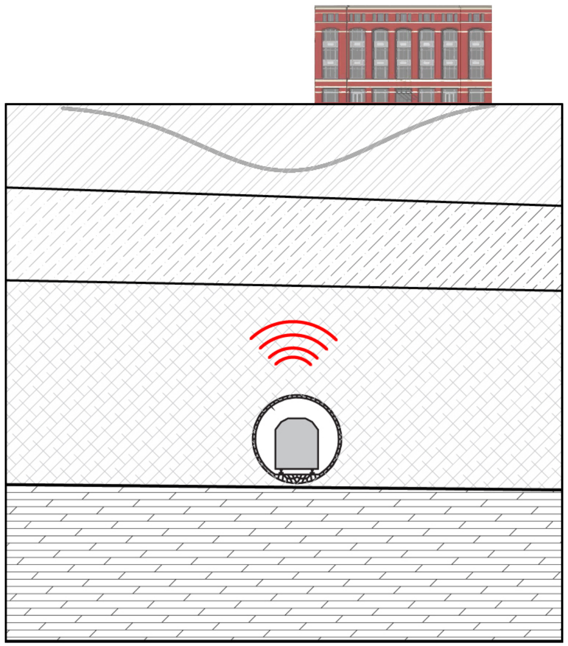
Infrastructures and Geotechnics

Risk management applied to cultural heritage buildings. The effect of soil settlements and vibrations induced by underground structures.

Georgios Karanikoloudis

Supervision: Paulo Lourenço (UMinho), João Bilé Serra (LNEC)



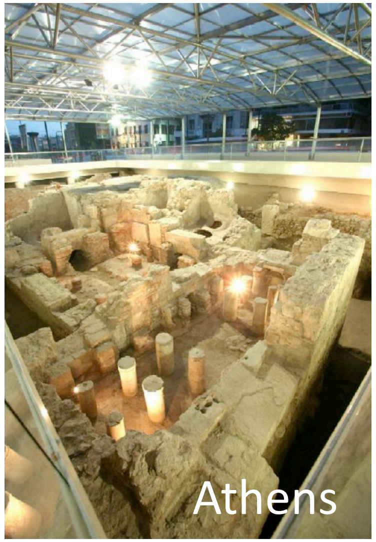
Overview

Underground structures in urban environment
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
- Emerging demand on underground constructions • aspects of efficacy, time transferring needs and obstruction in over-concentrated overground urban networks
- Often in close proximity of underlying networks • estimation of the related damage, employment of extensive monitoring and appropriate mitigation techniques



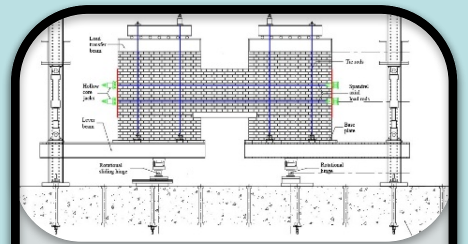
Thesis outline

Introduction

Literature review

- Soil-structure interaction
- Effects of underlying structures
- Prediction of settlements
- Assessment of vibrations
- Risk assessment on cultural heritage

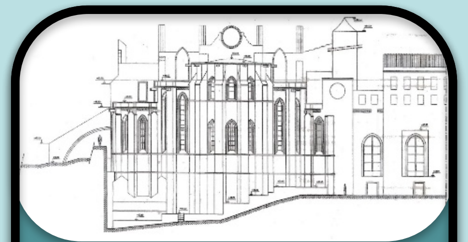
Experimental work



- Historic facades
- Masonry piers and spandrels

Parametric analyses

Monitoring of real case studies



- Lisbon, Isfahan
- Groundborne Vibrations

Modelling and assessment

Conclusions Recommendations

Thesis outline

Introduction

Literature review

Experimental work

Monitoring of real case studies

Objectives

- Applied methodology of risk management in buildings of cultural heritage
- Advanced numerical tools on the assessment of induced settlements and vibrations
- Thresholds of damage for elements of architecture; i.e. frescos
- Experimental and monitoring strategies for diagnosis; i.e. settlements and fatigue
- Assessment of current acceptable levels through international standards

Conclusions Recommendations

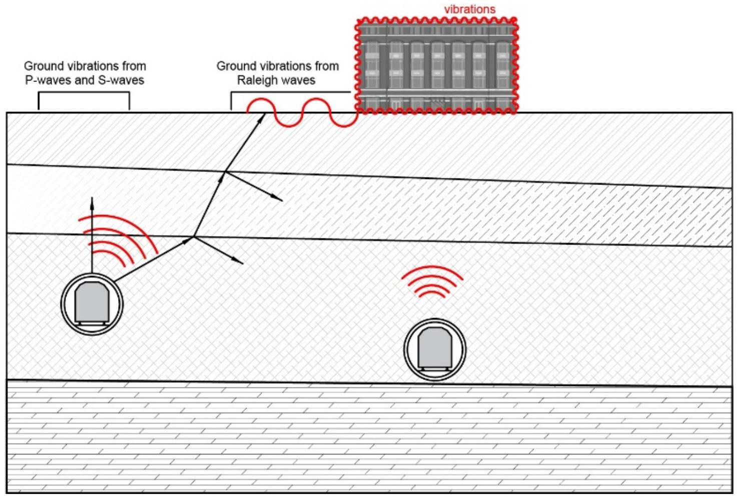
Underground structures in urban environment

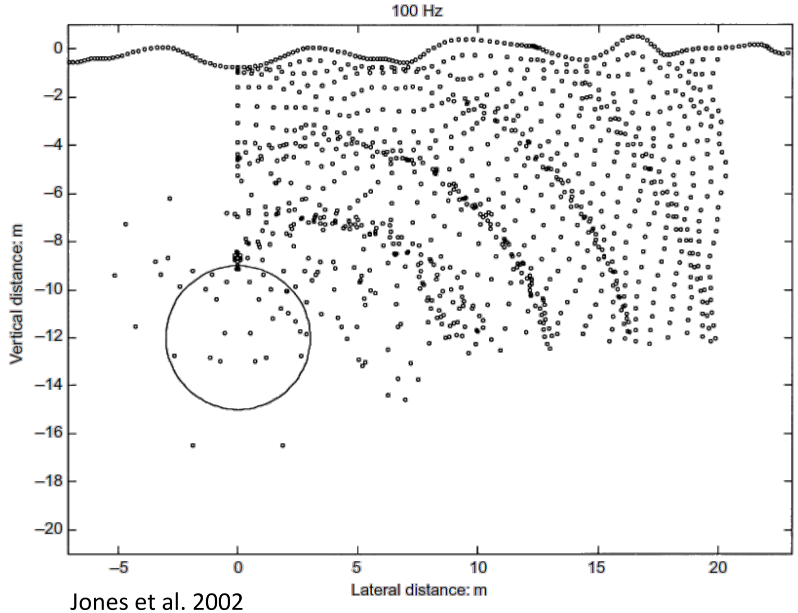
Induced vibrations from underground railway traffic
Thresholds from international standards

