OpenSees implementation of 3D embedded pile element for analysis of SSI problems

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Collaborators

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Sponsors

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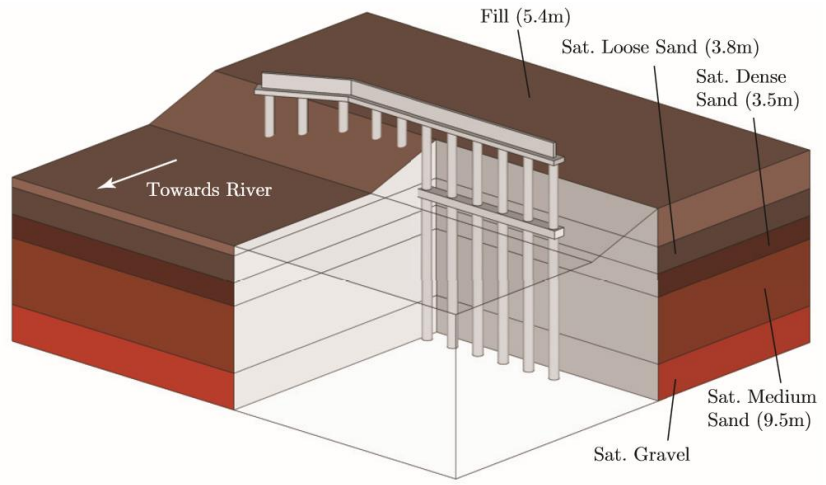
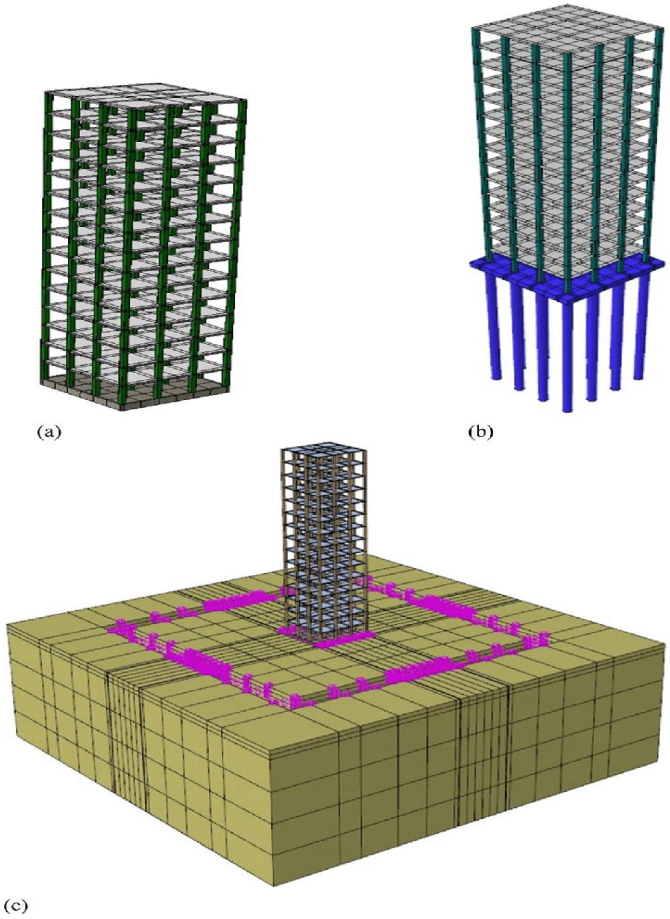
Motivation:
Modeling complex SSI systems



Bridge abutment



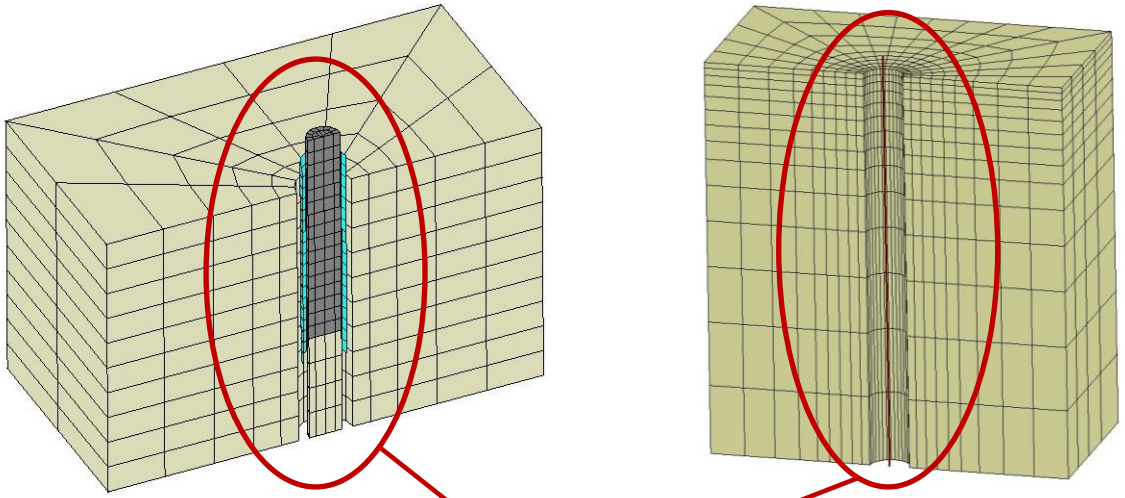
Building foundation

Numerical Simulation needs 3D FEM Models

- Total or Effective stress analysis
  - Single phase formulation: brick elements
  - Multi-phase formulation: u-P formulation using brickUP elements
- Soil constitutive model
  - Capture nonlinear behavior of the soil
  - Capture contractive/dilative behavior
  - Capture cyclic mobility
- **Soil-Foundation Interaction**
  - Interface behavior
    - Frictional behavior?
    - Gap forming?
  - Take advantage of 1D beam elements

In particular, **3D dynamic FEM** analysis of soil-structure interaction problems requires advanced numerical methods

