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

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SSI: Large scale numerical modelling
Presence of soil can have a detrimental impact on the behaviour of a structure.

Analytical solution of the PDE equations
- Capable of simulating complex behavior
- High Computational Cost

Direct FEM simulation
- Limited to the most common scenarios

Simplified closed form approximations
- Accurate
- Intensity or frequency independent

FEM method non viable under the framework of:

- Fragility assessment of structures
- Seismic Reliability-Based Design Optimization

SSI: Analytical LPM modelling

Direct FEM simulation

Model Order Reduction

Lumped Parameter (LP) modeling Method

Finite element formulation

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

Global Stability Issues

Limited to Viscous-Elastic Systems

Stability issues in LP method

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

\[ S_{LP}(s) = S_{LP,0} \cdot \frac{P(s)}{Q(s)} = S_{LP,0} \cdot \frac{p_0 + p_1 \cdot (s) + \cdots + p_{N+1} \cdot (s)^{N+1}}{q_o + q_1 \cdot (s) + \cdots + q_N \cdot (s)^N} \]

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):

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

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

Use of a predefined LP model:

**Pier base region:**

6x6 dynamic stiffness matrix

**Abutment-Embarkment 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

<table>
<thead>
<tr>
<th>Overall length</th>
<th>78</th>
</tr>
</thead>
<tbody>
<tr>
<td>Span Arrangement</td>
<td>19.00m -32.00m -19.00m</td>
</tr>
<tr>
<td>Deck Section</td>
<td>box girder, non prismatic</td>
</tr>
<tr>
<td>Piers(P1,P2)</td>
<td>solid circular section, height : 8.50 m</td>
</tr>
<tr>
<td>Abutments (A1,A2)</td>
<td>laying on PTFE pot bearings</td>
</tr>
</tbody>
</table>

Different soil Scenarios

<table>
<thead>
<tr>
<th>Soil type</th>
<th>Scenarios</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soft Clay</td>
<td>S1</td>
</tr>
<tr>
<td>Loose Sand</td>
<td>S2</td>
</tr>
<tr>
<td>Medium Clay</td>
<td>S3</td>
</tr>
<tr>
<td>Medium Sand</td>
<td>S4</td>
</tr>
<tr>
<td>Hard Clay</td>
<td>S5</td>
</tr>
</tbody>
</table>

Excitation sets based on the frequency content:
FE Modeling

Seismic Isolation:
Non linear Gap Model

Pot Bearing:
Velocity dependent friction model

Pier: Reinforced concrete Fiber Model

Abutment interface Region:
(a) Kelvin Voigt Assembly
(b) LP model Assembly

Pier interface Region:
(a) Kelvin Voigt Assembly
(b) LP model Assembly

Interface node P1

Interface node A1

Interface node A2

Interface node A3

Interface node A4

Transverse interface Node A1 (y)
Transverse interface Node A2 (y)
Transverse interface Node A3 (x,y,z,rx,ry,rz)
Longitudinal interface Node A4 (x)

Young Modulus Distribution

Extraction of dynamic Impedance functions from FEM model formulation.

FEM model in OpenSees.

37.1 m
30 m
60 m
57 m

60 m

60 m

37.1 m

50 m
Error induced when neglecting frequency-dependence

Percentage error in probability of reaching threshold limit states:

(a) \( m_{LS1} \) - Serviceability
(b) \( m_{LS2} \) - Damage control
(c) \( m_{LS3} \) - Collapse prevention
Inelastic LP modeling method

Selection and extraction of representative properties of target dynamic system:

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

Extraction of Dynamic stiffness matrix for selected variable states in inelastic range
SSI: Analytical LPM modelling

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

\[ \hat{F}^{\text{comp}} = k^{\text{comp}}(a_{\text{base}}, u_{\text{base}}) \cdot \dot{u}^{\text{comp}} \]

\[ k^{\text{comp}}(a_{\text{base}}, u_{\text{base}}) = \begin{cases} k_o & \text{if } [a_{\text{base}}, u_{\text{base}}]^T < c_o \text{ or Unloading} \\ \vdots \\ k_n & \text{if } c_{n-1} < [a_{\text{base}}, u_{\text{base}}]^T < c_n \end{cases} \]

Frequency- and intensity-dependent LPMs

Verification example

Sample of Dynamic Properties in the Frequency domain:

