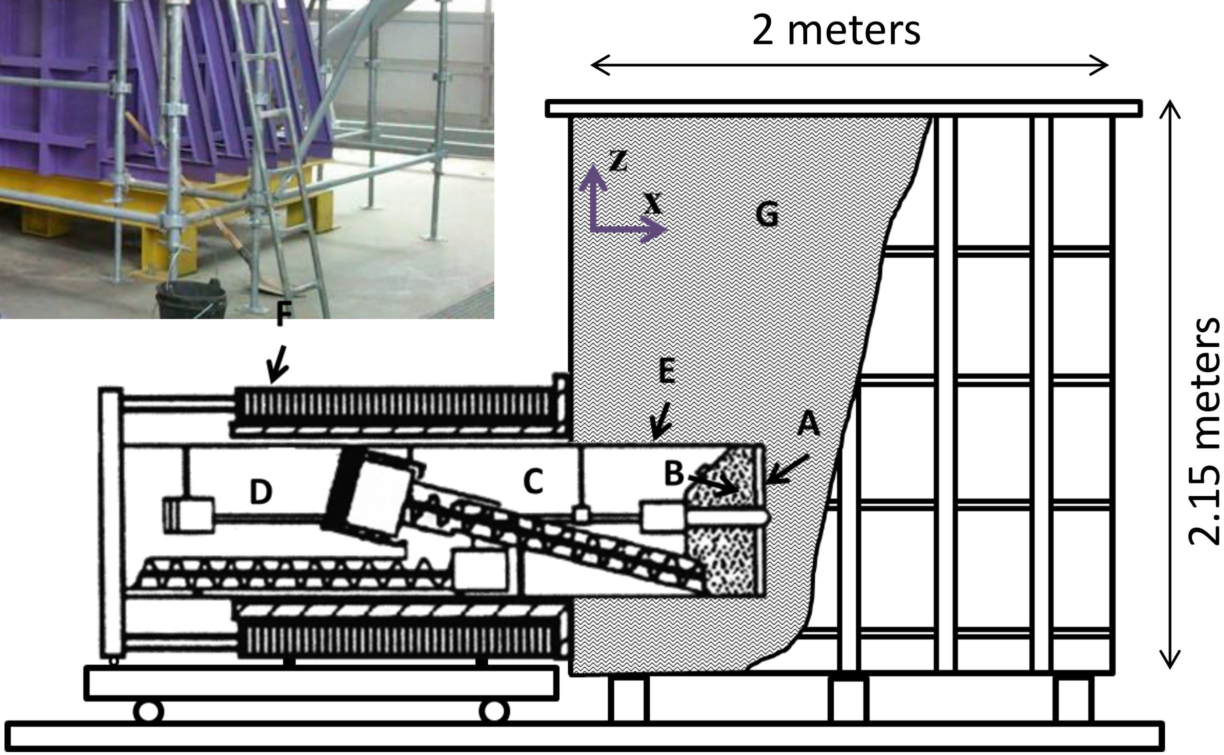
develop a numerical procedure to study the impact of EPB tunnelling on structures

