Delft University of Technology

Deltares Enabling Delta Life

New developments in numerical modelling of pile installation

Nguyen Phuong, Frits van Tol, Alexander Rohe

18 September 2014 | KIVI Geotechnical Lectures Evening | TU Delft

Displacement piles → installation effects

Bearing capacity (vertical/lateral) depending on :

- installation method
  - jacking
  - impact driving
  - vibratory driving
- soil type (sand, clay)
- initial soil conditions (density, OCR)
- pile type, shape and size (open, closed)

Application :

- onshore
- offshore

Installation methods (displacement piles)

jacking

impact driving

vibratory driving

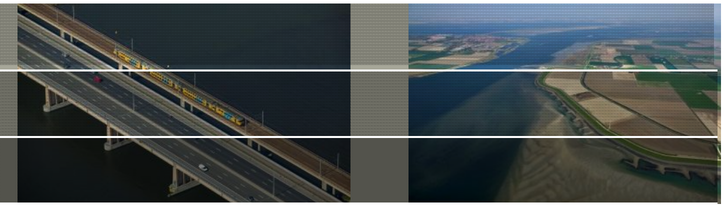
Testing pile capacity

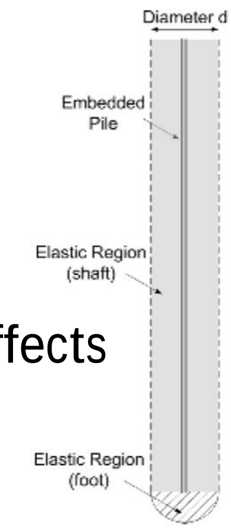
static load test (SLT)

lateral load test

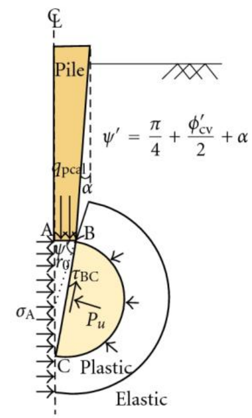
rapid load test (RLT)

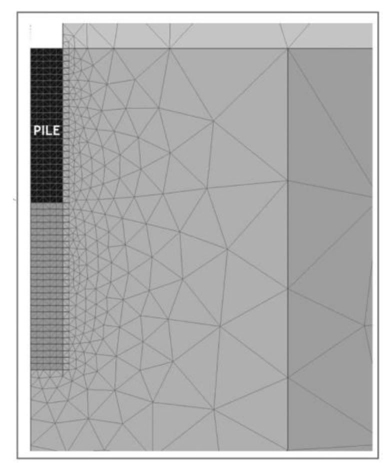
Current approaches

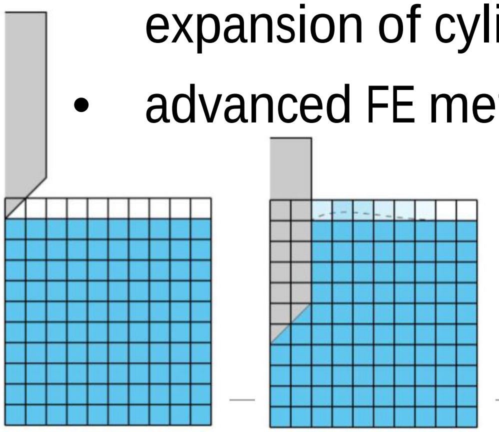




- empirical methods
  limited to very specific cases and conditions
- embedded piles / volume piles
  beam/volume elements with special interfaces, no installation effects
- press and replace techniques (Engin, 2013)
  displacement applied + geometry update
- wished-in-place pile
  imposing installation field around pile
- cavity expansion
  expansion of cylindrical cavity, shaft?
- advanced FE methods (large strain models, e.g. CEL, ALE)

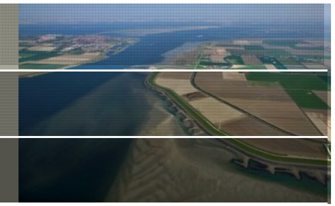






Deltares

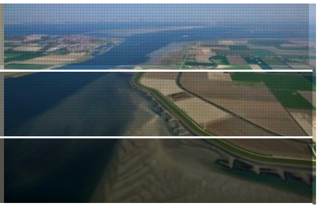
Modelling aspects



How to determine capacity of displacement piles?

Numerical model would require :

- numerical method allowing for large deformations (installation)
- model incorporating coupled two-phase material behaviour (soil and water, consolidation)
- a constitutive model coupling changes in density and stress to soil strength and stiffness properties (e.g. hypoplasticity)
- model including dynamics and cyclic behaviour (also high frequencies)
- a 3D model (e.g. lateral load test in non-symmetric conditions)
- model handling liquefaction and material softening with stable solution algorithm in such zero effective stress states

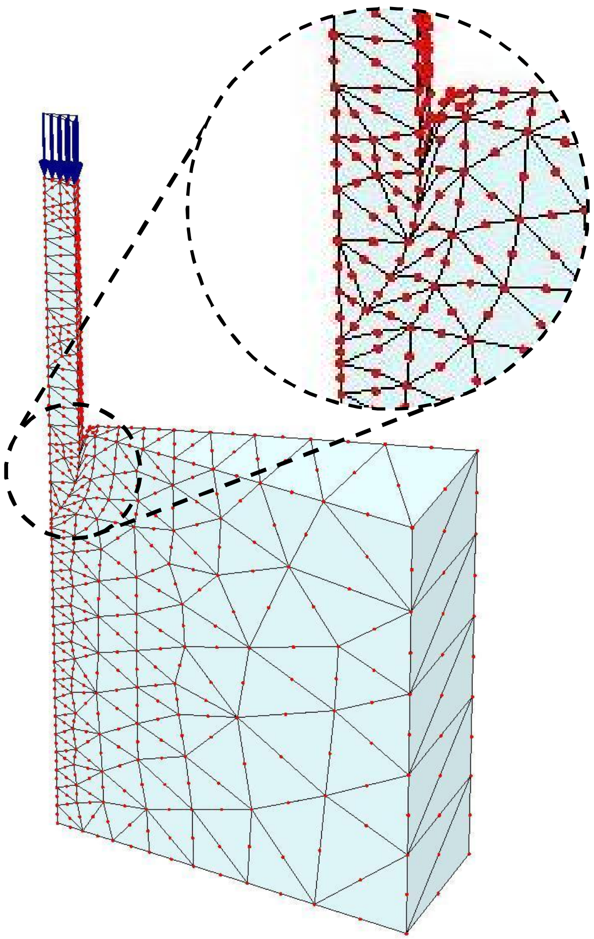


Numerical model

Material Point Method (MPM) with coupled two-phase behaviour

Deltares

Mesh distortion in classical FEM



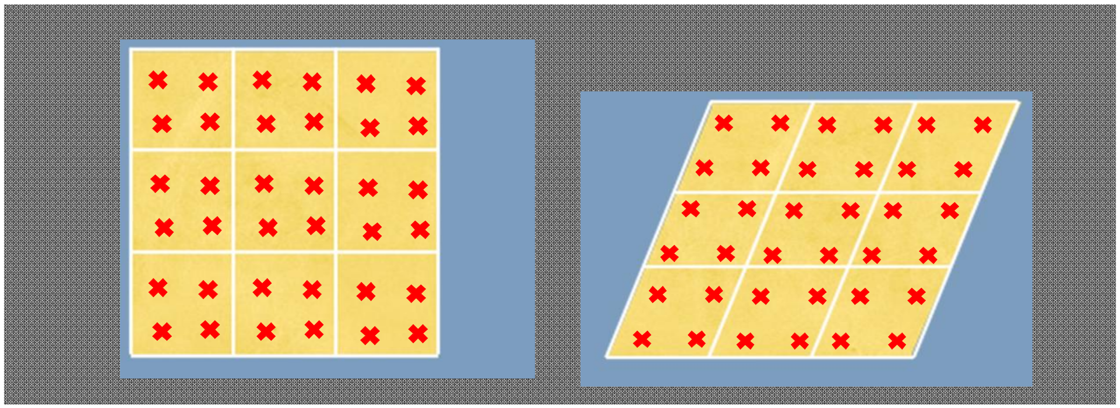
FEM

<u>Material Point Method (MPM)</u>

- can model large deformation
- no problems with mesh distortion
- state variables are traced by material points
- no need for remeshing
- enhancement of FEM
  → re-using established knowledge
- continuum approach

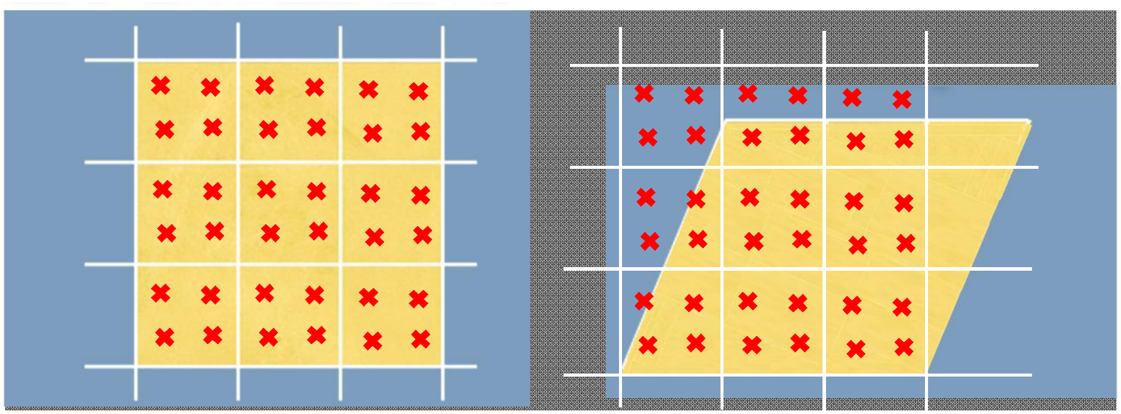
Basic FEM approaches

Lagrangian : mesh deforms as the body deforms → SOIL MECHANICS



- material does not cross elements
- nodes remain on boundary
- mesh distortion ?