- Moment My (KNm)
- Foundation Rotation (mrad)
- Horizontal Force at Foundation (KN)
- Foundation Displacement (mm)

Model verification results:

- FEM solution vs.2-vs.9
- Complete LP model (M.1) vs.2-vs.9
- Simplified LP model (M.2) vs.2-vs.9
- Simplified LP model (M.2) vs.1
- Complete LP model (M.1) vs.1
- FEM solution vs.1

Soil Properties:
- f_y = 100 MPa
- ν = 0.409
- E = 169090 MPa
- Ho = 20000

Static Properties Calibration:
- Moment My (KNm)
- Foundation Rotation (mrad)
- Horizontal Force at Foundation (KN)
- Foundation Displacement (mm)

Sample of Dynamic Properties in the Frequency domain:

Frequency (Hz)

Dynamic Stiffness Kx Real Part (KN/m)

Dynamic Stiffness Kx Imag Part (KN/m)

Foundation Rotation (mrad)

Foundation Displacement (mm)

Static Properties Calibration:
- Fo = 800 KN

Foundation Rotation (mrad)

Foundation Displacement (mm)
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

Final Selection:
Development of greedy search algorithm with constrained scaling

Preliminary selection:

- specific bridge structure (site faults properties known - M and Re)
- portfolio representative bridge (site faults properties generated by the system)
Automated FE model construction module

Procedural knowledge Base

- Element type selection rules
- Mesh refinement selection rules
- Constitutive law selection rules
- Reduced regions selection rules
- Damage state selection rules

User Interface

- bridge structure description

Inference Engine

Pier $i$ (a) elements type, (b) mesh Refinement, (c) constitutive laws (d)

Span $i$ (a) elements type, (b) mesh Refinement, (c) constitutive laws (d)

Interconnection regions, (a) Modelling approach (b) constitutive laws

(a) Bearing model
(b) Gap/bounce model
(c) EDP selection

Box section overpass Bridge

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

- Time dependent evolution of damage of each system component
- Components fragility curves
- Distribution of damage indicators and regression results

Sampled Realizations Analysis Results

Damage assessment for realization $i$
Damage assessment for overall sampled realizations

User Interface
SSI: Analytical LPM modelling

Displacement (Normalized)

Time (sec)

Measurements

LP model

Winkler Model

mx = 5 Ton

cp = 200 MN/m

dp = 50 kN · s/m

mx = 5 Ton

cp = 400 MN/m

dp = 100 kN · s/m

mx = 10 Ton

cp = 600 MN/m

dp = 200 kN · s/m

mx = 15 Ton

RSSB
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

- 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

<table>
<thead>
<tr>
<th>Reference</th>
<th>Relationship</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Audibert and Nyman (1977)</td>
<td>$F_{U,lateral} = \gamma'DHN_d$</td>
<td>For lateral loading of steel pipe in sand</td>
</tr>
<tr>
<td>Nyman (1984)</td>
<td>$F_{U,oblique} = R_yF_{U,vertical}$</td>
<td>For oblique loading in cohesionless soil</td>
</tr>
<tr>
<td>Trautmann and O’ Rourke (1985)</td>
<td>$F/F_U = \frac{\delta/\delta_y}{0.17 + 0.83\delta/\delta_y}$</td>
<td>For lateral loading; $\delta_y$ ranges from 0.03H to 0.13H depending on soil density</td>
</tr>
<tr>
<td>St. John and Zahrah (1987)</td>
<td>$k_a = \frac{16\pi}{l} \left( \frac{1-v}{3-4v} \right) GD$</td>
<td>For axial loading; elastic soil response</td>
</tr>
<tr>
<td>El Hmadi and O’ Rourke (1988)</td>
<td>$1.57G \leq k_a \leq 1.70G$</td>
<td>For axial loading</td>
</tr>
<tr>
<td>O’ Rourke and El Hmadi (1988)</td>
<td>$F_{U,axial} = \mu \gamma'H \left( \frac{1+k_\theta}{2} \right) \pi D$</td>
<td>For axial loading; sand backfill</td>
</tr>
<tr>
<td>Hsu et al. (2001)</td>
<td>$\begin{cases} F_{U,axial \text{-oblique}} = F_{U,axial} \cos a \ F_{U,lateral \text{-oblique}} = F_{U,lateral} \sin a \end{cases}$</td>
<td>For oblique loading in loose sand</td>
</tr>
</tbody>
</table>
Experimental verification of failure modes is very limited.

