Frequency-dependent LPMs for predicting seismic and mitigating non-seismic vibrations

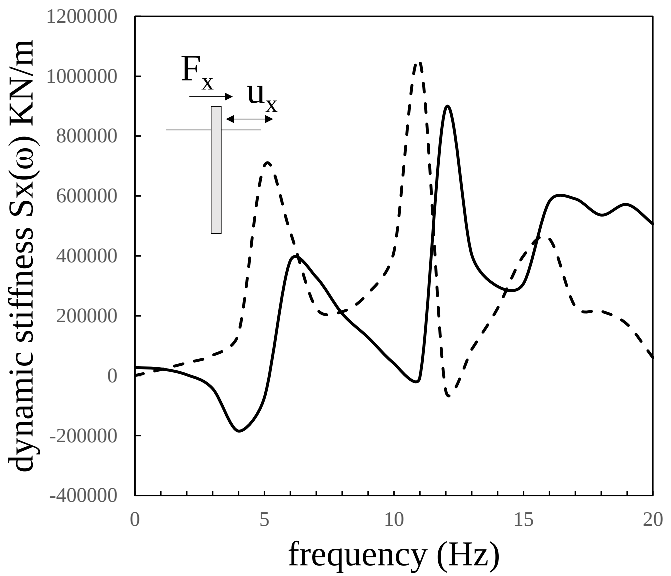
Nikolaos Lesgidis
Lukas Moschen
Thomas Jaquet
Anastasios Sextos

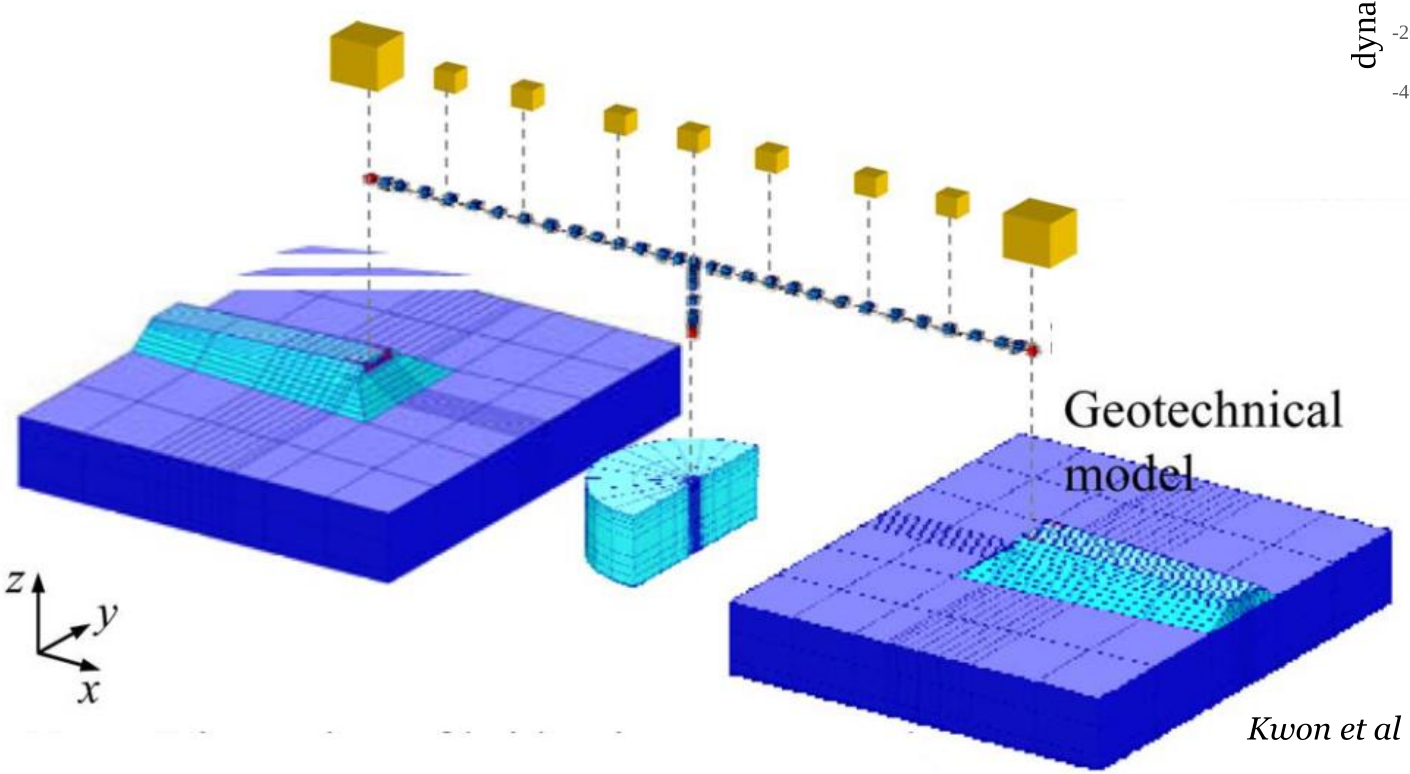
Frequency-dependent SSI in time domain analysis?

SSI would require a large soil domain or the use of a dynamic stiffness matrix

SSI is frequency dependent – analysis in the frequency domain

Several structural problems require response history analysis
(single frequency springs and dashpots + cross stiffness terms can be negative)





Kwon et al (2008)

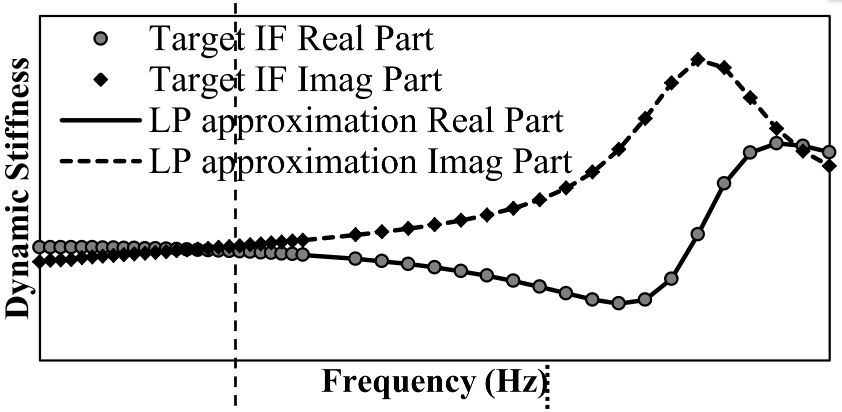
SSI: Analytical LPM modelling

Direct FEM simulation

Model Order Reduction

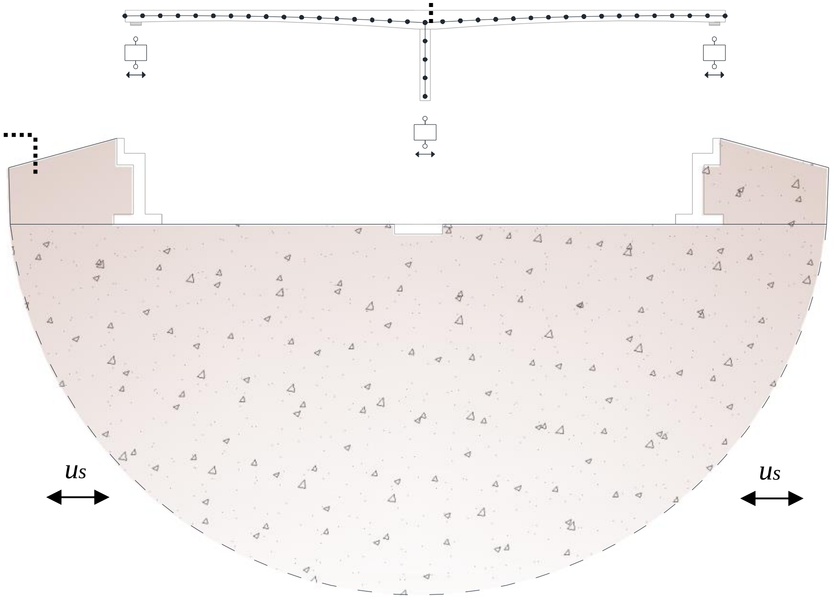
computationally viable

Lumped Parameter (LP) modeling Method



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

Finite element formulation



- ☐ 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*

Stability issues in LP methods

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

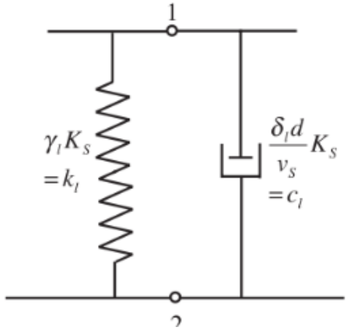
$$S_{LP}(s) = S_{LP,0} \cdot \frac{P(s)}{Q(s)} = S_{LP,0} \cdot \frac{p_o + p_1 \cdot (s) + \cdots + p_{N+1} \cdot (s)^{N+1}}{q_o + q_1 \cdot (s) + \cdots + q_N \cdot (s)^N}$$

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

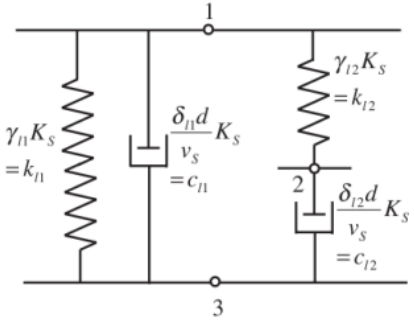
Translation to an ODE system (decomposition of polynomial fraction and term by term translation to physical components):

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

Example of 1st order term:



Example of 2nd order term:

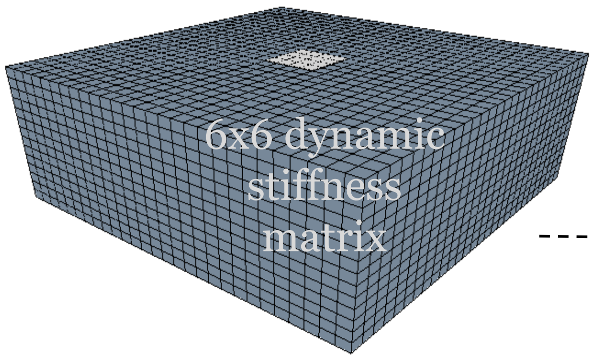


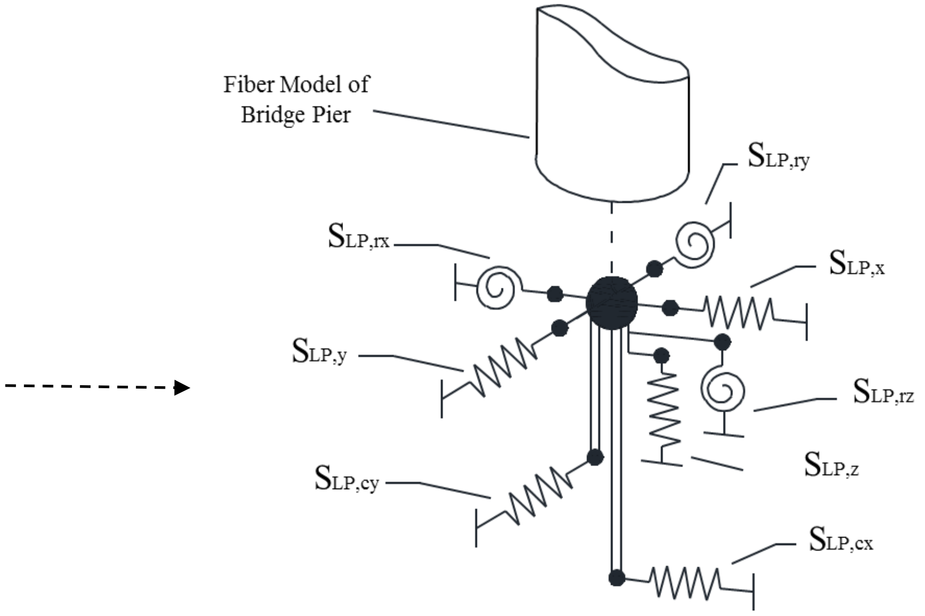
Sufficient condition to emulate the **Steady state** behavior. It will not necessarily lead to an ODE system with stable complementary solutions.

Proposed Stable Lumped Parameter model

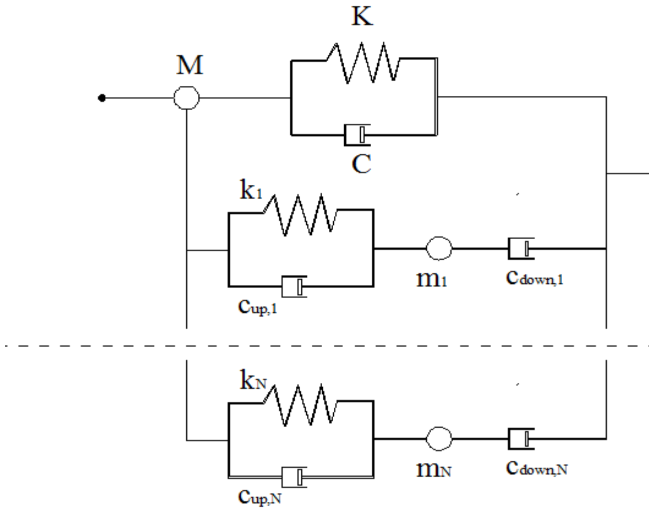
Restriction of LPM parameters to be positive through bound constraints in the calibration process.

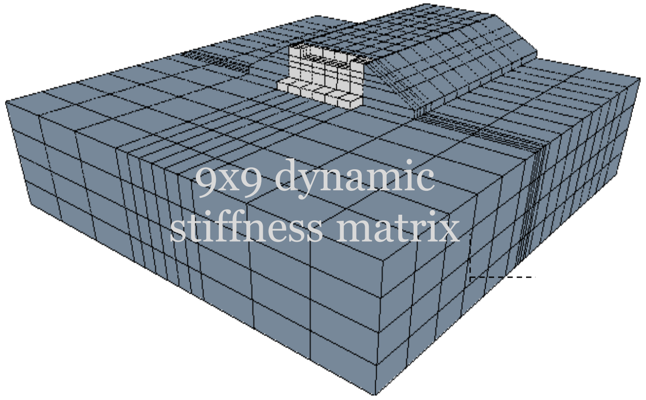
Pier base

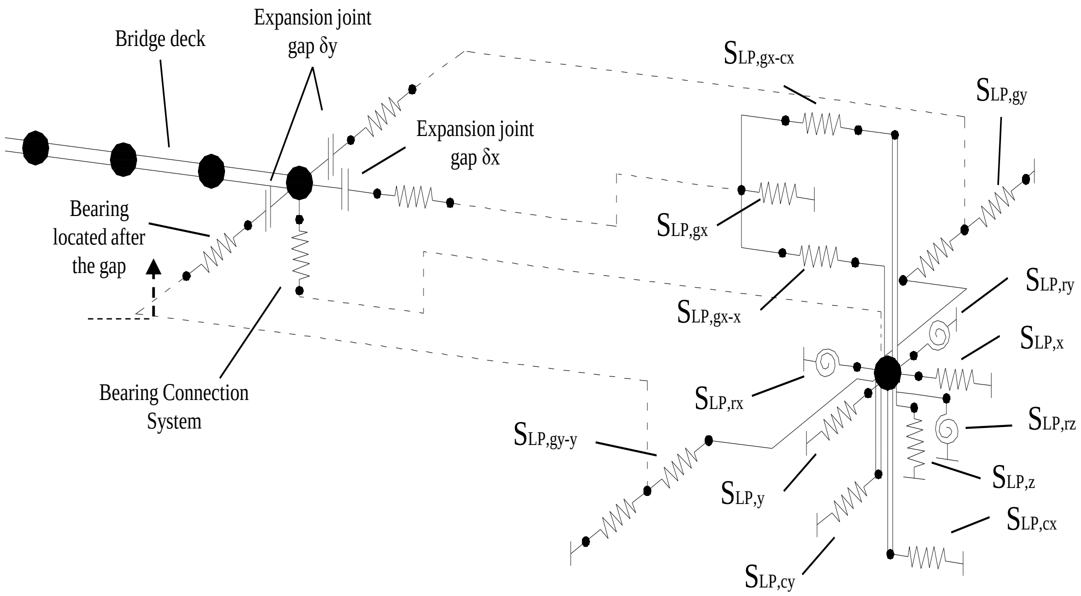




Abutment-Embankment





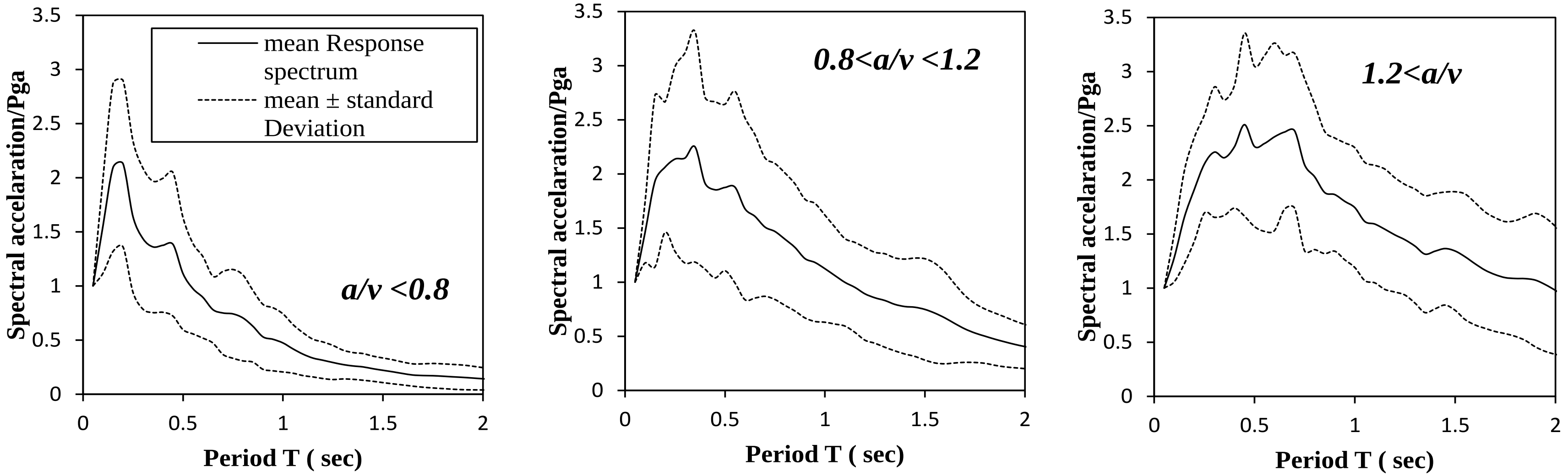


Frequency-dependent SSI effect on system fragility

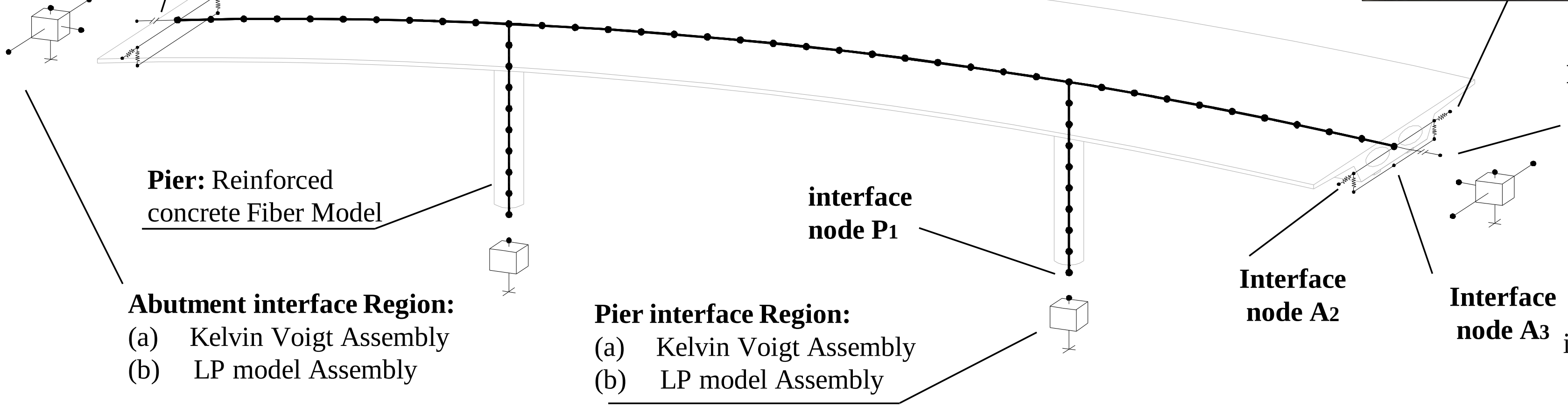
Pedini Overpass: Bridge Properties	
Overall length	78
Span Arrangement	19.00m -32.00m -19.00m
Deck Section	box girder, non prismatic
Piers(P1,P2)	solid circular section, height : 8.50 m
Abutments (A1,A2)	laying on PTFE pot bearings