Eulerian : material flows through a fixed mesh → FLUID MECHANICS

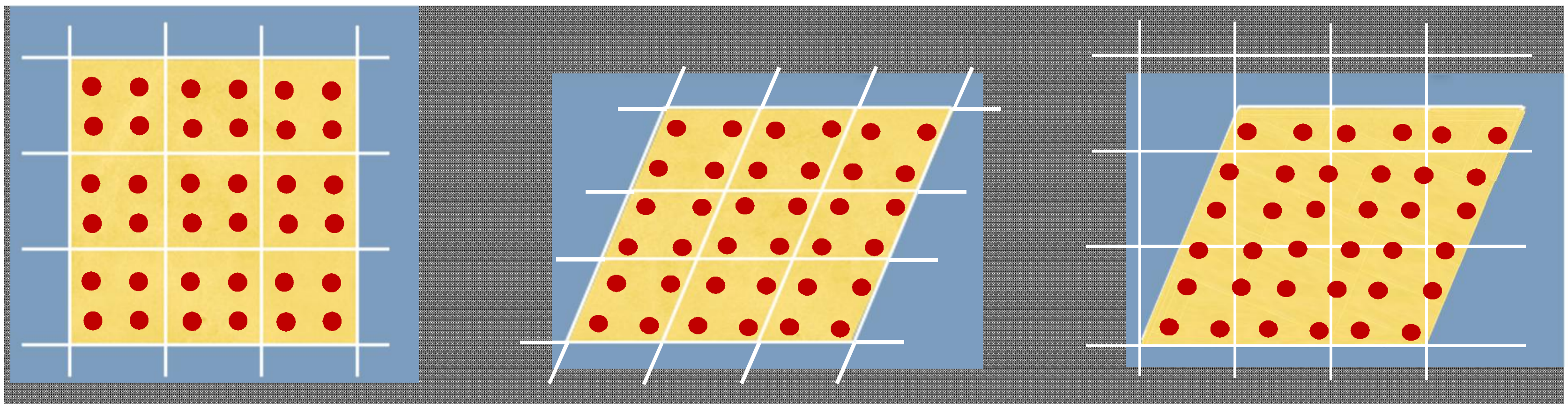


- material flows through a fixed mesh
- no mesh distortion
- state parameters ?

Deltares

Basic concept of MPM

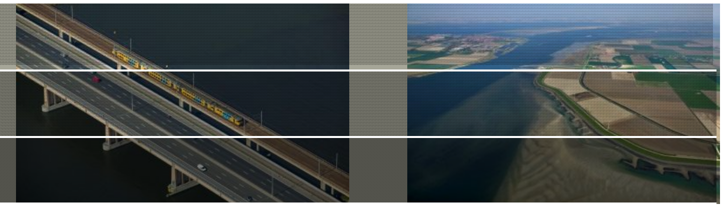
in each calculation step :



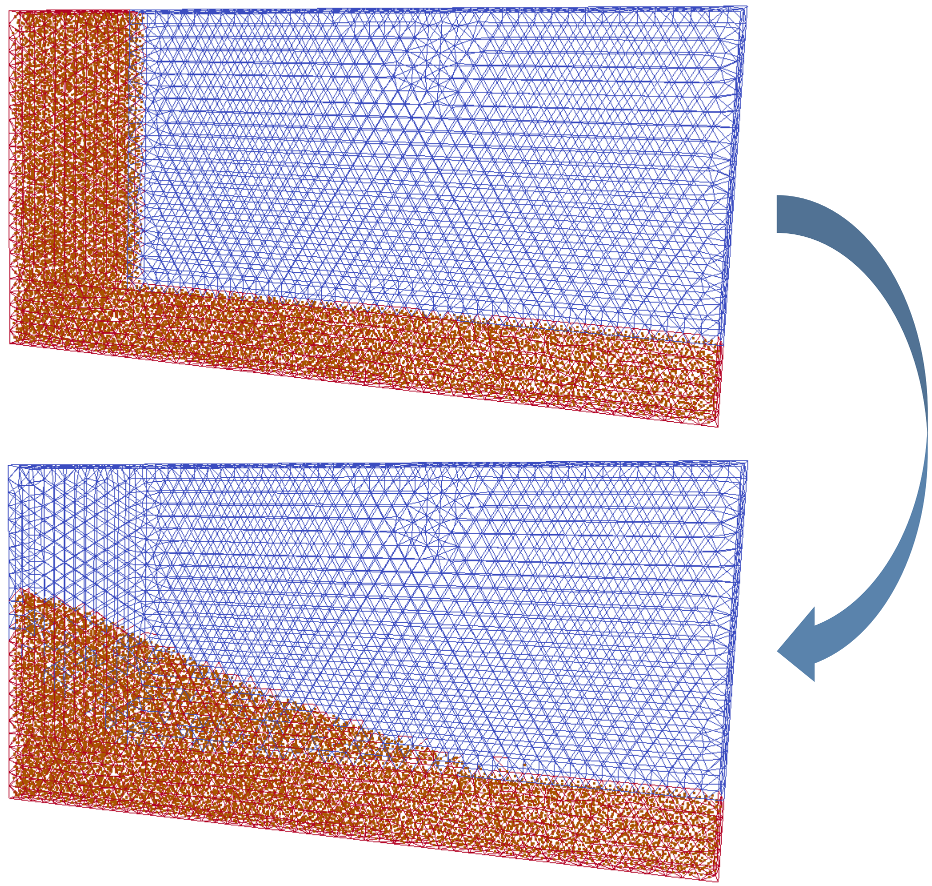
initial configuration | deformation | after resetting the mesh

Lagrangian (initial configuration, deformation) | Eulerian (after resetting the mesh)

