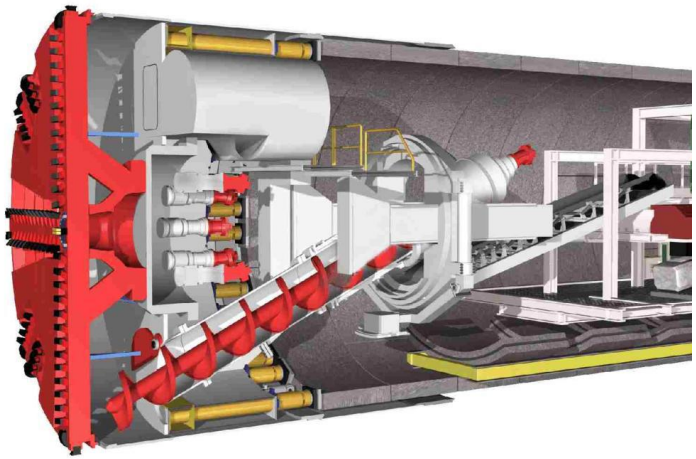
Infrastructures and Geotechnics

The effect of soil settlements on cultural heritage buildings, induced by underground structures. A preliminary study

Giorgos Karanikoloudis

Supervision: Paulo Lourenço (U Minho), João Bilé Serra (LNEC)



Overview

Underground structures
Cultural heritage

Underground structures in urban environment
Cultural heritage buildings

- Historical constructions • of high social and cultural value • extremely susceptible to damage and deterioration due to weathering and environmental actions • Low mechanical properties and brittle failure
- Often in close proximity of underlying networks • estimation of the related damage and employment of extensive monitoring and appropriate mitigation techniques

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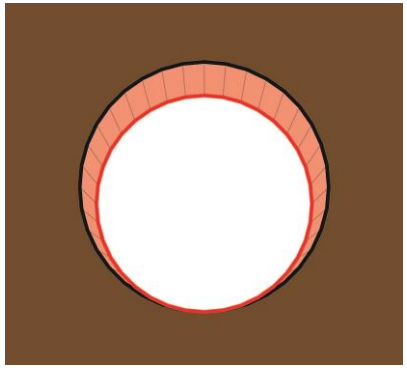
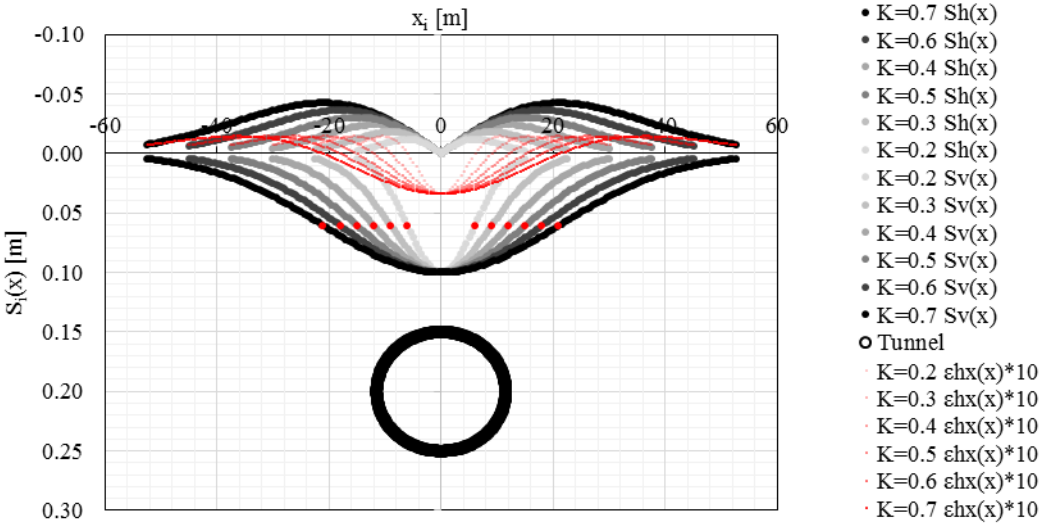
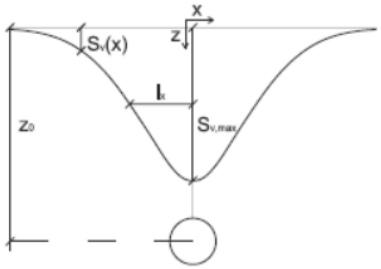
- Often in close proximity of underlying networks • estimation of the related damage and employment of extensive monitoring and appropriate mitigation techniques
- Emerging demand on underground constructions • aspects of efficacy, time transferring needs and obstruction in over-concentrated overground urban networks
- Induced settlements during excavation and service life • design and construction stages still remain an open challenge • efficient mitigation techniques

Underground structures in urban environment
Analytical approach

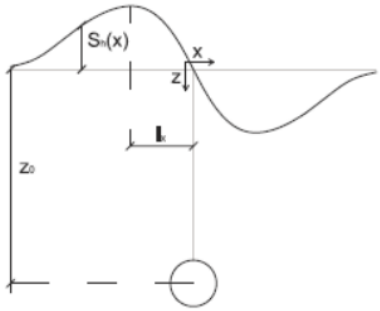
- 1st preliminary assessment • Greenfield settlement troughs in 3D space • overlying space with no structure accounted • verification through data collection







