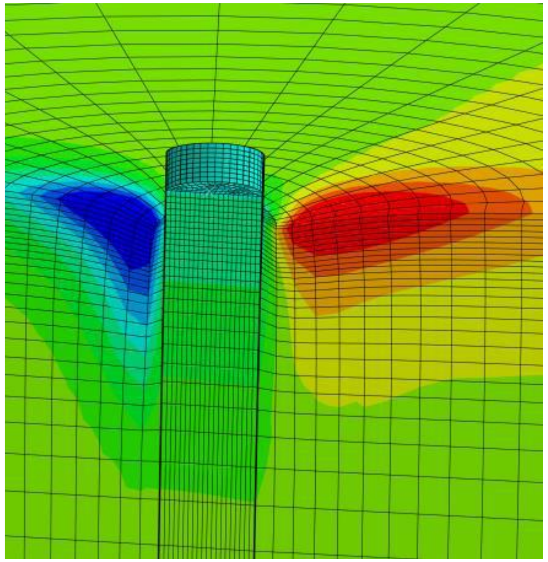
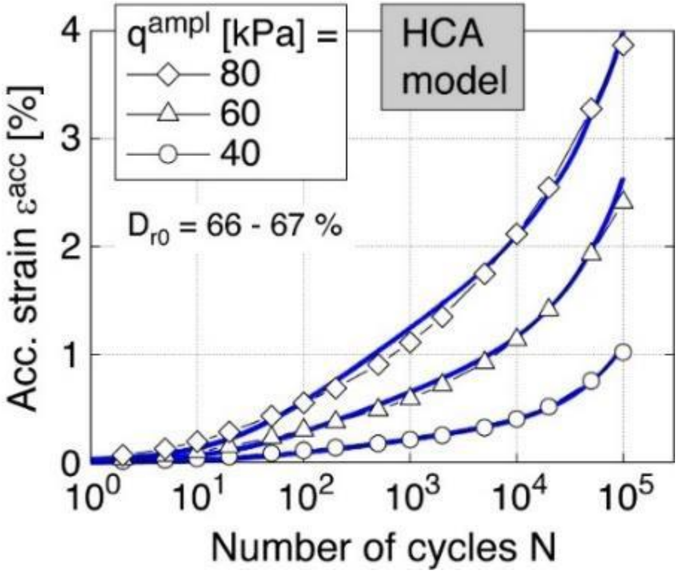
Installation of piles:
Simulation strategies and influence on the long-term behavior under high-cycling loading

Dr.-Ing. Jan Machaček, M.Sc. Patrick Staubach,
Prof. Dr. - Ing. habil., Dr. h. c. Theodoros Triantafyllidis





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Content:

Pile installation methods

- Conventional methods
- Combined axial and torsional driving

Numerical simulation of pile installation

- Why is it important?
- Simulation strategies
- Influence on the long-term behavior under (high-cycling) lateral loading

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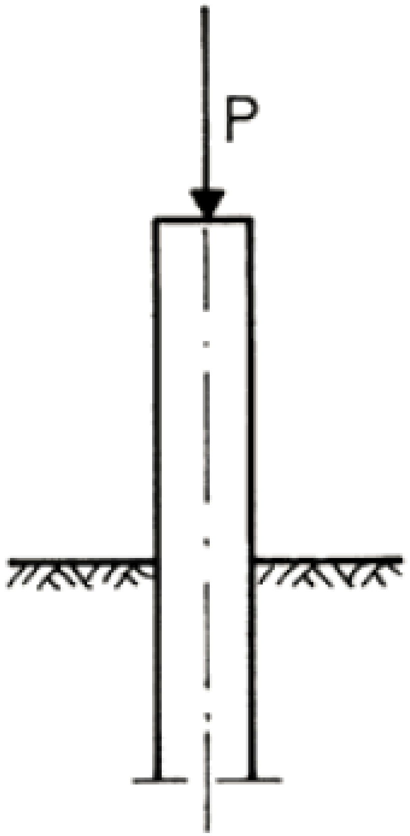
Pile installation methods

Pile installation methods

Conventional methods for pile installation



Jacking

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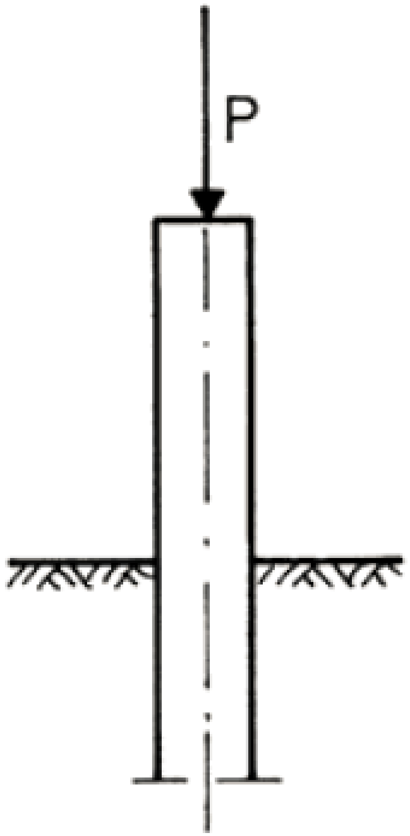

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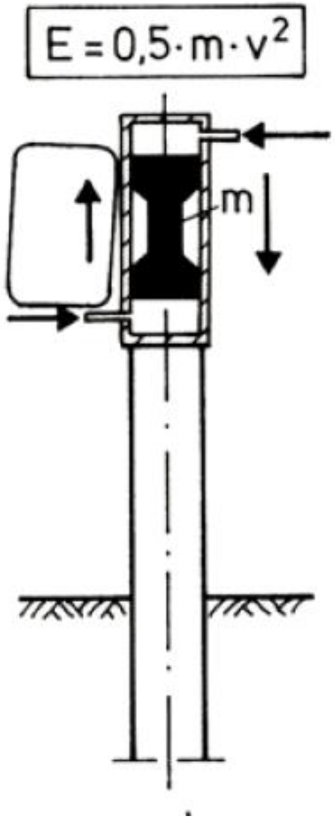

Impact driving

Pile installation methods

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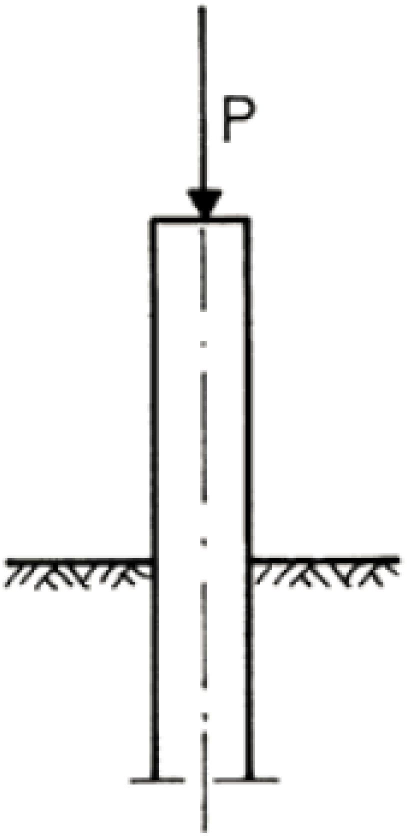

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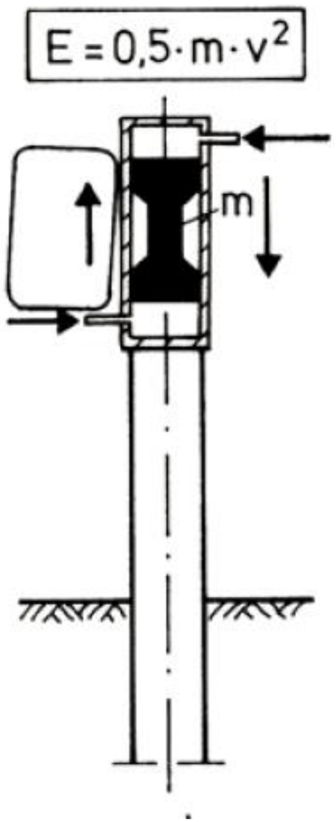

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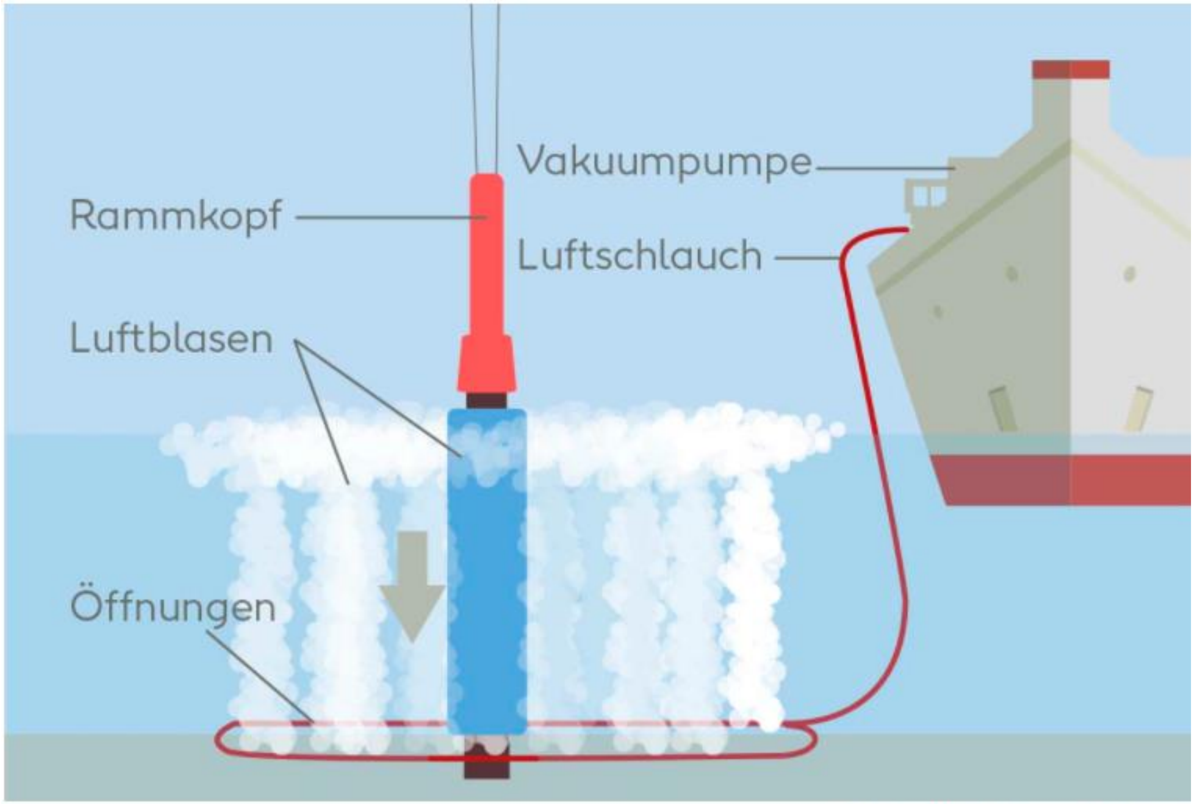

Infografik: Johannes Hofmann

www.energiewinde.orsted.de

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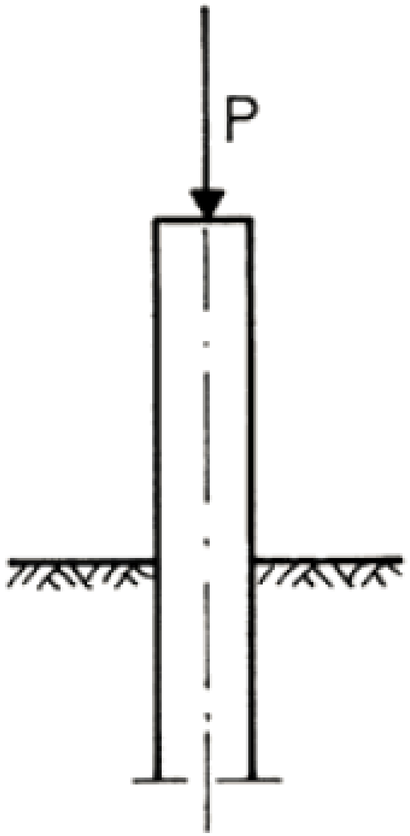

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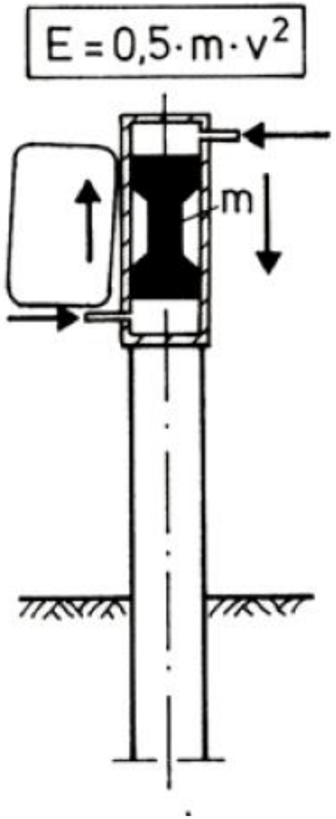

