Prague Geotechnical Days 2023

DESIGN OF PILE FOUNDATIONS FOR LARGE STORAGE TANKS UNDER SEISMIC LOADING

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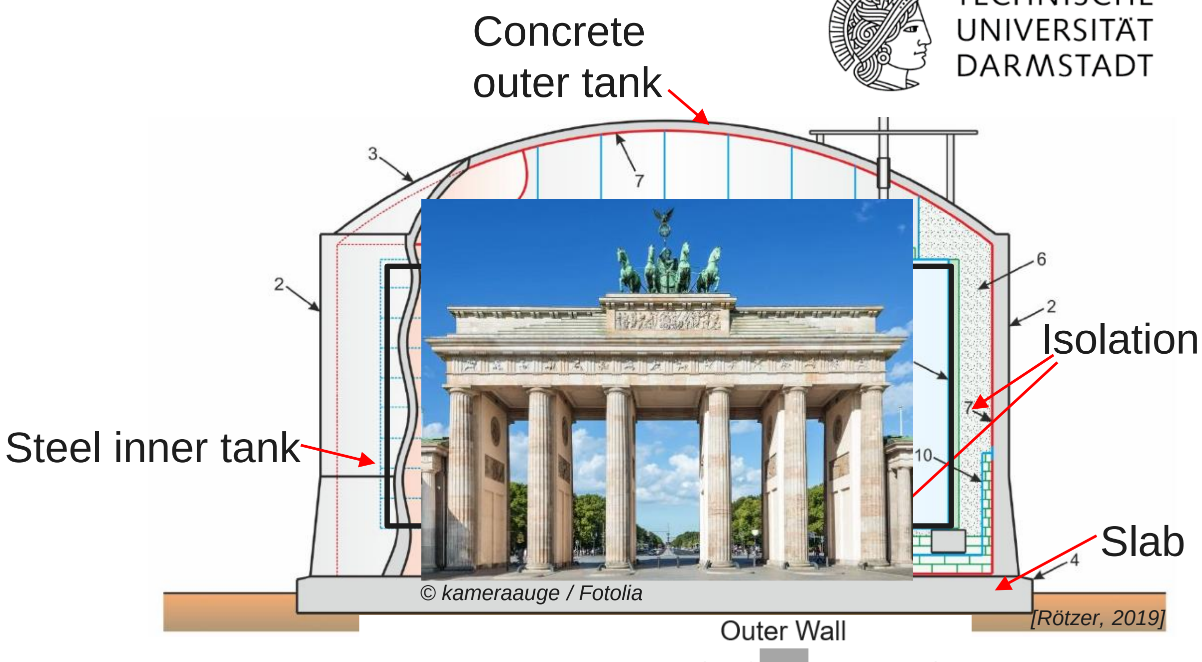
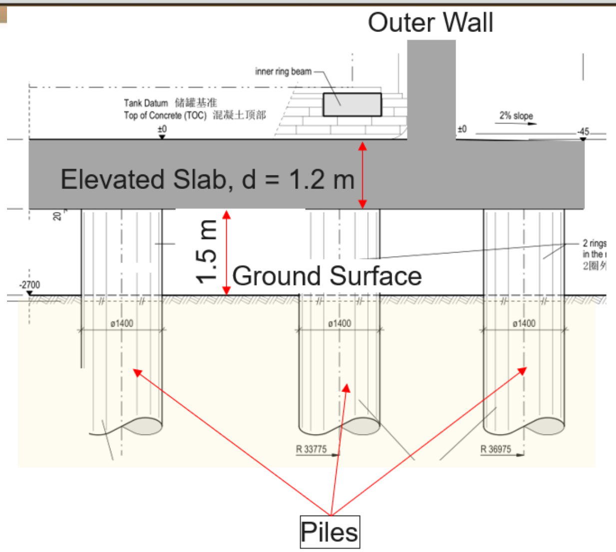
TGE Reference LNG Tank Zhoushan I

Introduction

- Filling: e.g. LNG (Liquified Natural Gas, T = -162 °C)
- Inner tank made of cryogenic steel
- Outer tank made of prestressed / reinforced concrete
- Tank volume up to 200 000 m^3
- 160 000 m^3 → D = ~85 m, H = ~50 m
- Piled foundation: elevated slab to avoid ice lenses
- High earthquake loads require large pile groups





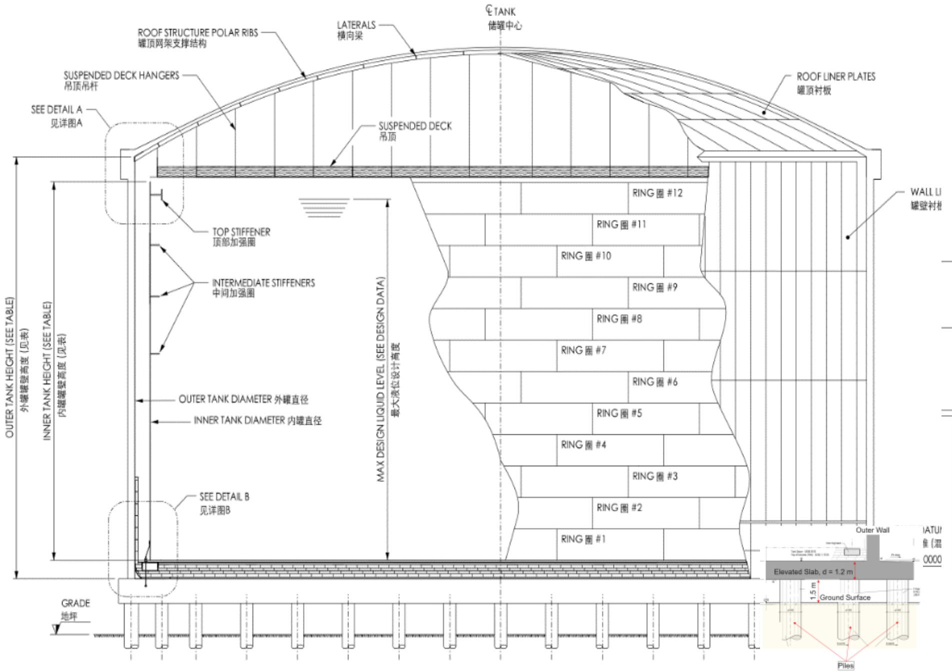
Agenda

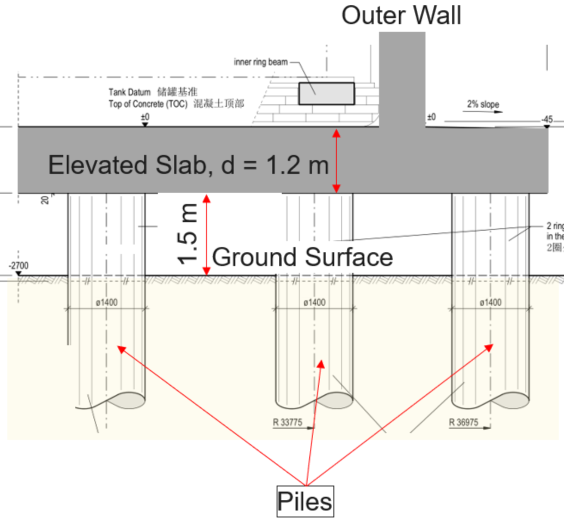
TGE Reference LNG Tank Zhoushan I

1 Tank Layout & Loads

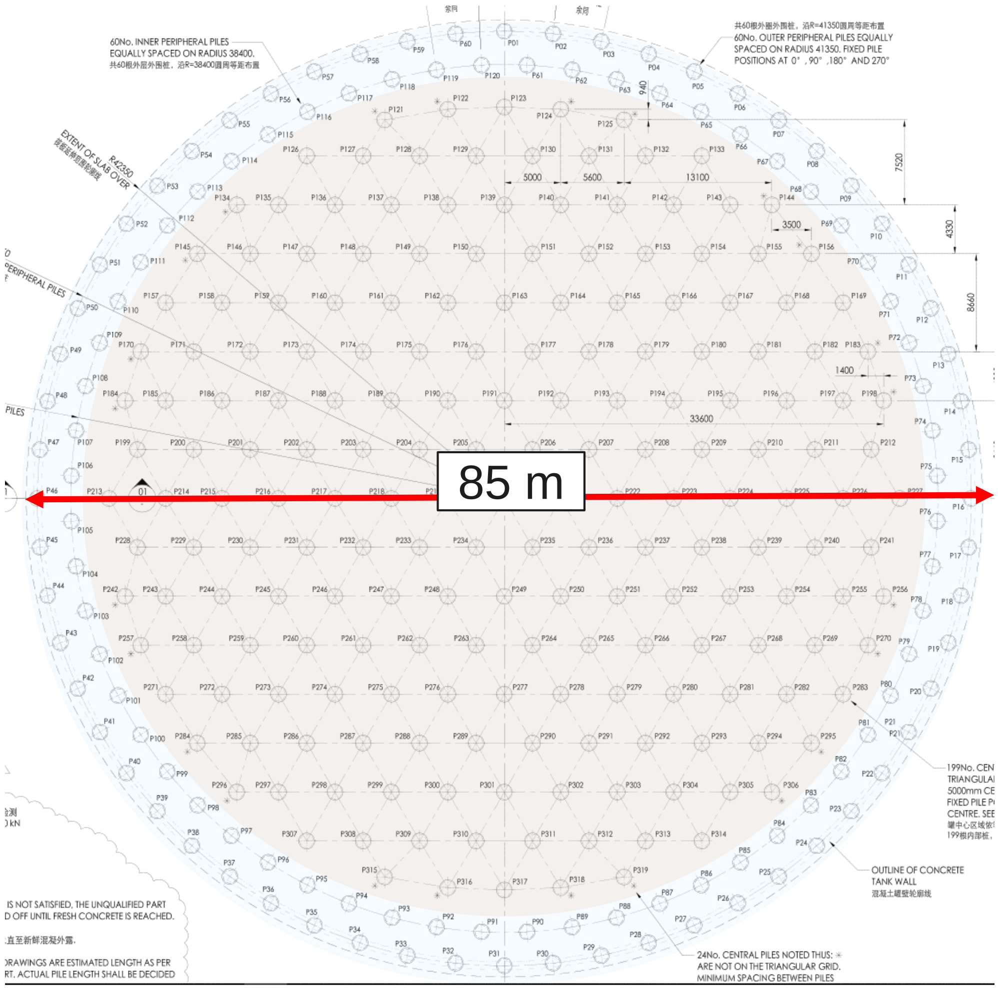
Typical tank layout

- Example of an LNG Tank in China
- 160 000 m^3 → D = ~85 m, H = ~50 m
- 319 bored concrete piles with diameter 1.4 m, L = 54 m
- 120 ring piles, 199 inner piles (triangular grid 5 m)





Pile layout



1 Tank Layout & Loads

Typical load cases

(Quasi-) Static

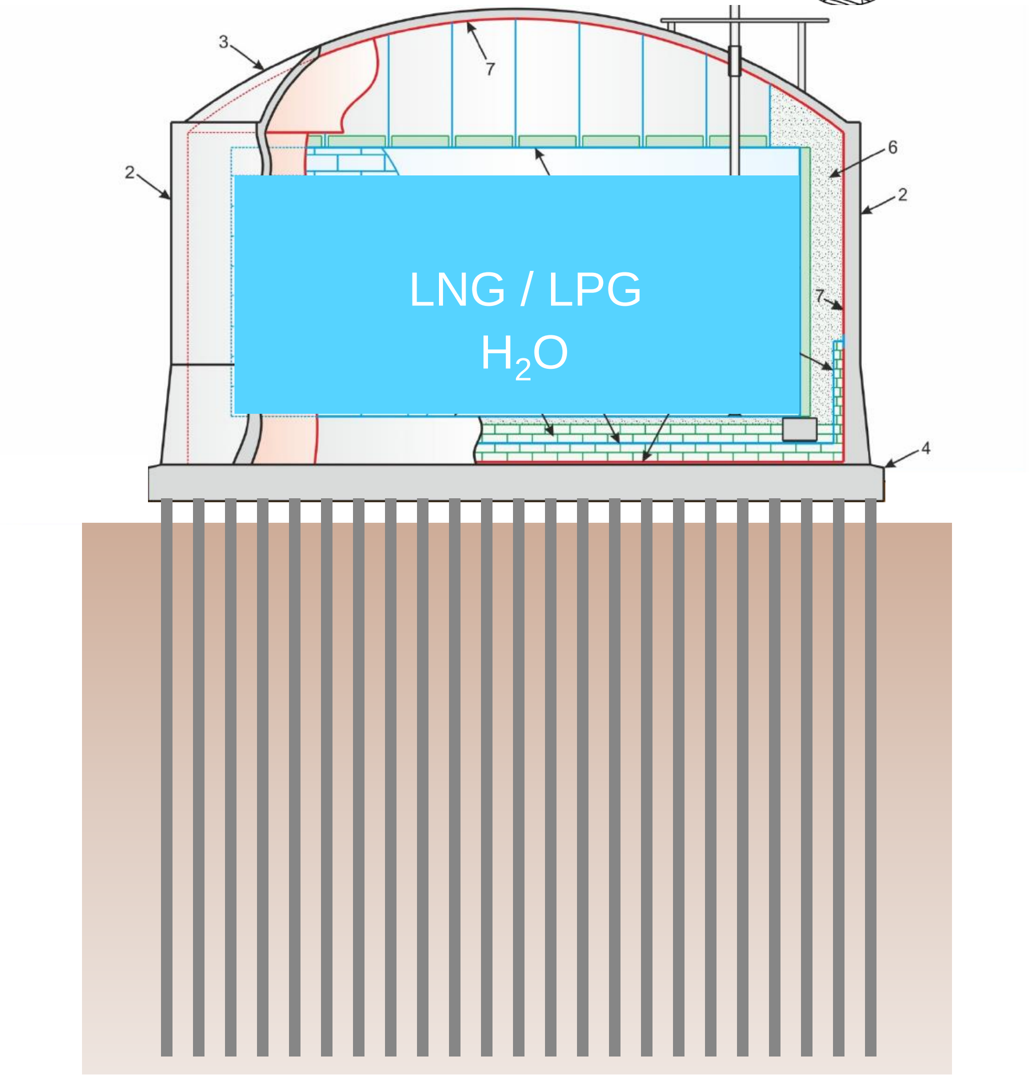
- Tank dead loads
- Hydro test ($\gamma_W = 10$ kN/m³)
- LNG-filling / operation ($\gamma_{LNG} \approx 4.5$ kN/m³)

Dynamic

- **Earthquakes (SSE & OBE)**
- Explosion

Others

- Leakage
- …



1 Tank Layout & Loads

Static load cases

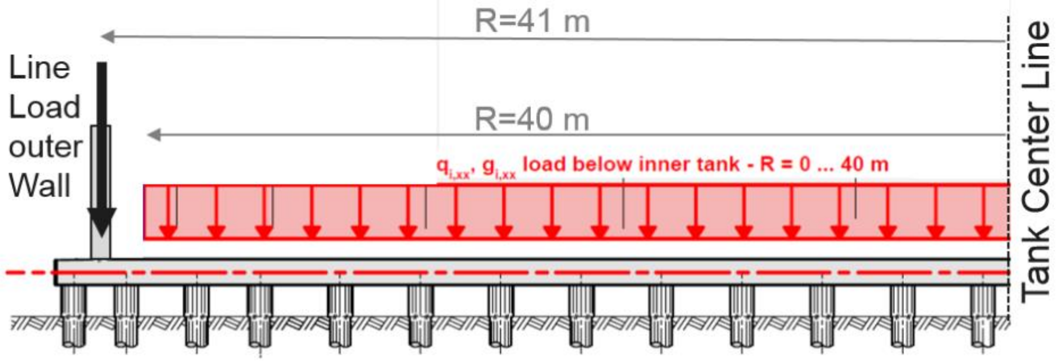
- Tank dead loads, Hydro test and LNG-filling
- Deformation requirements of the slab [ACI 376]
  - max. tilting 1/500 →16 cm (D=85 m)
  - max. settlement difference 1/300 (center vs. rim) →13 cm (D=85 m)
  - no limitation of the total settlements (but piping must be feasible)

