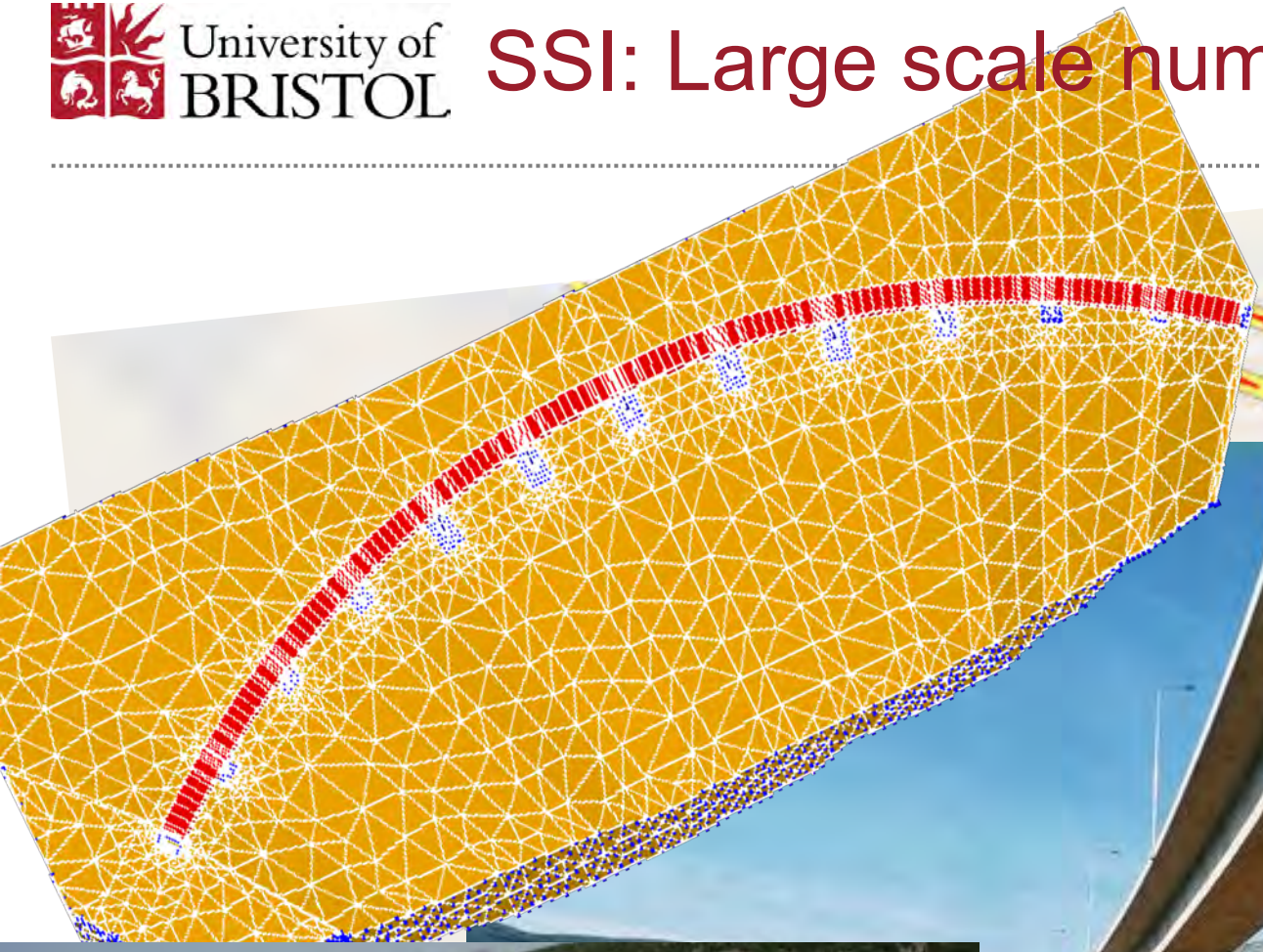
University of BRISTOL

Performance-based design and assessment of critical facilities considering soil-structure interaction

Anastasios Sextos

Professor of Earthquake Engineering

SSI: Large scale numerical modelling



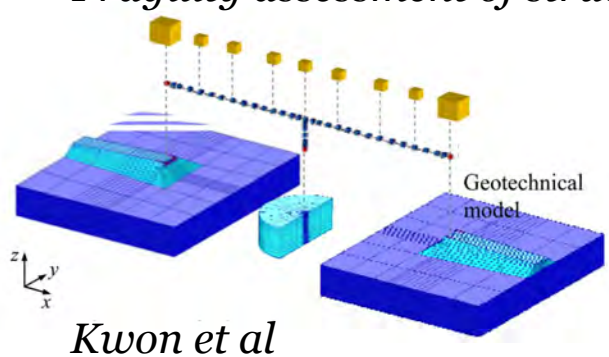
Introduction

Presence of soil can have a detrimental impact on the behaviour of a structure.

Analytical solution of the PDE equations	Direct FEM simulation	Simplified closed form approximations
most common scenarios	❑ Capable of simulating complex behavior ❑ High Computational Cost	accuracy ❑ Intensity or frequency independent

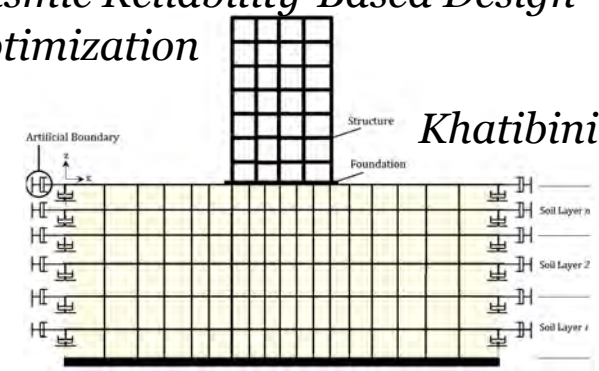
FEM method non viable under the framework of:

Fragility assessment of structures



Kwon et al (2008)

Seismic Reliability-Based Design Optimization

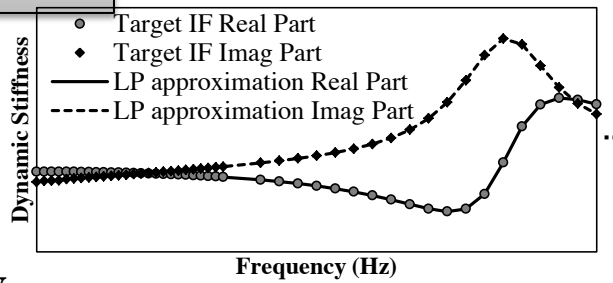


Khatibinia et al (2015)

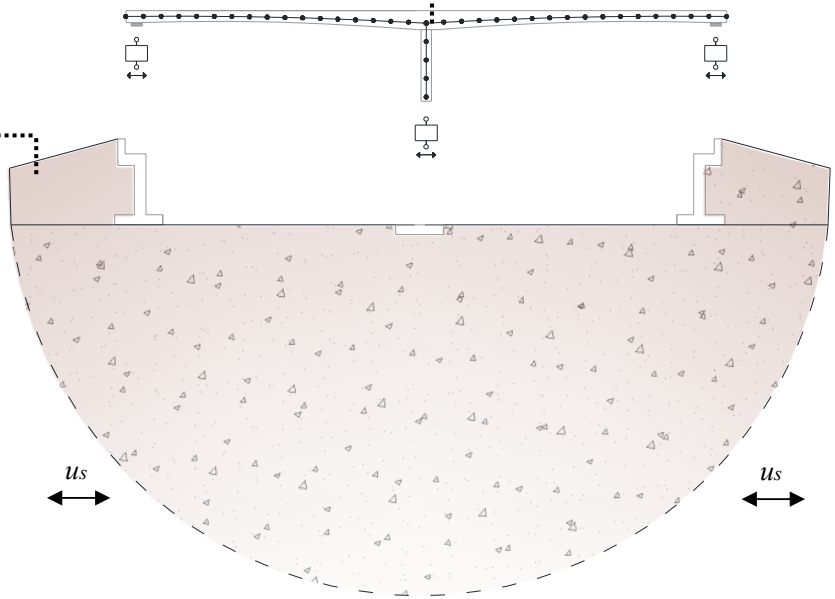
SSI: Analytical LPM modelling

Lumped Parameter (LP) modeling Method

Direct FEM simulation



Finite element formulation



computationally viable

Reduction of sub soil domain through internal DOF elimination in the frequency domain

Model Order Reduction

- ❑ Global Stability Issues
- ❑ Limited to Viscous-Elastic Systems

Lesgidis, N., Sextos, A.G. and Kwon, O.-S. (2018) "A frequency- and intensity-dependent macroelement for reduced order soil-structure interaction analysis", *Earthquake Engineering and Structural Dynamics* (available online, DOI: 10.1002/eqe.3063).

Stability issues in LP method

LP model represented as a polynomial fraction in the frequency domain:

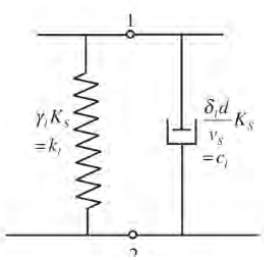
$$S_{LP}(s) = S_{LP,0} \cdot \frac{P(s)}{Q(s)} = S_{LP,0} \cdot \frac{p_o + p_1 \cdot (s) + \cdots + p_{N+1} \cdot (s)^{N+1}}{q_o + q_1 \cdot (s) + \cdots + q_N \cdot (s)^N}$$

Polynomial coefficients calibrated for: $S_{LP}(s) = S_{tar}(s)$

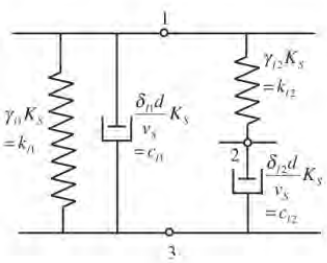
Translation to an ODE system (decomposition of polynomial fraction and term by term translation to physical components):

$$= \frac{P(s)}{Q(s)} = \sum_{i=1}^{M} \frac{q_i}{s - r_i} + \sum_{i=M}^{N+1-M/2} \frac{s - \alpha_i}{\left((s - \alpha_i)^2 + \beta_i^2\right)} + \sum_{i=M}^{N+1-M/2} \frac{\alpha_i - q_i}{\beta_i} \frac{\beta_i}{\left((s - \alpha_i)^2 + \beta_i^2\right)}$$

Example of 1st order term:



Example of 2nd order term:

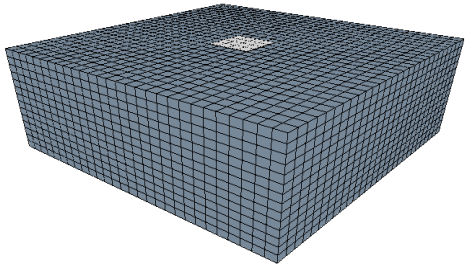


Sufficient condition to emulate the **Steady state** behavior. It will not necessarily lead to an ODE system with stable complementary solutions.

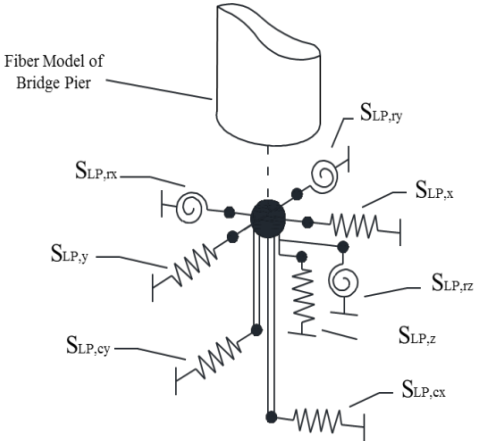
Proposed Stable LP method

Restriction of used components on positive region through bound constraints in the calibration process.

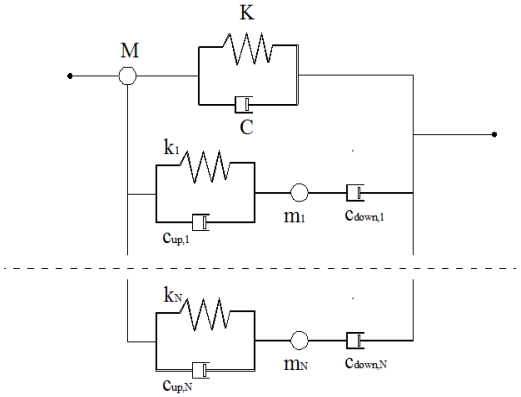
Pier base region:



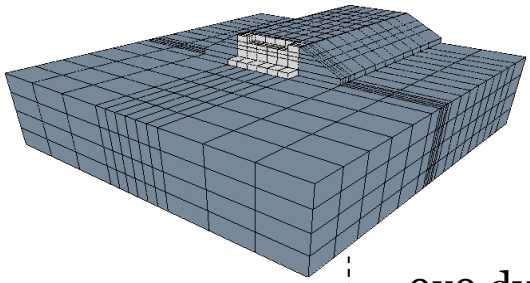
6x6 dynamic stiffness matrix

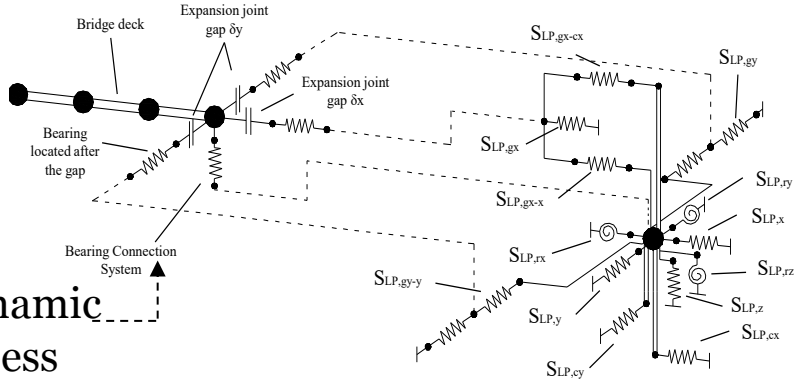


Use of a predefined LP model:



Abutment-Embankment region:





9x9 dynamic stiffness matrix

Frequency-dependent SSI effect on system fragility

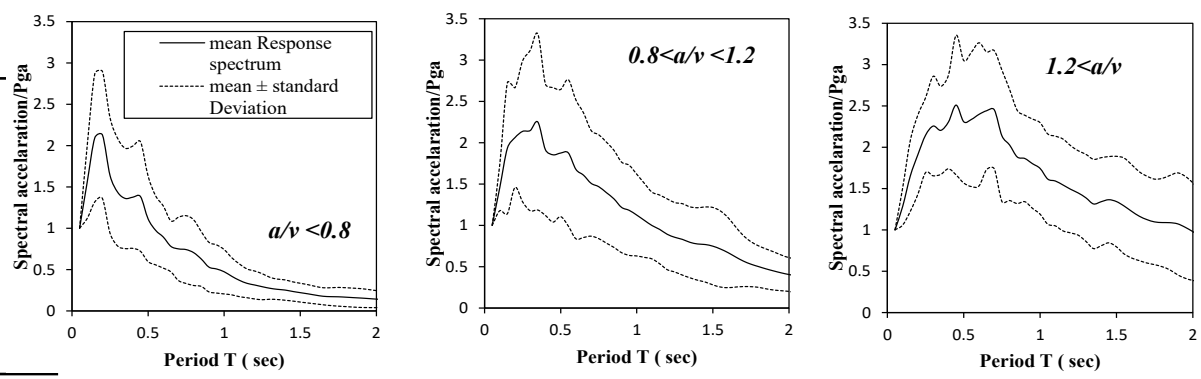
Case Study: investigation of the impact of frequency dependence for different bridge SSI configurations in their fragility.

Pedini Overpass: Bridge Properties	
Overall length	78
Span Arrangement	19.00m -32.00m -19.00m
Deck Section	box girder, non prismatic
Piers(P1,P2)	solid circular section, height : 8.50 m
Abutments (A1,A2)	laying on PTFE pot bearings

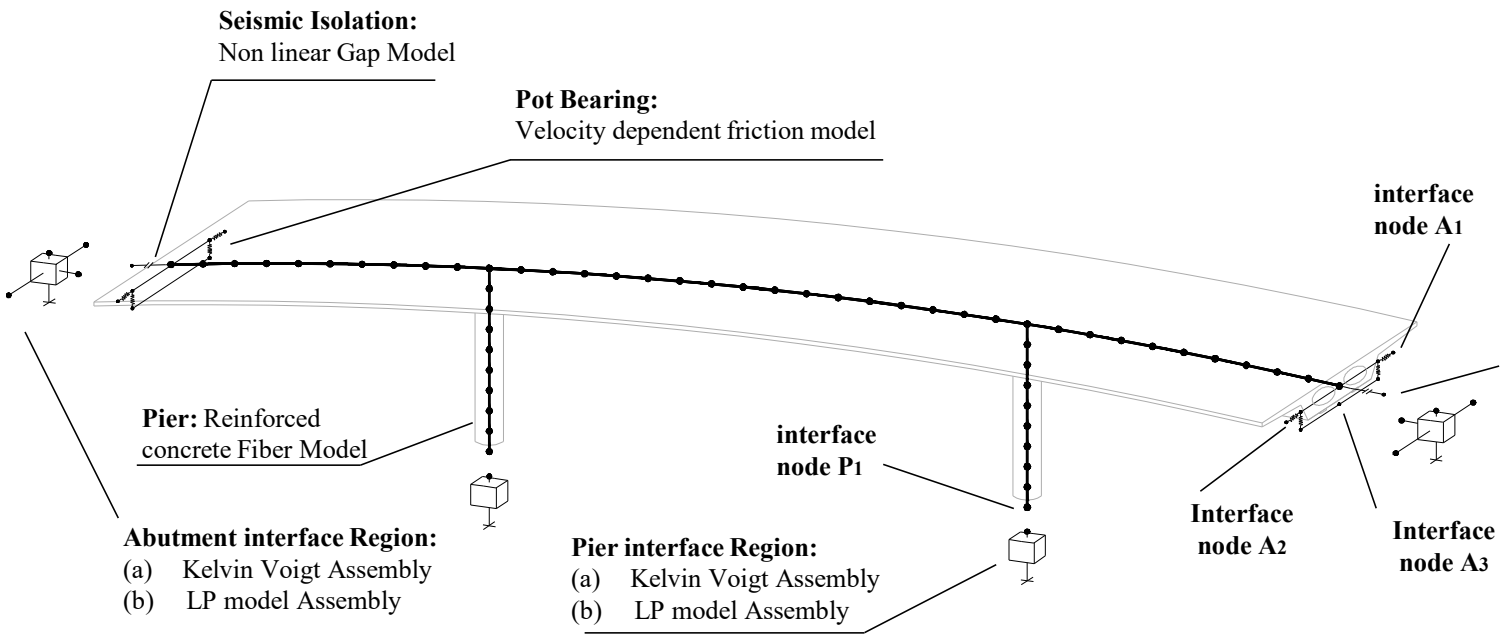
Different soil Scenarios

Scenarios	Soil type
S1	Soft Clay
S2	Loose Sand
S3	Medium Clay
S4	Medium Sand
S5	Hard Clay

Excitation sets based on the frequency content:

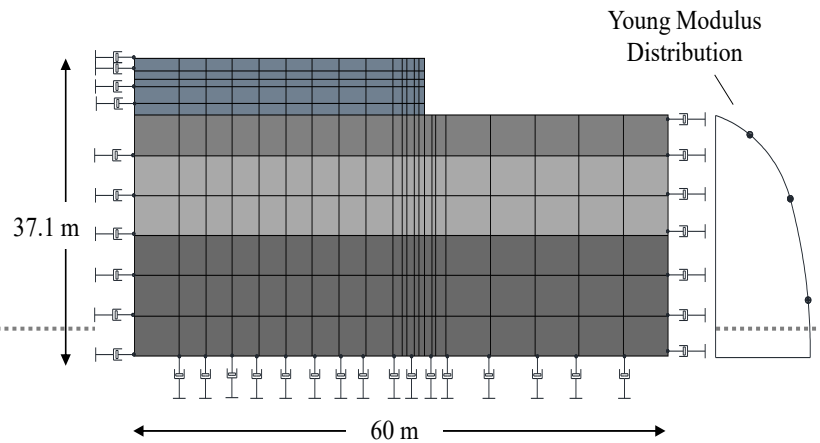


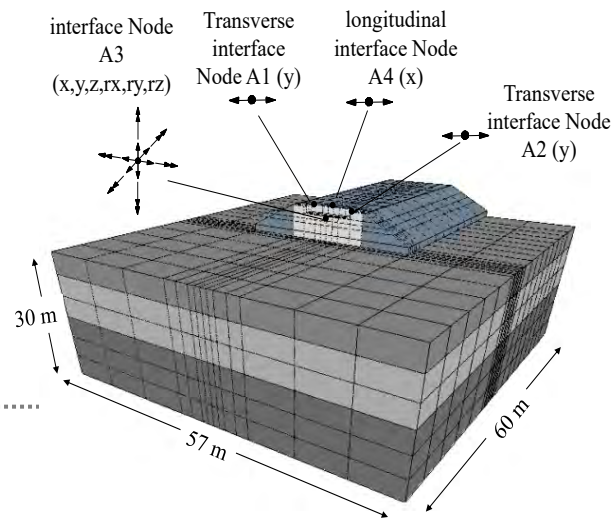
FE Modeling



FEM model in OpenSees.