Underground structures in urban environment

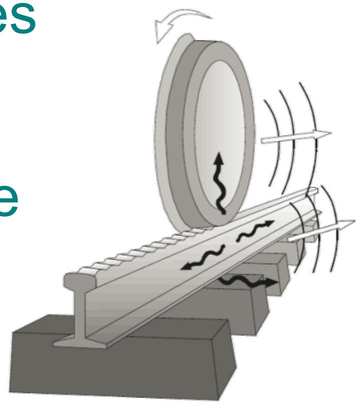
Groundborne vibrations • Underground railways

- ❑ Wave propagation in the elastic half-space
  P-wave, S-waves, Rayleigh waves
- ❑ Quasi-static, dynamic axle loads
  Unevenness of wheels and track lines
- ❑ High frequency content 30-250 Hz
- ❑ The type of building: dimensions,
  structural system and material properties
- ❑ The level of exposure: duration,
  amplitude, number of cycles
- ❑ Soil type: energy content
  in different frequency range





Jones et al. 2002



Underground structures in urban environment

Groundborne vibrations • Thresholds from international standards

- ❑ Guidelines on: Measurement / Instrumentation / Processing / Evaluation
- ❑ $|V_{max}|$, $|V_R|$
- ❑ Permanent / interminent type
- ❑ Dynamic magnification
- ❑ Indicative vibration levels
- ❑ Load bearing capacity
- ❑ Cosmetic damage
- ❑ Fatigue under low vibrations (10^{10} cycles)

Vibration limits for buildings of cultural heritage

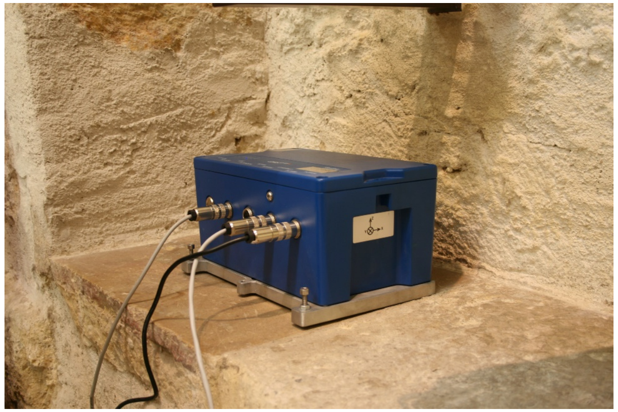
Type and condition of structure	Vibration source/type	Description	Dominant vibration frequency range (Hz)	Peak particle velocity (mm/s)	Indicator	Reference	Country
Structures of particular sensitivity to vibration and of great intrinsic value (e.g. listed buildings under preservation order)	Short-term	Vibrations at foundation level	1-10	3	$\|V_{max}\|$	DIN 4150-3 1999	Germany
			10-50	3-8			
			50-100	8-10			
		Vibration at a horizontal plane of highest floor	-	8	$\|V_{max}\|$		
	Long-term	Vibration in horizontal plane of highest floor	-	2.5	$\|V_{max}\|$		
Historical buildings or under protection	Occasional Frequent	Measures vibrations at foundation level	<30	1.5-3	$\|V_R\|$	SN 640312 1992	Switzerland
			30-60	2-4			
			>60	3-6			

Underground structures in urban environment

Induced vibrations from underground railway traffic
Structural monitoring in cultural heritage buildings

Underground structures in urban environment

Groundborne vibrations • Structural monitoring



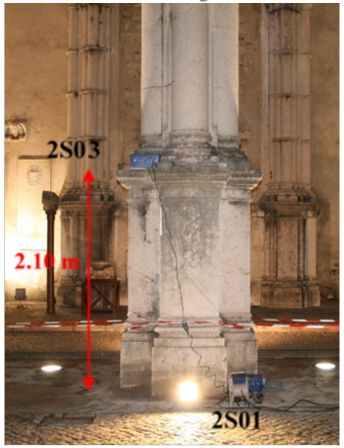
- Monitoring of metro induced vibrations during operational time in cultural heritage buildings
  3 reference case studies in Lisbon

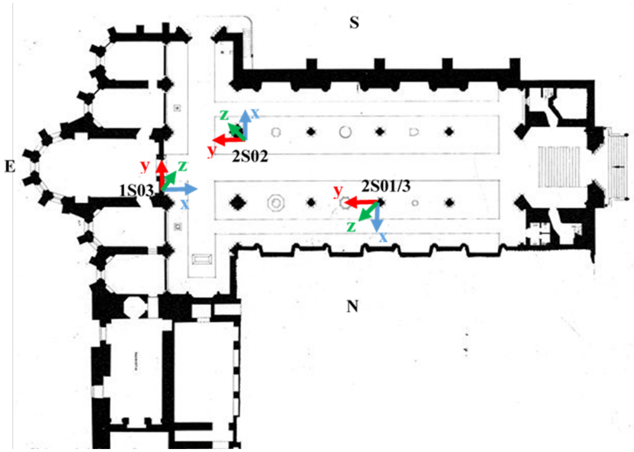
- Passing trains at regular intervals of 5-7 min
- Assessment through different national standards • use of kinetic quantities
- Expected high energy content at frequencies from 30 to 250 Hz
- Triaxial seismographers with GPS time base • continuous time intervals during night time and early morning (13^h)
- Dynamic identification tests
  Overall structural performance

Underground structures in urban environment

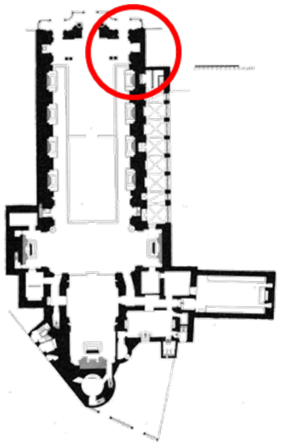
Groundborne vibrations • Structural monitoring

Carmo Convent, Lisbon: National Monument under protection (1907). Severely damaged by the earthquake of 1755. Metro tunnels directly under.





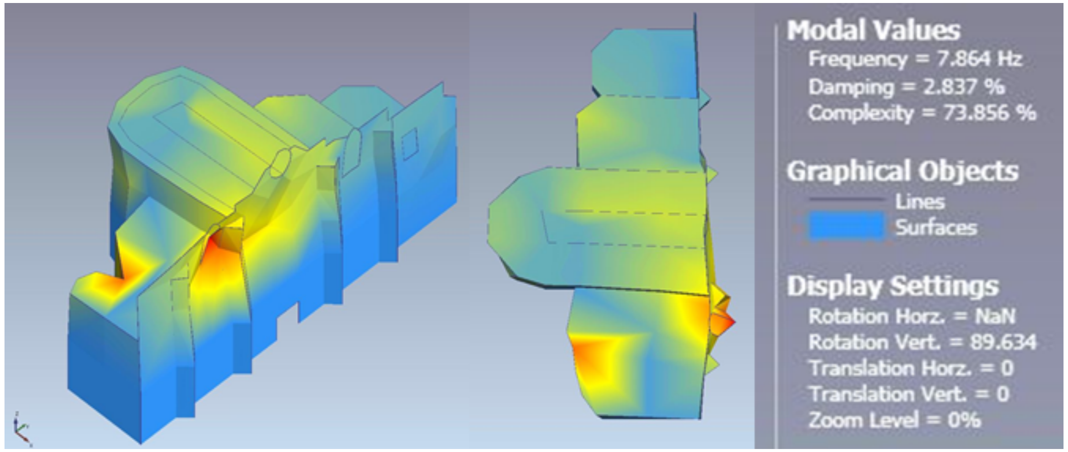
Church of São Domingos, Lisbon: Baroque architecture (13th c.). Severely damaged by fire in 1959. Metro line in close proximity to west facade.