Inside of LNG tank during hydro test

Testing LNG tank: https://www.youtube.com/watch?v=dk2bSqejg4Q

Typical loads 160 000 m³ LNG tank

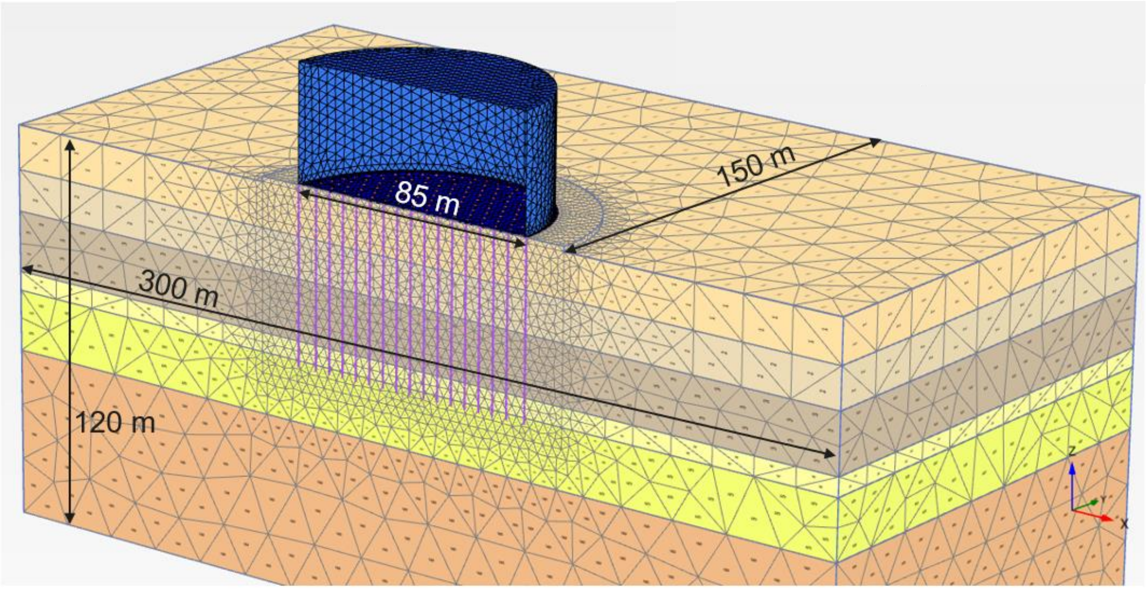
Load case	Line load below outer wall [kN/m]	Area load of concrete slab [kN/m²]	Area load of inner tank [kN/m²]	Total load [MN]
Dead load	1100	45	-	500
Hydro test			205	1500
Service			155	1300



1 Tank Layout & Loads

Static design

- Finite Element Model e.g. in PLAXIS 3D
  - static loading (Dead load, LNG filling, Hydro Test)
  - equivalent static earthquake loads
- Piles modeled as embedded beams
- Inner tank not modelled

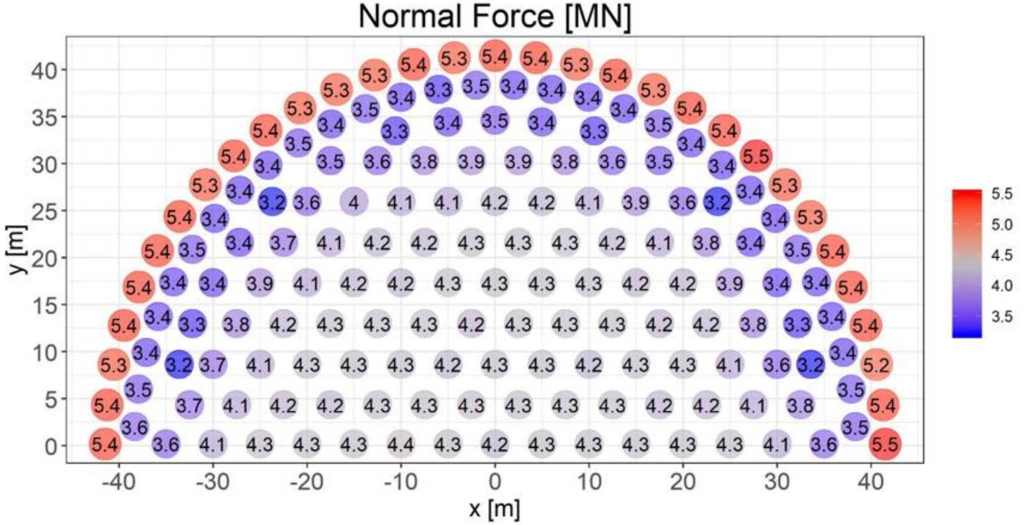


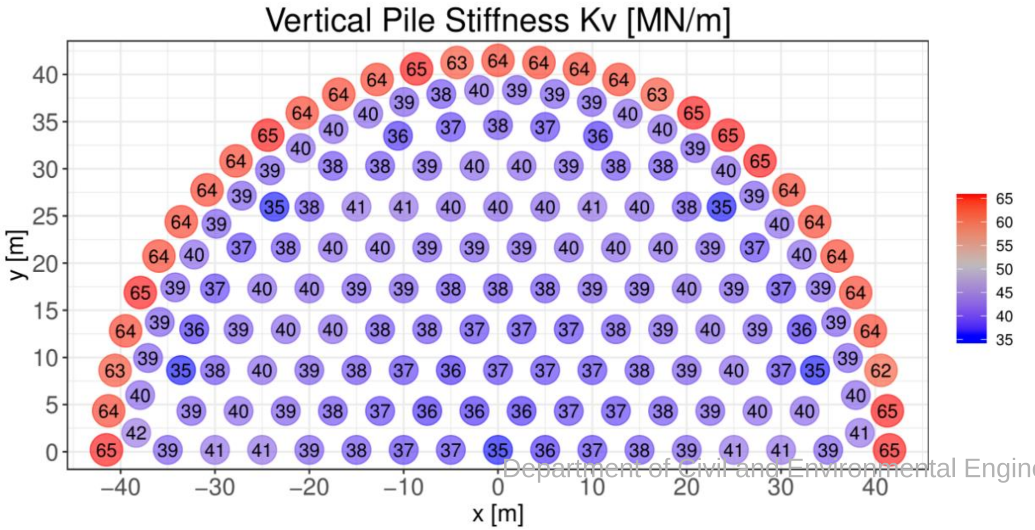
Soil Models: Mohr-Coulomb + HS

1 Tank Layout & Loads

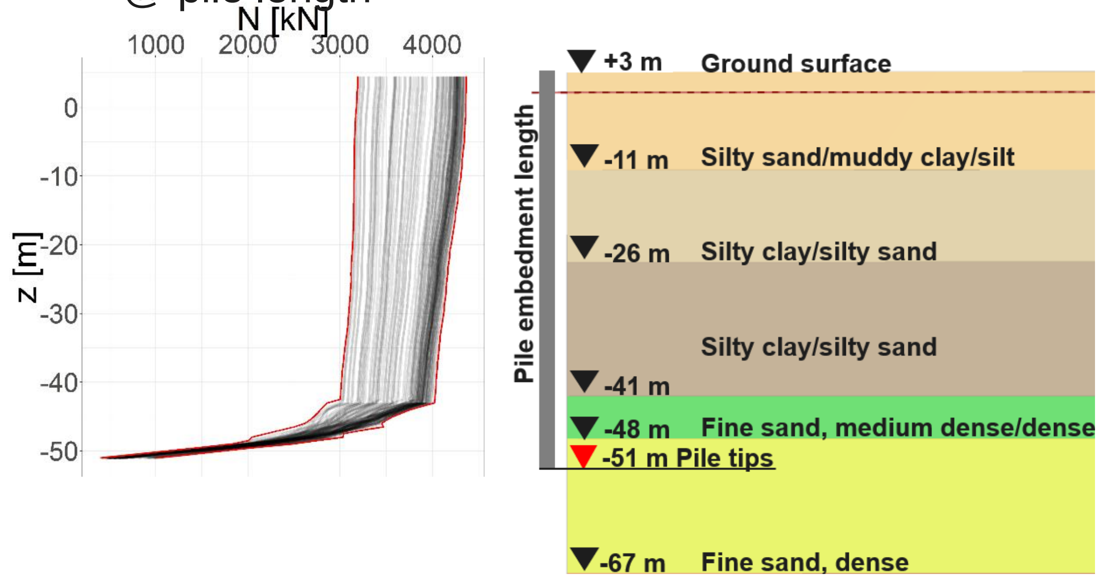
Pile forces due to STATIC loading

@ pile heads

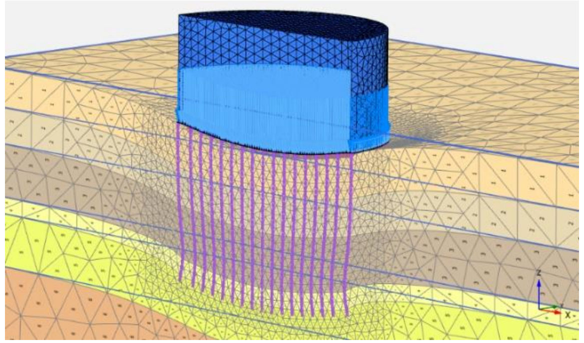




@ pile length



Displacement due to static loads

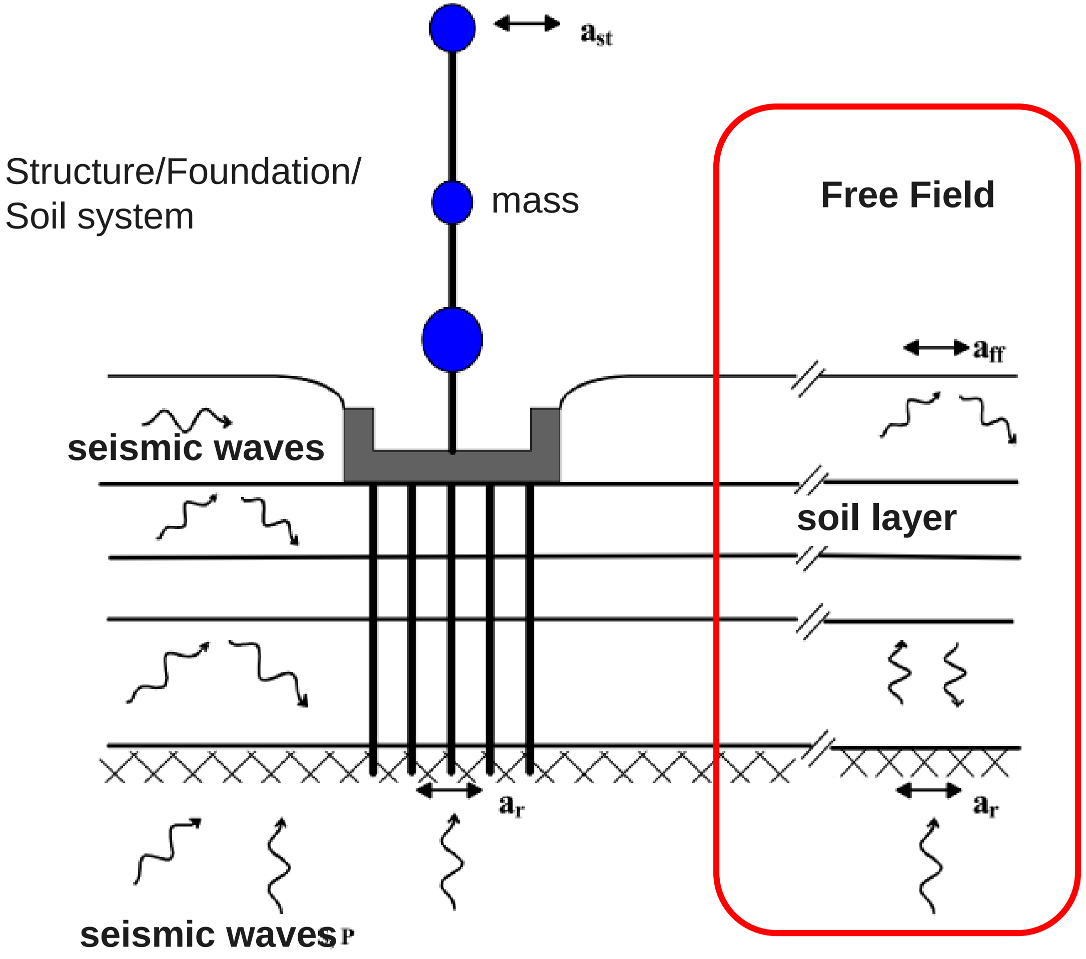


PART 2

Seismic Design Approaches

2 Seismic Design Approaches

Task definition



Far from the foundation: **free field**

- Geometry and characteristics of the soil and of the seismic source steer the free field response

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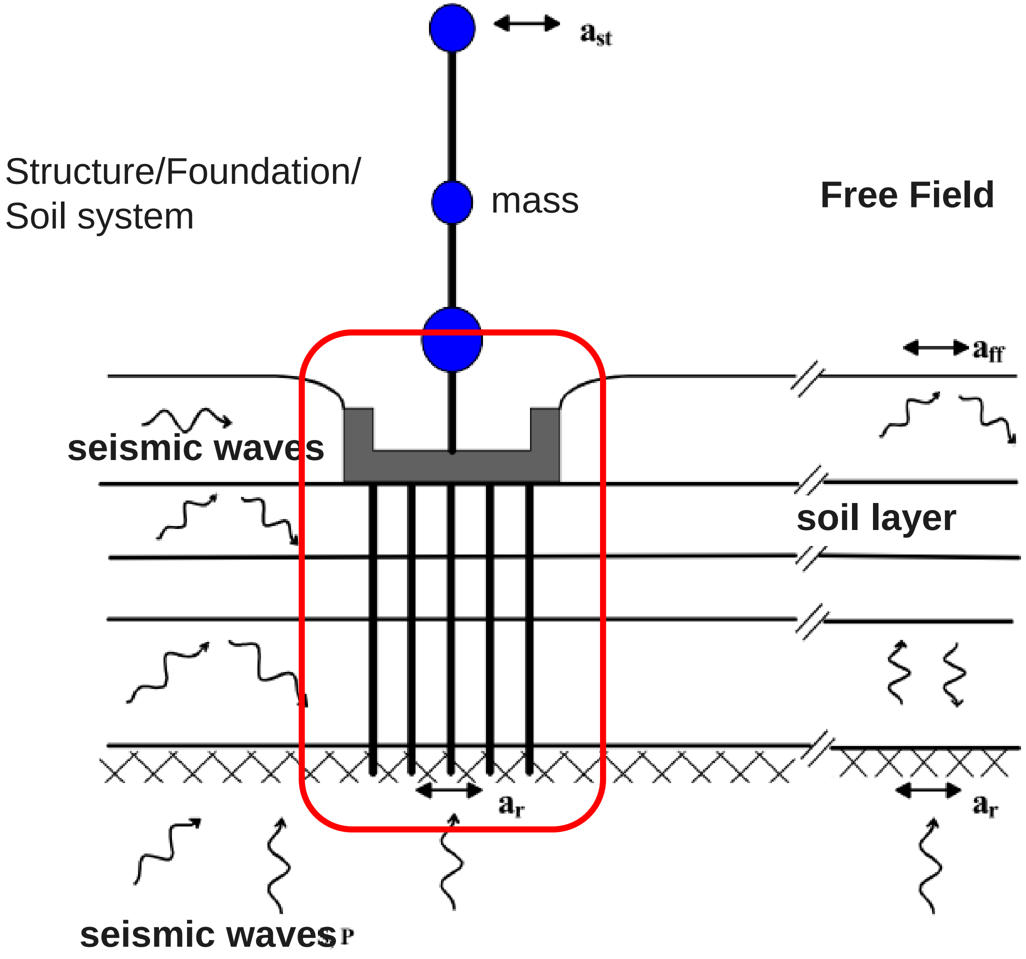
2 Seismic Design Approaches

Task definition



Far from the foundation: **free field**

- Geometry and characteristics of the soil and of the seismic source steer the free field response

Foundation movement

- ≠ free field movement
- Interacts with the surrounding soil

➔ **Kinematic interaction** depends on stiffness difference between soil and foundation

