BAM
Bundesanstalt für Materialforschung und -prüfung

Sicherheit in Technik und Chemie

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ALERT Workshop 2017

Modelling of compaction grouting using the implicit MPM

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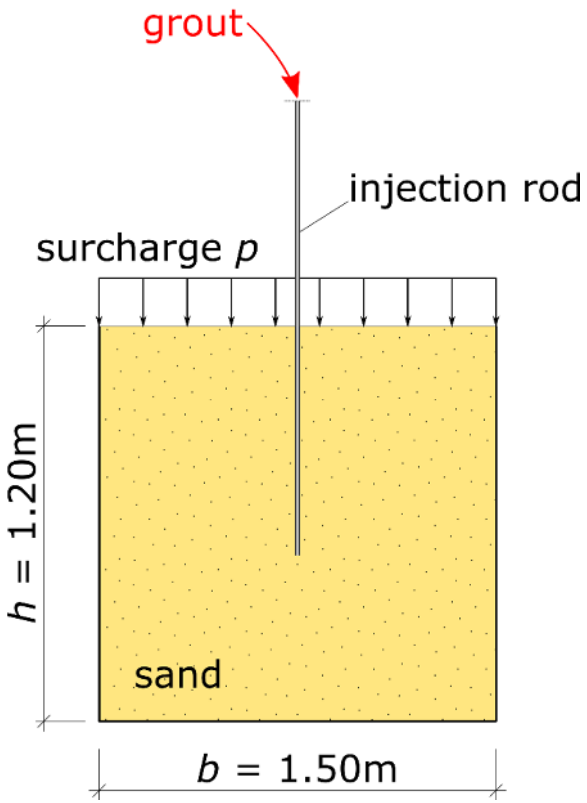
Compaction grouting

Definition (DIN EN 12715, October 2000)

"A displacement grouting method which aims at forcing a mortar of high internal friction into the soil to compact it without fracturing it."



- Distinct grout-soil interface (filter cake)
- Displace the surrounding soil
  - → increase the bulk density
  - → increase the bearing capacity

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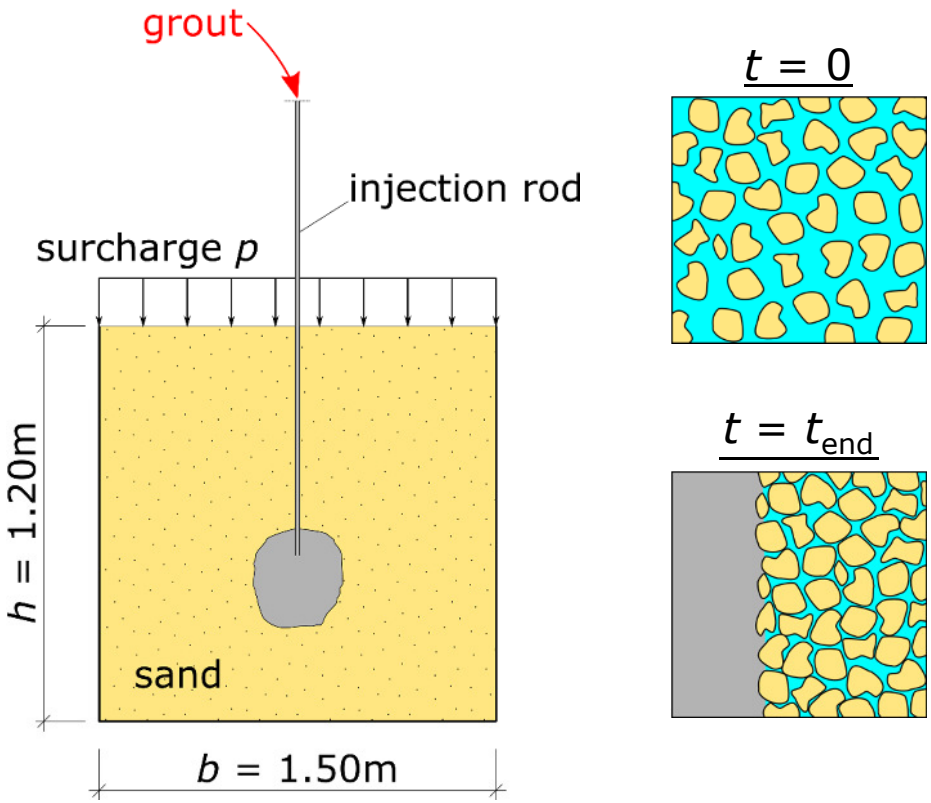

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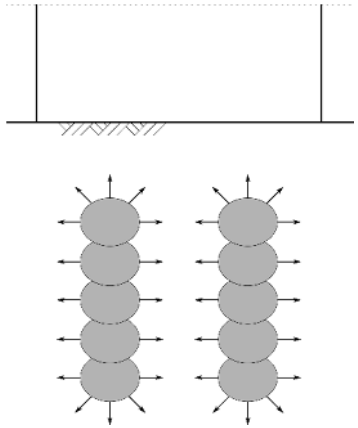
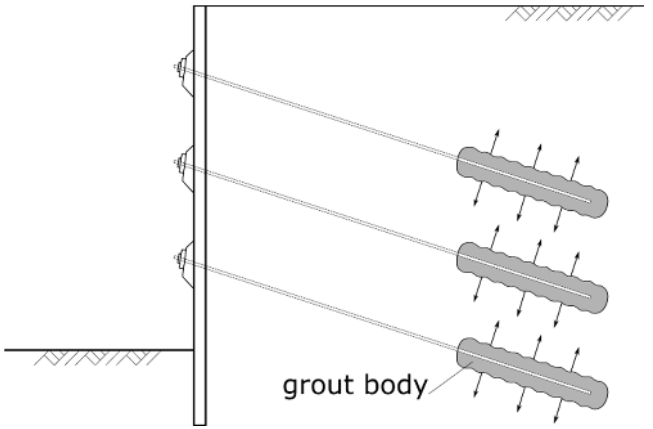
  → **increase the bearing capacity**

Compaction grouting – Fields of application

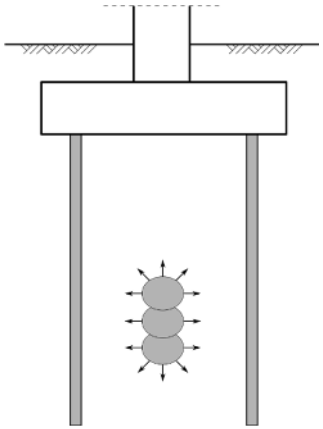


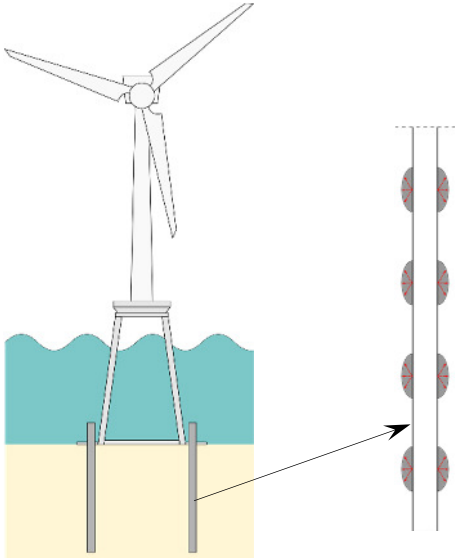
Settlement control (grouted columns)