develop a method for the early detection of over-excavation at tunnel face

evaluate effectiveness of mitigation measures

- physical modelling
- numerical modelling
- field monitoring

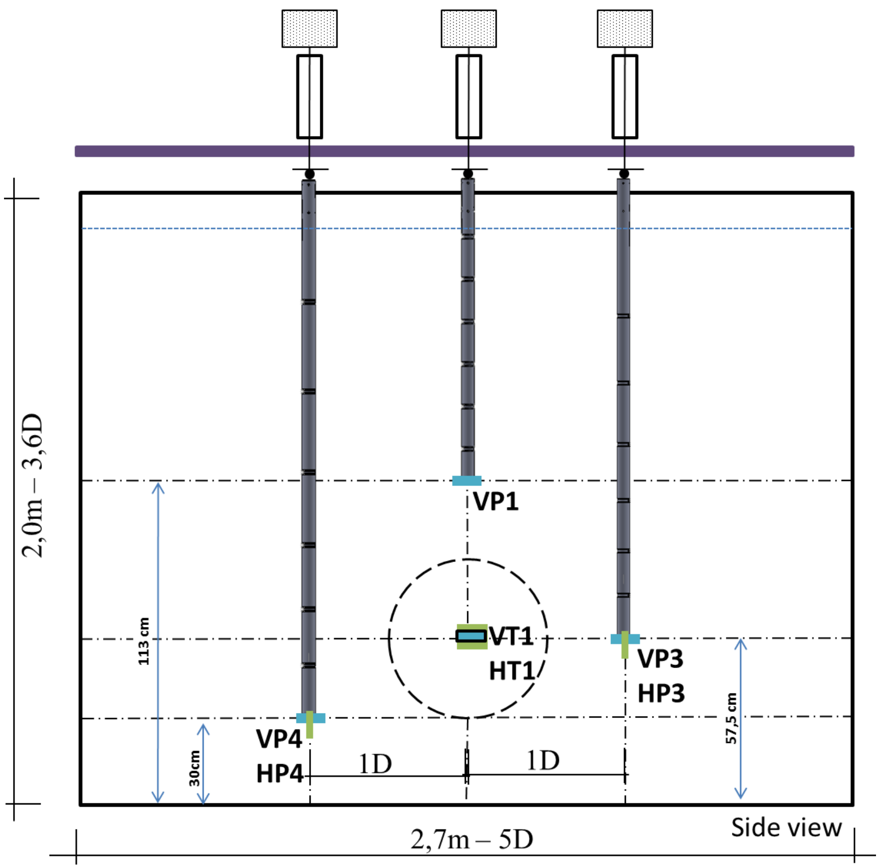



2 meters
2.15 meters
Z
X
G
F
E
A
B
C
D

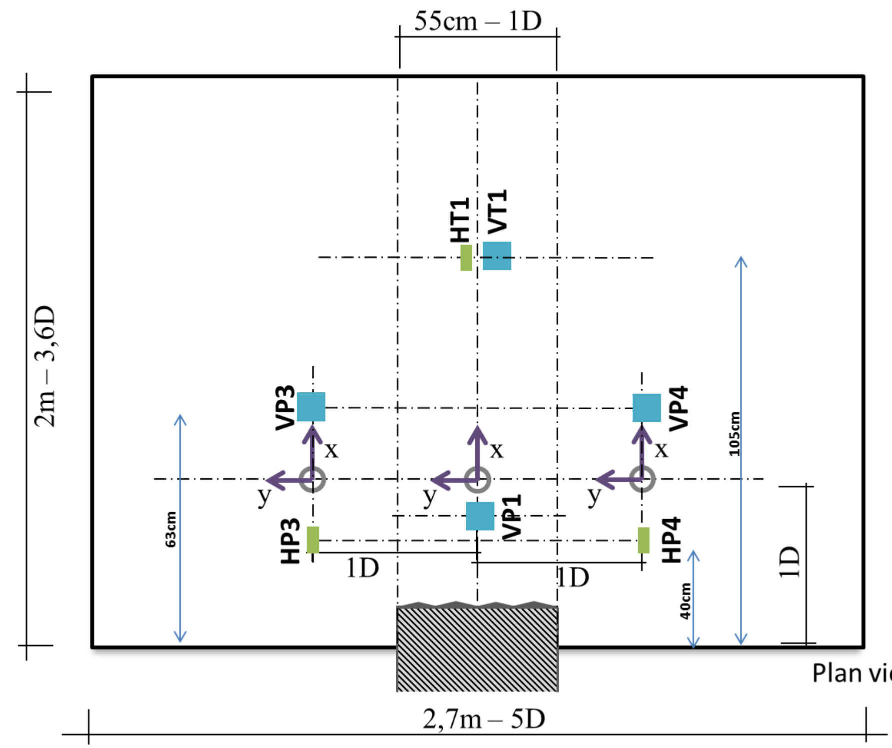
7 total stress cells

H – Horizontal

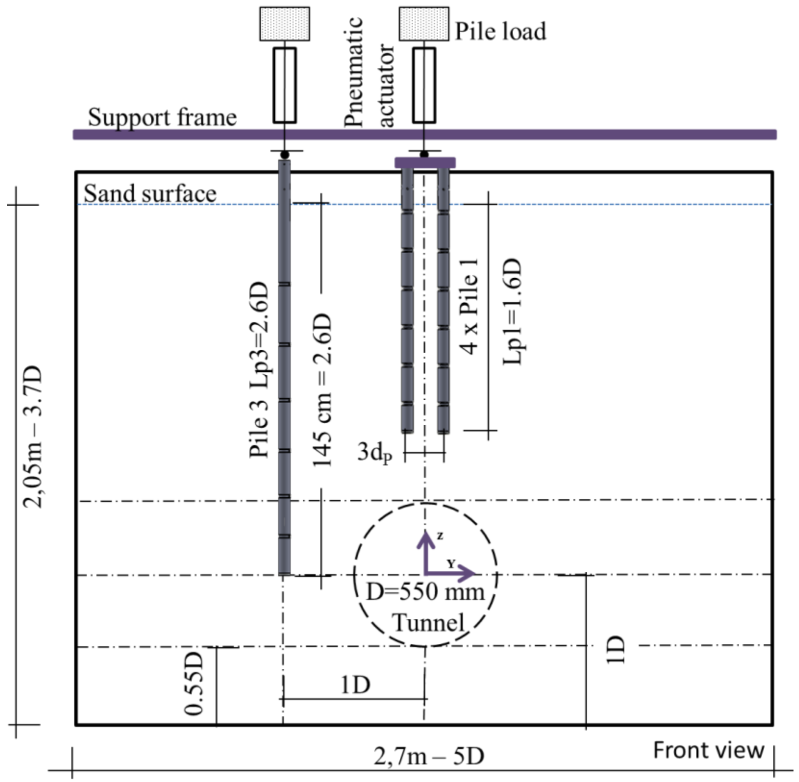
V – Vertical



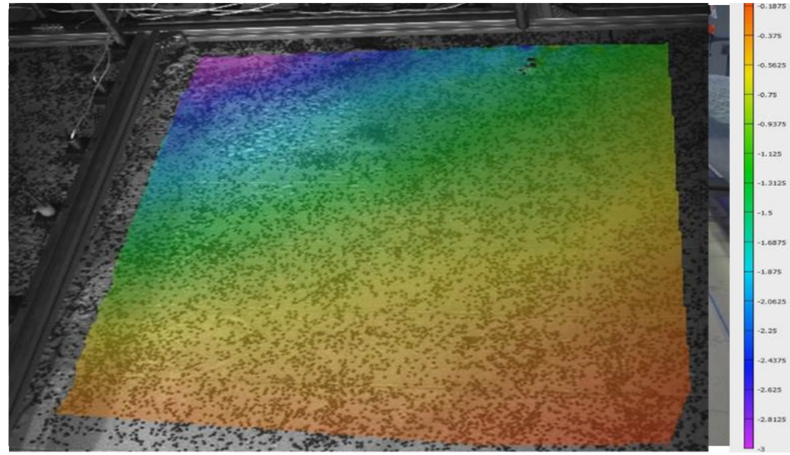
Side view



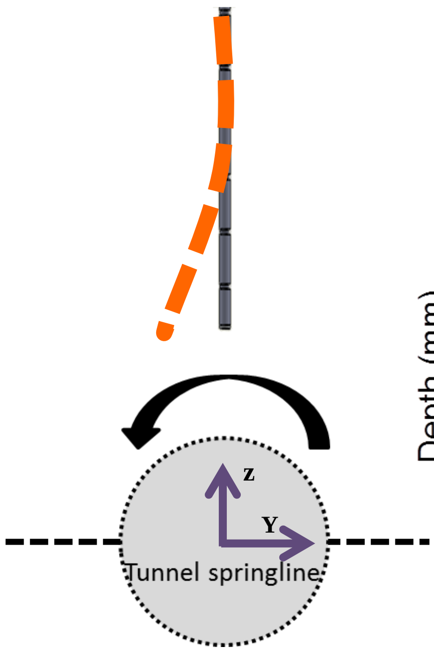
Plan view

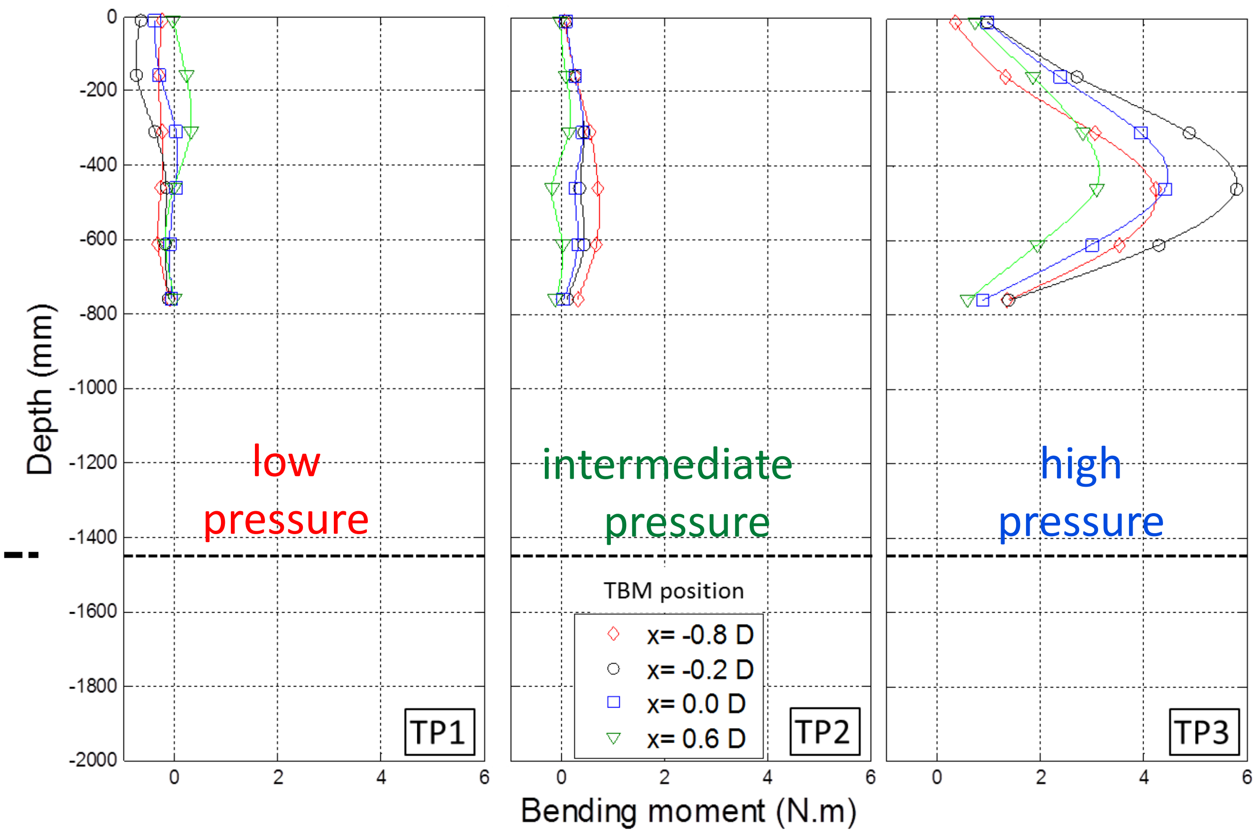

Pile load
Pneumatic actuator
Support frame
Sand surface