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

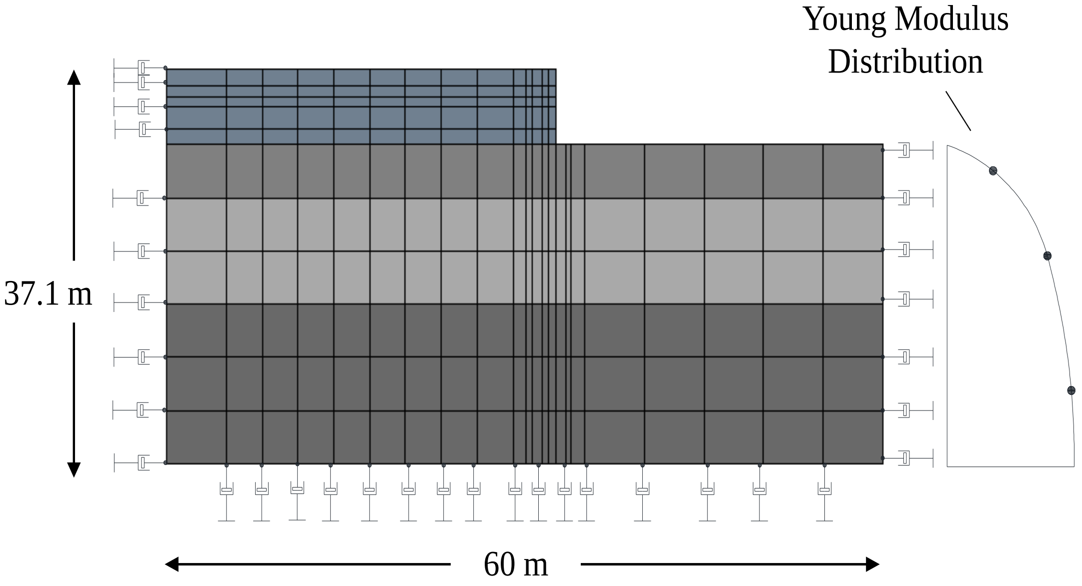
Excitation sets based on frequency content

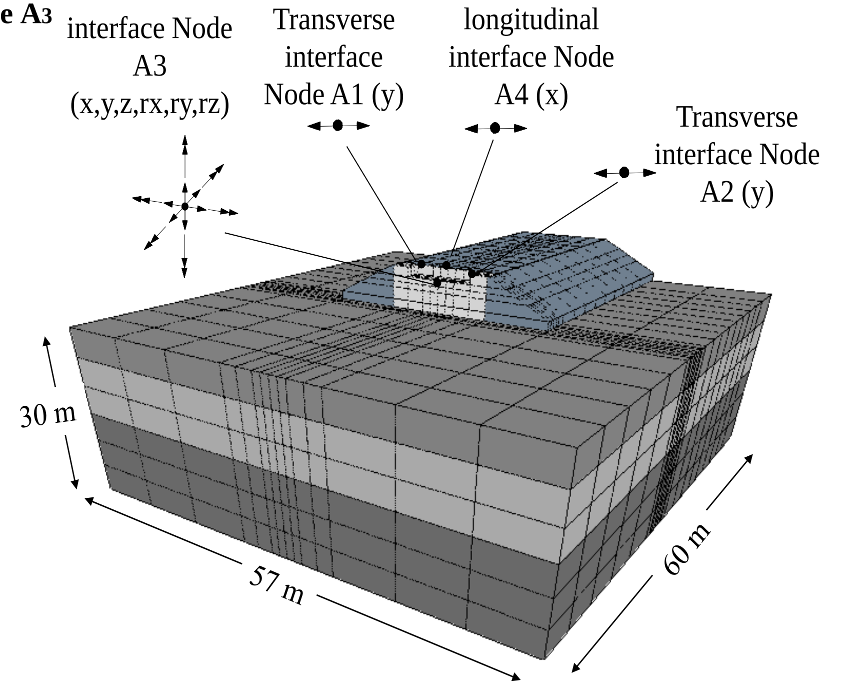


FE Modeling



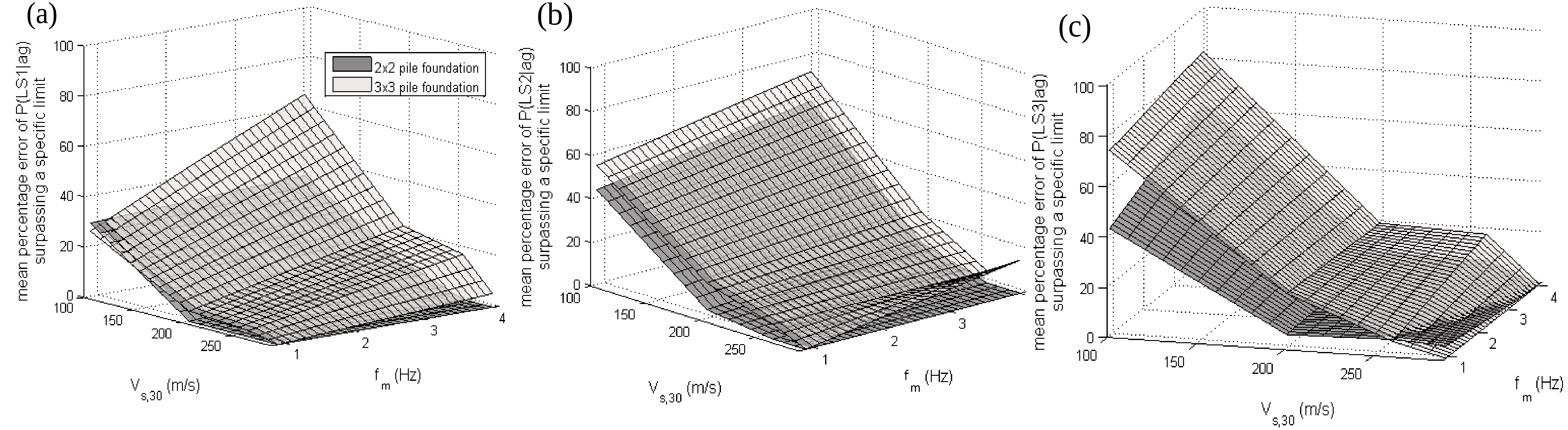
Extraction of dynamic Impedance functions from FEM model formulation.





Error induced when neglecting frequency-dependence

Percentage error in probability of reaching threshold limit states



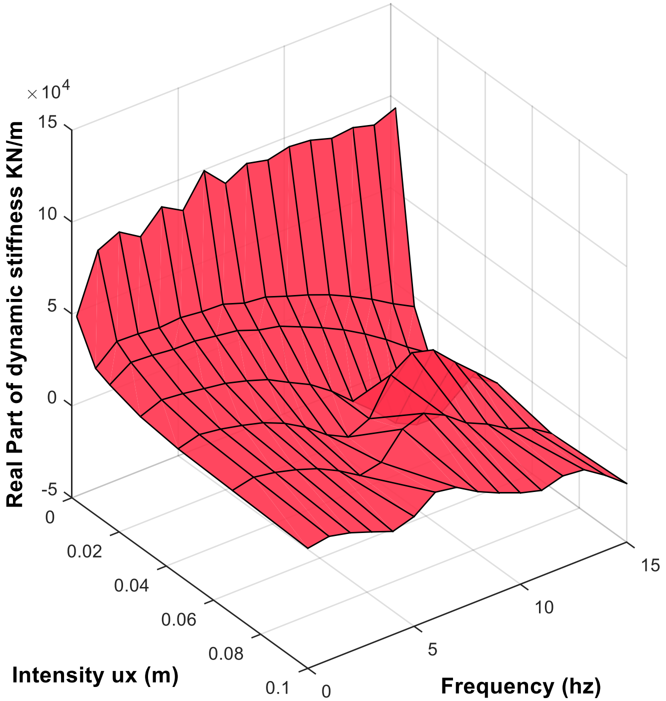
LS1 - Serviceability

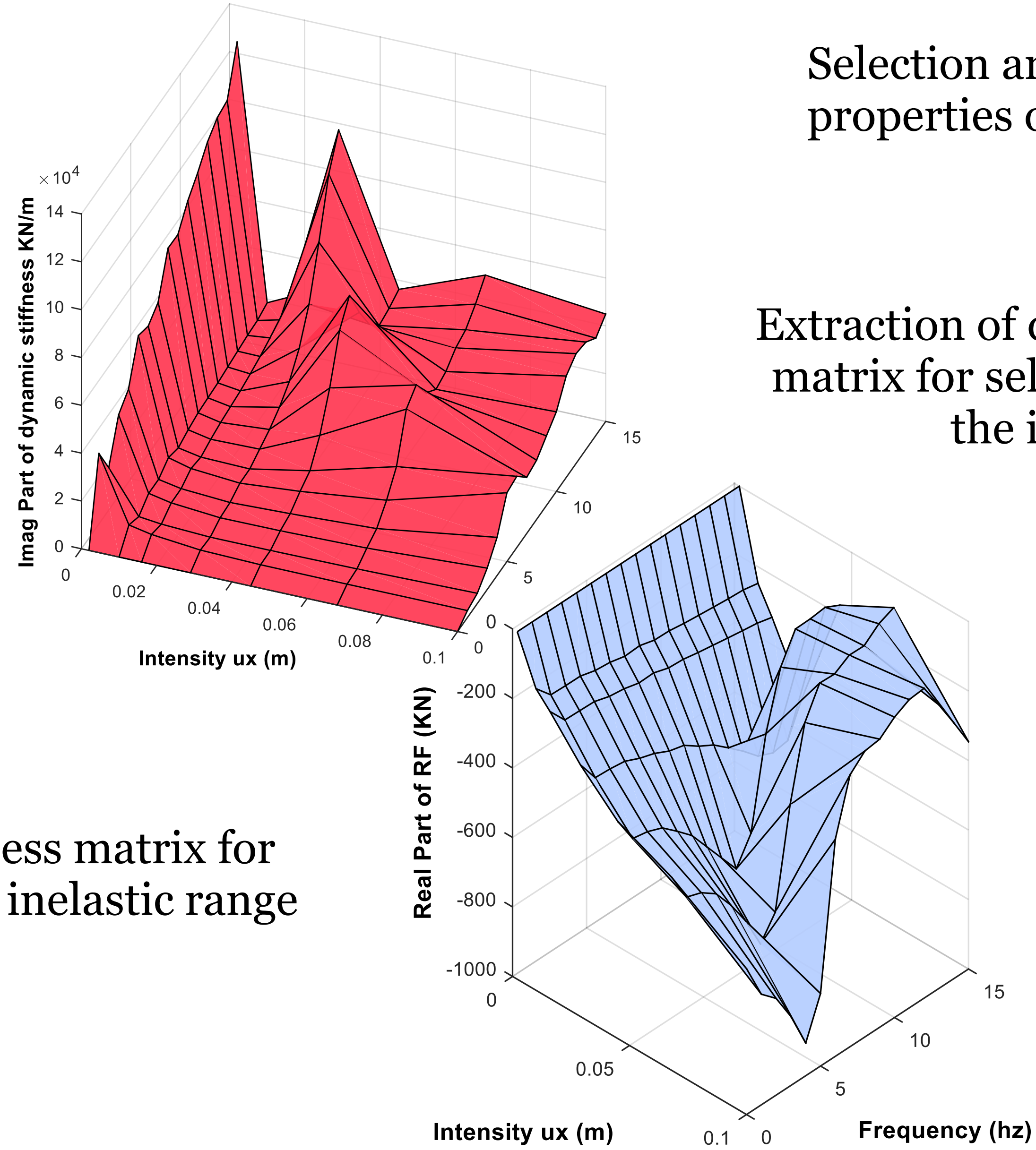
LS2 – Damage control

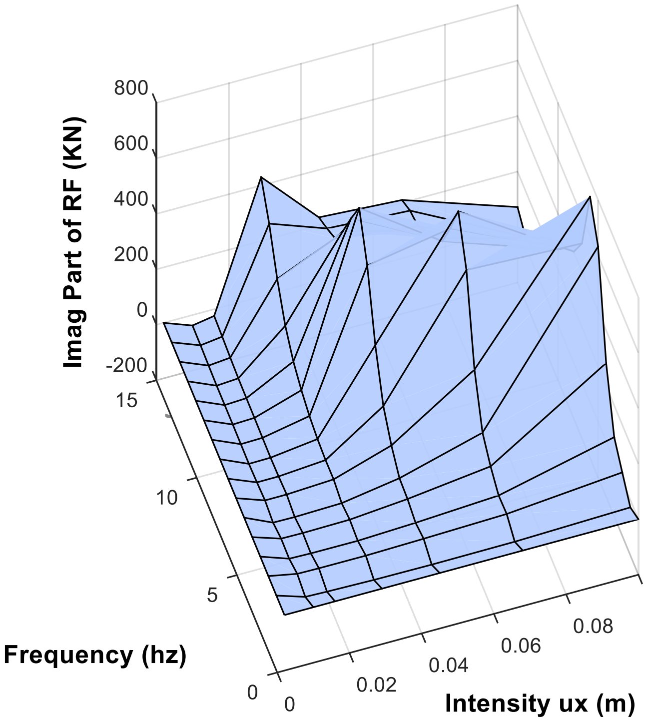
LS3 – Collapse prevention

Inelastic LP modeling method

Selection and extraction of representative properties of target dynamic system



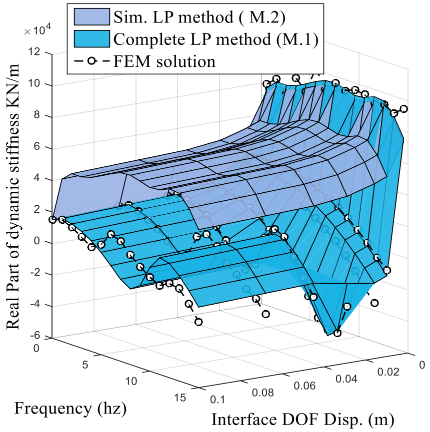


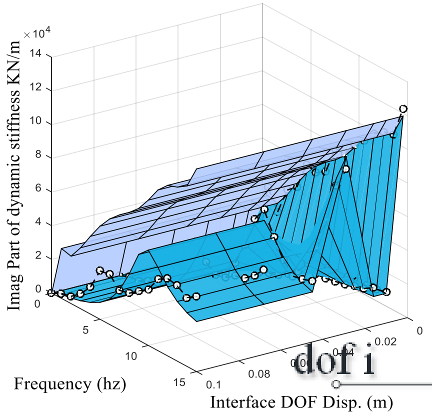


Extraction of dynamic returning force matrix for selected variable states in the inelastic range