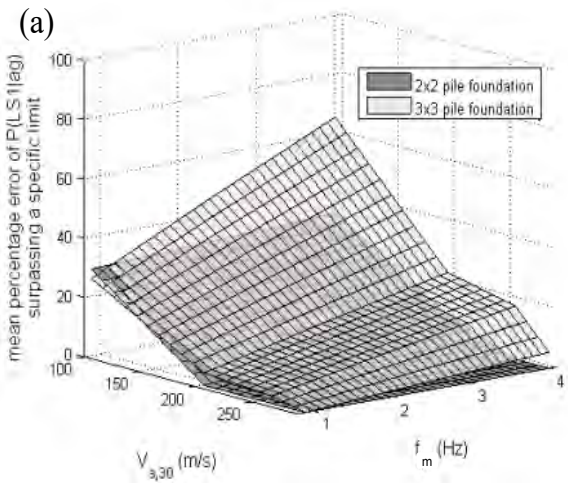
Extraction of dynamic Impedance functions from FEM model formulation.



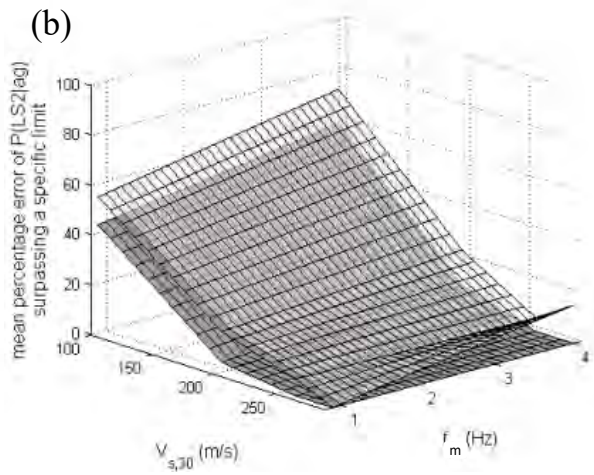


Error induced when neglecting frequency-dependence

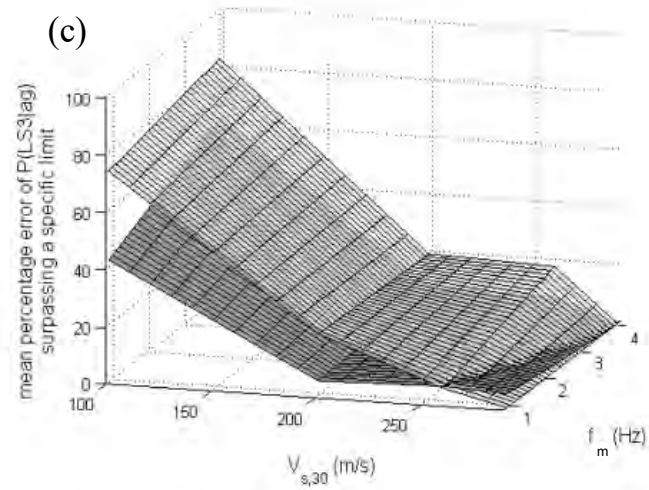
Percentage error in probability of reaching threshold limit states:



LS1 - Serviceability



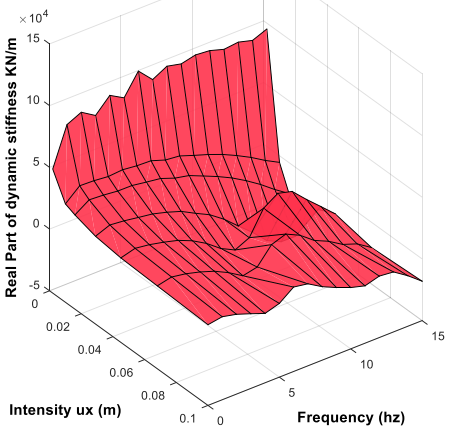
LS2 – Damage control

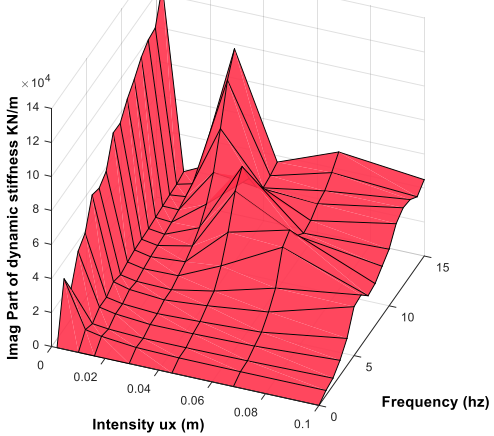


LS3 – Collapse prevention

Inelastic LP modeling method

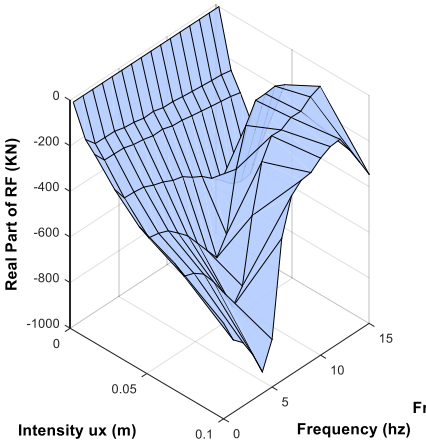
Selection and extraction of representative properties of target dynamic system:

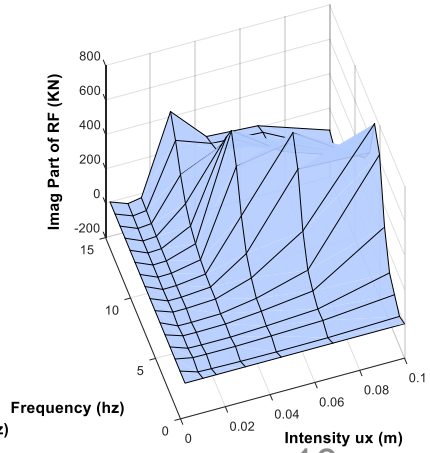




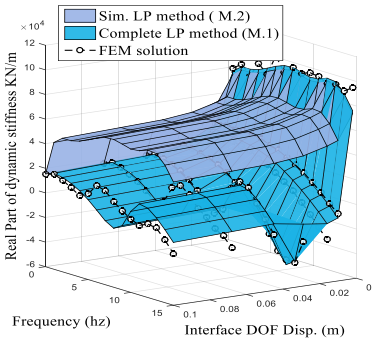
Extraction of Dynamic stiffness matrix for selected variable states in inelastic range

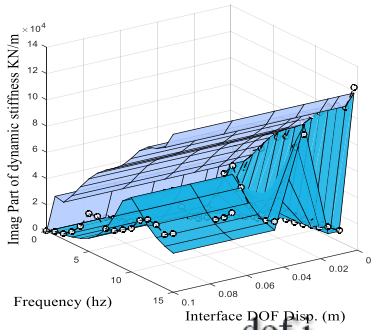
Extraction of dynamic returning force matrix for selected variable states in inelastic range

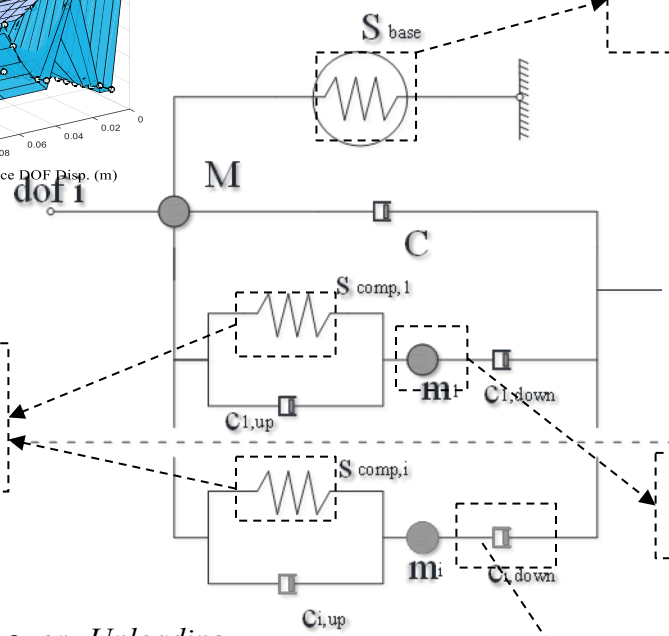




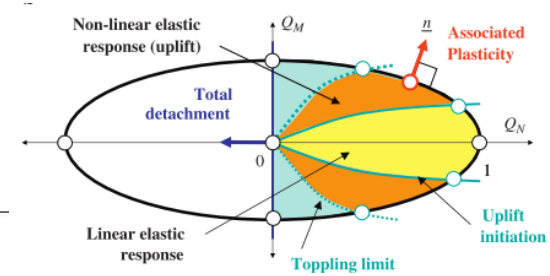
SSI: Analytical LPM modelling







Base Component:
Macroelement



Complementary Component:
(M.1): *Externally controlled Spring*
(M.2):Conventional spring

$$\dot{F}_{comp} = k_{comp}\left(\boldsymbol{\alpha}_{base}, u_{base}\right)\cdot \dot{u}_{comp}$$

$$k_{comp}\left(\boldsymbol{\alpha}_{base}, u_{base}\right) = \begin{cases} k_o & if\ [\boldsymbol{\alpha}_{base}, u_{base}]^{\mathrm{T}} < \mathbf{c}_o\ or\ \ Unloading \\ \vdots & \\ k_n & if\ \ \mathbf{c}_{n-1} < [\boldsymbol{\alpha}_{base}, u_{base}]^{\mathrm{T}} < \mathbf{c}_n \end{cases}$$

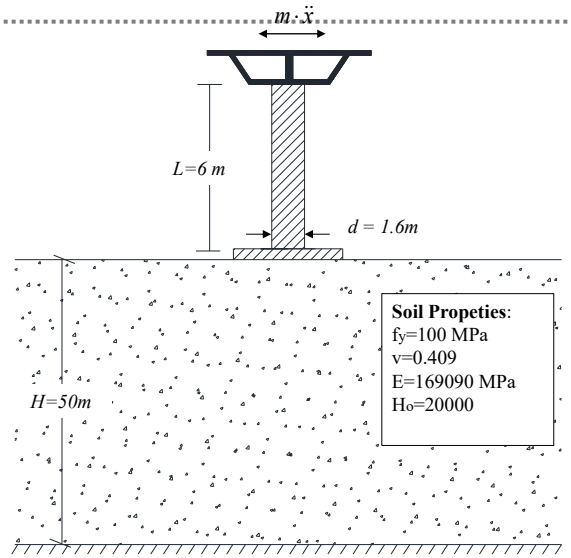
Complementary Component:
Conventional Mass

Complementary Component:
Conventional Dashpot

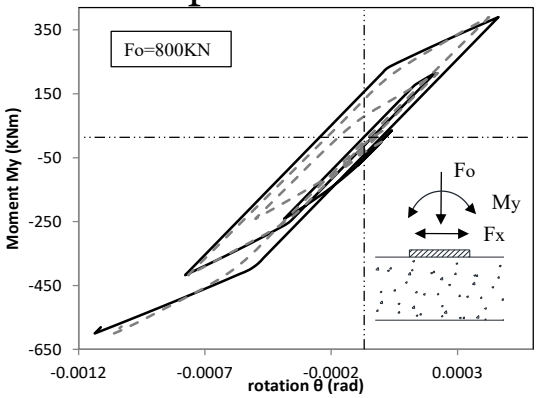
Frequency- and intensity- dependent LPMs

Lesgidis, N., Sextos, A.G. and Kwon, O.-S. (2018) “A frequency- and intensity-dependent macroelement for reduced order soil-structure interaction analysis”, *Earthquake Engineering and Structural Dynamics*

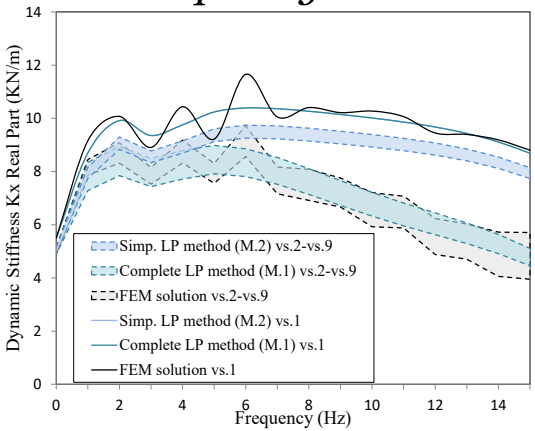
Verification example

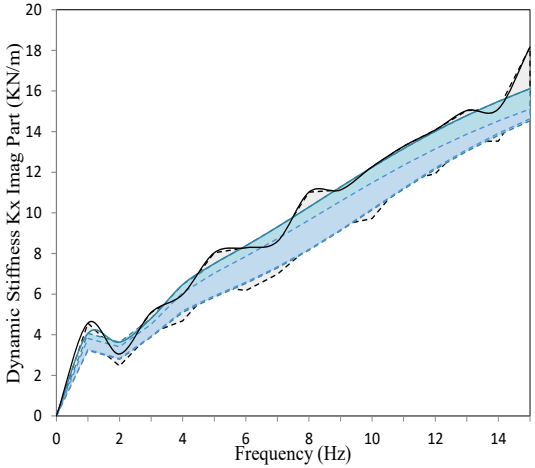


Static Properties Calibration:

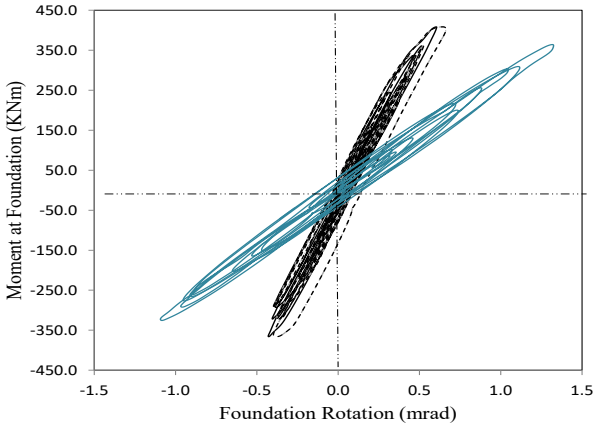


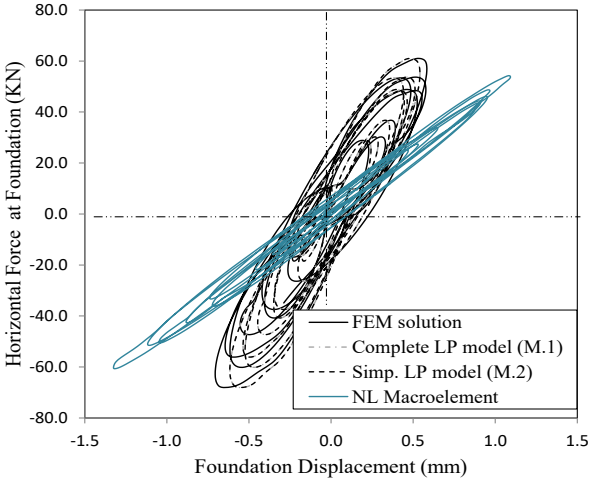
Sample of Dynamic Properties in the *Frequency domain:*