Basic principle of MPM



initial position of material points



material points move through mesh

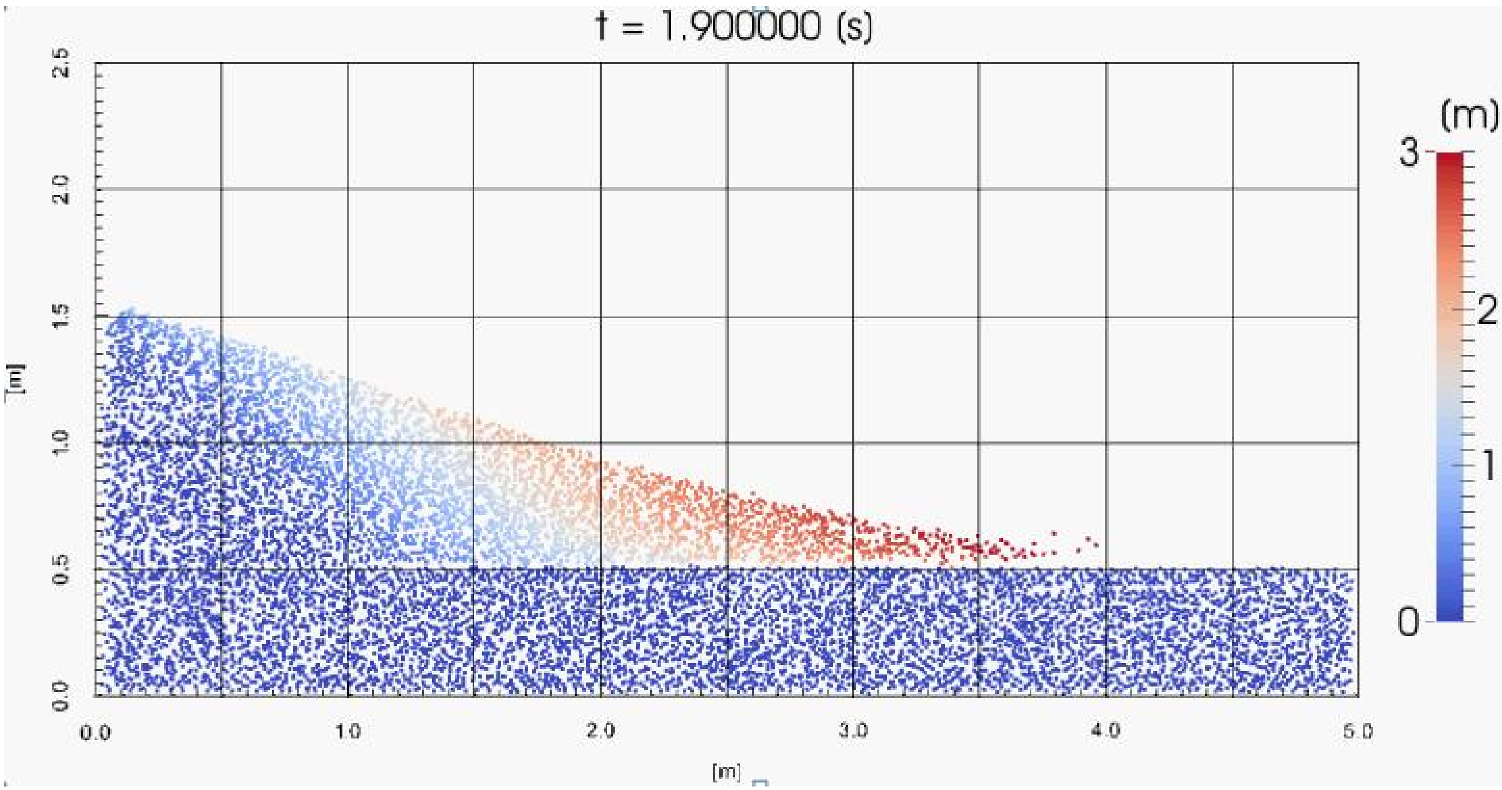
final position of material points

Eulerian background mesh & Lagrangian material points

Deltares

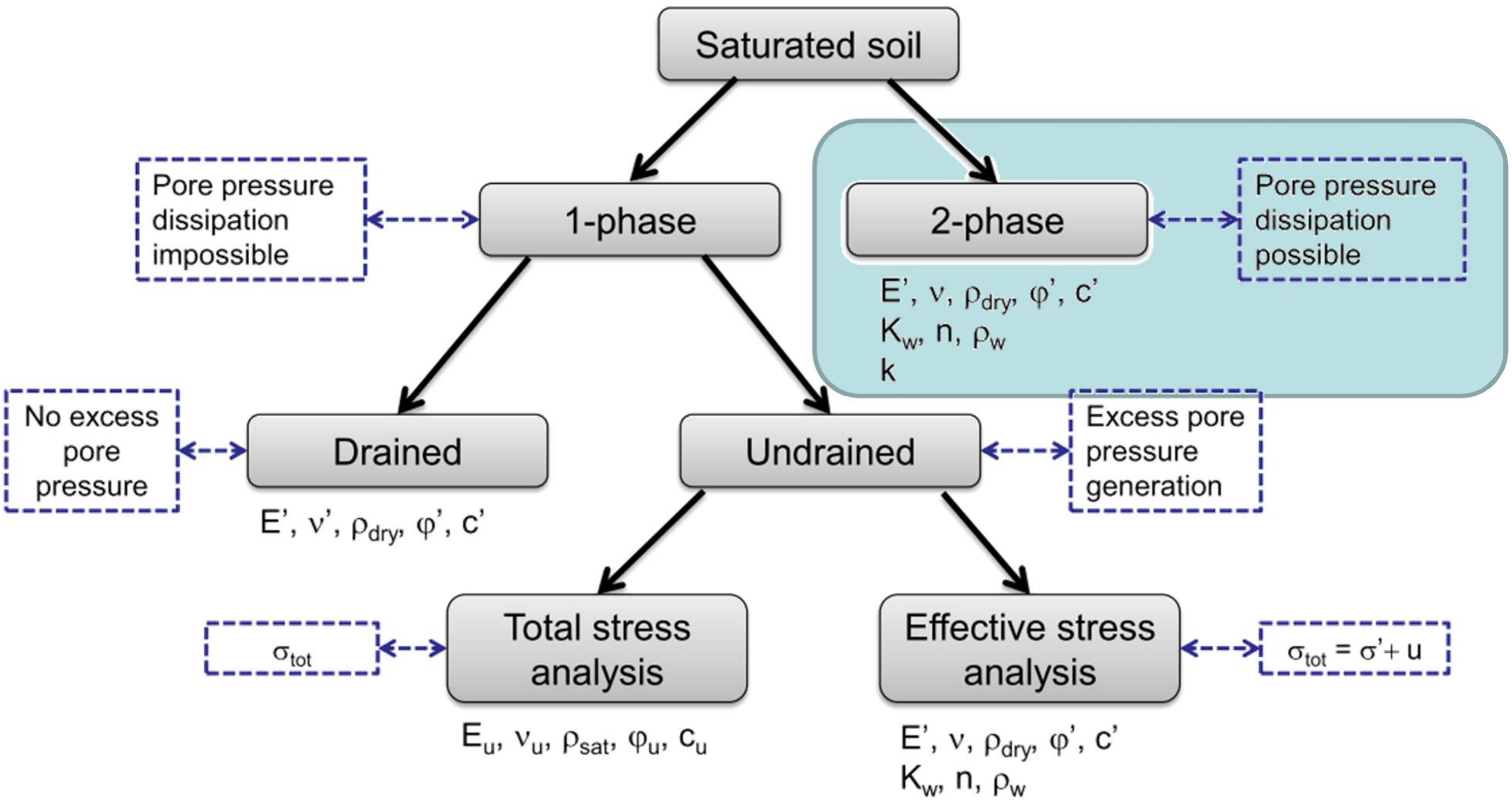
Example of MPM calculation

collapsing sand column: total displacements in [m]



Deltares

Modelling saturated soil



Deltares

Two-phase formulation (v-w-formulation)

$$\rho_w \dot{\mathbf{w}} + \frac{n\,\gamma_w}{k}(\mathbf{w}-\mathbf{v}) = \nabla p + \rho_w \mathbf{g}$$ *momentum of fluid*

$$(1\text{-}n)\rho_s \dot{\mathbf{v}} + n\,\rho_w \dot{\mathbf{w}} = \nabla \cdot (\boldsymbol{\sigma}' + \mathbf{I}\,p) + \rho_{sat}\,\mathbf{g}$$ *momentum of fluid and solid*

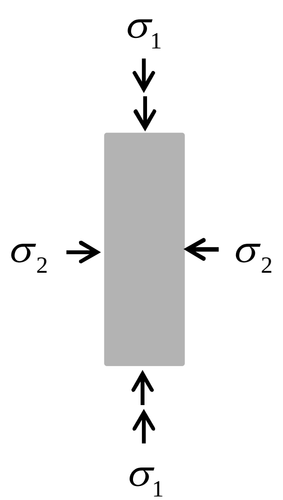
$$\frac{n}{K_w}\dot{p} = (1\text{-}n)\,\nabla \cdot \mathbf{v} + n\,\nabla \cdot \mathbf{w}$$ *mass balance*

$$\dot{\boldsymbol{\sigma}}' = \mathbf{D} : \dot{\boldsymbol{\varepsilon}} + \boldsymbol{\sigma}' \cdot \dot{\boldsymbol{\omega}} - \dot{\boldsymbol{\omega}} \cdot \boldsymbol{\sigma}' + (\mathbf{I} : \dot{\boldsymbol{\varepsilon}})\,\boldsymbol{\sigma}'$$ *stress-strain equation*

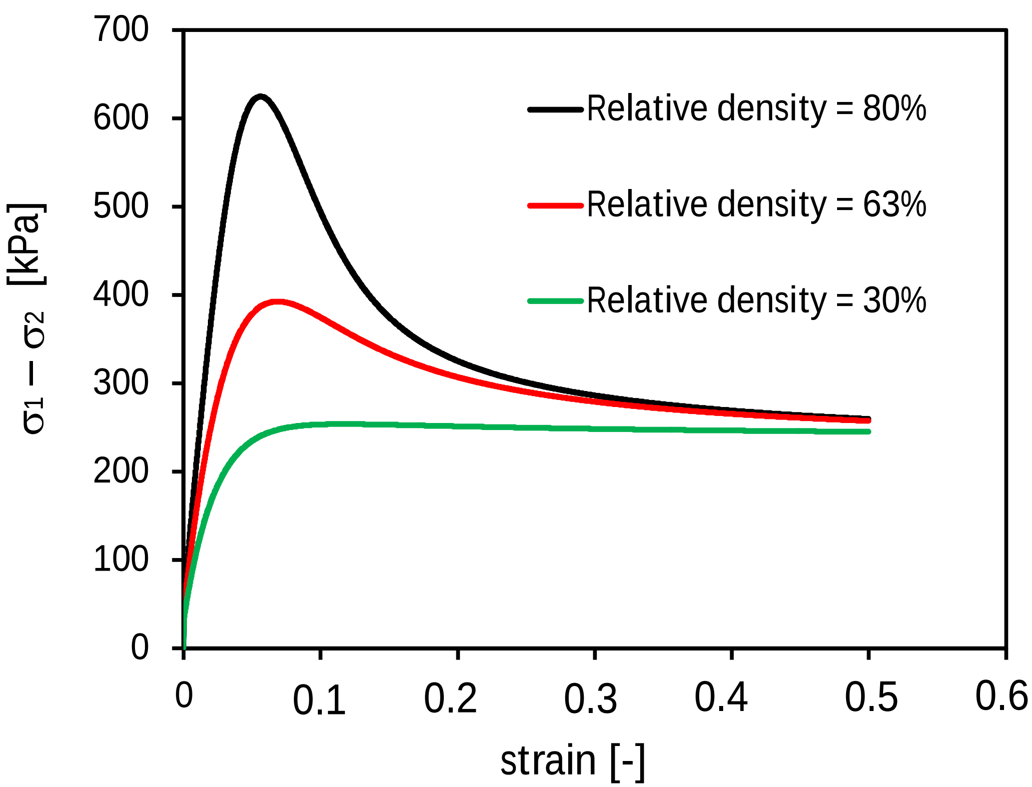
$\mathbf{v}$: soil skeleton velocity	$\mathbf{w}$: true water velocity	n : soil porosity
p : fluid tension	$\boldsymbol{\sigma}'$: effective stress tensor	$\mathbf{g}$: gravity vector
ρ_w : fluid particle mass density	ρ_s : soil particle mass density	$\rho_{sat} = (1\text{-}n)\,\rho_s + n\,\rho_w$
k : Darcy's permeability	K_w : fluid bulk modulus	$\mathbf{D}$: tangent stiffness
$\mathbf{I}$: identity tensor		