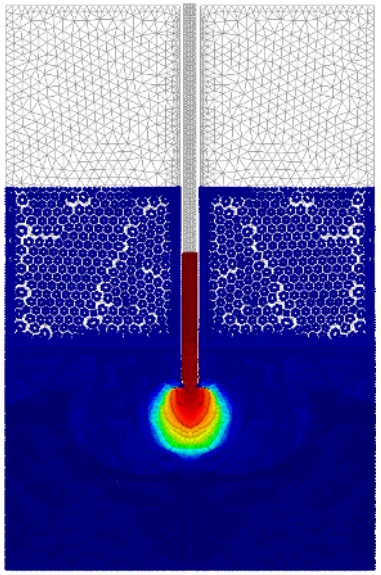
Stabilisation (ground anchors)

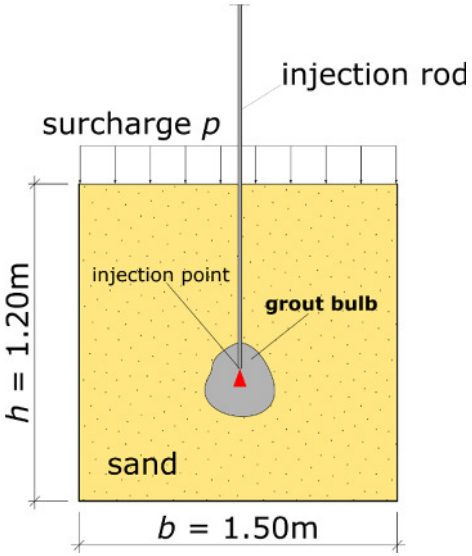
Retrofitting
(bearing capacity of pile foundations)

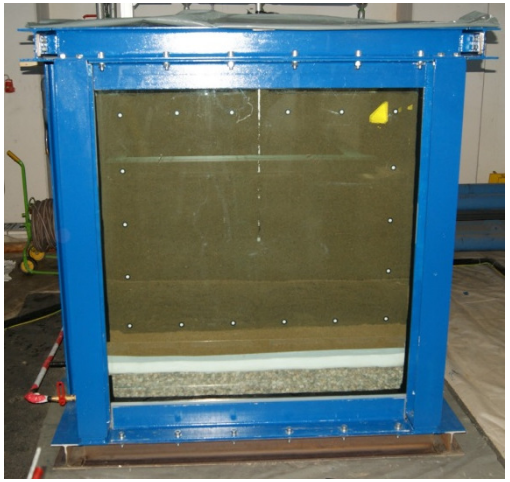




Challenges







Numerical simulation

Numerical method
- large deformations
- constitutive models

Software
- open source
- easily adaptable

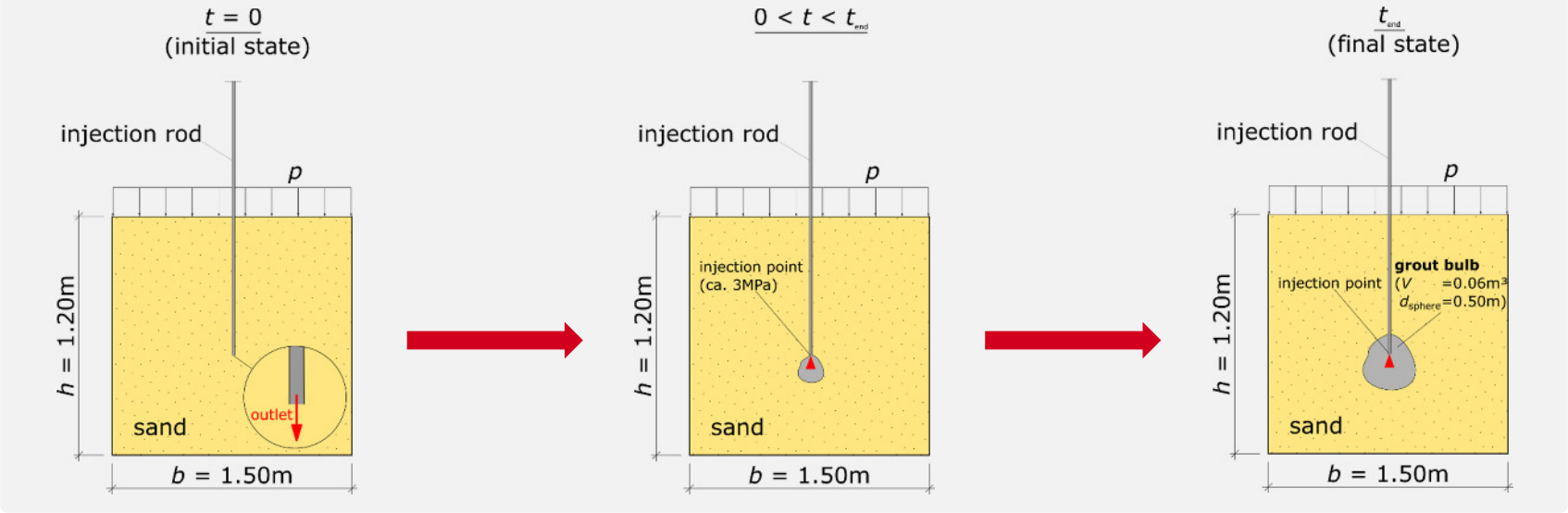
Experiments

General concept
- setup
- procedure

Measurement methods
- Digital image processing (Aramis)

Numerical simulation

Experimental setup (water saturated sand, drained condition)



Challenges

- "free growth" of the grout bulb
- large deformations (mesh distortion)
- proper constitutive laws
- geometric and material nonlinearity

Numerical simulation

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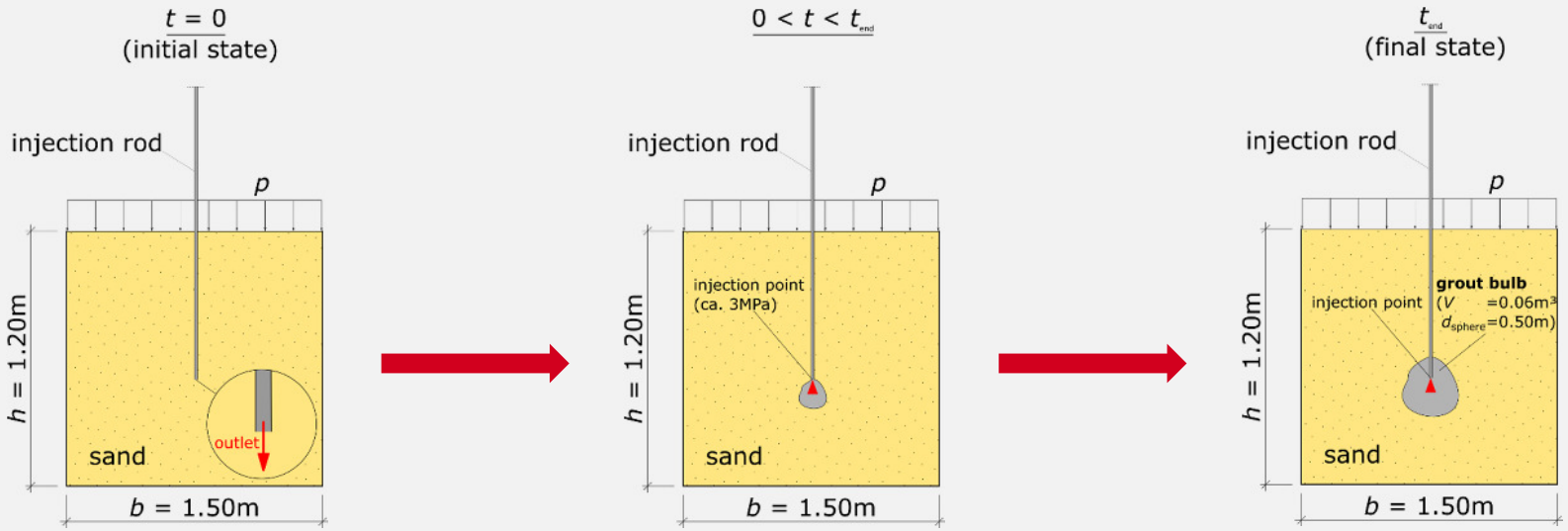