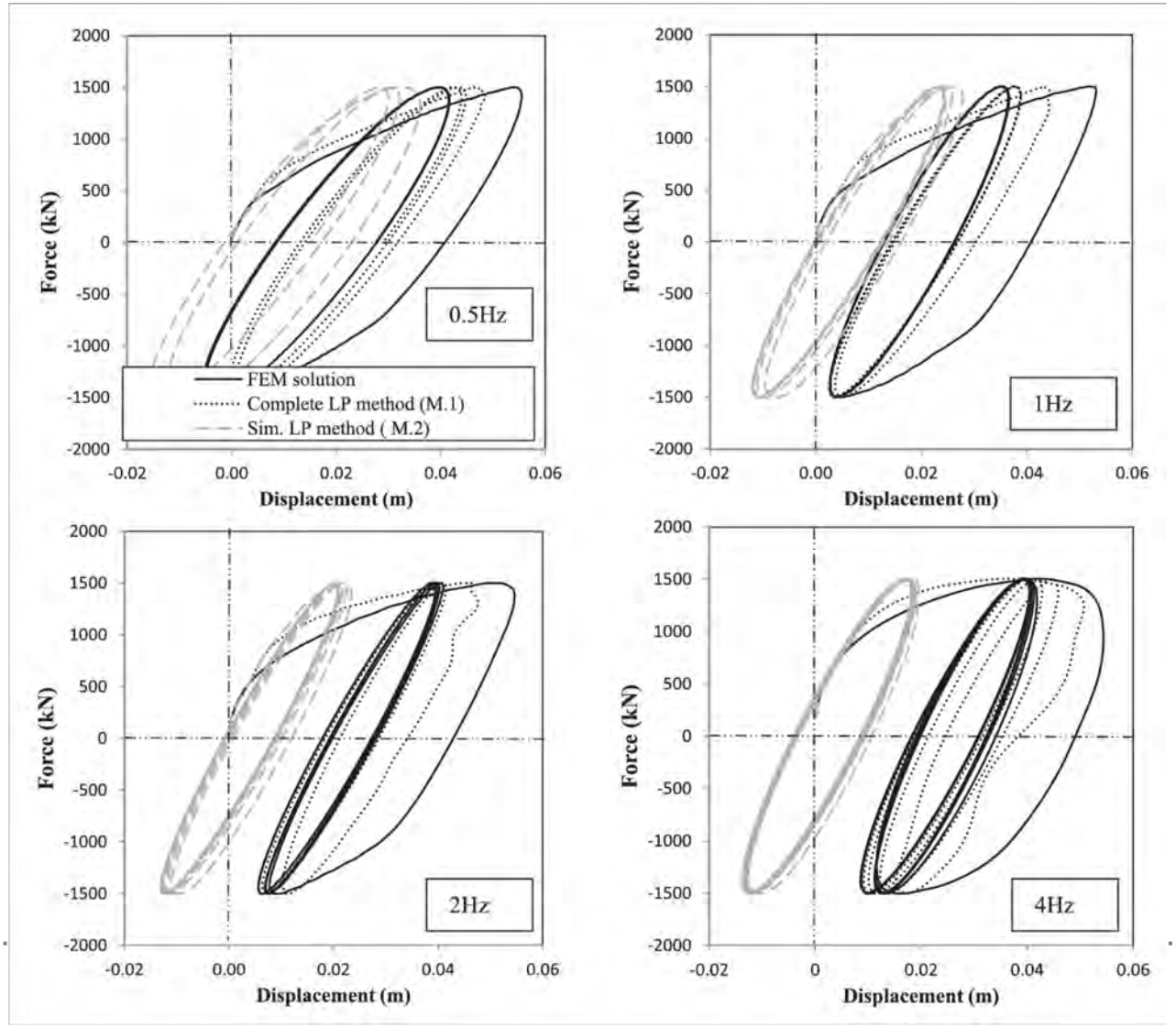


Model verification results:

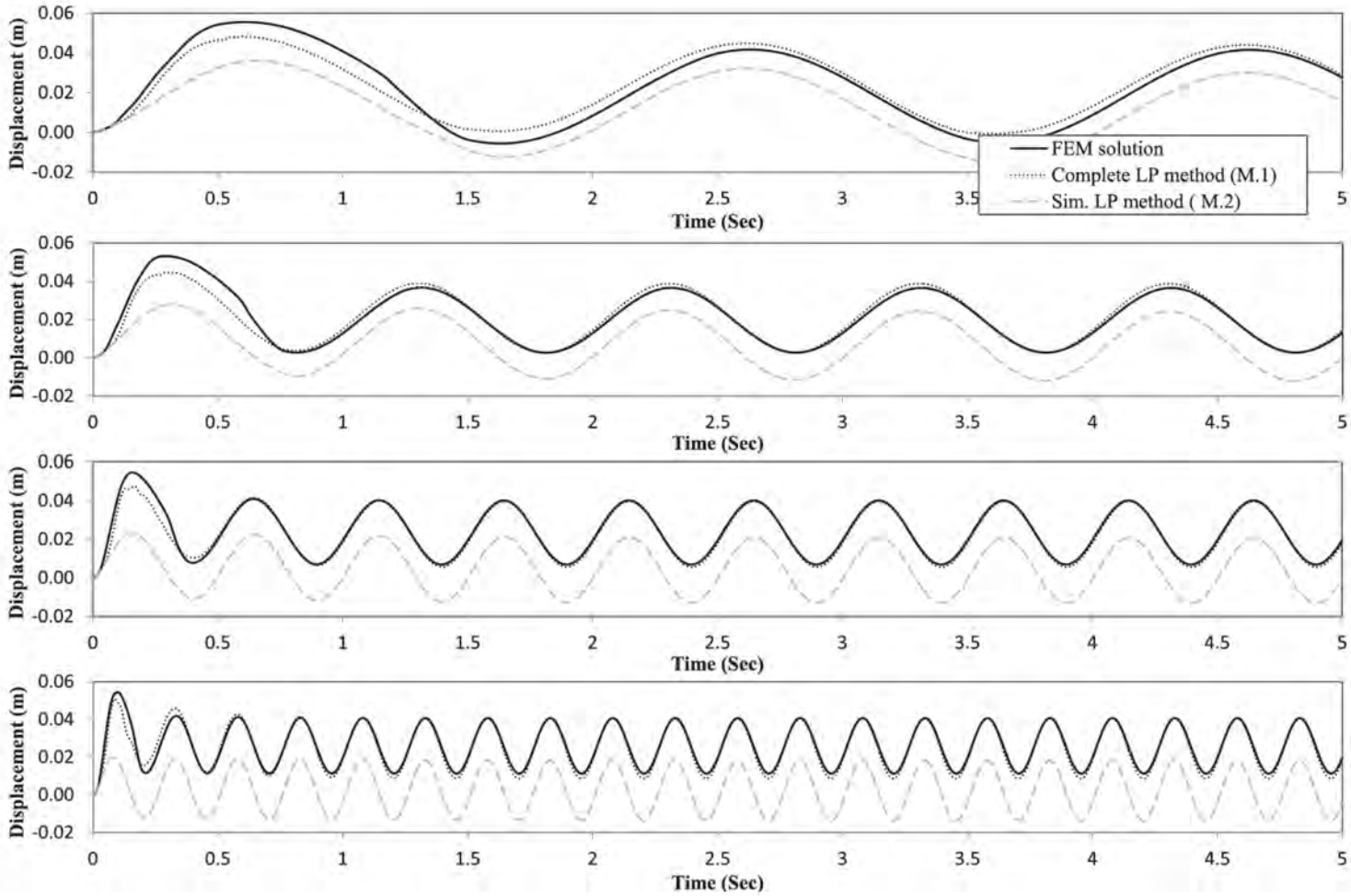




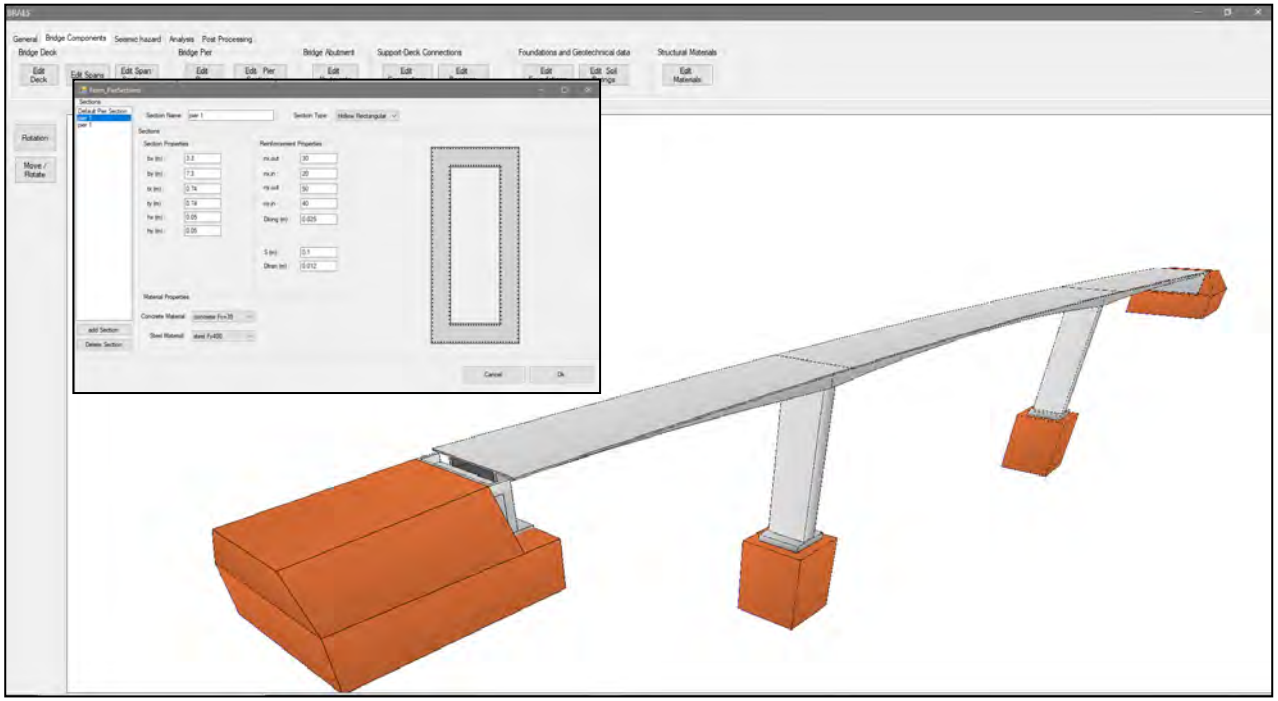
High intensity dynamic response (F-d & d(t))



High intensity dynamic response (F-d & d(t))



BRAIS: Bridge Risk Assessment Integrated System



- Smooth automations to minimize the time required for pre-processing.
- Expert decision making at every step of the simulation and order reduction process.
- Computationally optimized stochastic sampling procedures for the assessment of the conditional probability failure.
- Ad-hoc developed 3D visualization engine that allows the inspection of the fragility assessment results.

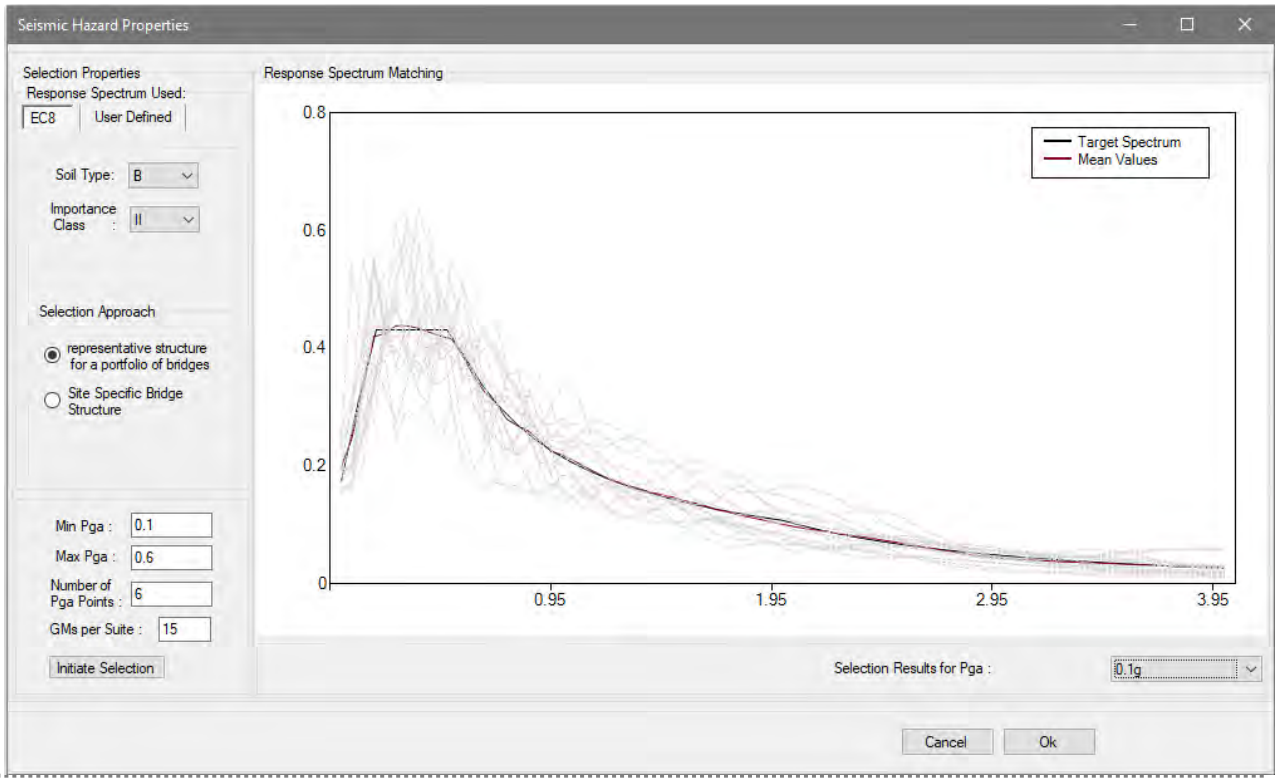
Ground Motion Selection Module

Preliminary selection:

- specific bridge structure (site faults properties known- M and Re)
- portfolio representative bridge (site faults properties generated by the system)

Final Selection:

Development of greedy search algorithm with constrained scaling



Automated FE model construction module

Flow chart of modelling expert system Architecture.

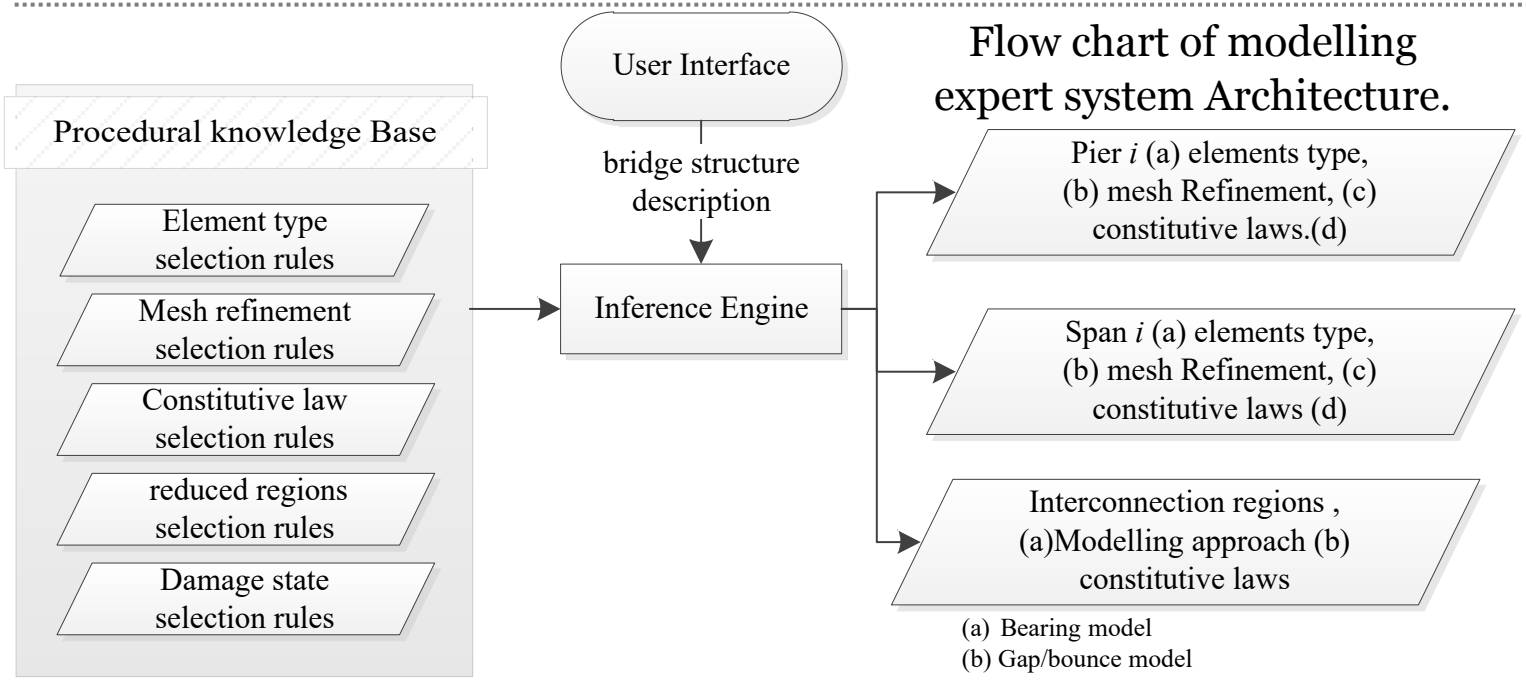
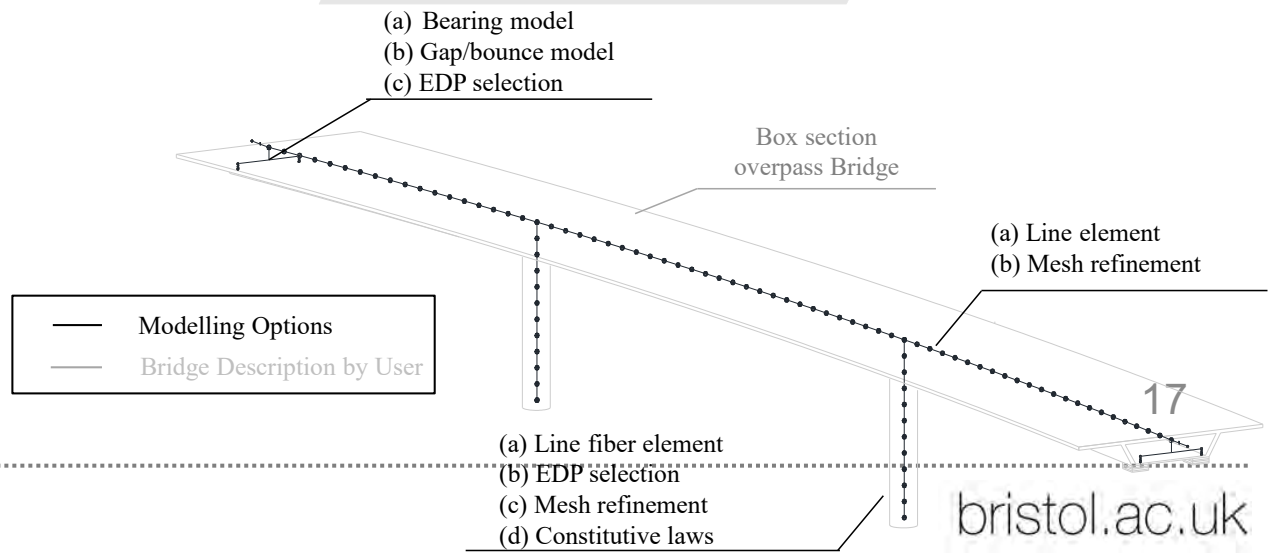
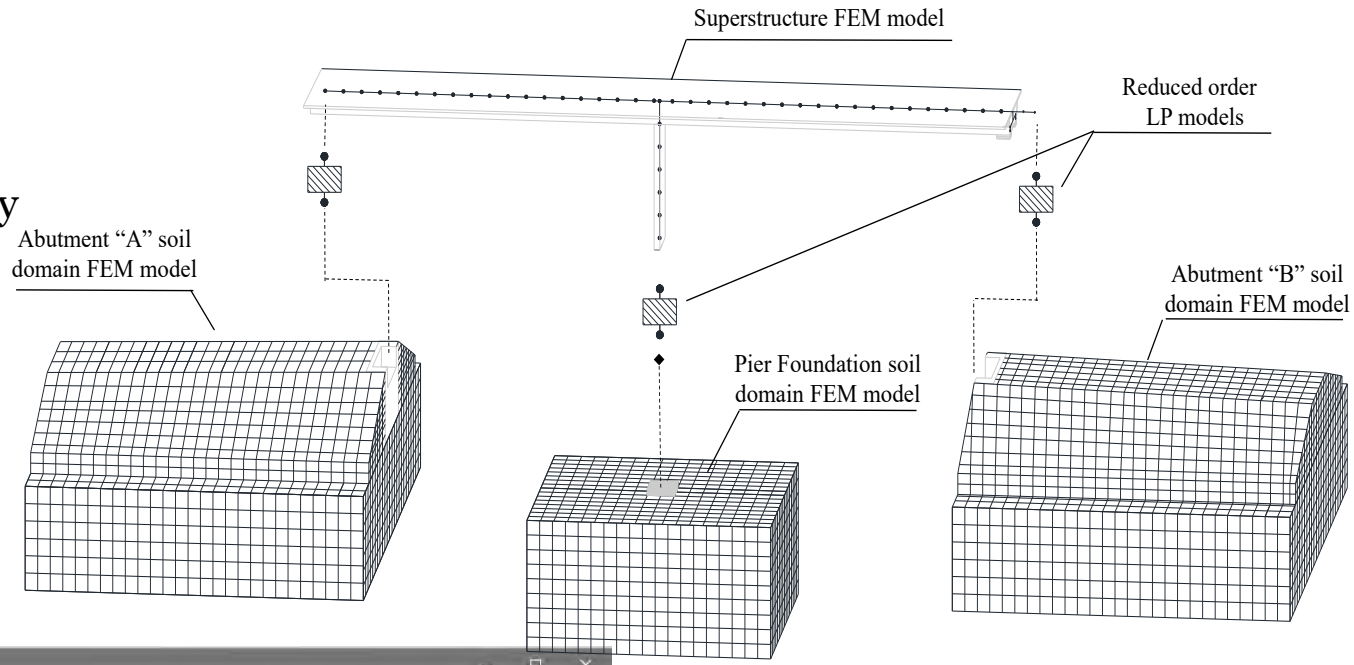