Solid-solid and beam-solid contact
Mesh difficulties/challenges



Solid-Solid Model

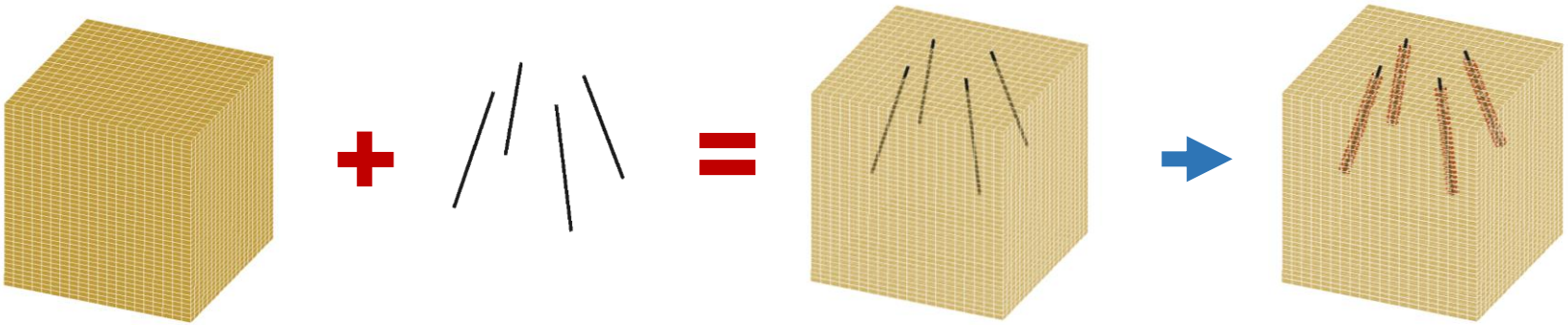
Beam-Solid Model

?

Embedded element

meshing challenges

Proposed approach: Embedded Elements



Regular FEM mesh

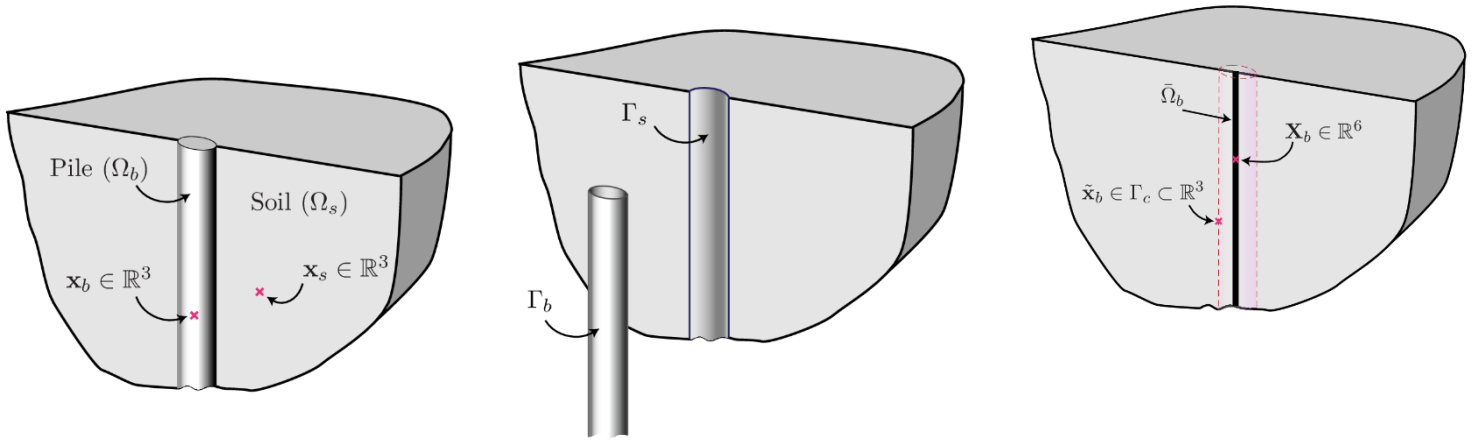
Beam elements

Embedded beam element

Embedded beam element with interface surface

Embedded Elements

Perfect Bonding Condition



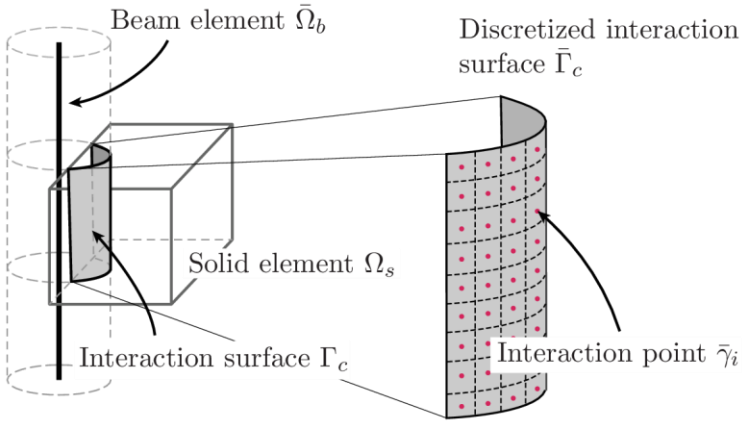
Perfect bonding condition: $\tilde{\mathbf{x}}_b(\gamma) - \tilde{\mathbf{x}}_s(\gamma) = 0 \quad \forall \gamma \in \Gamma_c, \forall t$

This constraint between the soil and an imaginary surface forms the fundamental component of the embedded element formulation

Embedded Element

Perfect Bonding Condition

Point Collocation Method
(Interaction condition applied in a strong sense)



Lagrange Multipliers Method:

$$\delta W^{\text{internal}} = \delta W^{\text{internal}}_{\text{system}} + \underbrace{\sum_{\bar{\gamma}\in\bar{\Gamma}_c} \boldsymbol{\lambda}\cdot(\delta\tilde{\mathbf{x}}_b - \delta\tilde{\mathbf{x}}_s)}_{\text{Virtual work of interaction forces}} + \underbrace{\sum_{\bar{\gamma}\in\bar{\Gamma}_c} \delta\boldsymbol{\lambda}\cdot(\tilde{\mathbf{x}}_b - \tilde{\mathbf{x}}_s)}_{\text{Constraint enforcement}}$$

$$\forall \text{ admissible } \delta\tilde{\mathbf{x}}_b, \delta\tilde{\mathbf{x}}_s, \delta\boldsymbol{\lambda}.$$

Penalty Method:

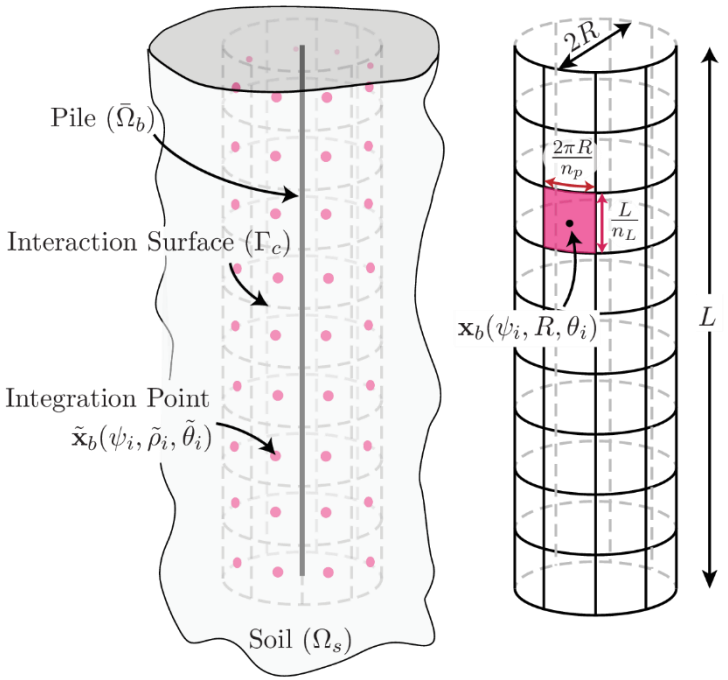
$$\delta W^{\text{internal}} = \delta W^{\text{internal}}_{\text{system}} + \sum_i \epsilon_p\,(\tilde{\mathbf{x}}_b - \tilde{\mathbf{x}}_s)\cdot(\delta\tilde{\mathbf{x}}_b - \delta\tilde{\mathbf{x}}_s) \quad \forall \text{ admissible } \delta\tilde{\mathbf{x}}_b, \delta\tilde{\mathbf{x}}_s$$

Embedded Element (mortar)

Perfect Bonding Condition

Mortar Method
(Interaction condition applied in a weak sense)

$$\int_{\Gamma_c} \boldsymbol{\lambda}(\gamma) \cdot (\tilde{\mathbf{x}}_b(\gamma) - \tilde{\mathbf{x}}_s(\gamma)) \; \mathrm{d}\gamma = 0 \quad \forall t$$



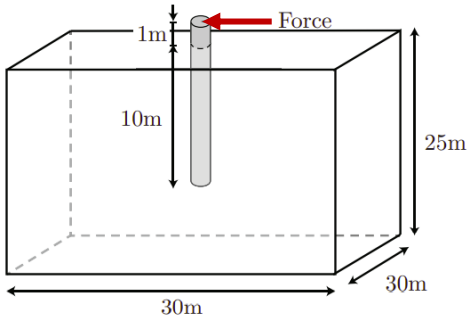
Embedded Beam-Solid Interface element currently available in OpenSees (3.6.0)