Deltares

Constitutive model: hypoplasticity



triaxial conditions



stress and strain (rate) dependent, density dependent

→ *therefore correct handling of state parameters extremely important*

Software tool: Material Point Method (MPM)

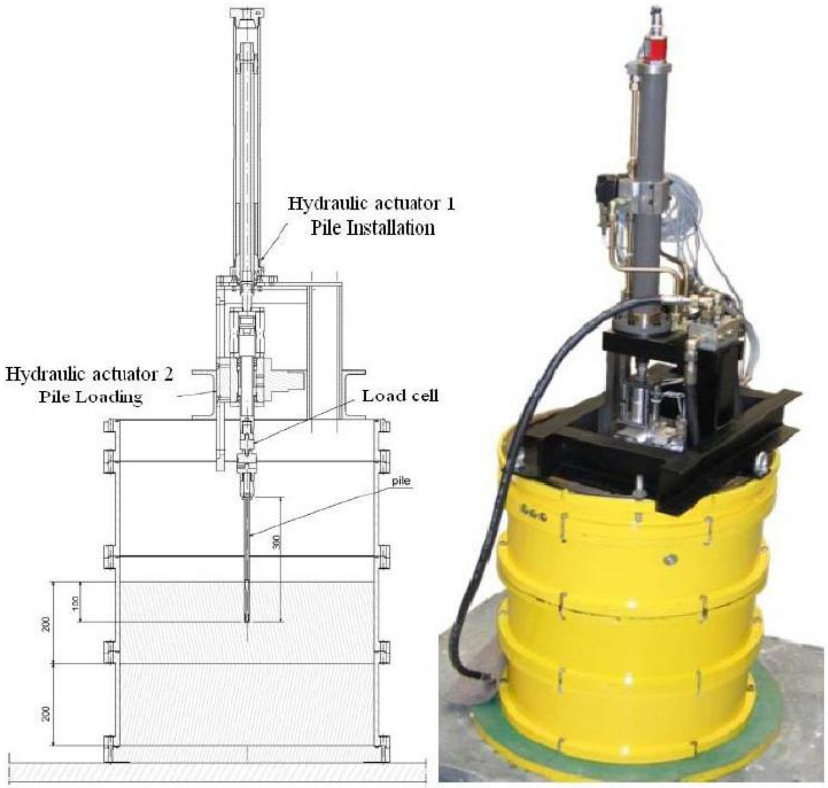
MPM Software is a tool for analysis of :

- large deformation problems (FEM, UL-FEM, MPM)
- 3D dynamic problems (explicit solver)
- multi-phase problems (fully coupled consolidation calculation)
- soil-structure interaction problems (no need for interface elements)
- advanced material models (continuum models as in FEM)
- soil-water interaction problems
- phase transition problems

Pile jacking and static load test (SLT)

Validation with centrifuge tests

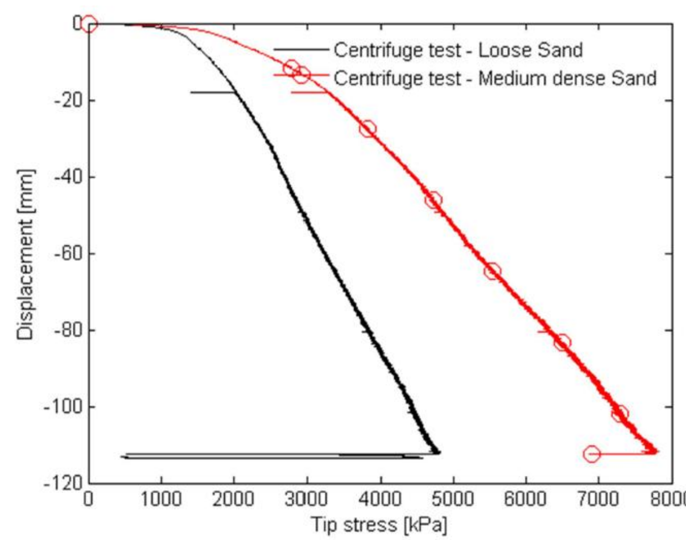
Centrifuge tests



centrifuge tests at Deltares (Huy, 2008) in a steel container (0.6 m diameter and 0.79 m height) filled with sand

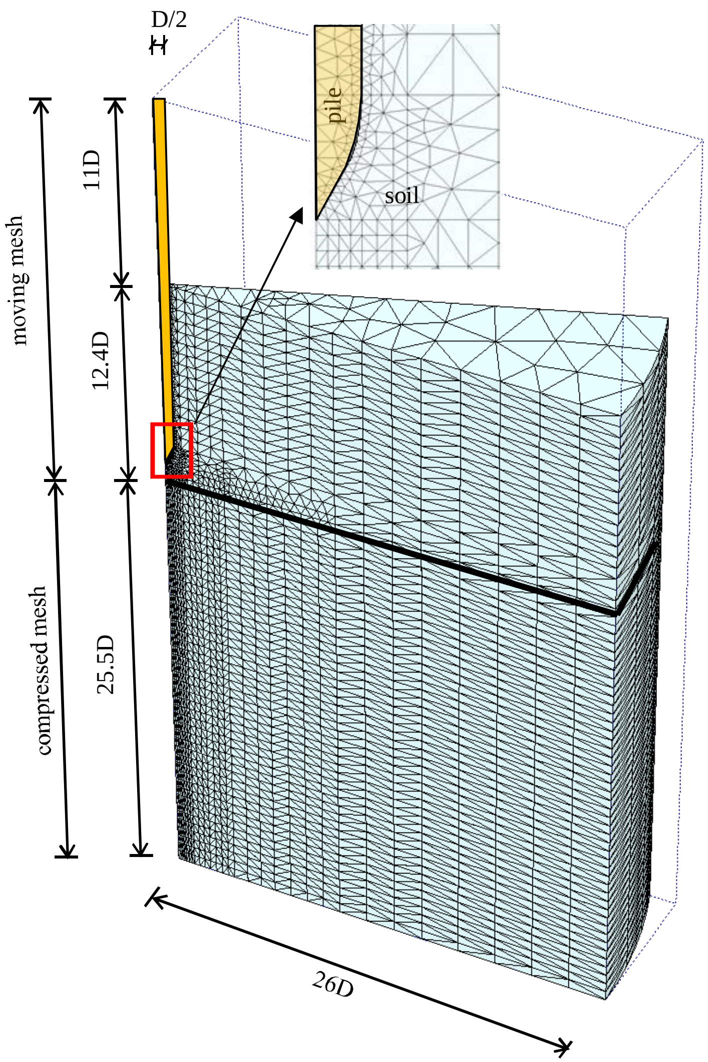
<u>modelling phases:</u>

- preparation at 1g, pile embedded 10D
- spin-up to 40g, pile still embedded 10D
- installation at 40g
  v = 10 mm/min, Δd=10D
- static load test (SLT) at 40g
  v = 0.00167 mm/s, Δd=0.1D



Deltares

Modelling approach



numerical model:

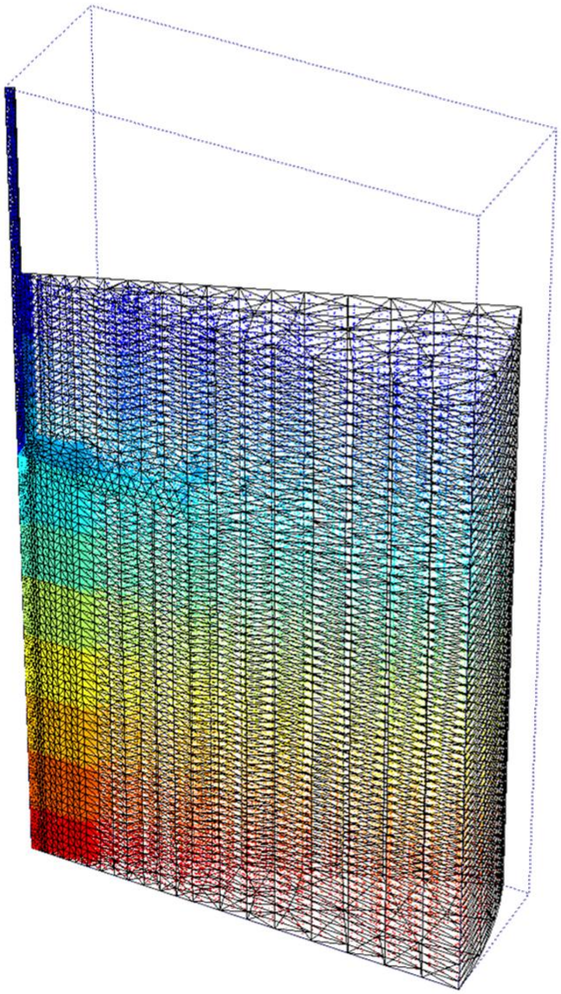
- soil wedge of 20°
- pile diameter D = 11.3 mm
- 26,826 tetrahedral elements (including initially inactive elements)
- 152,020 material points
- side boundary at 26D distance (as in centrifuge)
- bottom boundary fully fixed
- side boundaries as rollers
- moving mesh concept
- frictional contact

material behaviour:

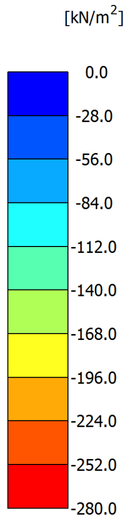
- Mohr-Coulomb
- Hypoplasticity
- two initial densities
  - medium dense sand, RD = 54%, $e_0 = 0.68$
  - loose sand, RD = 36%, $e_0 = 0.75$

Deltares

Results using Mohr-Coulomb model (1)



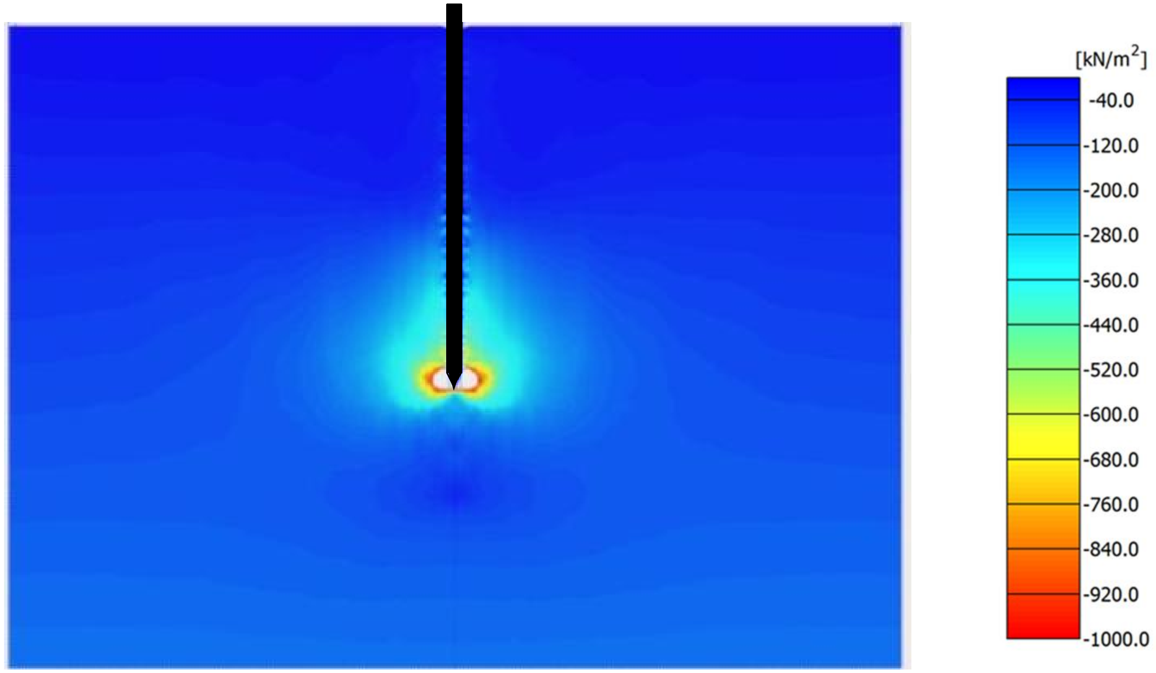
vertical effective stress [kPa]
after spin-up at 40g



sand	RD [%]	E [kPa]	φ_{max} [°]	ψ_{max} [°]	c [kPa]	ν [-]
medium dense	54	40 000	30	0	1.0	0.3
loose	36	22 000	30	0	1.0	0.3

Results using Mohr-Coulomb model (2)

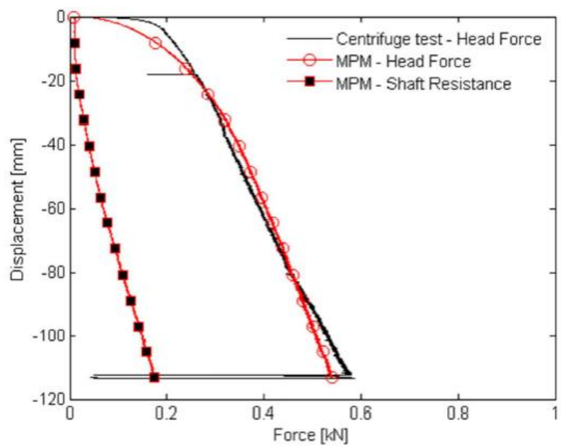
horizontal effective stress [kPa] during installation at 40g

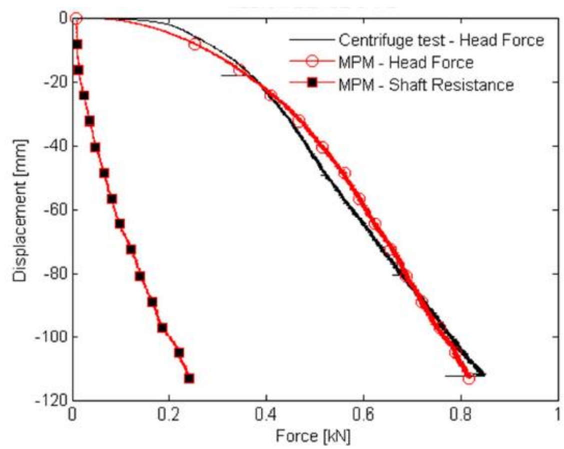


Deltares

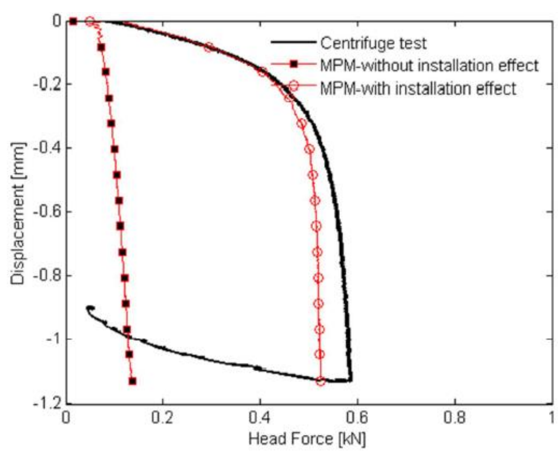
Results using Mohr-Coulomb model (3)