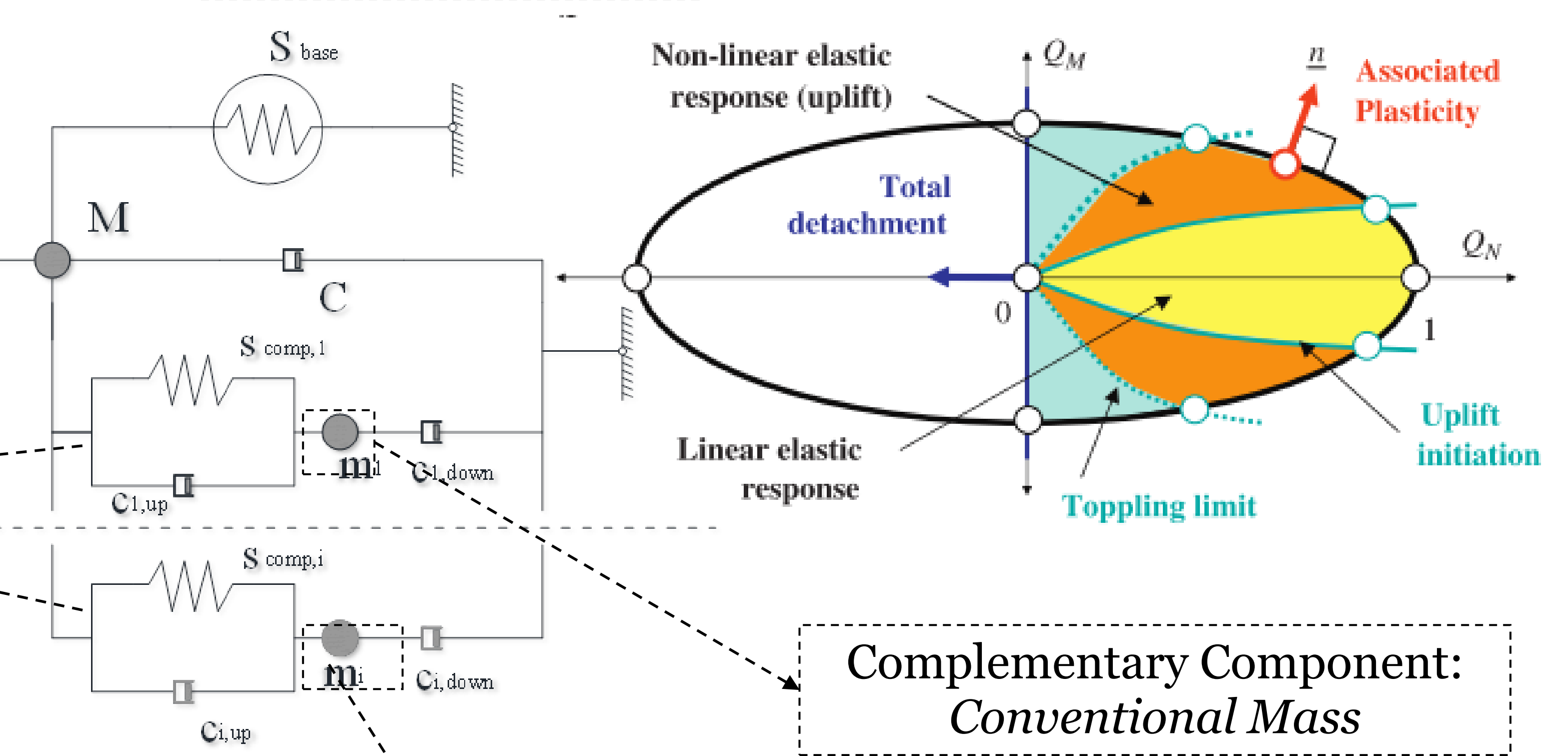
Extraction of Dynamic stiffness matrix for selected variable states in the inelastic range

Frequency- and intensity-dependent LPMs





Base Component:
Macroelement



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

Complementary Component:
Conventional Mass

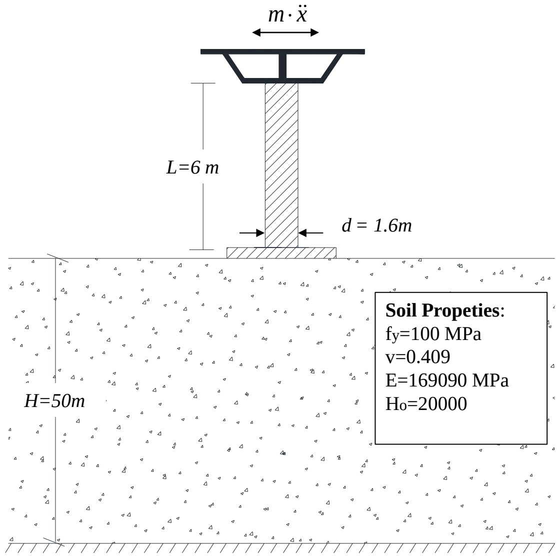
Complementary Component:
Conventional Dashpot

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

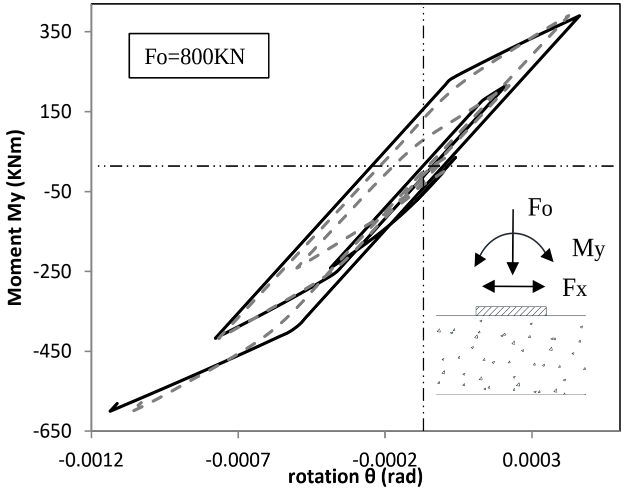
$$k_{comp}\left(\boldsymbol{\alpha}_{base,}u_{base}\right) = \begin{cases} k_o & if\ \ [\boldsymbol{\alpha}_{base,}u_{base}]^{\mathrm{T}} < \mathbf{c}_o\ or\ \ Unloading \\ \vdots & \\ k_n & if\ \ \mathbf{c}_{n-1} < [\boldsymbol{\alpha}_{base,}u_{base}]^{\mathrm{T}} < \mathbf{c}_n \end{cases}$$

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*

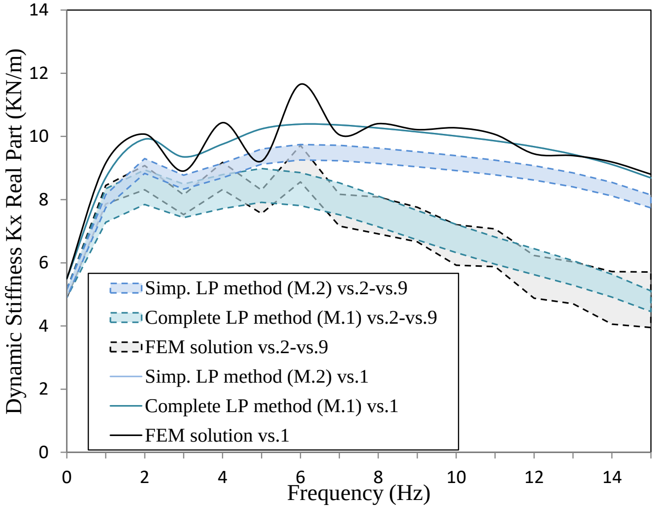
Verification example

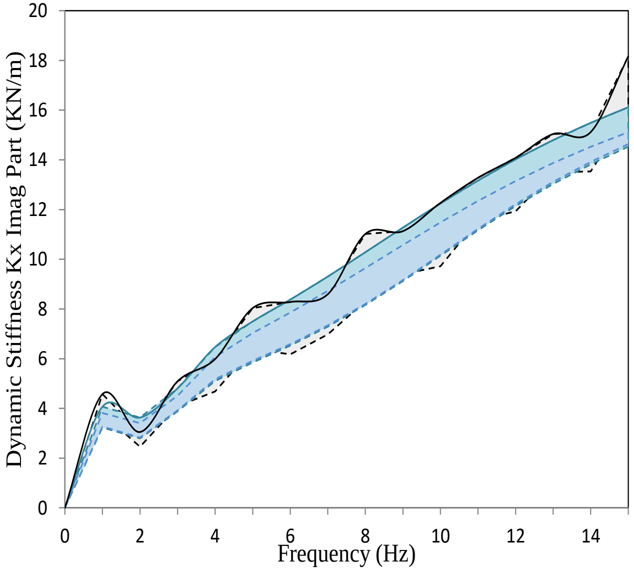


Static Properties Calibration:

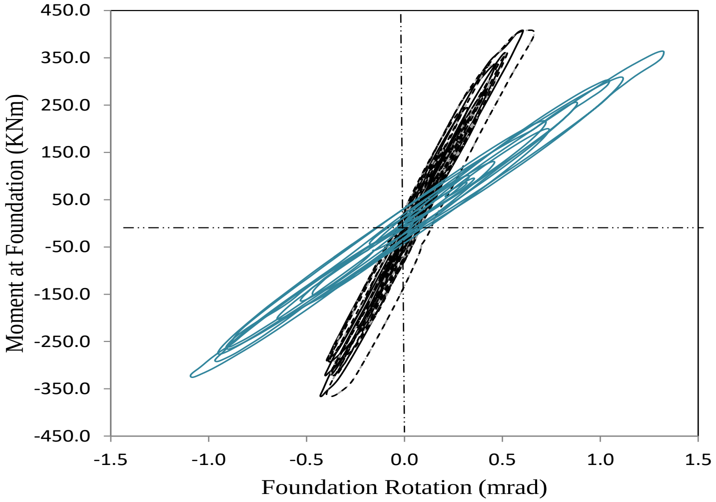


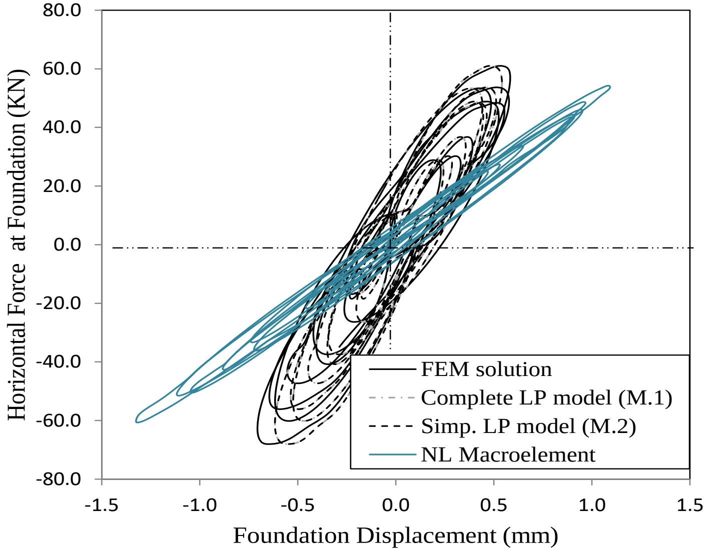
Sample of Dynamic Properties in the *Frequency domain:*



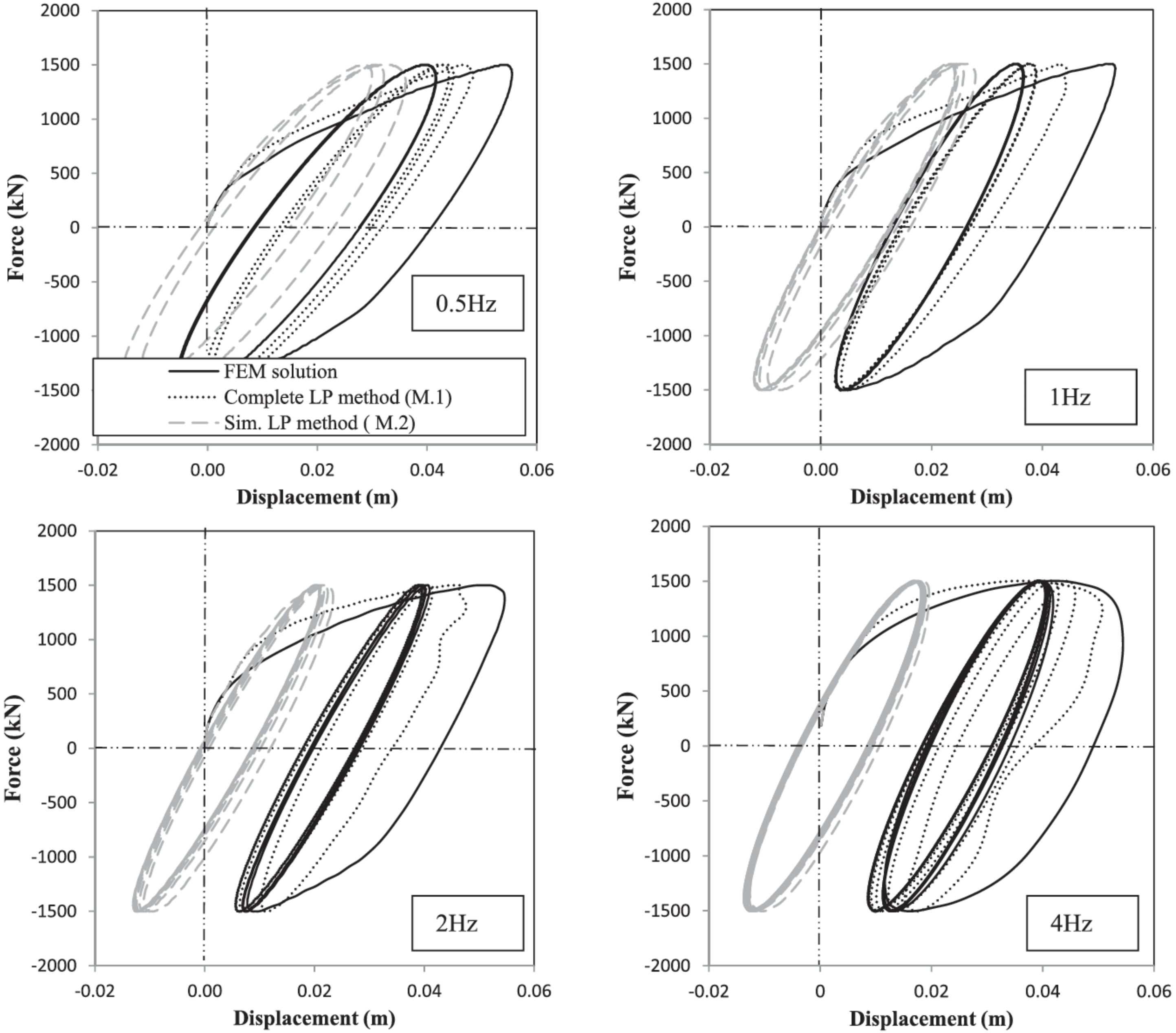


Model verification results:

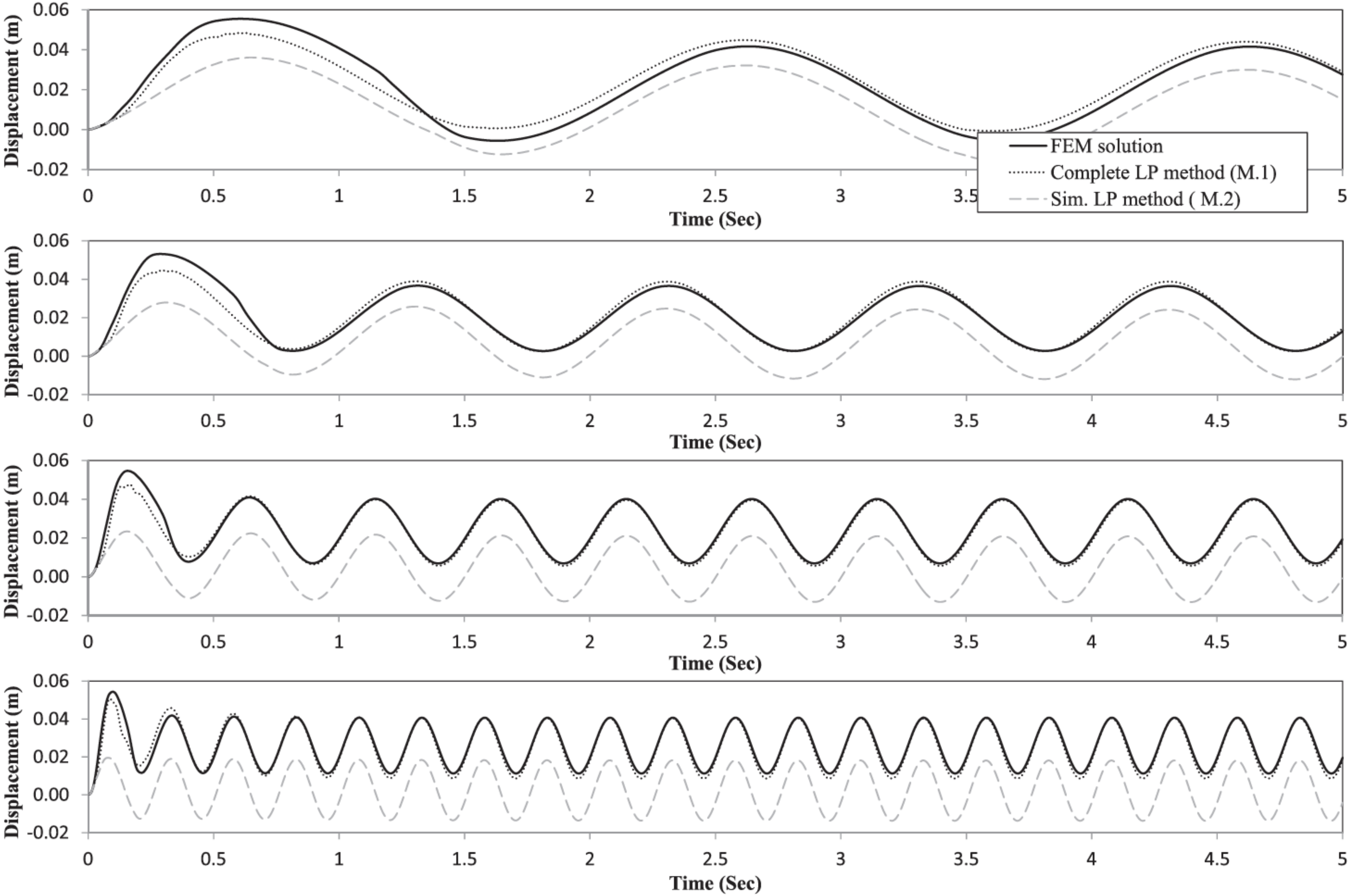




High intensity dynamic response (F-d & d(t))

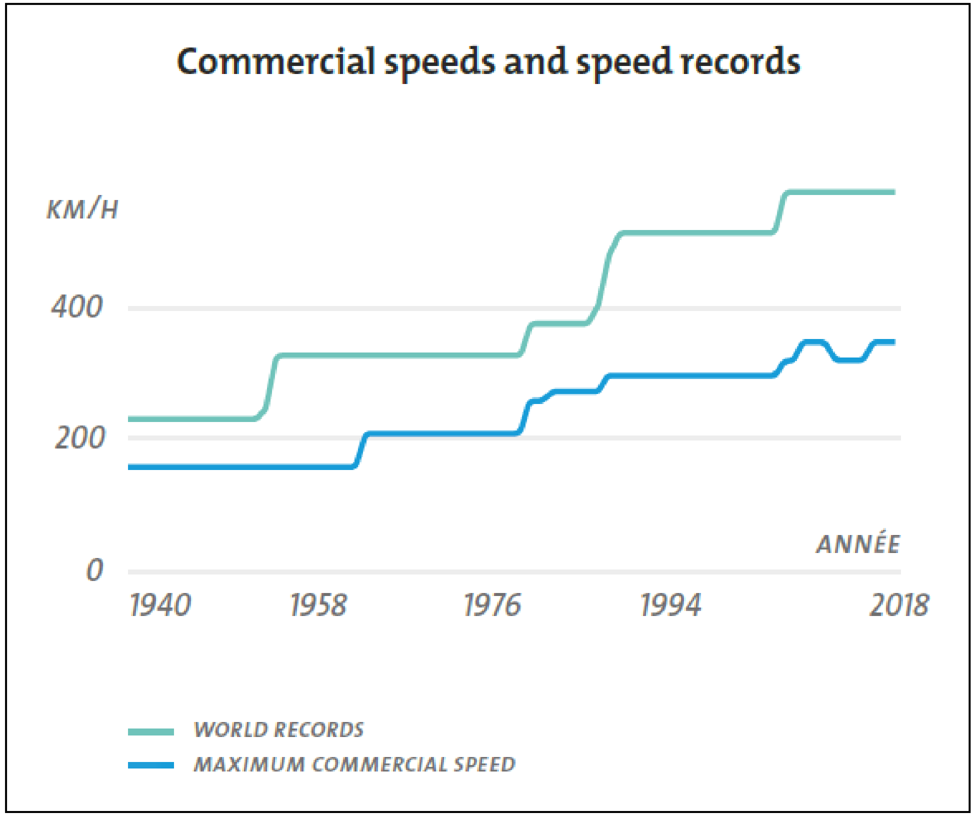


High intensity dynamic response (F-d & d(t))



Application in railway engineering

Key goal of railway industry: Increase of the **speed** and allowable carried load of railway trains.