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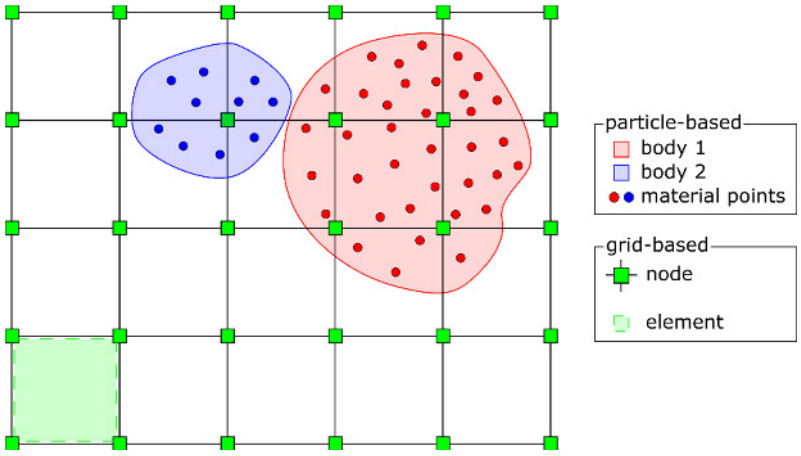
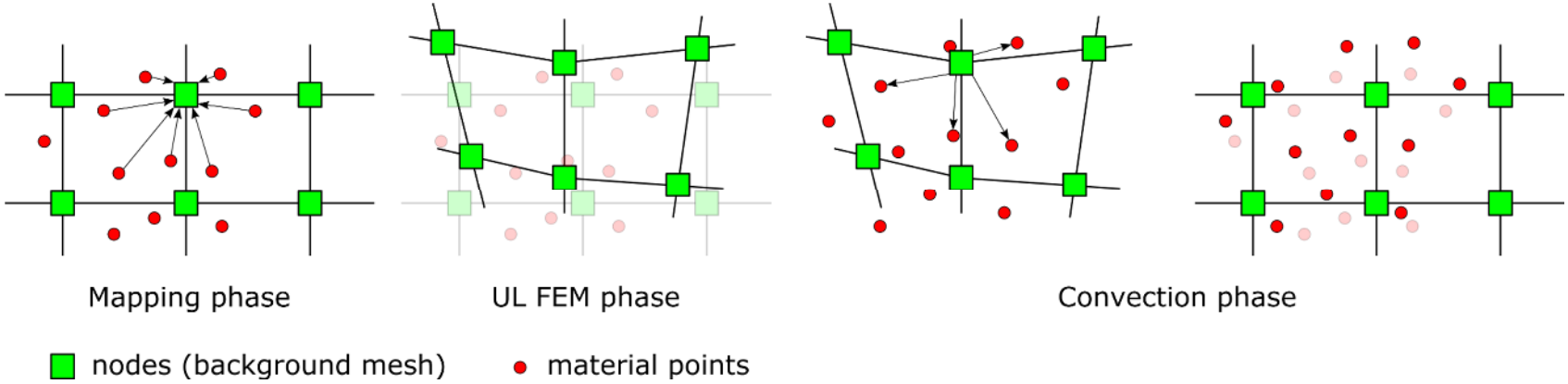
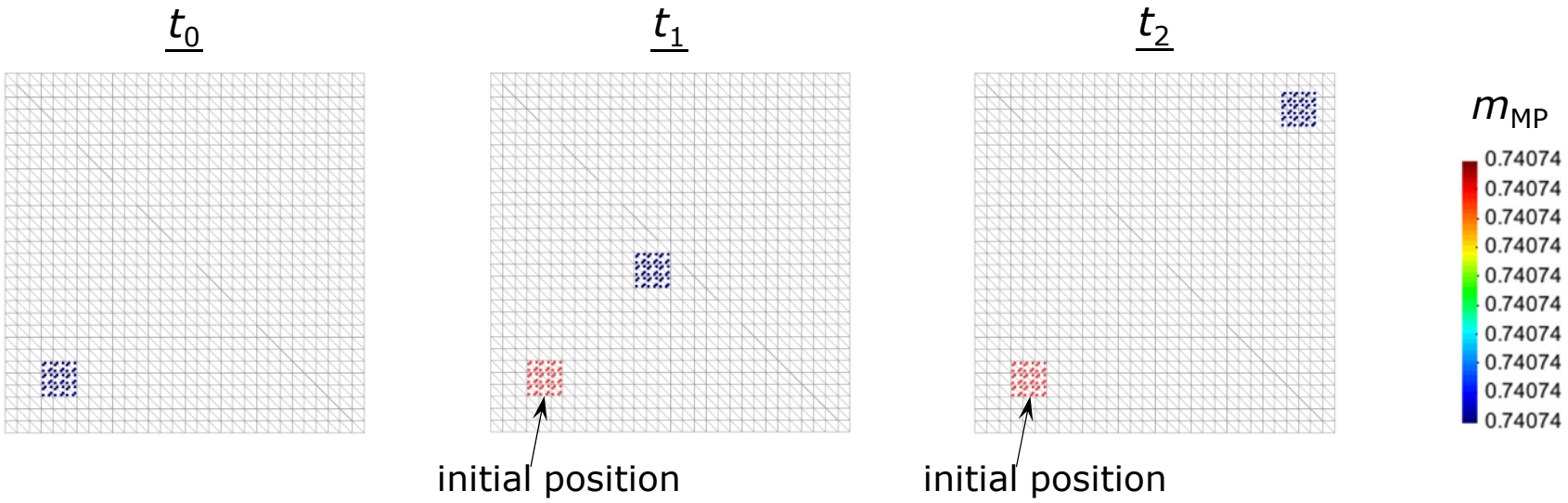
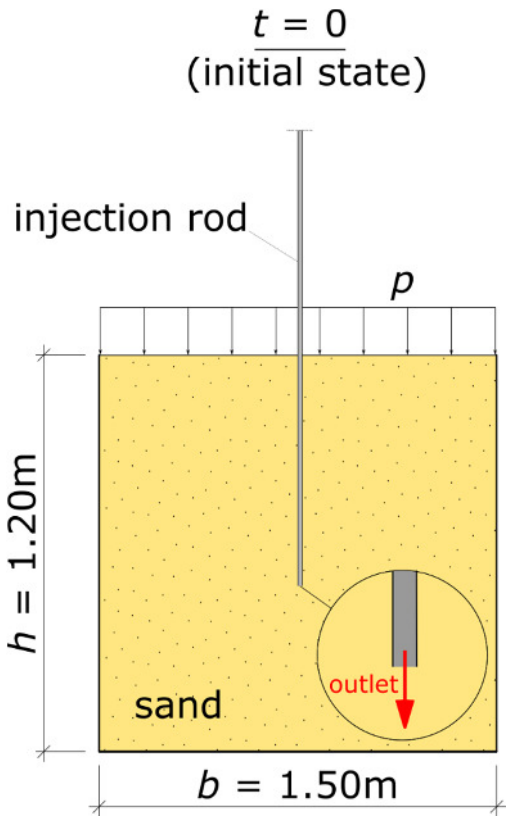