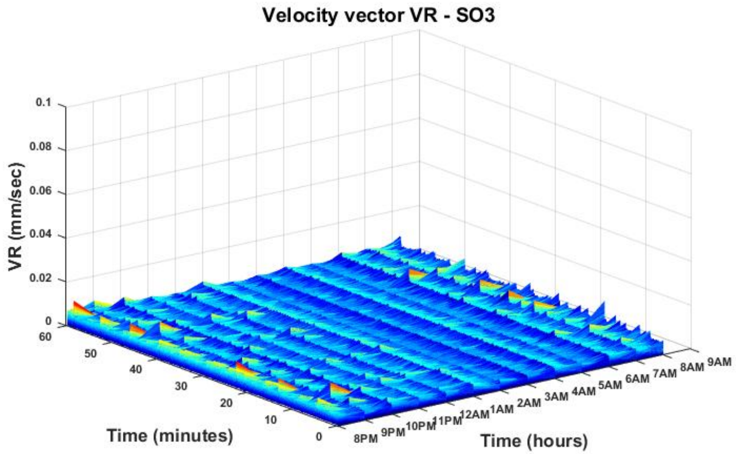


Underground structures in urban environment

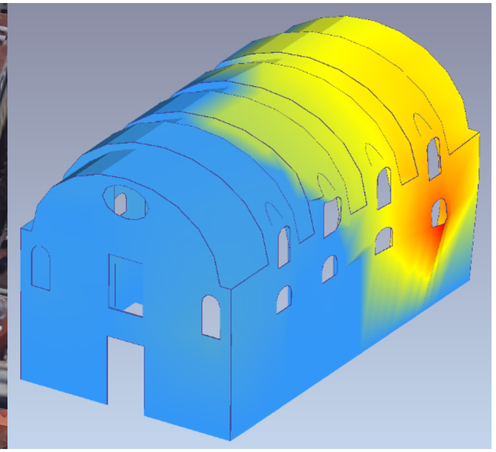
Groundborne vibrations • Structural monitoring

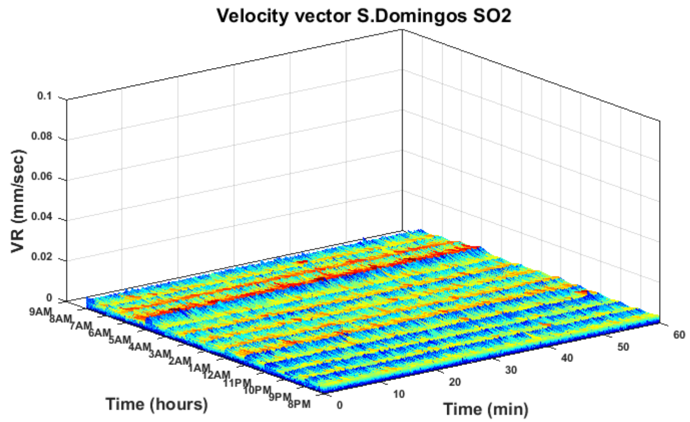
Carmo Convent, Lisbon: Monitoring points at the base and in elevation. Velocities in the range of 0.012 mm/s.





Church of São Domingos, Lisbon: Measurements close to the base of stone masonry pillars. Max velocity vectors: 0.005-0.008 mm/s.





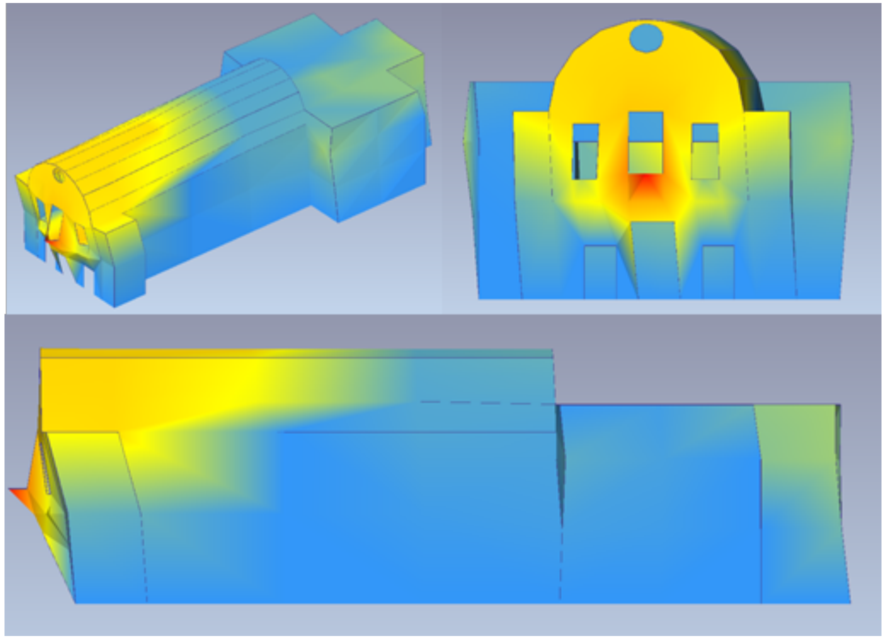
Underground structures in urban environment

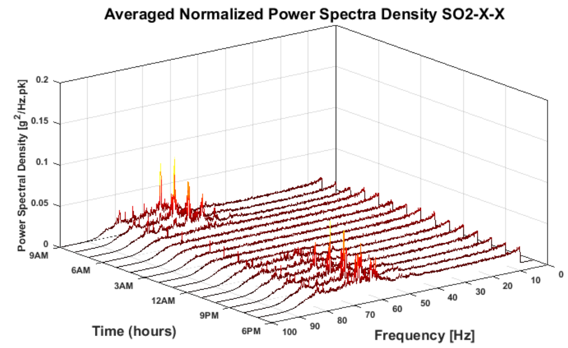
Church of the Angels, Lisbon

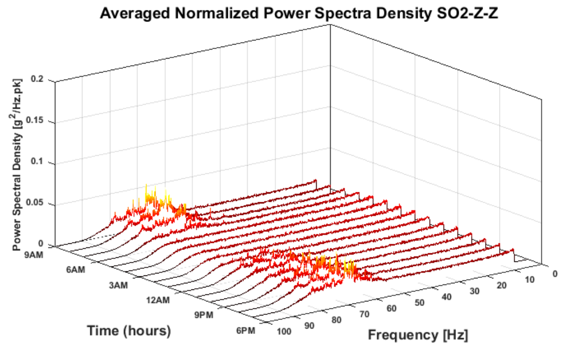
- Baroque and neoclassical style. Constructed in 1910 as a replica of a former demolished church
- Barrel vault with baroque gilded carvings
- Evident settlements in the front part
- Monitoring points at the base and at intermediate heights in the front façade
- Amplification during metro operation
- Higher energy content x-x and z-z frequency range 50-85 Hz
- Maximum vector of velocities in the range of 0.02 mm/sec