(a) vertical displacements



(b) horizontal displacements

$$S_v(x) = S_{v,max} \cdot e^{-\frac{x^2}{2 \cdot i_x^2}} \qquad S_v(x) = \sqrt{\frac{\pi}{2}} \cdot \frac{V_L \cdot D^2}{4 \cdot i_x} \cdot e^{-\frac{x^2}{2 \cdot i_x^2}}$$

$$i_x = K \cdot (z_o - z) \qquad V_L = \frac{V_S}{\pi \cdot D^2 / 4}$$

$$S_h(x) = S_v(x) \cdot \frac{x}{z_o} \qquad \varepsilon_{hx}(x) = \frac{S_v(x)}{z_o} \cdot \left(\frac{x^2}{i_x^2} - 1 \right)$$

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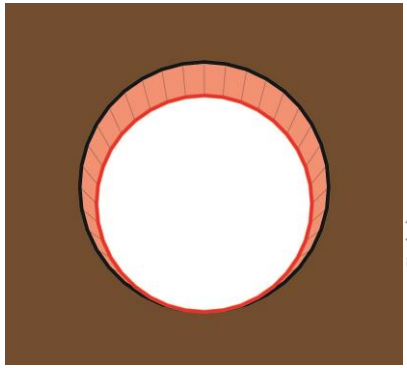
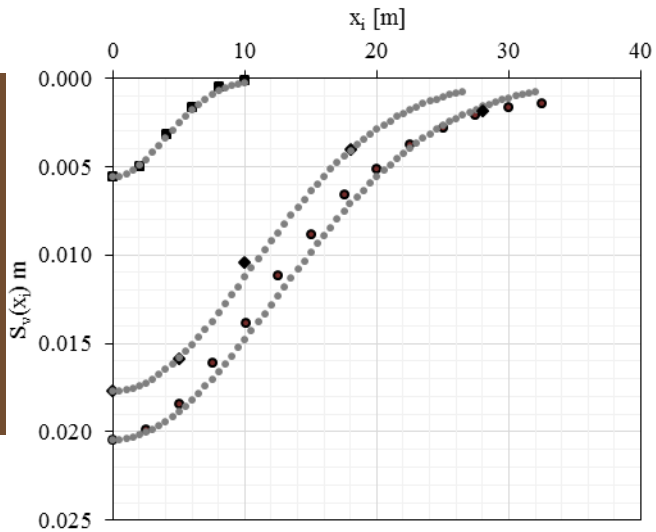
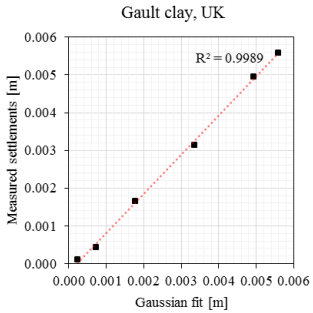
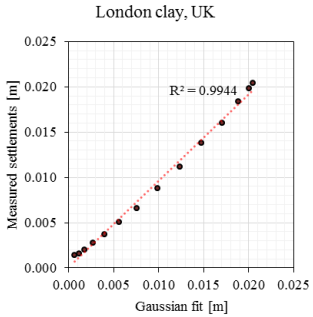
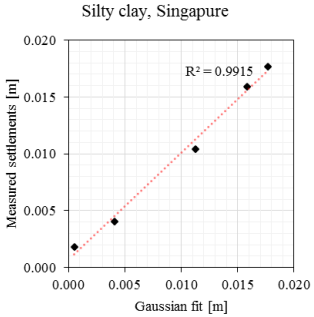


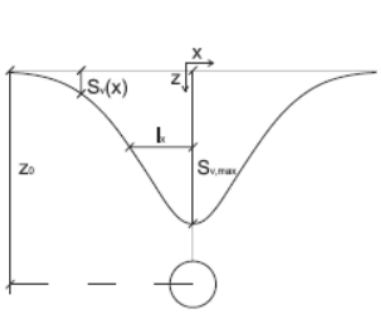


1.London clay, UK
1.Gaussian fit K=0.4
2.Gault clay, UK
2.Gaussian fit K=0.4
3.Silty clay, Singapure
3.Gaussian fit K=0.5









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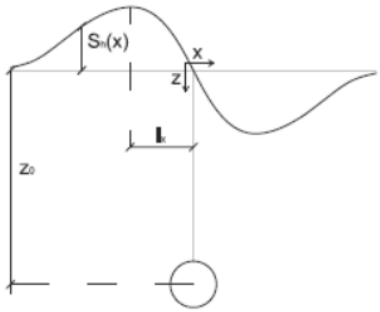

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Analytical approach

- More than one tunnels • relative depth and distance from centre points, • settlement troughs is derived as the superposition of troughs from single tunnels • lower the quality of Gaussian fitting

Table 1. Geotechnical properties of soil layers at the construction site (γ = unit weight of volume; e = void ratio; w = natural water content; K_0 = coefficient at rest; k = permeability coefficient; ν = Poisson ratio; G_0 = shear modulus at small strains; G = shear modulus; φ' = friction angle; c' = cohesion; c_u = undrained strength)

Unit	γ: kN/m^3	e	w: %	K_0	k: m/s	ν	G_0: MPa	G: MPa	φ': °	c': kPa	c_u: kPa
R	17·0	1·2	43	0·5	$1·0 \times 10^{-5}$	0·3	40	16	31	10	–
VS-PN	17·5	0·9	35	0·4	$3·0 \times 10^{-6}$	0·3	80	32	37	12	–
T2	16·0	1·5	45	0·4	$4·0 \times 10^{-6}$	0·3	250	150	35	40	–
TA	16·0	1·5	47	0·6	$9·0 \times 10^{-6}$	0·3	210	84	25	27	–
T1	16·0	1·5	45	0·4	$4·0 \times 10^{-6}$	0·3	250	150	35	40	–
ST-AR	19·5	0·7	25	0·6	$3·0 \times 10^{-7}$	0·3	150	60	25	15	130