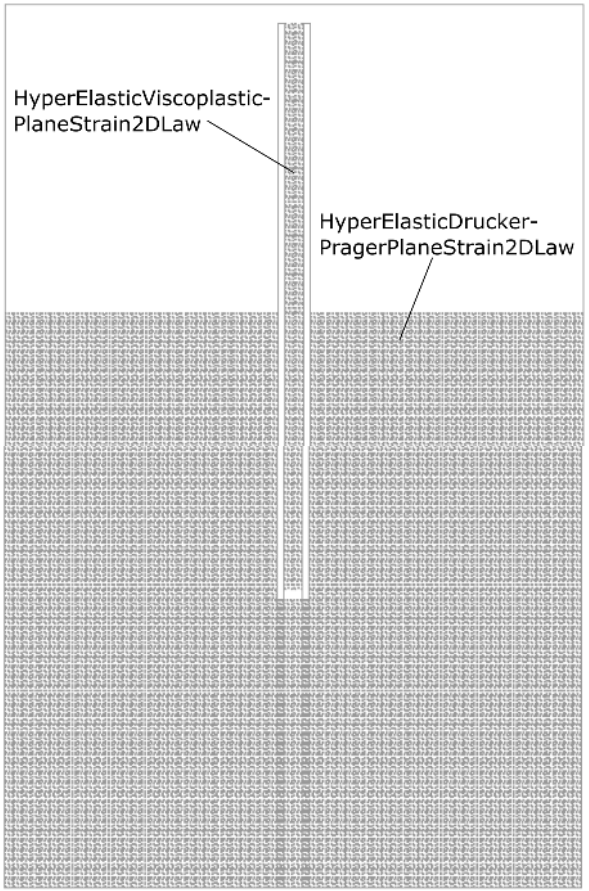
Numerical simulation – Material Point Method (MPM)





MPM (DOF: *u* formulation)





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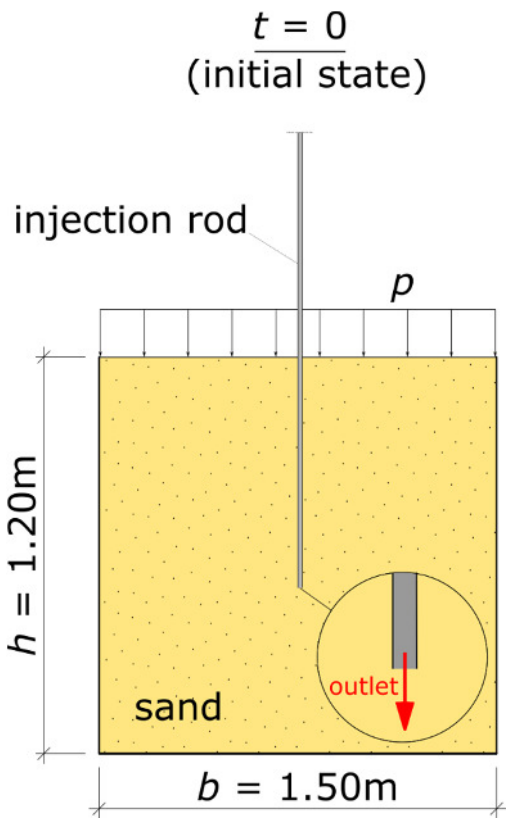
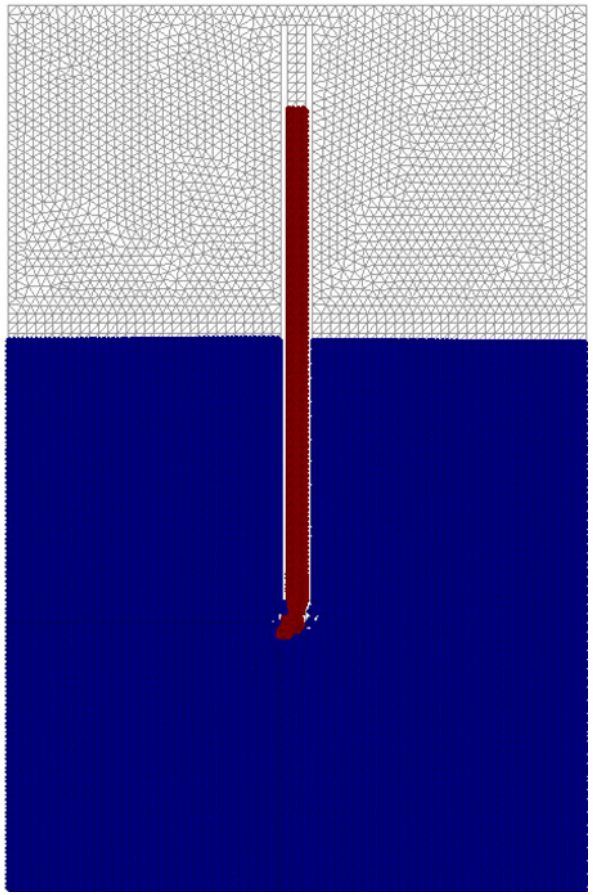


Problem:
only applicable to low soil stiffness



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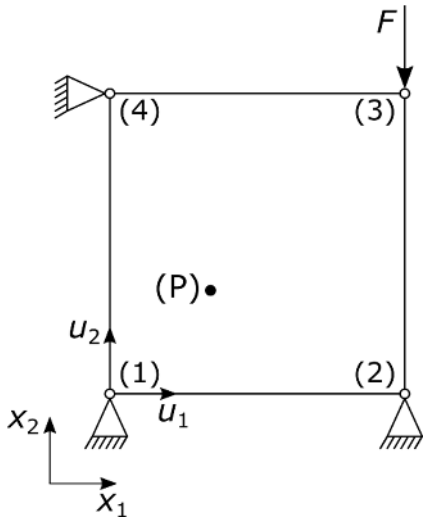

$$\varepsilon_V = 0 = \mathrm{tr}(\boldsymbol{\varepsilon}) = \varepsilon_{11} + \varepsilon_{22} + \varepsilon_{33}$$

$$= \frac{\mathrm{d}u_1}{\mathrm{d}x_1} + \frac{\mathrm{d}u_2}{\mathrm{d}x_2} \text{ (2D)}$$

$$\rightarrow \underline{\underline{u_{(3)} = 0}} \rightarrow \text{element locks (zero displacement field)}$$