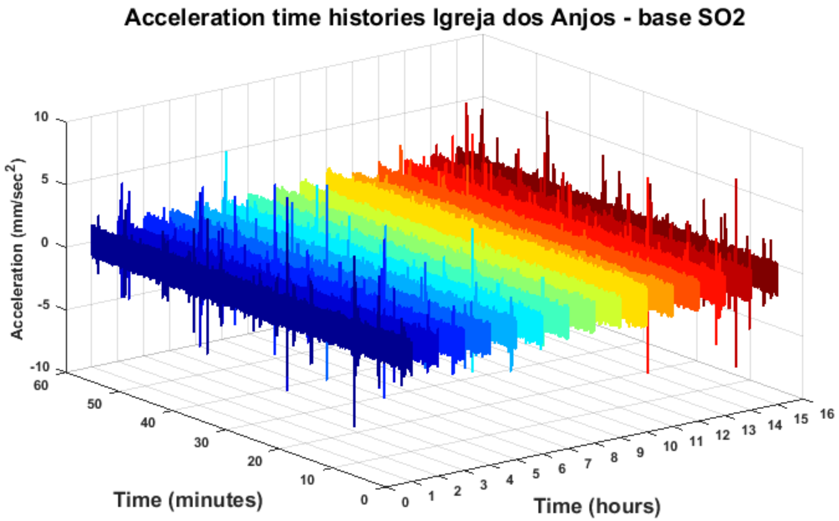
Underground structures in urban environment

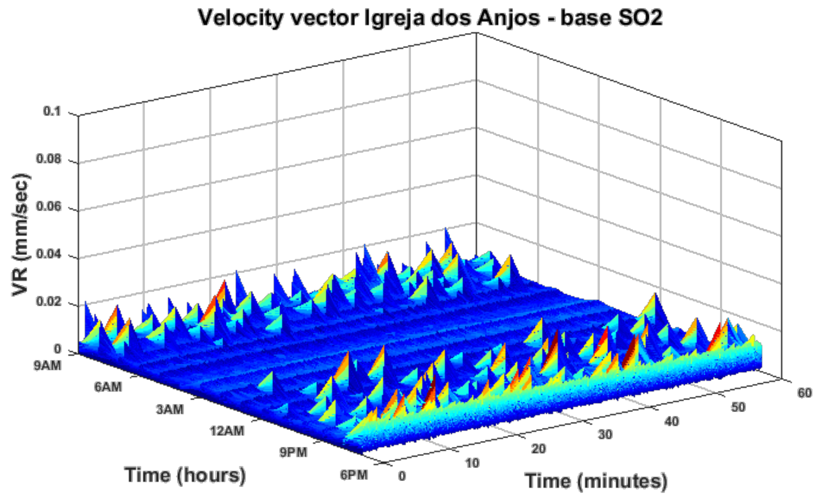
Church of the Angels, Lisbon







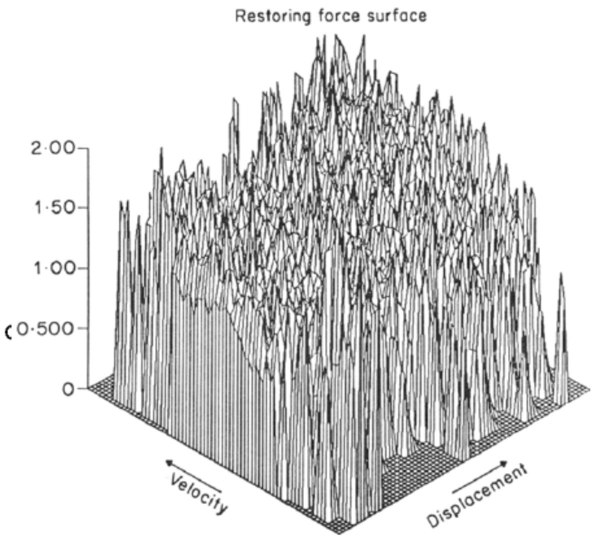


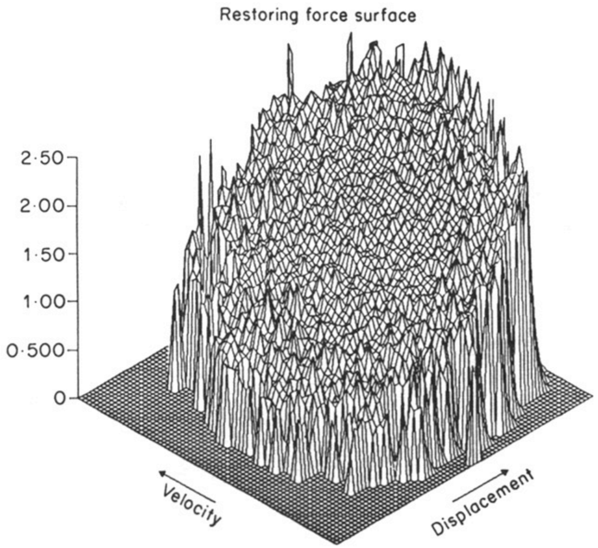


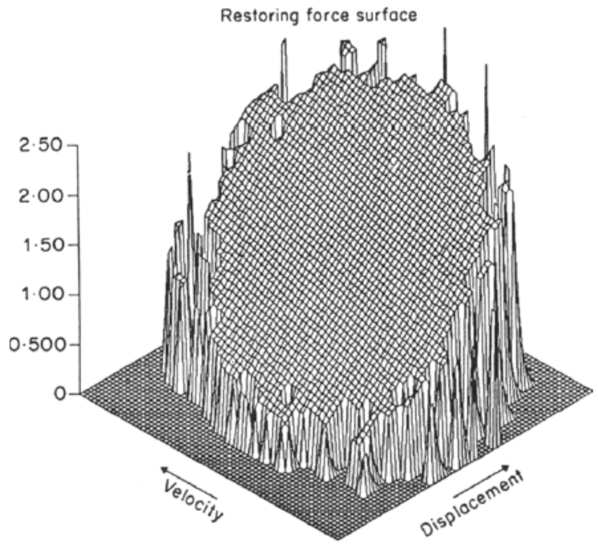
Underground structures in urban environment

Groundborne vibrations • Structural monitoring • Aspects of consideration

- ❑ Church of the Angels: induced vibrations of very low amplitude
- ❑ Further investigation and monitoring
- ❑ New equipment: triaxial velocity sensors
  Increased accuracy and correlation
- ❑ In-situ measurement of shear wave velocities: Soil stiffness at low strains