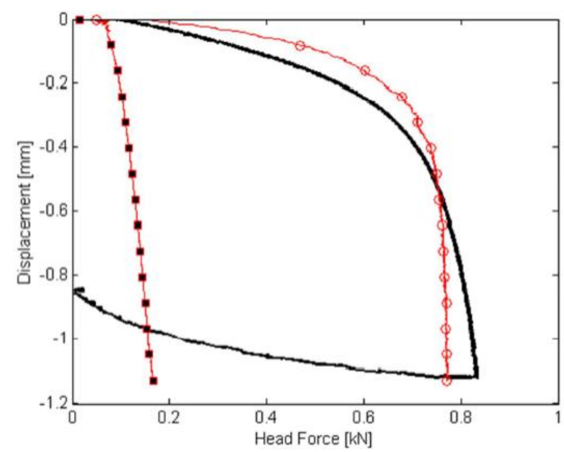
loose sand | medium dense sand





installation phase



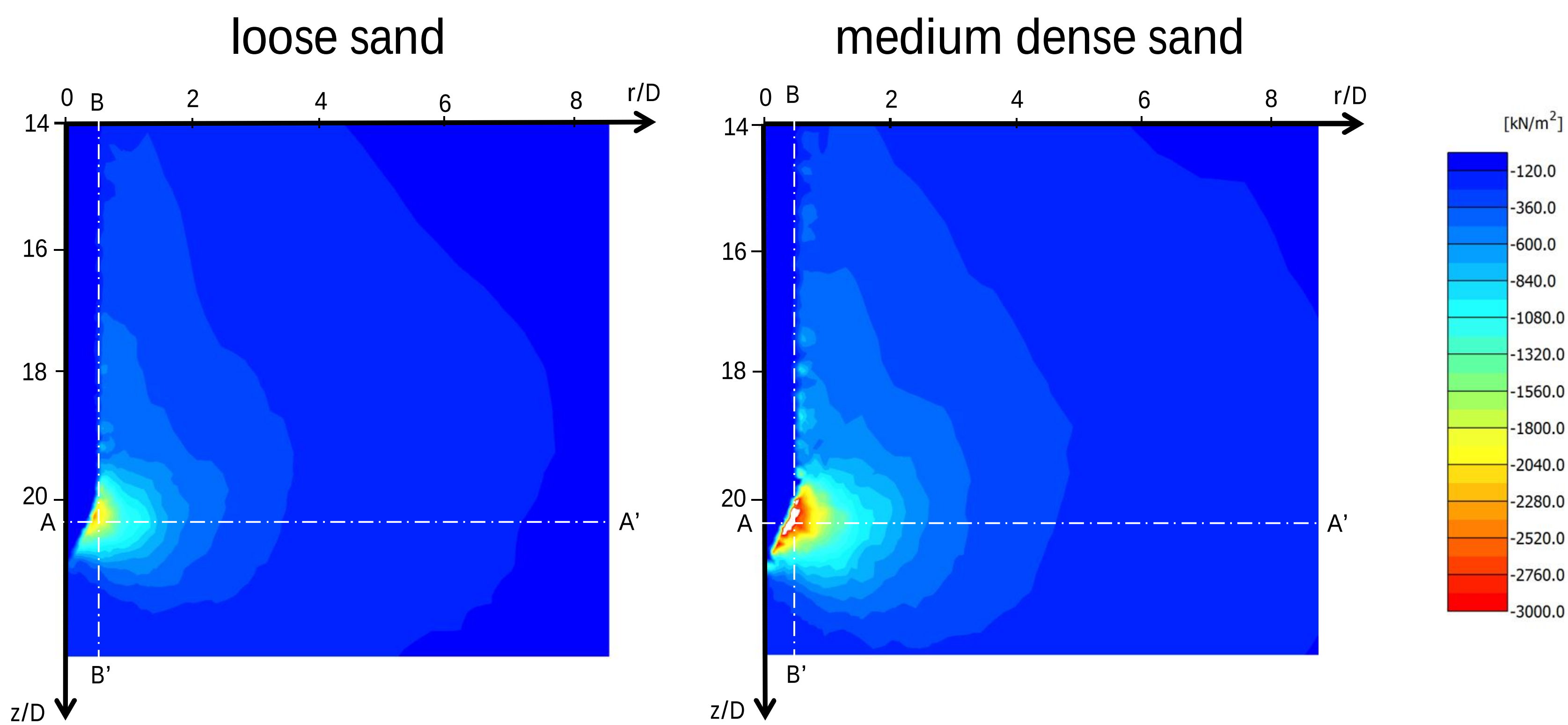


static load test (SLT)

Deltares

Results using Mohr-Coulomb model (4)

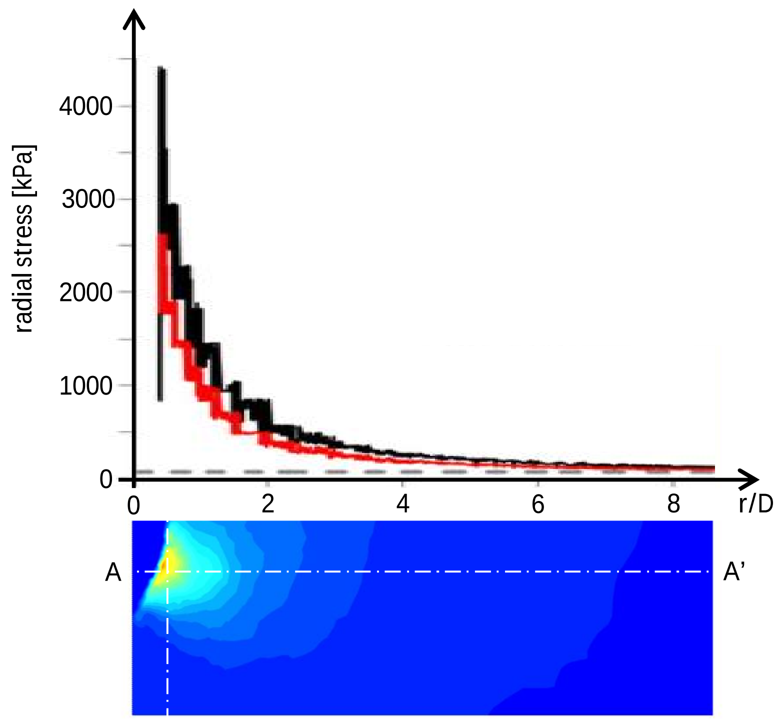
horizontal effective stress [kPa] after installation



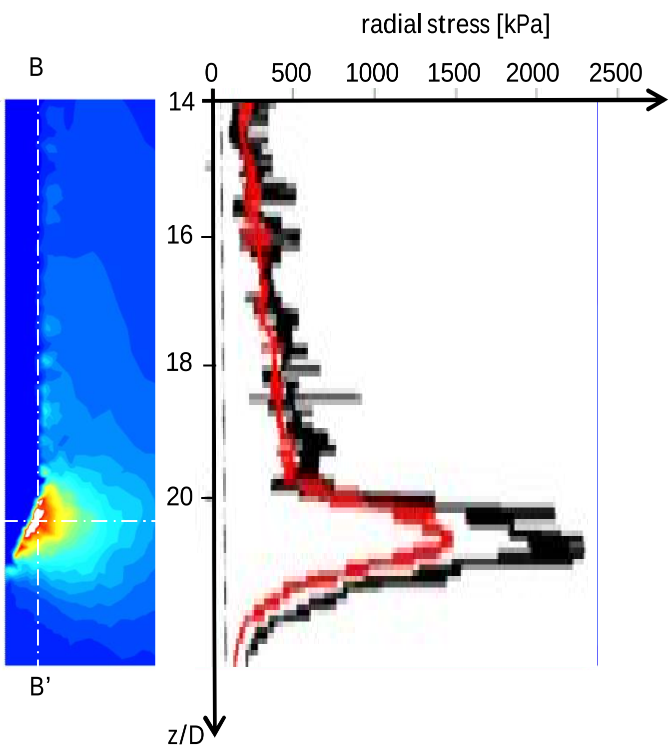
Deltares

Results using Mohr-Coulomb model (5)

horizontal cross section A-A'



vertical cross section B-B'



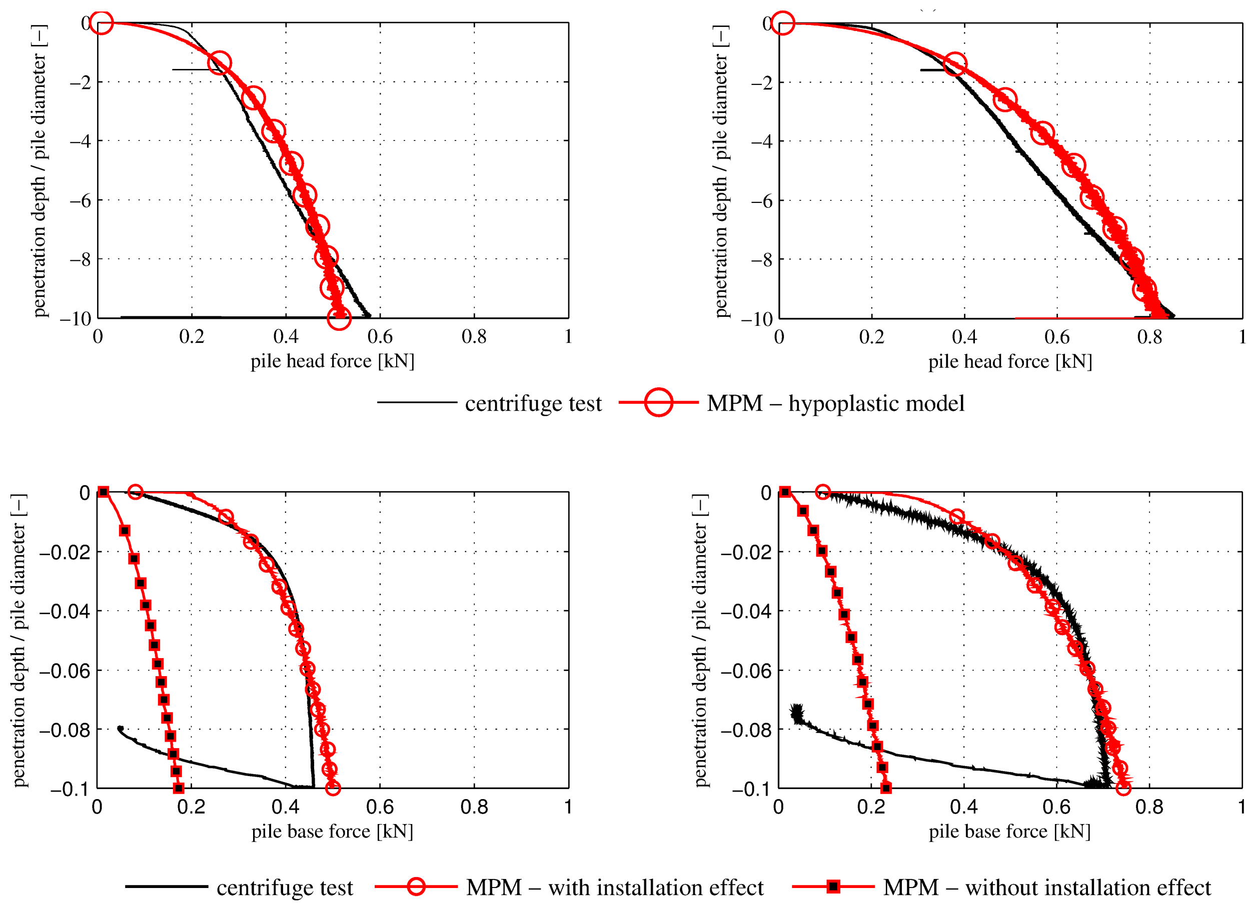
- - - - - K0-state
——— medium dense sand
——— loose sand