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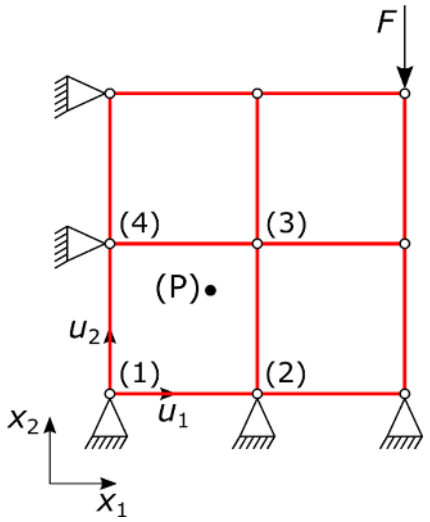

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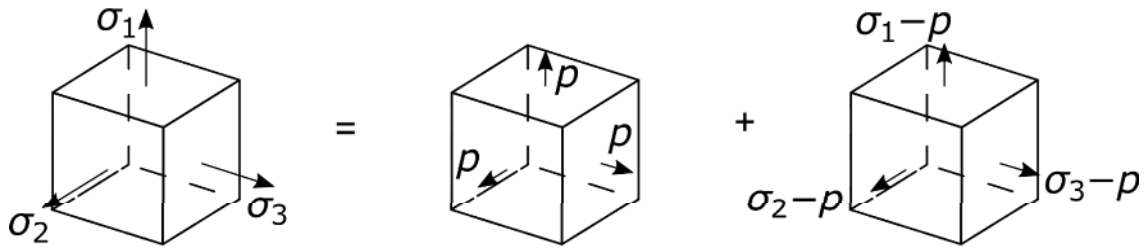
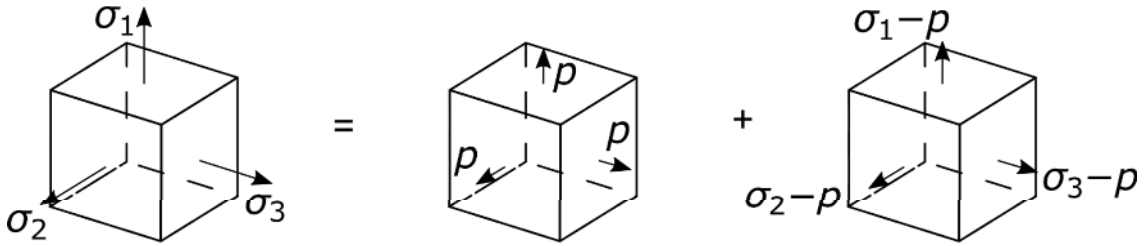


principal stress state = hydrostatic stress + deviatoric stress

MPM (DOF: *u-p* formulation)



principal stress state = hydrostatic stress + deviatoric stress

$$g_{\mathrm{mom}} = \int_{\varphi(B)} \delta\underline{u} \cdot \ddot{\underline{u}} \cdot \rho_{\mathrm{c}} \mathrm{d}v + \int_{\varphi(B)} \delta\boldsymbol{\varepsilon} : \underbrace{(\boldsymbol{p} \cdot \boldsymbol{I} + \boldsymbol{\sigma}_{\mathrm{dev}})}_{\boldsymbol{\sigma}} \mathrm{d}v = \delta W_{\mathrm{ext}}$$

$$r_{\mathrm{press}} = \int_{\varphi(B)} \left(\underbrace{\boldsymbol{I} : \boldsymbol{\varepsilon}}_{\varepsilon_{\mathrm{V}}} - p/K \right) \mathrm{d}v = 0$$

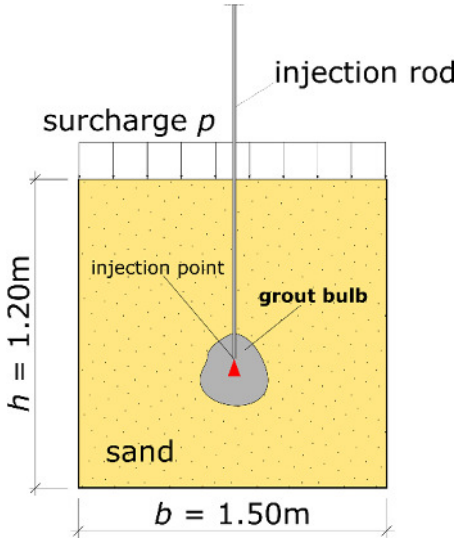
$$\boldsymbol{k}_{\mathrm{T}} \cdot \underline{u}_{\mathrm{DOF}} = \begin{pmatrix} \mathrm{D_u}[g_{\mathrm{mom}}(\overline{\varphi})] & \mathrm{D_p}[g_{\mathrm{mom}}(\overline{\varphi})] \\ \mathrm{D_u}[r_{\mathrm{press}}(\overline{\varphi})] & \mathrm{D_p}[r_{\mathrm{press}}(\overline{\varphi})] \end{pmatrix} \cdot \begin{pmatrix} \Delta\underline{u} \\ \Delta\underline{p} \end{pmatrix} = \begin{pmatrix} \underline{f}_{\mathrm{ext}} \\ \underline{0} \end{pmatrix}$$

→ stabilisation necessary

(e.g. direct pressure stabilisation by Dohrmann & Bochev)

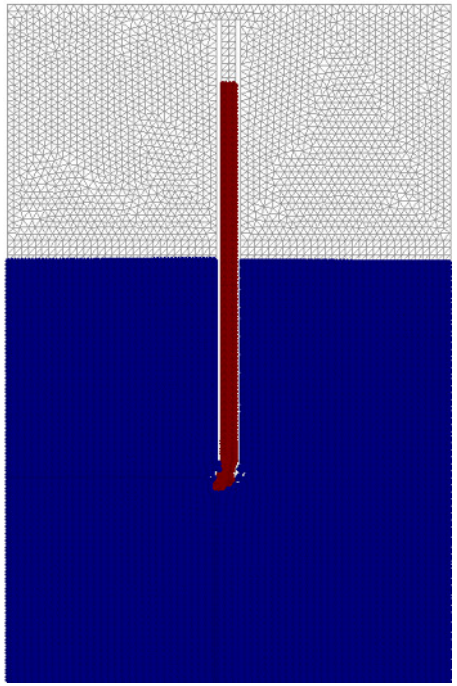
MPM (DOF: *u-p* formulation)

idea



DOF: *u* formulation

(E_{soil} = 1e+5 N/m²)