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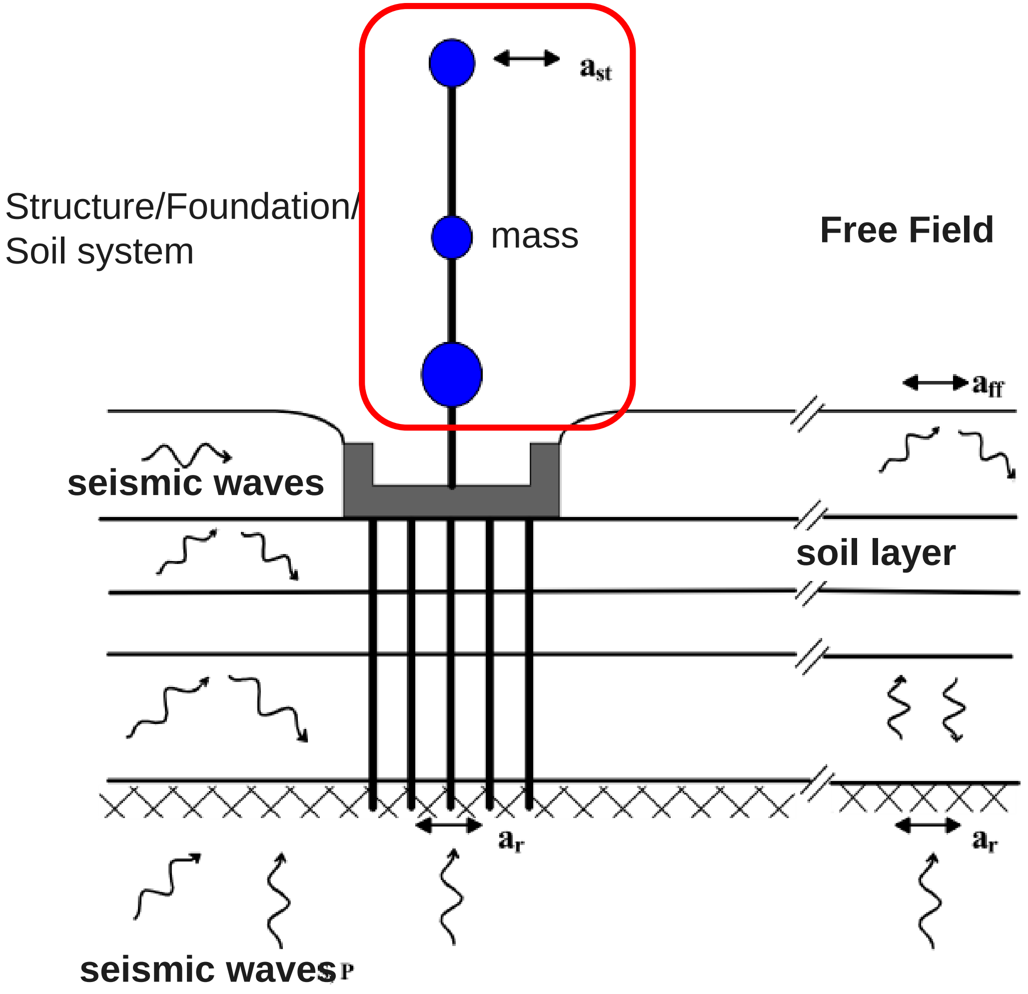
2 Seismic Design Approaches

Task definition



Far from the foundation: **free field**

- Geometry and characteristics of the soil and of the seismic source steer the free field response

Foundation movement

- ≠ free field movement
- Interacts with the surrounding soil

➔ **Kinematic interaction** depends on stiffness difference between soil and foundation

- Induces superstructure oscillations

➔ **Inertial interaction** depends on mass difference between soil and structure

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2 Seismic Design Approaches

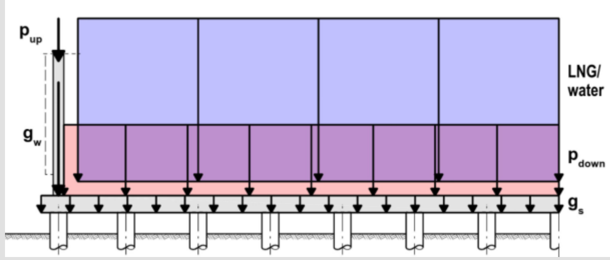
Static equivalent loads

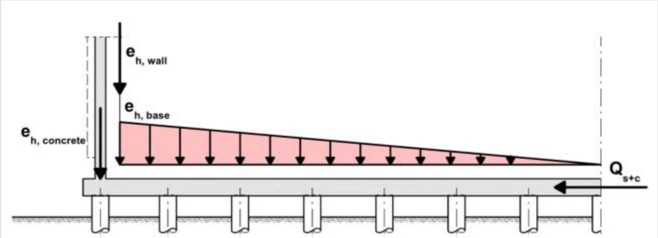
Simplified approach

Earthquake actions are replaced by static loads

Very fast and easy design

No economic design



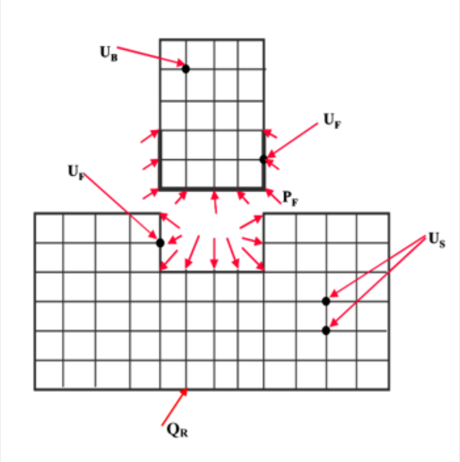


Substructure

Decoupled design of tank and foundation

Rigorous seismic design of the pile group

Foundation impedance matrix can be gained



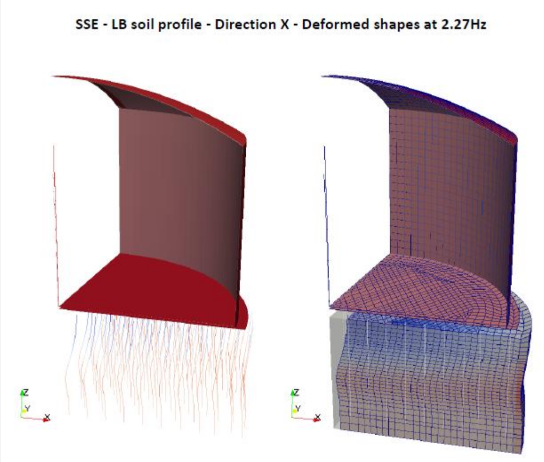
Full Frequency Coupling

Tank, foundation and soil are treated in one model

Tank and Piles modeled in FEM, Soil in BEM

Rigorous seismic design

Time consuming but precise



PART 3

Static Equivalent Loads

3 Static Equivalent Loads

Seismic loads are transferred to static loads

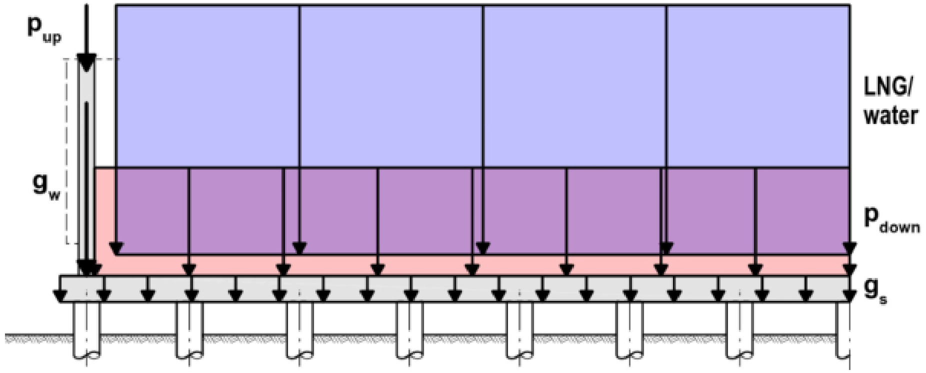
- Strongly simplified approach
- Equivalent loads are considered in the static design model (e.g. Plaxis 3D)
- Applicable in good soil conditions & if the earthquake demand is rather small
- Benefits: fast & cheap & accepted
- Downsides: no economic design, no foundation impedance matrix, no soil damping, ...

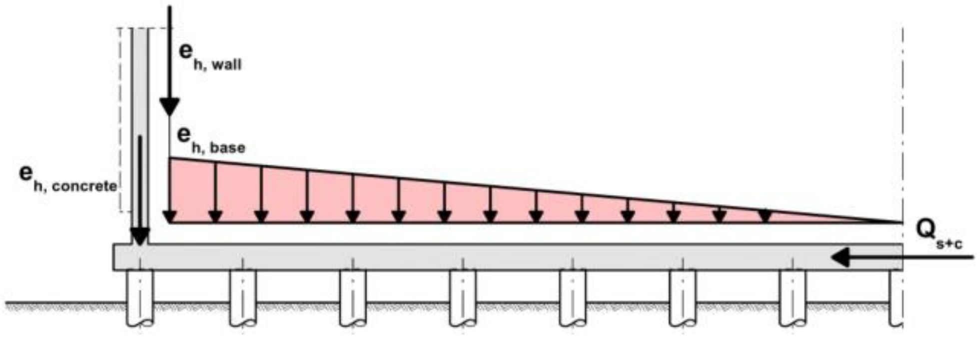
- Impulsive mass acc. to EN 1998-4 § A.2.1.2
- Convective mass (sloshing) acc. to EN 1998-4 § A.2.1.3

$$m_i = m\,2\gamma \sum_{n=0}^{\infty} \frac{I_1(\nu_n/\gamma)}{\nu_n^3\, I_1'(\nu_n/\gamma)}$$

$$m_{cn} = m \frac{2\tanh(\lambda_n \gamma)}{\gamma \lambda_n (\lambda_n^2 - 1)}$$

Base shear & overturning moment





3 Static Equivalent Loads

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Superposition of internal forces

“Static” and “dynamic” internal forces are combined for the final pile design

- Combination of dynamic earthquake demands acc. to EC 8
- Combination of static loads due to LNG filling and earthquake loads

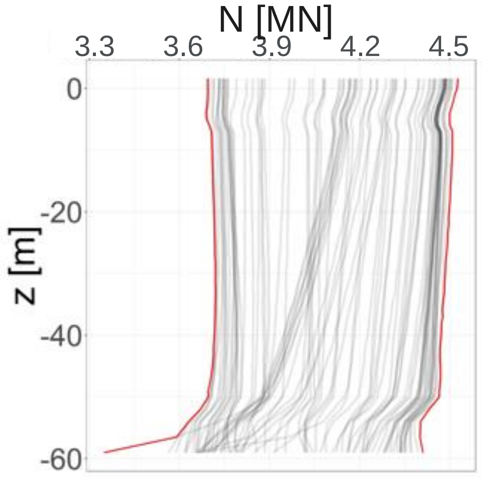
Dynamic combination rule acc. to EC 8

a) $E_{\mathrm{Ed}x}$ "+" 0,30 $E_{\mathrm{Ed}y}$ "+" 0,30 $E_{\mathrm{Ed}z}$

b) 0,30 $E_{\mathrm{Ed}x}$ "+" $E_{\mathrm{Ed}y}$ "+" 0,30 $E_{\mathrm{Ed}z}$

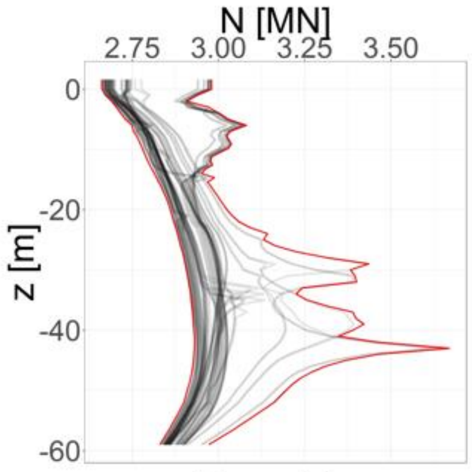
c) 0,30 $E_{\mathrm{Ed}x}$ "+" 0,30 $E_{\mathrm{Ed}y}$ "+" $E_{\mathrm{Ed}z}$

(In China: 100 % + 40 % + 40 %)



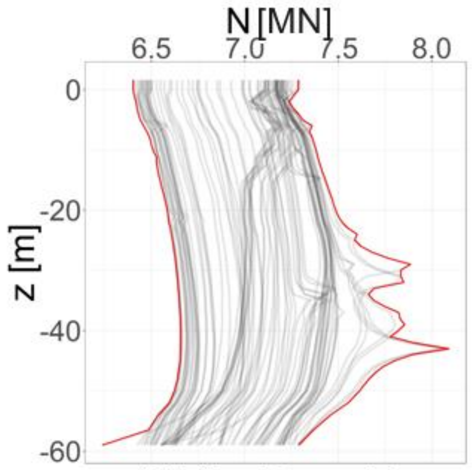
“Static”

“+”



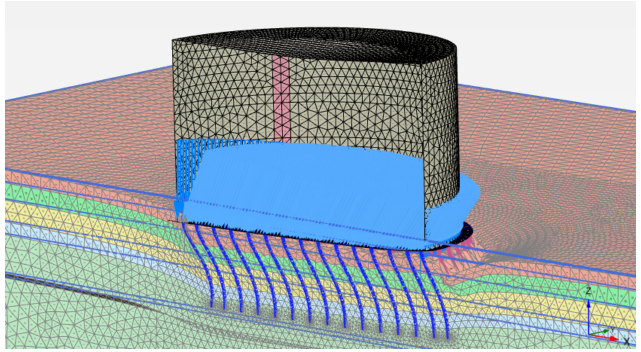
“Dynamic”

=



“Static + Dynamic”