Experimental campaign

Historic masonry facades

Brick masonry piers and spandrels

Numerical model validation and parametric analysis

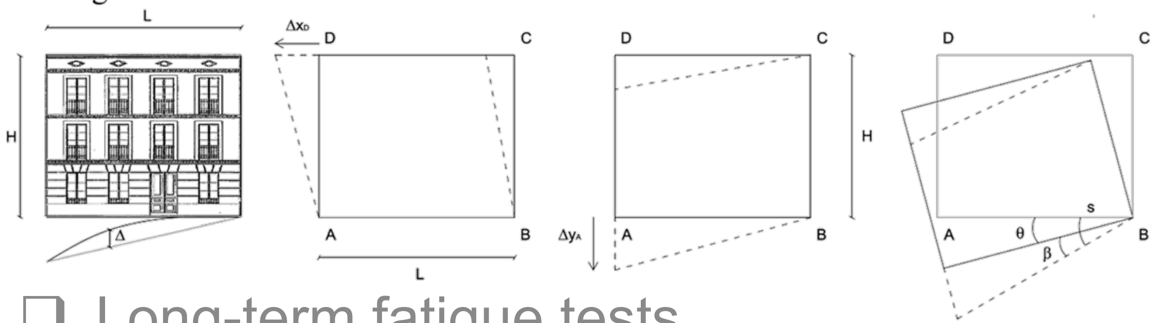
Experimental campaign

Historic masonry facades • Brick masonry piers and spandrels

- ❑ Basic mechanical characterization tests (brick, mortar, prisms, wallets)

- ❑ Produce reliable experimental results on cracking, due to differential settlements

Damage indicators under differential settlements



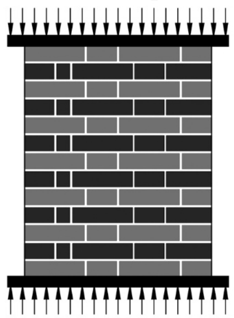
- ❑ Long-term fatigue tests

Vibration-fatigue tests

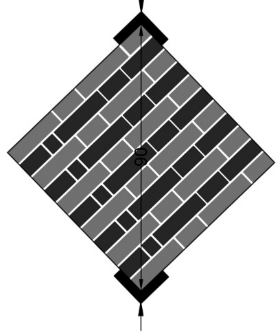
Uniaxial compression strain state → drop mass; dynamic actuator

Diagonal compression strain state → drop mass; dynamic actuator

Uniaxial compression

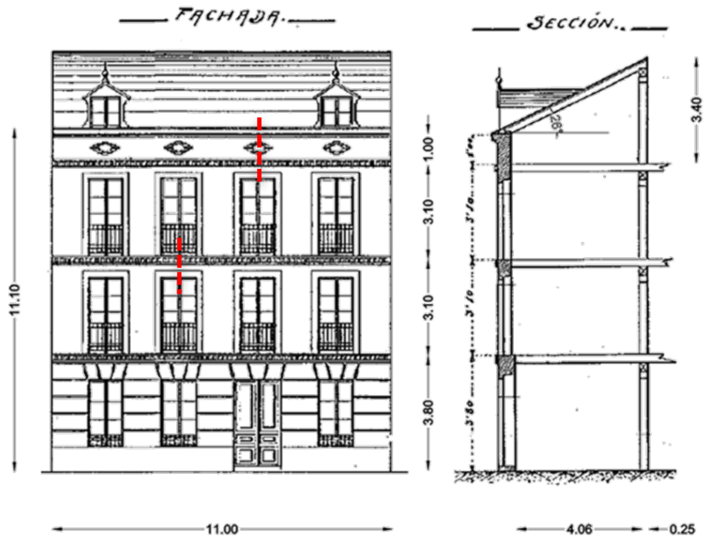


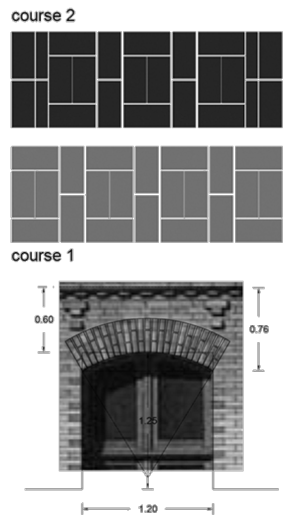
Diagonal compression

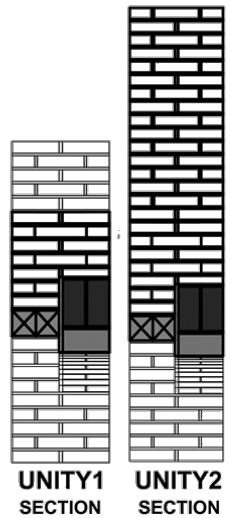


- ❑ FE model validation
  Testing assembly - historic façade – block

Reference facade / brick masonry with lime mortar
Location: Valladolid, Spain / Construction date: 1908
Source: Camino Olea,M.S. (2001) PhD Thesis: Construcción y ornamentación de las fachadas de ladrillo prensado, al descubierto, en la ciudad de Valladolid University of Valladolid, Spain.