Pile 3 Lp3=2.6D
145 cm = 2.6D
4 x Pile 1
Lp1=1.6D
3dp
2,05m – 3.7D
D=550 mm
Tunnel
1D
0.55D
1D
2,7m – 5D
Front view

PHYSICAL MODELLING



transversal bending moment

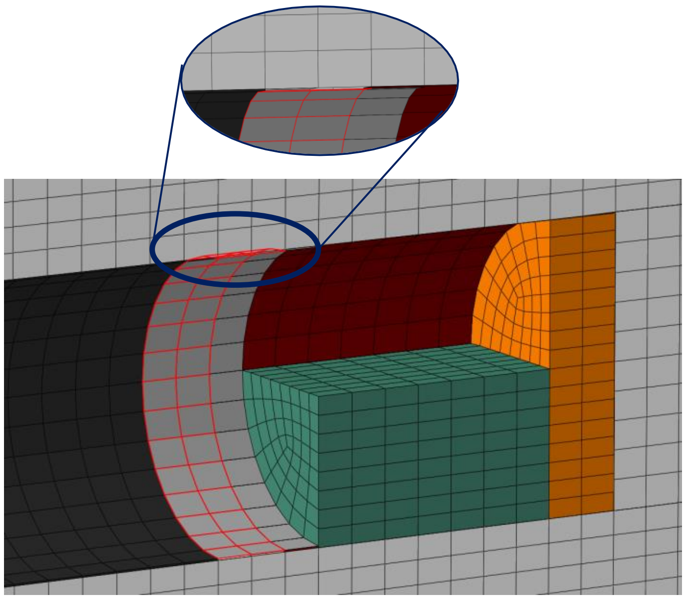




Bel *et al.*, 2015

L FE modelling of main construction processes

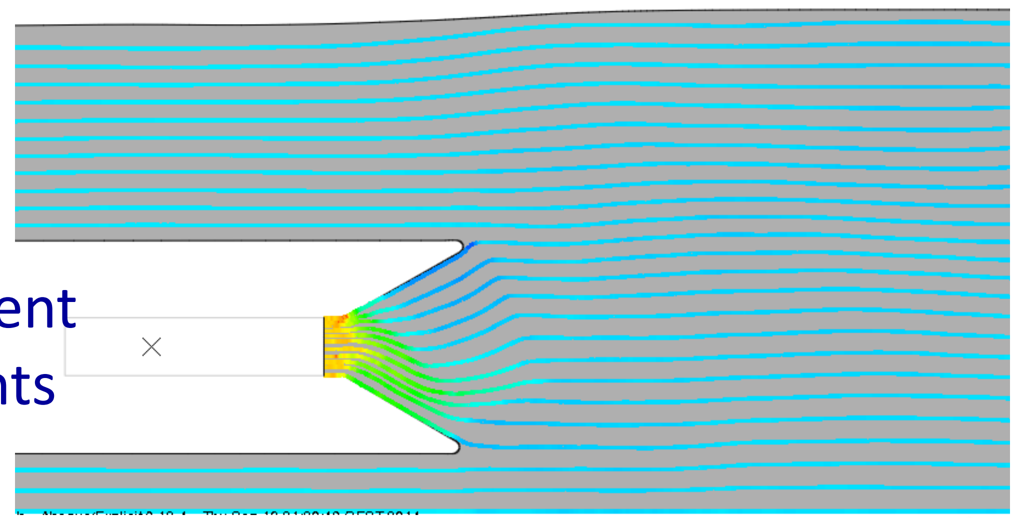
(Litsas *et al.*, 2015)



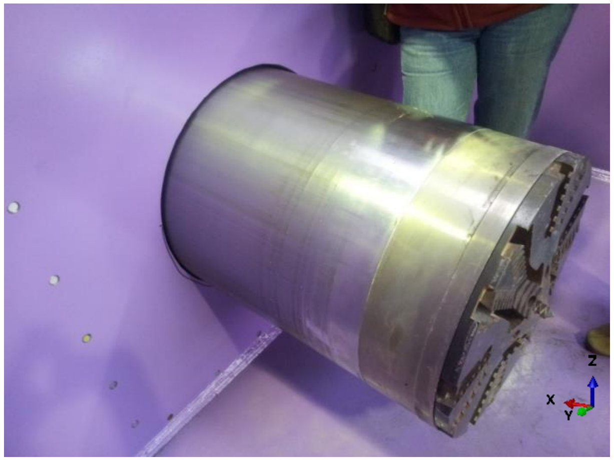
- overcut
- shield tapering
- tail void
- segmental lining with joint contacts
- gap grouting
- soil-fluid interaction

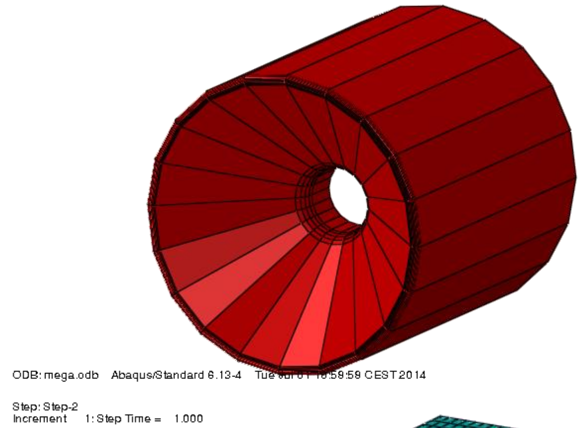
ALE FE modelling of development of face pressure and settlements