- Local buckling
- Axial strain-rupture
- Upheal buckling
- 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
Hybrid experimentation on principle failure modes of the soil-pipeline system

- Preliminary Tests on Sand Box
- Development of SSI macroelements
- Pipeline Connection Test
- Preparatory Tests on failure modes

Analytical solutions for spatially variable pattern
3D FE modelling
**Scenario 1**

- Elastic rock halfspace
- Transition zone
- SV-waves
- $V_{s1}, \xi$
- $V_{s2}, \xi$
- $x_1, x_2, L_{1/2}$

**Scenario 2**

- Elastic rock halfspace
- Valley
- SV-waves
- $V_{s1}, \xi$
- $V_{s2}, \xi$
- $s, L_v, H_v$
SSI: nonlinear numerical modelling

SV- waves

P- waves
Time-variation of $\varepsilon_{a,g}$ at the surface of the equivalent-linear site at $t_{cr}$.

Axial displacement (top), vertical displacement (bottom) at $t_{cr}$. 
2D plane strain site response analysis

\[ \ddot{u}_x(t) + \ddot{u}(t) + \dddot{u}_x(t) = \dddot{u} \]

Instantaneous ground motion X-profiles

\[ u_{gx} = \min \epsilon_{gx} \]

\[ t = t_{cr} \] when \[ \epsilon_{gx} = \min \]
SSI: nonlinear numerical modelling

<table>
<thead>
<tr>
<th>Reference section 1</th>
<th>Control section</th>
<th>Reference section 2</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Image 1" /></td>
<td><img src="image2.png" alt="Image 2" /></td>
<td><img src="image3.png" alt="Image 3" /></td>
</tr>
</tbody>
</table>

![Image 4](image4.png)

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SSI: experimental investigation (shaking table + shear stack)
SSI: experimental investigation (shaking table + shear stack)

- Modal analysis

Empty: $f_{o,1} = 2.97$ Hz (after tuning of rubber stiffness)
SSI: experimental investigation (shaking table + shear stack)

• Minimum required pipe anchorage length

\[ L_{an} = ? \]

Free pipe ends

\[ t_u L_{an} = P_o \Rightarrow L_{an} = \frac{P_o}{t_u} \]

Exact expression

\[ t_u = \mu \gamma \left( \frac{1+2K_o}{3} \right) \left( H + R \right) 2\pi R + 4\mu \gamma \left( \frac{1+2K_o}{3} \right) R^2 \]

Prototype scale

\[ L^p \geq L_{an,\max}^p \]

\[ n_\ell = \frac{L^p}{L^m} = \frac{L^p}{4.8} = \frac{L_{an,\max}^p}{4.8} \]
SSI: experimental investigation (shaking table + shear stack)
SSI: experimental investigation (shaking table + shear stack)

Model-to-prototype scale 1:45

Shear stack

Shake table

Auxiliary retaining structure

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
SSI: experimental investigation (soil isolation)
BSI: hybrid testing

Static DOF
Dynamic DOF
Bearing modeled numerically
Bearing physically tested

**SSI: geometrically nonlinear numerical modelling**

<table>
<thead>
<tr>
<th>Material</th>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete</td>
<td>Compressive Strength $f_c$ (MPa)</td>
<td>35</td>
</tr>
<tr>
<td></td>
<td>Tensile Strength $f_t$ (MPa)</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Modulus of Elasticity (GPa)</td>
<td>28</td>
</tr>
<tr>
<td></td>
<td>Poisson's Ratio</td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td>Strain at compressive strength</td>
<td>0.0035</td>
</tr>
<tr>
<td></td>
<td>Density (kg/m³)</td>
<td>2500</td>
</tr>
<tr>
<td>Steel</td>
<td>Modulus of Elasticity (GPa)</td>
<td>200</td>
</tr>
<tr>
<td></td>
<td>Yield Stress (MPa)</td>
<td>460</td>
</tr>
<tr>
<td></td>
<td>Density (kg/m³)</td>
<td>7850</td>
</tr>
</tbody>
</table>

![Diagram showing a containment structure and foundation dimensions](image-url)
SSI: FEM substructuring & effect on equipment

SSI: geometrically nonlinear numerical modelling
National Soil-Foundation-Structure Interaction Laboratory

Creating world-class national infrastructure research capability
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.
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