Loaded pile foundation



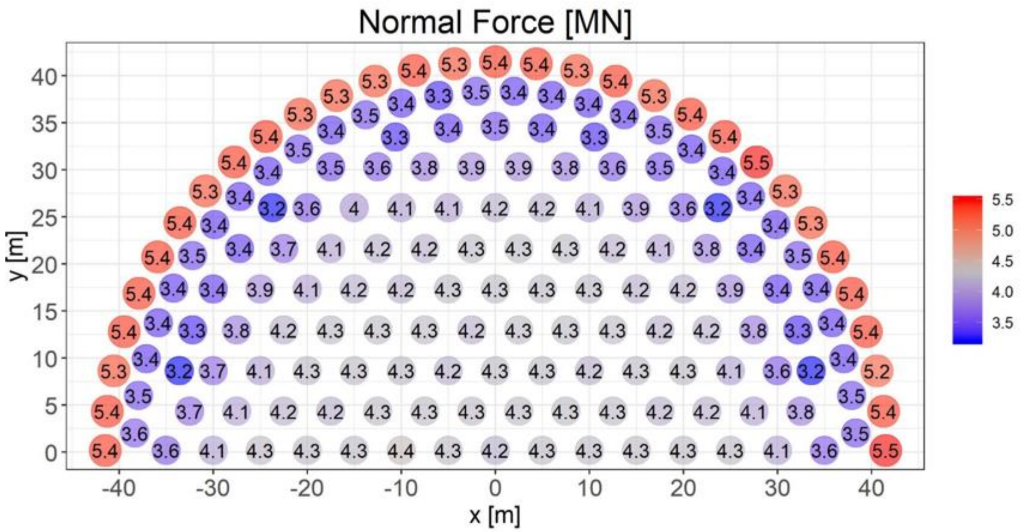
3 Static Equivalent Loads

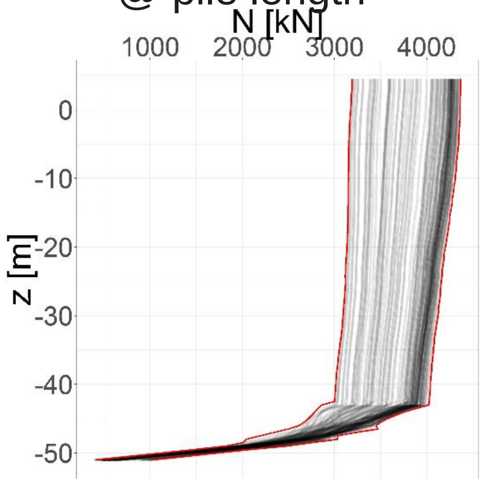
Pile forces of a 160 000 m³ tank

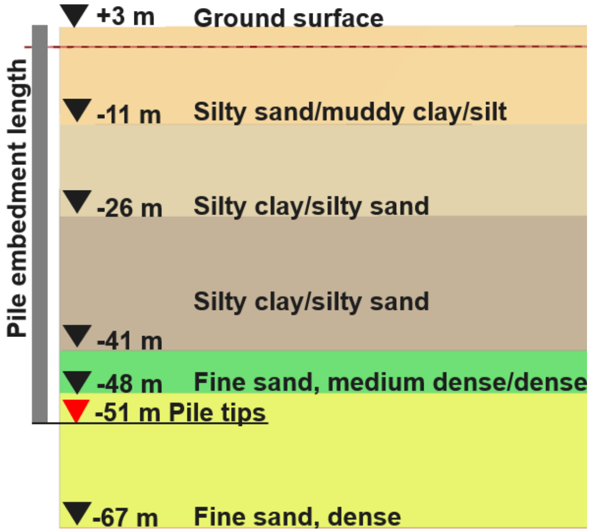
@ pile heads

@ pile length

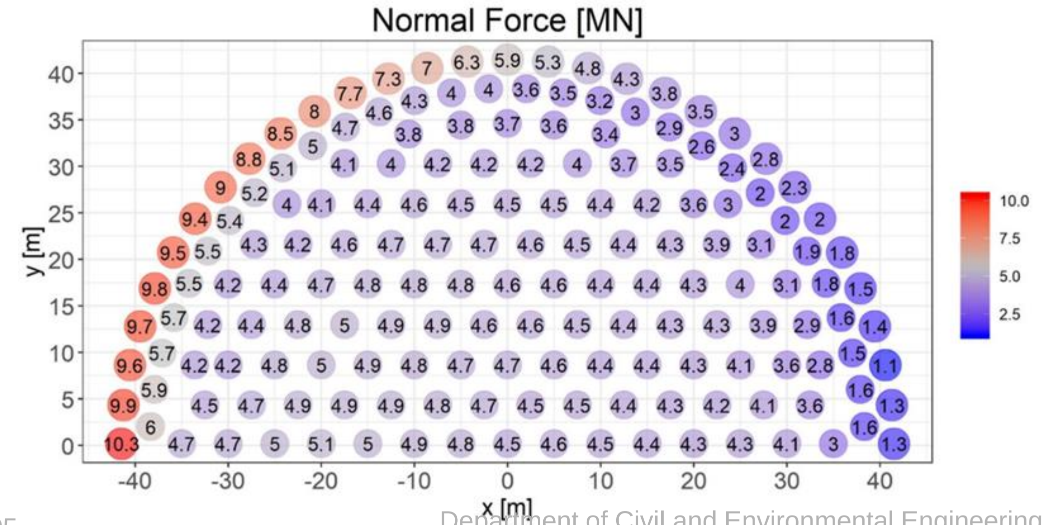
Pure static loads

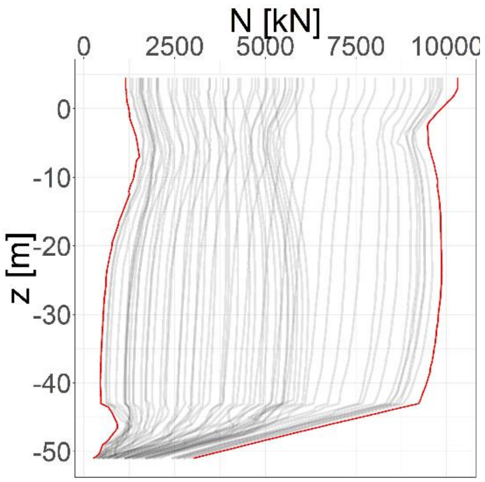


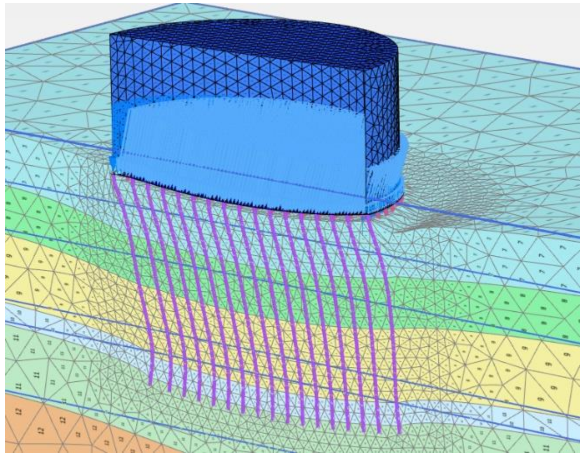




Static + equivalent „dynamic“ loads







Displacement: combined loading

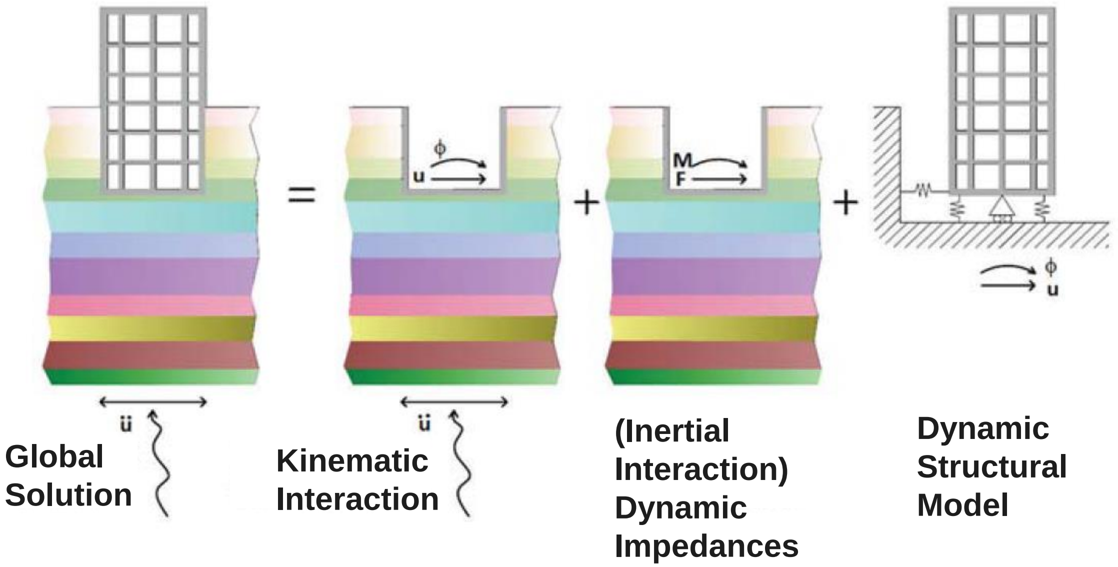
PART 4

Substructure Approach

4 Substructure Approach

General approach

- Superposition principle: decouples two substructures:
  - soil and foundation
  - tank
- Equilibrium equations of each subsystem
- Compatibility conditions at the interface: continuity of displacements and stresses
- Tank is modeled with the FEM method
- Soil and foundation replaced by a frequency dependent **impedance matrix**
- Internal forces along the piles need to be calculated separately



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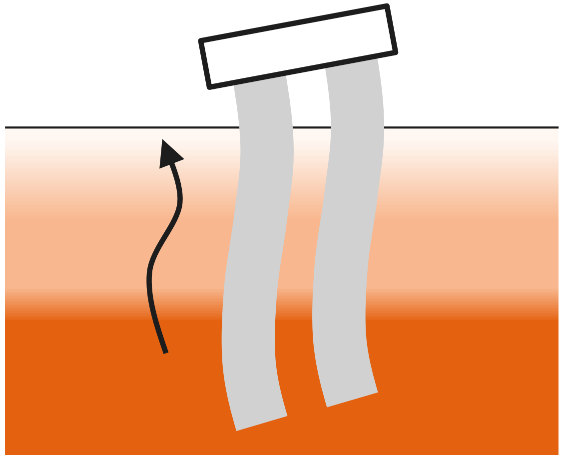
4 Substructure Approach

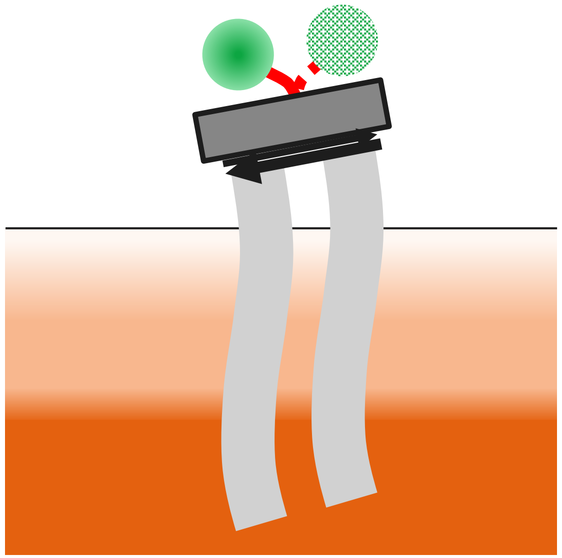
Pile internal forces

Two-fold seismic impact on the piles

1. Kinematic interaction due to **wave passage**



2. Pile head forces due to **inertial action** on superstructure



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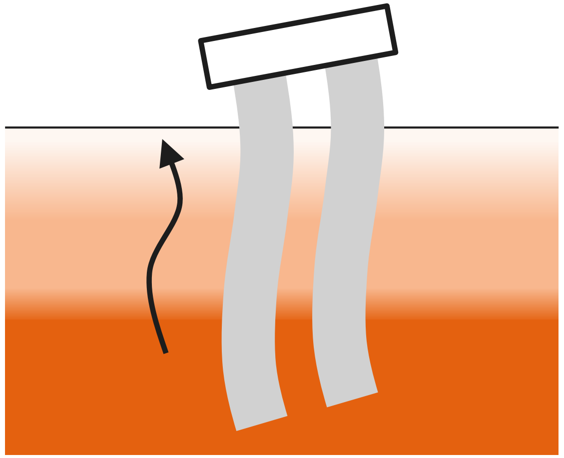
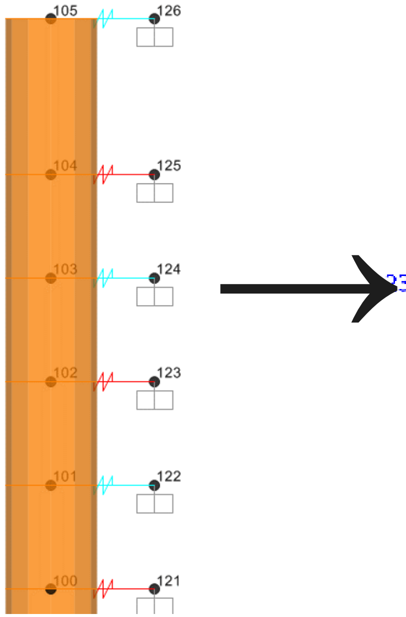
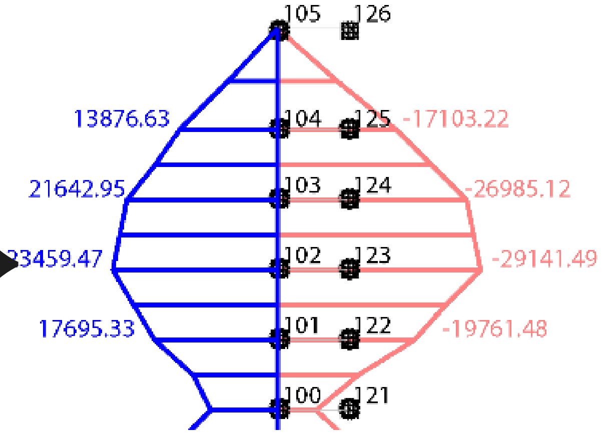


- Solution procedure: Pile on dynamic Winkler foundation
- Enforced motion





Bending Moments
[Nm]

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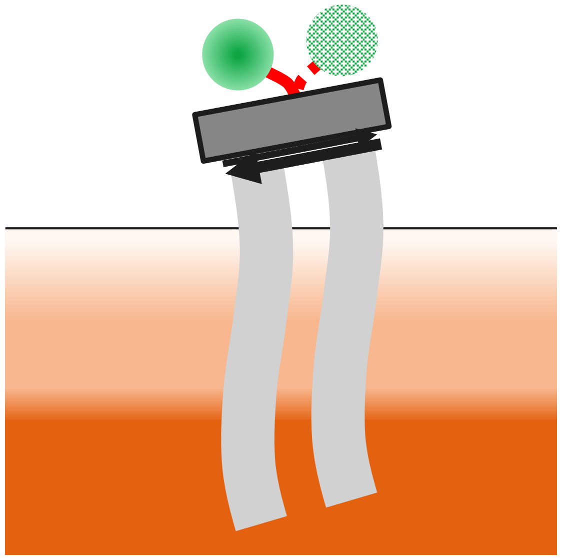

Solution procedure: Dynamic pile impedance method after Kaynia and Kausel

$$\begin{bmatrix} K_{TT} & K_{TB} \\ K_{BT} & K_{BB} + K_P \end{bmatrix} \cdot \begin{bmatrix} u_T \\ u_H \end{bmatrix} = \begin{bmatrix} P_T \\ P_B \end{bmatrix} + \begin{bmatrix} 0 \\ K_P \, u_0 \end{bmatrix}$$

Index T: Dofs at tank superstructure

Index B: Dofs at pile heads

$K_{ij} = K_{ij}(\Omega)$: Complex valued dynamic stiffness ($K = k + i\Omega c - m\Omega^2$)

P_i: external forces on tank (if any)

K_P: Pile head stiffness matrix

u_0: Free field motion

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4 Substructure Approach

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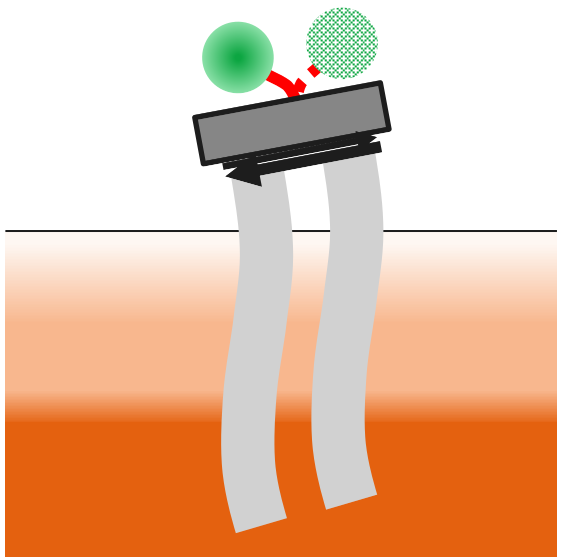
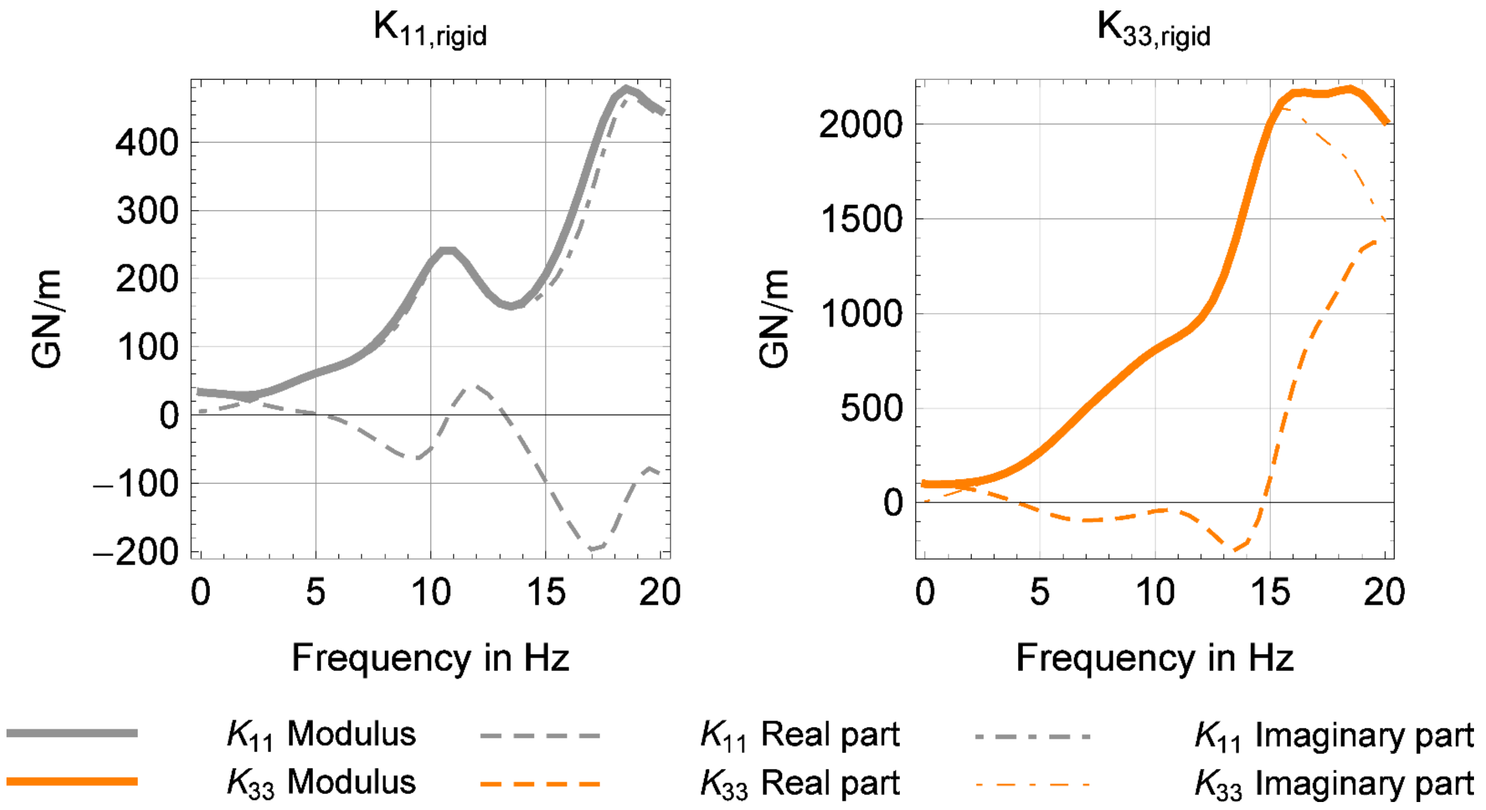