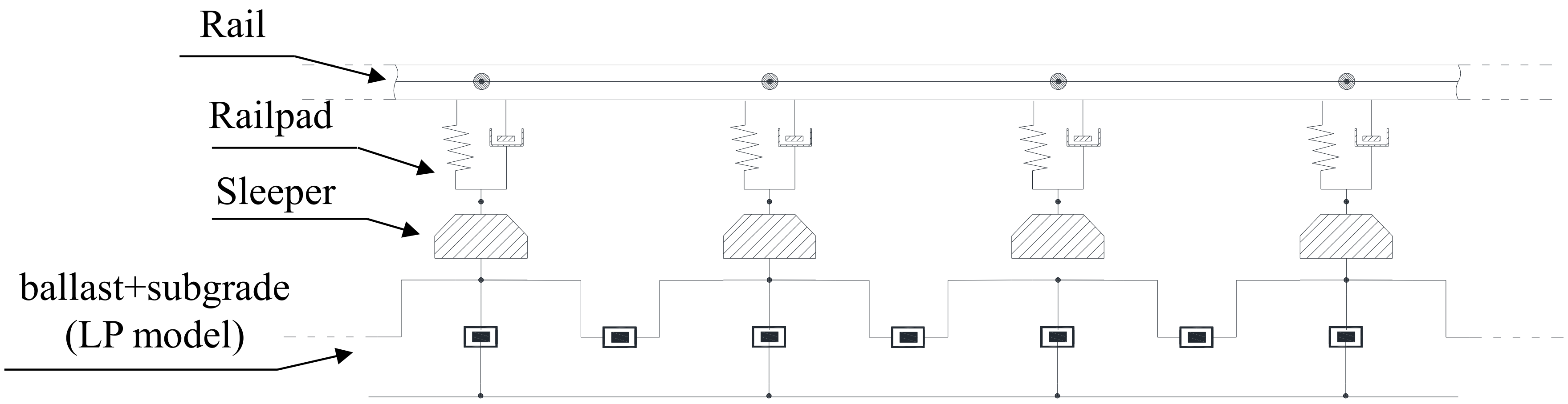
Commercial speeds and speed records

Michel Leboeuf, UIC high speed rail report (2018)

RSSB 2413 – T1073 “Loading Requirements for Track Systems”

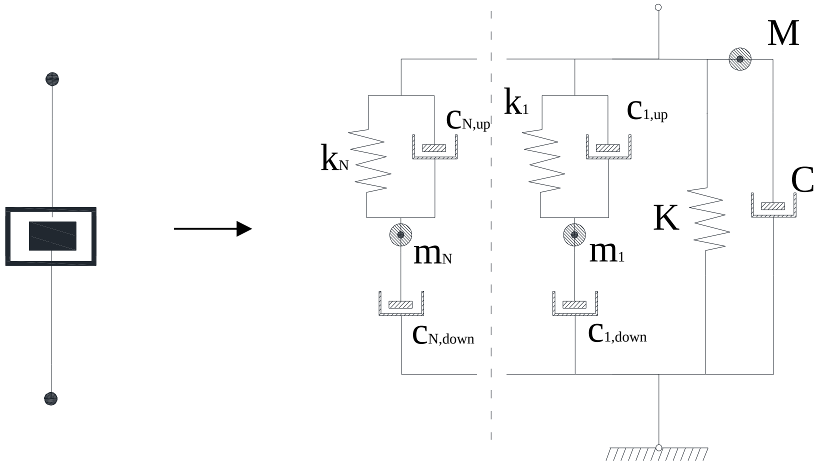
Order reduction method

Infinite series of LP model assembly

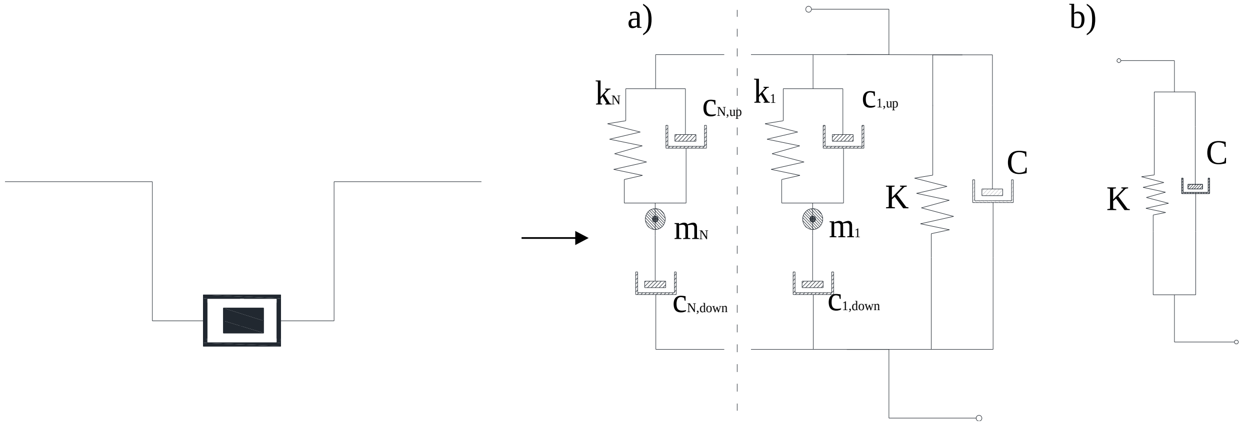


Finite set of LP subcomponents:

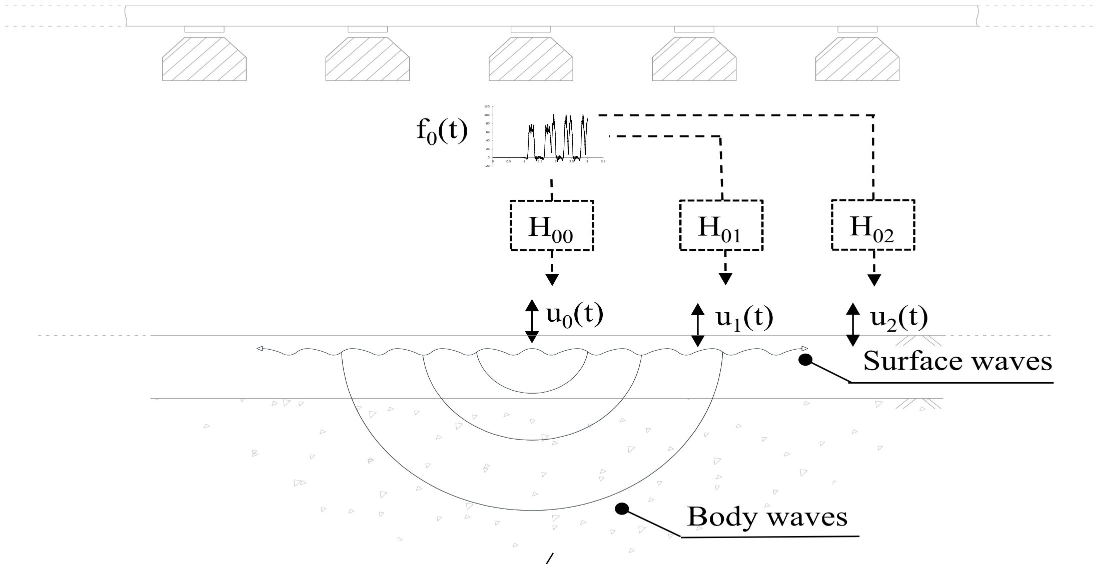
Main LP component



Cross LP component



Order reduction method

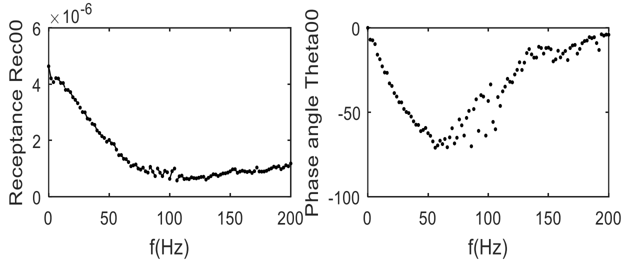


$$\begin{bmatrix} H_{00} & H_{01} & \cdots & H_{0N} \\ H_{10} & H_{11} & & \vdots \\ \vdots & & \ddots & \\ H_{N0} & \cdots & & H_{NN} \end{bmatrix}$$

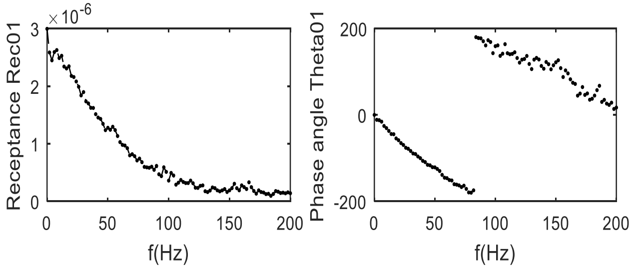
Where

Dynamic Flexibility matrix (Frequency domain)

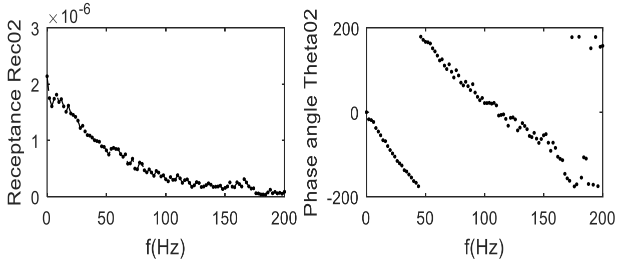
$H_{00} = H_{11} = H_{NN} \longrightarrow$



$H_{01} \longrightarrow$

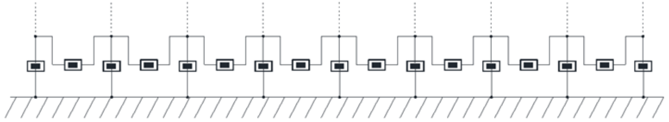


$H_{02} \longrightarrow$



⋮

Calibration through optimization



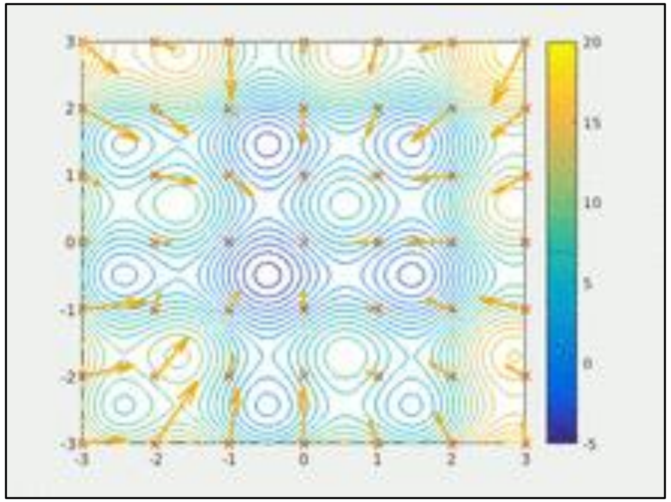
Calibration through multi-objective optimization

$$\min_{\mathbf{x}_{com}} \; g_{com}(\mathbf{x}_{com}) = \sum_{j=1} w_j \cdot f_j(\mathbf{x}_{com})$$

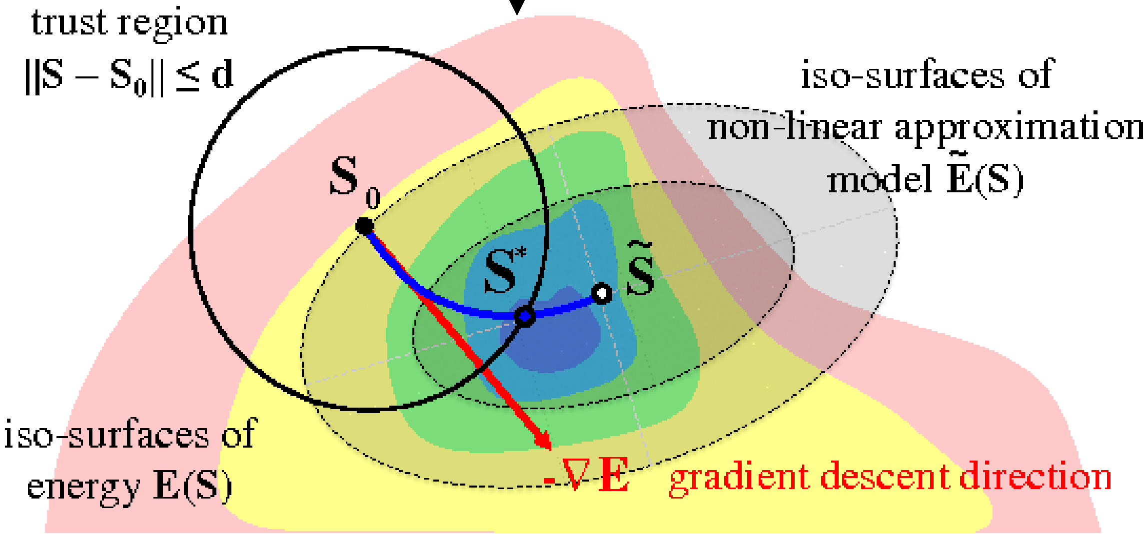
$$subject\ to\ \mathbf{x} \geq 0$$

Global level

Local level

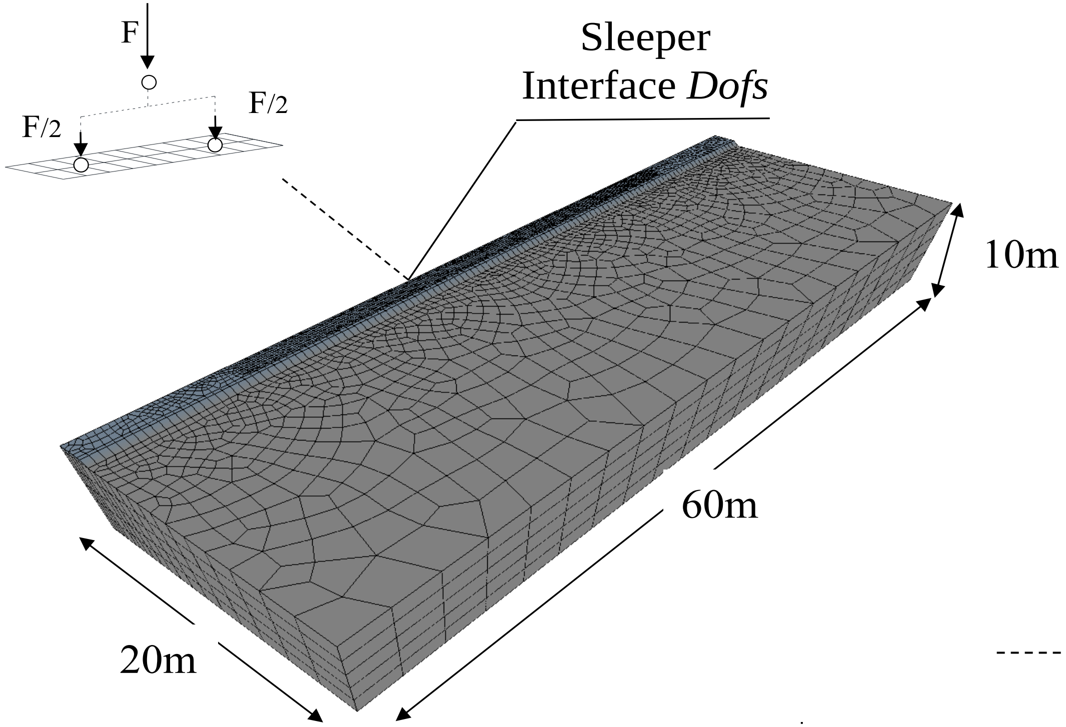


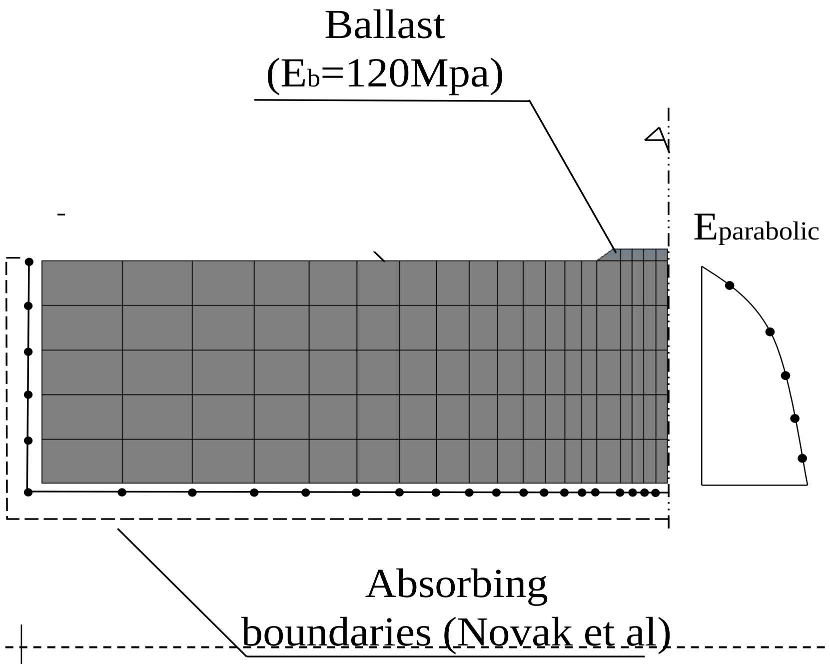
Particle swarm optimization



Interior point trust region

Numerical verification case study





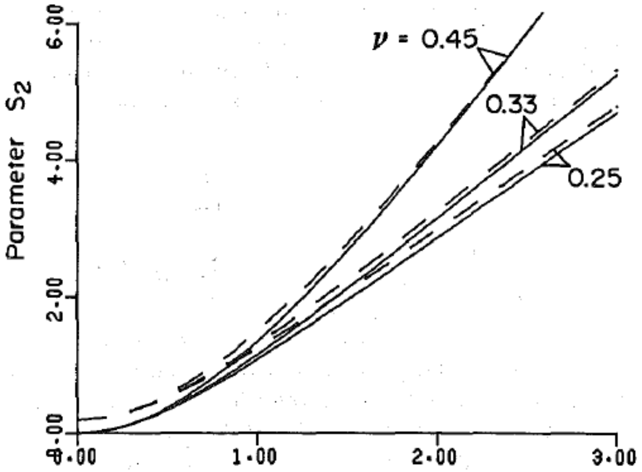
Novak Boundaries

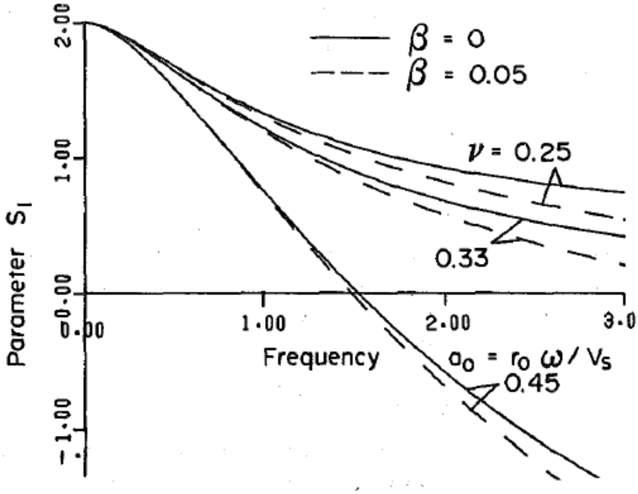
Fundamental Solution of wave equation in infinite disc:

$$\rho\frac{\partial^2 u}{\partial t^2} = (\lambda+\mu)\frac{\partial\bar{\varepsilon}}{\partial x} + \mu\nabla^2 u$$