Deltares

Results using hypoplastic model (1)

loose sand

medium dense sand



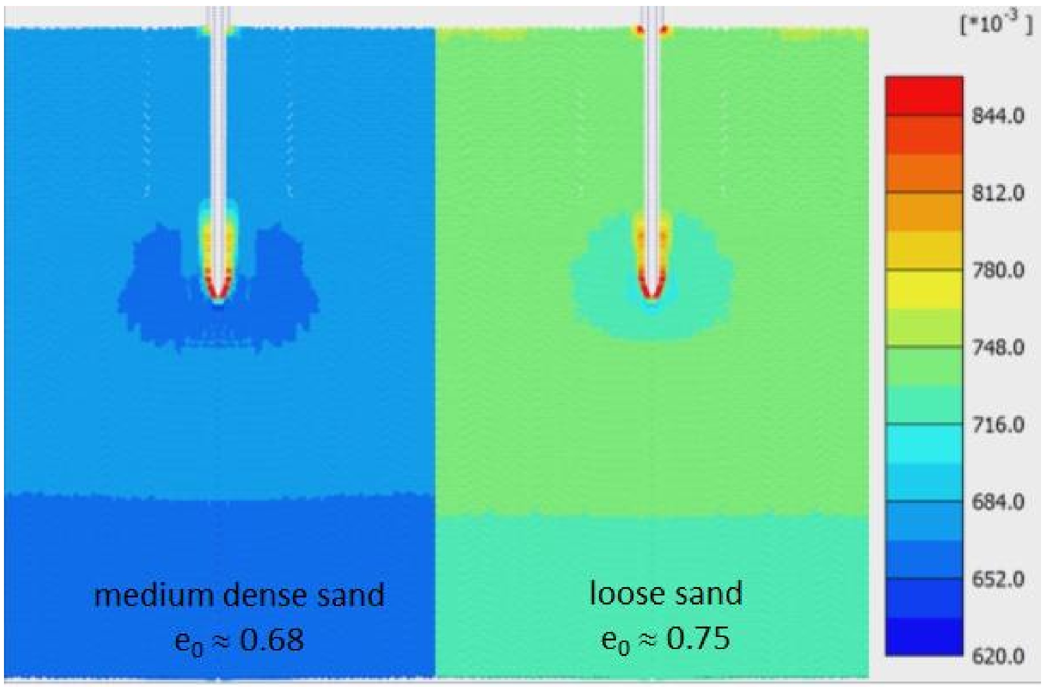
installation phase

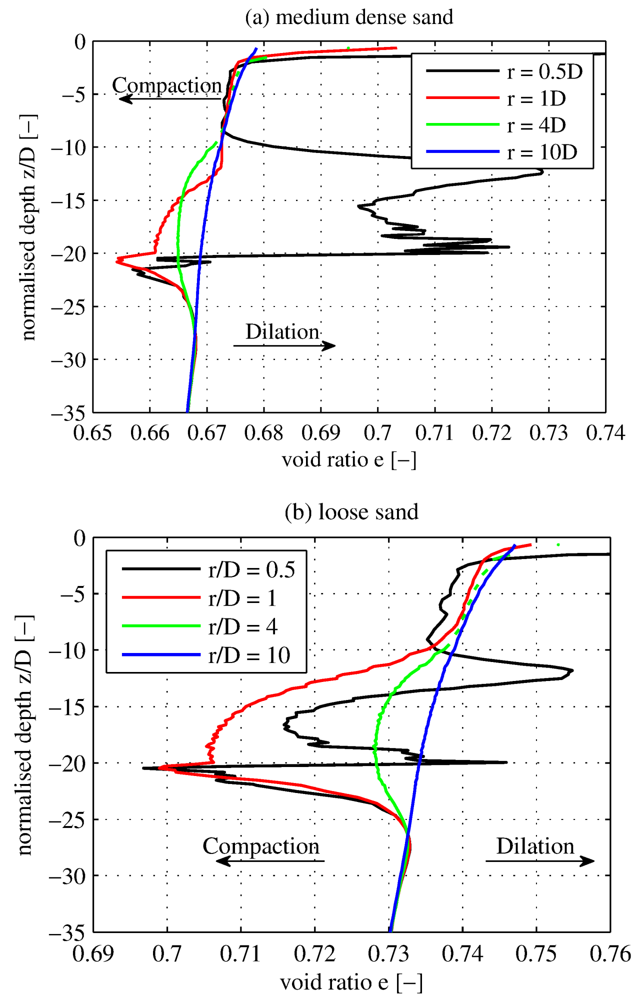
static load test (SLT)

Deltares

Results using hypoplastic model (2)

void ratio during installation

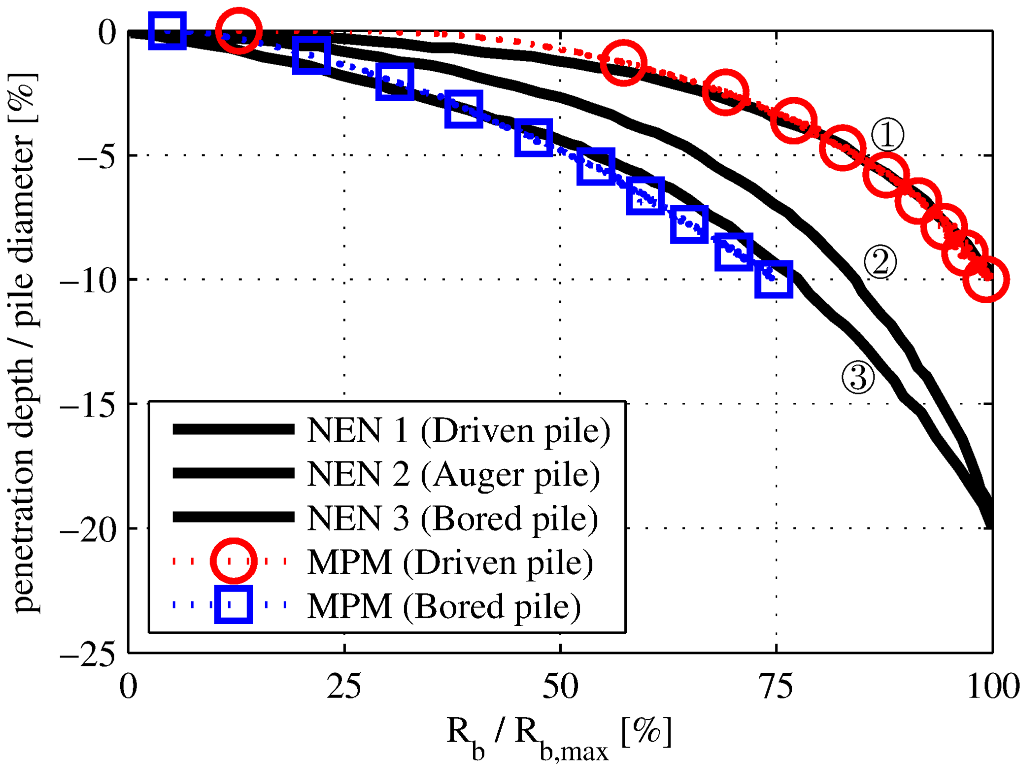




Deltares

Comparison to NEN 9997-2011

determination of pile capacity



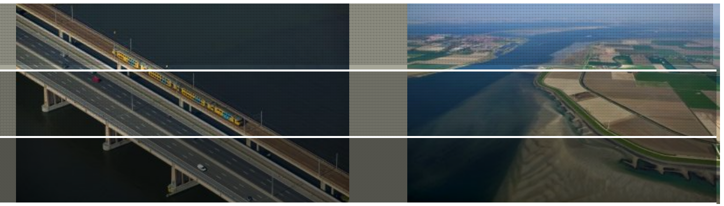
Normalised plots showing the relative stiffness of load-displacement curve response from the numerical simulations in comparison with the design curves in NEN 9997-2011. For a reliable design using this code, the ultimate base capacity is determined at 0.1D displacement for a driven pile (with installation effect) and at 0.2D displacement for a bored pile (without installation effect).

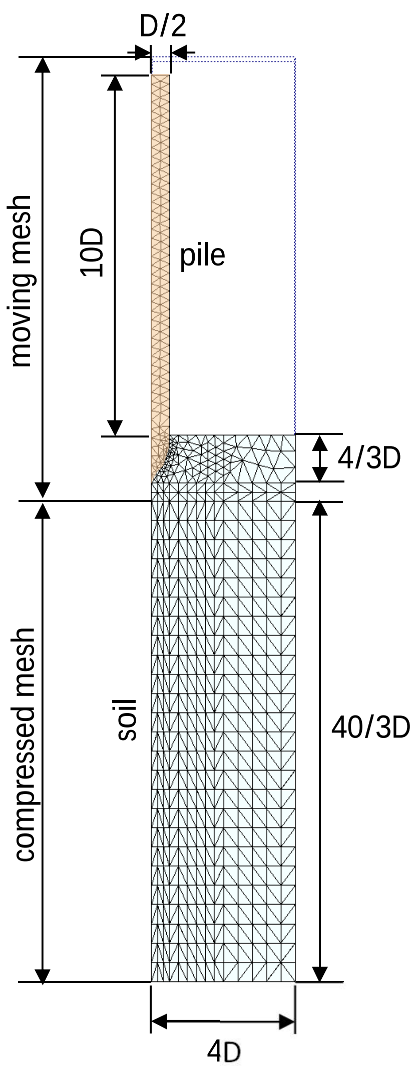
The normalised base resistance curve of the MPM simulation of the SLT is in good agreement with **curve 1** for driven piles. This demonstrates the importance of using an advanced soil model e.g. hypoplastic model in modelling pile load tests. The curve that simulates the pre-embedded pile shows a good correspondence with the curve suggested by **curve 3** for a bored pile.