Dynamic Pile Group Stiffness



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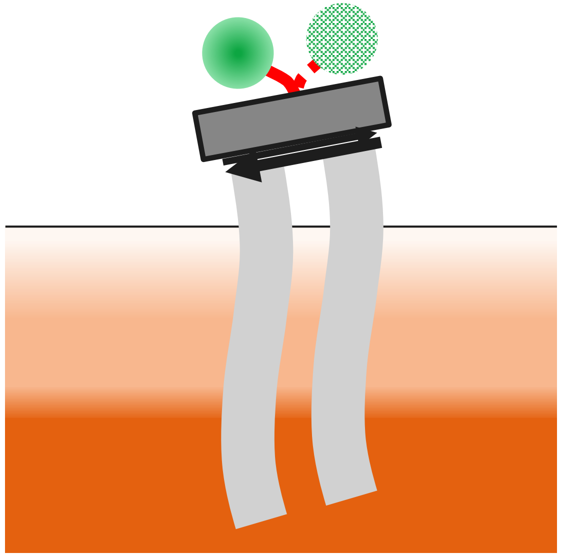
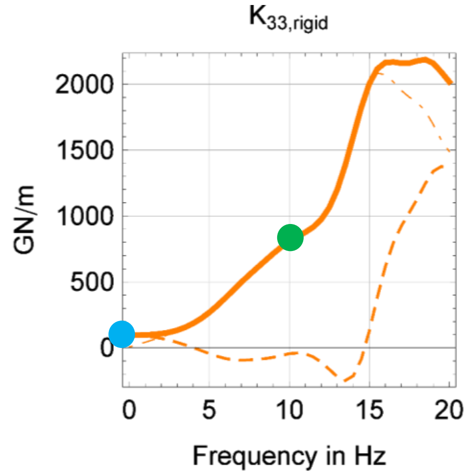
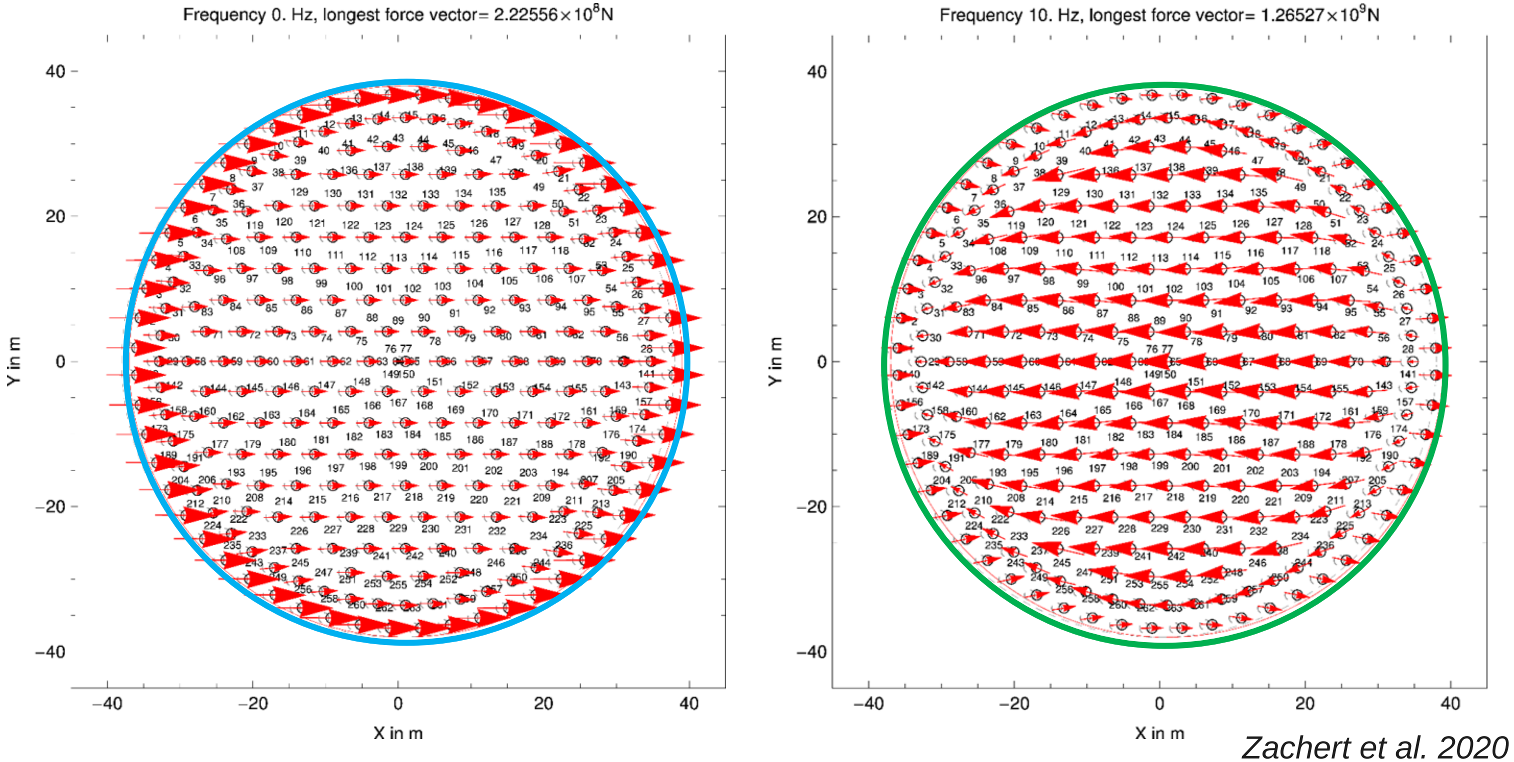


Pile head forces due to unit horizontal pile cap motion



f=0 Hz

f=10 Hz



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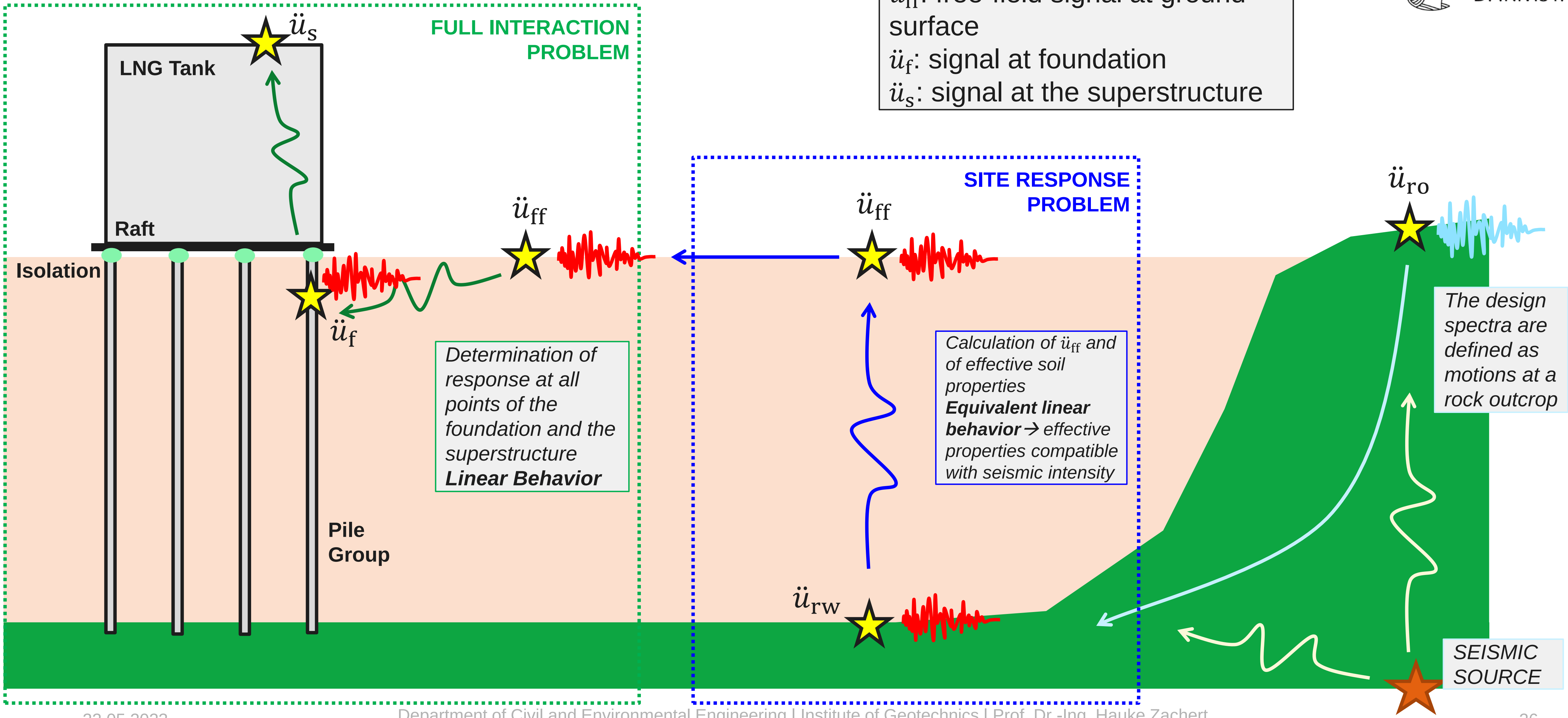
PART 5

Full Frequency Coupling Approach

5 Full Frequency Coupling

Schematic idealization

$\ddot{u}_{ro}$: signal at the rock outcrop
$\ddot{u}_{rw}$: signal at the substratum
$\ddot{u}_{ff}$: free-field signal at ground surface
$\ddot{u}_{f}$: signal at foundation
$\ddot{u}_{s}$: signal at the superstructure



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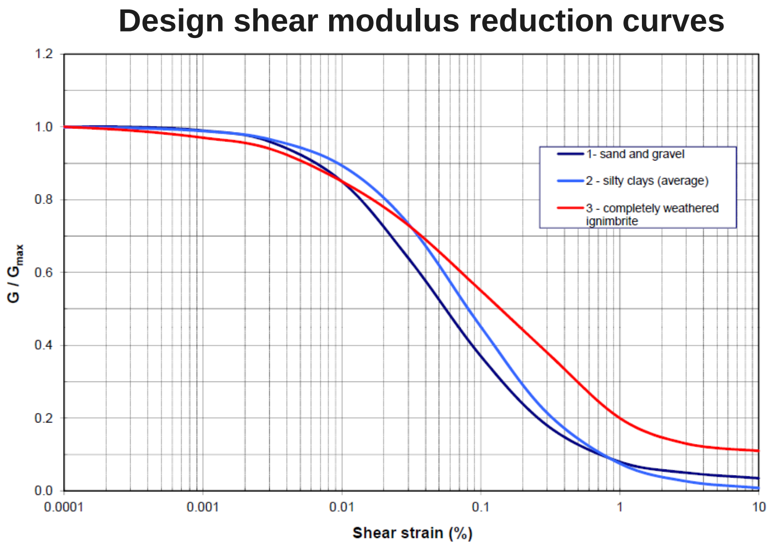
5 Full Frequency Coupling

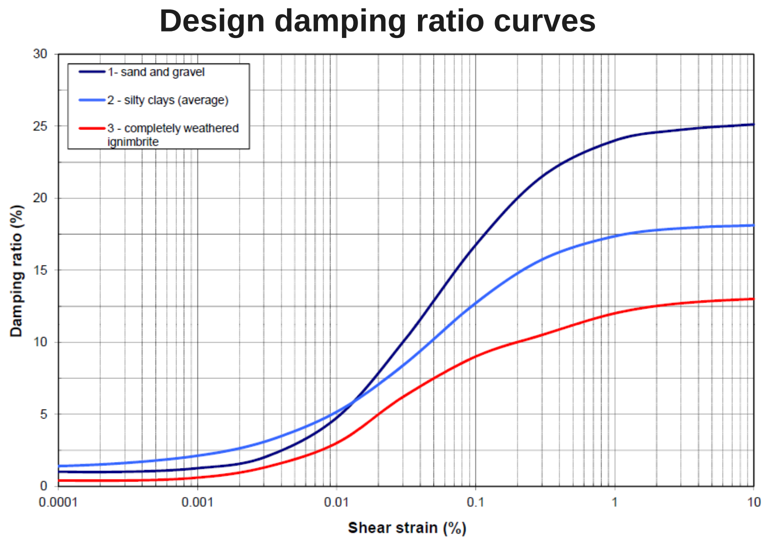
1D Site response analyses

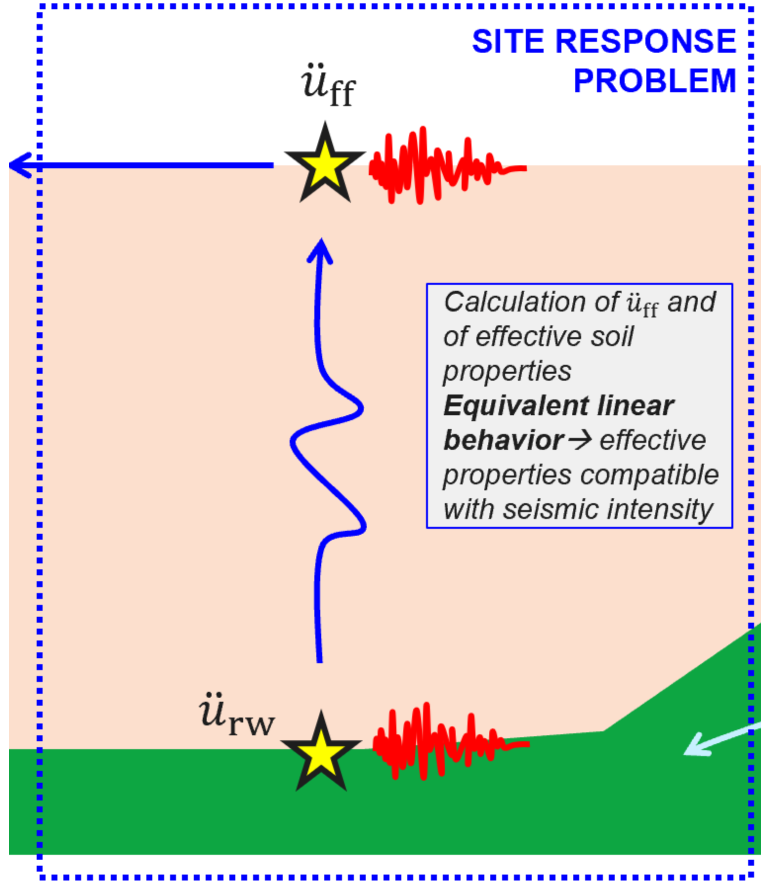
Solved with e.g. SHAKE91 / DEFI_SOL_EQUI / EERA

Provides:

- effective soil properties compatible with the levels of shear distortions
- motions $\ddot{u}_{ff}$ at the ground surface (free-field motions)