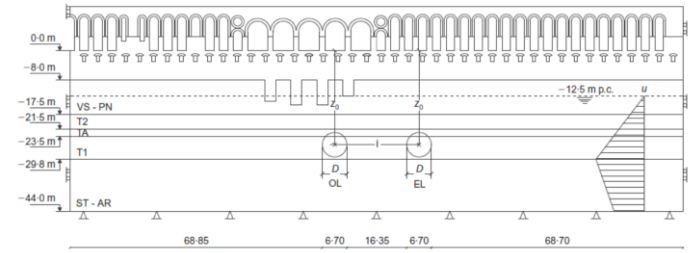
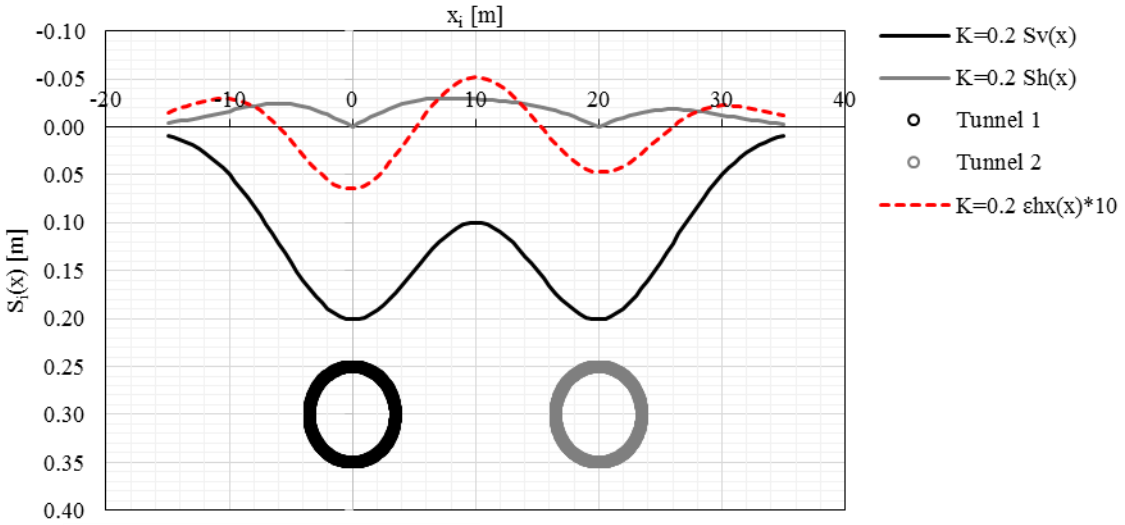
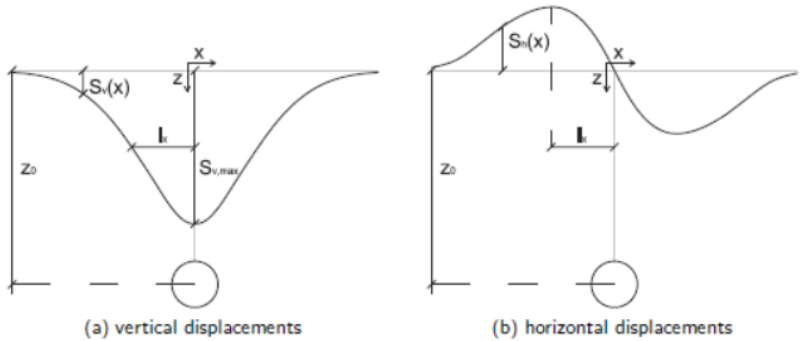
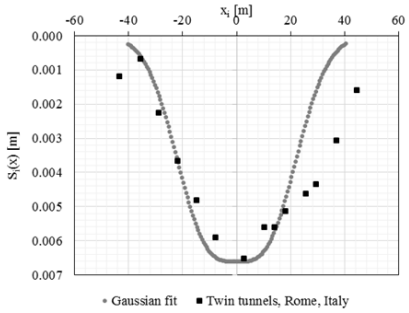
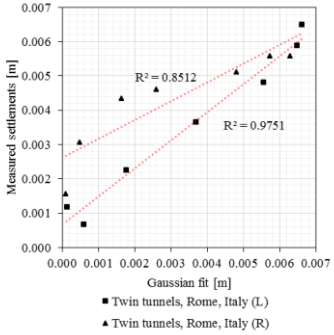


Fig. 8. Schematisation of the Felice aqueduct and of the geotechnical conditions









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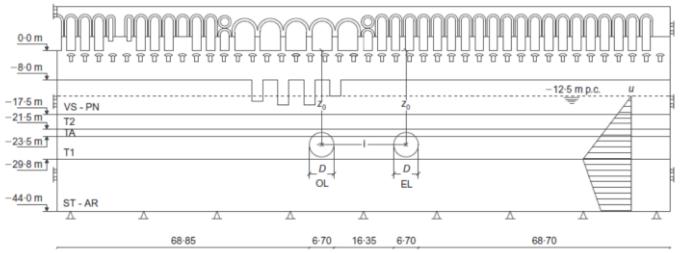