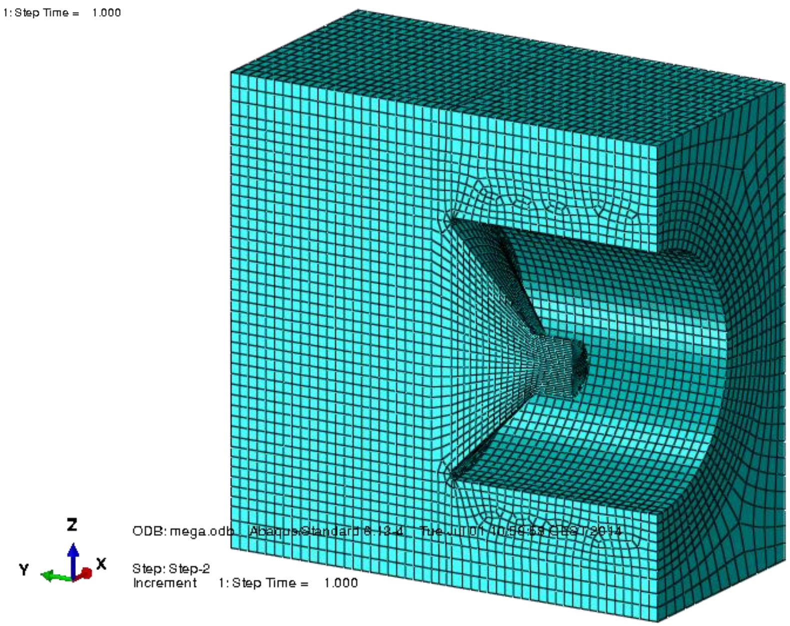
(Losacco *et al.*, 2015)