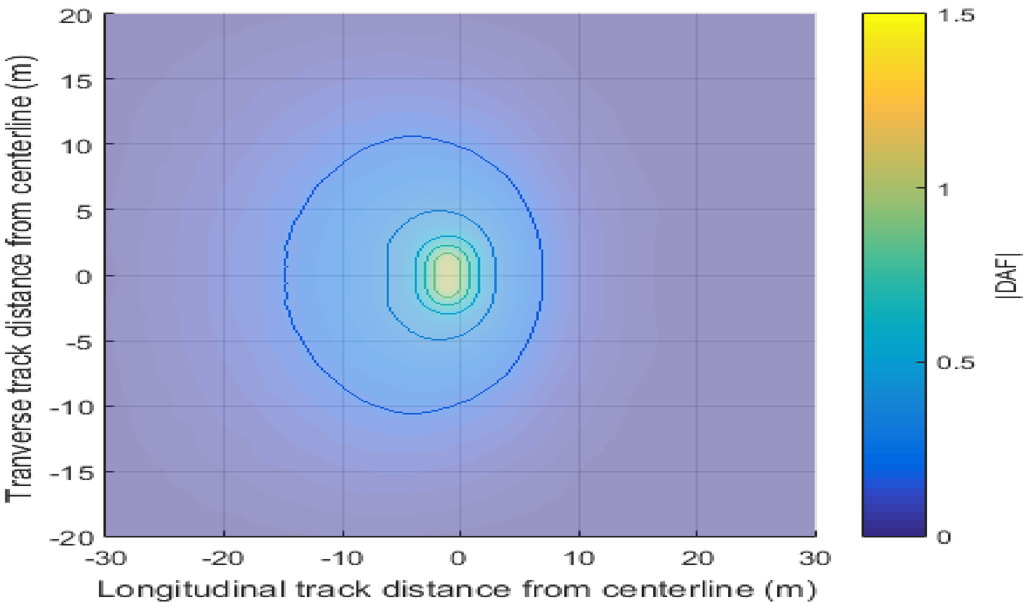
$$\rho\frac{\partial^2 v}{\partial t^2} = (\lambda+\mu)\frac{\partial\bar{\varepsilon}}{\partial y} + \mu\nabla^2 v$$

$$\rho\frac{\partial^2 w}{\partial t^2} = (\lambda+\mu)\frac{\partial\bar{\varepsilon}}{\partial z} + \mu\nabla^2 w$$

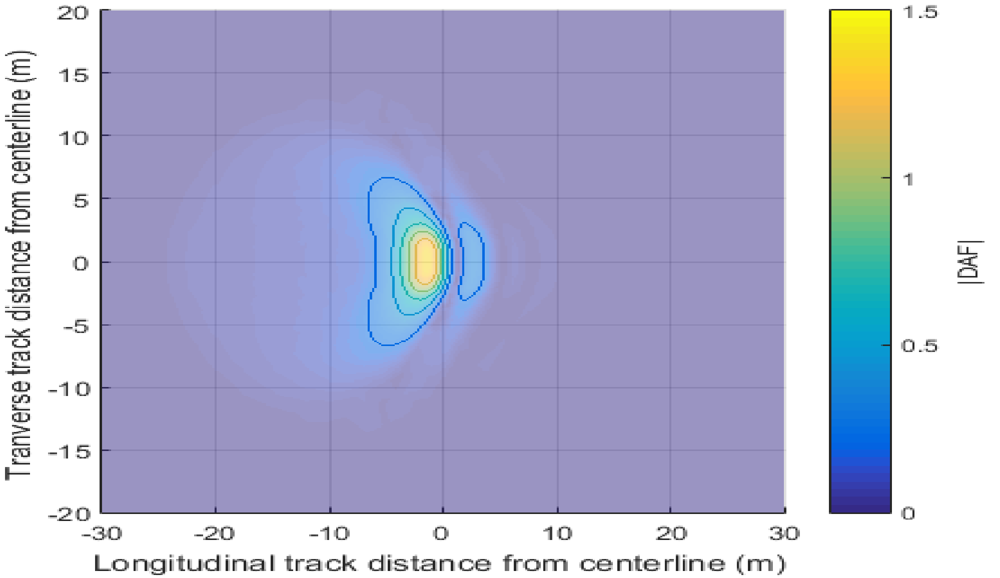




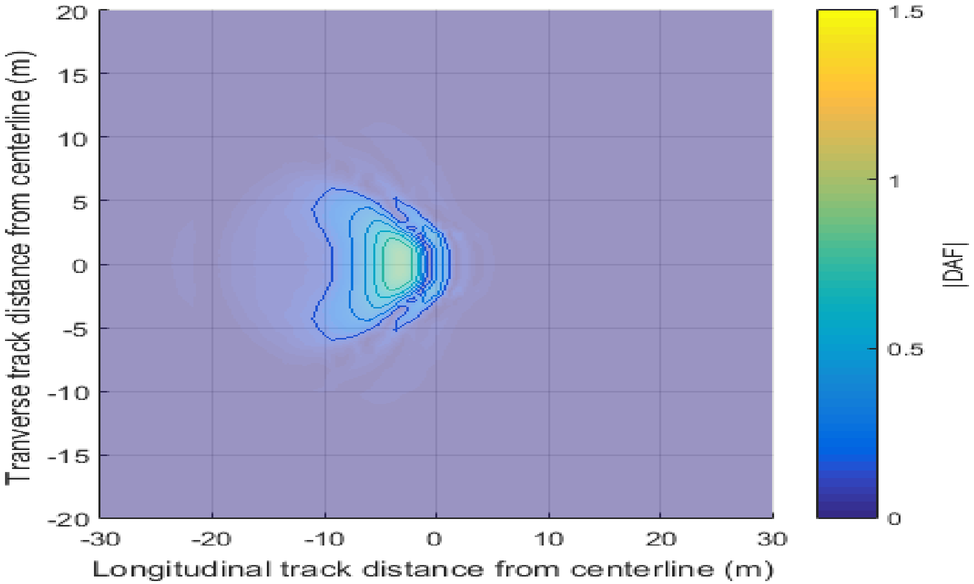
Numerical verification case study



V_{load}=68km/h

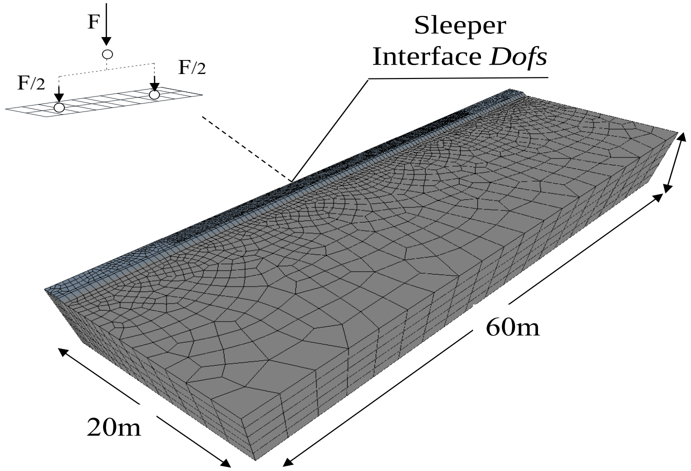


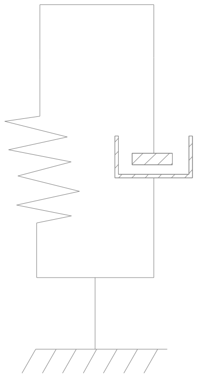
V_{load}=347km/h



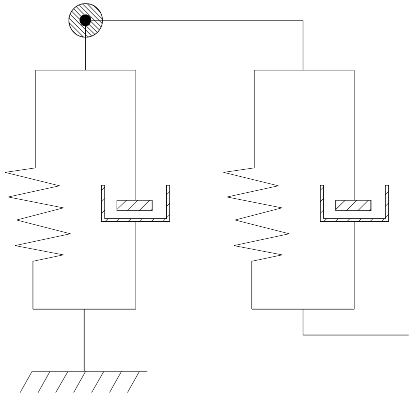
V_{load}=470km/h

4 different methodologies for the subgrade system to compare

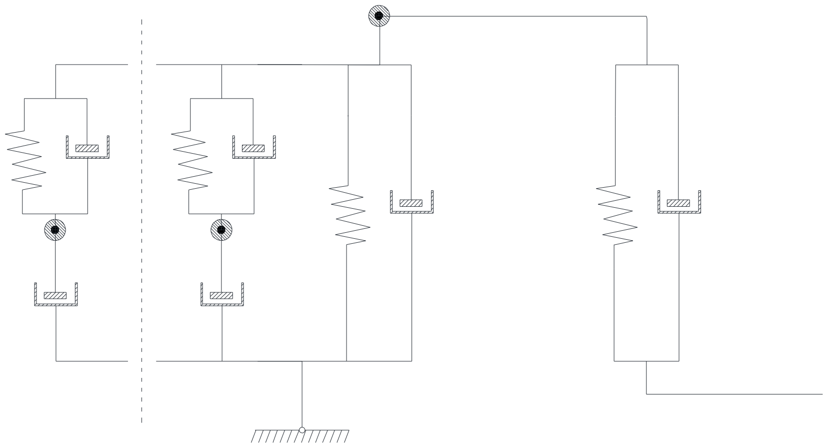




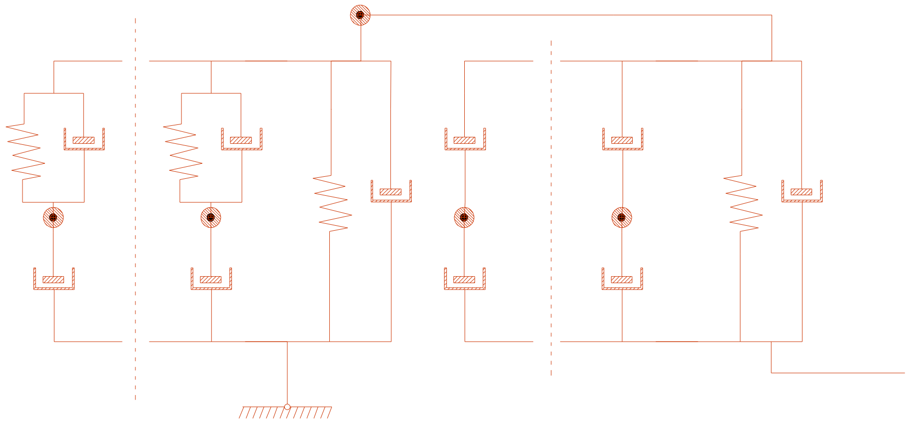
Model: Kelvin - Voigt
Calibration: targeting direct
Receptance at predominant frequency



Model: Kouroussis et al
Calibration: targeting direct Receptance
and use proposed closed form for cross terms.

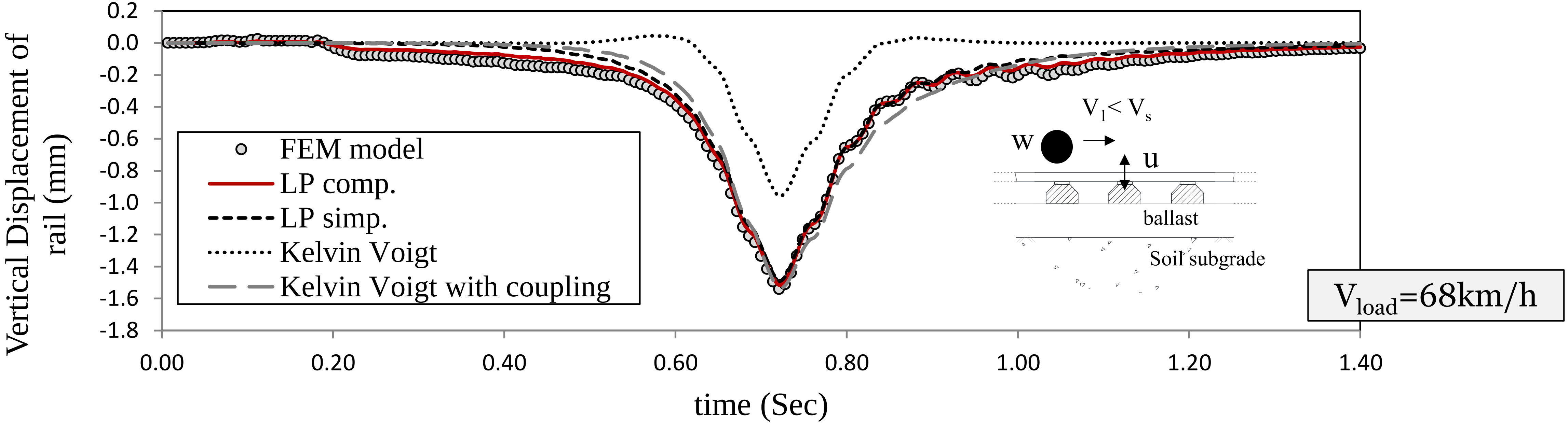


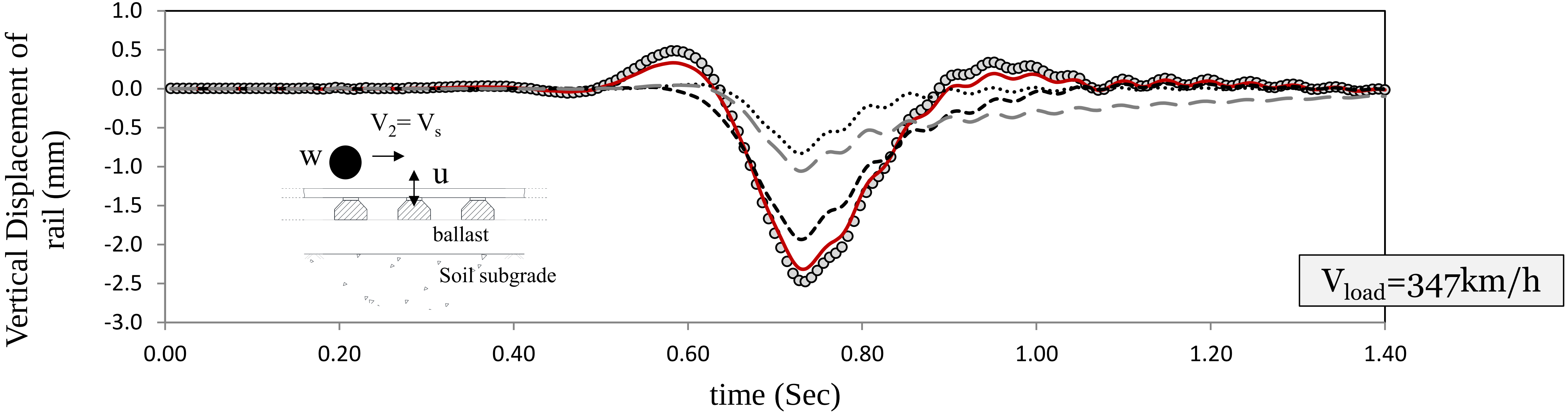
Model: simplified LP
Calibration: PSO + interior point trust region



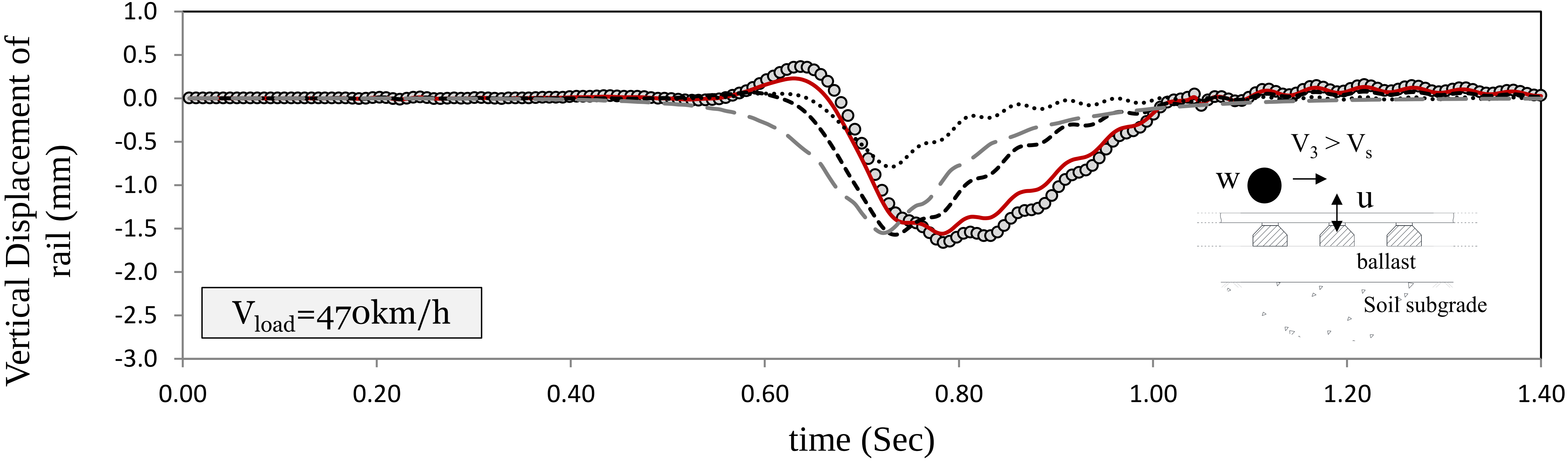
Model: complete LP
Calibration: PSO + interior point trust region