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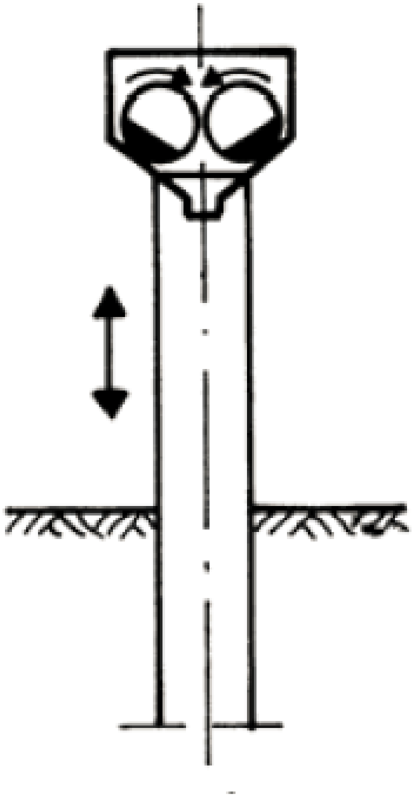
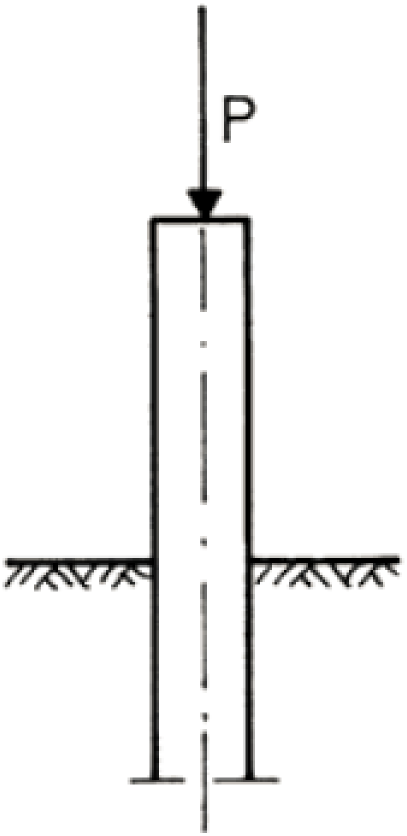


Vibrational driving

Pile installation methods

Conventional methods for pile installation



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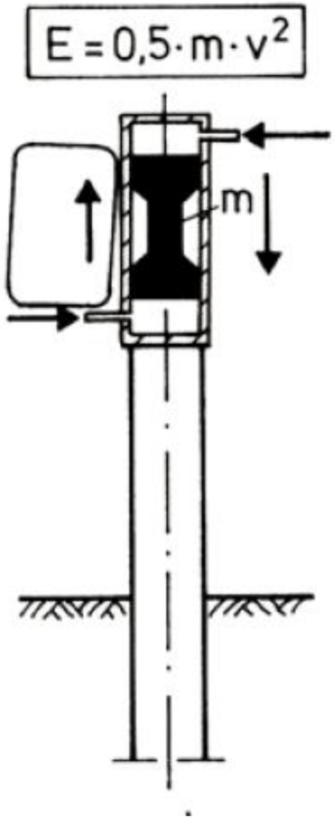

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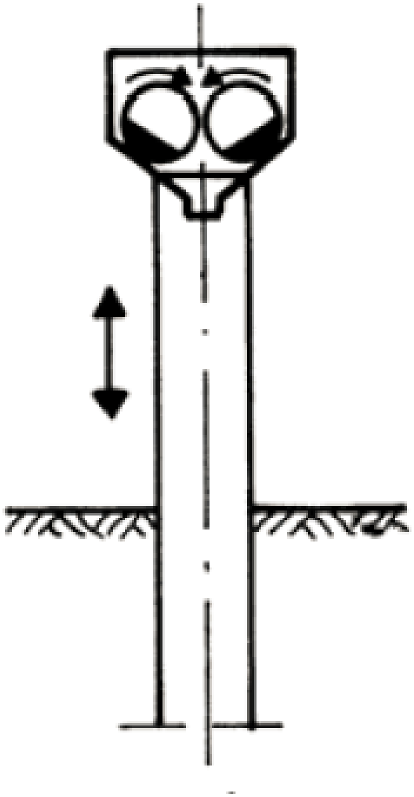

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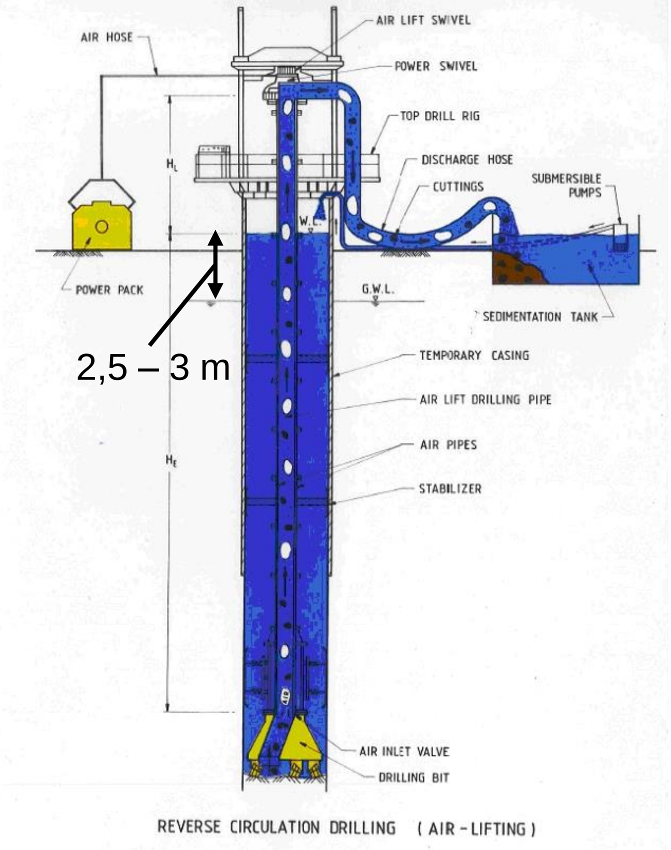
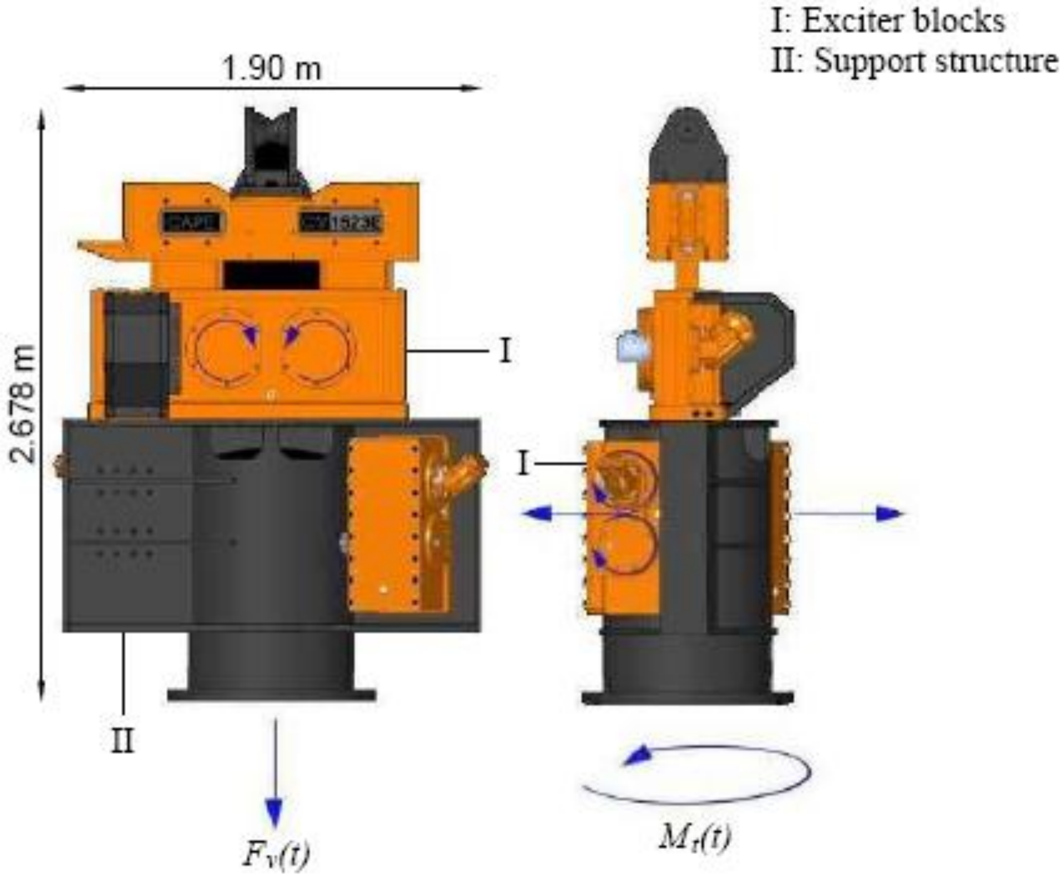


Boring

Pile installation methods

Combined axial and torsional driving, GDP, TU Delft



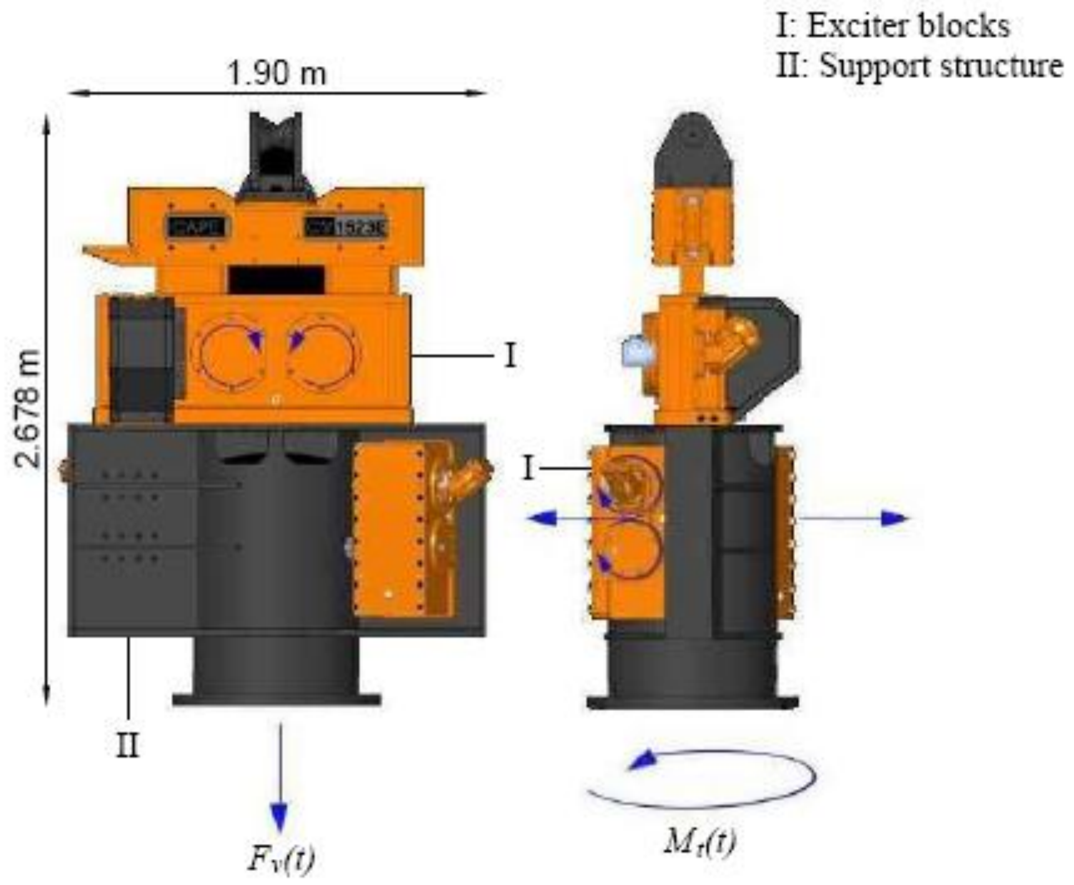
Metrikine et al. 2020

Pile installation methods

Combined axial and torsional driving, GDP, TU Delft

- GDP Schaker with high frequency torsional oscillations in oder to reduce the shaft resistance in the circumferential direction, so that the resultant axial vibratory forces are smaller compared to the pure axial vibrodriving.