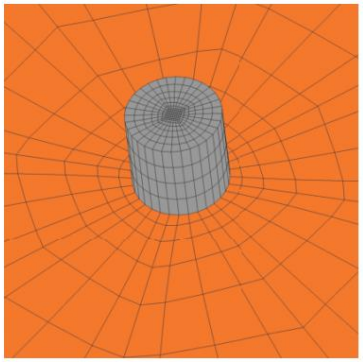
Quasi Static Example

Quasi Static Example

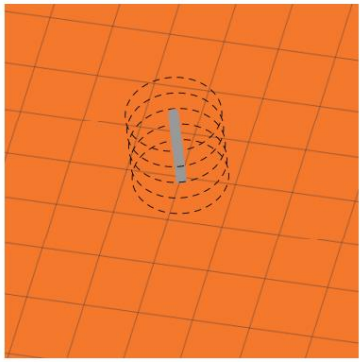
Embedded Element

Laterally loaded pile

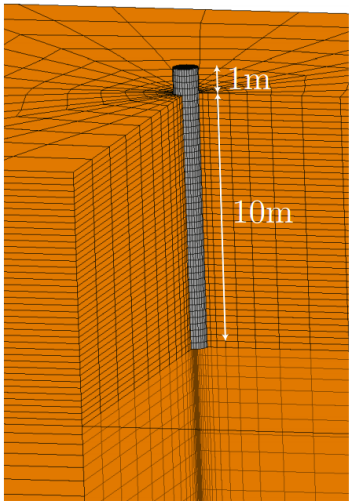




3D Solid



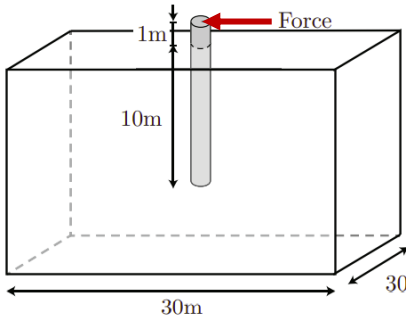
Embedded Interface

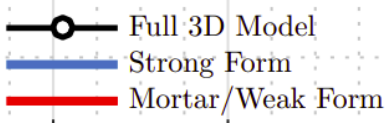


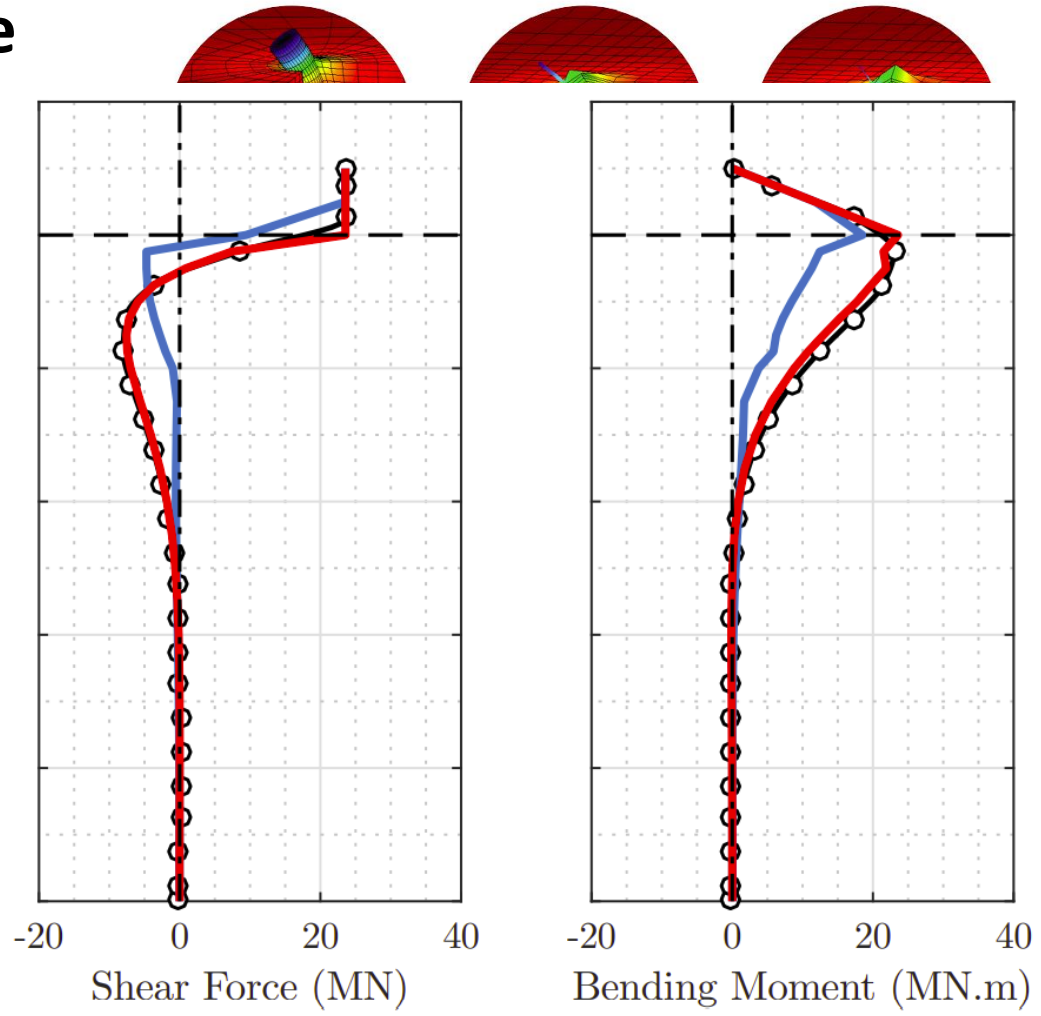
Close-up View of the Mesh

Embedded Element

Laterally loaded pile

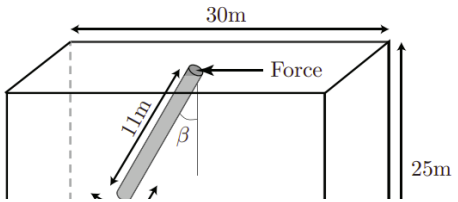


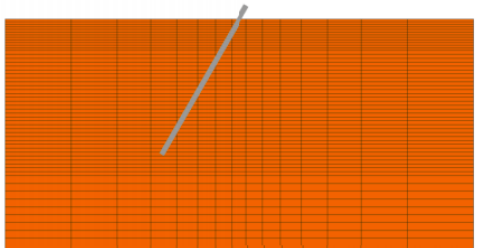


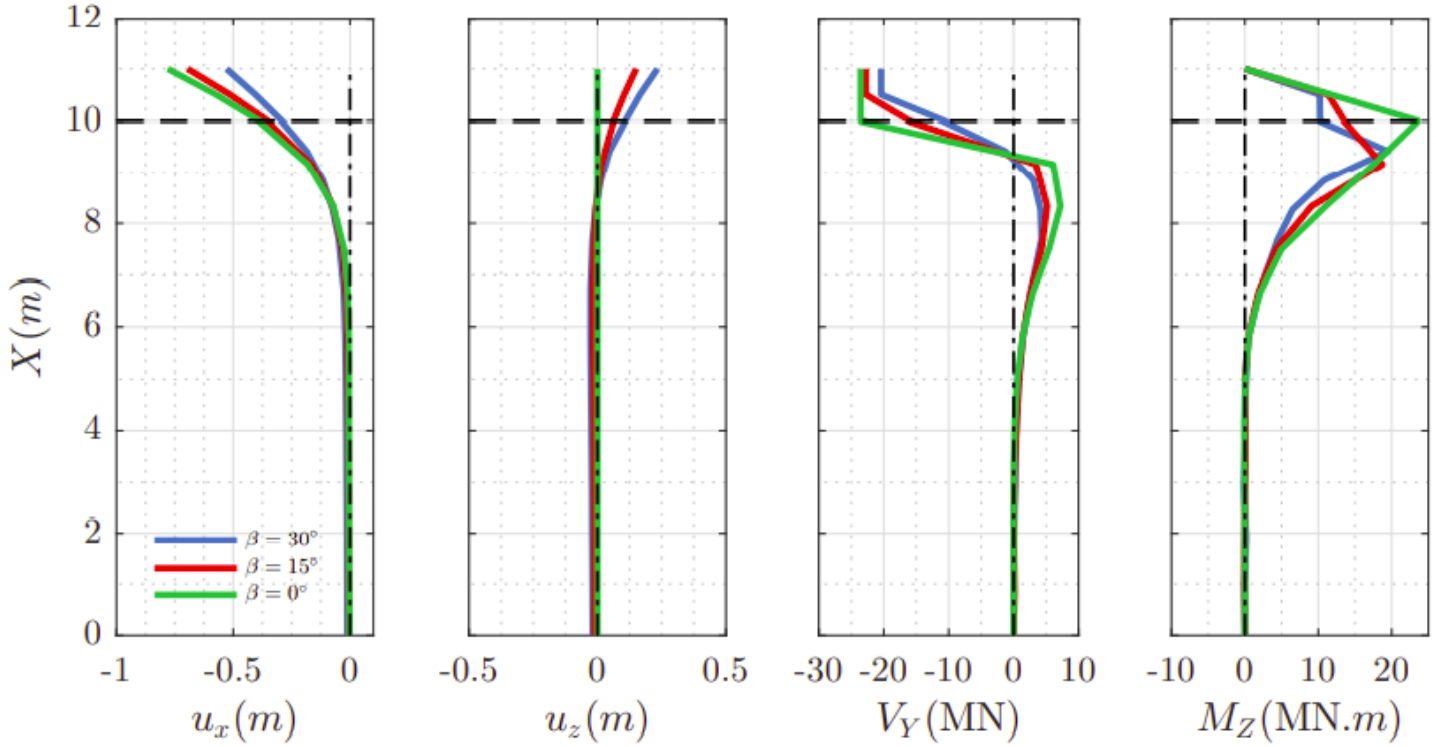


Embedded Element

Battered pile response







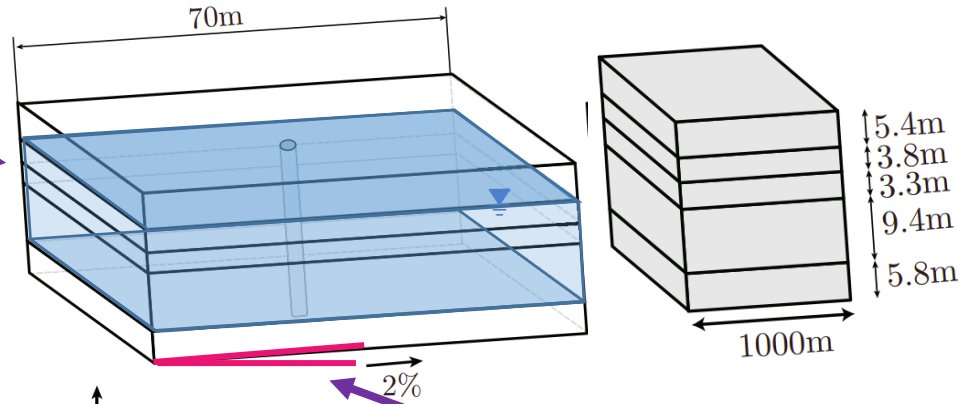
Dynamic Example

Dynamic Example

Dynamic Examples

Lateral Spreading

A massive soil column (1000m x 1000m) represents the free-field response.