Four different methodologies for the subgrade system to compare



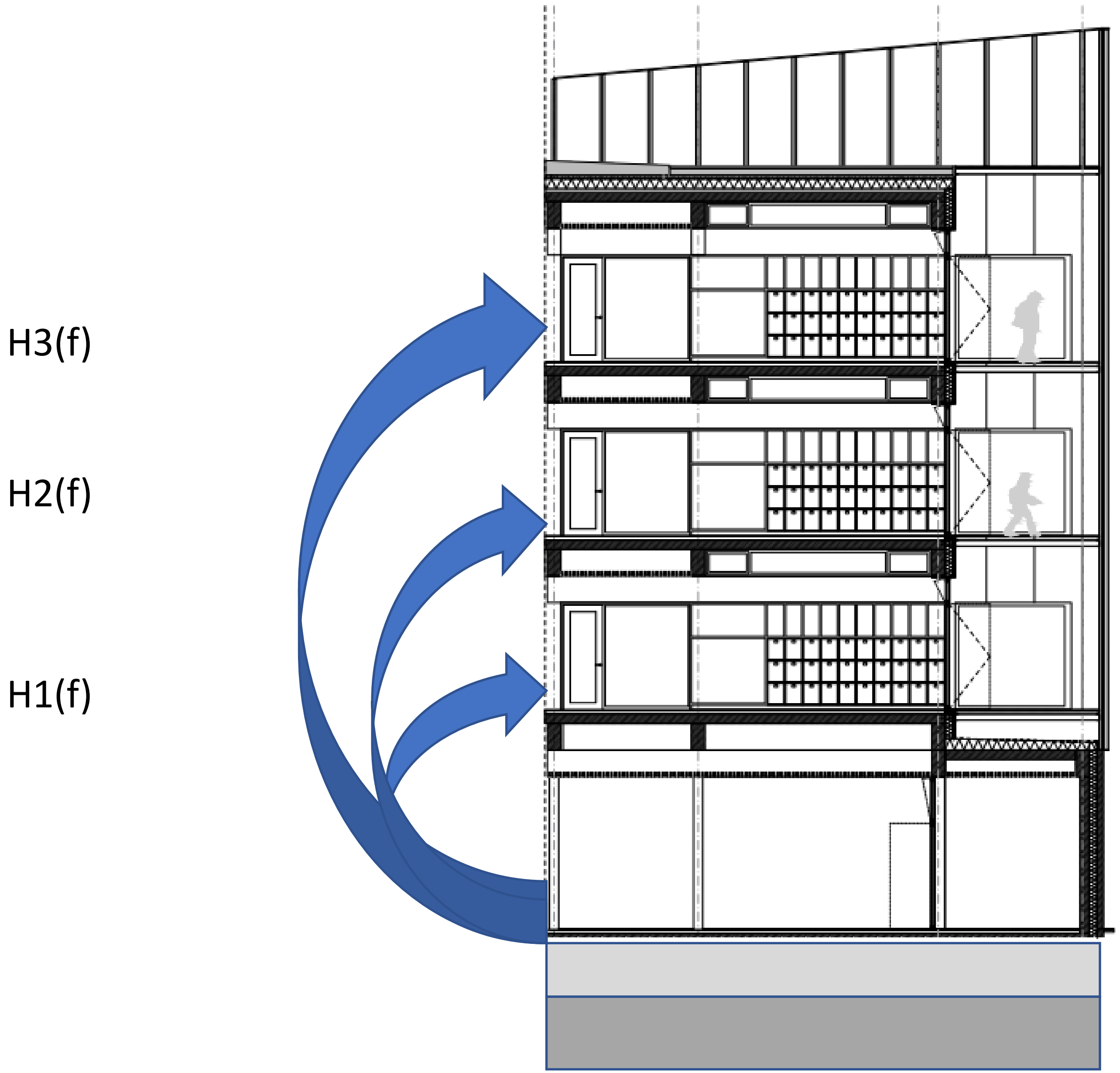


Four different methodologies for the subgrade system to compare



The problem of structural vibrations

Prediction Model



Vibration:

V(f) = Soil(f) x SSI(F) x SS(f) x Hi(f)

Conversion. V(f) to KB (FTM) according to RIL

$$KB_{FTm} = \sqrt{\frac{1}{N}\sum_{i=1}^{N} KB_{FTi}^{2}}$$

$$KB_{FTr} = \sqrt{\frac{1}{T_r}\sum_{j} T_{e,j}\cdot KB_{FTm,j}^{2}}$$

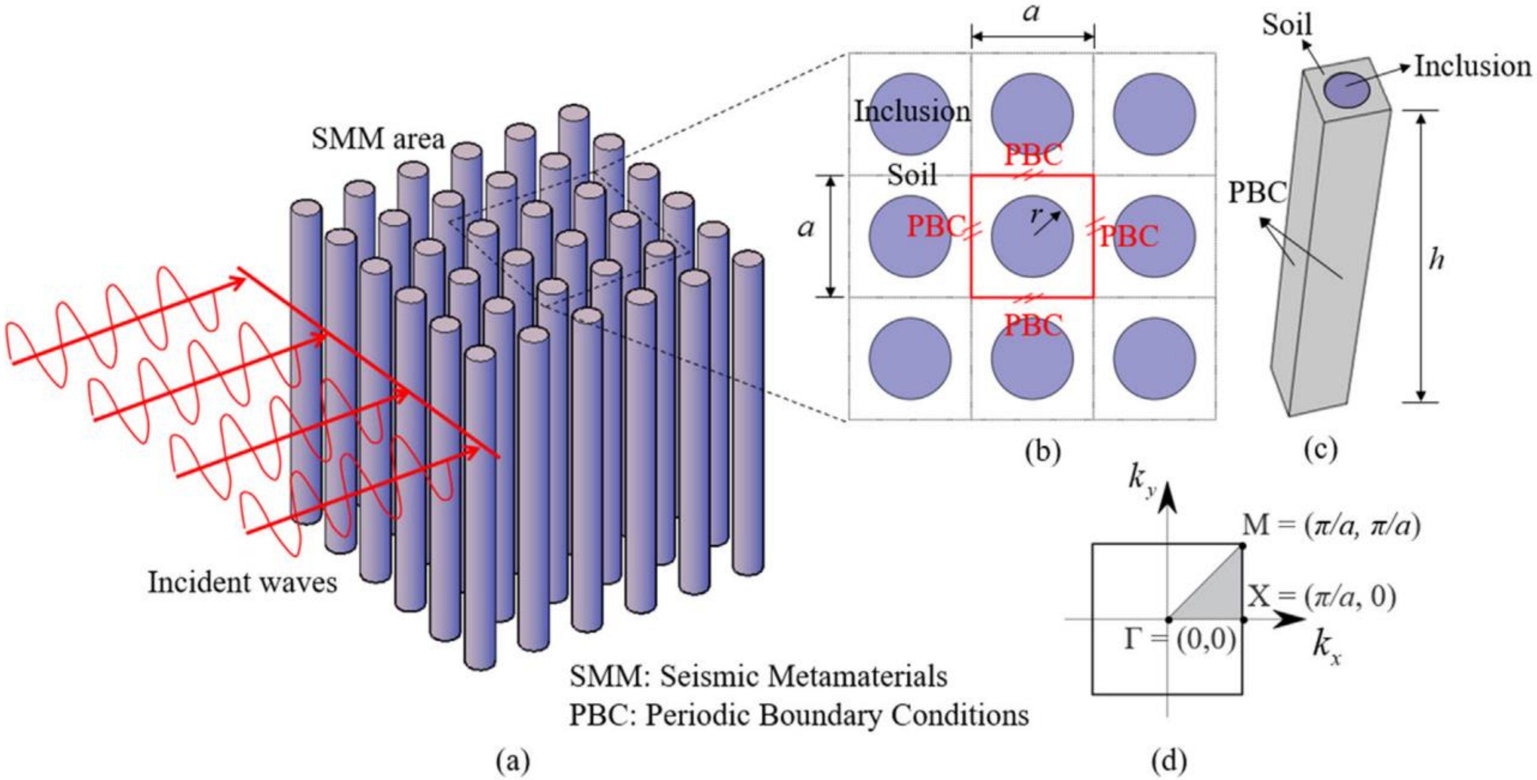
KBFTR < Ar (DIN 4150)

Ground Borne Noise:

LpA=LvA+10log (4S/A)+10logs

Vibration Mitigation below the perception level

- Seismic isolation / Springs ?
- Meta-surfaces? (seismic soil-metamaterials, buried mass-resonators, above-surface resonators, auxetic materials)
- Soft Barriers?
- Pile Group foundation
- Deterministic vs. Probabilistic



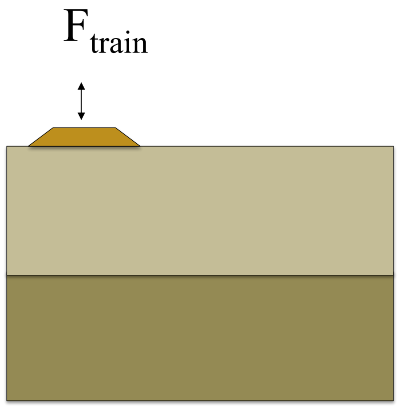
Li, T., Su, Q., Kaewunruen, S. (2020) Seismic metamaterial barriers for ground vibration mitigation in railways considering the train-track-soil dynamic interactions, Construction and Building Materials

Prediction

Pile foundation to mitigate vibrations

Soil report,
on-site tests

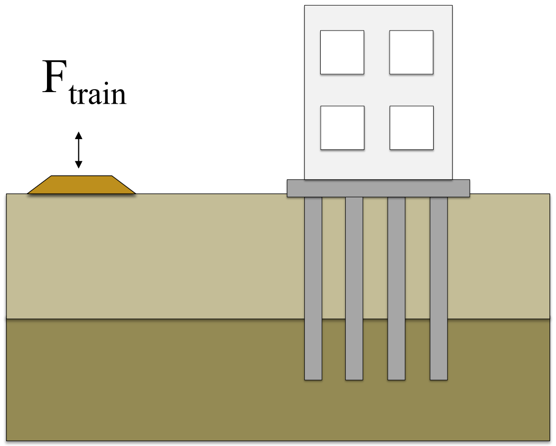
Free field model A:
vibration source and soil medium



System Identification

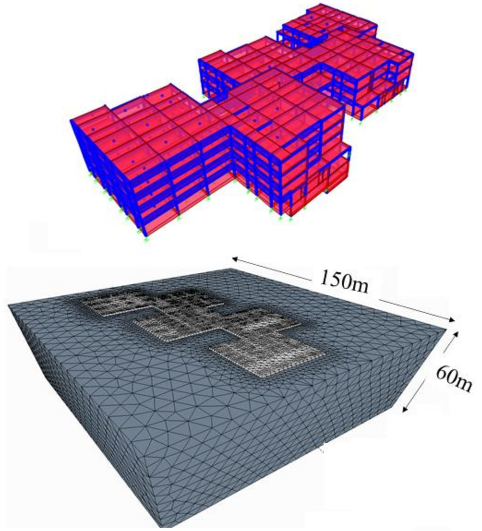
Soil, track, train properties,
simulation options

Archetype model B:
pilegroup foundation with
archetype building

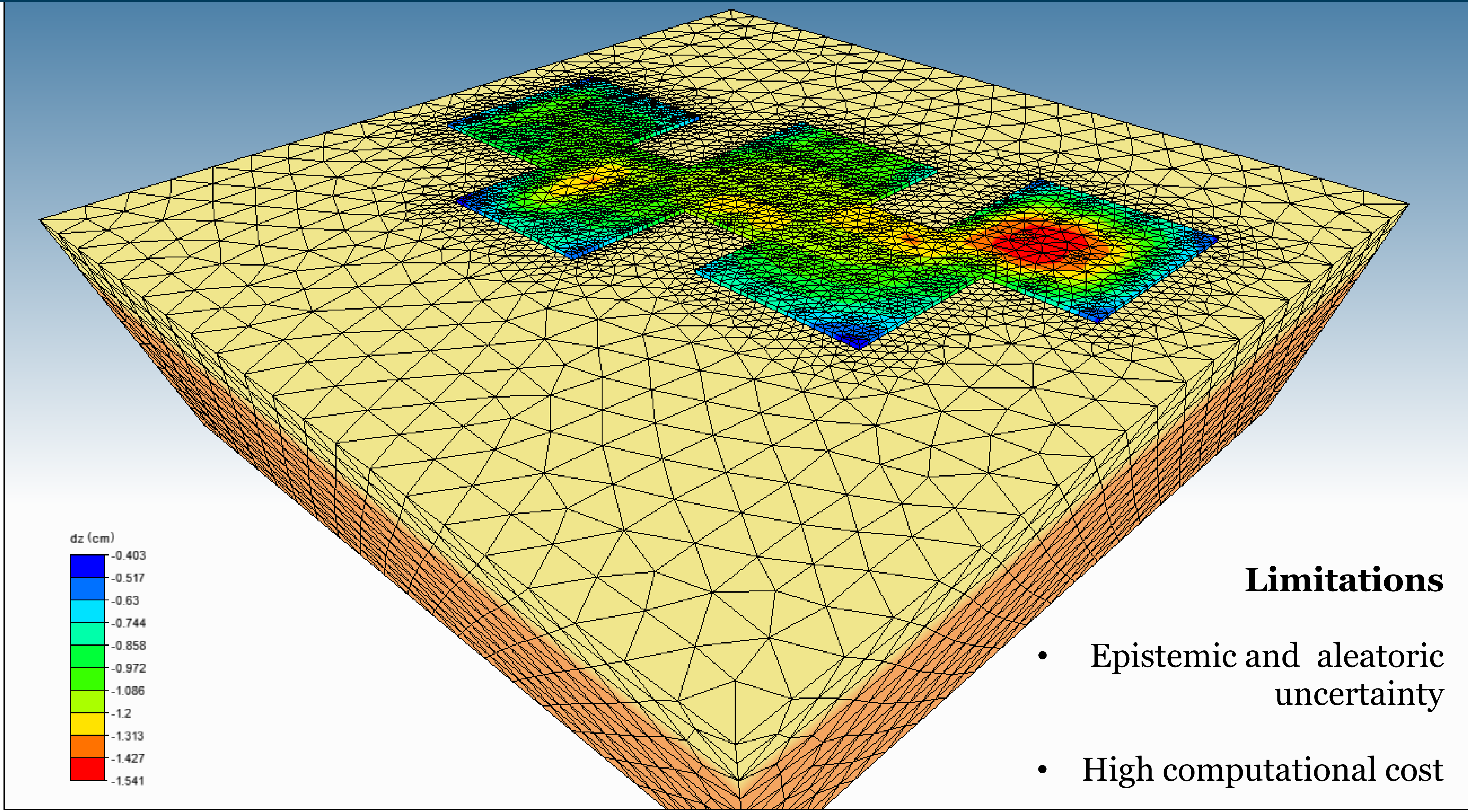


Pilegroup
efficiency

Complete model C:
Detailed foundation and building



Holistic FE model

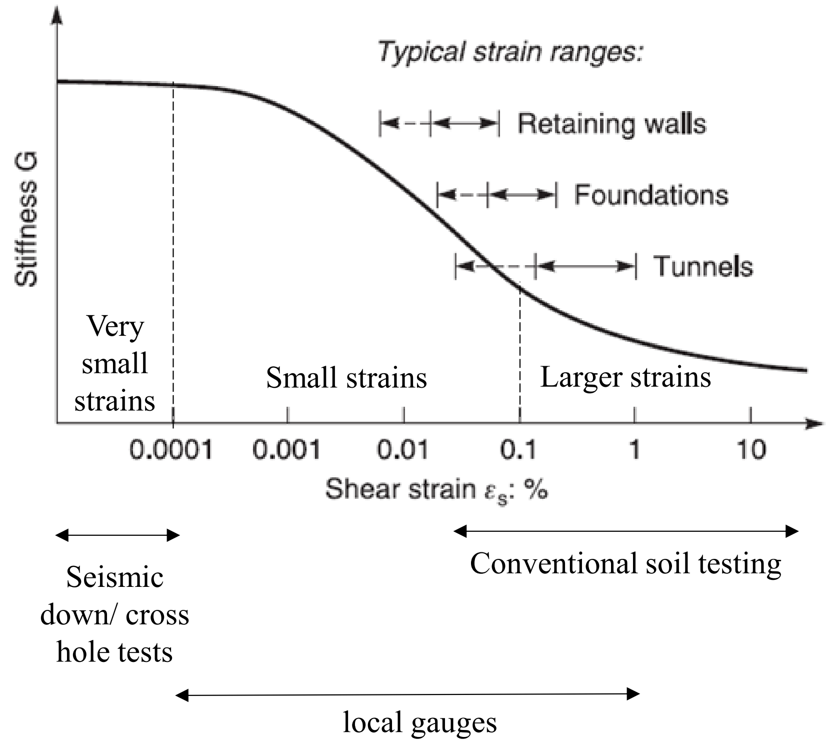


Limitations

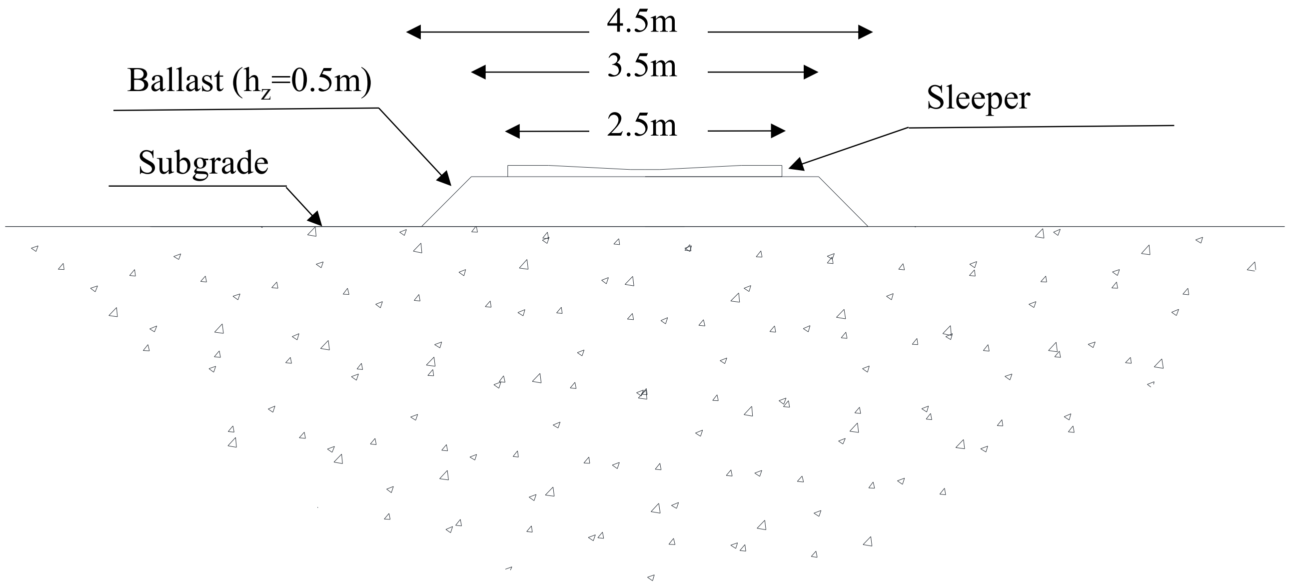
- Epistemic and aleatoric uncertainty
- High computational cost