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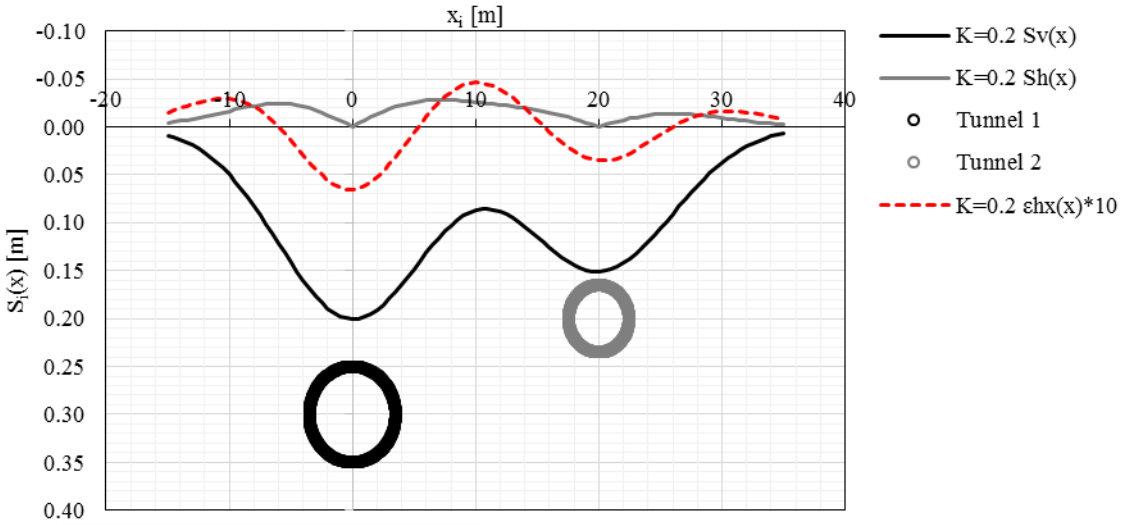

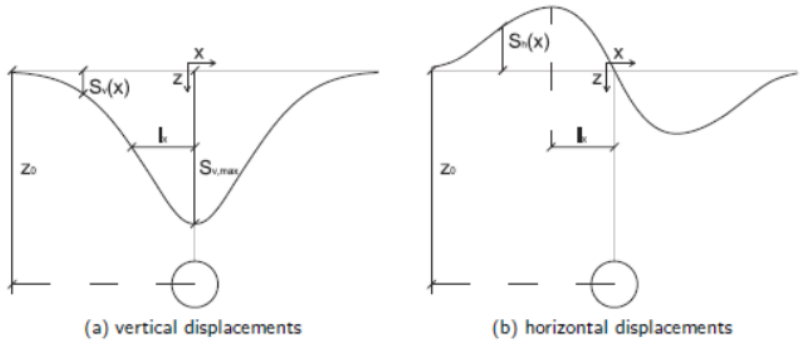

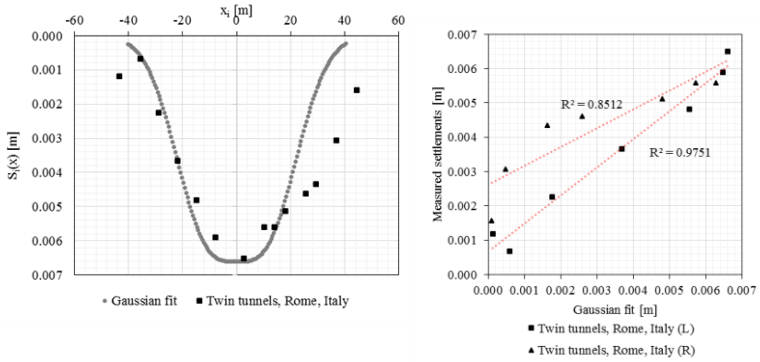

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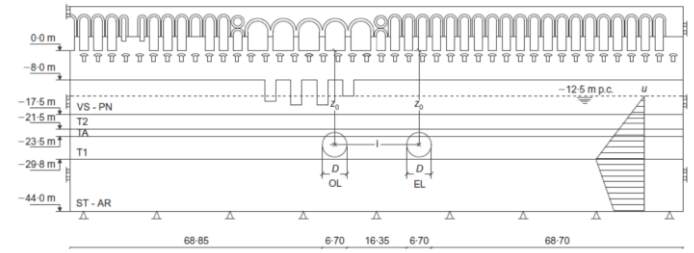