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DOF: *u-p* formulation

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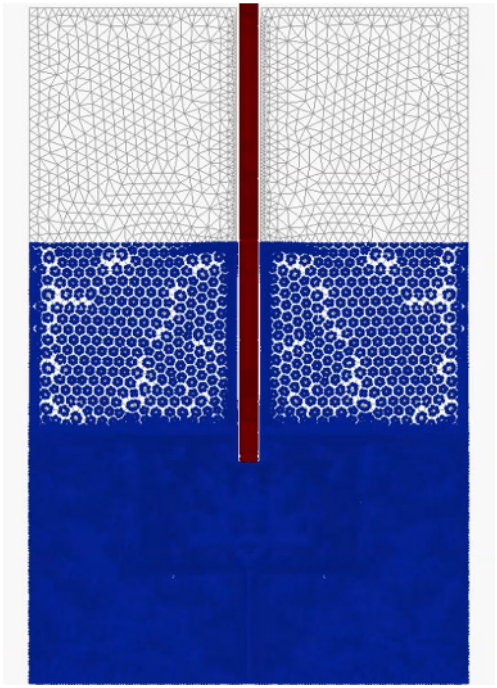
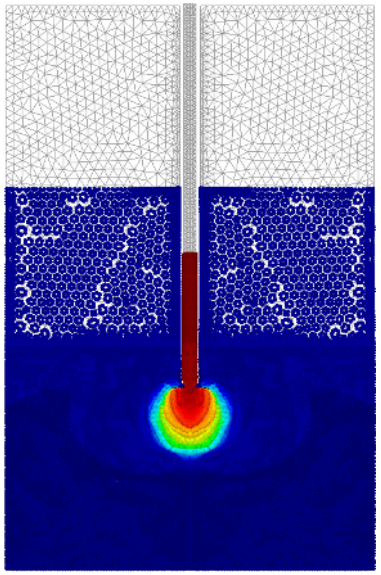
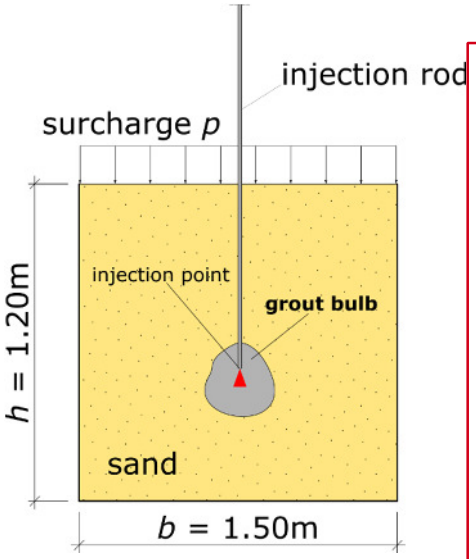


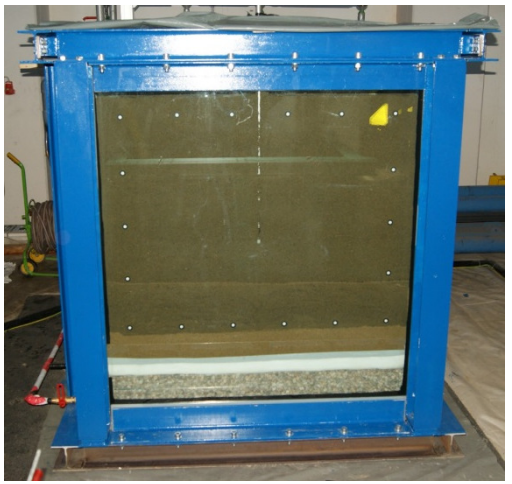
Next steps:

- constitutive models
- rotational symmetry
- validation

Challenges







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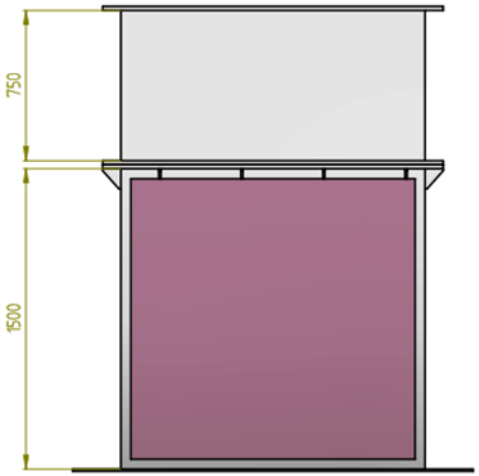
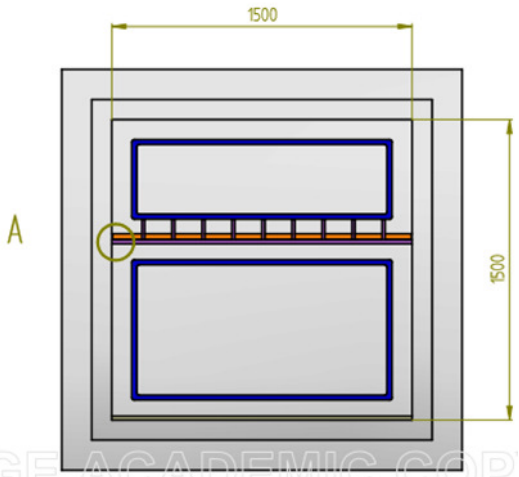
Test container – Setup



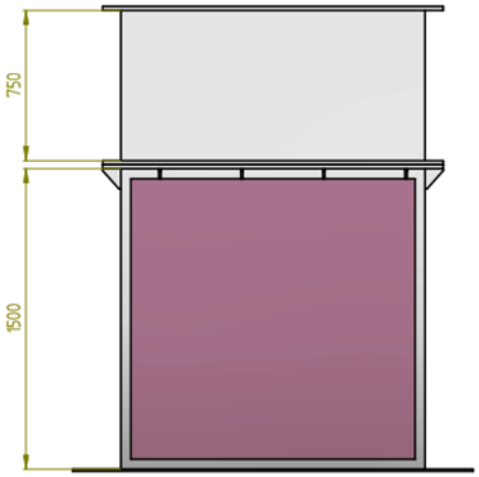


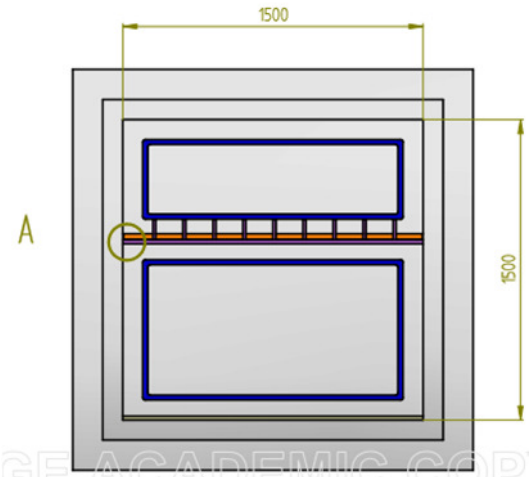
Basic characteristics

- b x h x t: 1.50m x 1.50m (+0.75m) x 1.50m
- glass pane: 110mm thick
- surcharge *p*: 160kN/m²
- drainage: one-sided on the bottom
- injection rod: two locations

(Compaction Grouting Consensus Guide, 2007)