Uncertainty treatment

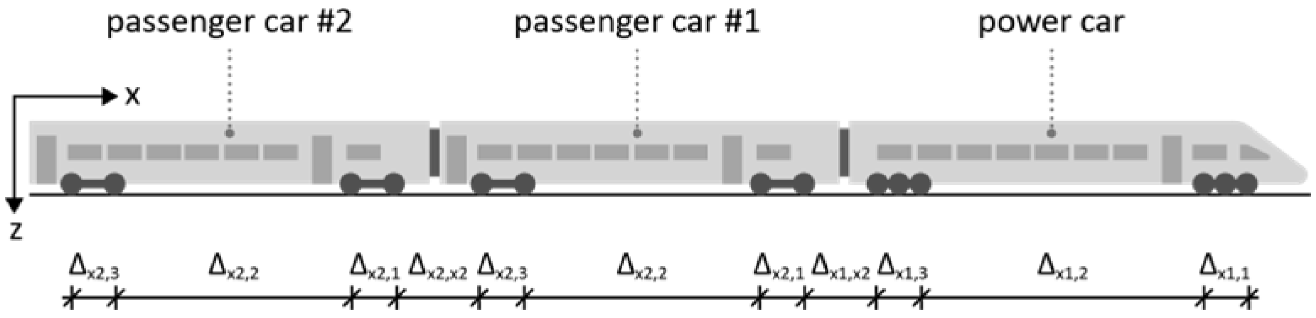
Soil properties (stiffness and damping)



Track properties (height of ballast)

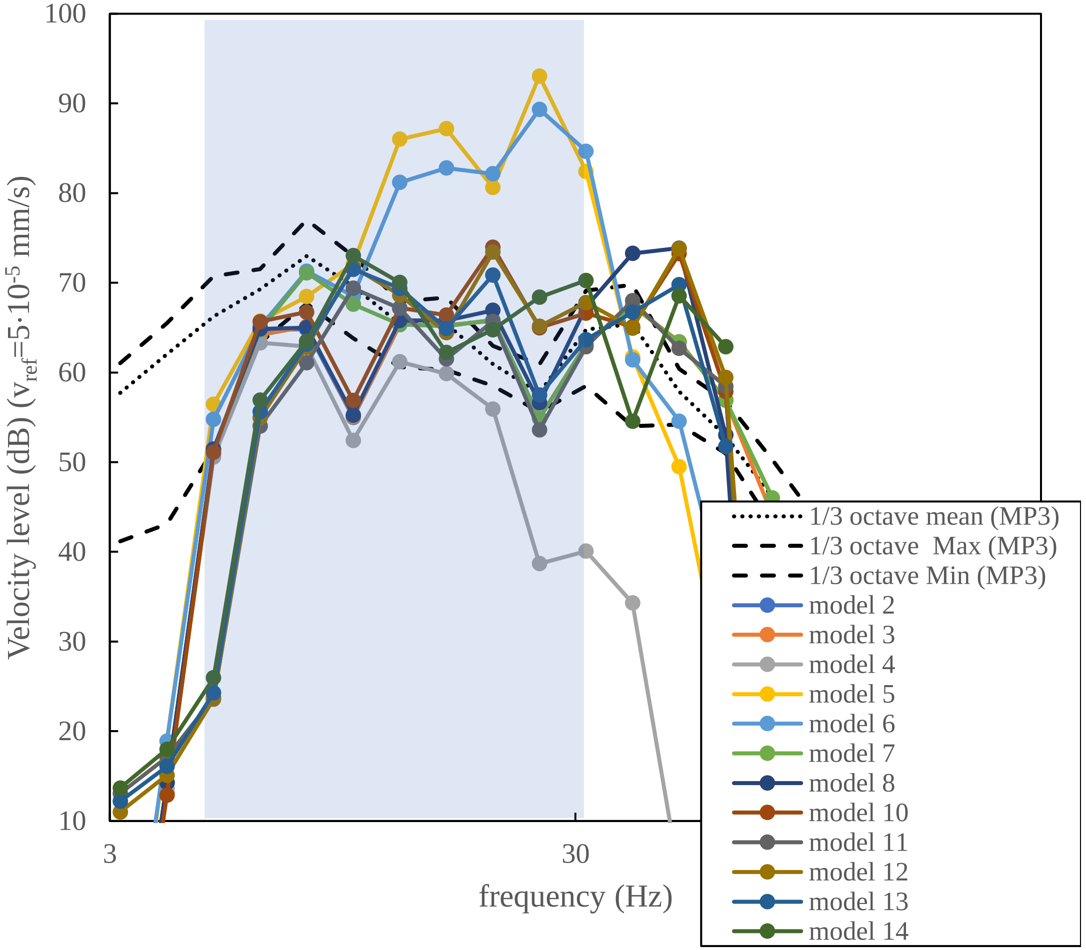


Train properties (speed)

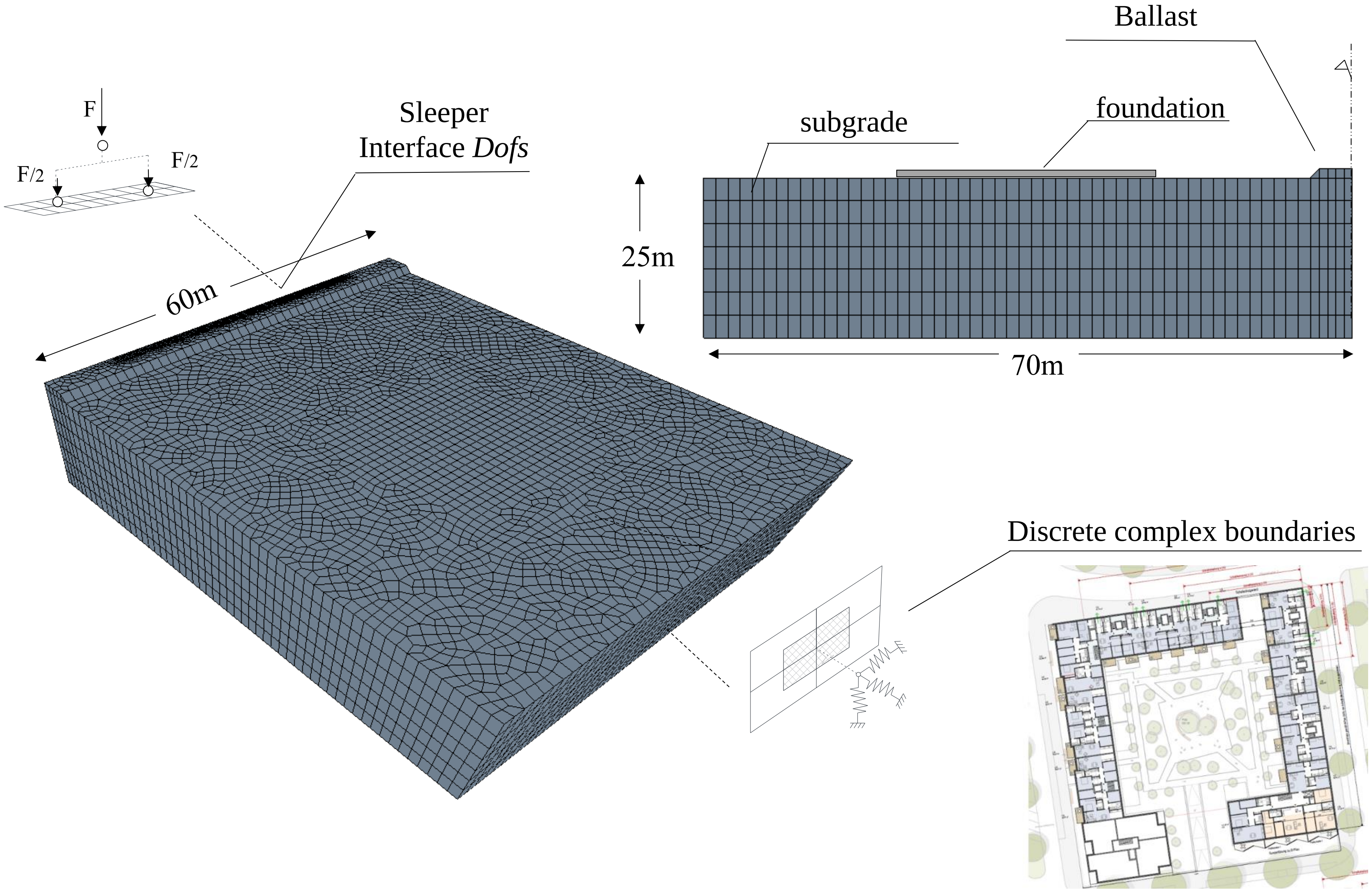


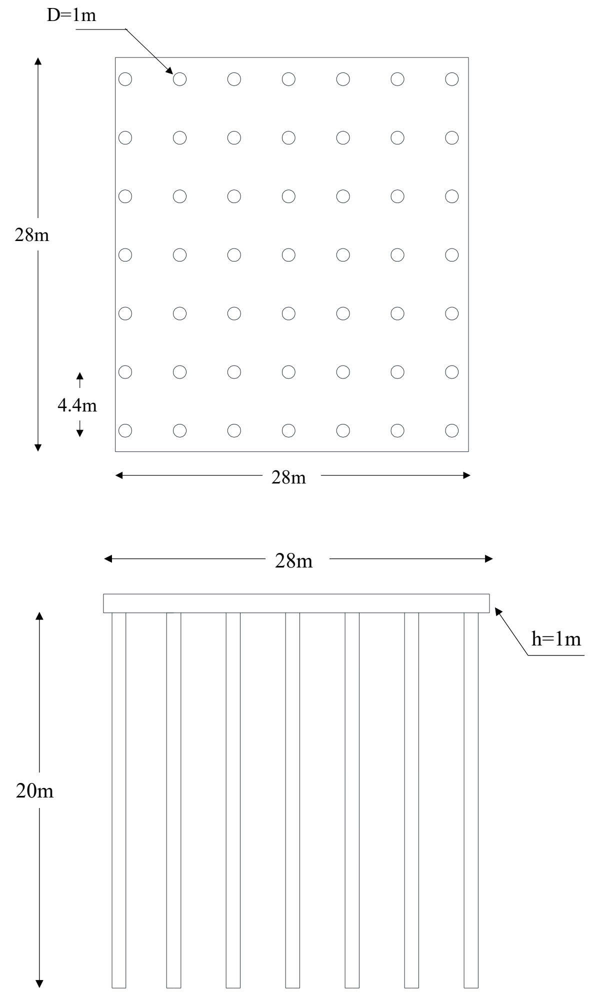
System Identification

Model id	Dimensions (Lx, Ly)	depth	mesh ver.	mesh hor.	Damping f=10Hz	Half-space Boundaries	Train model	Rail pad stiffness
model 1	80x20	15.1	2.1m	3m	0%	frequency dependent LP	Locomotive Class 66 Train+ Y25 Bogie Wagons	255MN/m
model 2	80x40	15.1	2.1m	1.3m		Lysmer		
model 3	80x40	15.1	2.1m	1.3m		frequency dependent LP		
model 4	80x40	15.1	2.1m	1.3m	2% Rayleigh (1Hz,12Hz)			
model 5	80x40	15.1	2.1m	1.3m	0%			
model 6	80x40	15.1	1.5m	1.3m				
model 7	80x40	15.1	1.5m	1.3m				
model 8	80x40	15.1	2.1m	1.3m				50MN/m
model 9	80x40	15.1	2.1m	1.3m				100MN/m
model 10	80x40	15.1	2.1m	1.3m				255MN/m
model 11	80x40	15.1	2.1m	1.3m			adjusted X2000 power car + Y25 Bogie Wagons	
model 12	80x40	15.1	2.1m	1.3m				
model 13	80x40	15.1	2.1m	1.3m				
model 14	80x40	15.1	1.5m	1.3m				
model 15	140x80	15.1	1.5m	1.3m				