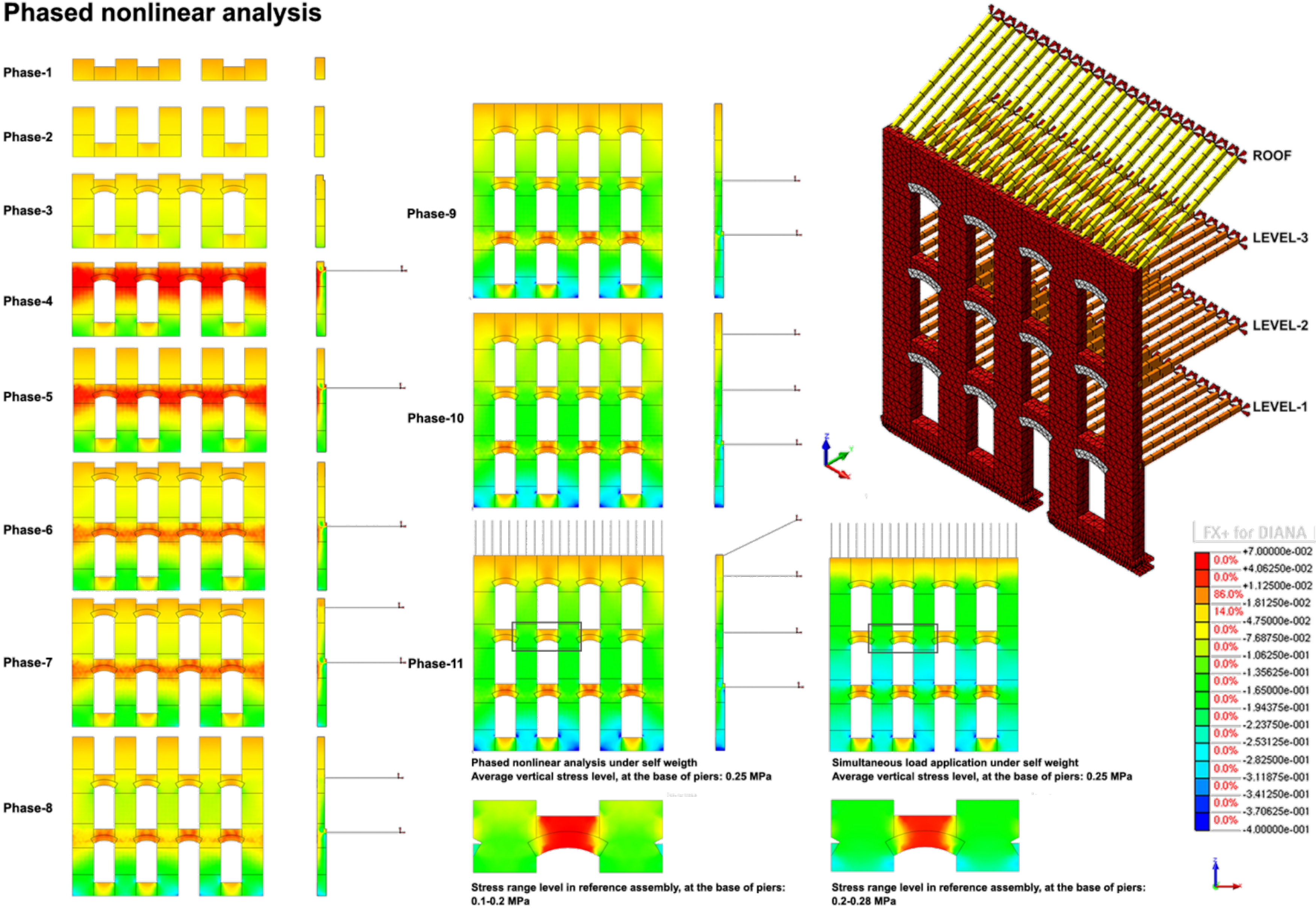




Experimental campaign

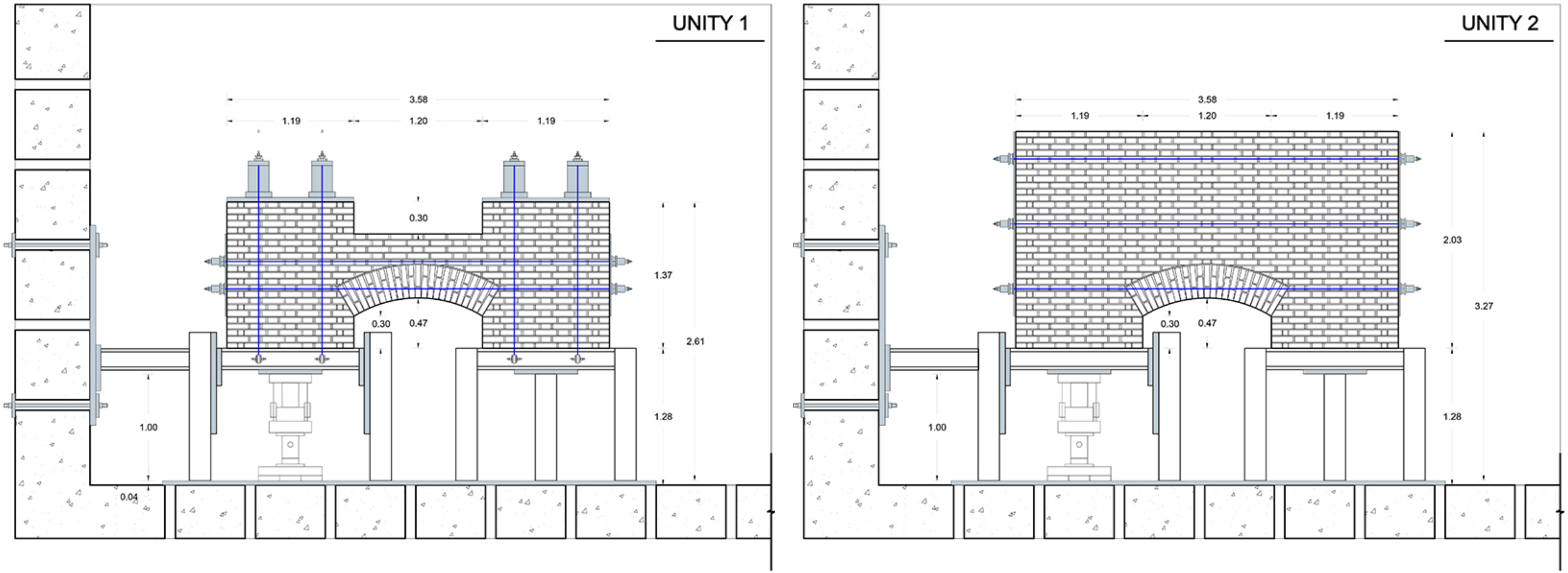
Historic masonry facades • Brick masonry piers and spandrels

Phased nonlinear analysis



Experimental campaign

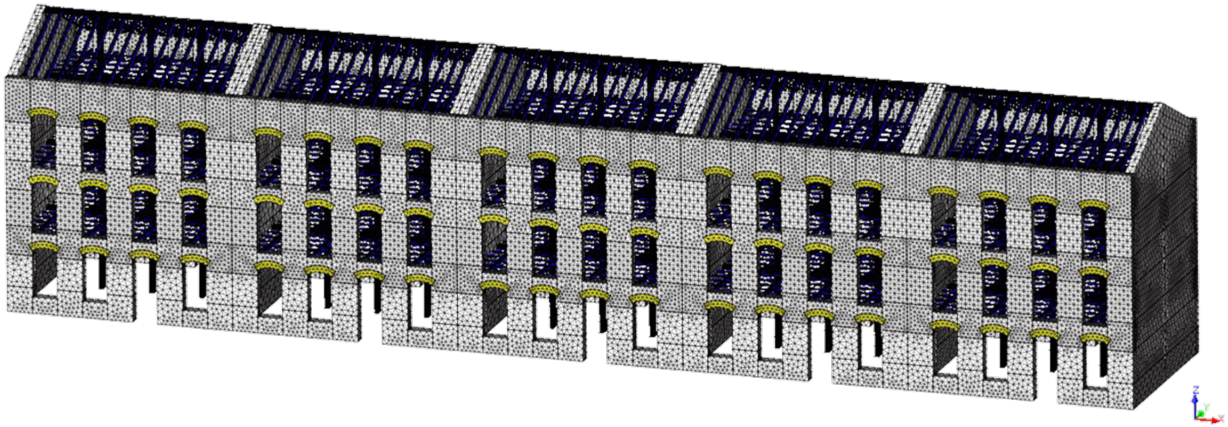
Historic masonry facades • Brick masonry piers and spandrels