- Advantages of such a combined vibratory driving:
  - Smaller axial load for longitudinal excitation are required for the pile penetration
  - Poisson‘s effects of radial vibrations are reduced
  - The under water acoustic emission is reduced



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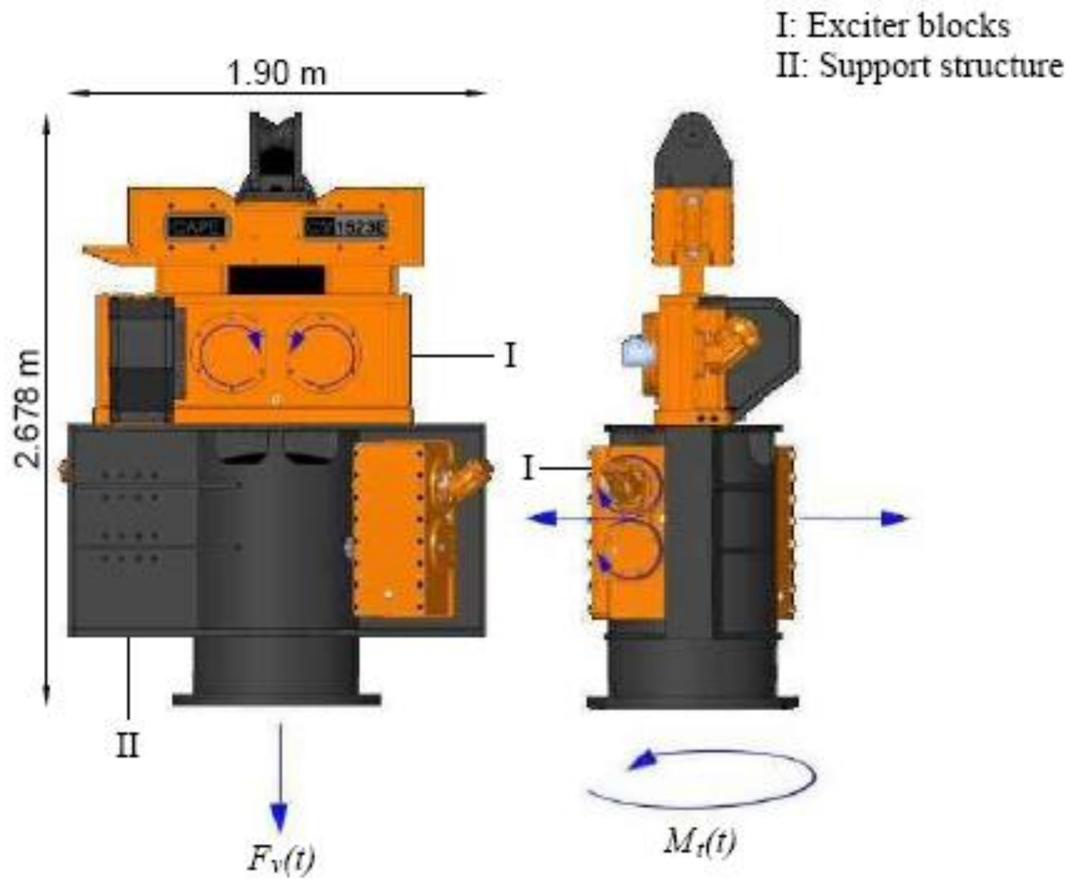
  - But: is the serviceability better for the pile installed than the axial vibratory driving or the impact driving due to less constraining effects?



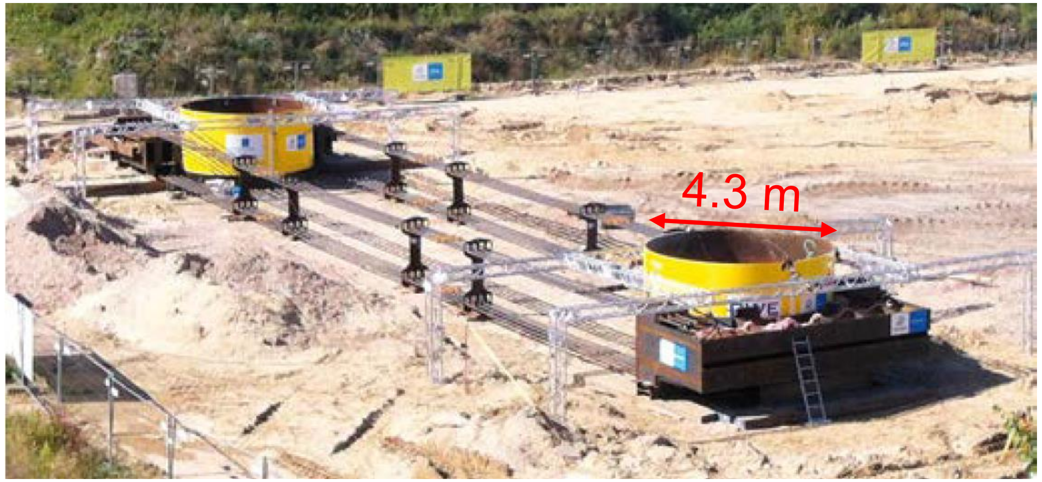
Metrikine et al. 2020

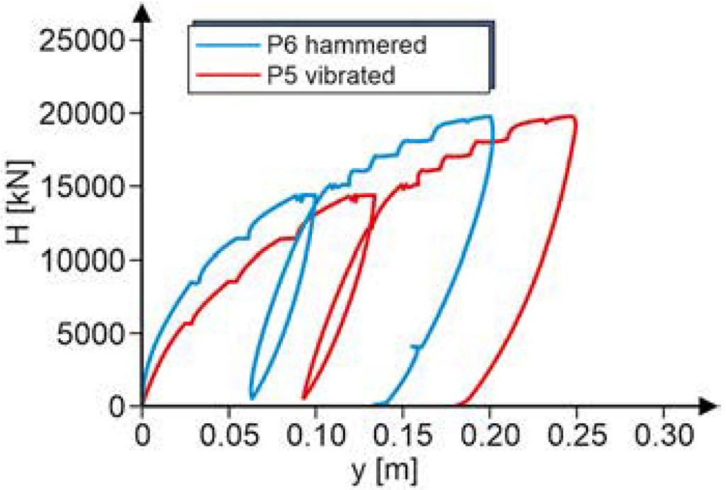
Simulation strategies

Simulation strategies – Why?

Fatigue and serviceability limit states can be critical in design

- … the foundation stiffness plays an important role!
- … field measurements have shown:
  - significantly higher stiffness than predicted
  - the pile response to (subsequent) loading depends on the installation method





Achmus et al. 2020

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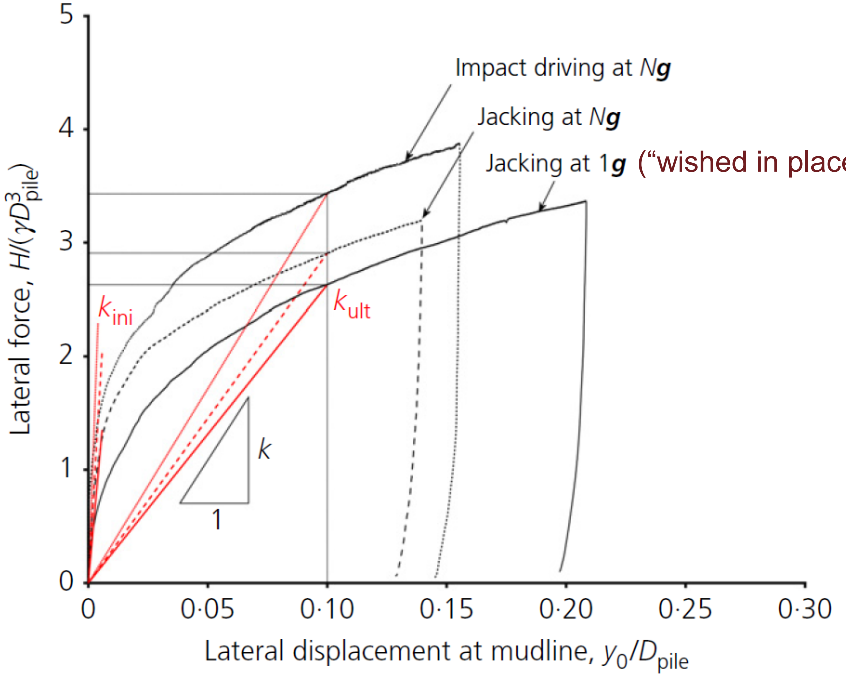

Fan et al. 2019

Bienen 2021

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Installation of piles into sand is a process involving large-deformation and thus results in significant changes to the soil state

- These changes are difficult to characterize experimentally
- The effect of the installation process on monopile lateral response is not yet well understood
- Numerical modelling has the potential to reveal the changes in the soil state

Simulation strategies – Challenges?

Large deformations

- outside the application limits of the classical FEM
  - strong assumptions/simplifications are required for open ended piles
- Novel simulation methods required
  - Not yet state of the art
  - Still “experimental” for complex BVPs

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Predominantly saturated soils
(Exceptions: Model tests, centrifuge tests, …)

- Build-up and/or dissipation of excess pore water pressure
- Dynamic process (Inertia forces matter!)
- Special requirements for the simulation method

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Soil behaviour

- Cyclic loading of the soil
  - Shearing along the pile shaft
  - Compaction + shearing below the pile tip
  - Up to tens of thousands of load cycles for large diameter monopiles (vibro driving)
- Grain breakage?

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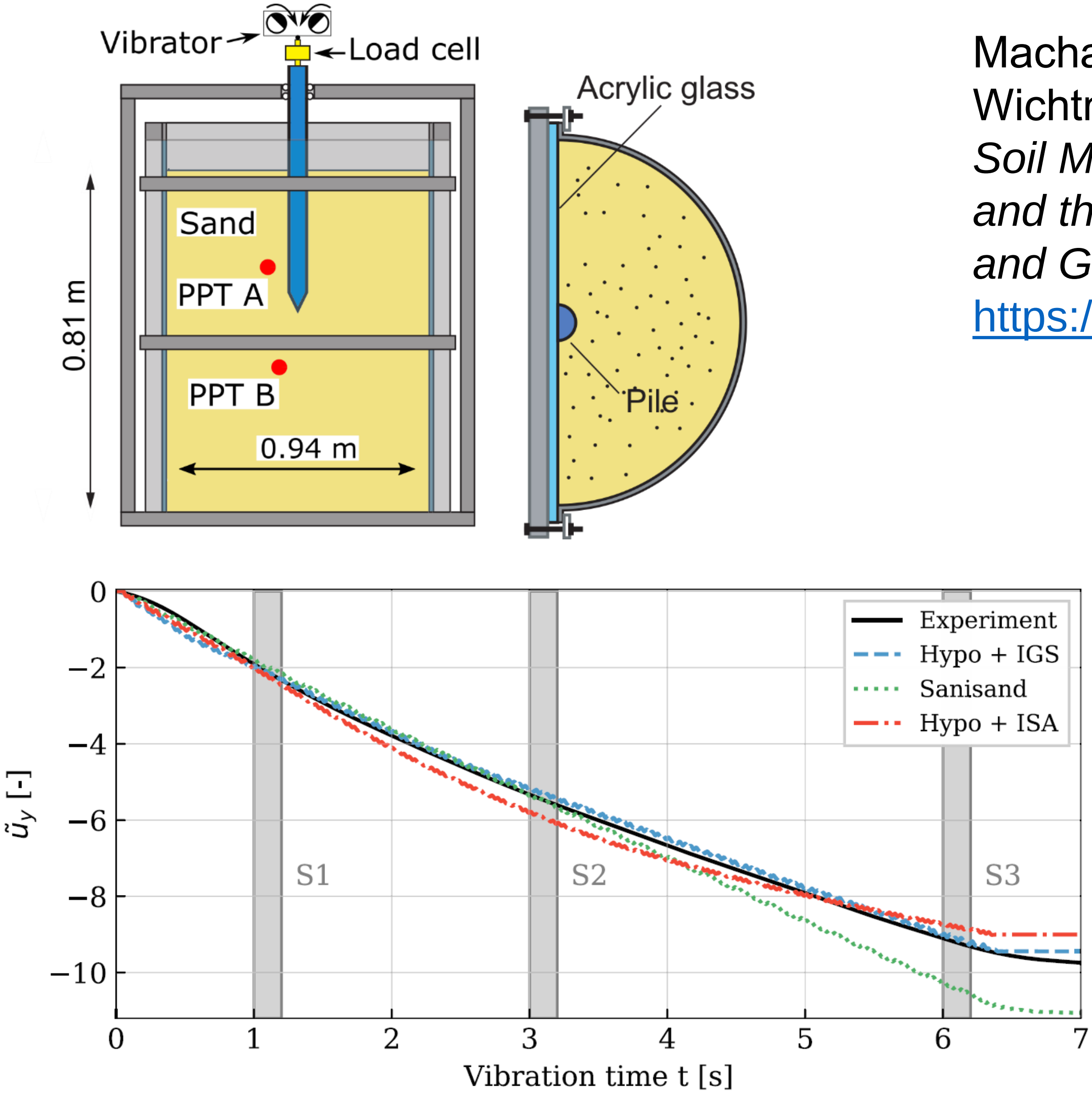
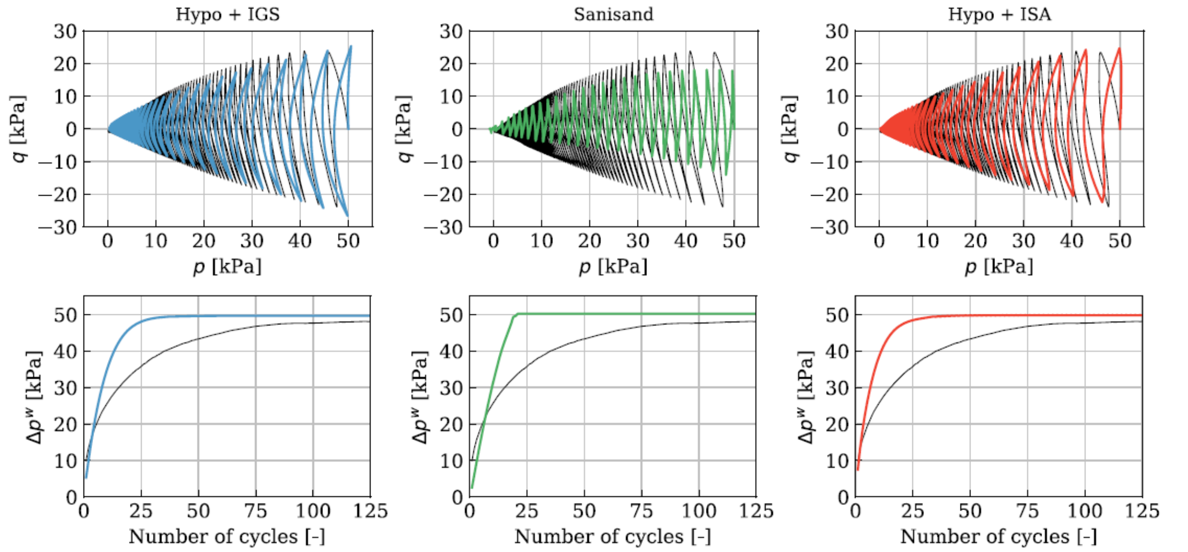
Simulation strategies – Constitutive models