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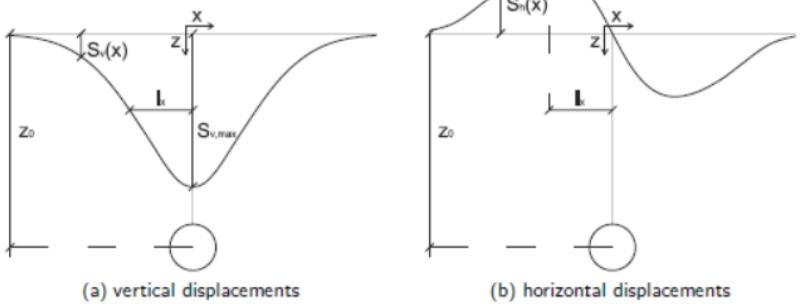
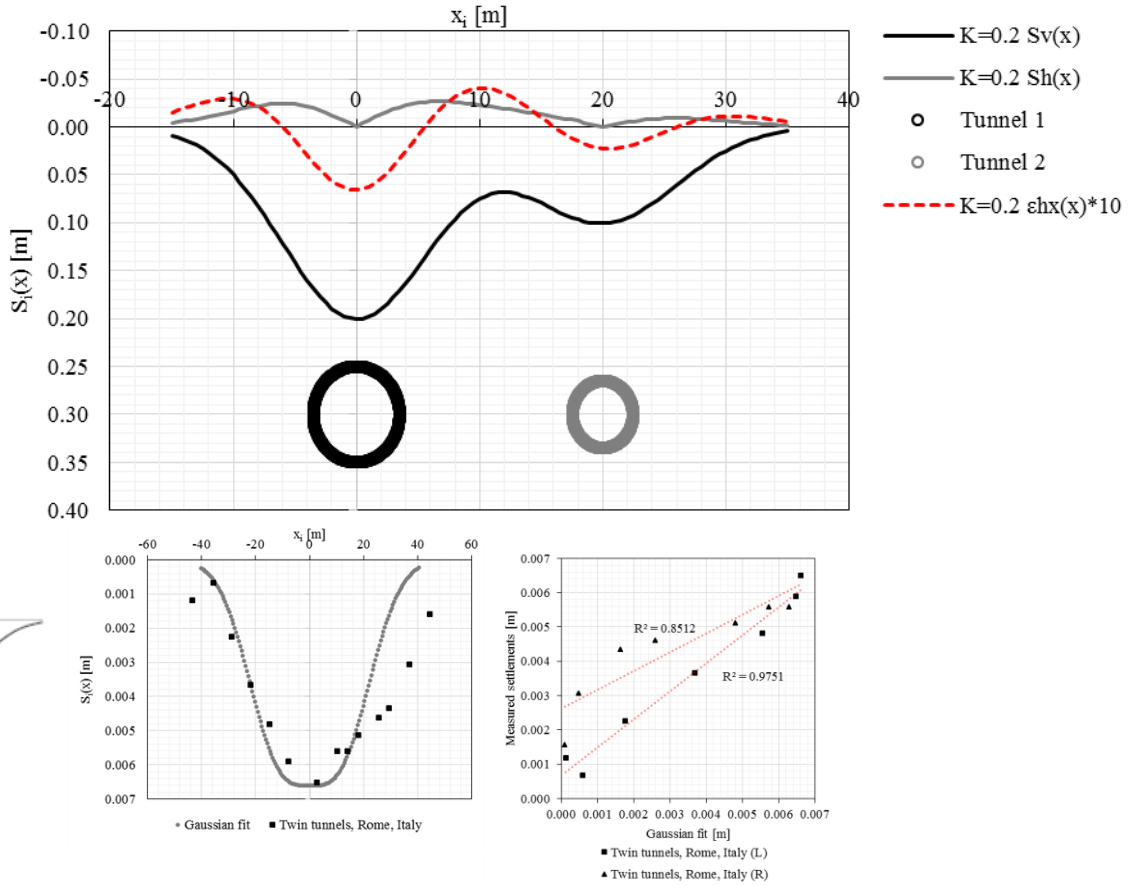
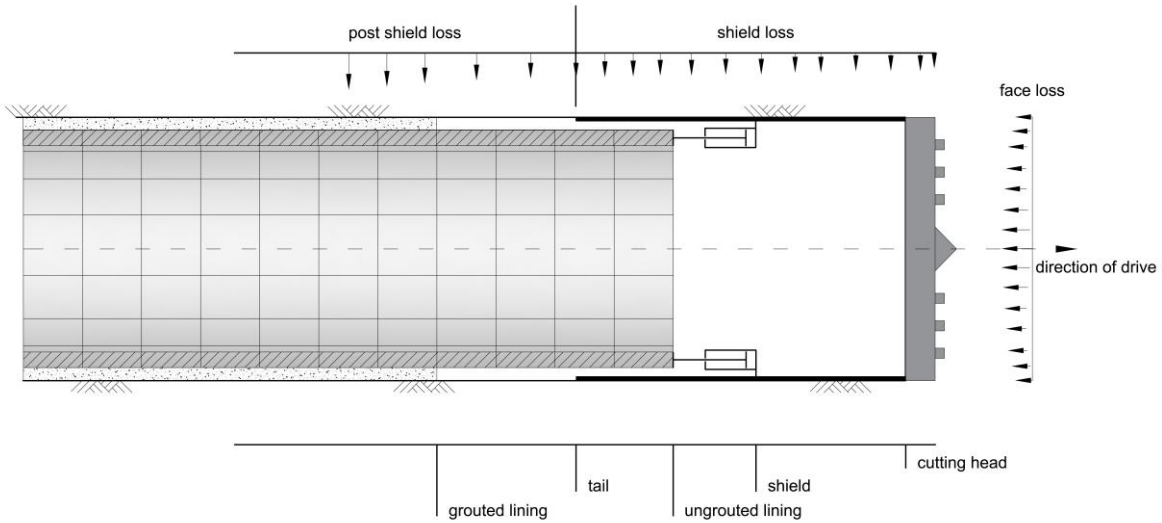




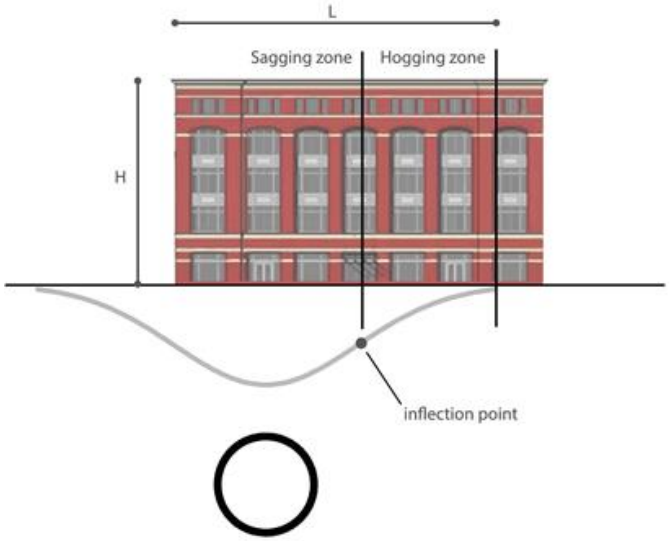
Underground structures in urban environment
Short-term settlement profile – Construction process

- Face loss: Counteracting applied pressure in the plane of the cutter head • the induced settlement can be controlled and minimized
- Radial loss in shield: By the use of EPB, the soil pressure in the circumference of the boring machine can be reduced
- Radial loss behind the shield (tail void): Portion of the face is unsupported and radial deformations evolve • common practice to directly inject grout under pressure and can keep the deformation of the tunnel face within certain limits (V_L).