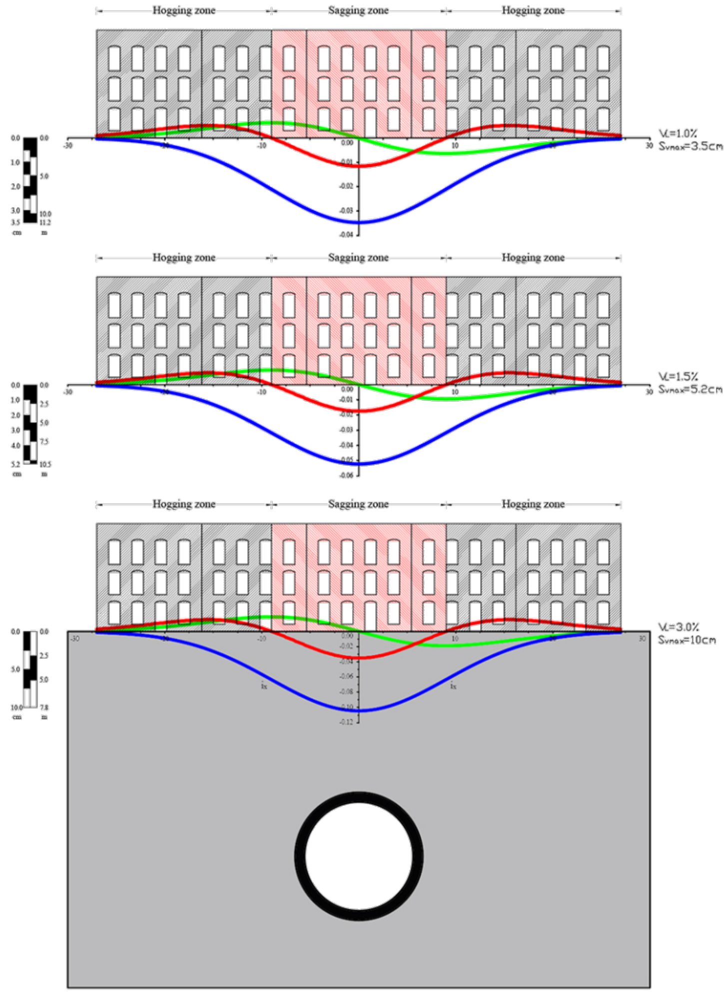
Experimental campaign

Numerical model validation and parametric analysis

- Differential settlements: global performance and interaction with adjacent buildings ‘block effect’



- Boundary conditions – Level of confinement
- Indicators of increased complexity
  From preliminary to detailed evaluation
- Influence on deflection ratios and strains
- Comparison with threshold values
  and damage categories

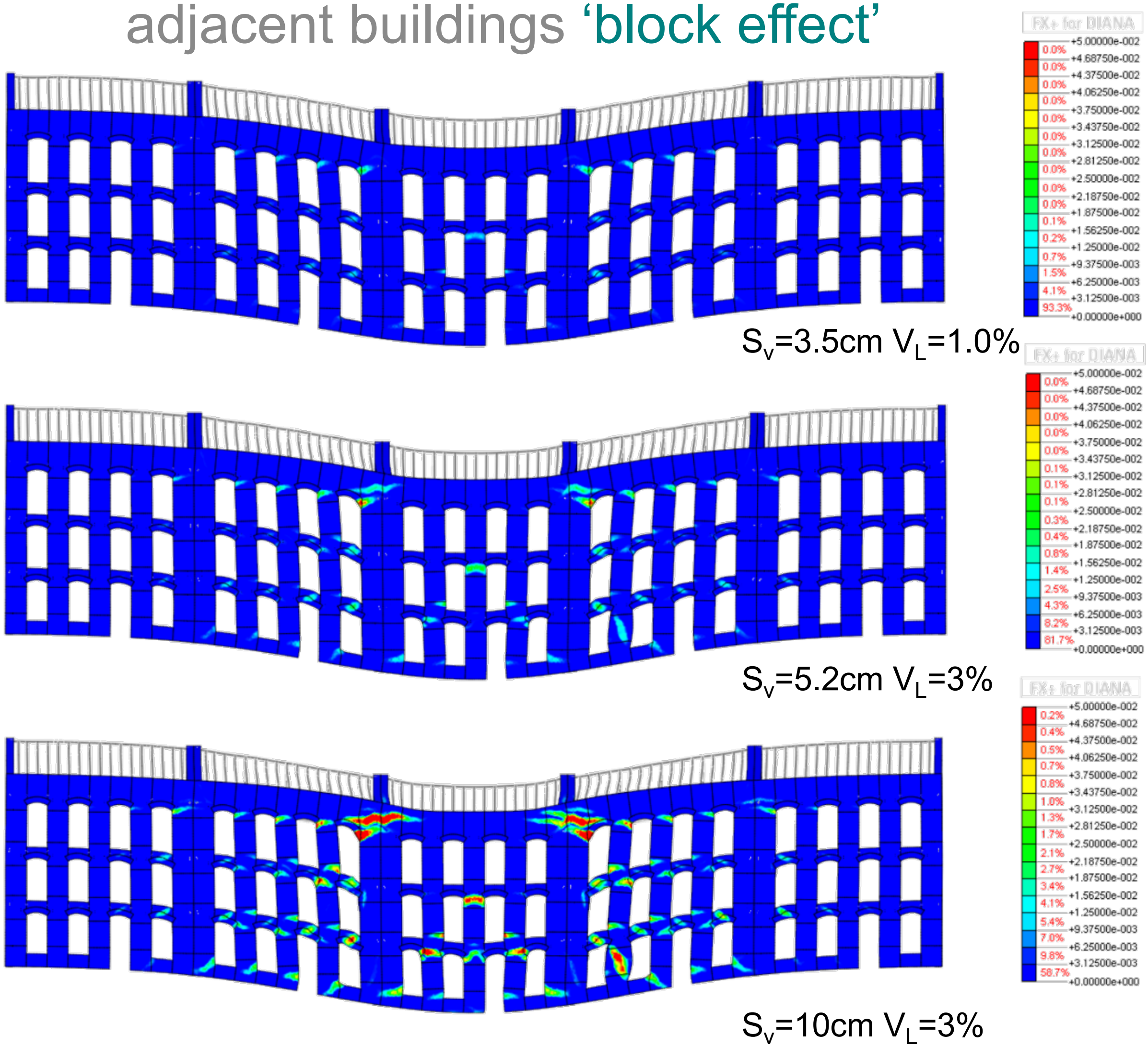


Greenfield deformations
- $S_v(x)$: Vertical settlment profile
- $S_h(x)$: Horizontal settlement profile
- $\varepsilon_h(x)$: Horizontal strain