Test container – Setup





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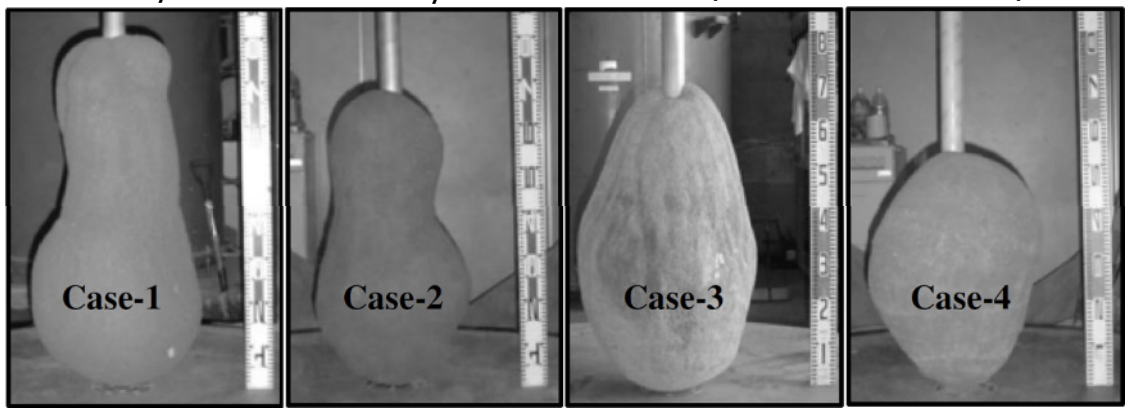
p = 85kN/m² 125kN/m² 165kN/m² 205kN/m²



(El-Kelesh et al., 2007)

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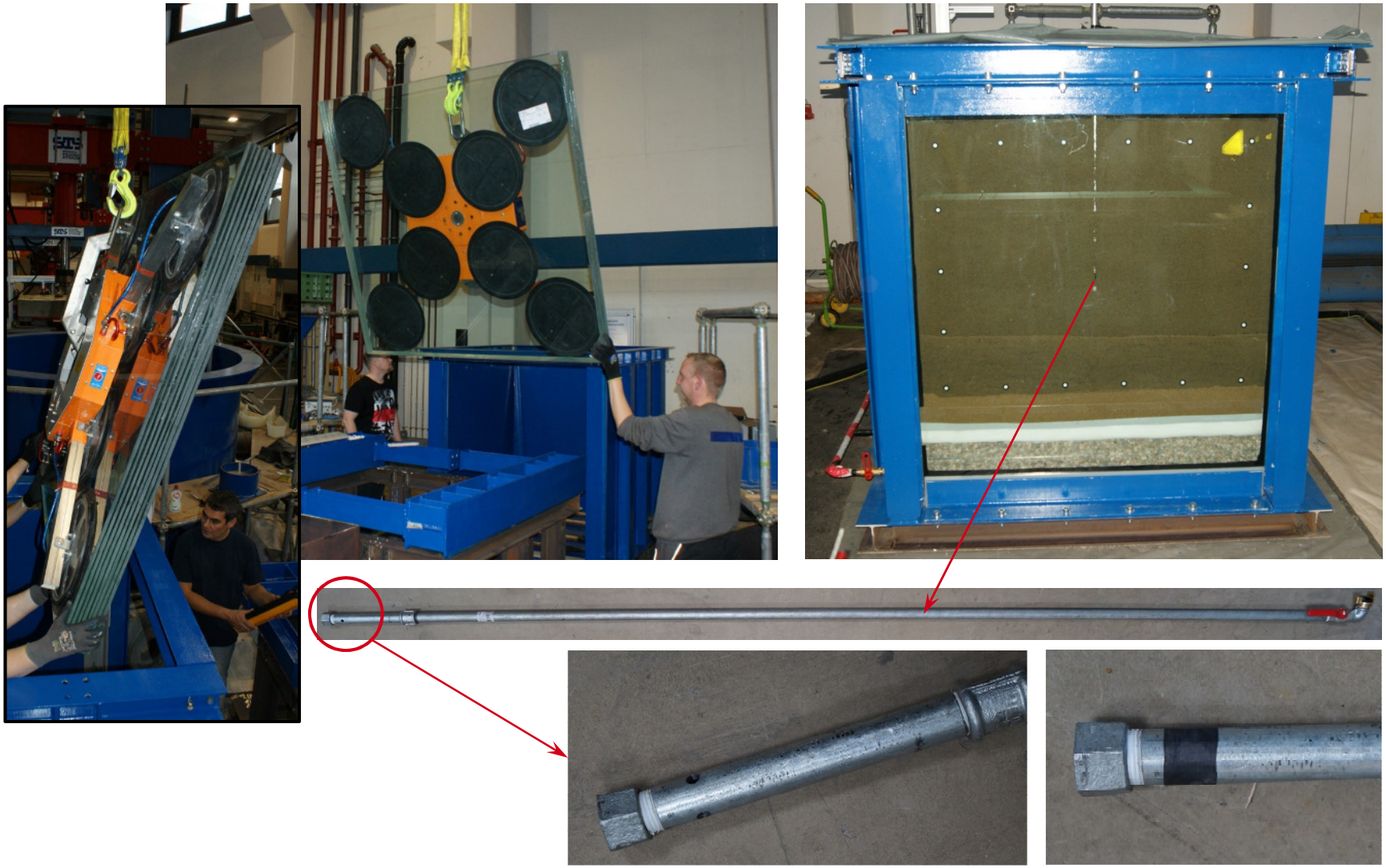
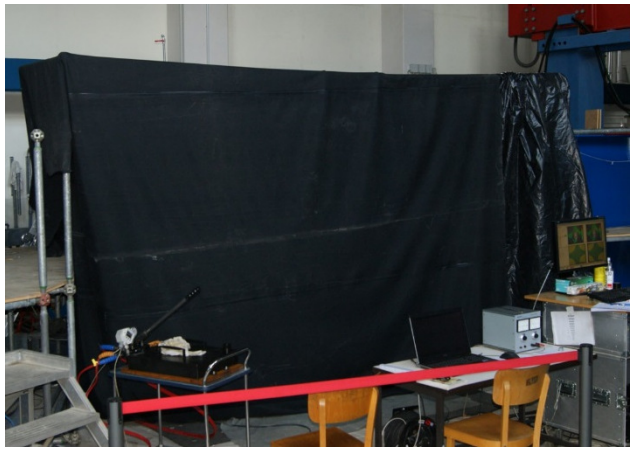