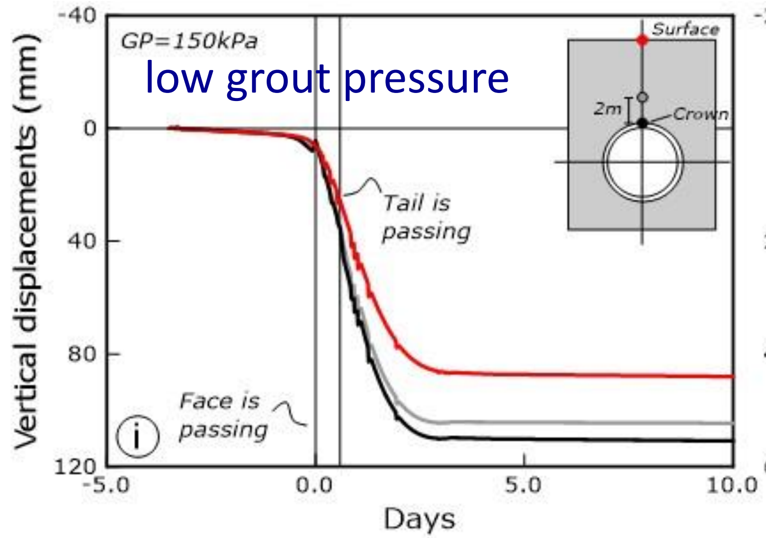
NUMERICAL MODELLING

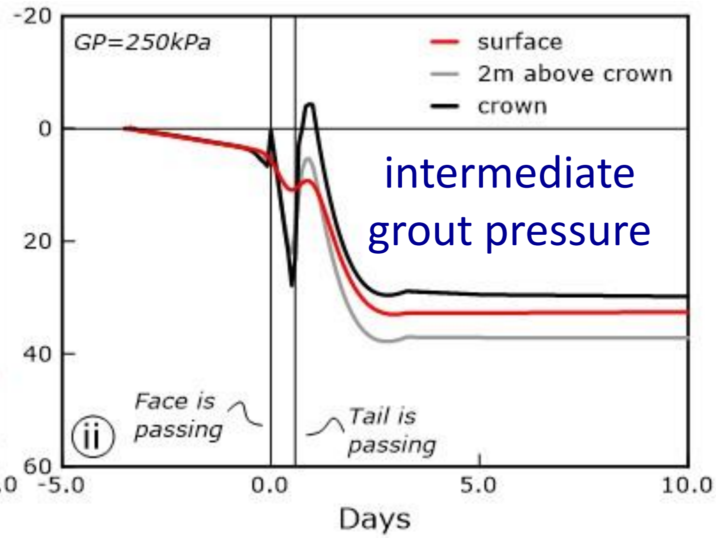


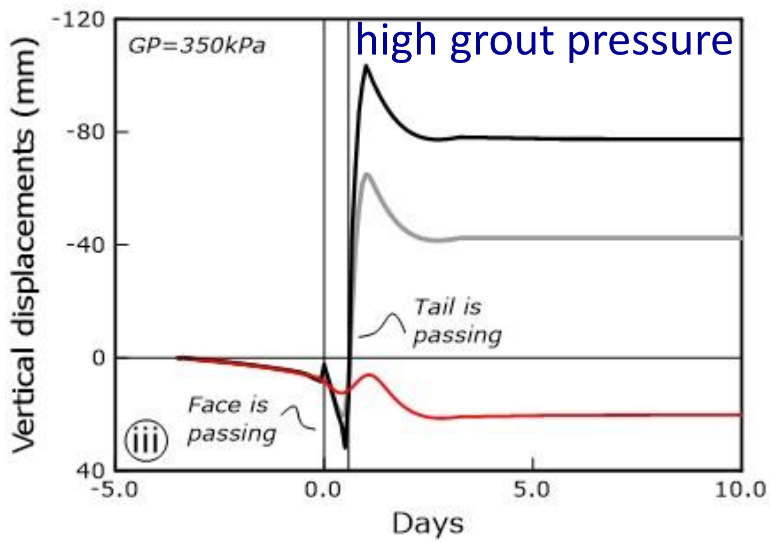




NUMERICAL MODELLING

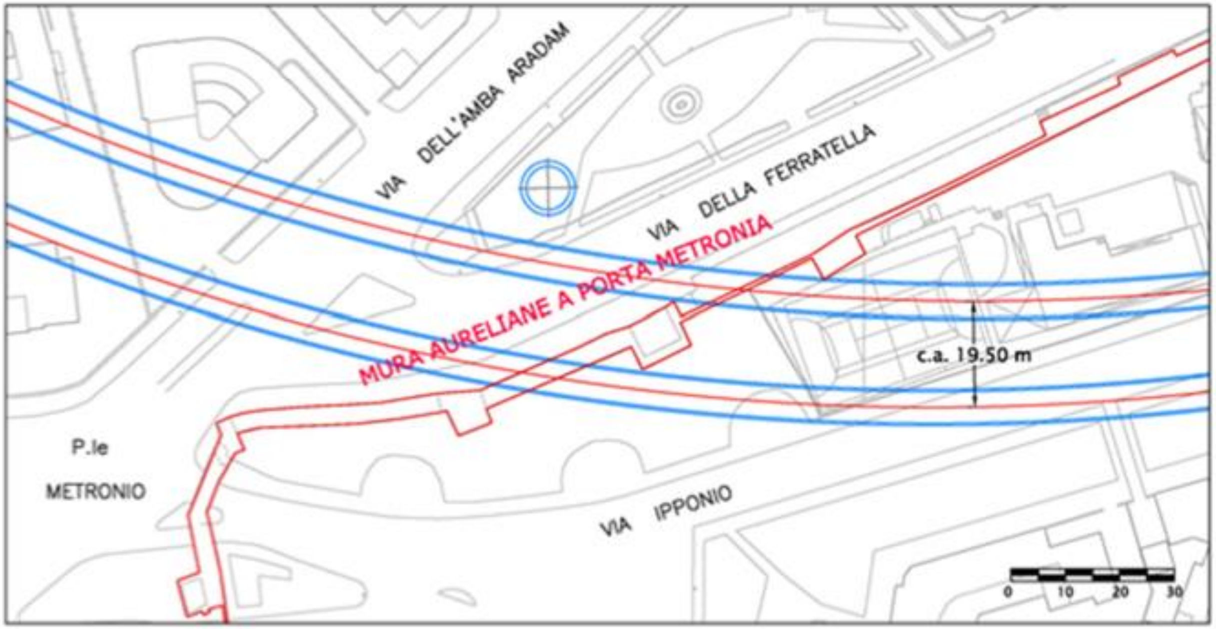


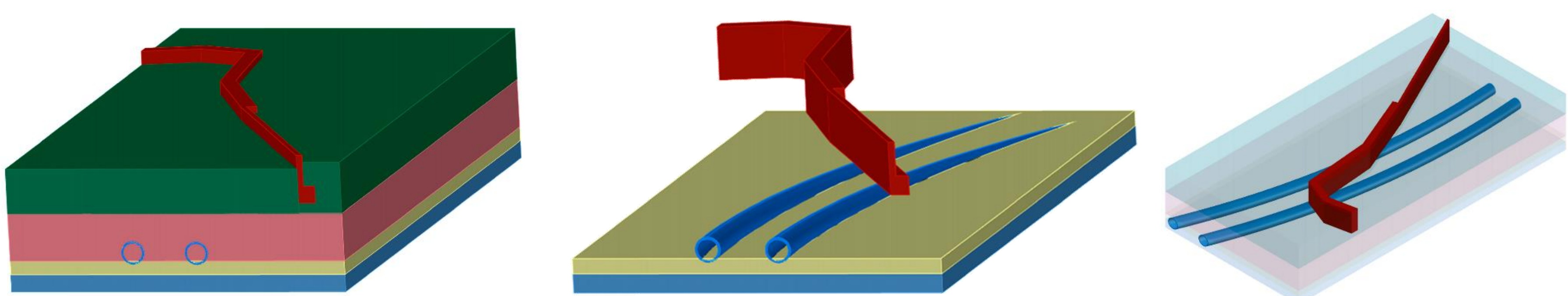


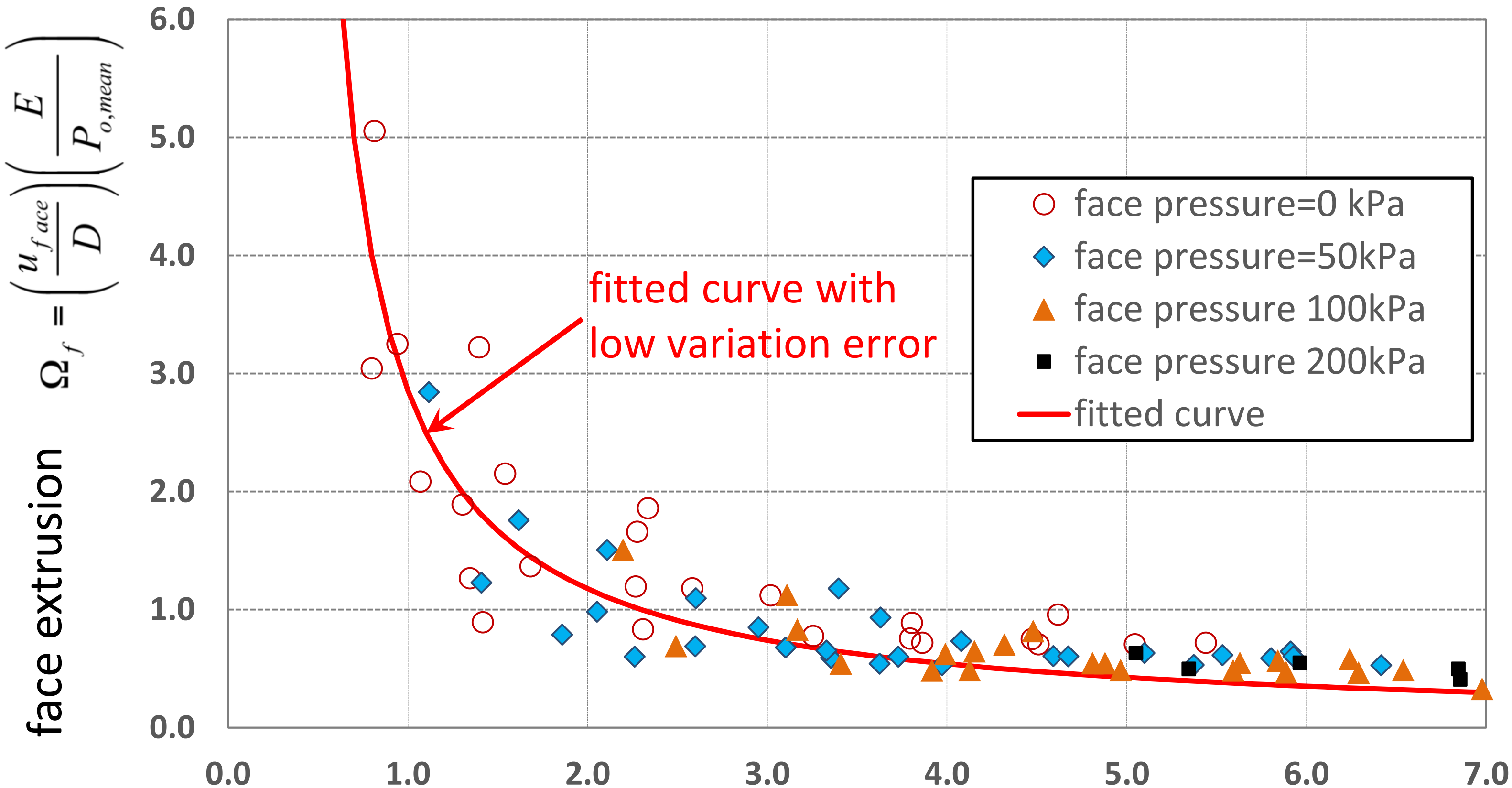


fully coupled Lagrangian

TBM advance


VIA DELL'AMBA ARADAM
VIA DELLA FERRATELLA
MURA AURELIANE A PORTA METRONIA
c.a. 19.50 m
P.le
METRONIO
VIA IPPONIO
0
10
20
30