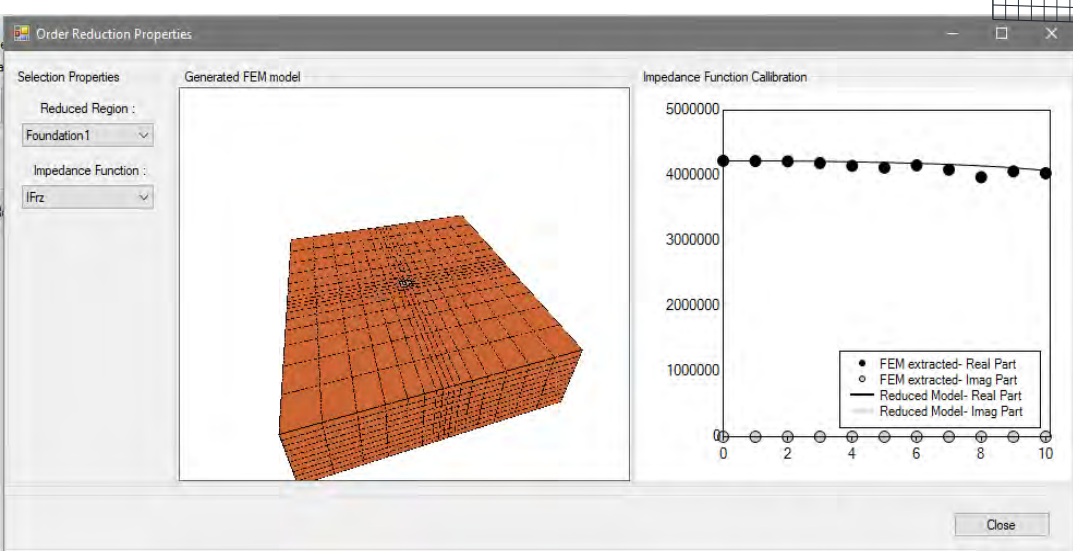
Illustration of Bridge description and Model generated by the integrated System.



Order reduction module

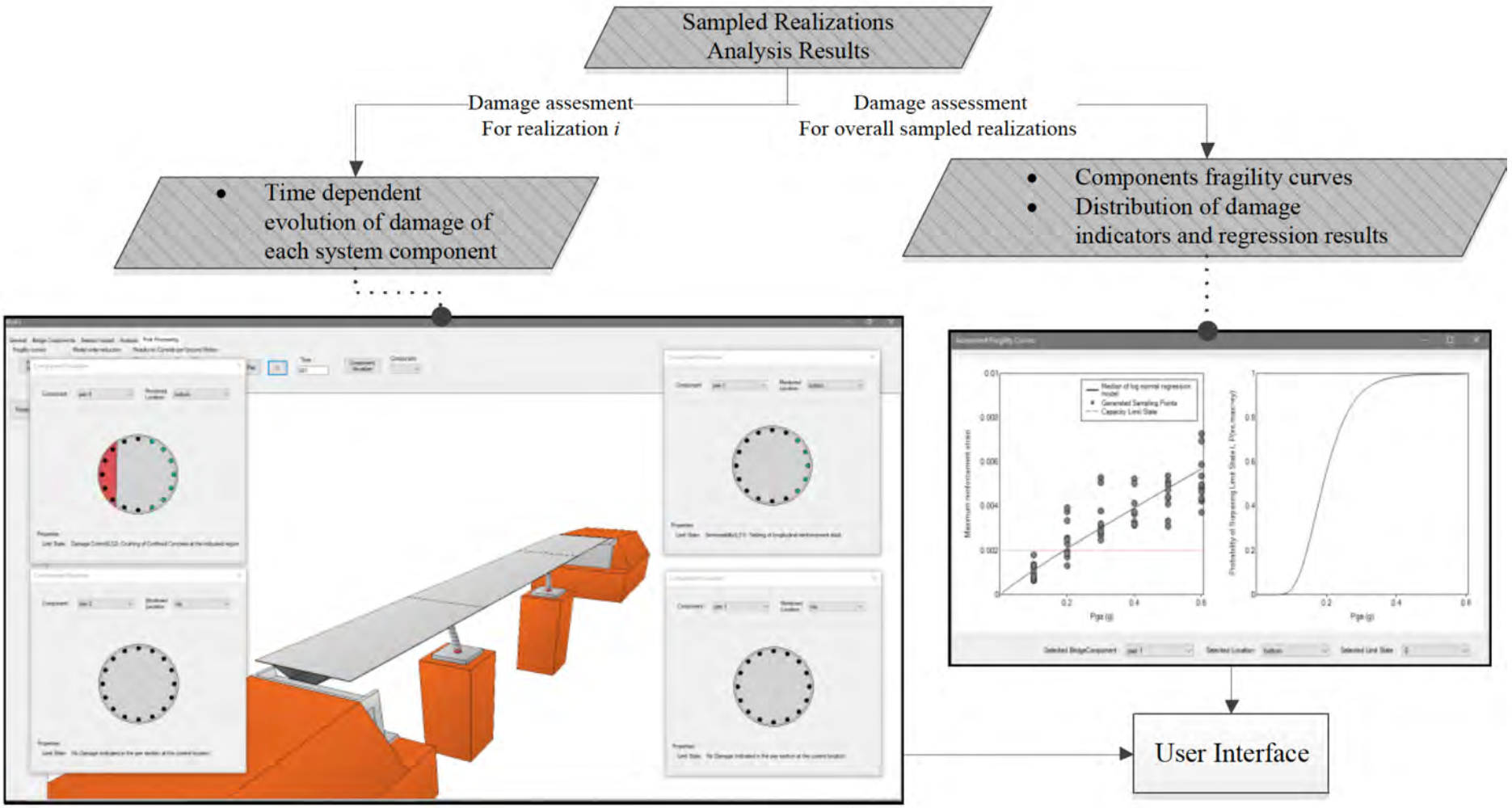
Order reduction in accordance to previously presented LP methods.



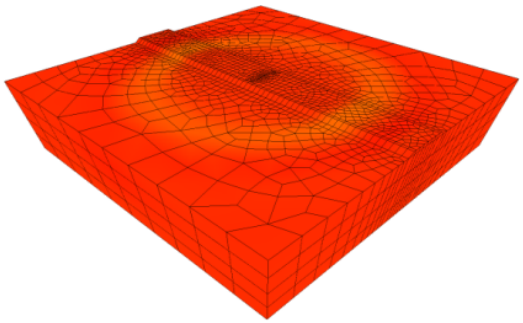


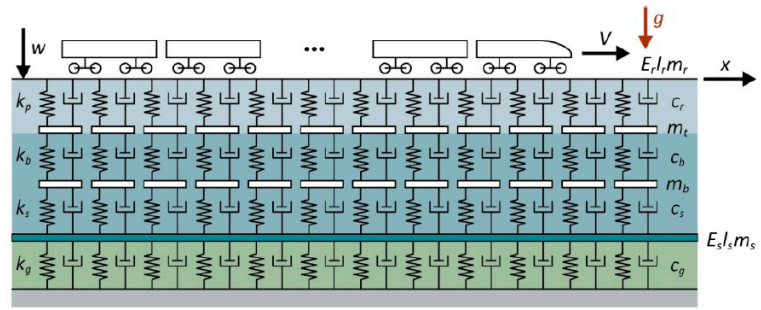
Automated construction of FEM models of subsoil interface regions.

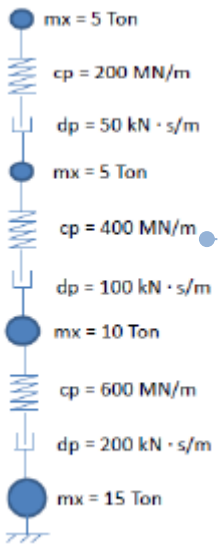
Fragility assessment

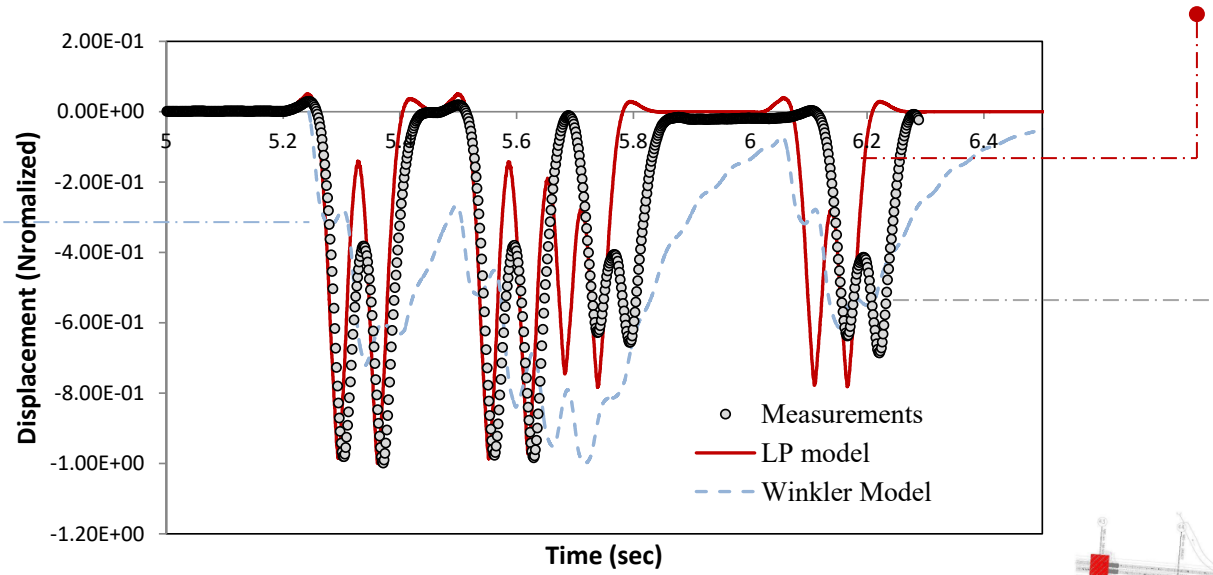


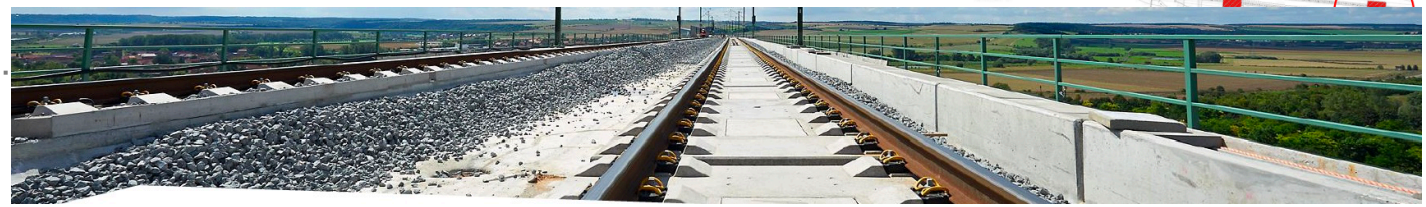
SSI: Analytical LPM modelling











ExchangeRisk Challenges

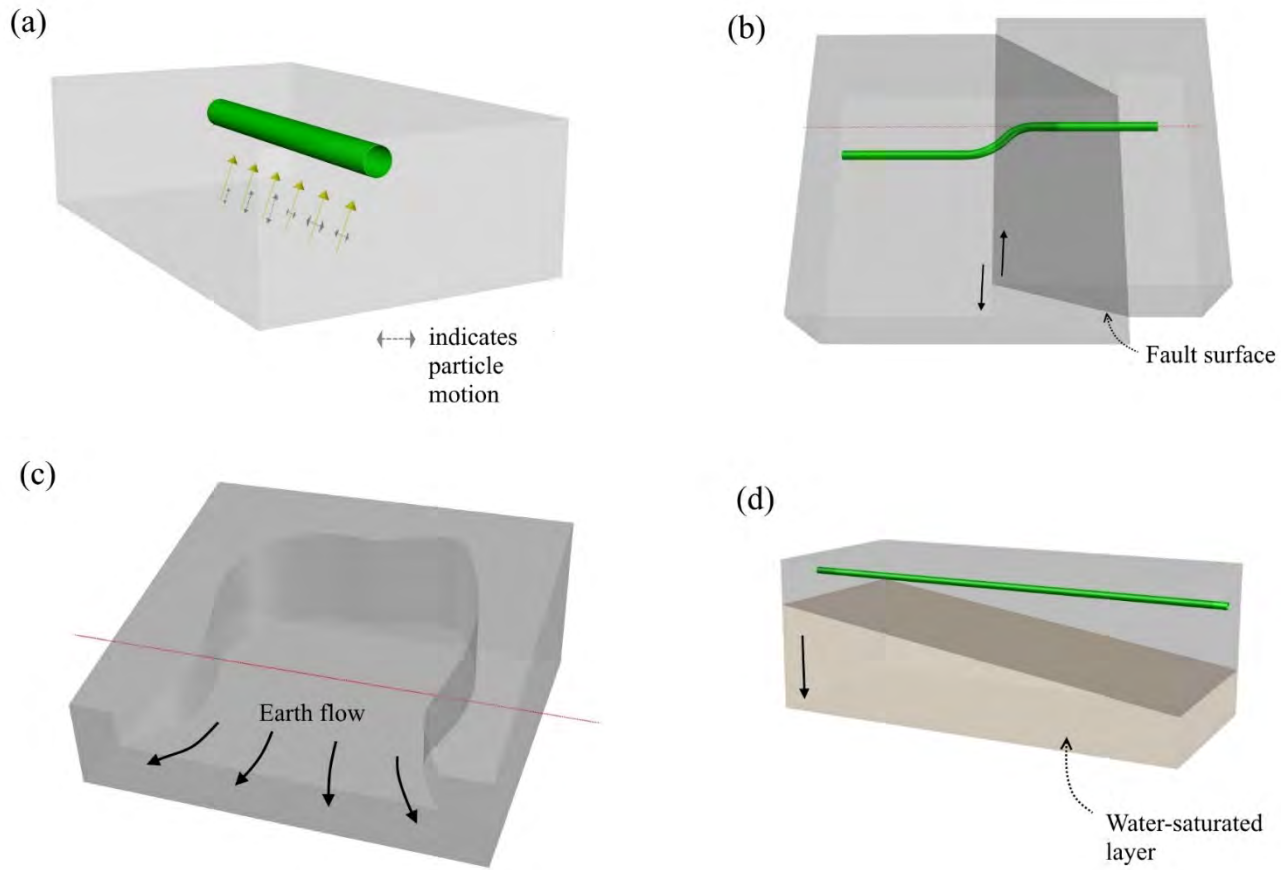
Project objectives

- R&I project implemented via secondments
- Brain circulation between Europe, US, Canada; Academia and Industry
- Have a big structural effect in EU
- Shift from research culture to innovation culture
- Establish sustainable networking

Limited EU & US design guidelines for construction and assessment of NG pipelines is seismic areas

EUROCODES

- In Eurocodes there is no procedure prescribed as to mitigate seismic risk of NG pipelines
- No means for quick inspection and rehabilitation in case of an earthquake event.
- Guidelines too general (summarized in 4 pages)
- Wave-induced earthquake loading in 2 pages informative Annex based 1967 Newmark method

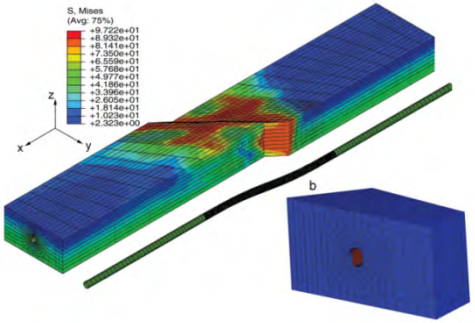


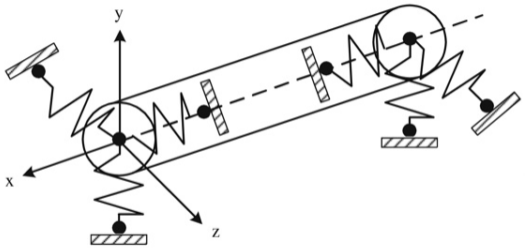
Spatially variable earthquake induced displacements along the pipeline axis are ignored

- Seismic loading is not deemed critical for buried pipelines
- Deformations are not uniform along the pipe length
- (particularly for abruptly changing and/or liquefiable soil profiles)
- Analytical and experimental justification is required

Soil-pipeline interaction modeling is simplified

Reference	Relationship	Remarks
Audibert and Nyman (1977)	$F_{U,lateral} = \gamma' DHN_q$	For lateral loading of steel pipe in sand
Nyman (1984)	$F_{U,oblique} = R_i F_{U,vertical}$	For oblique loading in cohesionless soil
Trautmann and O' Rourke (1985)	$F/F_U = \dfrac{\delta/\delta_y}{0.17 + 0.83\delta/\delta_y}$	For lateral loading; δ_y ranges from to $0.03H$ to $0.13H$ depending on soil density
St. John and Zahrah (1987)	$k_a = \dfrac{16\pi}{1}\dfrac{(1-\nu)}{(3-4\nu)}GD$	For axial loading; elastic soil response
El Hmadi and O' Rourke (1988)	$1.57G \le k_a \le 1.70G$	For axial loading
O' Rourke and El Hmadi (1988)	$F_{U,axial} = \mu\gamma' H\left(\dfrac{1+k_0}{2}\right)\pi D$	For axial loading; sand backfill
Hsu *et al.* (2001)	$\begin{cases} F_{axial-oblique} = F_{axial}\cos a \\ F_{lateral-oblique} = F_{lateral}\sin a \end{cases}$	For oblique loading in loose sand