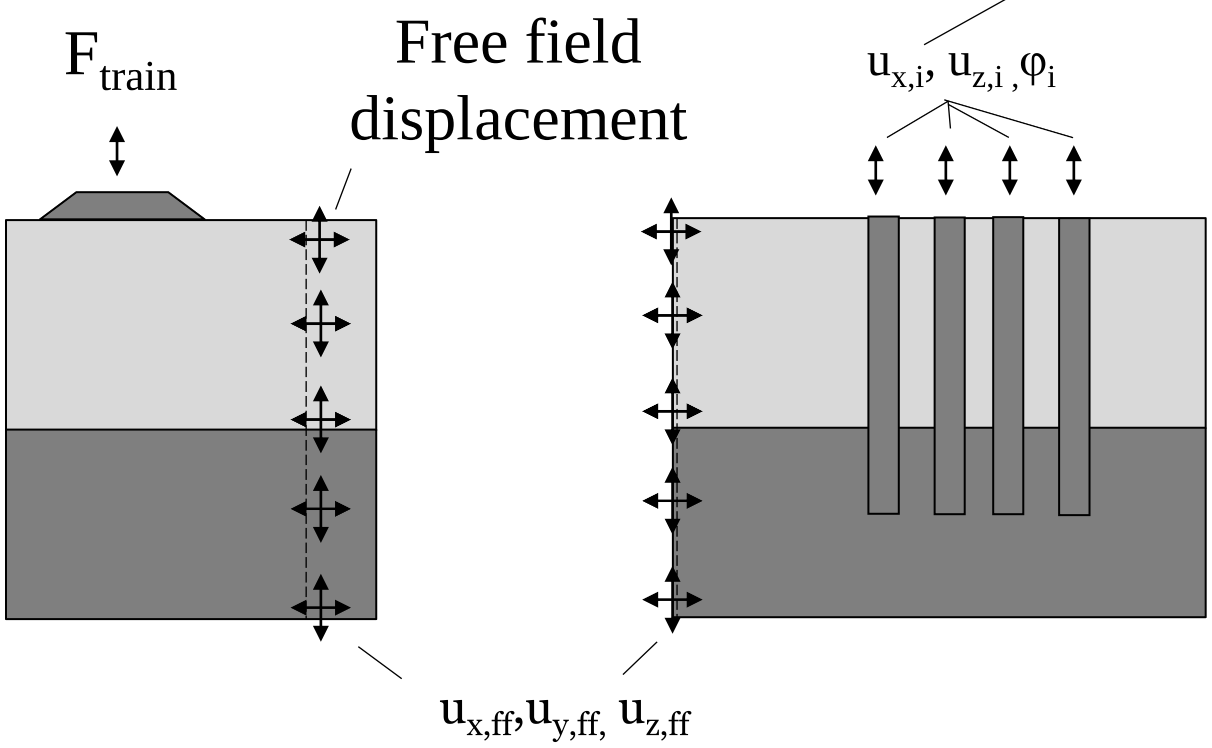
Pile group configuration





Kinematic interaction

Pile Foundation Input Motions

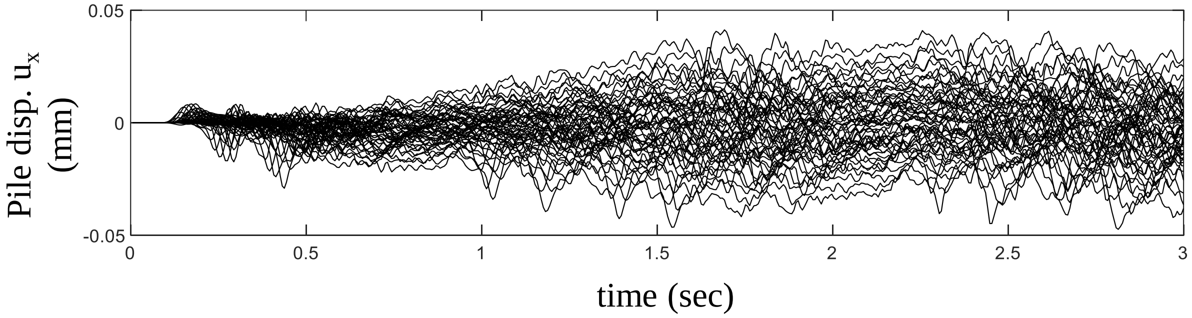


F_{train}

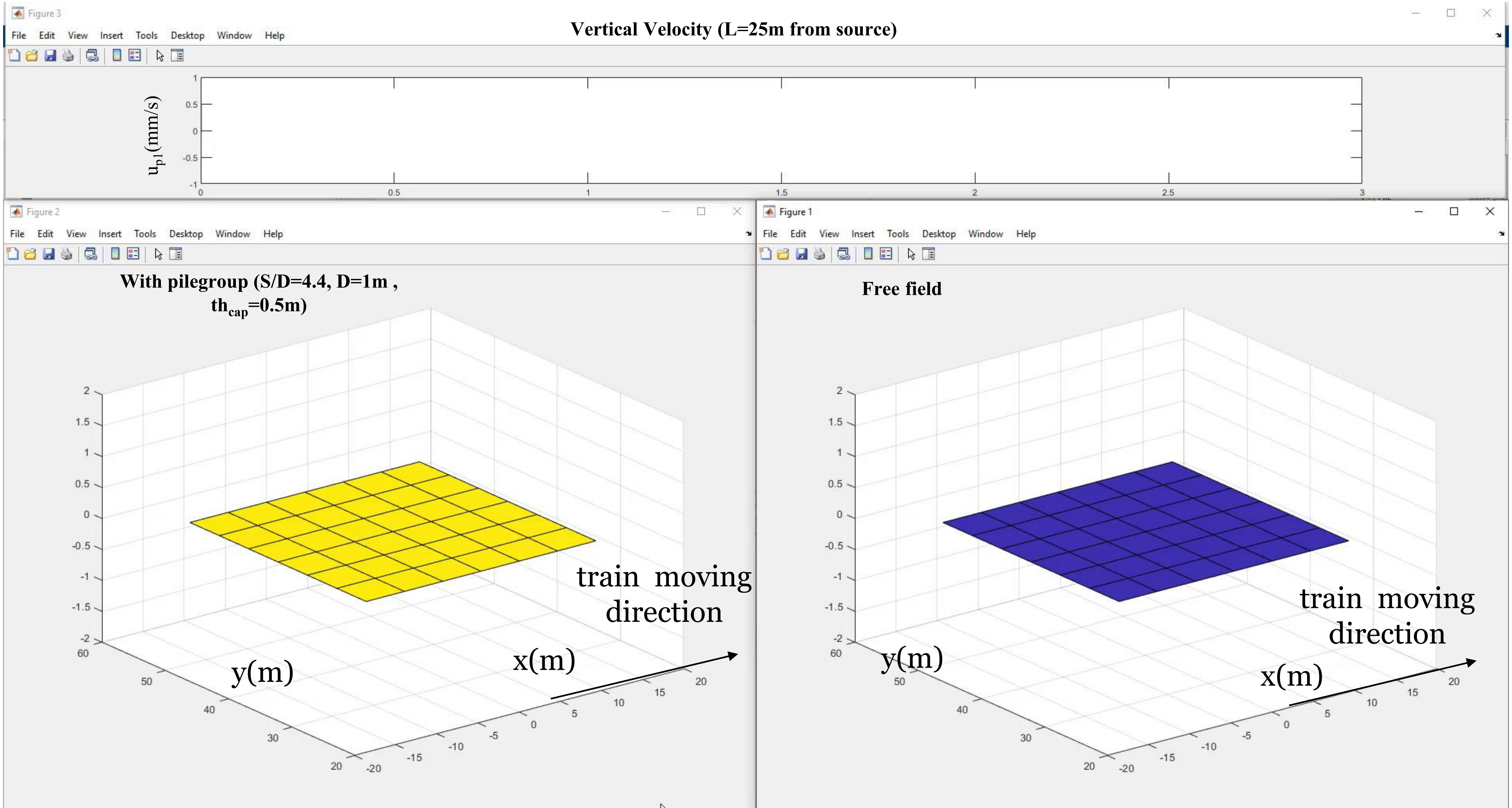
Free field displacement

$u_{x,i}$, $u_{z,i}$, φ_i

$u_{x,ff}$, $u_{y,ff}$, $u_{z,ff}$



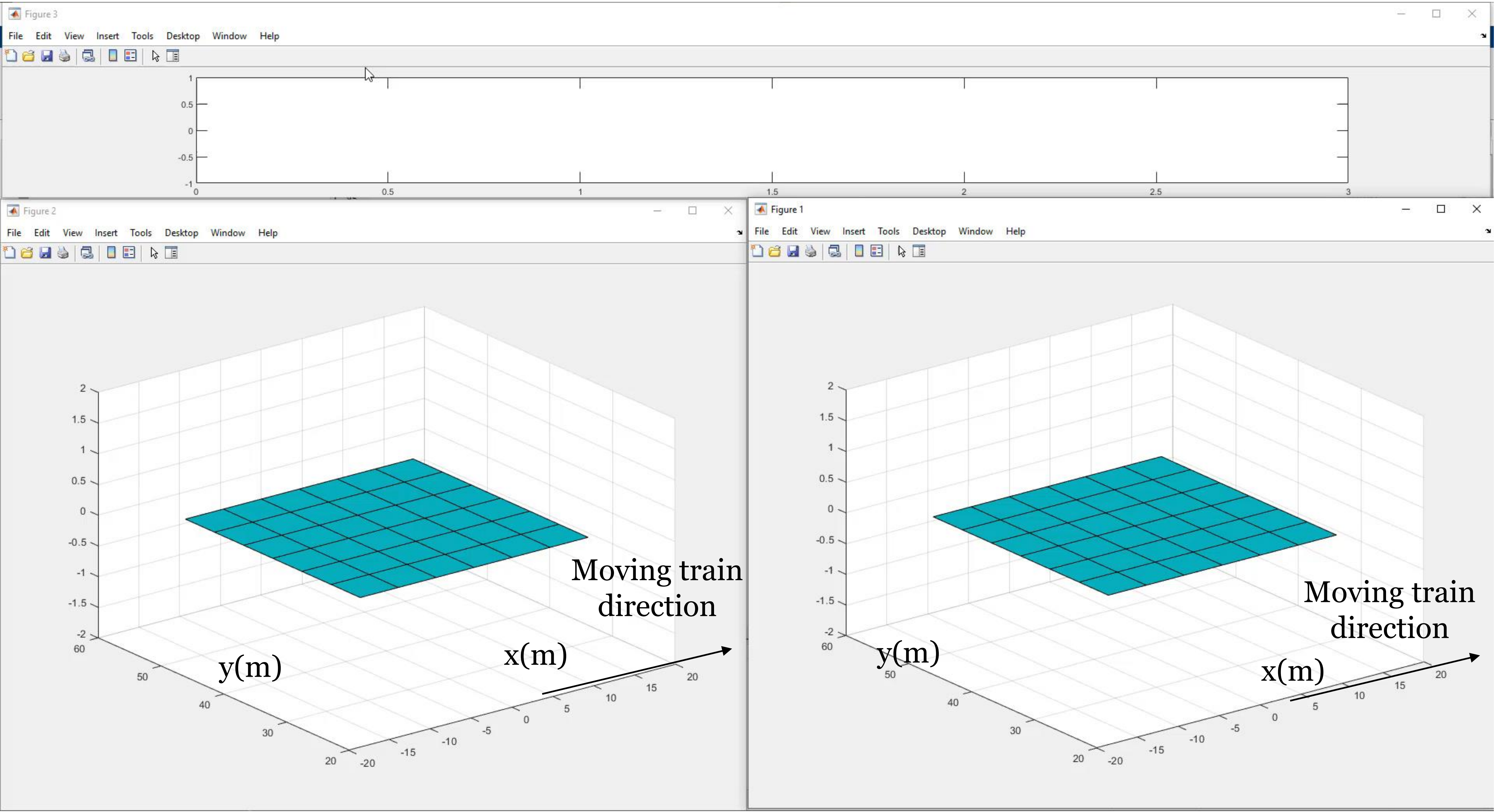
Vibration mitigation by means of a pile group foundation



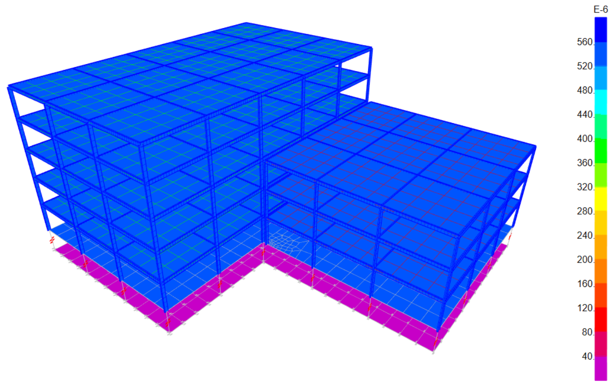
train moving direction

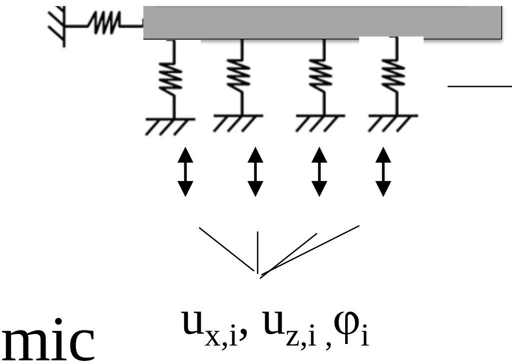
train moving direction

Vibration mitigation by means of a pile group foundation



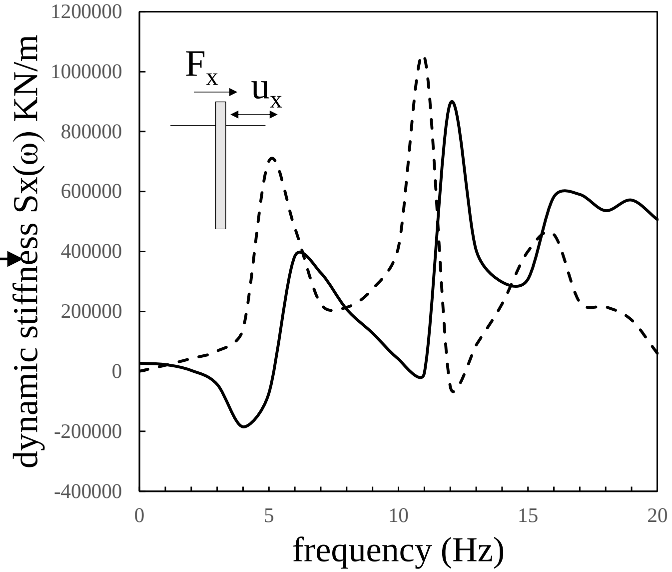
Inertial interaction: use of frequency-dependent LPMs

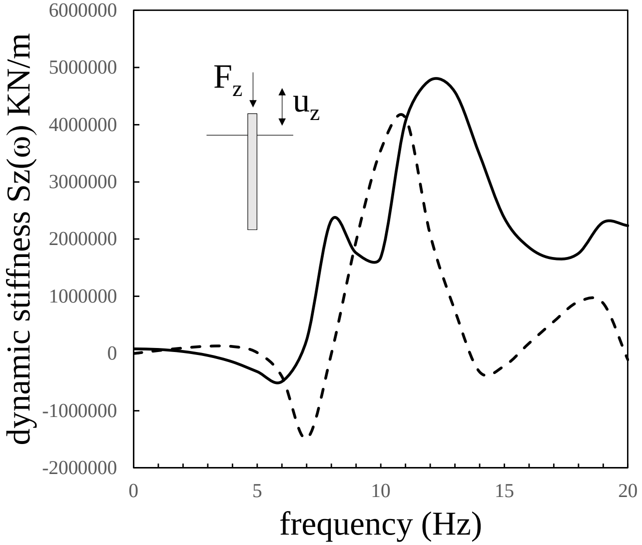


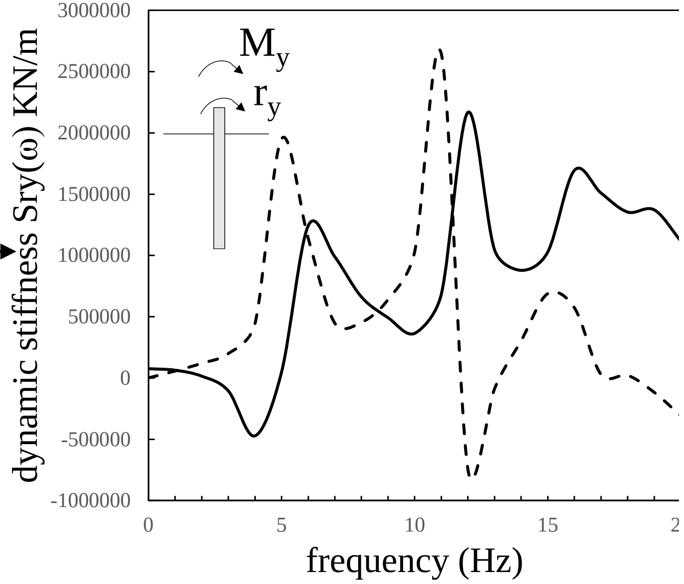


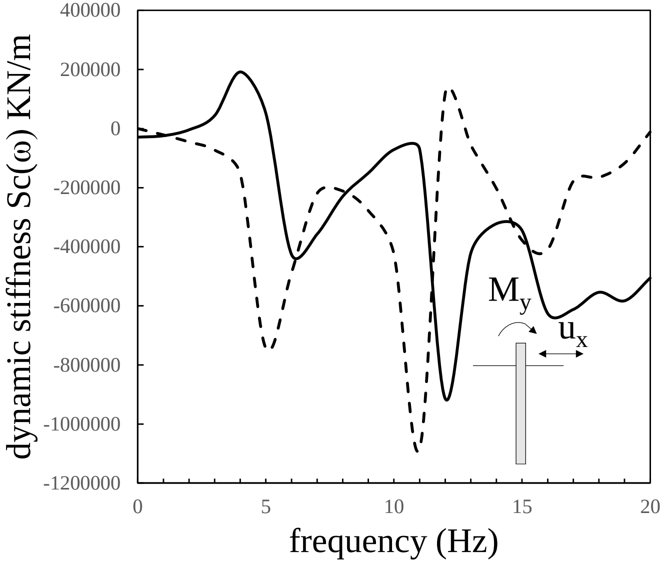
Dynamic Stiffness matrix

$$\mathbf{S}_{IB}(\omega) = \begin{bmatrix} \mathbf{S}_{11}(\omega) & \cdots & \mathbf{S}_{1N}(\omega) \\ \vdots & \ddots & \vdots \\ \mathbf{S}_{N1}(\omega) & \cdots & \mathbf{S}_{NN}(\omega) \end{bmatrix}$$



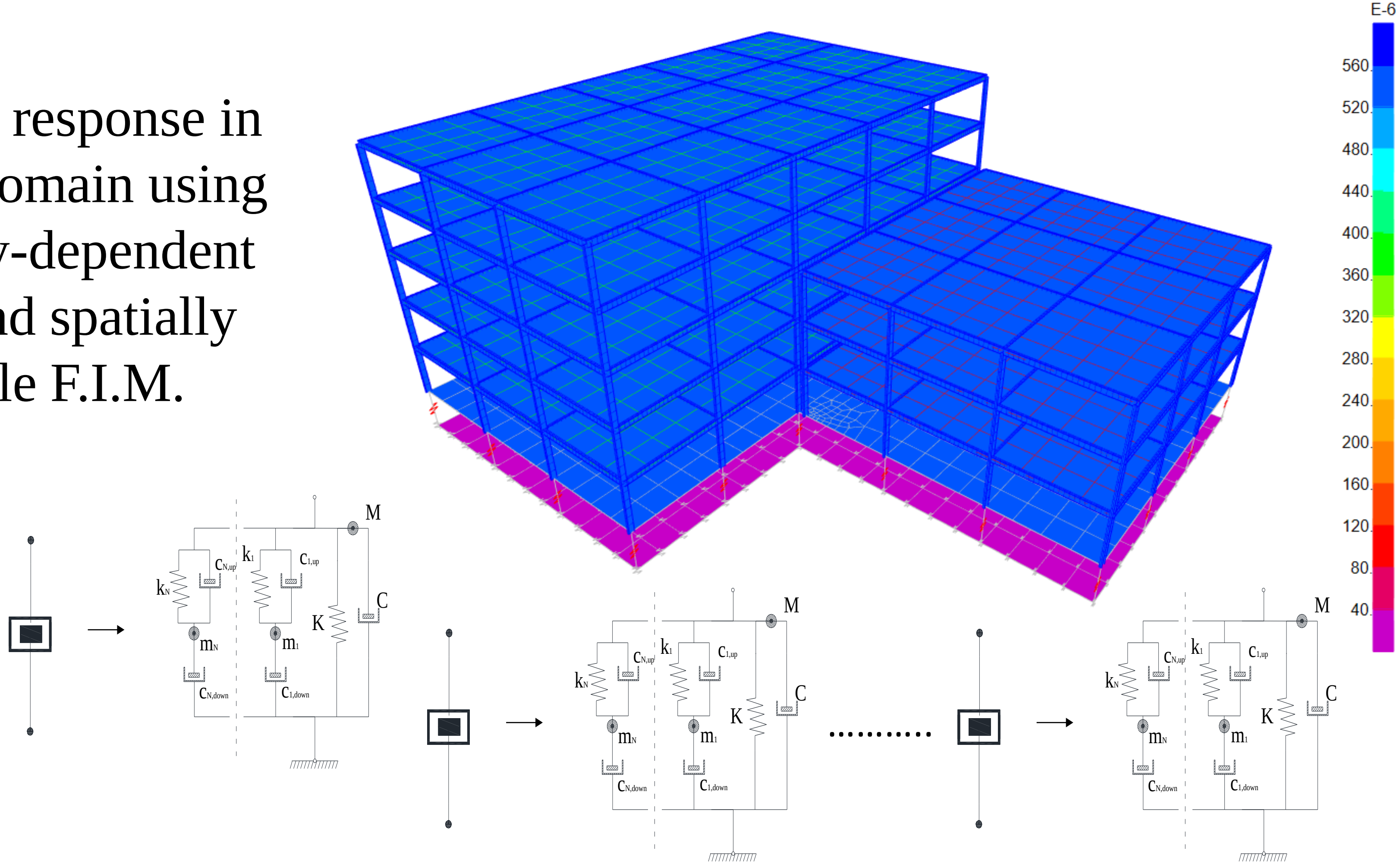


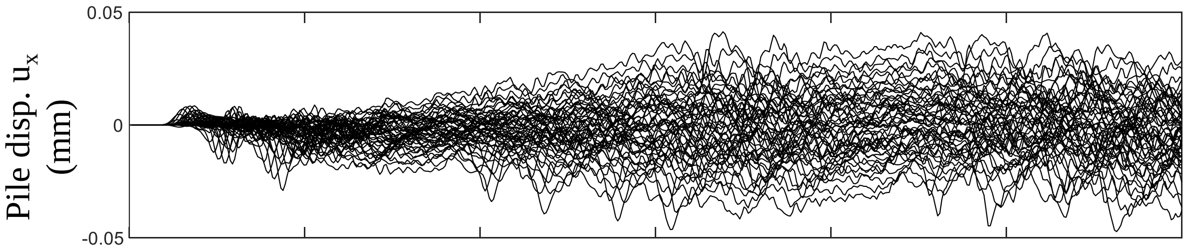




Inertial interaction: use of frequency-dependent LPMs

Structural response in the time domain using frequency-dependent LPMs and spatially variable F.I.M.





Kinematic and inertial interaction sub-structuring just like in earthquake engineering application <u>+ coupled terms (for the surface foundation case) and surface wave induced F.I.M. at an angle θ</u>