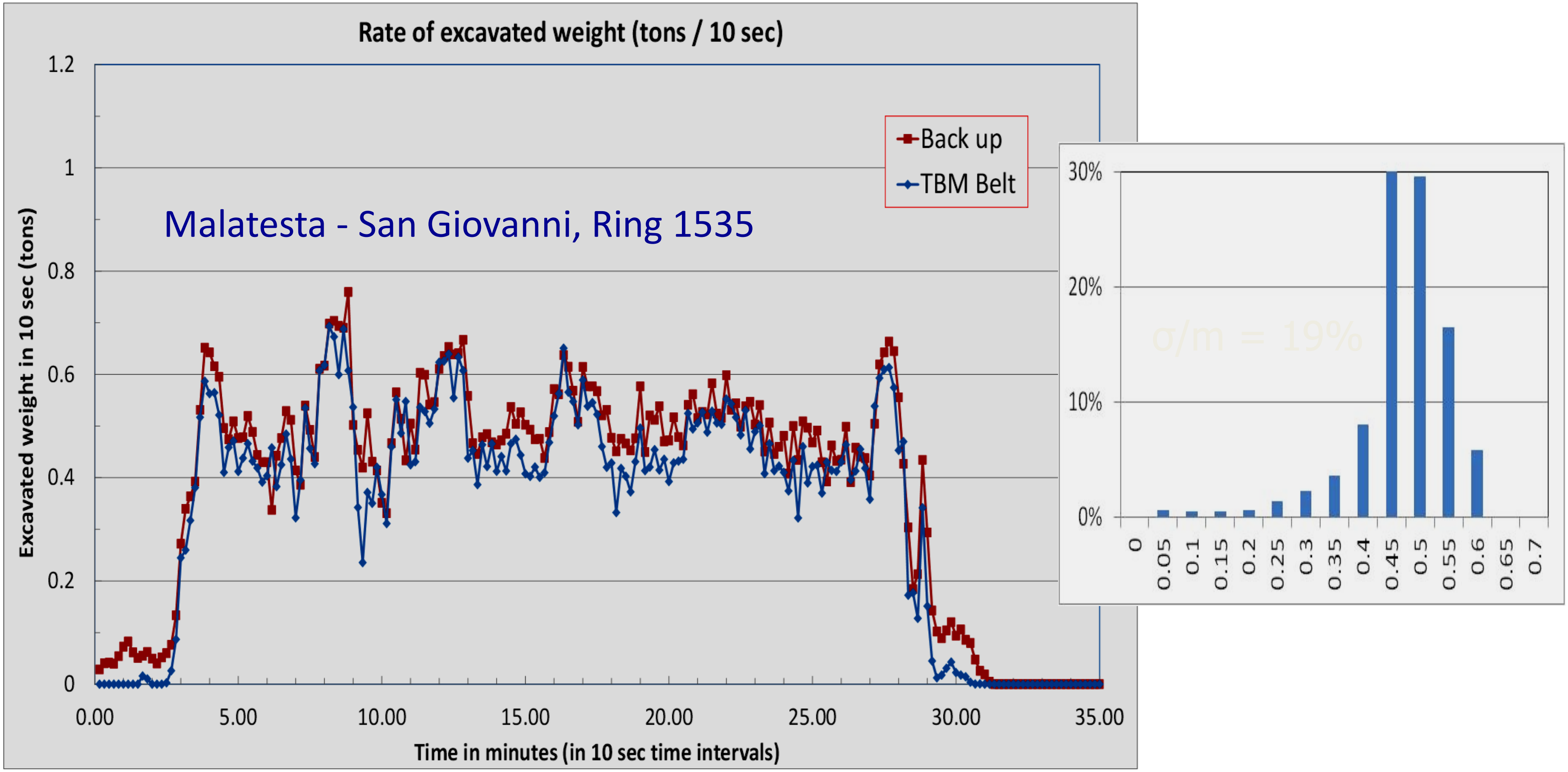




$$\Omega_f = \left(\frac{u_{face}}{D}\right)\left(\frac{E}{P_{o,mean}}\right)$$

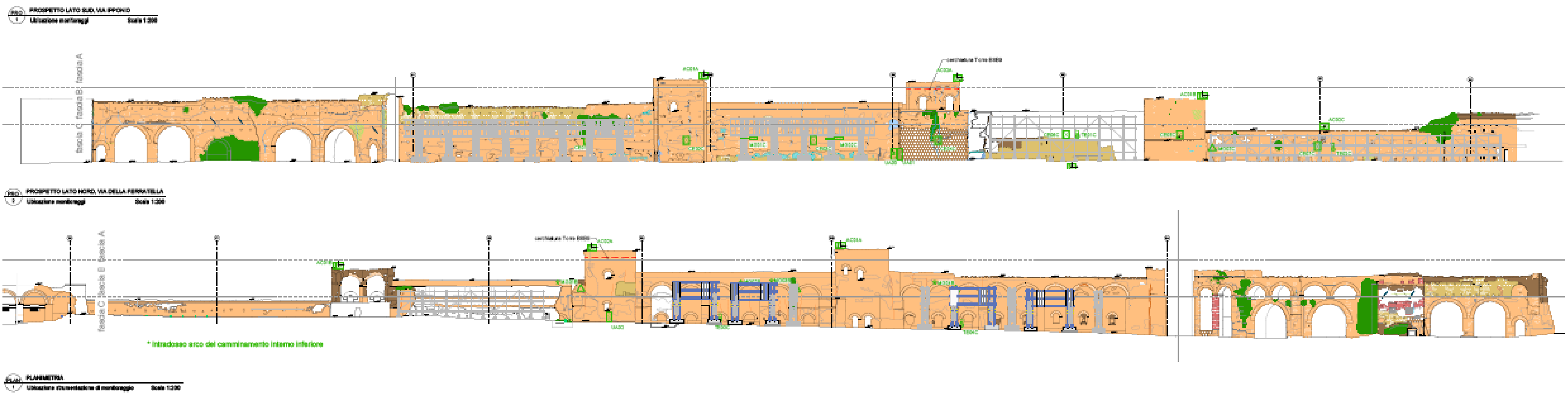
TBM face pressure, soil

$$\Lambda_f = \frac{5.25\, c\, N_\phi^a}{\gamma\, H^{1-b}\, D^b} + 8\left(\frac{H}{D}\right)\left(\frac{P_{face}}{P_{ho}}\right)^{1+0.1\left(H/D\right)}$$


Rate of excavated weight (tons / 10 sec)
Excavated weight in 10 sec (tons)
1.2
1
0.8
0.6
0.4
0.2
0
0.00
5.00
10.00
15.00
20.00
25.00
30.00
35.00
Time in minutes (in 10 sec time intervals)
Malatesta - San Giovanni, Ring 1535
Back up
TBM Belt
30%
20%
10%
0%
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
0.55
0.6
0.65
0.7