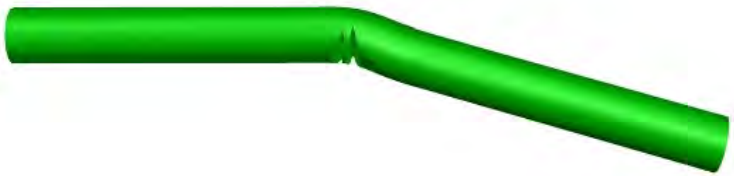




- Only bi-linear, force-displacement relationships, similar to those adopted by ALA(2001) document in the U.S. are most commonly used
- Challenge is to develop reliable cyclic force-deformation relationships for (a) axial, (b) transverse horizontal and (c) transverse vertical springs

Experimental verification of failure modes is very limited

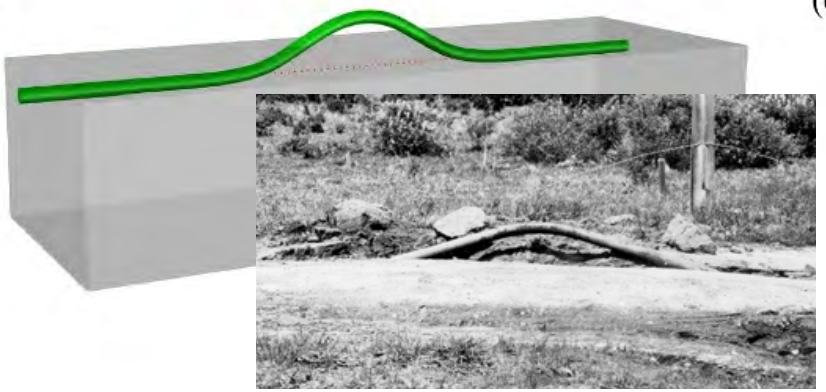
(a) Local buckling



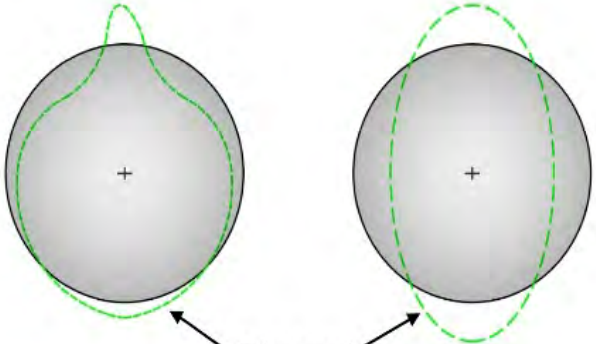
(b) Axial strain-rupture

Upheal buckling

(c)



(d)



Cross-section distortion
(e.g. section ovalization)

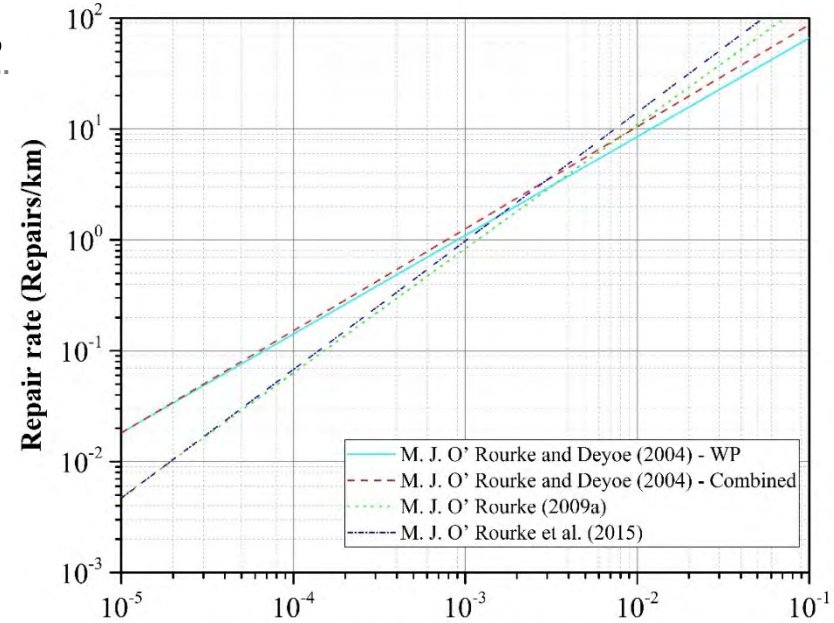
- Need for reliable laboratory testing of soil-pipe systems

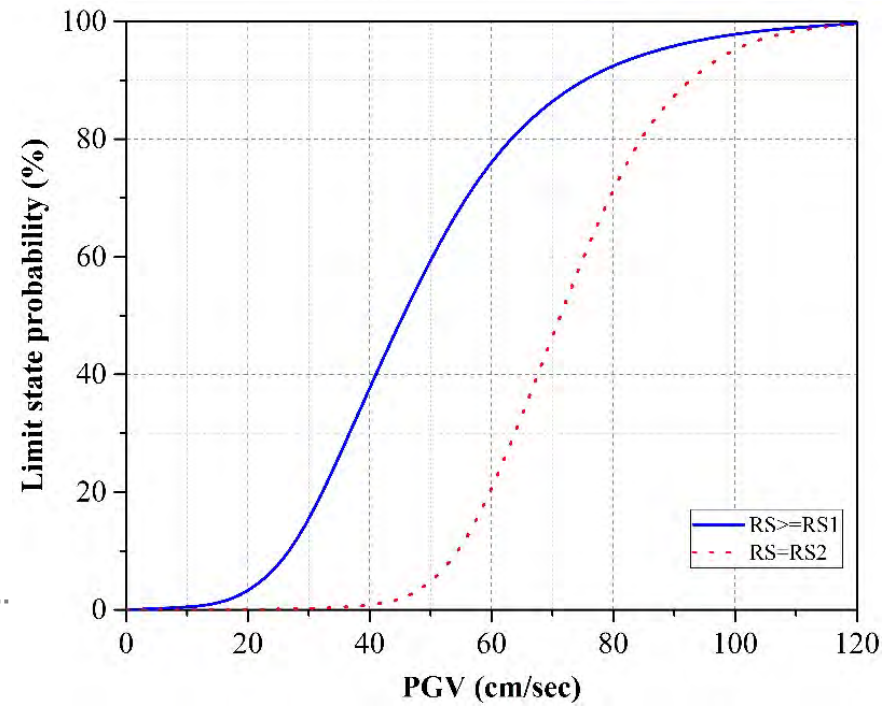
Empirical fragility assessment of natural gas pipelines

- Current fragility curves are empirical based on the Repair Ratio

$$RR = aIM^b$$

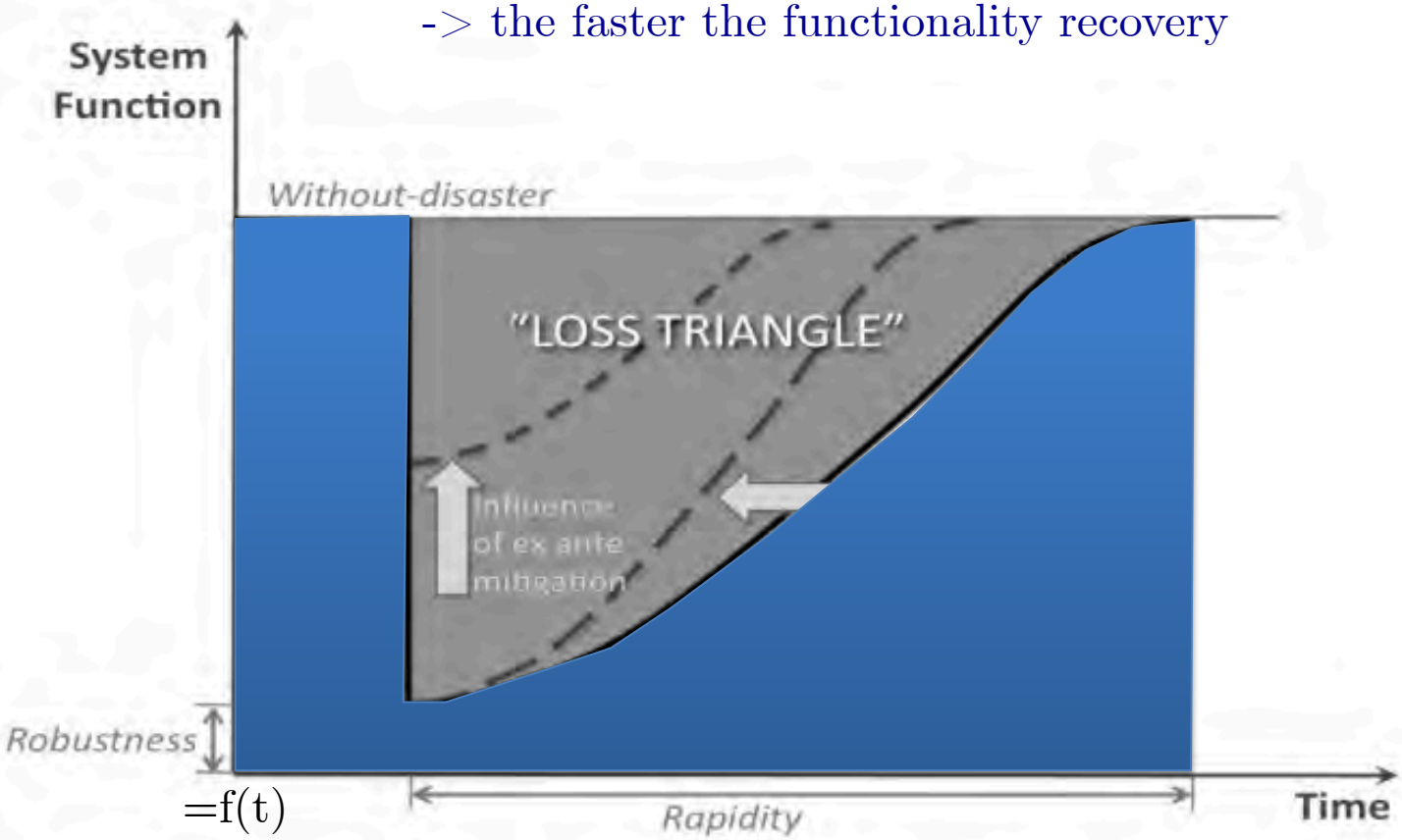
- Few works on local damage (tension cracks; local buckling; beam buckling)
- No consideration of spatially variable ground displacements and soil-pipeline interaction
- Fragility expressions for the Metering/Regulating stations linking the High Pressure Natural Gas Transmission System to the local Natural Gas Distribution Network are only empirical.





Need for optimal pre-earthquake retrofit

The less vulnerable the critical components (pipeline segments. connections)
-> the less the initial functionality loss
The more efficient the post-earthquake mitigation
-> the faster the functionality recovery



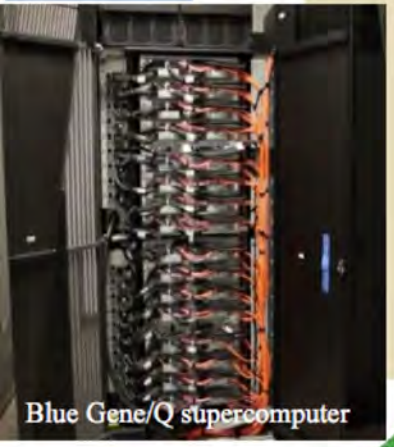
=f(t) due to aging

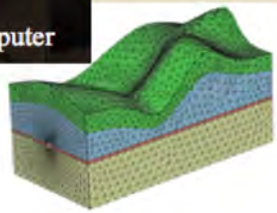
National Research Council (2011) National Earthquake Resilience, Washington, DC

Hybrid experimentation on principle failure modes of the soil-pipeline system

UNIVERSITY OF TORONTO

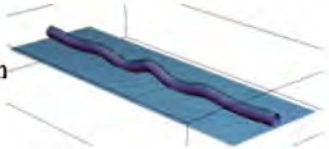
Spatially variable displacement time histories





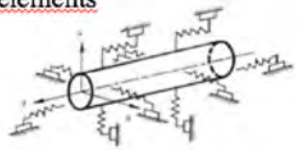
$$x_i(t) = A_i(t) \cdot 2\sum_{m=1}^{n}\sum_{l=1}^{N}\left|L_{jm}(\omega_{ml})\right|\sqrt{\Delta\omega}\cdot\cos[\omega_{ml}t + \theta_{jm}(\omega_{ml}) + \phi_{ml}]$$