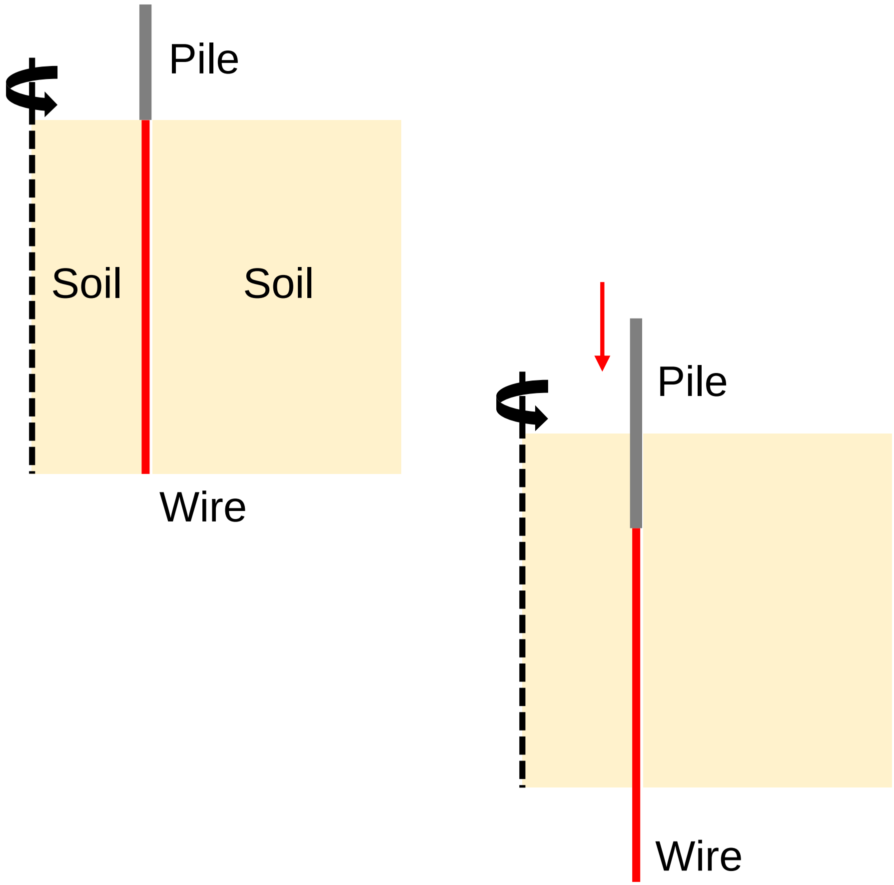


Machaček, J., P. Staubach, M. Tafili, H. Zachert, und T. Wichtmann. „*Investigation of Three Sophisticated Constitutive Soil Models: From Numerical Formulations to Element Tests and the Analysis of Vibratory Pile Driving Tests*". *Computers and Geotechnics* 138 (Oktober 2021): 104276. https://doi.org/10.1016/j.compgeo.2021.104276.



Simulation strategies – Large deformations

“Zipper-Method” (classical FEM)



- Thin extension (wire) of the pile constraints the soil
- For open ended piles, the soil needs to be “pre-slit”
- Contact algorithm between pile-soil and wire-soil
- Pile displaces extension and soil during penetration

See e.g. Henke & Grabe 2008, Staubach & Machacek 2019, Chrisopoulos & Vogelsang 2019 amongst others

Simulation strategies – Large deformations

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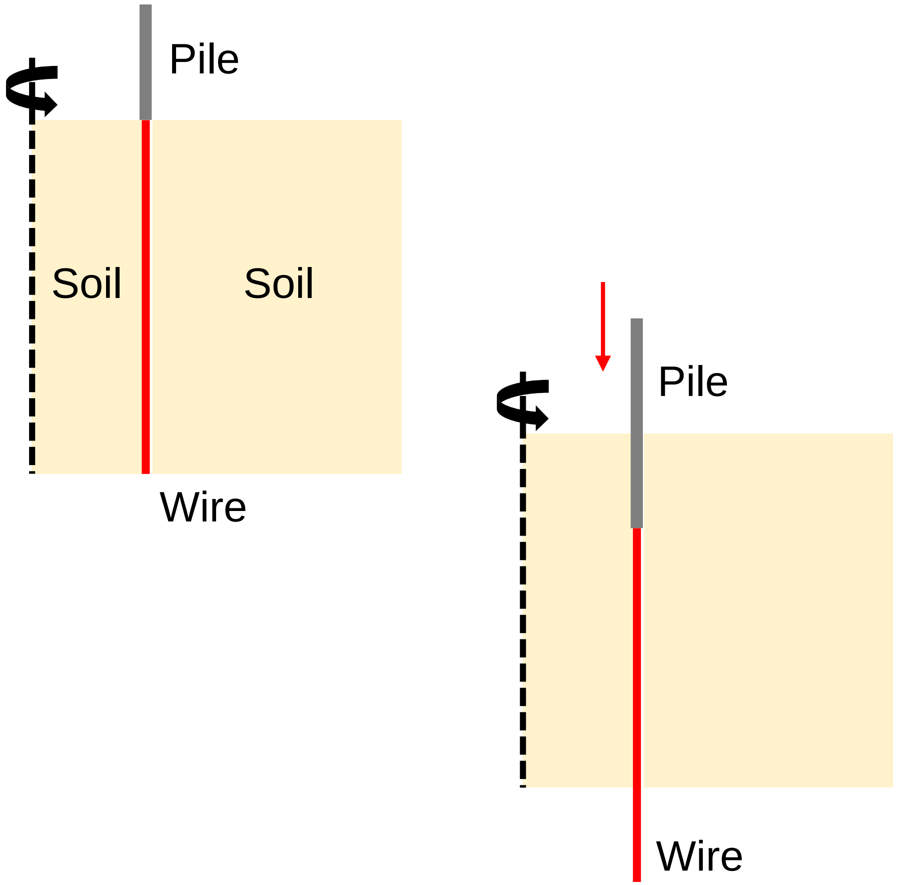

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- Can be implemented in almost any FEM program
- Contact algorithms suitable for large deformations
- Still prone to (excessive) mesh distortion

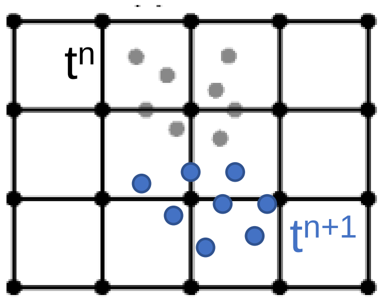
See e.g. Henke & Grabe 2008, Staubach & Machacek 2019, Chrisopoulos & Vogelsang 2019 amongst others

Simulation strategies – Large deformations

Large Deformation Methods:

MPM

Material Point Method



- „Hybrid“ approach
- Available e.g. Anura3D, cb-geo
- Mostly explicit schemes, some implicit
- Computational expensive
- Universal application

SPH

Smoothed Particle Hydrodyn.

DEM

Discrete Element Method

CEL

Coupled Eulerian Lagrangian

…of course there are even more…ALE, MMALE, PFEM, …

Simulation strategies – Large deformations

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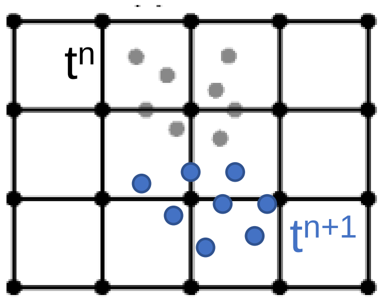

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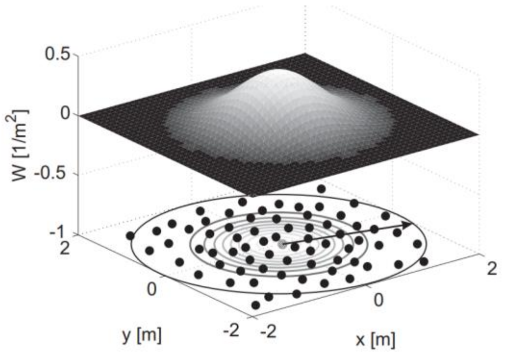

- Truely meshless
- Available e.g. via Abaqus
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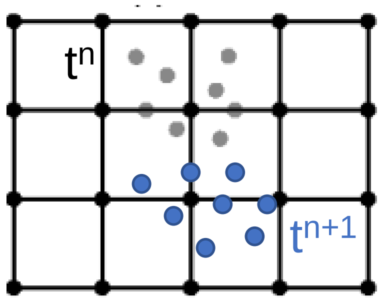

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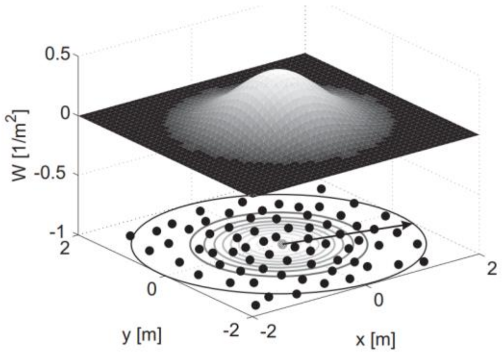

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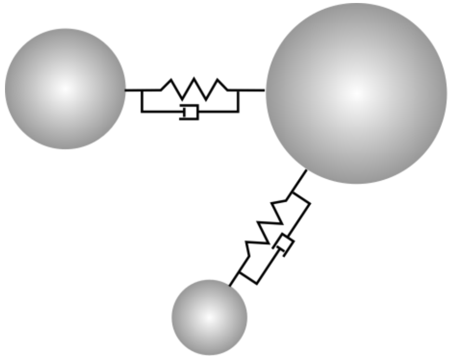


- Truely meshless
- Contact model acts as constitutive model
- (Unrealistic) particle shapes and sizes
- Nontrivial for fluid-coupled simulations
- Computational expensive

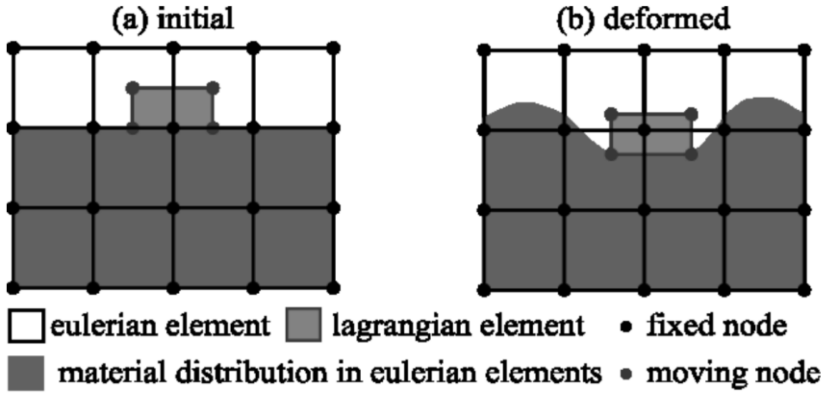
CEL

Coupled Eulerian Lagrangian

…of course there are even more…ALE, MMALE, PFEM, …

Simulation strategies – Large deformations

Coupled Eulerian Lagrangian Method for fluid saturated soils



- Originally developed for the simulation of fluid structure interaction (FSI)
- Coupling of the Lagrangian and the Eulerian formulation
- Contact algorithm between Eulerian and Lagrangian elements

- For the problem at hand:
  - The pile is modelled using a Lagrangian framework
  - And the soil using a Eulerian framework

Pros:
  - Available in commercial package Abaqus
  - Can be coupled to advanced constitutive models and extended for fully-coupled simulations