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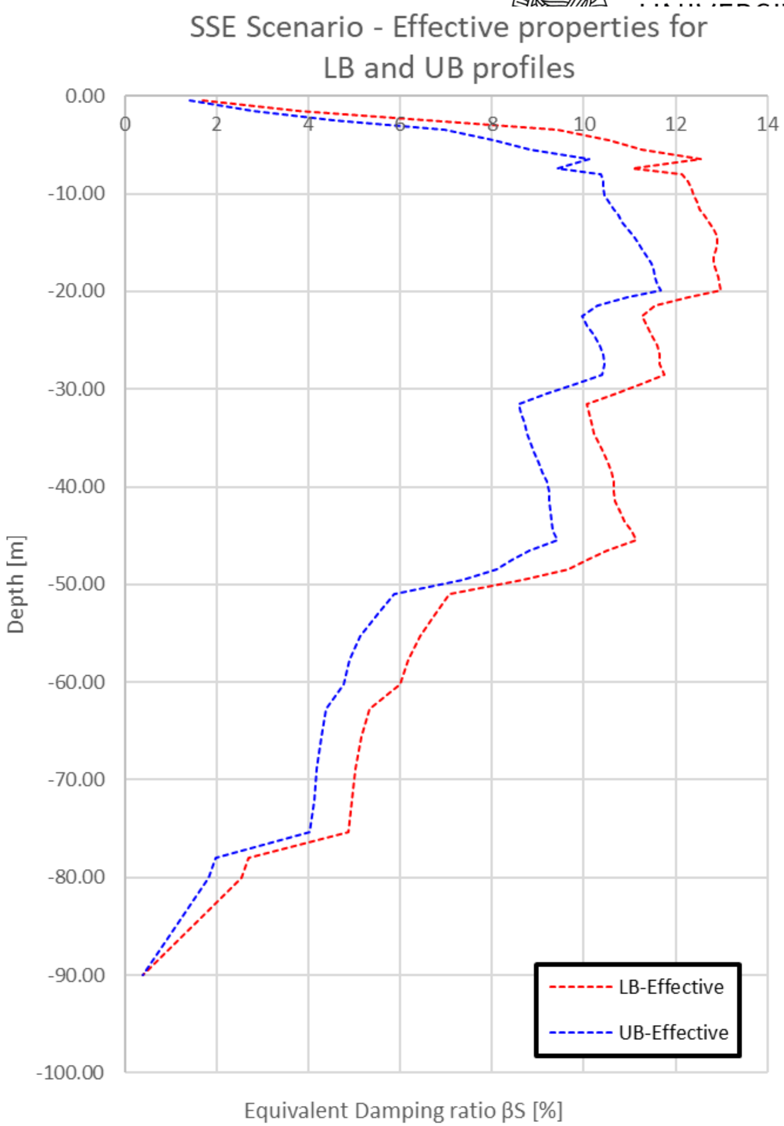
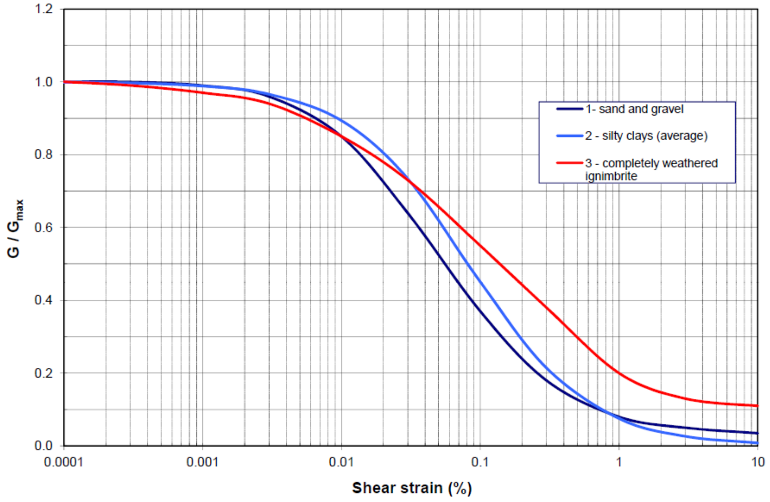
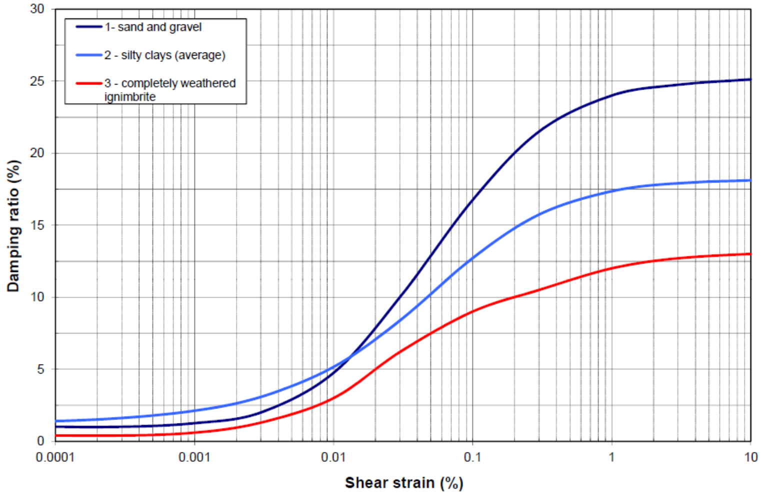


Design shear modulus reduction curves

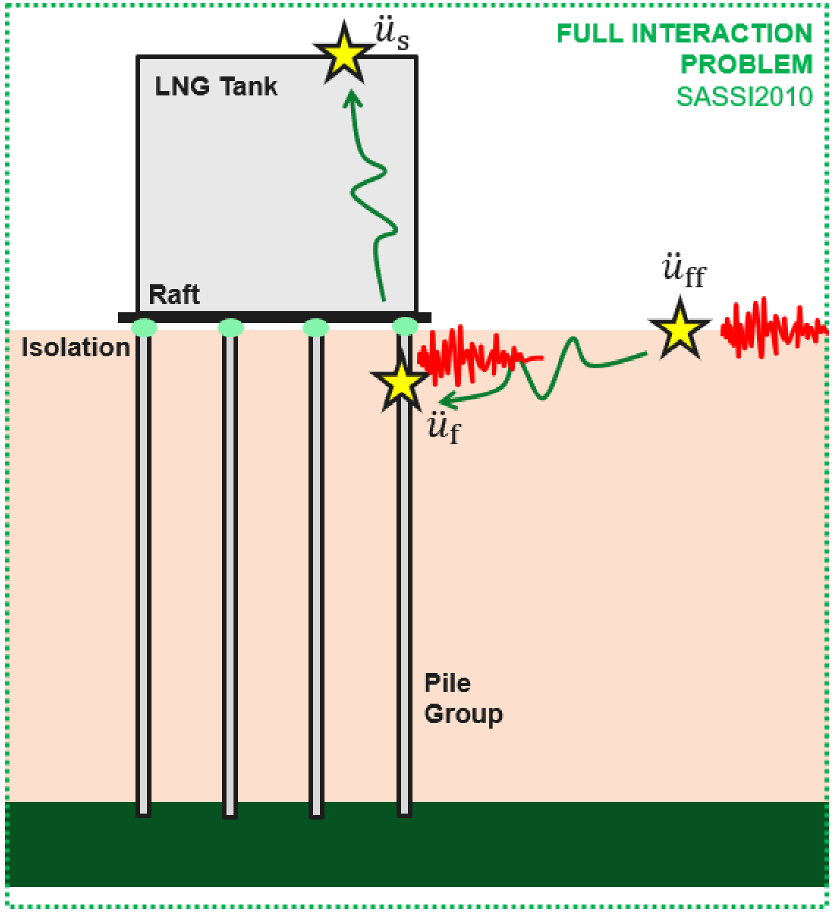


Design damping ratio curves



5 Full Frequency Coupling

Full interaction problem



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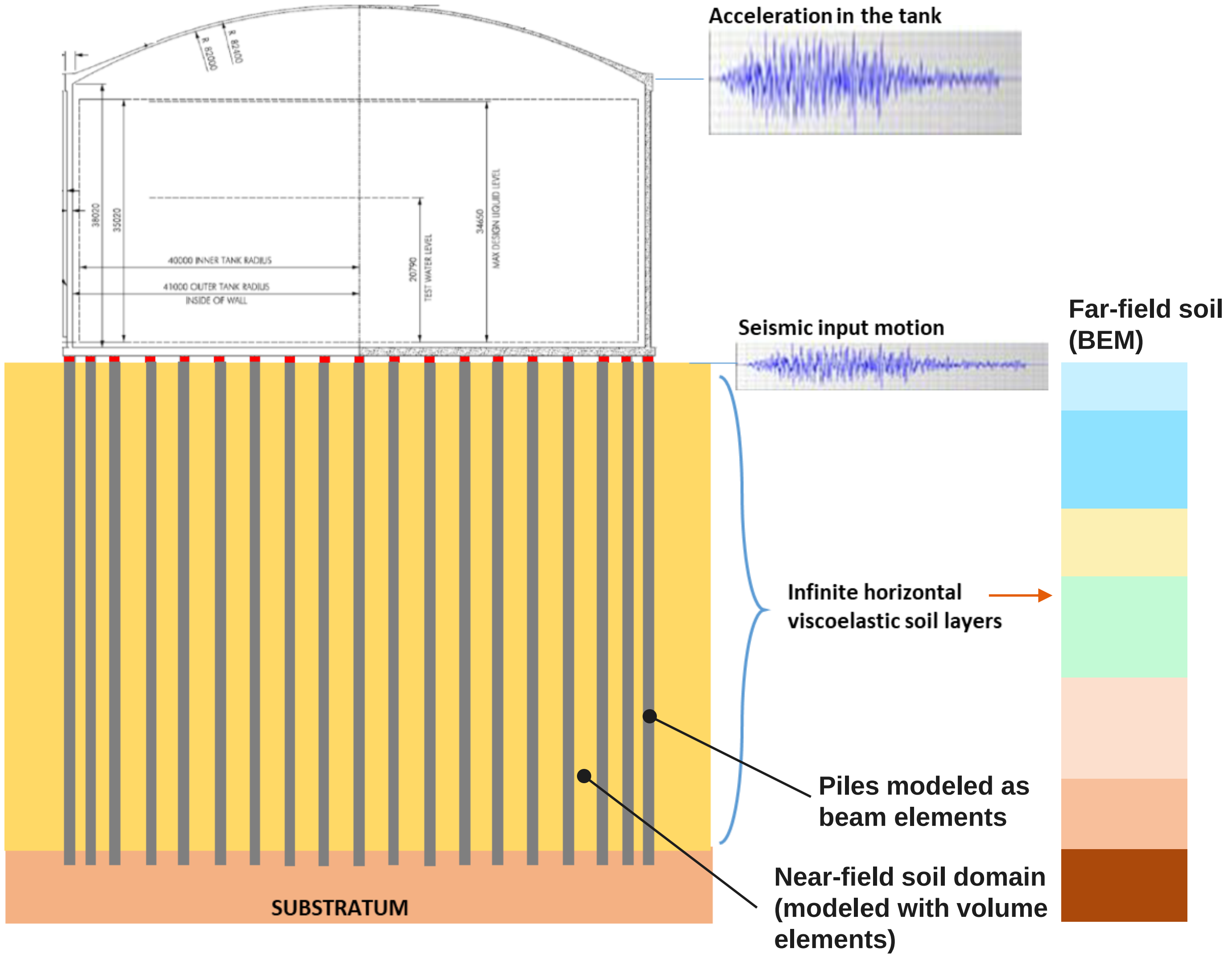
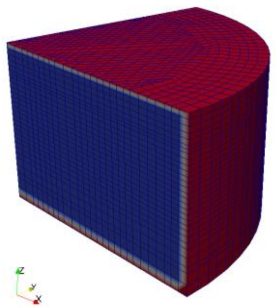
Performed in SASSI

- Soil-foundation-tank system in a unique model
- Tank and foundation are modeled with the FEM method
- Soil is modeled via boundary element (BEM) formulation (Thin Layer Method = TLM)
- Resolution in the frequency domain: **frequency-dependent impedance matrix**
- **Seismic forces** at the foundation (along the piles) are obtained directly from the analyses and account for both **inertial and kinematic effects**
- **Combination** with static design required

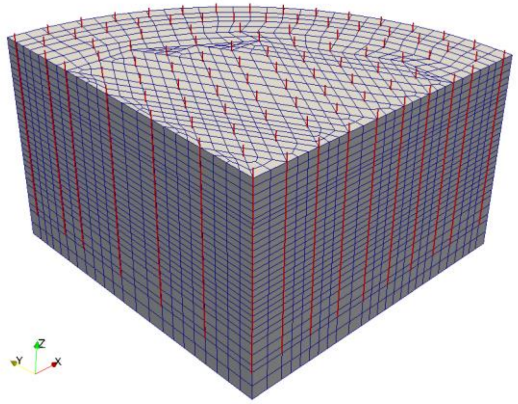
5 Full Frequency Coupling

Full interaction problem

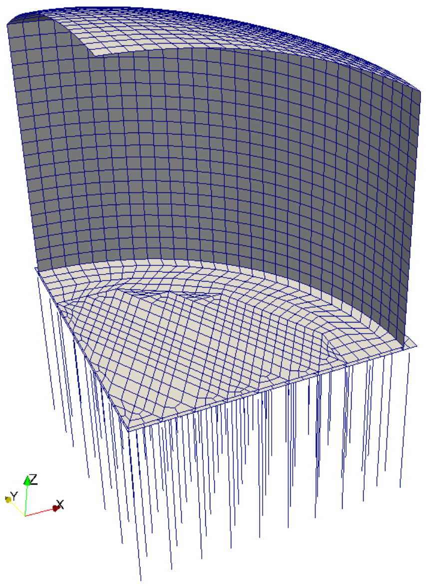




FEM-BEM coupling



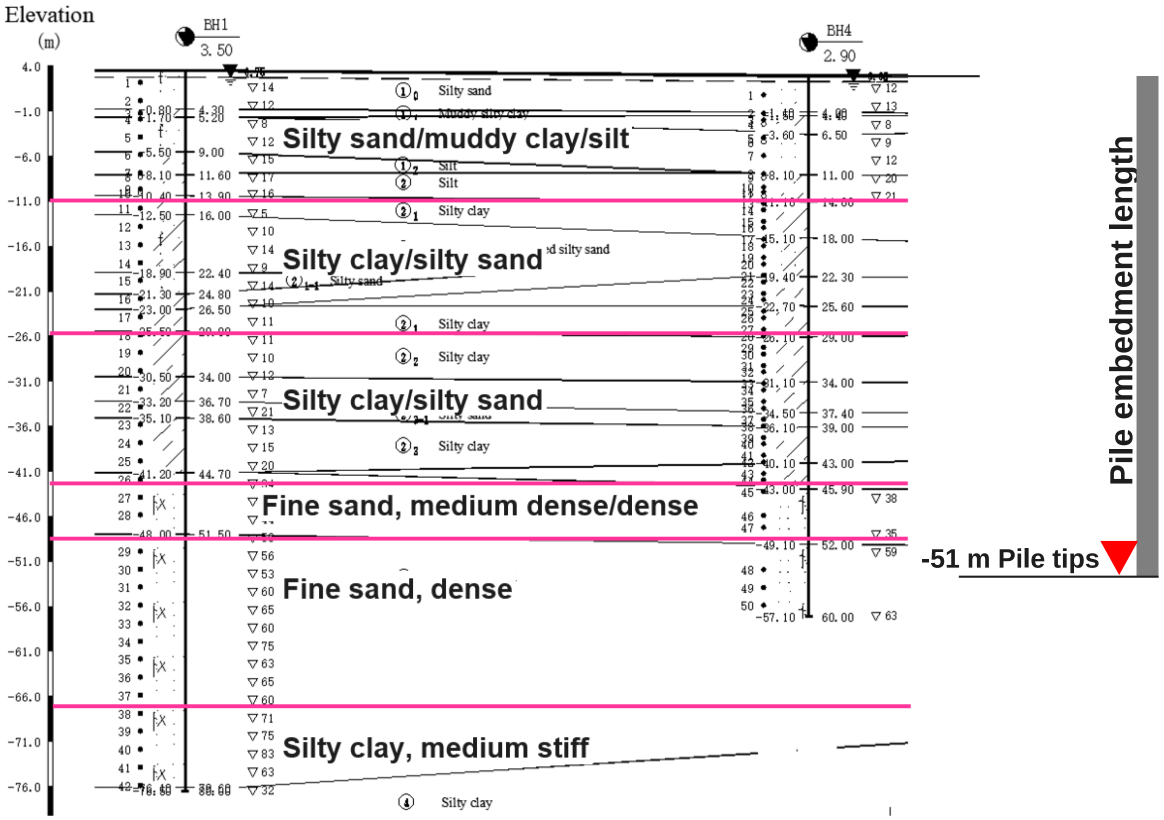
Foundation near-field soil model and piled foundation