Underground structures in urban environment

Overlying structures – Damage categories



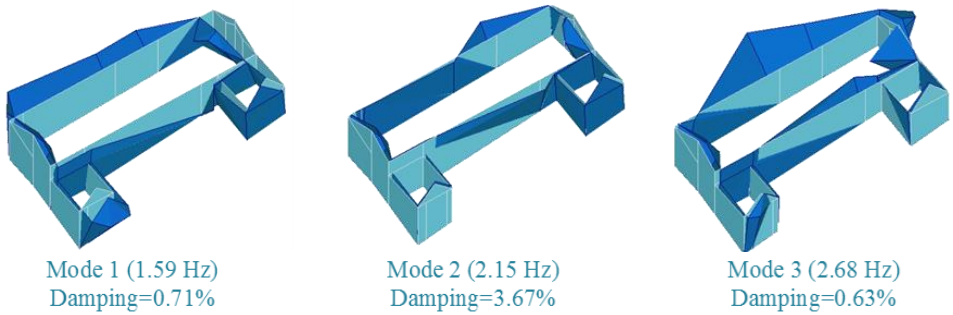
Category of damage	Degree of damage	Description of typical damage and form of repair	Typical crack widths (mm)	Maximum tensile strain %	Δ* cm	δ/L **
0	Negligible	Hairline cracks of less than about 0.1 mm width.	0-0.1	0-0.05	<3	$< 1/300$
1	Very slight	Fine cracks which can easily be treated during normal decoration. Perhaps isolated slight fracturing in building. Cracks in external brickwork visible on close inspection.	0.1-1	0.05-0.075	3-4	$1/300$ to $1/240$
2	Slight	Cracks easily filled. Redecoration probably required. Several slight fractures inside building. Exterior cracks visible; some repointing may be required for weather-tightness. Doors and windows may stick slightly.	1-5	0.075-0.15	4-5	$1/240$ to $1/175$
3	Moderate	Cracks may require cutting out and patching. Recurrent cracks can be masked by suitable linings. Repointing and possibly replacement of a small amount of exterior brickwork may be required. Doors and windows sticking. Utility services may be interrupted. Weather tightness often impaired.	5-15	0.15-0.3	5-8	$1/175$ to $1/120$
4	Severe	Extensive repair involving removal and replacement of sections of walls, especially over doors and windows required. Windows and door frames distorted. Floor slopes noticeably. Walls lean or bulge noticeably, some loss of bearing in beams. Utility services disrupted.	15-25	>0.3	8-13	$1/120$ to $1/70$
5	Very severe	Major repair required involving partial or complete reconstruction. Beams lose bearing, walls lean badly and require shoring. Windows broken by distortion. Danger of instability.	>25		>13	$> 1/70$

*Maximum vertical differential settlement

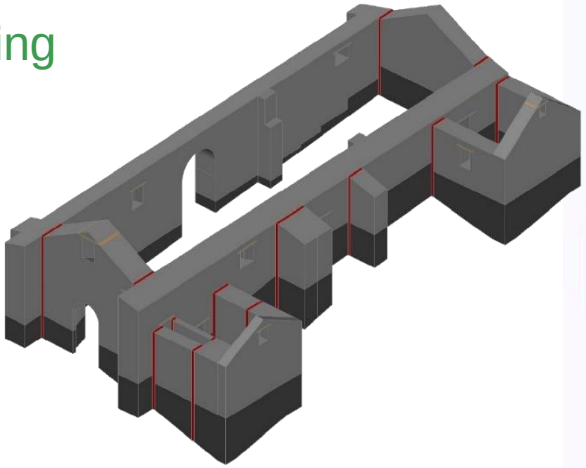
**Deflection slope

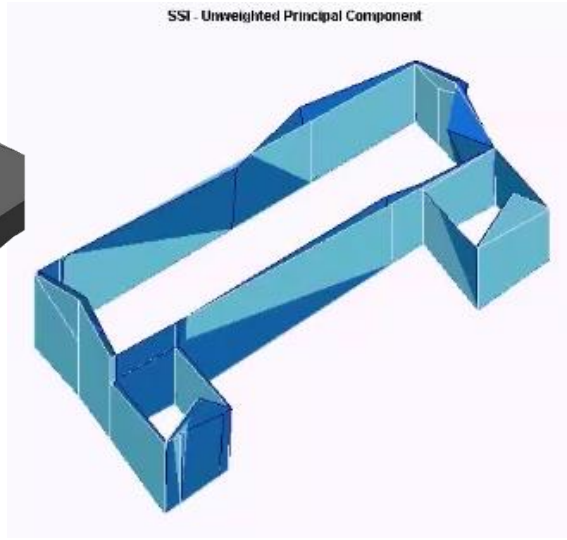
Underground structures in urban environment
Cultural heritage buildings – Soil/structure interaction