Cons:
  - Fine mesh is required to obtain good quality results in Eulerian elements
  - Difficulties in free surface tracking
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Simulation strategies – Large deformations

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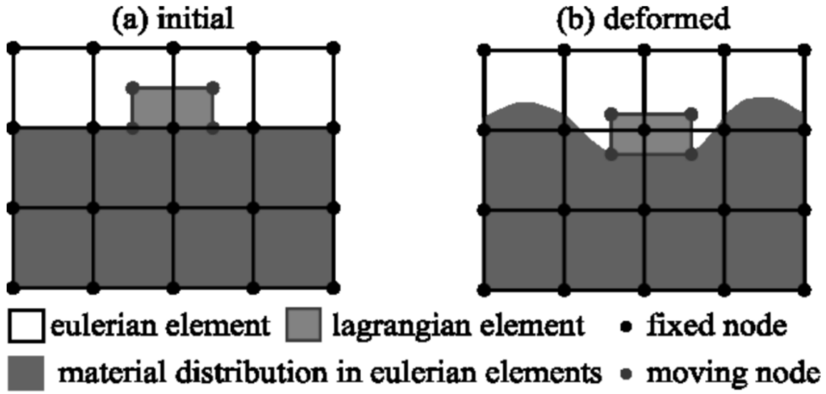

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Coupled Eulerian Lagrangian Method for fluid saturated soils

- Abaqus/CEL does not offer fluid-coupled simulations…restricted to
  - Ideally drained or dry conditions
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Hamann et al. 2015, Staubach et al. 2020, Staubach et al. 2021

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- There exists a workaround:

1. **Coupled temperature-displacement analysis**

   Energy balance for thermal processes: $\rho c\dot{\theta} + \lambda \mathrm{div}\big(-\mathrm{grad}(\theta)\big) = -\dot{m}_T$

   Model parameters: c and λ

2. **Temperature dependent material behavior (VUMAT)**

   User defined material (VUMAT) to define: $\dot{m}_T$

ρ = Density
c = Specific heat
θ = Temperature
λ = Thermal conductivity
$\dot{m}_T$= Int. heat production

Hamann et al. 2015, Staubach et al. 2020, Staubach et al. 2021

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We are looking for a way to perform a fluid coupled calculation

How do we get from u-θ to u-p?

Only option: reinterpretation of c, λ and $\dot{m}_T$

Hamann et al. 2015, Staubach et al. 2020, Staubach et al. 2021

Simulation strategies – Large deformations

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- **Mass balance of pore water**
  - U-p formulation, assumption: $\ddot{u}^w = \ddot{u}^s$

Staubach & Machacek 2019

$$\frac{nS}{K^w}\dot{p}^w + \mathrm{div}\left\{\frac{\boldsymbol{K}^{\mathrm{perm}}}{\eta^w}\left[-\mathrm{grad}(p^w) + \rho^w(\boldsymbol{b} - \ddot{\boldsymbol{u}}^s)\right]\right\} + \mathrm{div}(\dot{\boldsymbol{u}}^s) = 0$$

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  - Some similarities are already visible, but…
    - How to identify λ ?
    - No information on $\boldsymbol{b}$ and $\ddot{\boldsymbol{u}}^s$ on the material level
  - Further steps required!

Hamann et al. 2015, Staubach et al. 2020, Staubach et al. 2021

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$$\frac{nS}{K^w}\dot{p}^w + \frac{K^{\mathrm{perm}}}{\eta^w}\mathrm{div}\{[-\mathrm{grad}(p^w) + \rho^w(\boldsymbol{b} - \ddot{\boldsymbol{u}}^s)]\} + \mathrm{div}(\dot{\boldsymbol{u}}^s) = 0$$

  - Using the relationship $\rho^w\boldsymbol{b} - \mathrm{grad}(p^w) = -\mathrm{grad}(\Delta p^w)$ and rearranging

$$\frac{nS}{K^w}\Delta\dot{p}^w + \frac{K^{\mathrm{perm}}}{\eta^w}\mathrm{div}[-\mathrm{grad}(\Delta p^w)] - \frac{K^{\mathrm{perm}}}{\eta^w}\mathrm{div}(\ddot{\boldsymbol{u}}^s) + \mathrm{div}(\dot{\boldsymbol{u}}^s) = 0$$

(get rid of $\boldsymbol{b}$!)

Hamann et al. 2015, Staubach et al. 2020, Staubach et al. 2021

Simulation strategies – Large deformations

Coupled Eulerian Lagrangian Method for fluid saturated soils

- **Coupled temperature-displacement analysis**

  Energy balance for thermal processes: $\rho c\dot{\theta} + \lambda \mathrm{div}\left(-\mathrm{grad}(\theta)\right) = -\dot{m}_T$

- **Mass balance of pore water**
  - U-p formulation, assumption: $\ddot{u}^w = \ddot{u}^s$
  - Assuming an isotropic permeability ($\boldsymbol{K}^{\mathrm{perm}} = K^{\mathrm{perm}}$):
  - Using the relationship $\rho^w \boldsymbol{b} - \mathrm{grad}(p^w) = -\mathrm{grad}(\Delta p^w)$ and rearranging

$$\frac{nS}{K^w}\Delta\dot{p}^w + \frac{K^{\mathrm{perm}}}{\eta^w}\mathrm{div}[-\mathrm{grad}(\Delta p^w)] - \frac{K^{\mathrm{perm}}}{\eta^w}\mathrm{div}(\ddot{\boldsymbol{u}}^s) + \mathrm{div}(\dot{\boldsymbol{u}}^s) = 0$$

Staubach & Machacek 2019

Hamann et al. 2015, Staubach et al. 2020, Staubach et al. 2021

Simulation strategies – Large deformations

Coupled Eulerian Lagrangian Method for fluid saturated soils

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  Energy balance for thermal processes: $\rho c\dot{\theta} + \lambda \mathrm{div}\big(-\mathrm{grad}(\theta)\big) = -\dot{m}_T$

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$$\frac{nS}{K^w}\Delta\dot{p}^w + \frac{K^{\mathrm{perm}}}{\eta^w}\mathrm{div}[-\mathrm{grad}(\Delta p^w)] - \frac{K^{\mathrm{perm}}}{\eta^w}\mathrm{div}(\ddot{\boldsymbol{u}}^s) + \mathrm{div}(\dot{\boldsymbol{u}}^s) = 0$$

- **Perform a coupled temperature-displacement analysis**
  - Reinterpret $\dot{\theta}$ as $\Delta\dot{p}^w$
  - Provide the constants c and as follows:
    - $c = nS/\rho K^w$
    - $\lambda = K^{\mathrm{perm}}/\eta^w$
  - Use the VUMAT to provide $\dot{m}_T$
    - $\dot{m}_T = \mathrm{div}(\dot{\boldsymbol{u}}^s) - K^{\mathrm{perm}}/\eta^w \,\mathrm{div}(\ddot{\boldsymbol{u}}^s)$
    - Estimate $\mathrm{div}(\ddot{\boldsymbol{u}}^s)^{t+\Delta t} = \dfrac{\mathrm{tr}(\dot{\boldsymbol{\varepsilon}})^{t+\Delta t} - \mathrm{tr}(\dot{\boldsymbol{\varepsilon}})^{t}}{2\Delta t} + \dfrac{\mathrm{div}(\ddot{\boldsymbol{u}}^s)^{t}}{2}$

Hamann et al. 2015, Staubach et al. 2020, Staubach et al. 2021

Simulation strategies – Large deformations

Coupled Eulerian Lagrangian Method for fluid saturated soils

- **Validation and Application:**

Staubach, P., J. Machaček, M.C. Moscoso, und T. Wichtmann. „Impact of the Installation on the Long-Term Cyclic Behaviour of Piles in Sand: A Numerical Study“. *Soil Dynamics and Earthquake Engineering* 138 (November 2020): 106223. https://doi.org/10.1016/j.soildyn.2020.106223.

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- **The implementation is freely available from Patrick Staubach upon request!**
  - **patrick.staubach@uni-weimar.de**

Hamann et al. 2015, Staubach et al. 2020, Staubach et al. 2021

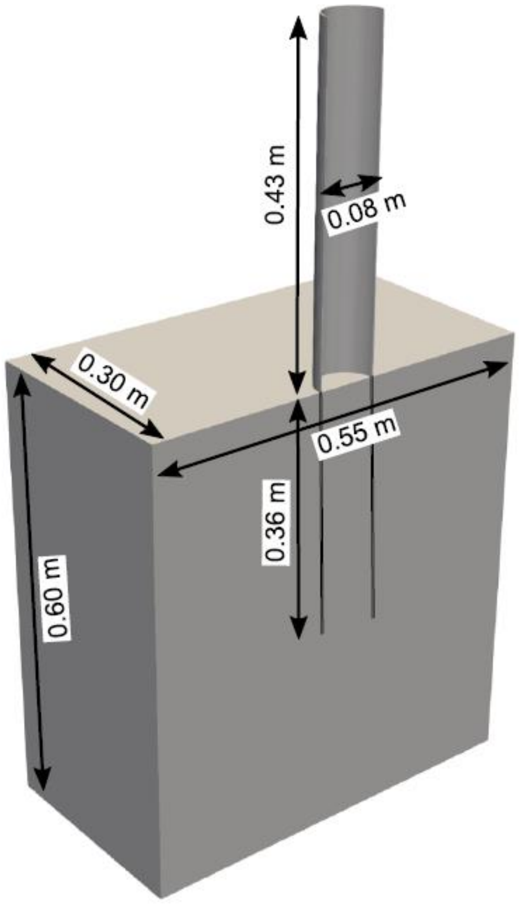
Influence on the long-term behavior under high-cycling loading

-

Model tests by Le Blanc et al. 2010

Application of the CEL and impact of the installation on long-term behavior

Model tests by Le Blanc et al. 2010



- Yellow Leighton Buzzard Sand
  - $D_{r0} = 4\ \%$
  - $D_{r0} = 38\ \%$
- Pile was driven into the soil with a plastic hammer
- Unknown specification of the hammer and the drop height
- Loading scenarios:
  - Monotonic loading to failure
  - Cyclic lateral loading (N = 10.000 cylces)

Staubach et al. 2021-2

Application of the CEL and impact of the installation on long-term behavior

Model tests by Le Blanc et al. 2010

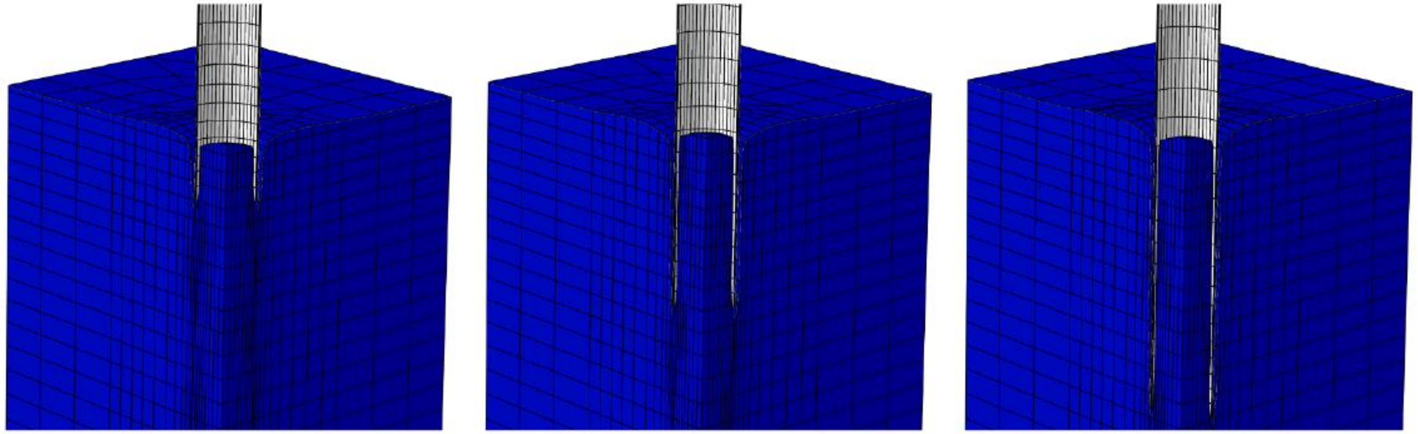
1. How does the pile installation alter/changes the soil state?