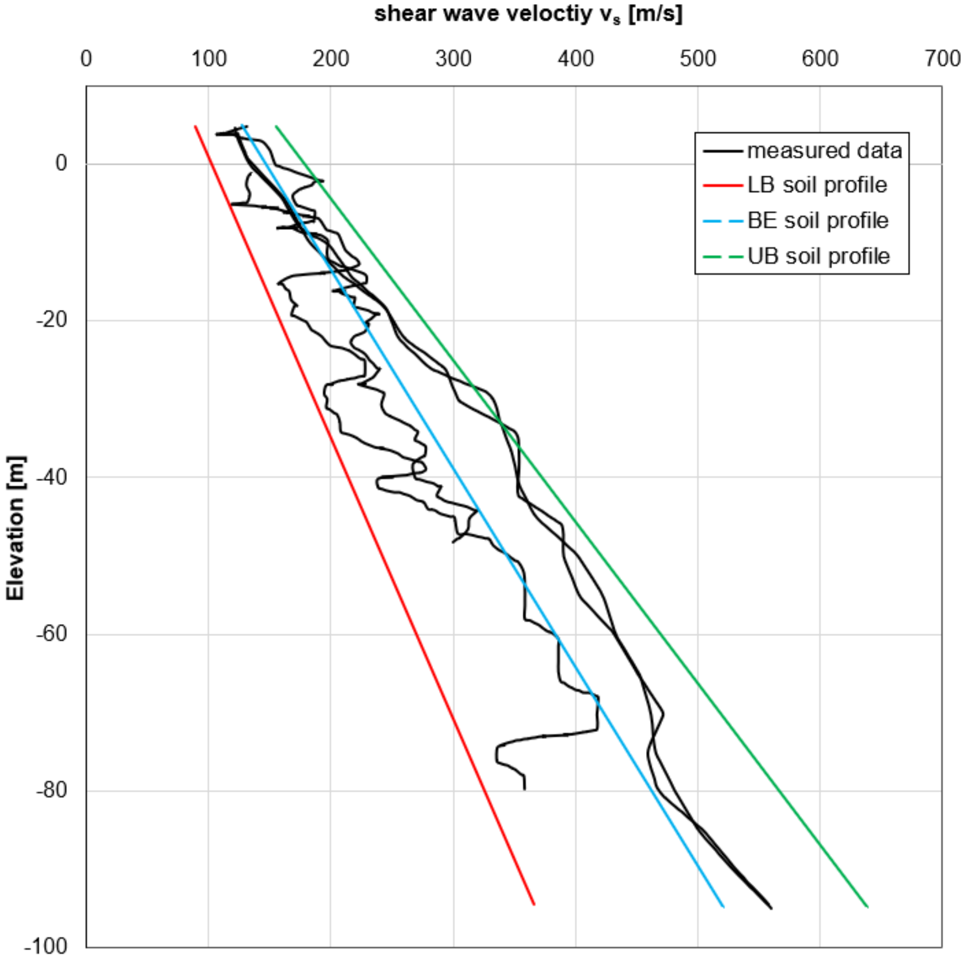
Concrete slab and outer tank model

Project example 1: 160 000 m³ LNG-tank

Geotechnical cross section



Shear wave velocity profiles

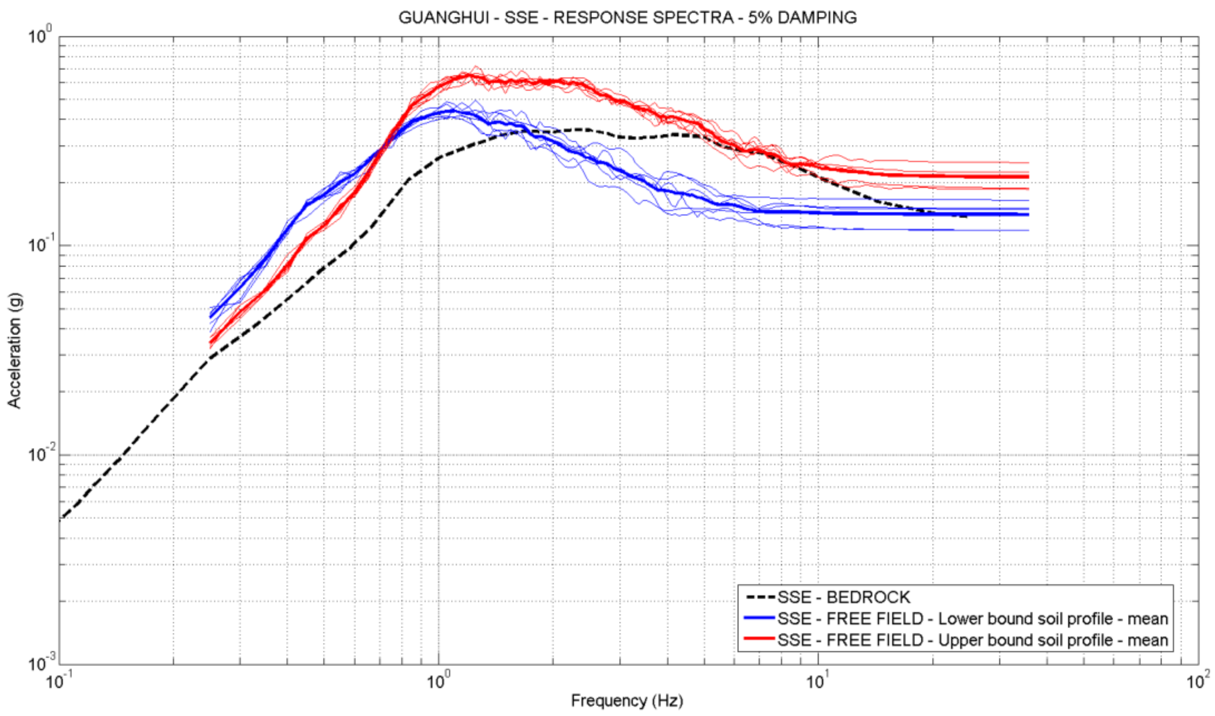


5 Full Frequency Coupling

Project example 1: 160 000 m³ LNG-tank

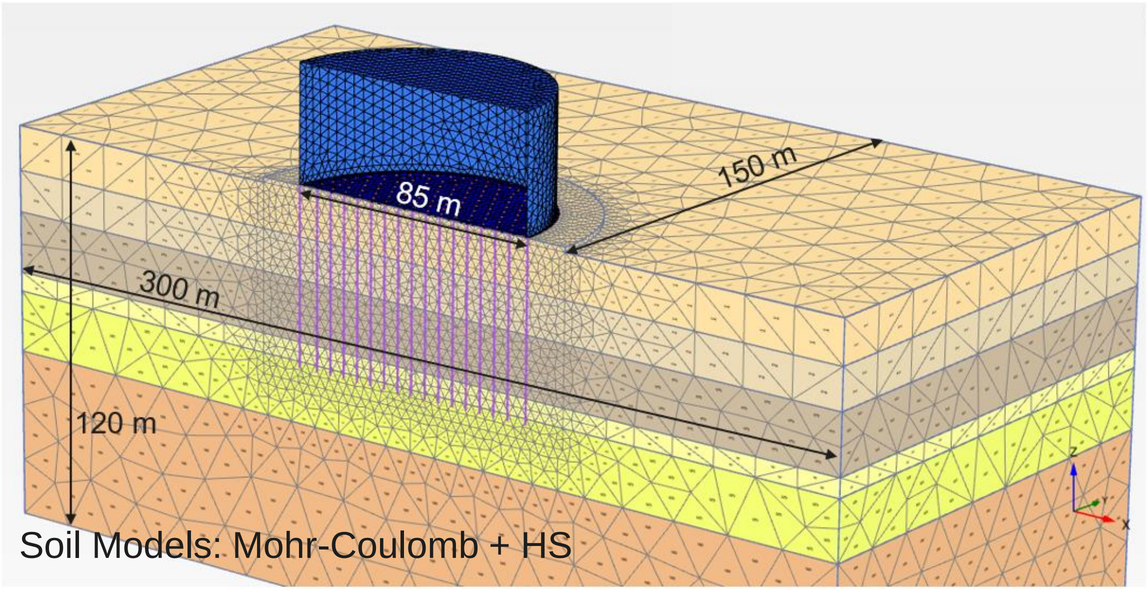
Seismic Demand: Design Spectra

- PGA_{OBE} = 0.12g (OBE = 475 years return period)
- PGA_{SSE} = 0.22g (SSE = 4975 years return period)



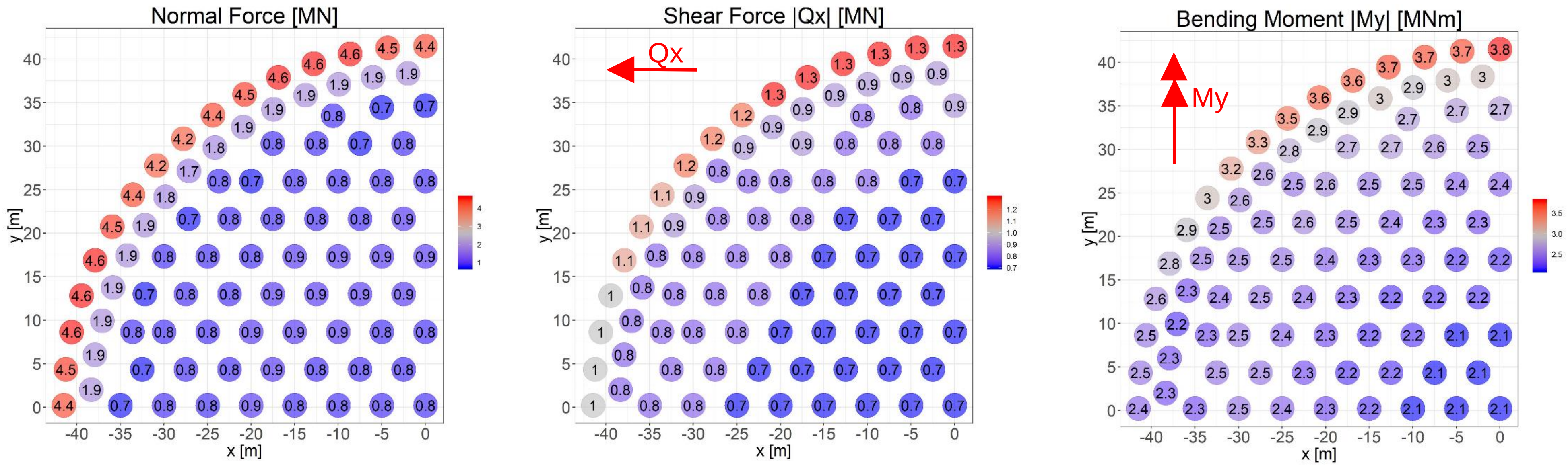
FEM in PLAXIS 3D

- Applied for
  - **Static loading** (Dead Load, LNG filling, Hydro Test)
  - Simplified SSI (Static Equivalent Loads)
- Inner tank not modelled

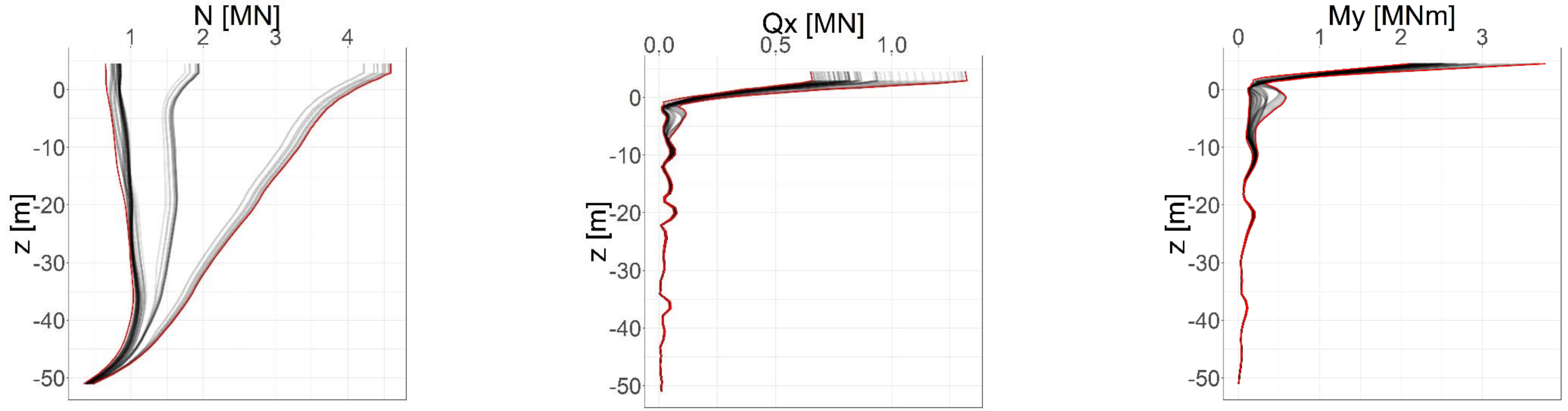


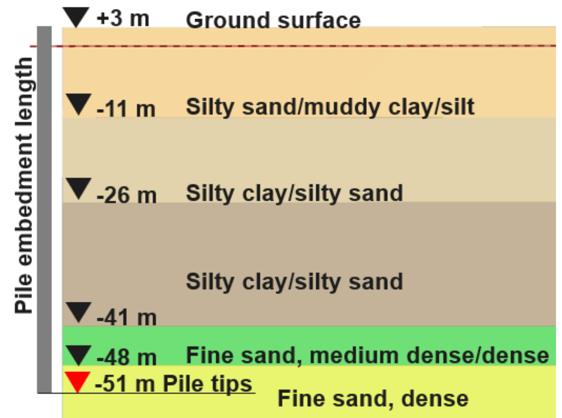
5 Full Frequency Coupling

Project example 1: 160 000 m³ LNG-tank



Pile forces
@ pile heads and
@ pile length
due to **PURELY DYNAMIC** Loading

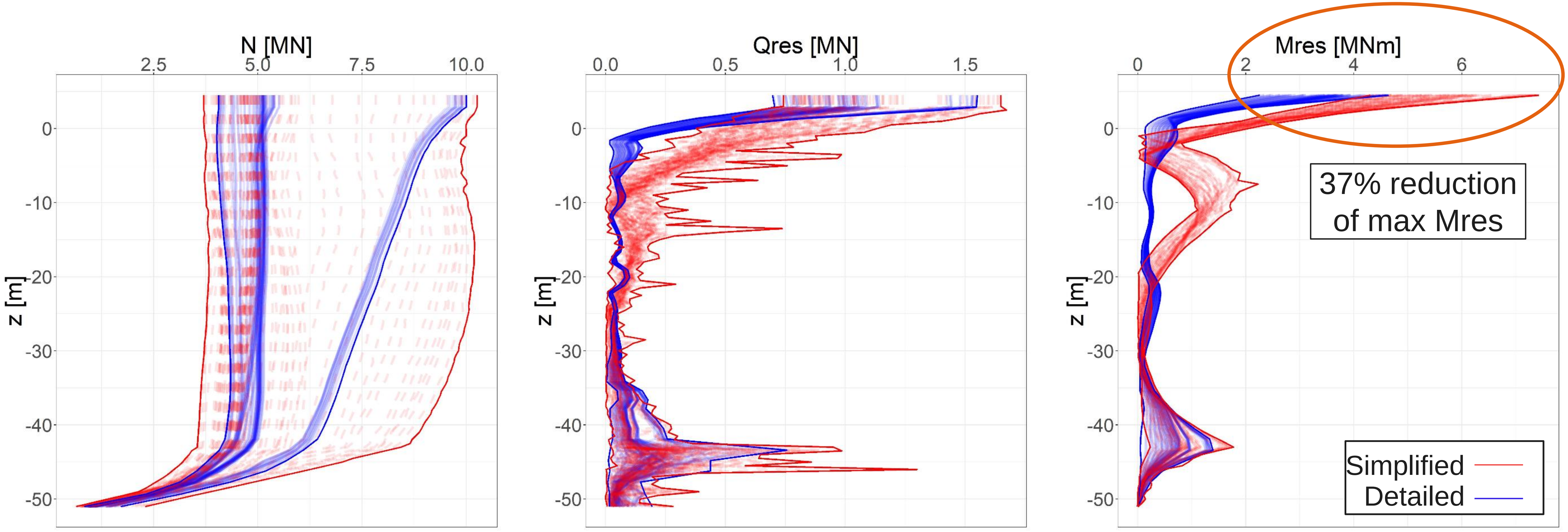




5 Full Frequency Coupling

Project example 1: 160 000 m³ LNG-tank

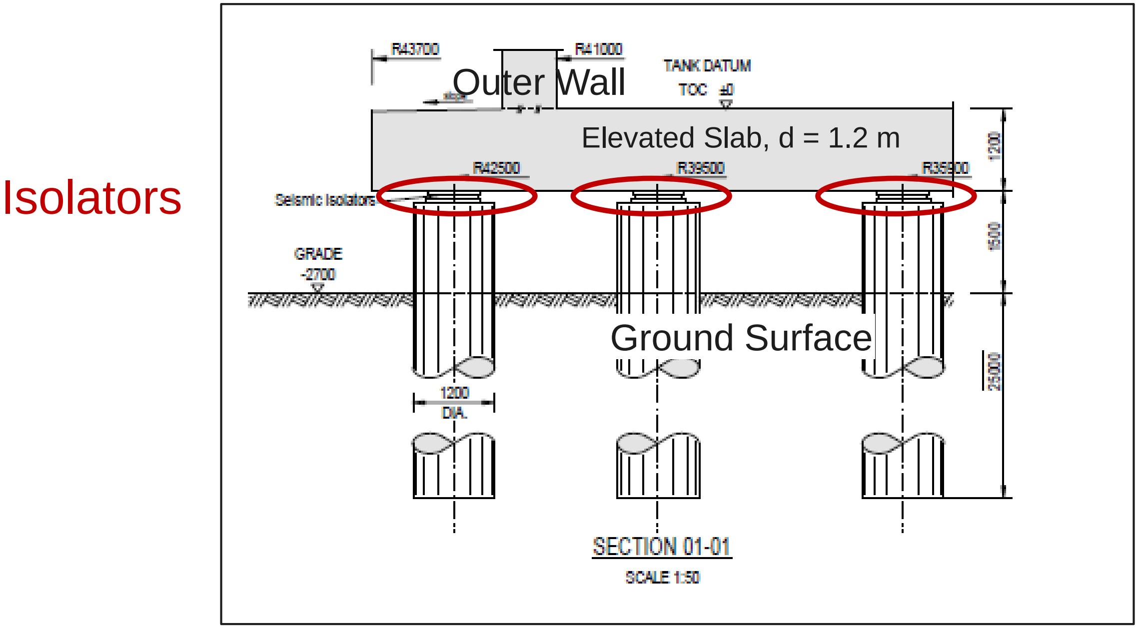
Comparison: Full Frequency Coupled “detailed” vs. Static Equivalent Loads “simplified” Approach