- analytical solutions for spatially variable pattern
- 3D FE modelling



University of BRISTOL

- Preliminary Tests on Sand Box
- Development of SSI macroelements



Pipeline Connection Test

ΠΑΝΕΠΙΣΤΗΜΙΟ ΠΑΤΡΩΝ
UNIVERSITY OF PATRAS

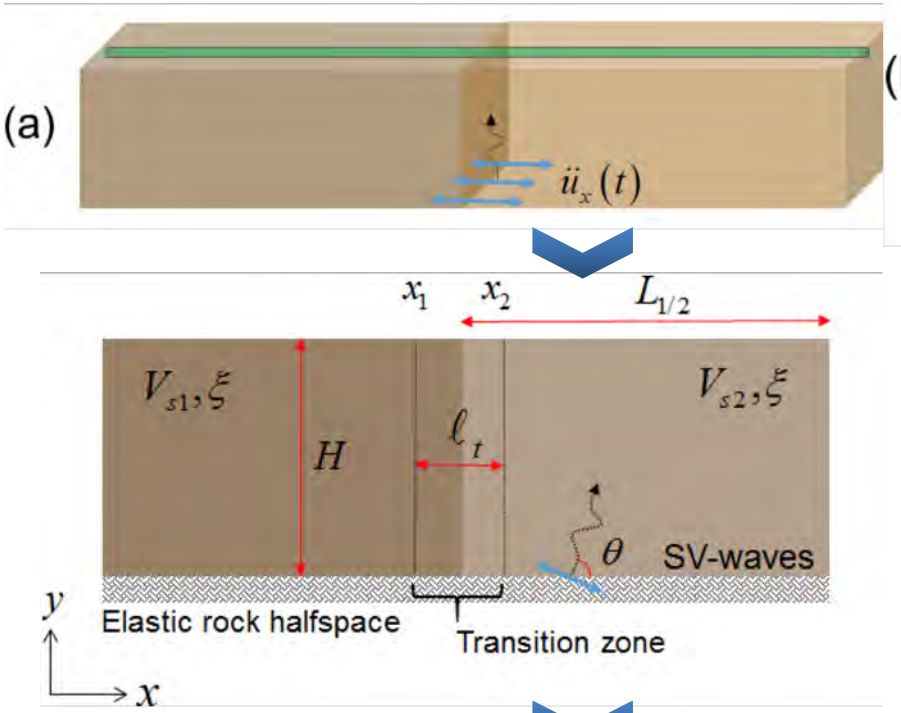
Preparatory Tests on failure modes

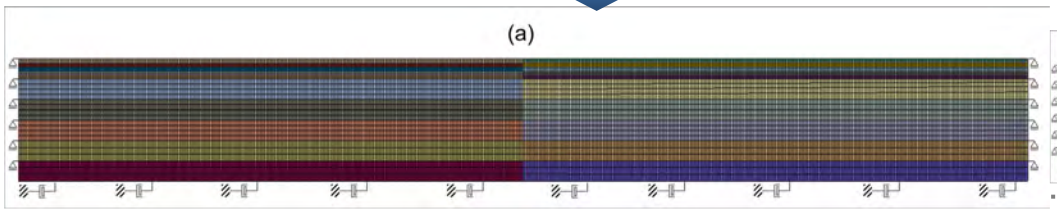
ExchangeRisk

WP02

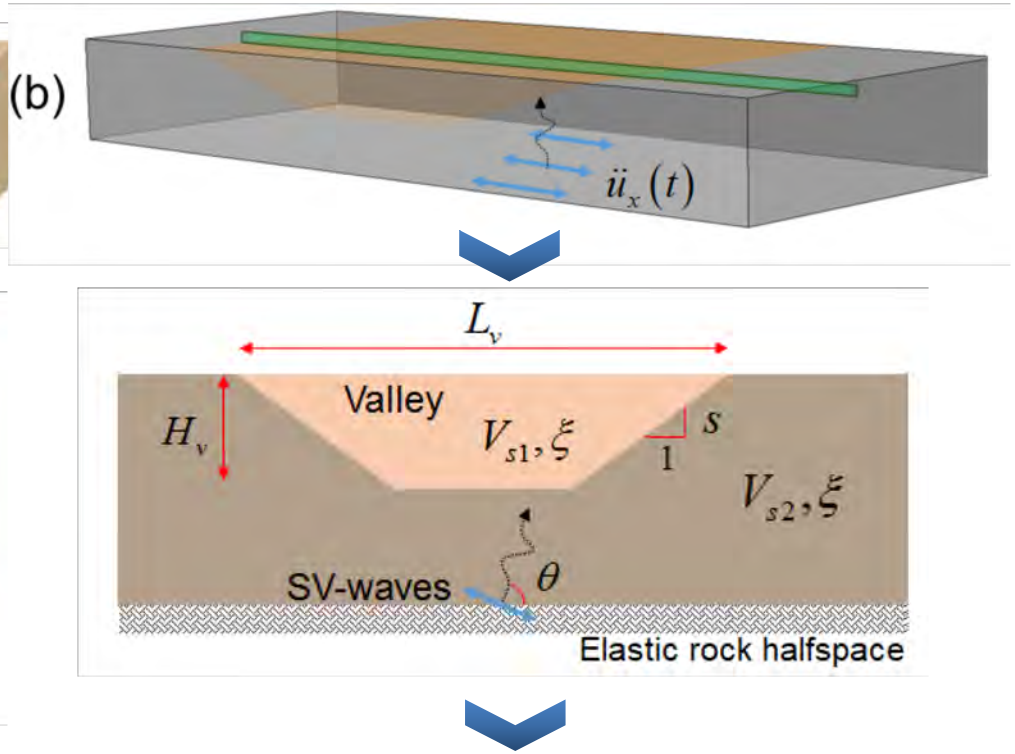
SSI: nonlinear numerical modelling

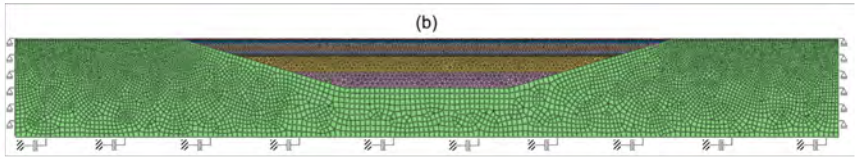
Scenario 1





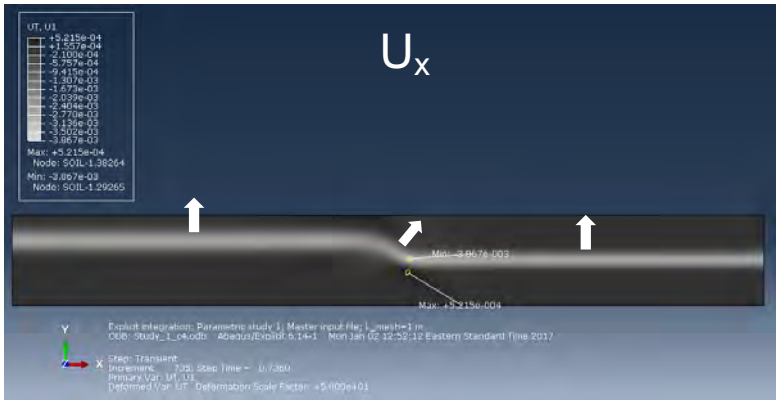
Scenario 2



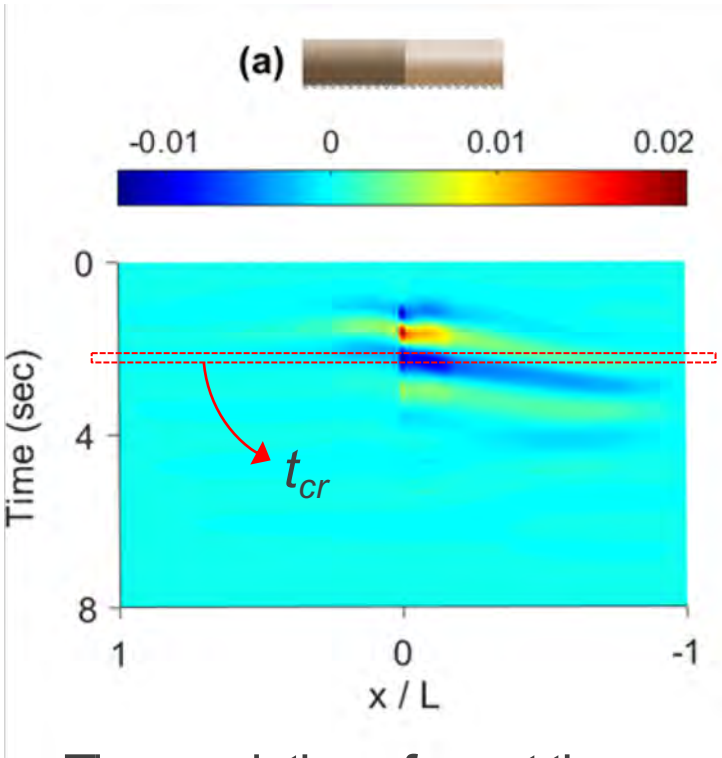


SSI: nonlinear numerical modelling

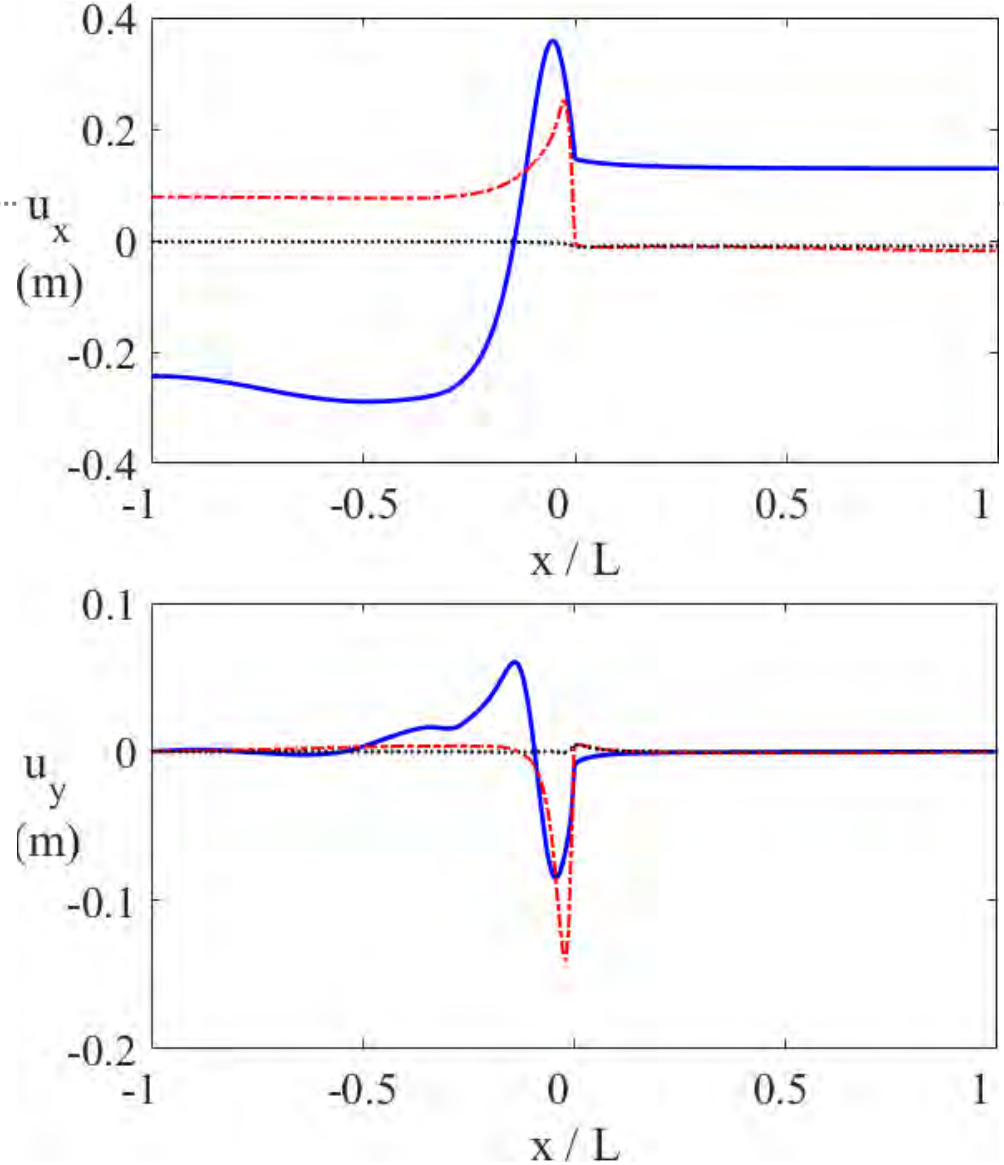
SV- waves



P- waves

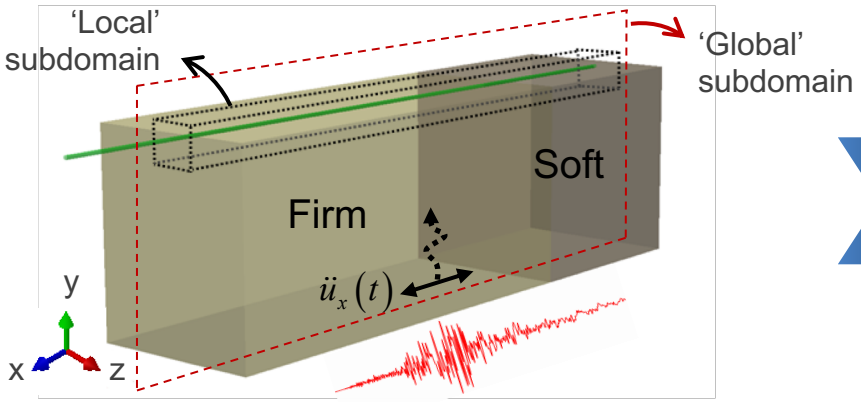


Time-variation of $\varepsilon_{a,g}$ at the surface of the equivalent-linear site

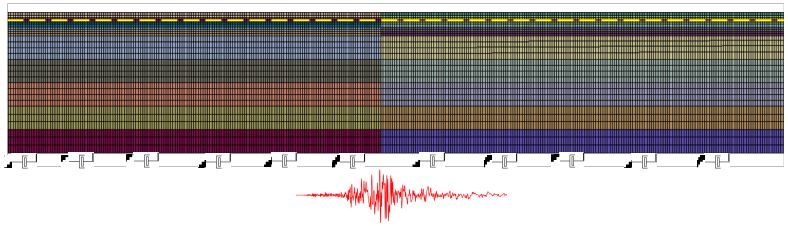


axial displacement (*top*), vertical displacement (*bottom*) at t_{cr}

SSI: FEM substructuring

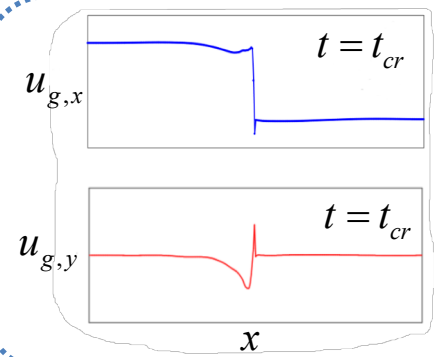


2D plane strain site response analysis



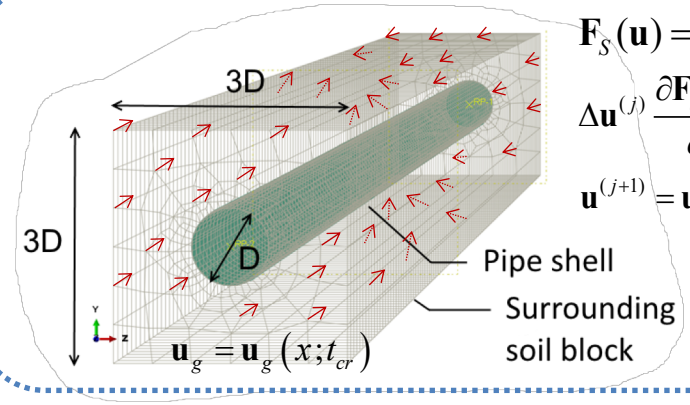
$$\mathbf{M}\ddot{\mathbf{u}}_g(t)+\mathbf{C}\dot{\mathbf{u}}_g(t)+\mathbf{K}\mathbf{u}_g(t)=\mathbf{J}\rho_r V_{s,r}\dot{u}_b(t)$$

Instantaneous ground motion X-profiles



t_{cr} when $\varepsilon_{g,xx}$ = min

2 3D soil-pipe interaction analysis

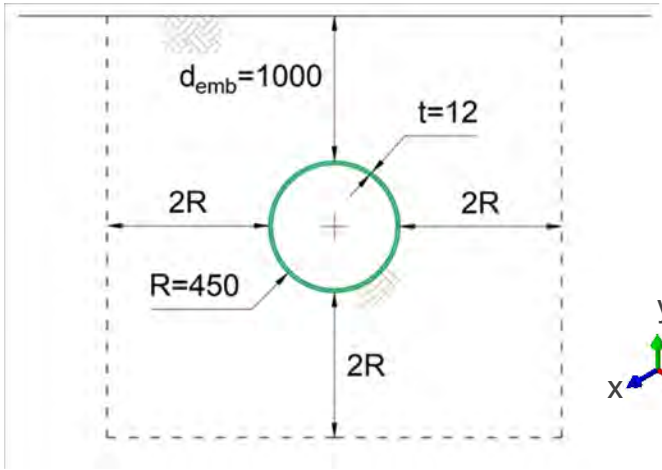


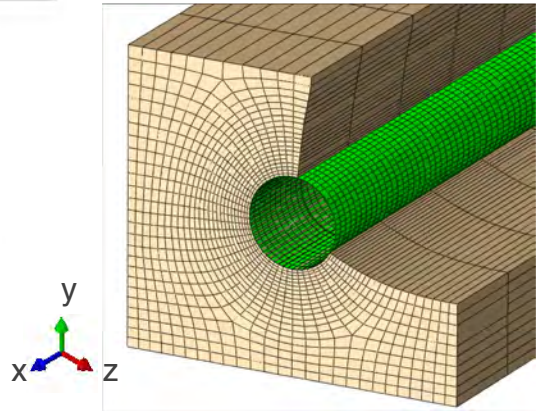
$$\mathbf{F}_S(\mathbf{u})=\mathbf{p}_{ext}$$

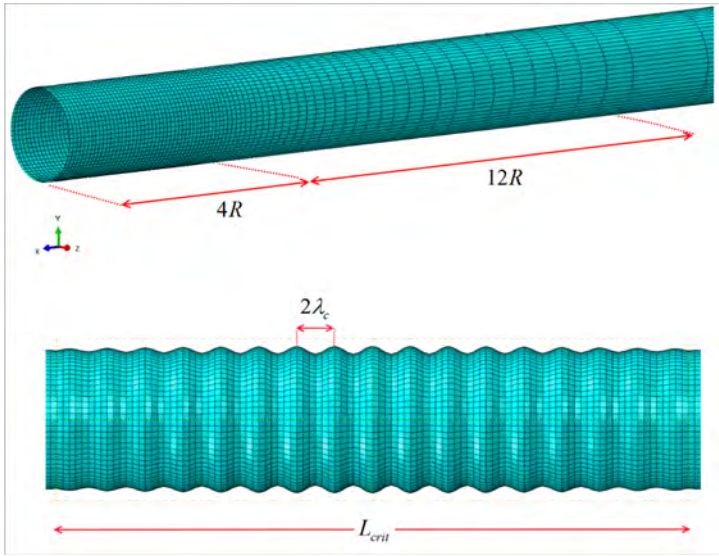
$$\Delta\mathbf{u}^{(j)}\left.\frac{\partial\mathbf{F}_S(\mathbf{u})}{\partial\mathbf{u}}\right|_{\mathbf{u}^{(j)}}=\mathbf{R}^{(j)}$$

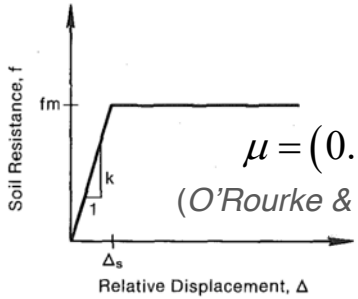
$$\mathbf{u}^{(j+1)}=\mathbf{u}^{(j)}+\Delta\mathbf{u}^{(j)}$$

SSI: nonlinear numerical modelling



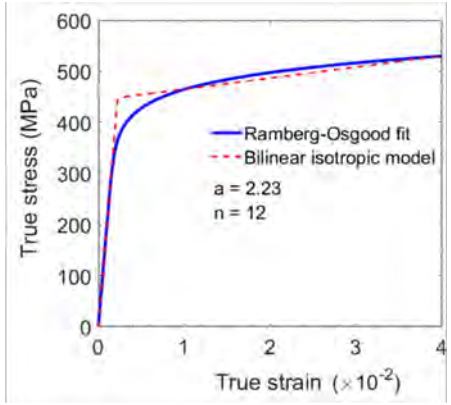






$$\mu = (0.5 \sim 0.9)\tan\varphi$$

(O'Rourke & El Hmadi, 1988)



R (mm)	t (mm)	R/t (-)	σ_y (MPa)	P/P_y	h_{emb} (m)	ε_u (%)
450	12	37.5	450	0.63	1000	4

University of Toronto · University of Massachusetts Amherst

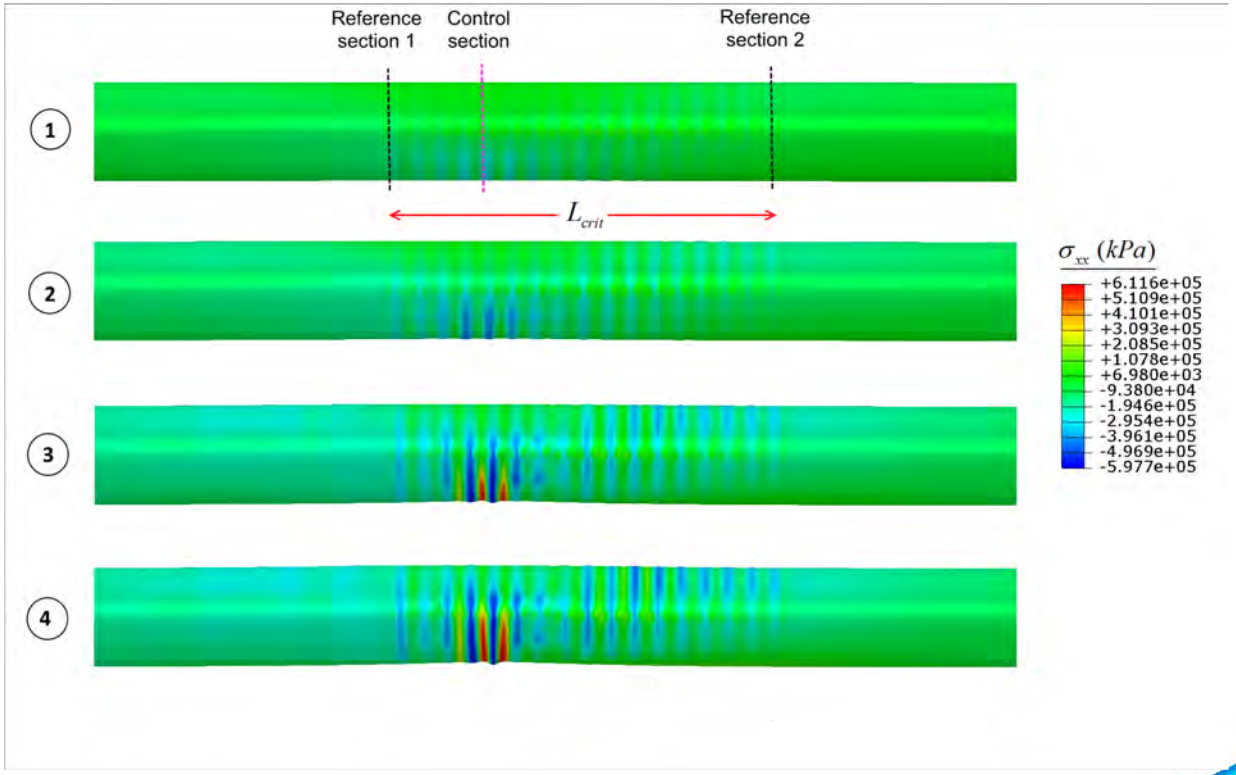
Nick Psyrras, PhD student

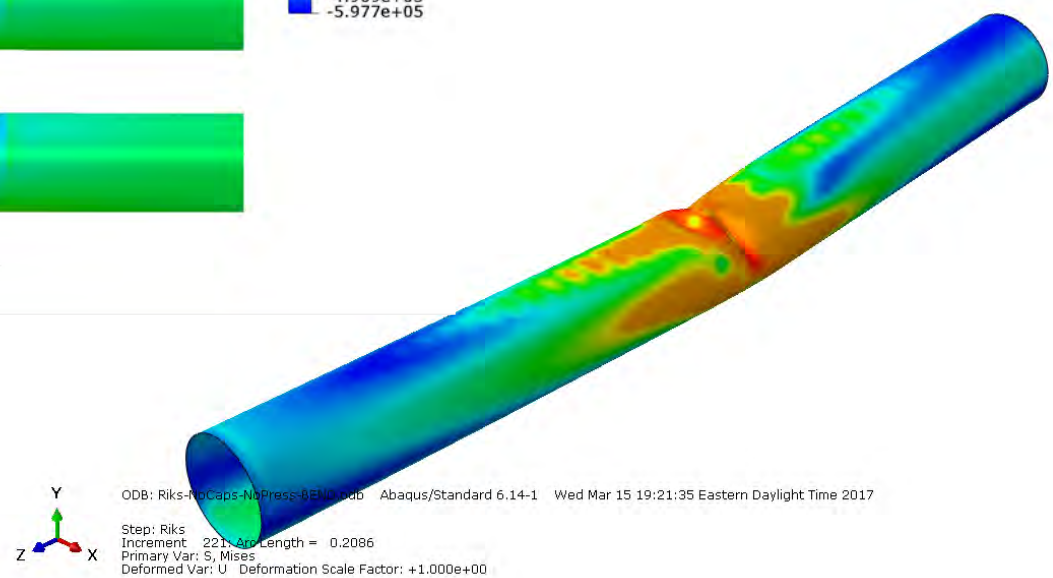
HORIZON 2020

ExchangeRisk

Psyrras, N., Gerasimidis, S., Kwon, O-S. & Sextos, A.G. (2018) "Can a buried natural gas pipeline buckle locally during earthquake ground shaking?", *Soil Dynamics and Earthquake Engineering* (accepted for publication).