Contract T3 - NeTTUN stretch

FIELD MONITORING MONUMENTS

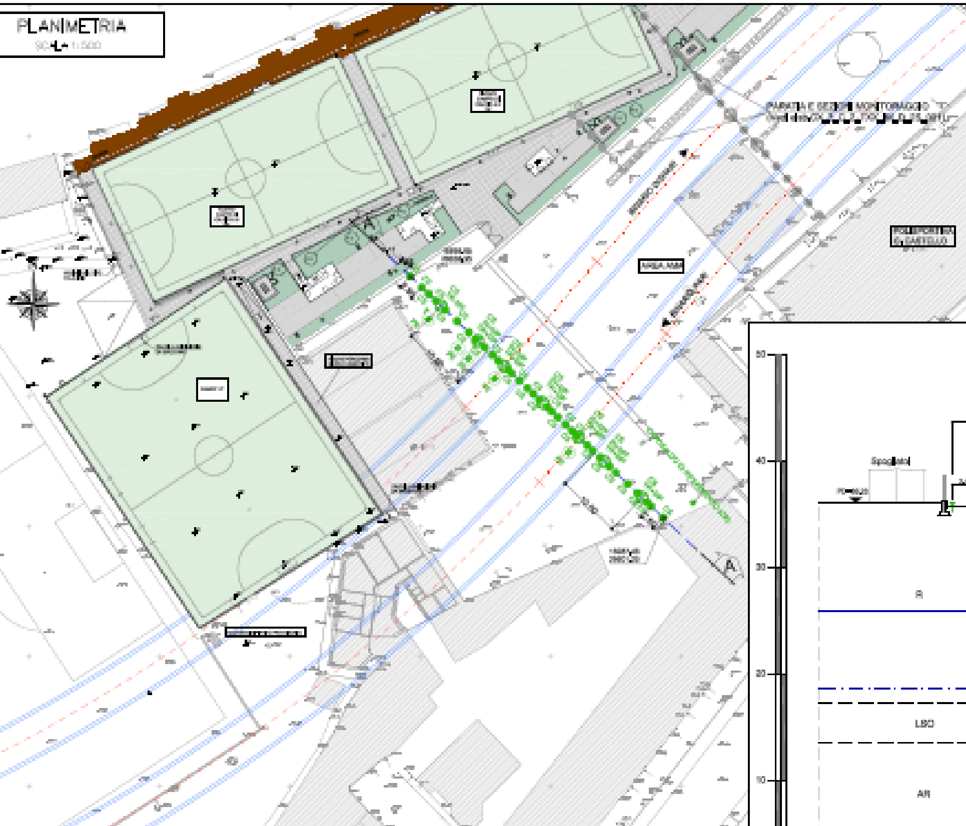


acquired instrumentation includes:

5 accelerometers (AC)
7 digital MEMS tilt meters (CE)
7 electrical crack meters (MG)
4 thermometers (TE)
74 mini-prisms (MP)
20 levelling pins (CS)
48 levelling staffs (SL)
48 settlement gauges (TL)
4 vibrating wire piezometers (PE)

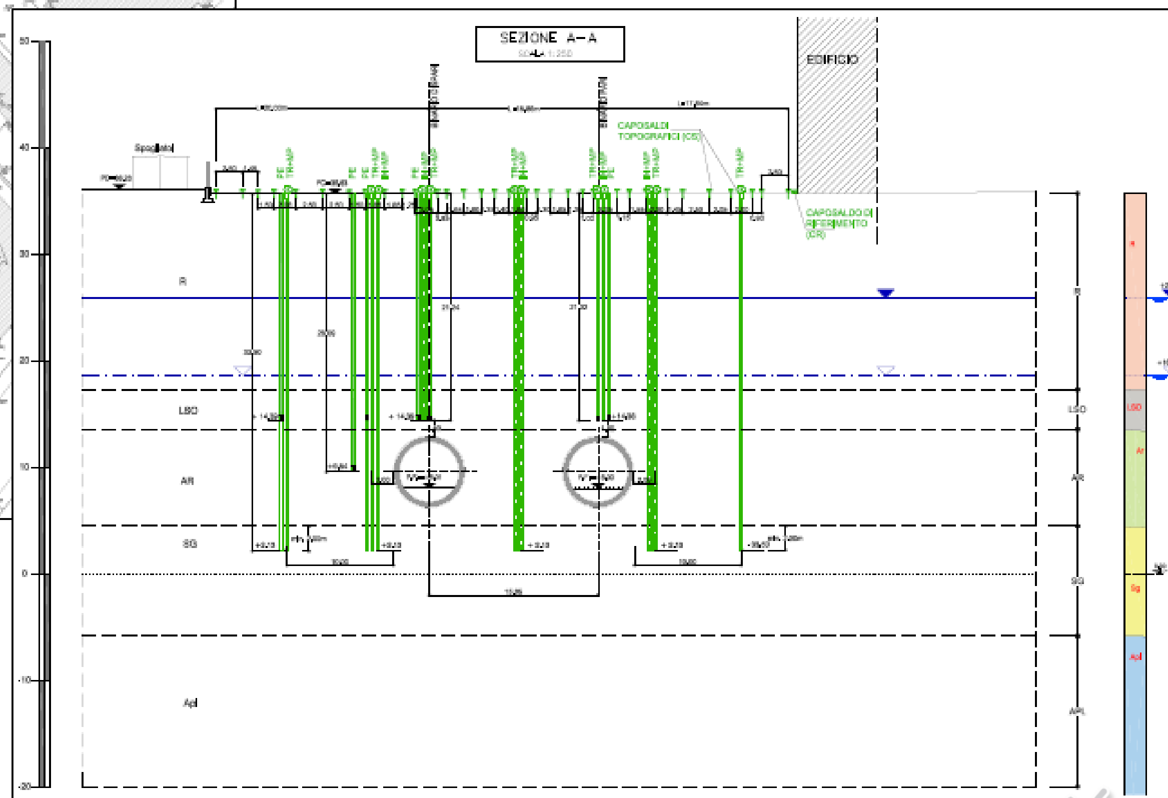
installation completed by December 2015

FIELD MONITORING GREEN FIELD SECTIONS



Instrumentation:

8 inclinometers (IN)
10 Trivec (TR)
58 levelling pins (CS)
5 vibrating wire piezometers (PE)