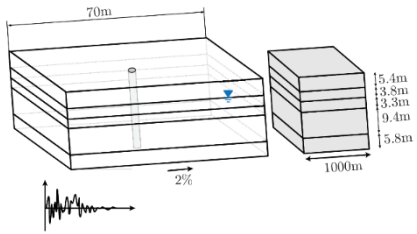
Liquefiable soil with different degrees of susceptibility

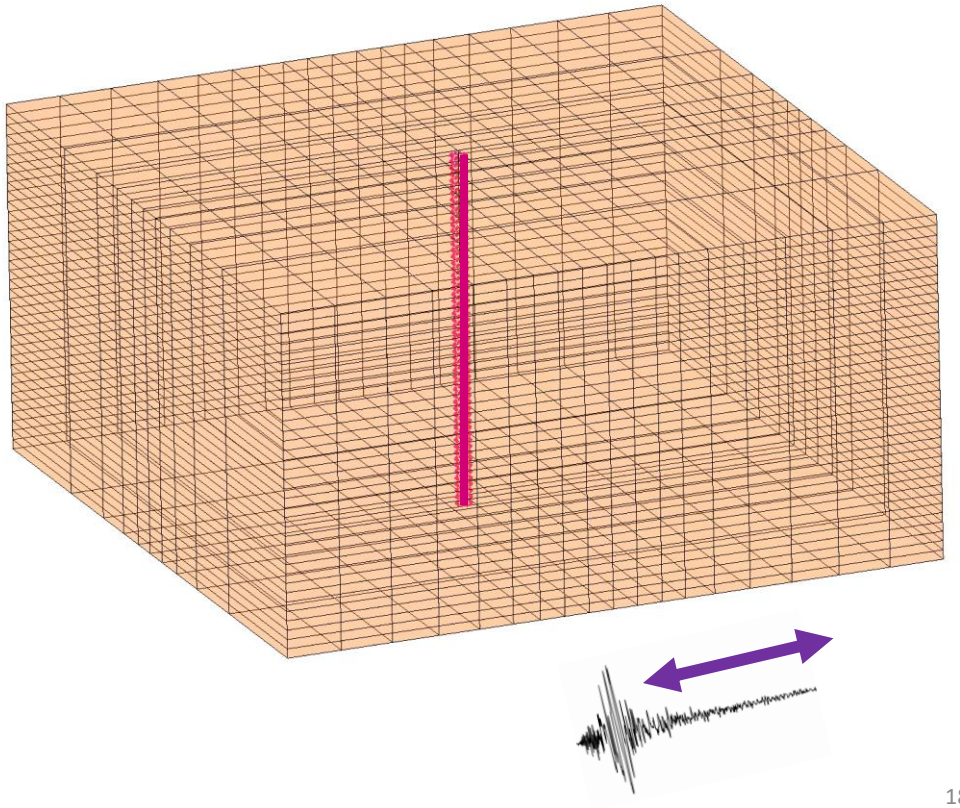
Motion applied to the base.

2% slope to push lateral spreading

Dynamic Examples

Lateral Spreading

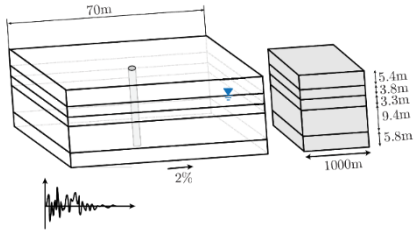




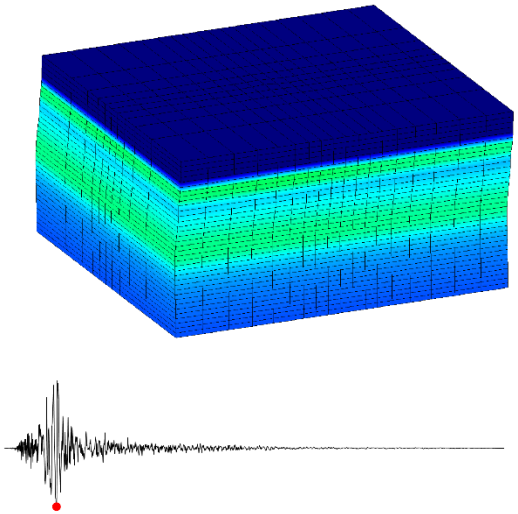
Soil-Pile interaction compatible displacement