Test container – Digital Image Processing



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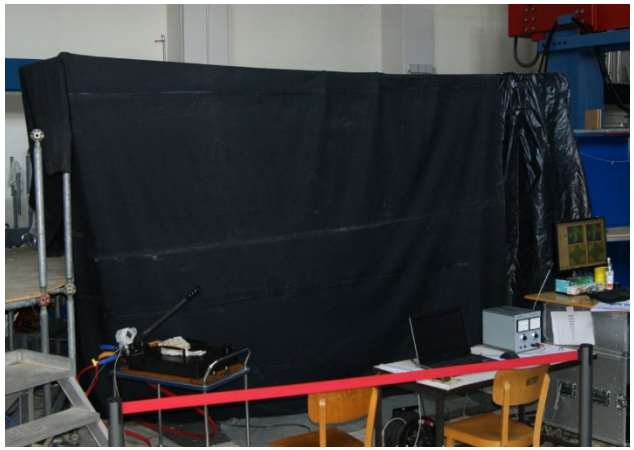
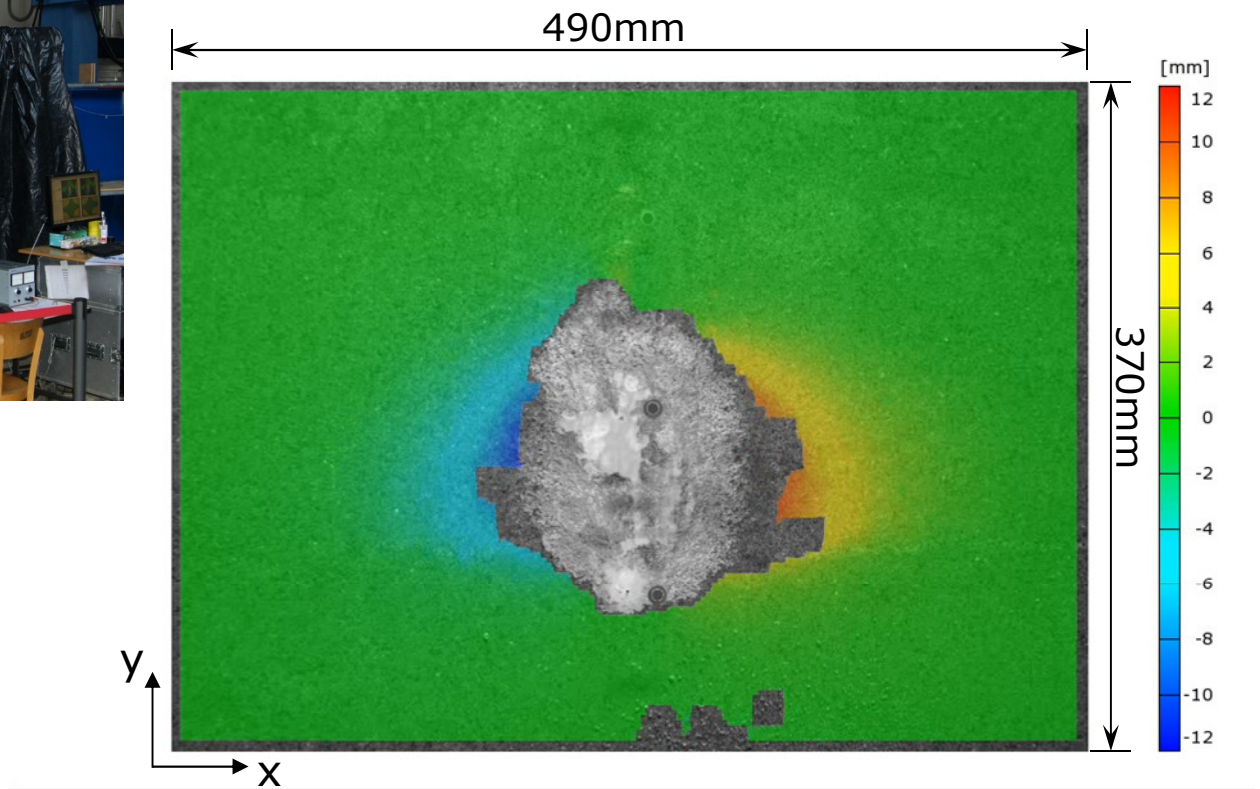
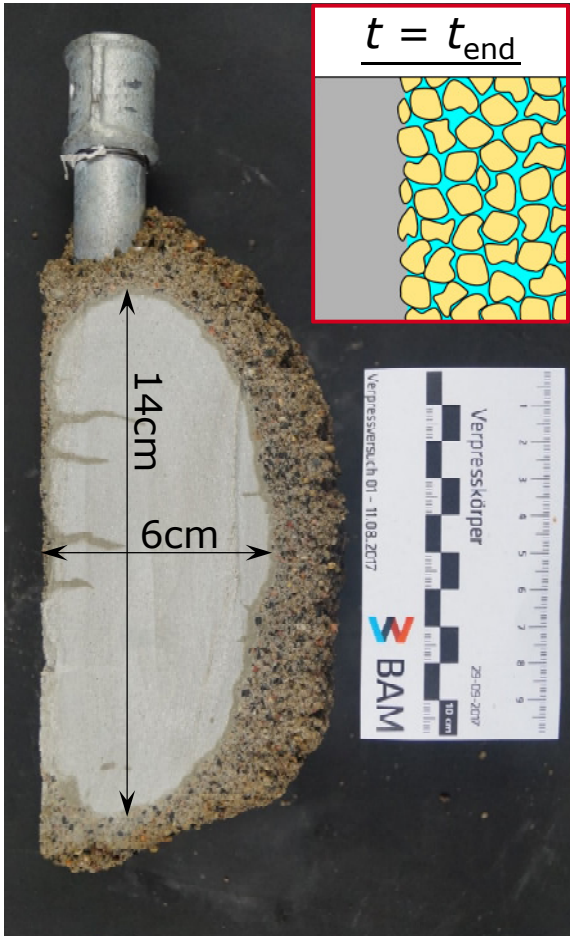




Test container – Grout bulb



Conclusion – Compaction Grouting

Definition (DIN EN 12715, October 2000)

"A displacement grouting method which aims at forcing a mortar of high internal friction into the soil to compact it without fracturing it."

Applications

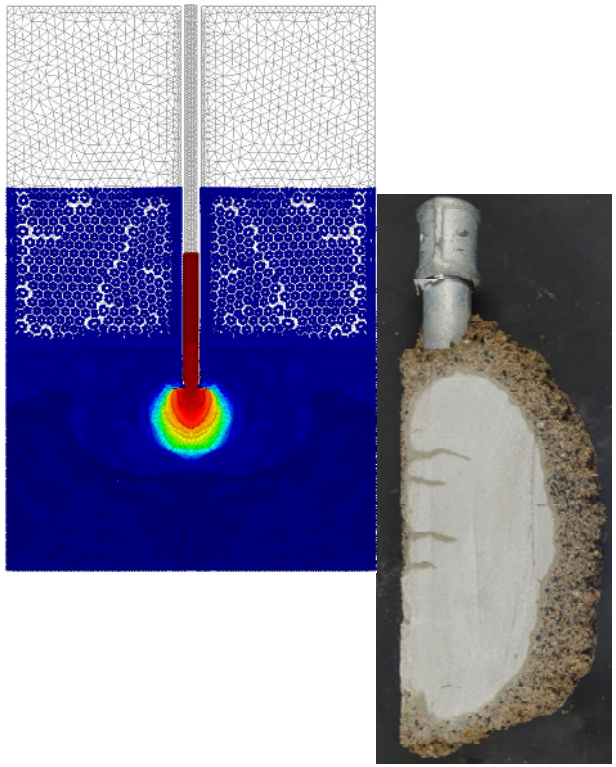
- retrofitting, stabilisation, settlement control

Numerical simulations

- large deformation (Material Point Method)
- incompressibility (*u*-*p* formulation)
- nonlinear behaviour of soil and grout (proper constitutive models)

Experiments

- lab tests (variation of parameters (e.g. surcharge, relative density of sand))
- large-scale tests on pile foundations



Thank you for listening.