The Kuño Tambo Church, Peru



- Dynamic identification tests
- Independent orthogonal bending modes, of 1st and 2nd order
- Mode shapes in out-of-phase symmetric patterns, with high peaks and similar amplitudes
- Low level of connectivity
- Damage related



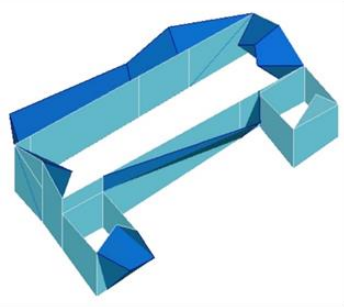


Underground structures in urban environment
Cultural heritage buildings – Soil/structure interaction

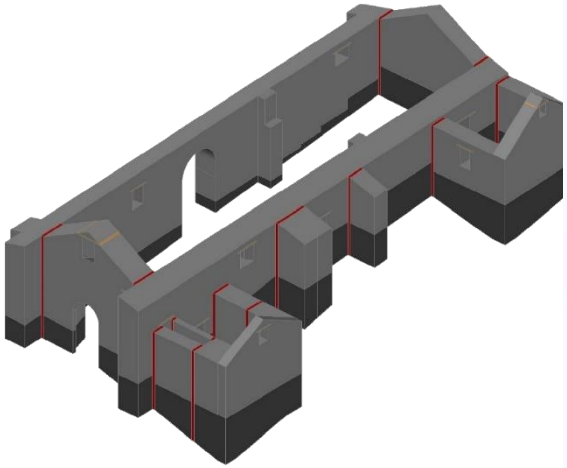
The Kuño Tambo Church, Peru

Global model with material properties from sonic tests [3]											
Springs at base		Interfaces									
		South façade		North façade		Sacristy		Buttresses		Baptistery	
K_z (N/mm)	$K_{x,y}$ (N/mm)	K_n (N/mm^3)	K_s (N/mm^3)	K_n (N/mm^3)	K_s (N/mm^3)	K_n (N/mm^3)	K_s (N/mm^3)	K_n (N/mm^3)	K_s (N/mm^3)	K_n (N/mm^3)	K_s (N/mm^3)
2900	1160	0.0022	0.0011	0.0022	0.0012	0.0022	0.0012	0.0022	0.0011	0.0022	0.0011

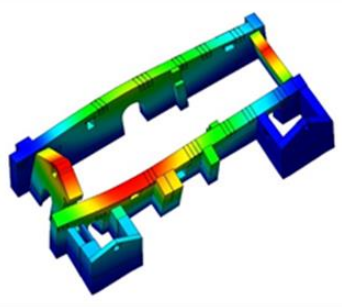
Dynamic test



Mode 1 (1.59 Hz)
Damping=0.71%



Modal analysis



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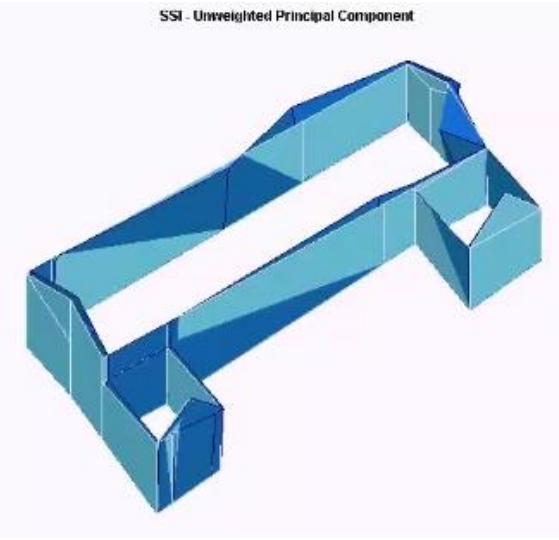
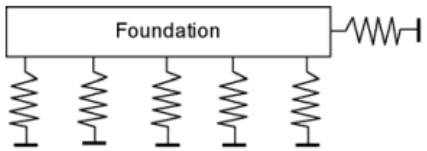


- Correlation of experimental and numerical modal results
- Adjusting the frequency and mode vectors of the 1st Mode (1.59 Hz)

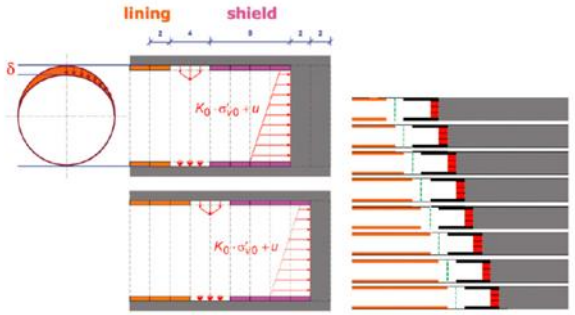


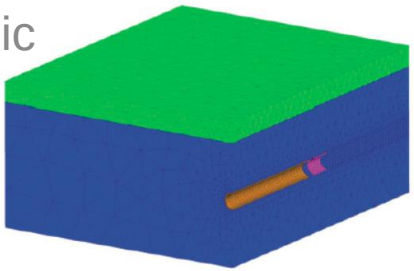
Underground structures in urban environment