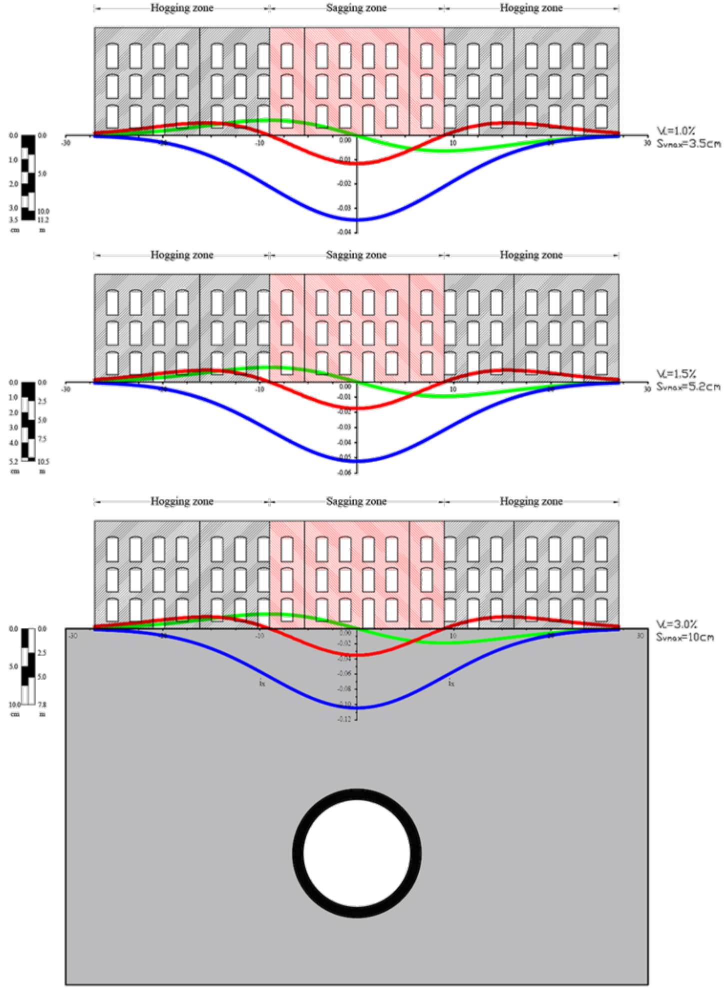
Experimental campaign

Numerical model validation and parametric analysis

- Differential settlements: global performance and interaction with adjacent buildings ‘block effect’



Max. Principal strain E1



Greenfield deformations

— $S_v(x)$: Vertical settlment profile

— $S_h(x)$: Horizontal settlement profile

— $\varepsilon_h(x)$: Horizontal strain

Experimental campaign

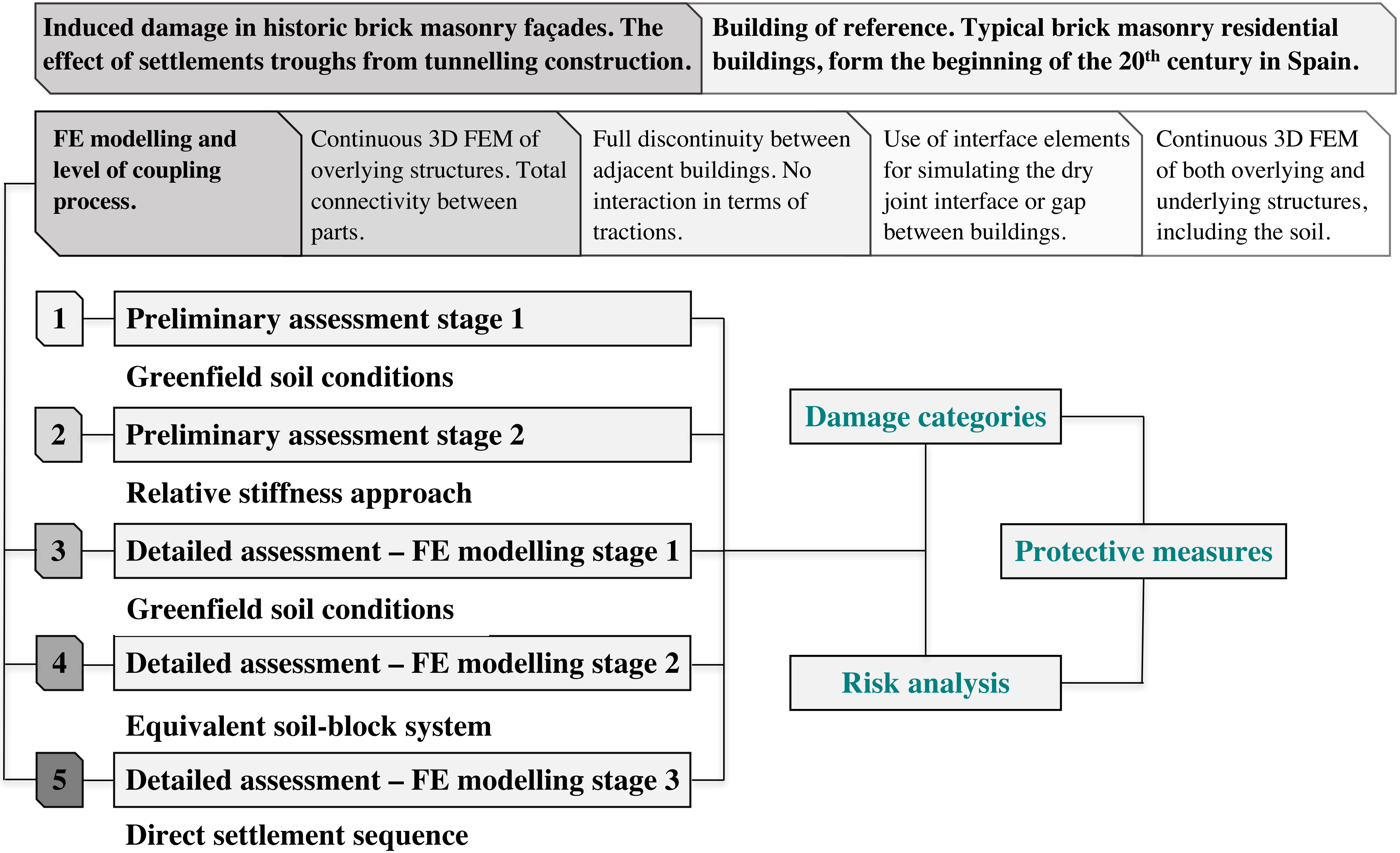
Numerical model validation and parametric analysis

Induced damage in historic brick masonry façades. The effect of settlements troughs from tunnelling construction.	Building of reference. Typical brick masonry residential buildings, form the beginning of the 20th century in Spain.

Analysis indicators in order of complexity. From preliminary to detailed evaluation.	A	B	C	D
Structural configuration, detailing and situation in unban context.	Increased stiffness in corner junctions from transversal walls.	Diaphragmatic stiffness from timber floors. Quality of connections.	Structural interaction in terms of frictional, shear and normal resistance. 'Block effect'.	Foundation configuration and corresponding stiffness.
Material properties, softening functions and constitutive laws.	Material properties from tests on brick masonry wallets. Correlation with values from literature.	Softening inelastic functions regarding fracture energy.	Nonlinear constitutive models for masonry.	Soil constitutive models of increased complexity.
Settlement profiles as input and relative distance from source.	Vertical and horizontal settlement profiles from greenfield conditions.	Analytical settlement profile, accounting for the relative stiffness of the soil-structure system.	Numerical output from equivalent soil-block system and phased tunnelling evolution.	Direct settlement sequence from phased tunnelling evolution.
FE modelling and level of coupling process.	Continuous 3D FEM of overlying structures. Total connectivity between parts.	Full discontinuity between adjacent buildings. No interaction in terms of tractions.	Use of interface elements for simulating the dry joint interface or gap between buildings.	Continuous 3D FEM of both overlying and underlying structures, including the soil.

Experimental campaign

Numerical model validation and parametric analysis



Thank you

Acknowledgments

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