SSI: nonlinear numerical modelling





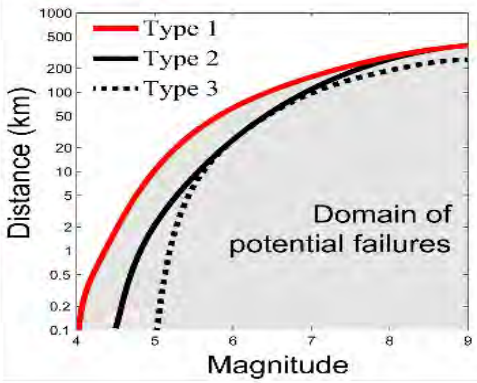
SSI: probabilistic assessment of geohazards (including seismic risk and loss)

Three-phase geotechnical models

Landslide model

(g) Susceptibility

- Keefer 1984



(h) Triggering

- Planar landslides: Newmark's method

- Safety factor:

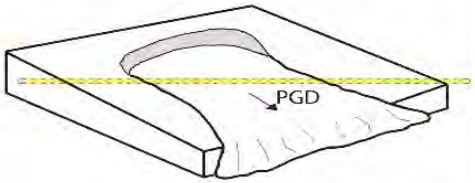
$$SF = \frac{c'}{\gamma \cdot t \cdot \sin\alpha} + \frac{\tan\phi'}{\tan\alpha} - \frac{u \cdot \gamma_w \cdot \tan\phi'}{\gamma \cdot \tan\alpha}$$

- Critical acceleration:

$$a_c = (SF - 1) \cdot g \cdot \sin\alpha$$

(i) Landslide-induced PGD

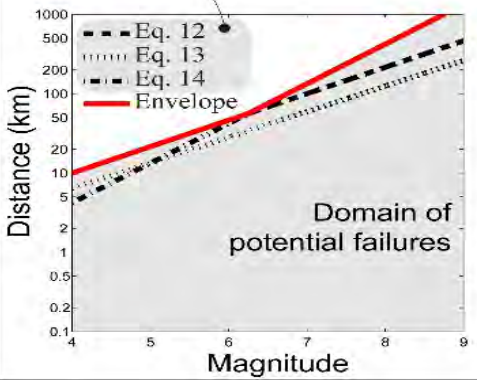
- Empirical function of PGA and PGV: Saygili & Rathje 2008



Liquefaction model

(j) Susceptibility

- Galli 2000



(k) Triggering

- Semiempirical method: Seed & Idriss 1971

$$SF = \frac{CSR}{CRR}$$ Cyclic Stress Ratio / Cyclic Resistance Ratio

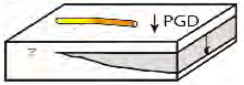
- Vs30-based approach: Goda et al. 2011; Kayen et al. 2013
- Liquefaction Potential Index

$$LPI = \int_0^{20} SF \cdot w(z) \cdot dz$$

- 0 ÷ 5; Failure potential LOW
- 5 ÷15; Failure potential HIGH
- >15; Failure potential VERY HIGH

(l) Liquefaction-induced PGD

- LPI: 0 ÷ 5 → PGD = 0
- LPI: 5 ÷ 15 → Sand Boiling Settlements
- Takada & Tanabe 1988



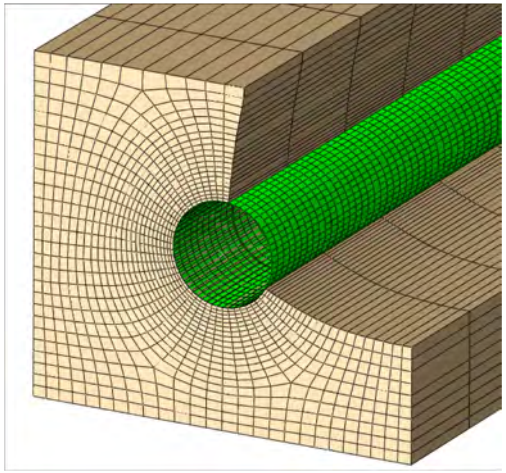
$PGD = PGD_{Settlements}$

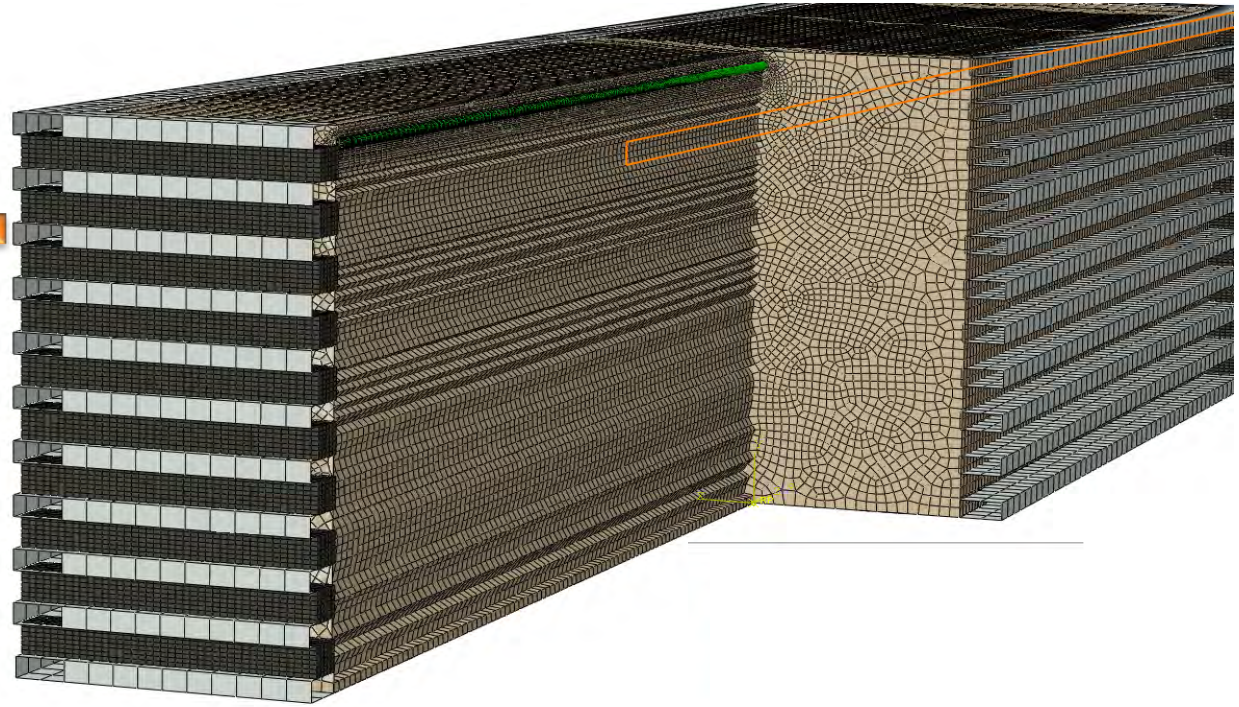
- LPI: > 15 → Sand Lateral Spread
- Bardet et al. 1999

$PGD^2 = (PGD^2_{Settlements} + PGD^2_{Lateral\ Spread})$

De Risi, R., De Luca, F. Kwon, O.-S., Sextos, A.G. (2018) "Post-earthquake risk assessment for buried gas pipelines at regional scale", ASCE Journal of Pipeline Systems (accepted for publication).

SSI: experimental investigation (shaking table + shear stack)





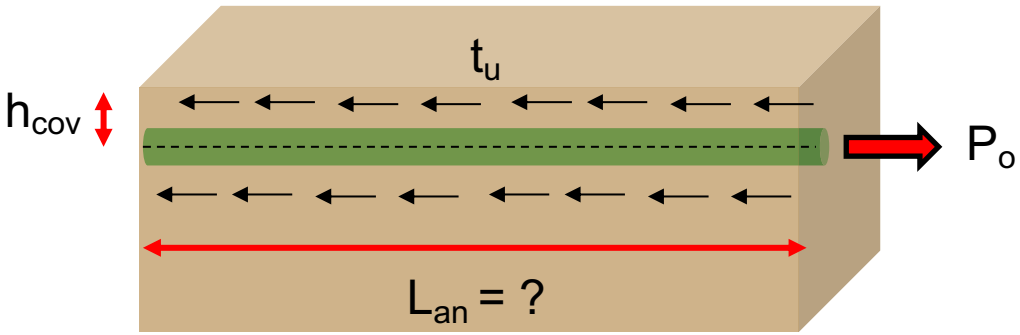
SSI: experimental investigation (shaking table + shear stack)

- Modal analysis

<u>Empty</u>: $f_{o,1}$ = 2.97 Hz (after tuning of rubber stiffness)

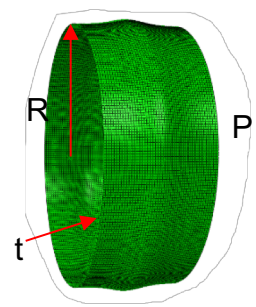
SSI: experimental investigation (shaking table + shear stack)

- Minimum required pipe anchorage length



Free pipe ends

$$L^p \geq L^p_{an,\max}$$



$$n_\ell = \frac{L^p}{L^m} = \frac{L^p}{4.8} = \frac{L^p_{an,\max}}{4.8}$$

Prototype scale

$$t_u L_{an} = P_o \Rightarrow L_{an} = \frac{P_o}{t_u}$$

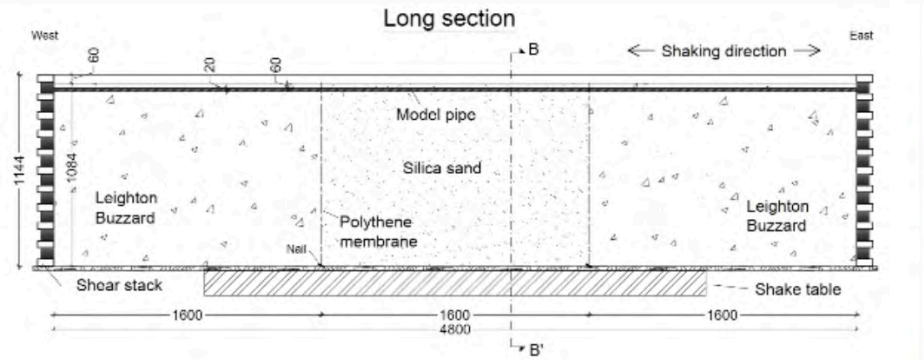
Exact expression

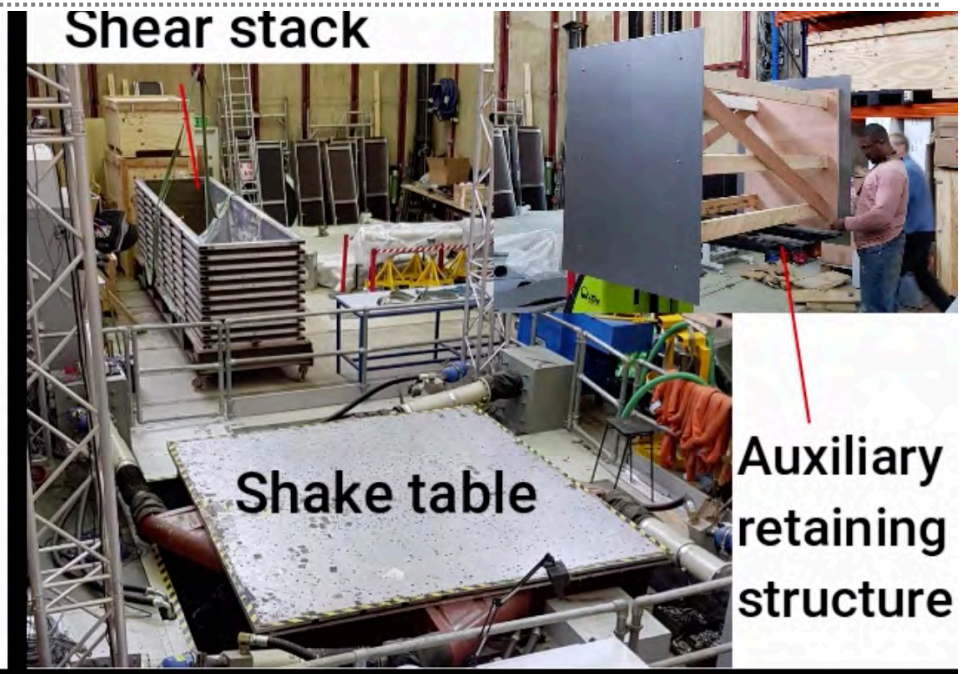
$$t_u = \mu\gamma\left(\frac{1+2K_o}{3}\right)\underbrace{(H+R)}_{h_{cov}}2\pi R + 4\mu\gamma\left(\frac{1+2K_o}{3}\right)R^2$$

SSI: experimental investigation (shaking table + shear stack)

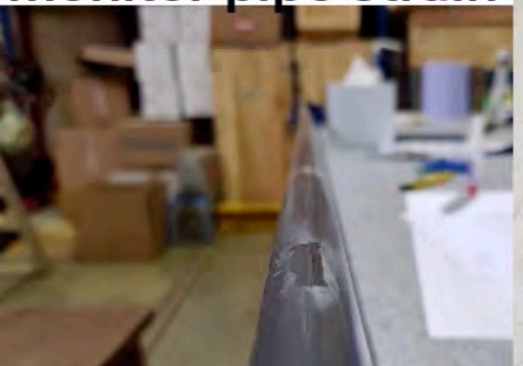
SSI: experimental investigation (shaking table + shear stack)

Model-to-prototype scale 1:45

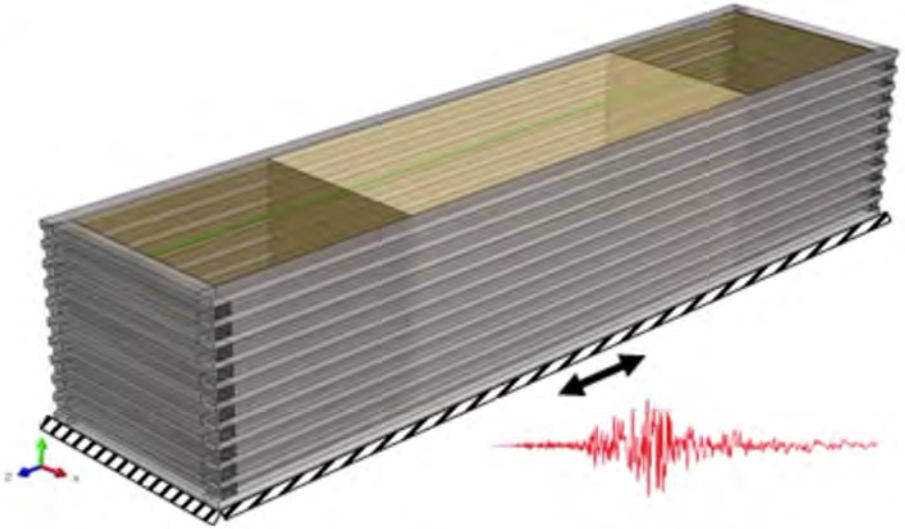




Bare FBG cables to monitor pipe strain



Shake table tests of gas transmission pipelines crossing laterally graded soil



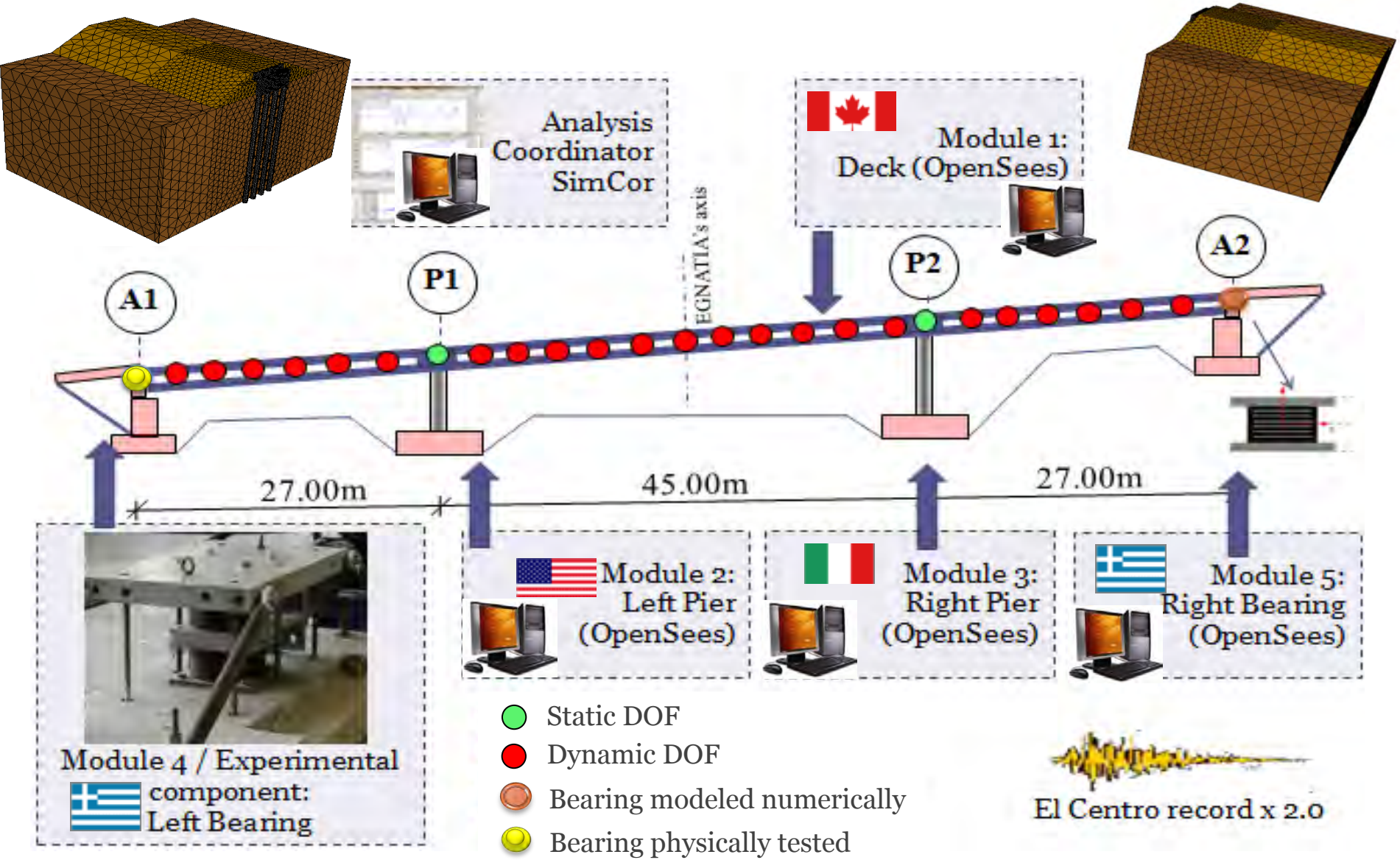
Nick Psyrras
Anastasios Sextos
Adam Crewe
Matt Dietz