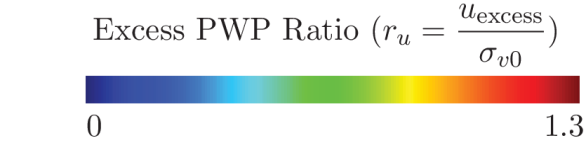
Dynamic Examples

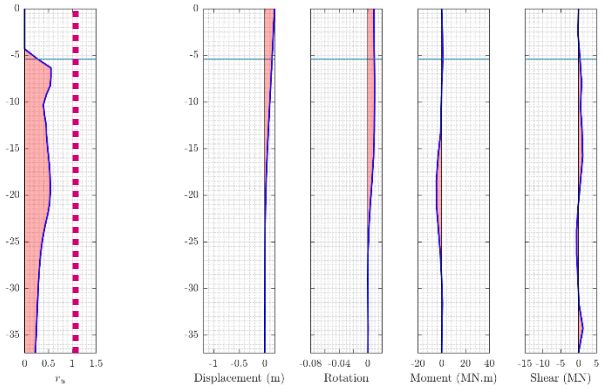
Lateral Spreading



$t \approx 4$ s

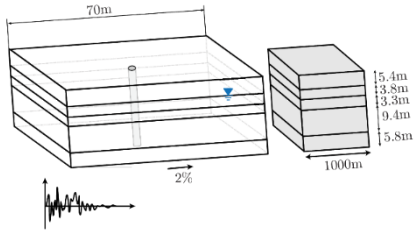




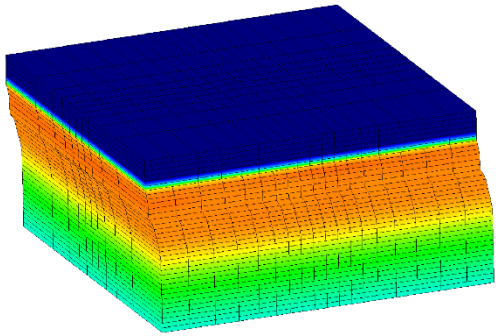


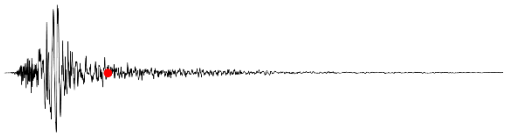
Dynamic Examples

Lateral Spreading



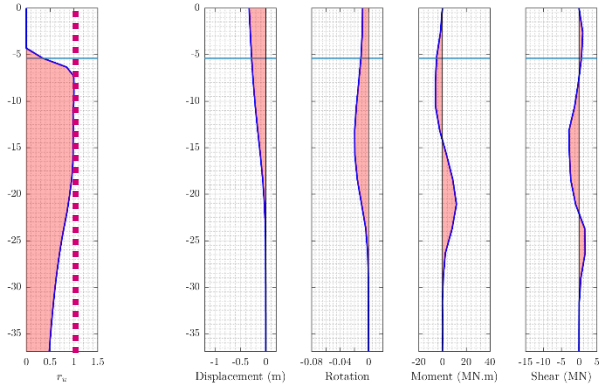
$t \approx 8\,\mathrm{s}$





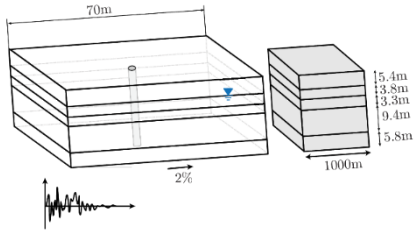
Excess PWP Ratio ($r_u = \frac{u_{\mathrm{excess}}}{\sigma_{v0}}$)