2. How do these effects influence the long term behavior?

Application of the CEL and impact of the installation on long-term behavior

Model tests by Le Blanc et al. 2010

1. How does the pile installation alter/changes the soil state?
   - CEL-Simulation (Abaqus)
   - Changes in:
     - (Relative) Density
     - Stresses
     - Pore water pressure



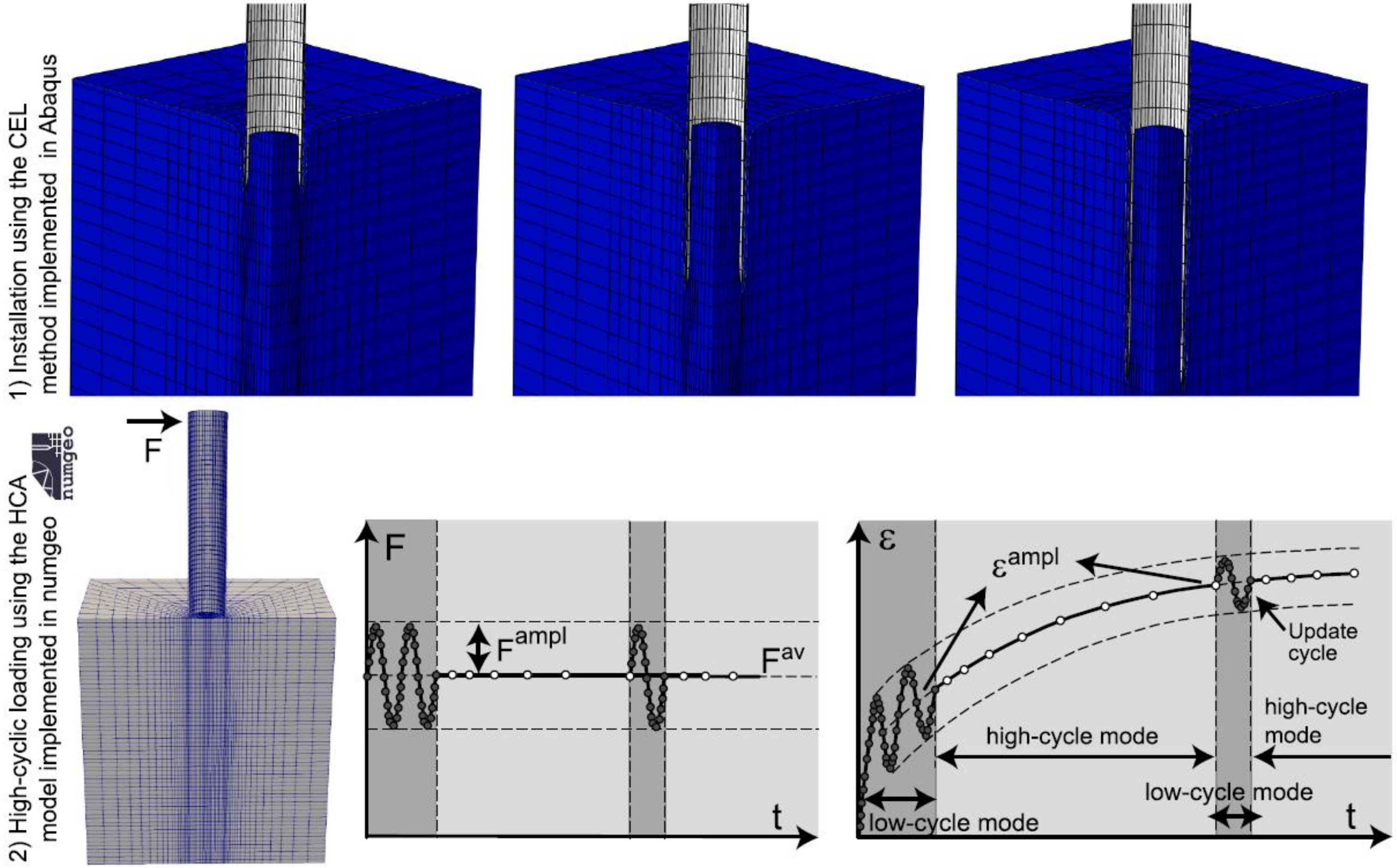
2. How do these effects influence the long term behavior?

Application of the CEL and impact of the installation on long-term behavior

Model tests by Le Blanc et al. 2010

1. How does the pile installation alter/changes the soil state?
   - CEL-Simulation (Abaqus)
   - Changes in:
     - (Relative) Density
     - Stresses
     - Pore water pressure

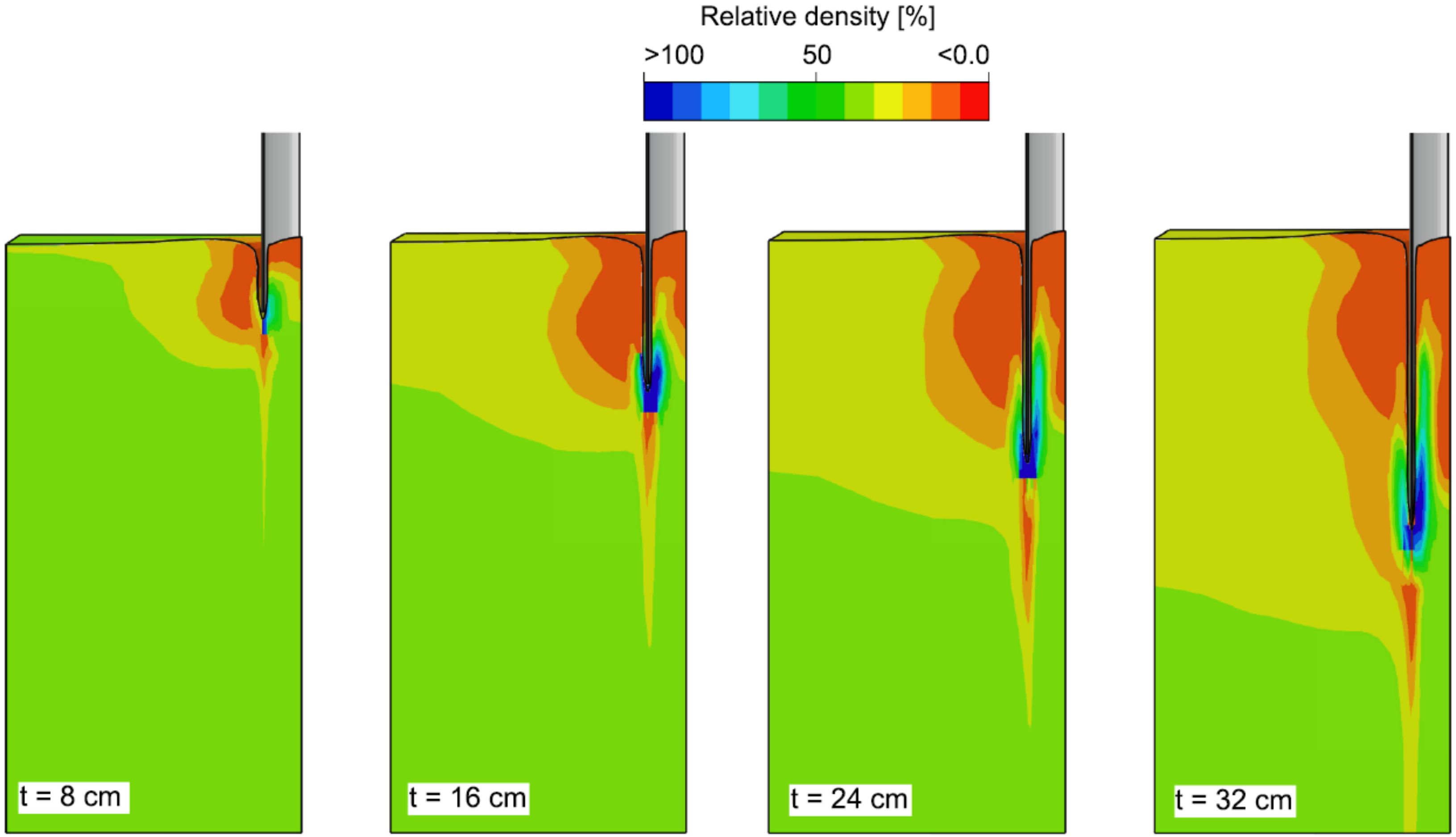
2. How do these effects influence the long term behavior?
   - FEM-Simulation (numgeo)
     - Import of soil state
     - Simulation of 1 Mio. Cycles
     - High-cycle accumulation model



Staubach et al. 2021-2

Application of the CEL and impact of the installation on long-term behavior

Model tests by Le Blanc et al. 2010 – Change of relative density for test $D_{r0} = 38\ \%$

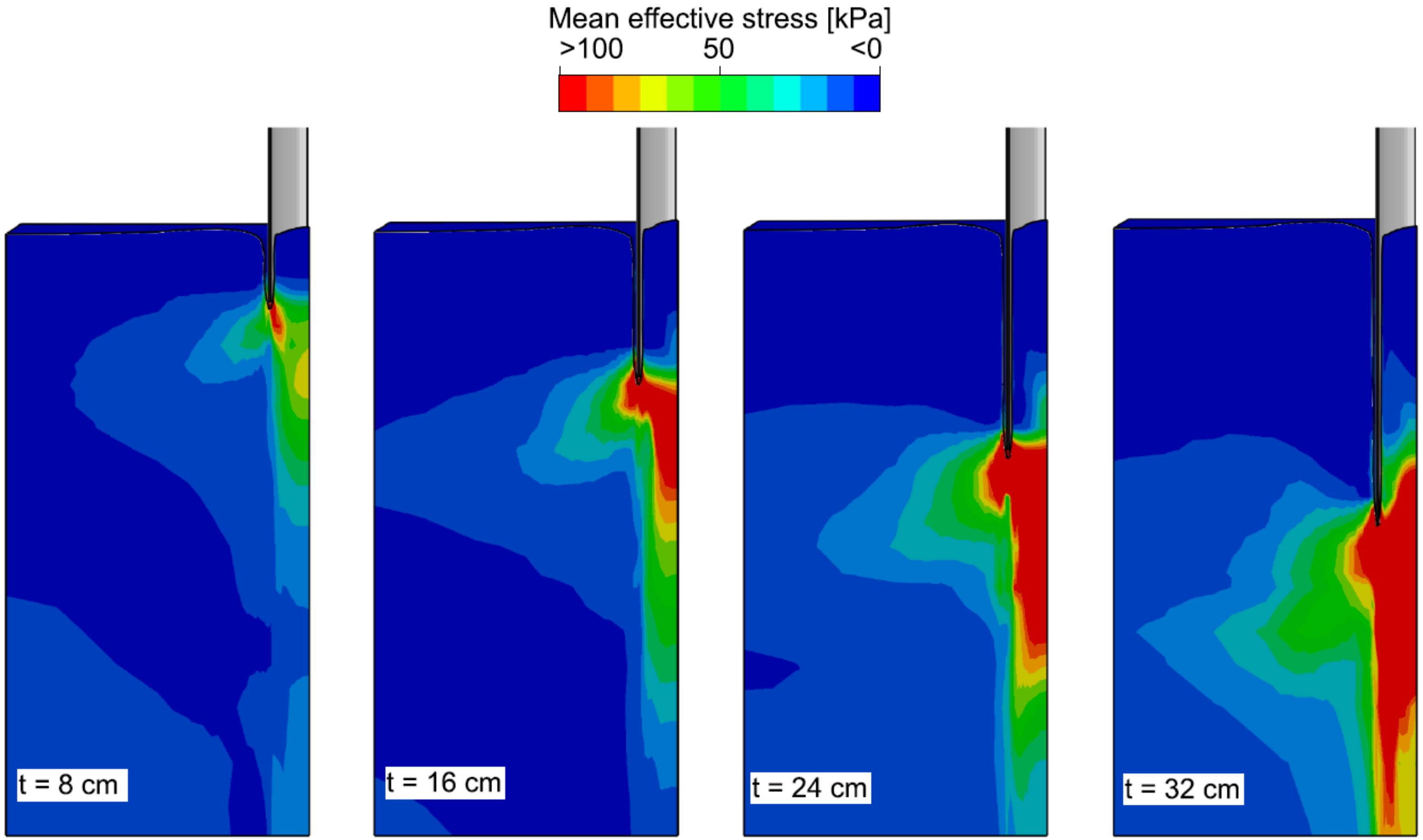


- The soil near the top surface heaves and reaches a very loose state
- Considerable densification in the vicinity of the pile tip
  - More pronounced in the inside than the outside
  - Restricted to areas close to the pile shaft
- Results comparable to simulations of impact driving or jacking of real-scale piles, cf. Staubach et al. 2021 and 2020

Staubach et al. 2021-2

Application of the CEL and impact of the installation on long-term behavior

Model tests by Le Blanc et al. 2010 – Change of mean effective stress for test $D_{r0} = 38\ \%$