ExchangeRisk HORIZON 2020

University of BRISTOL

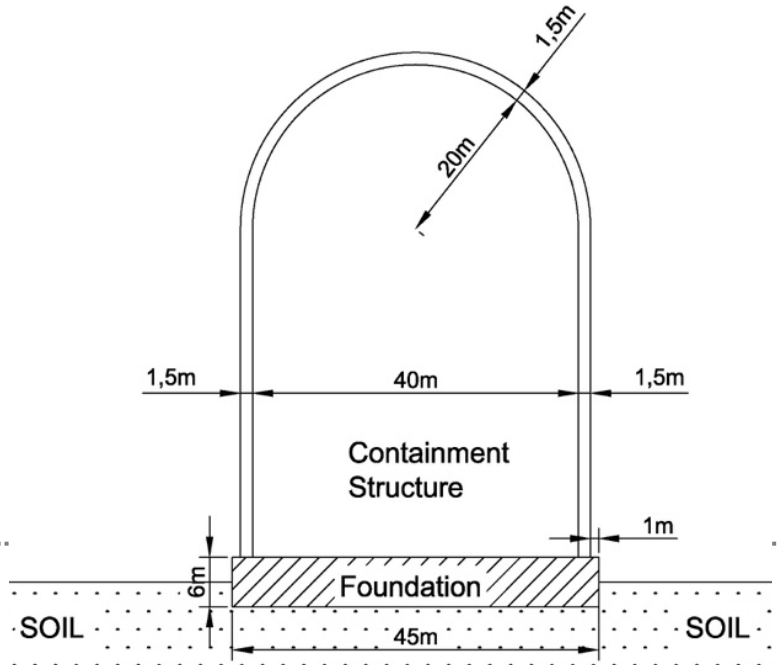
SSI: experimental investigation (soil isolation)

Nick Alexander, Anastasis Tsiavos, Anastasios Sextos



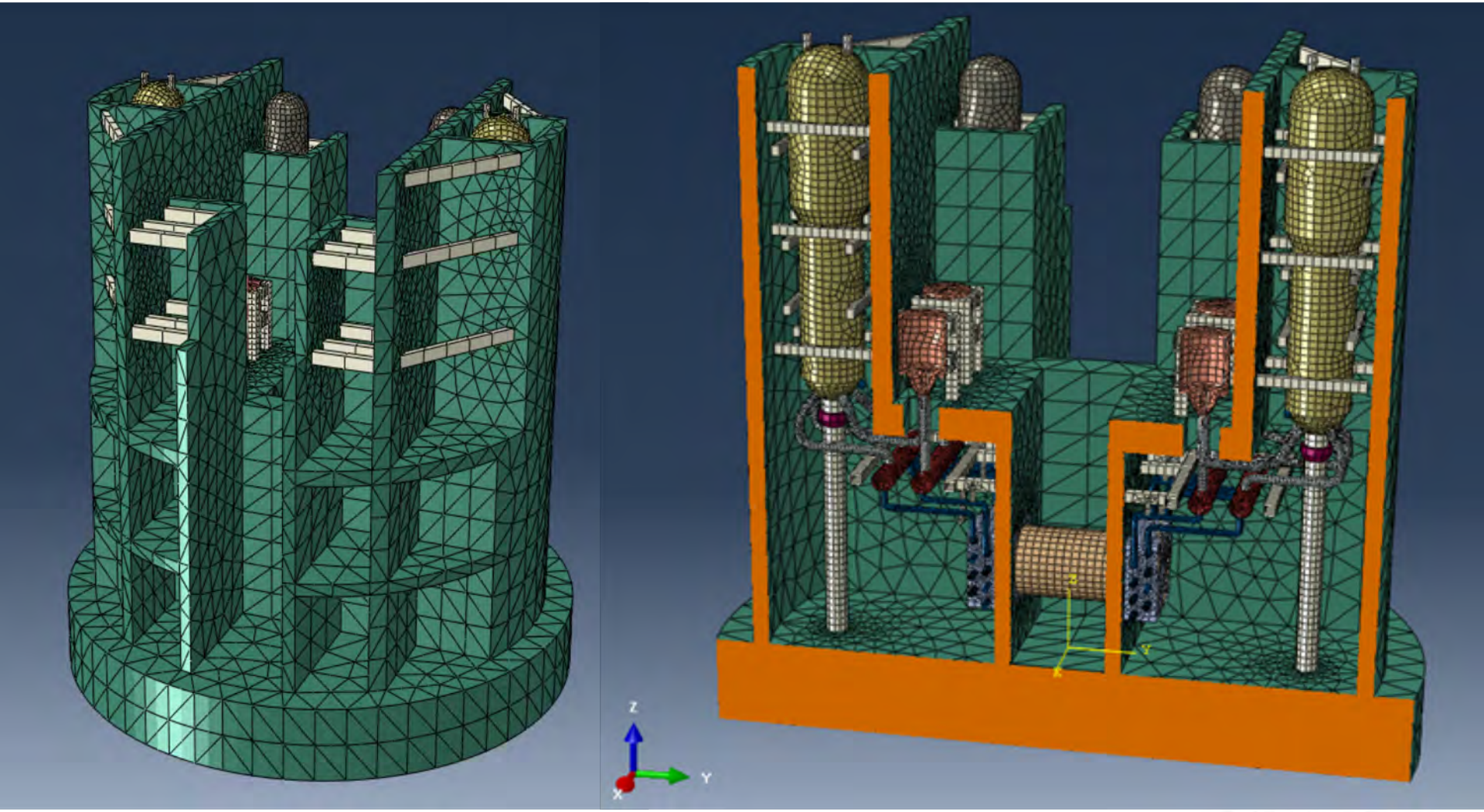
Bousias, S., Sextos, A.G., Kwon, O.-S., Taskari, O., Elnashai, A., Evangeliou, N. and Di Sarno, L. (2017) "Intercontinental Hybrid Simulation for the Assessment of a Three-span R/C Highway Overpass", Journal of Earthquake Engineering

SSI: geometrically nonlinear numerical modelling



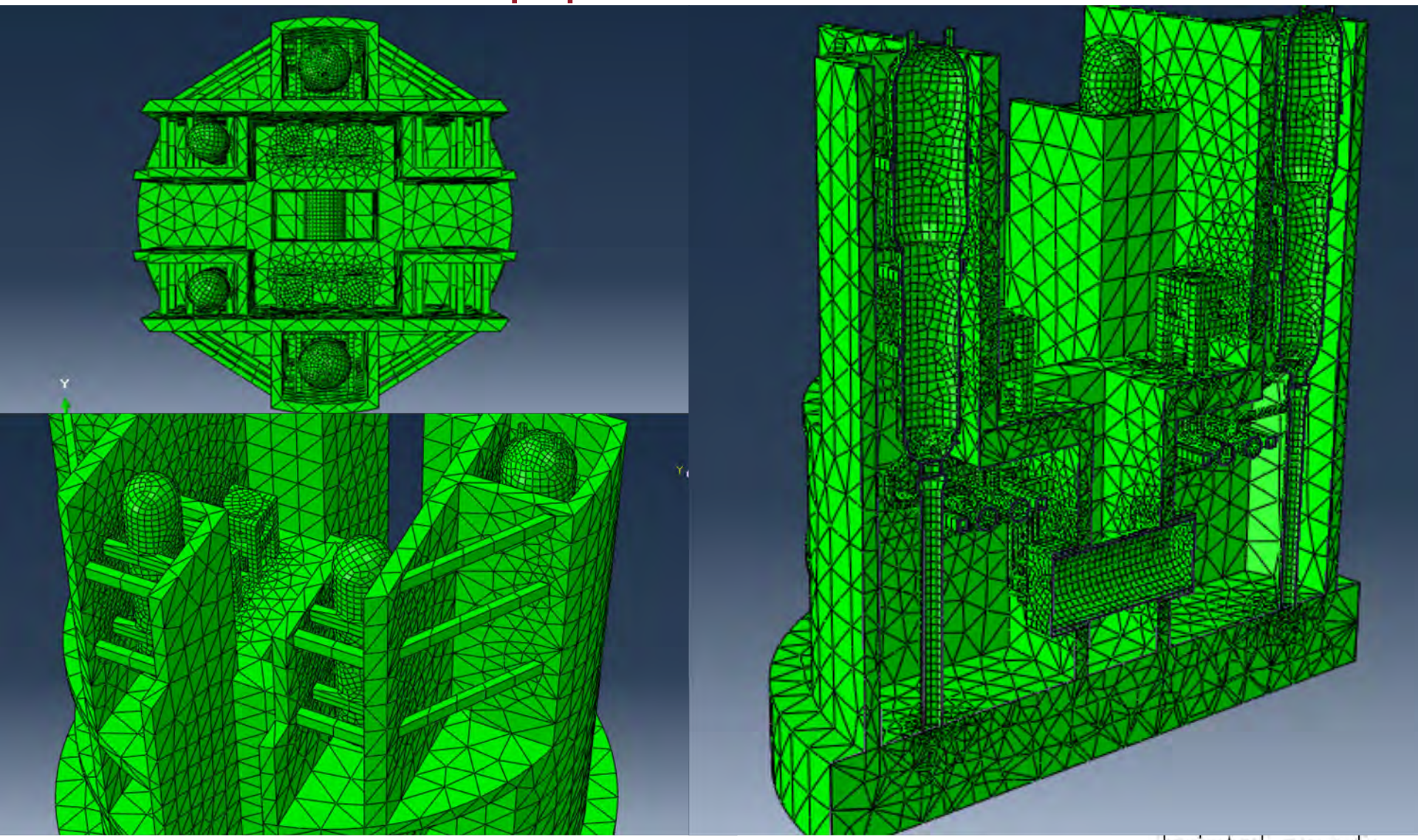
Concrete	
Compressive Strength f_c (MPa)	35
Tensile Strength f_t (MPa)	2
Modulus of Elasticity (GPa)	28
Poisson's Ratio	0.2
Strain at compressive strength	0.0035
Density (kg/m^3)	2500
Steel	
Modulus of Elasticity (GPa)	200
Yield Stress (MPa)	460
Density (kg/m^3)	7850

SSI: FEM substructuring & effect on equipment



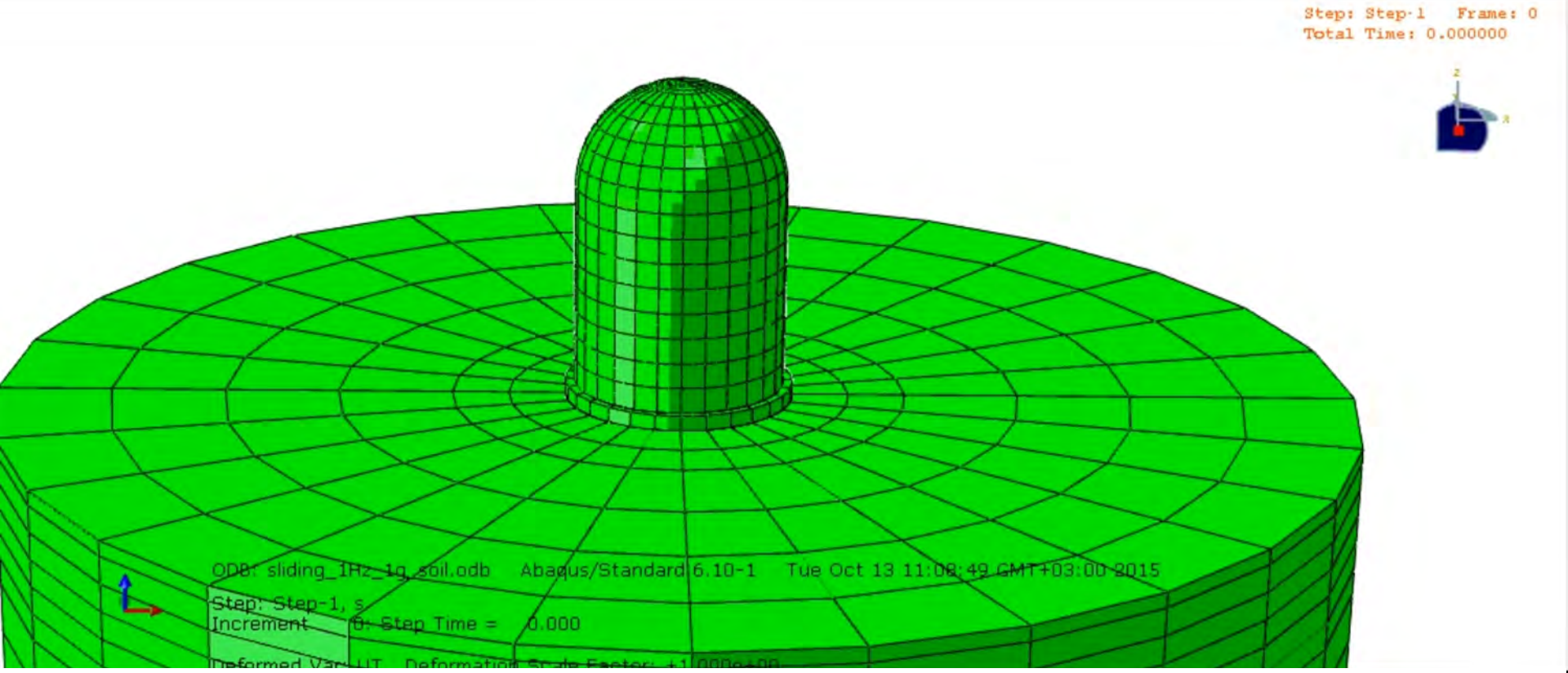
Sextos, A.G., Manolis, G.D., Ioannidis, N., Athanasiou, A. (2016) “Seismically induced uplift effects on nuclear power plants. Part I&II: Containment building rocking spectra”, Nuclear Engineering and Design

SSI: FEM substructuring & effect on equipment



Sextos, A.G., Manolis, G.D., Ioannidis, N., Athanasiou, A. (2016) “Seismically induced uplift effects on nuclear power plants. Part I&II: Containment building rocking spectra”, Nuclear Engineering and Design

SSI: geometrically nonlinear numerical modelling



University of BRISTOL

UKCRIC

National Soil-Foundation-Structure Interaction Laboratory

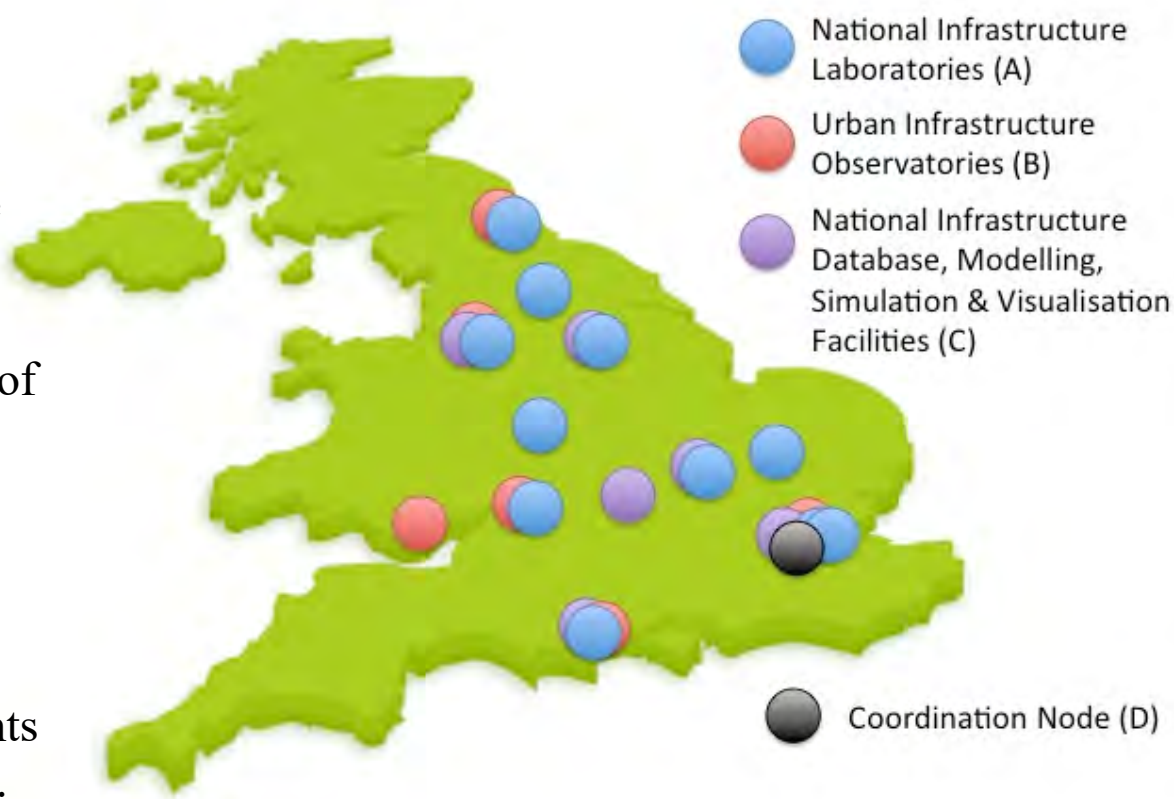
bristol.ac.uk

University of BRISTOL

UKCRIC

The £12m National Soil-Foundation-Structure Interaction (SoFSI) Facility, is a nationally shared facility to be hosted at the University of Bristol.

SoFSI will be a core component of the Government's £138m UK Collaboratorium for Research in Infrastructure and Cities (UKCRIC) initiative, which will drive forward the national infrastructure research investments for the next 30 years and beyond.



Inspired infrastructure for better living

UKCRIC
UK COLLABORATORIUM FOR RESEARCH ON INFRASTRUCTURE & CITIES

Earthquake Shaking Table at the existing lab

3m by 3m platform supported by 8 hydraulic actuators that carry up to 15t
Acceleration up to 5g with peak displacements of ±150mm