installation to be completed by January 2016

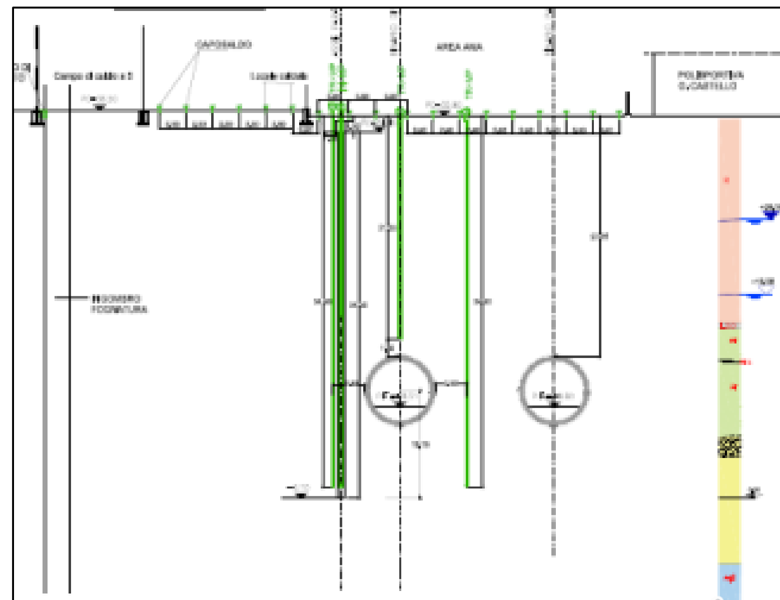
FIELD MONITORING BARRIERS

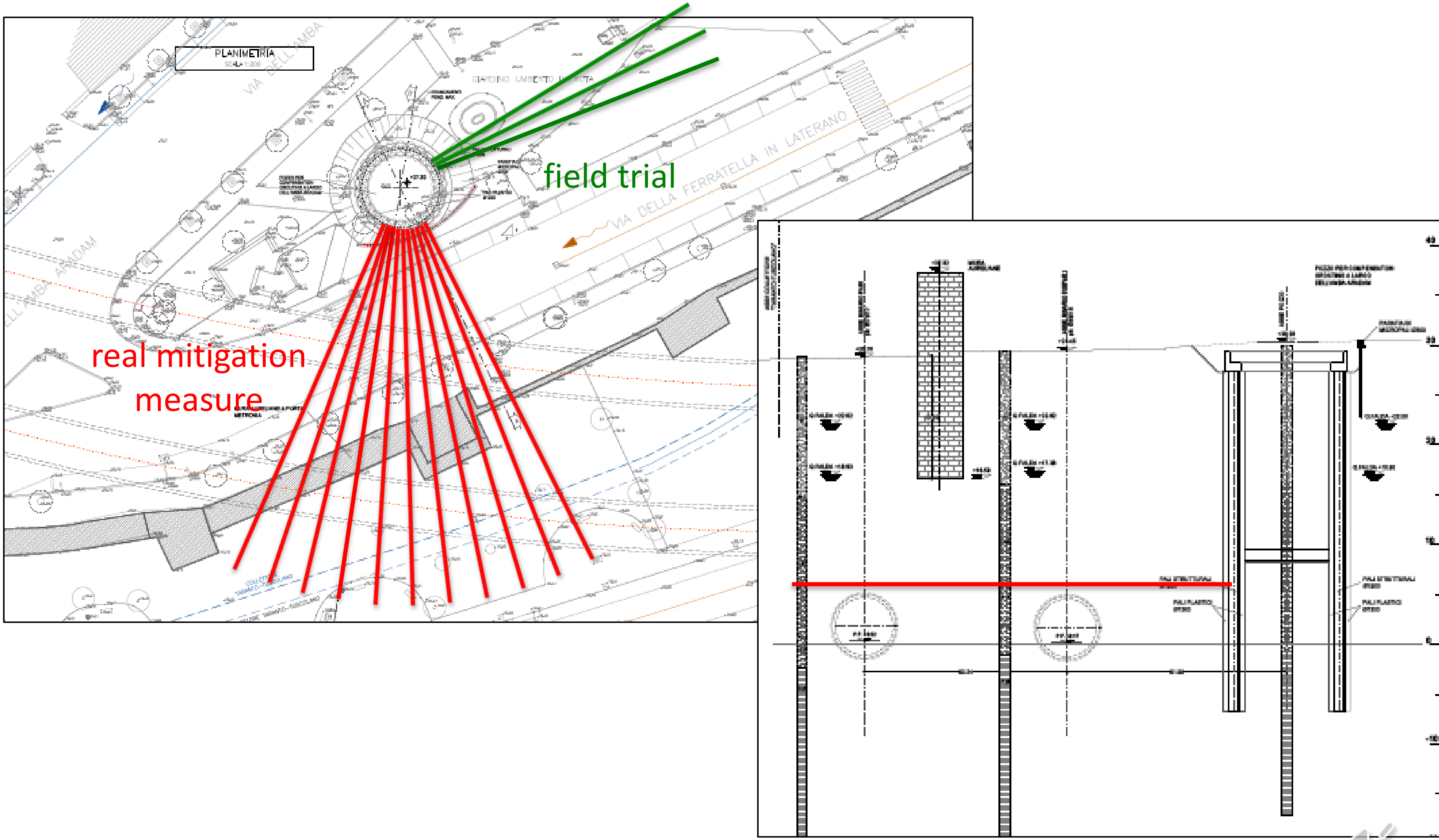
48 concrete piles
D = 600 mm; L = 34.5 m
spacing = 900 mm (=1.5 D)

instrumentation:

3 inclinometers (IN)
3 Trivec (TR)
24 levelling pins (CS)

installation to be completed
by January 2016

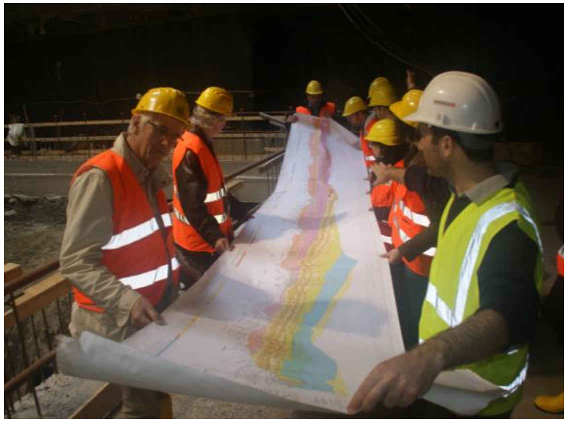



PLANIMETRIA
VIA DELLA FERRATELLA IN LATERANO
field trial
real mitigation measure

WORKING TOGETHER

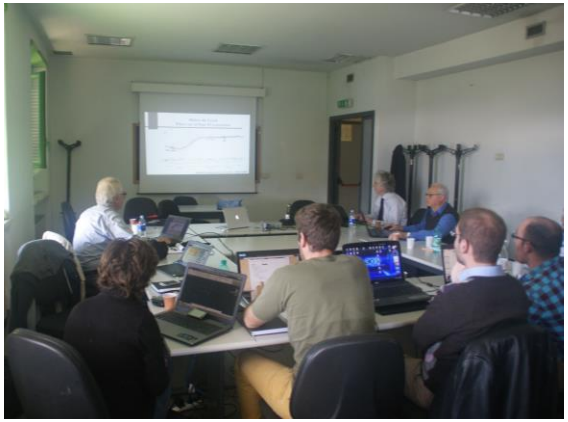
visiting sites

sharing knowledge



brainstorming

having fun!



CONCLUDING REMARKS

- many buildings to be studied
- need for handy but reliable procedures
- the entire process hinges on the geotechnical analyses
  - careful geotechnical characterisation
  - use of reliable models
  - levels of analysis of increasing complexity
  - two independent evaluations of damage
- close co-operation with other disciplines:
  - building features and history
  - geology
  - structural engineering
  - geomatics and monitoring
- **great opportunities for research & co-operation (friendship?)**