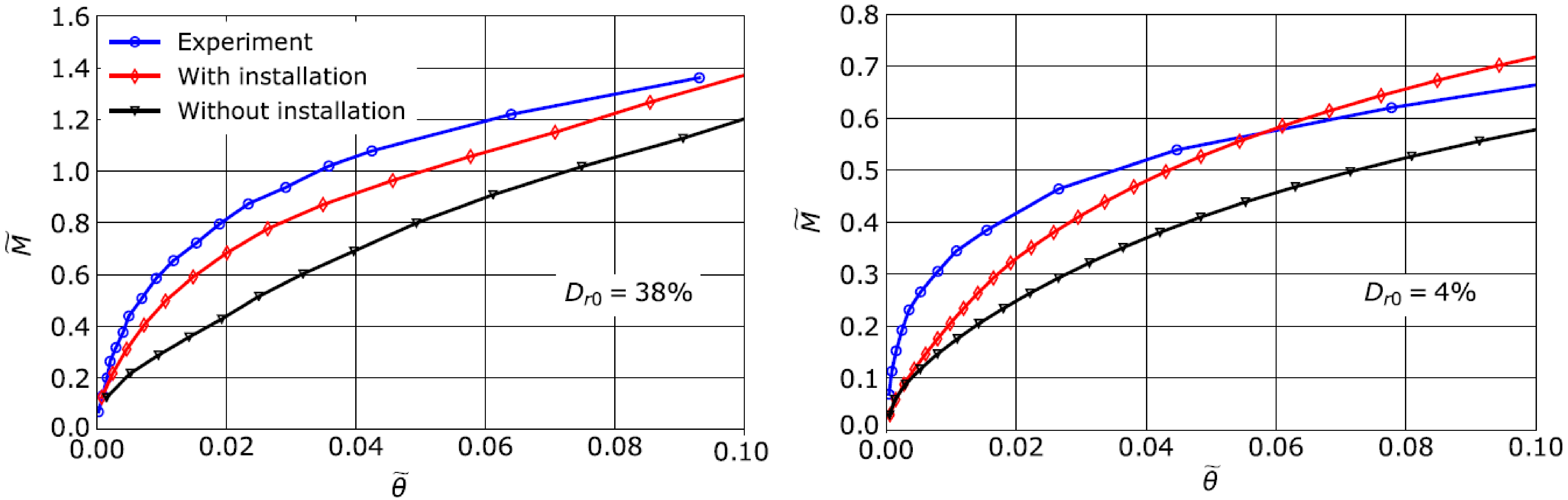


- Strong increase of mean eff. stress below the pile tip
- During the driving process, the area of high eff. stress increases and eventually reaches the fixed bottom of the model (container)
- Strong decrease of eff. Stress alongside the (outer) pile shaft is
- Results comparable to simulations of impact driving or jacking of real-scale piles, cf. Staubach et al. 2021 and 2020 and experiments cf. White & Bolton 2004, White & Mark 2011

Staubach et al. 2021-2

Application of the CEL and impact of the installation on long-term behavior

Model tests by Le Blanc et al. 2010 – Influence on monotonic loading to failure

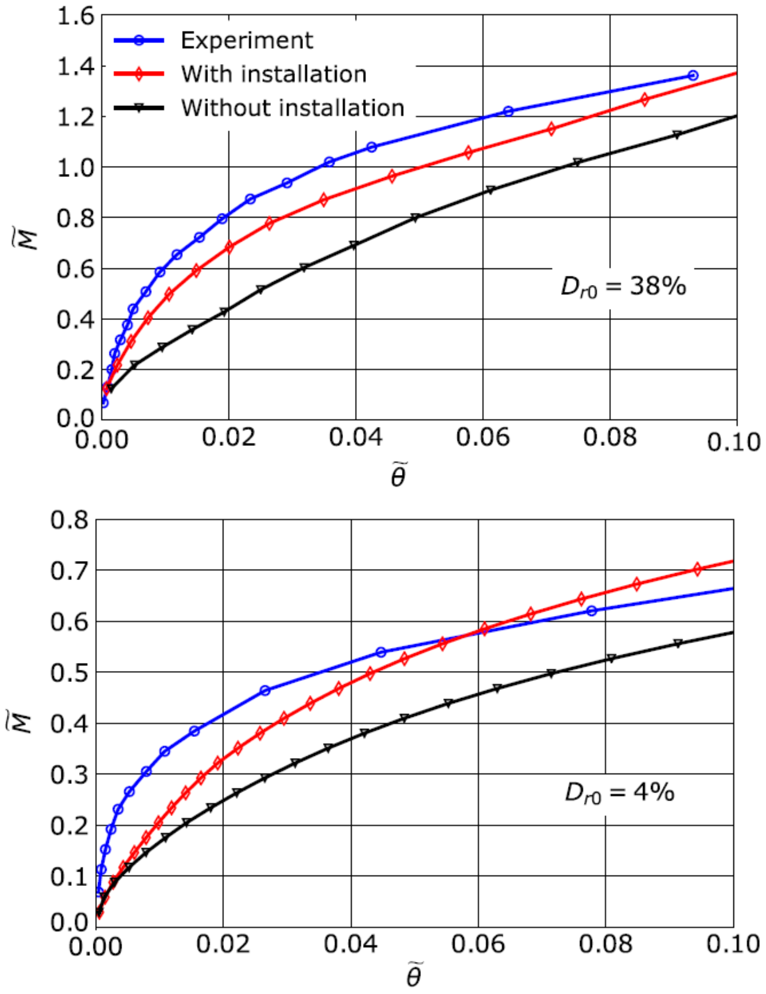


$$\widetilde{M} = \frac{M}{L^3 D \gamma} \qquad \widetilde{\theta} = \theta \sqrt{\frac{p_a}{L\gamma}}.$$

Staubach et al. 2021-2

Application of the CEL and impact of the installation on long-term behavior

Model tests by Le Blanc et al. 2010 – Influence on monotonic loading to failure

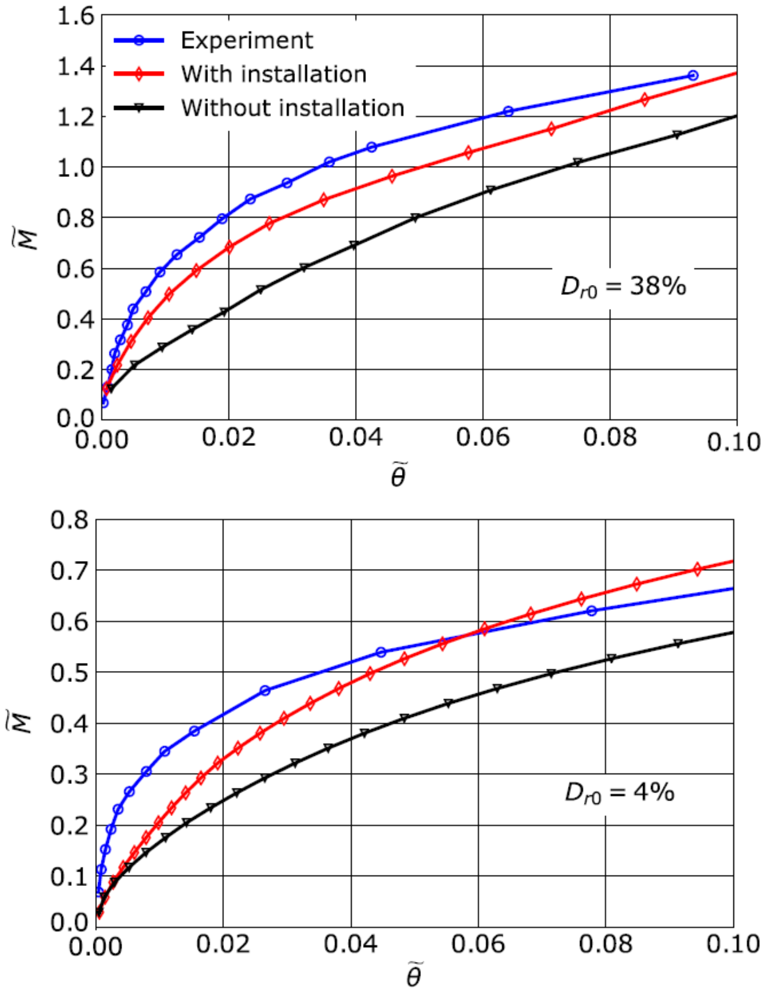


- Without consideration of the installation process the resistance of the pile is strongly underestimated
- This is especially true for initial stiffness of the pile

Staubach et al. 2021-2

Application of the CEL and impact of the installation on long-term behavior

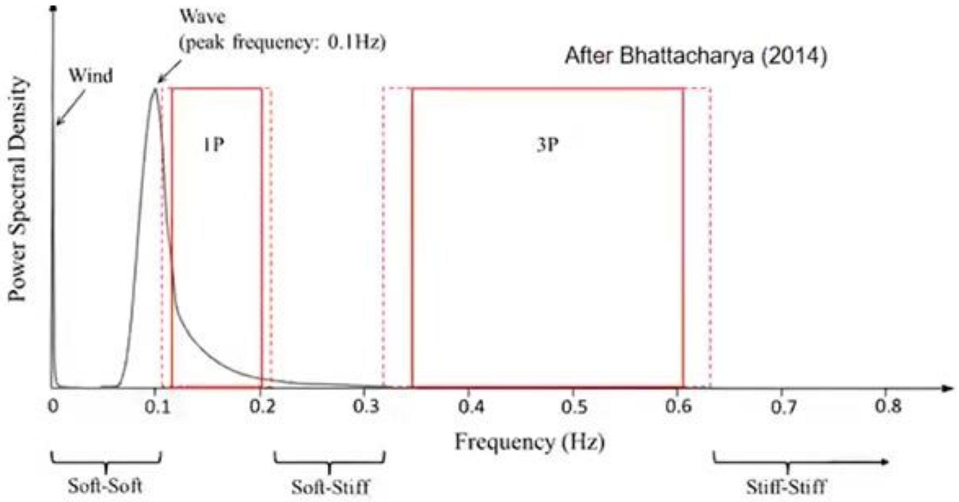
Model tests by Le Blanc et al. 2010 – Influence on monotonic loading to failure



Staubach et al. 2021-2

- Without consideration of the installation process the resistance of the pile is strongly underestimated
- This is especially true for initial stiffness of the pile

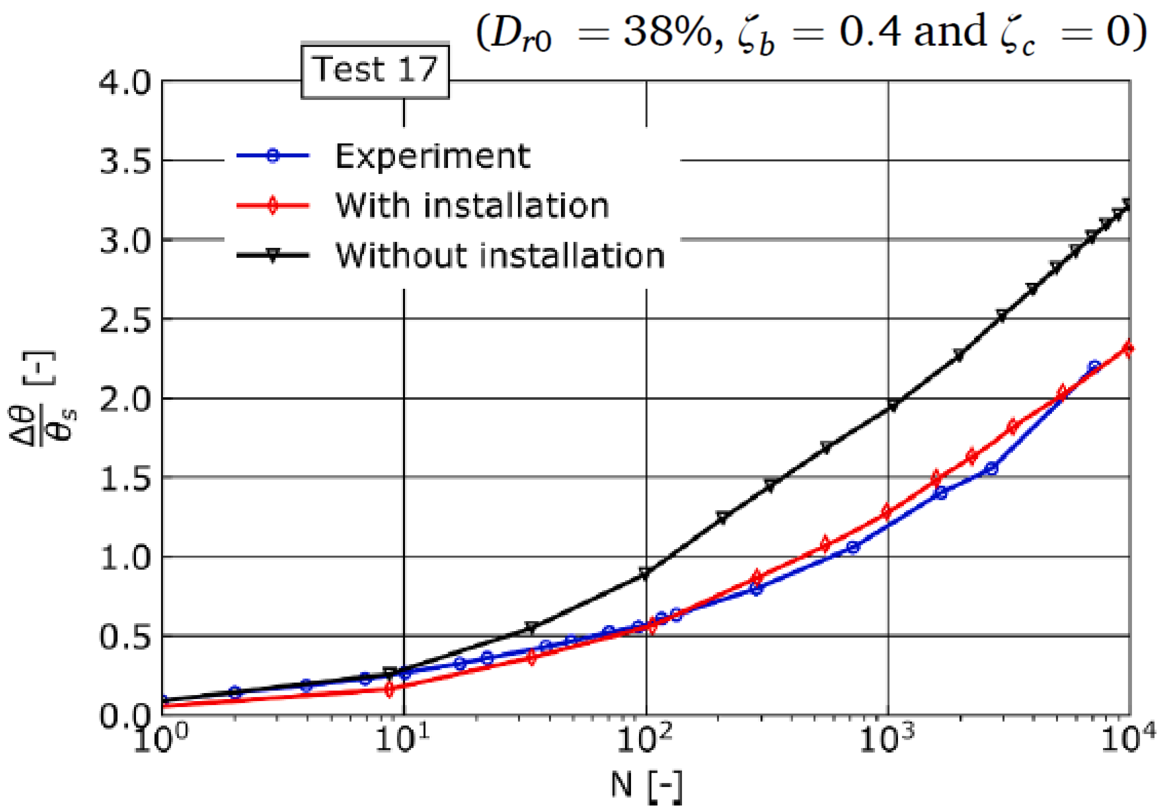
- Are wished-in-place conditions conservative assumptions?
  - … the stiffness and hence the natural frequency of the pile is underestimated…
  - Remember:



Bienen 2021

Application of the CEL and impact of the installation on long-term behavior

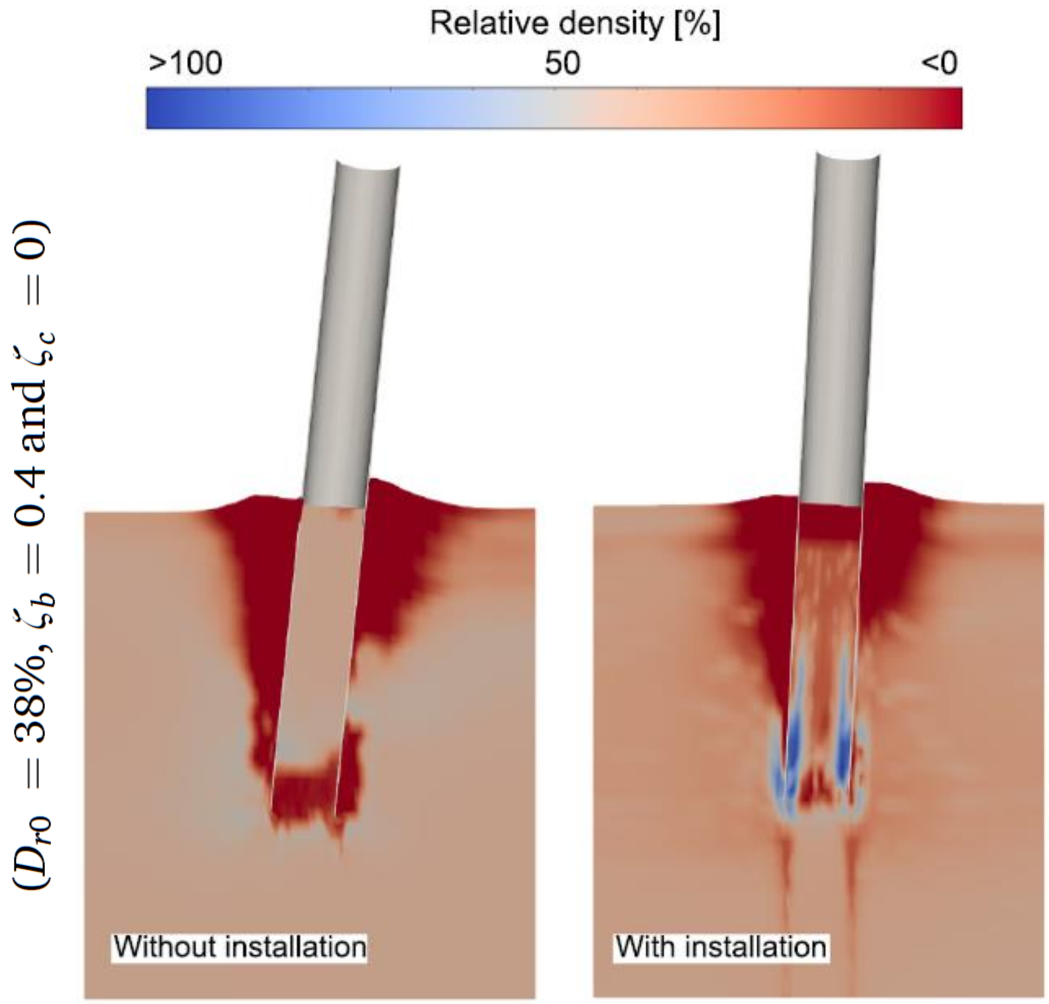
Model tests by Le Blanc et al. 2010 – Influence on long-term behavior



- Without consideration of the installation process the accumulated rotation is overestimated

Application of the CEL and impact of the installation on long-term behavior

Model tests by Le Blanc et al. 2010 – Influence on long-term behavior



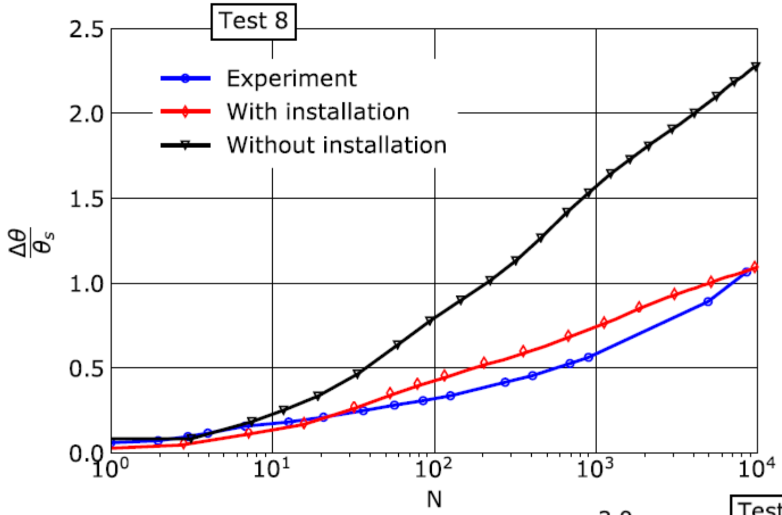
Staubach et al. 2021-2

- Without consideration of the installation process the accumulated rotation is overestimated
- Strong decrease in soil density accompanied by a heave of the soil around the pile at the top surface
- Even after 10.000 cycles the effects of the installation process are clearly visible (higher relative density at the pile tip)
  - Other studies have shown that these differences equalize with ongoing cyclic loading (5 Mio. cycles) , cf. Staubach et al. 2021

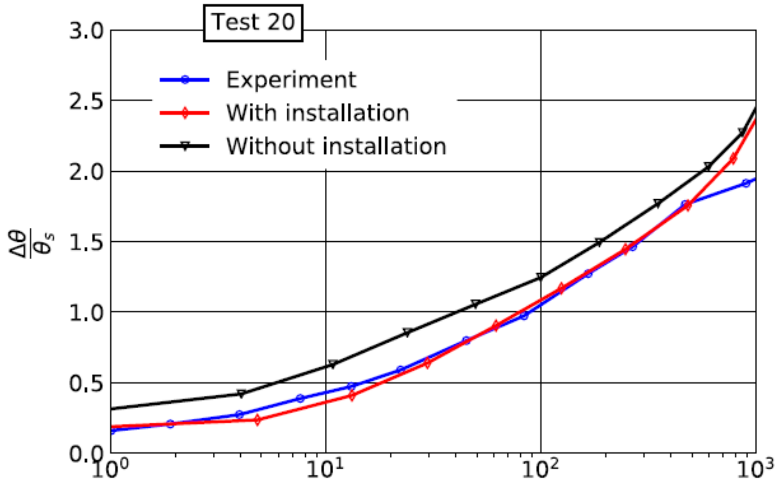
Application of the CEL and impact of the installation on long-term behavior

Model tests by Le Blanc et al. 2010 – Influence on long-term behavior

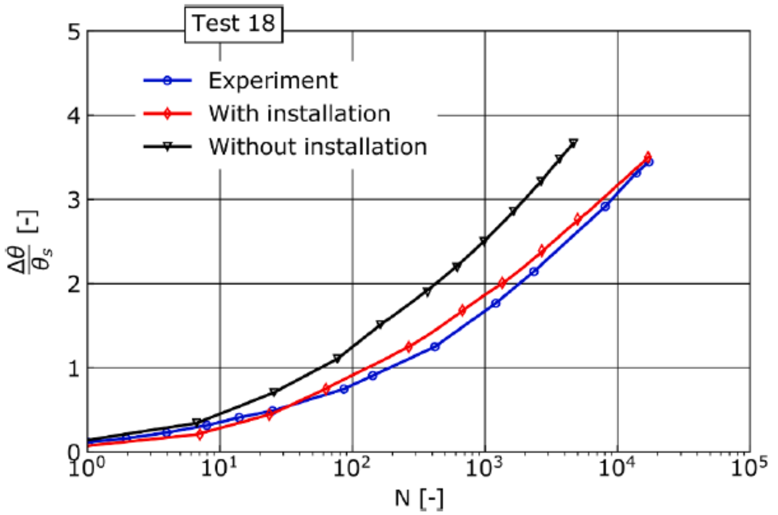
$(D_{r0} = 4\%,\ \zeta_b = 0.34 \text{ and } \zeta_c = 0)$

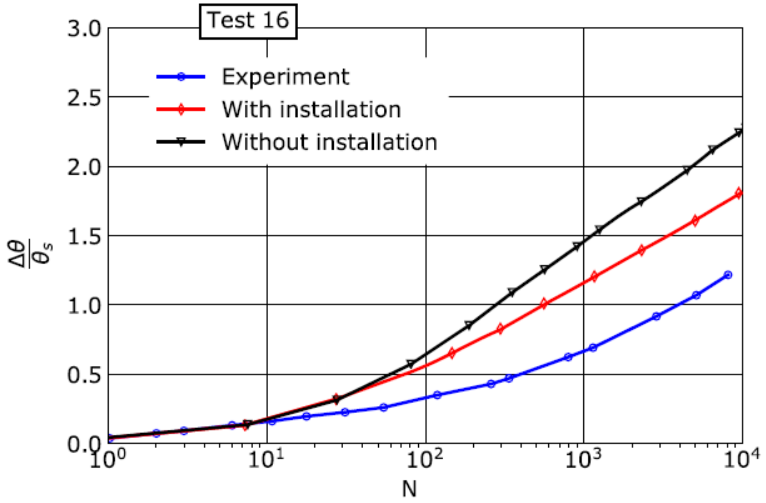


$(D_{r0} = 38\%,\ \zeta_b = 0.4 \text{ and } \zeta_c = -0.8)$



$(D_{r0} = 38\%,\ \zeta_b = 0.52 \text{ and } \zeta_c = 0)$





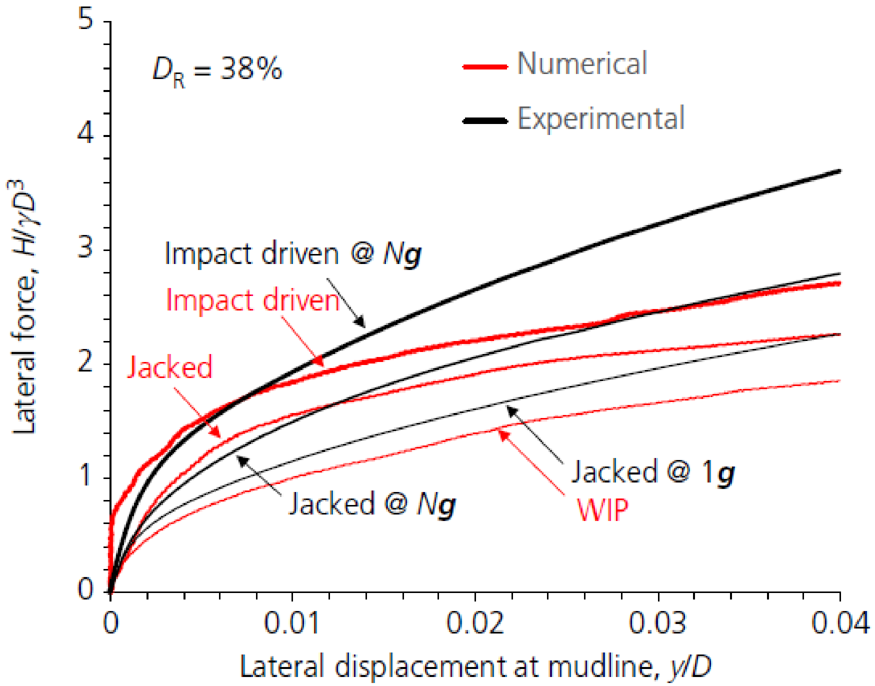
- The same can be observed in all tests

Staubach et al. 2021

Application of the CEL and impact of the installation on long-term behavior

Centrifuge tests by Fan et al. 2019 (and Bienen et al. 2021)

- ➢ The same approach was used by an independent research group at the University of Western Australia (restricted to dry or ideally drained conditions)
- ➢ Back calculation of centrifuge tests (see slide "*Simulation strategies – Why?*")



- ➢ Similar observations regarding installation induced changes in stress and density
- ➢ Tests an simulations were performed on two different sands
  - ➢ Although similar behavior is observed, the extend may differ noticeably depending on the material!

See Bienen et al. 2021

Summary

Simulation strategies – Summary

I. Pile installation methods

- Conventional methods
- Combined axial and torsional driving
- A nice introduction to the topic is offered, for example, by the presentation of Harnett and Hippe:

(2) Installation of large monopiles as offshore wind foundations using impact hammers or drills - YouTube

Summary

I. Pile installation methods
   - Conventional methods
   - Combined axial and torsional driving

II. Numerical simulation of pile installation
   - The pile response to (subsequent) loading depends on the installation method
   - Not yet fully understood – numerical modelling might help
   - Challenges:
     - Large deformation analyses
     - Fully coupled dynamic simulations
     - Constitutive models
     - Contact models
   - Methods for large deformations: MPM, SPH, DEM, CEL, …
   - Fully coupled CEL with Abaqus

Summary

I. Pile installation methods
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     - Constitutive models
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   - Methods for large deformations: MPM, SPH, DEM, CEL, …
   - Fully coupled CEL with Abaqus

III. Application of the CEL to the installation of monopiles
   - Influence on subsequent lateral loading
   - Comparison to experimental data

Summary

Note that…

- There is no single publication showing the simulation of pile installation using vibratory pile driving (of monopile foundations) taking into account all installation parameters!
  - Frequency
  - Static load
  - Penetration velocity
  - Dynamic force
- All these parameters are crucial for the bearing capacity of piles after installation

Labenski 2019, Achmus et al. 2020

- Simulations considering large scale Monopiles ($d \geq 10$ m) are still missing

- Incorporation of grain crushing (and ist effects) still pending

- So far, only simple contact formulations have been used

- There is a lot of work to do! ☺

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MPM-Codes:

Anura3D	Anura3D (mpm-dredge.eu)
Cb-geo	GitHub - cb-geo/mpm: CB-Geo High-Performance Material Point Method

Applicability of constitutive models by means of an example