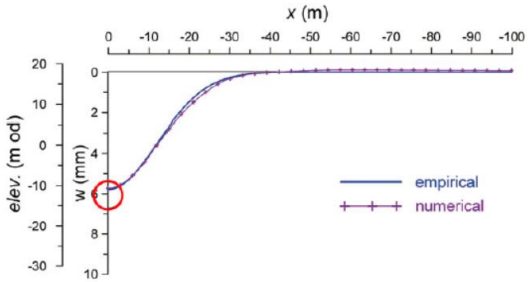
Cultural heritage buildings

Advanced numerical modelling

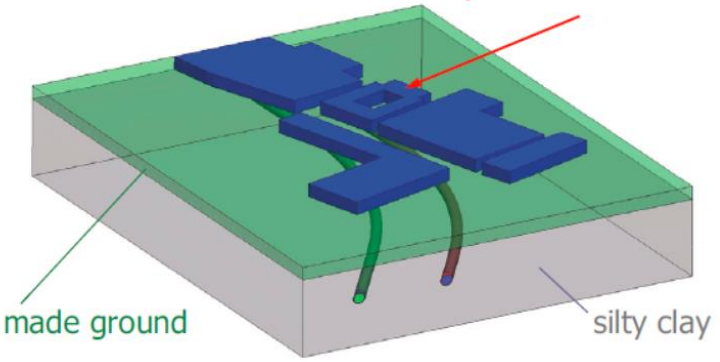
- Tunnel construction sequence and techniques
- Multiple tunnel construction
- Arbitrary alignment of tunnels' main axis with structures of interest
- Complex soil stratigraphy and hydraulic conditions
- Local ground treatments (i.e. grouting)
- Adjacent overlying structures and services
- Long term settlement conditions and brittle failure



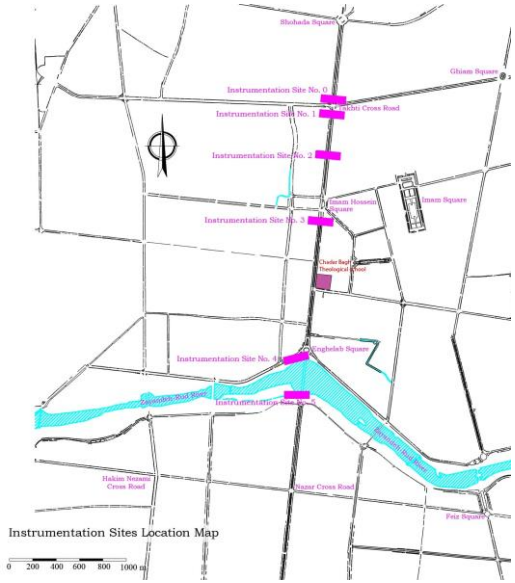


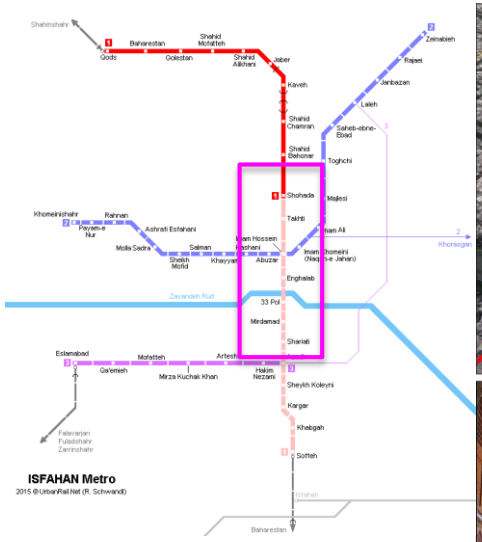


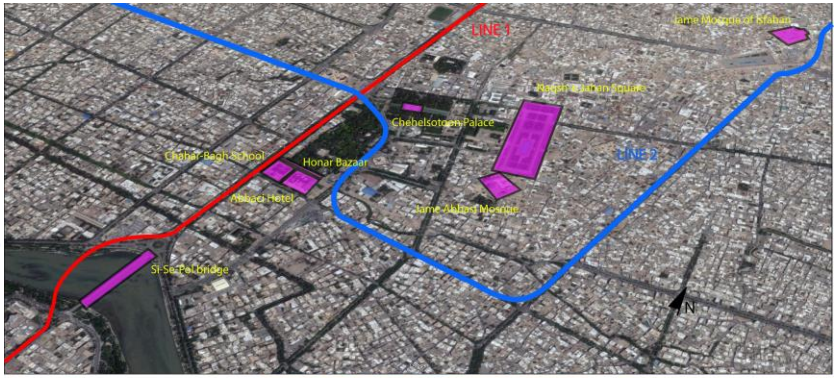
Palazzo Grazioli – equivalent solid

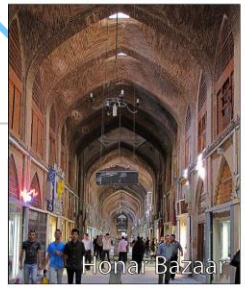


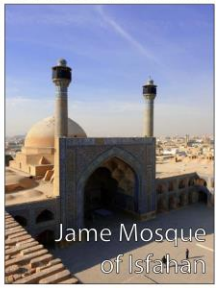
Underground structures in urban environment
Cultural heritage buildings





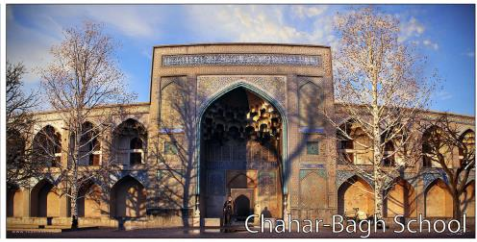






The subway metro project in Esfahan, Iran

- Excavations underneath the historic center
- Monitoring of the evolution and magnitude of the induced settlements
- Design recommendations for 2nd construction phase



Thank you

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