0 1.3

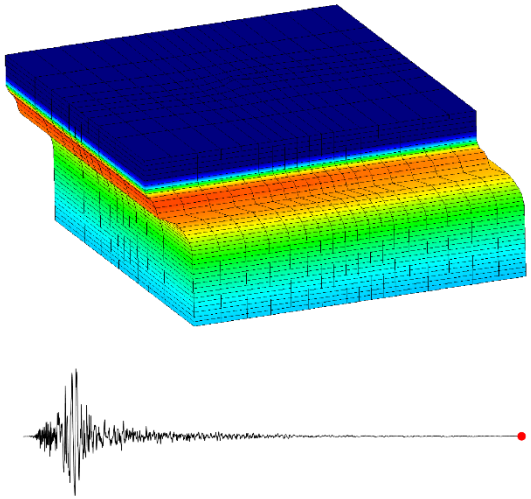


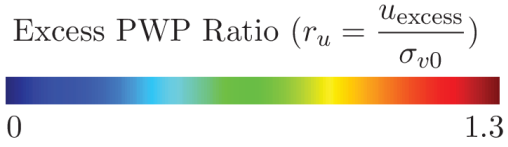
Dynamic Examples

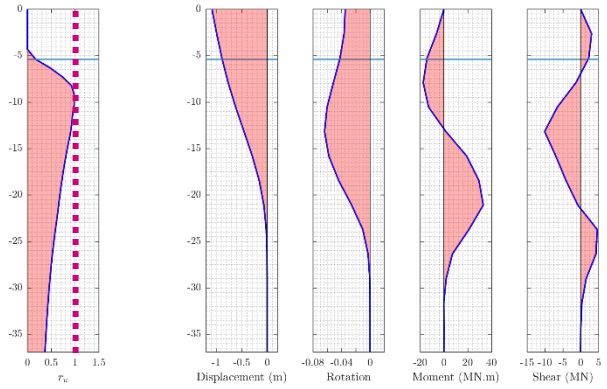
Lateral Spreading



$t \approx 40$ s







Building Foundation

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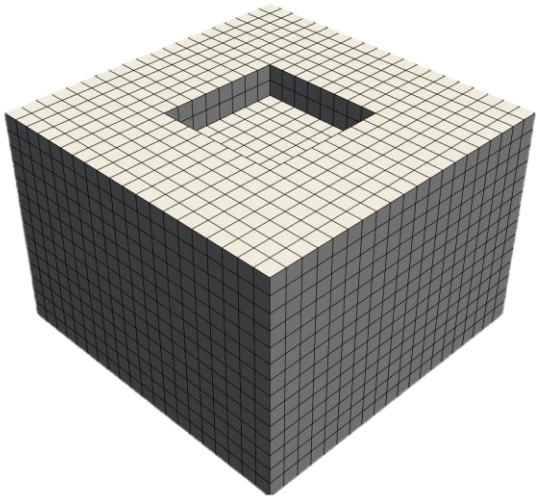
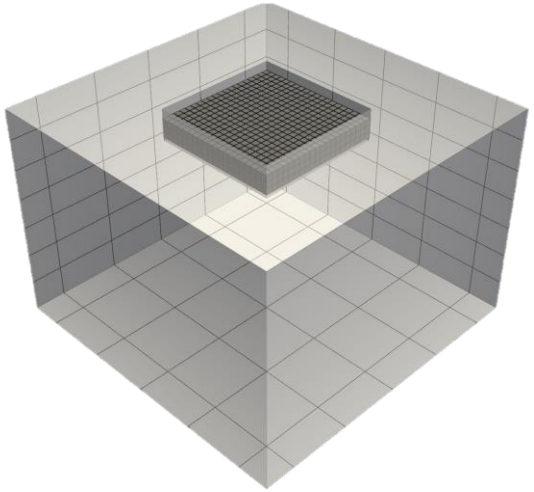
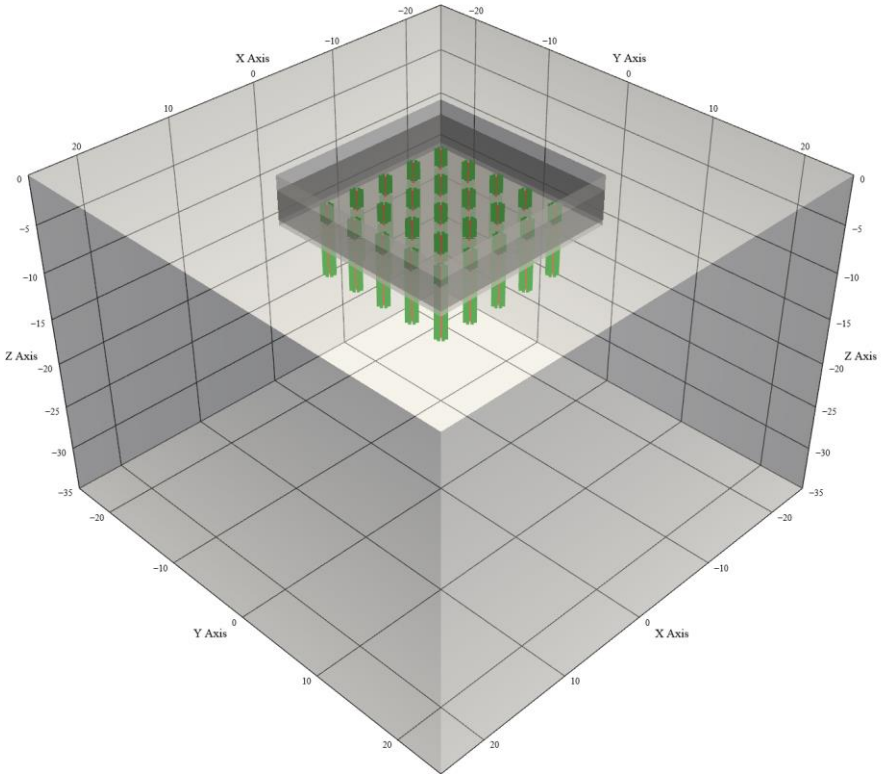
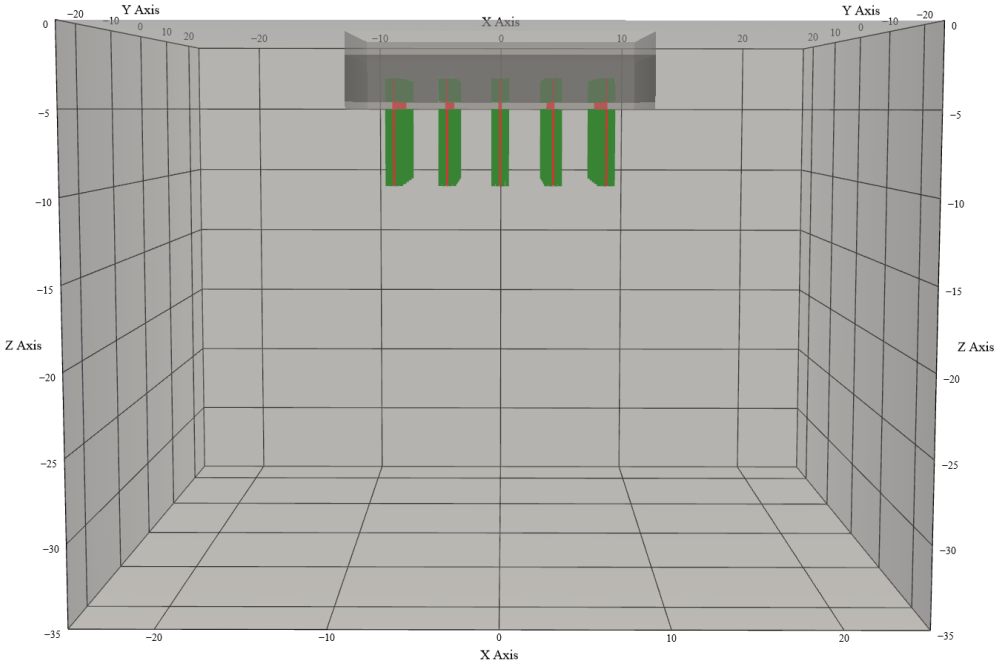




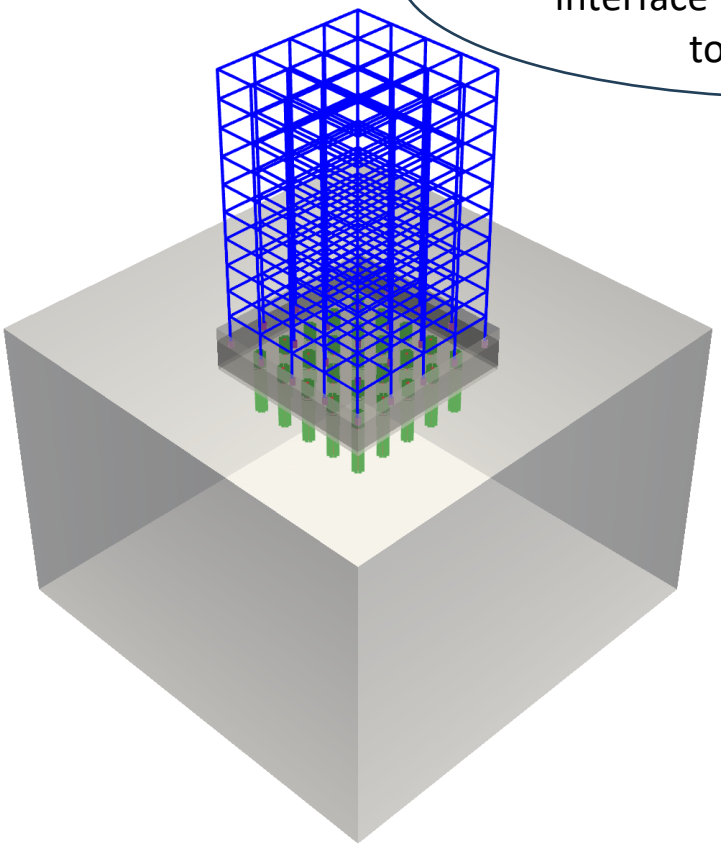
Building Foundation
Mat on pile foundation