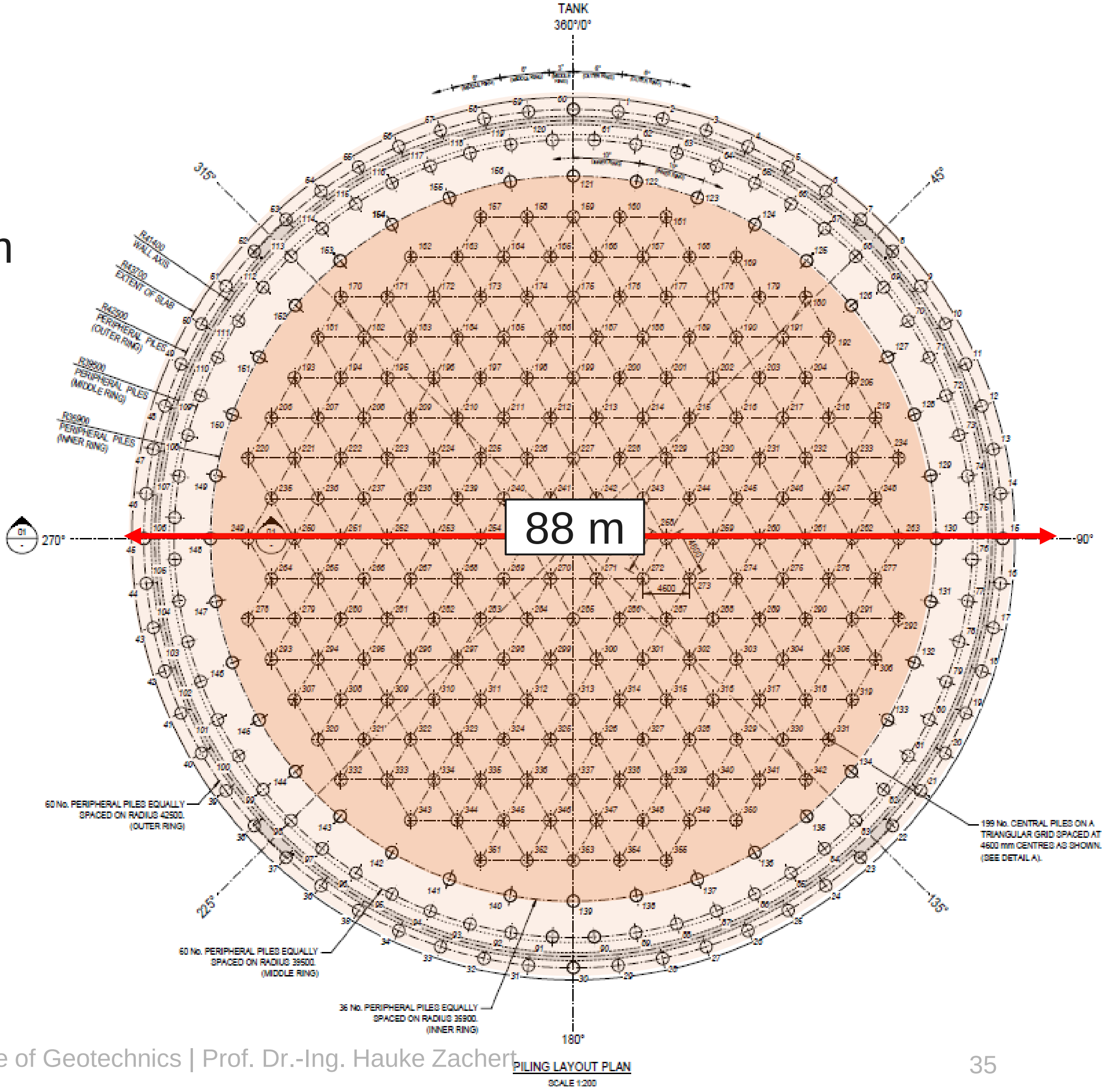
5 Full Frequency Coupling

Project example 2: 160 000 m³ LNG-tank with Isolators

- Location: China
- 160 000 m^3 → D = 88 m, H = 50 m
- 355 bored concrete piles with diameter 1.2 m, L = 25 m
- 156 ring piles, 199 inner piles (triangular grid 4.6 m)



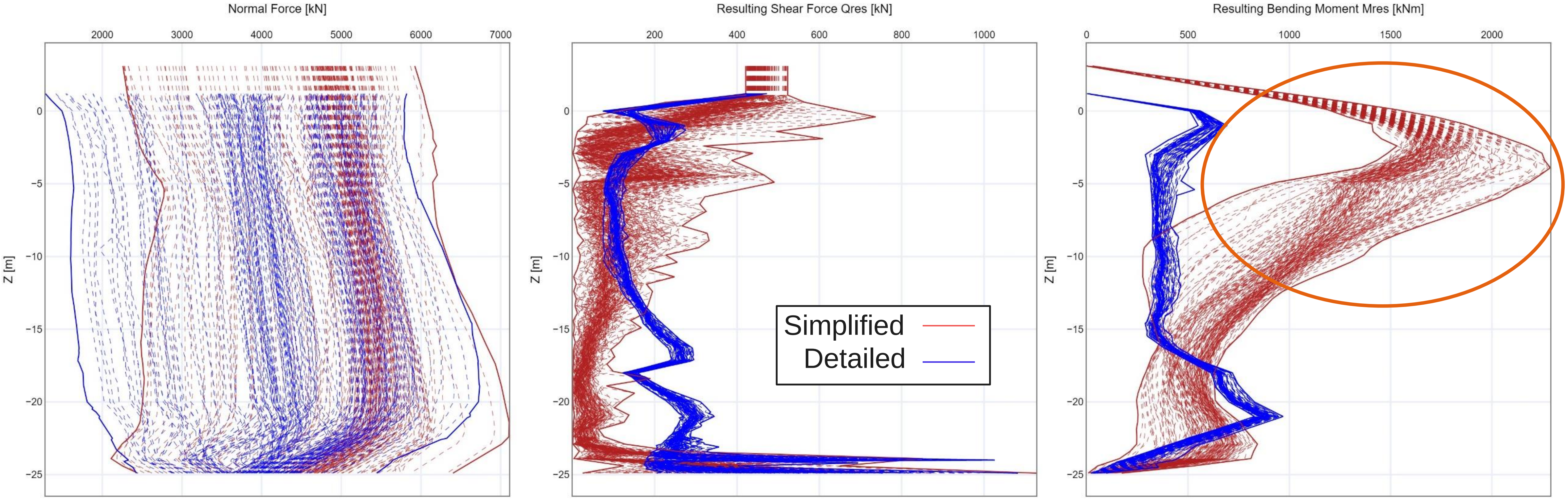
Pile layout



5 Full Frequency Coupling

Project example 2: 160 000 m³ LNG-tank with Isolators

Comparison: Full Frequency Coupled “detailed” vs. Static Equivalent Loads “simplified” Approach



PART 5

Conclusion

Conclusion

- Static equivalent Loads approach
  - Simplified approach, easy to integrate in the “static” design
  - Applicable in moderate PGAs and tanks without isolators
  - Shows reasonably good agreement with more sophisticated approaches
  - Typically overestimates internal forces compared with other approaches

- Substructure approach
  - Allows rigorous modelling of dynamic actions on soil and structure
  - Considers pile-soil-pile-interaction
  - Delivers complex foundation impedance matrix which can be incorporated in the tank design
  - Economic design process because soil + foundation are treated separately from the tank

- Full Frequency Coupling
  - Allows rigorous modelling of dynamic actions on soil and structure
  - Considers pile-soil-pile-interaction
  - Fully mobilizes soil damping
  - Can reduce internal pile forces significantly and lead to a sustainable design
  - Requires a huge effort due to many variants to be simulated

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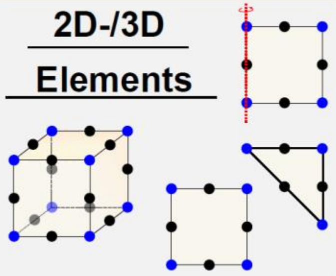
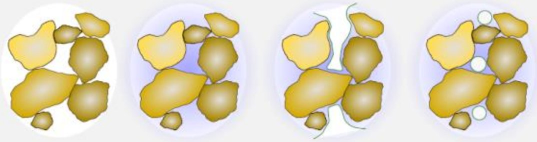
Elements

2D-/3D Elements



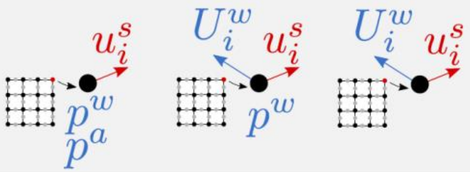
Multiphase Elements

Phases 1 2 3 5



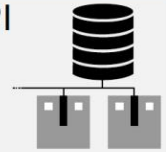
Formulations

up upU uU



Performance

Mixed open-MP and MPI parallelisation



Direct Solvers

→ MUMPS (MPI+OMP)
→ Pardiso (OMP)
→ LAPACK

Iterative Solver/Preconditioner

→ BICGSTAB + ILU0 (OMP)
→ LIS Library

Extensibility

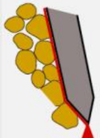
User subroutines (Fortran, loaded at runtime)

→ Initial conditions
→ Boundary conditions
→ Loading
→ Constitutive models σ(σ,ε,S,s,sv)
→ Amplitudes
→ ...

Generic solver interface

→ MUMPS + MPI
→ ILUPACK
→ PasTiX (GPU)
→ ...

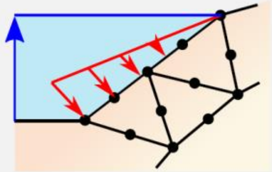
Contact formulations



Mortar Methods

Coulomb
Hypoplasticity + IGS
Sanisand
HCA Models

Multi-phase contact



Mechanical models

Hypoplasticity + IGS
Sanisand
Sanisand-F
ISA - Sand (W. Fuentes)
Hypoplasticity + ISA

Modified Cam Clay (MCC)
AVISA (M. Tafili)
ISA-Clay (M. Tafili)
Clay-Hypoplasticity (D. Masin)
Barodesy + ISA (Bode & Tafili)

HCA sand
(coupled with HPP or Sanisand)
HCA clay
(coupled with AVISA)

Hydraulic models

Van Genuchten
Brooks & Corey
Fredlung & Xing
Nguyen
Karlsruhe model

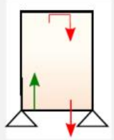
Air entrapment model

Analyses

"Static"
"Transient"
"Dynamic"
"Explicit Dynamic"
"Updated Lagrangian"
"Strength reduction"

Miscellaneous

Transparent BC



Multi-point constraints
Special elements (Mass/Spring)
"Nonlocal smoothing"
Restart Analyses
Submodel Analyses

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Automatic parameter calibration

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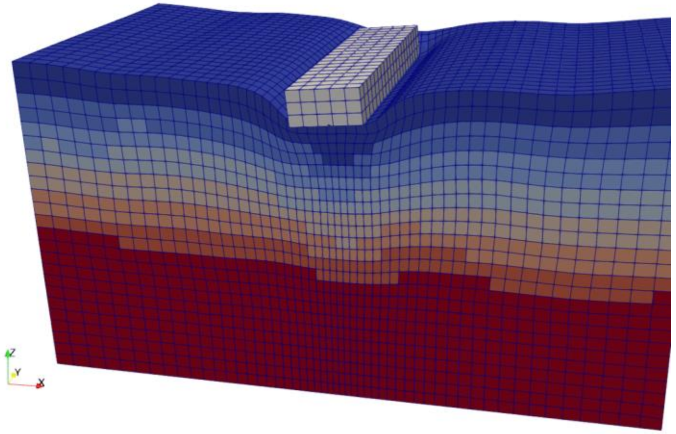
at a glance

- Implicit and explicit simulation of **coupled dynamic problems** with 3-phases and more
- **Contact interactions** with large relative motions such as required for pile driving
- **Cyclic response of soils** using the most advanced constitutive models
- **Automatic parameter calibration** of advanced constitutive soil models
- Direct and iterative solvers, Multi-threading, Large deformations and much more…

Earthquake assessment of Rhinish lignite opencast mine slopes



Benchmark problems for validation

GEOLAB

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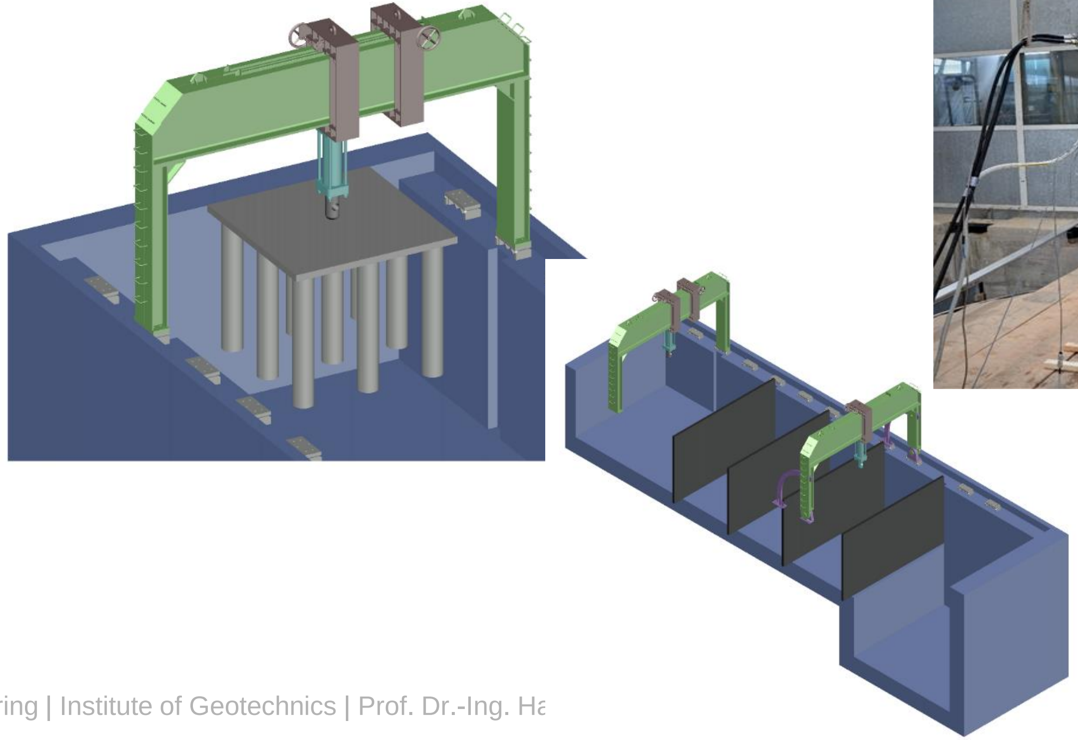
GEOLAB

GEOLAB offers you **free access** to large European experimental geotechnical facilities

3rd Call for proposals is now open (project-geolab.eu):

Experiments to validate advances in numerical modelling and data science leading to a better engineering design

Geotechnical Test Pit @ TU Darmstadt



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Thank you for your attention