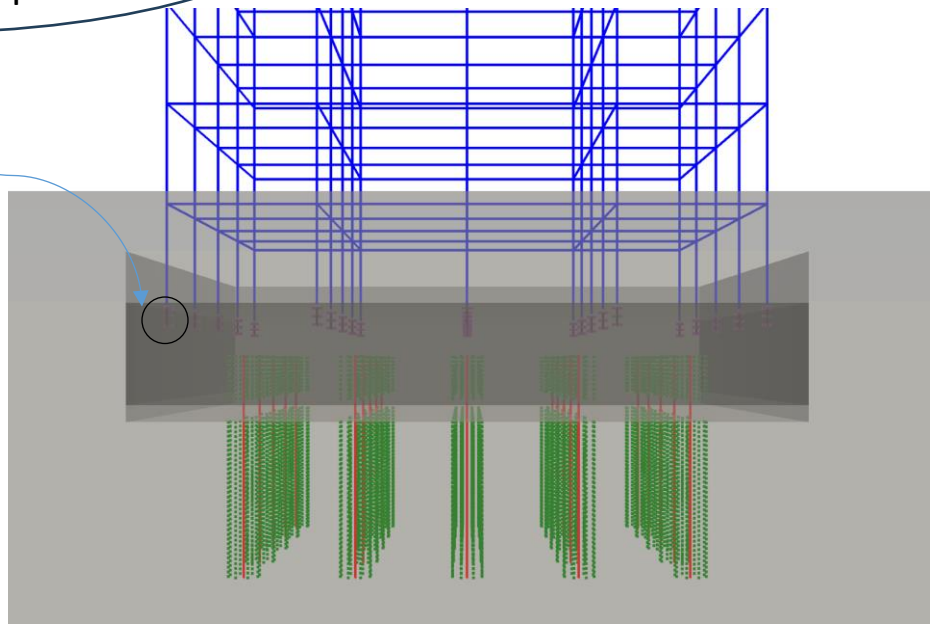




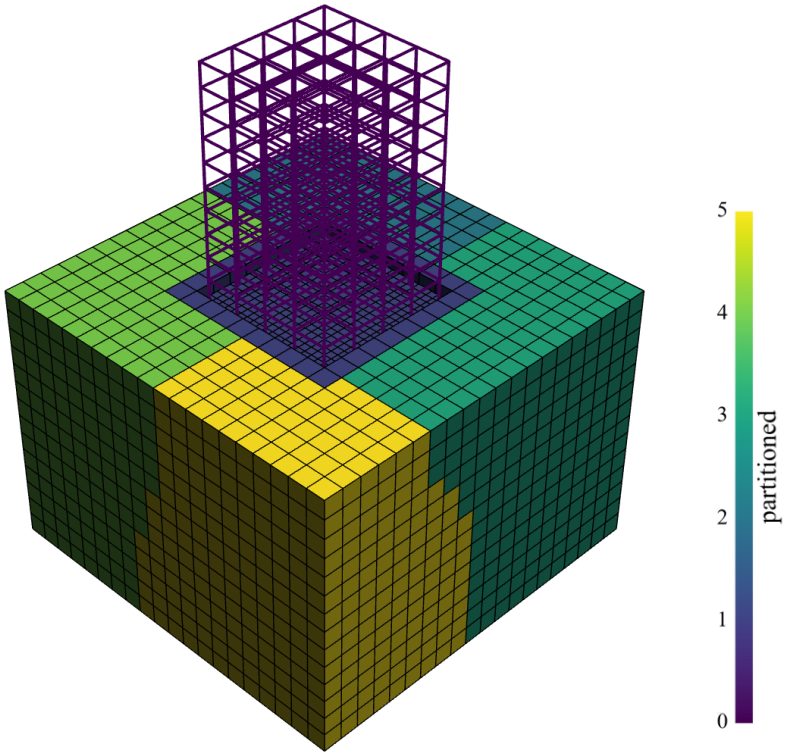
Building Foundation
Structure connection

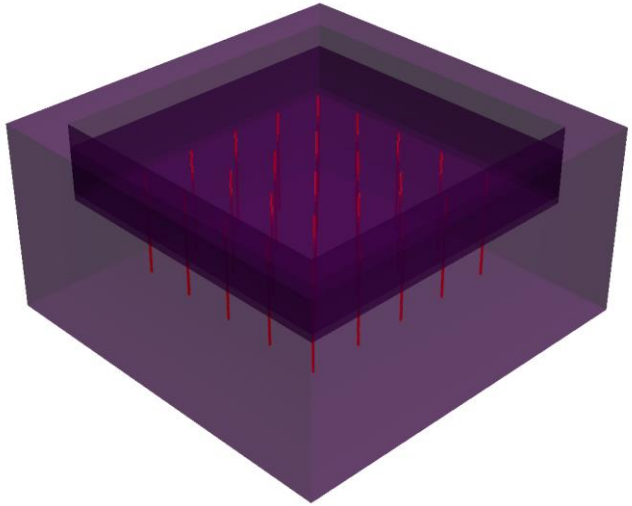
Using embedded length for the column and embedded interface to connect structure to the pile cap





Building Foundation
Distributed computing

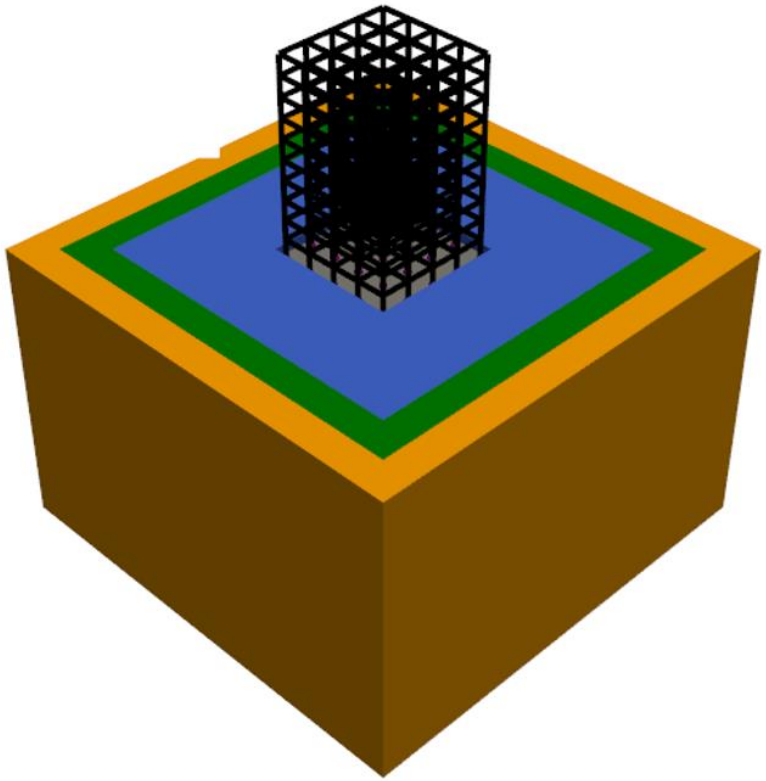




The only challenge is that the interface nodes and their associated brick elements should be kept on a same processor in parallel processing analysis

Building Foundation Dynamic analysis

- Structure
- Soil Layer
- Foundation
- Domain Reduction Layer
- Perfectly Matched Layer



Concluding Remarks

- **Soil Structure Interaction (SSI) analysis continues to be an important and challenging problem to tackle numerically.**
- **Conventional and embedded contact formulations useful to represent SSI.**
- **Mortar embedded interface element effectively applies the interaction condition.**
- **Preliminary results show the potential of the proposed embedded element implemented in OpenSees.**
- **Future work includes more validation and verification studies, and simulation of complex building and bridge foundation systems.**

Thank you!!