Deltares

Pile driving

Modelling approach





numerical model:

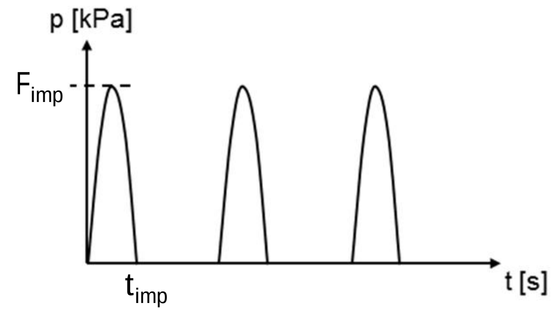
- soil wedge of 20°
- pile diameter D = 0.3 m
- bottom and right side boundary are full viscous boundaries
- other side boundaries are rollers
- moving mesh concept
- frictional contact

material behaviour:

- Hypoplasticity

modelling phases:

- initialisation by K_0-procedure
- gravity loading for self-weight pile
- impulse loading
  F_{imp} = 1000 kPa
  t_{imp} = 0.012 s
  t_{blow} = 0.25 s



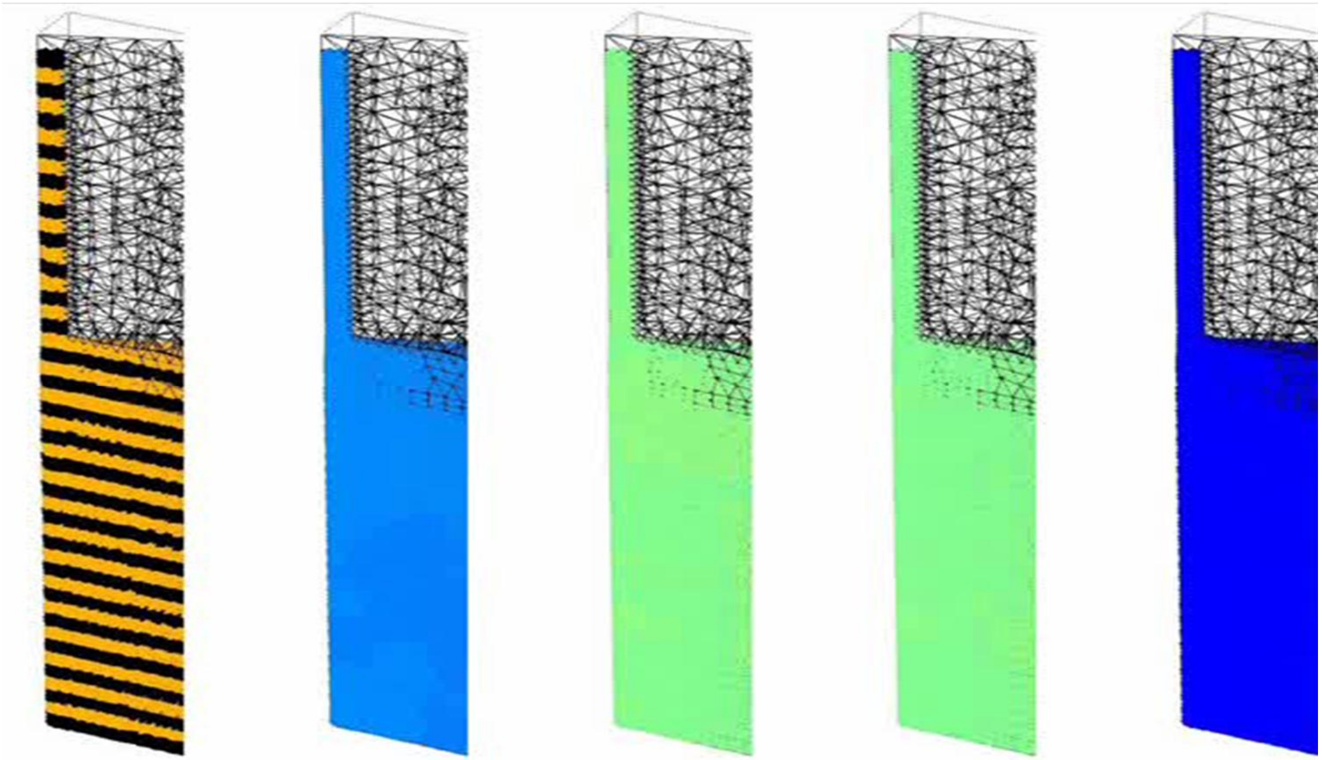
Hypoplastic parameters of Schlabendorfer sand [Mahutka, 2008]

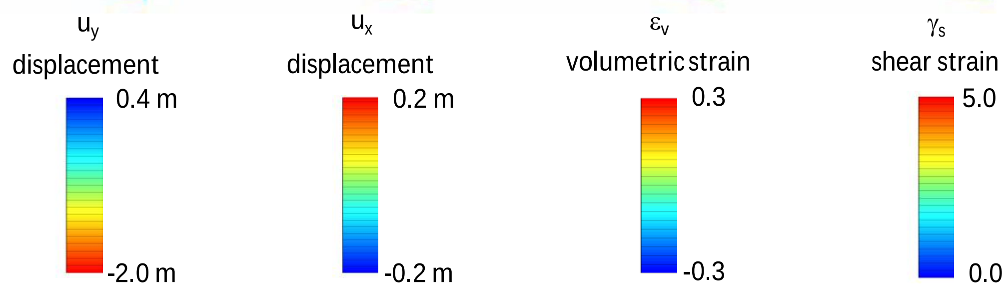
φ_c [°]	h_s [Mpa]	n	e_{d0}	e_{c0}	e_{i0}	α	β	e_0	P_t[kPa]	γ[kN/m³]
33	1600	0.19	0.44	0.85	1.00	0.25	1.00	0.645	1	16

m_t	m_r	R_{max}	β_r	χ
2	5	0.0001	0.5	6

Deltares

Results for loose sand

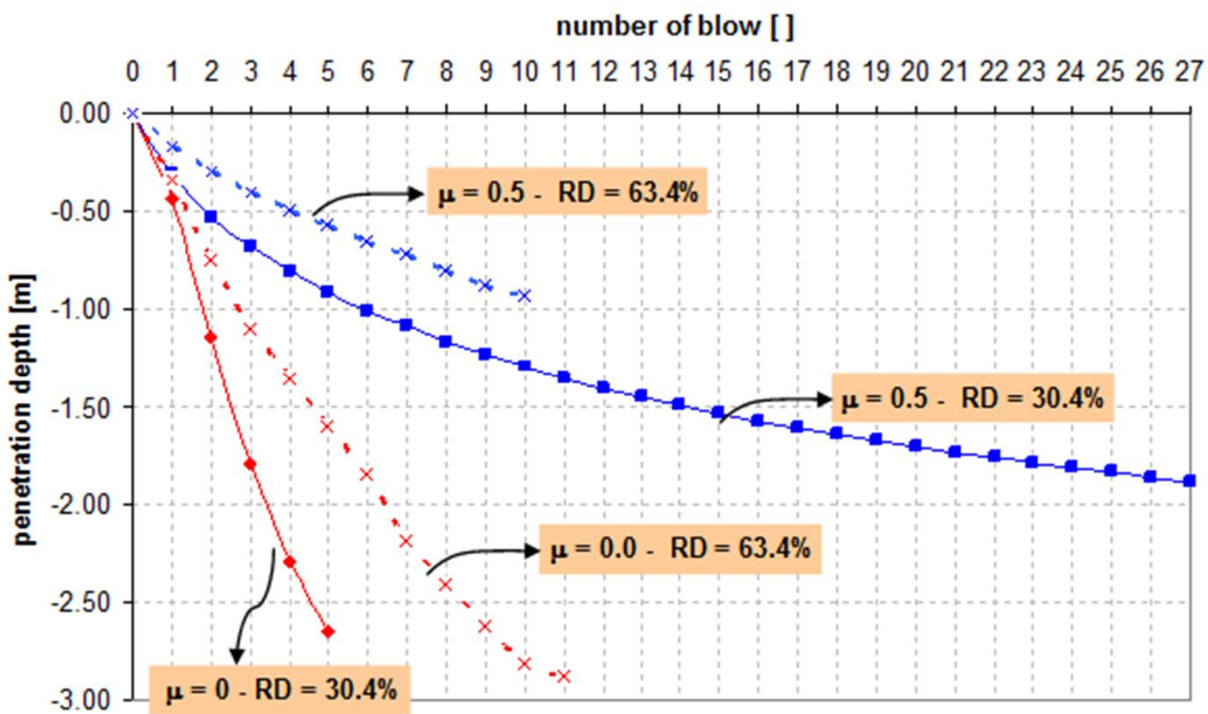


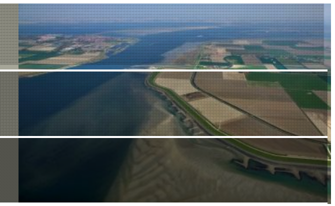


RD = 30.4%, μ = 0.5

each step represents one blow

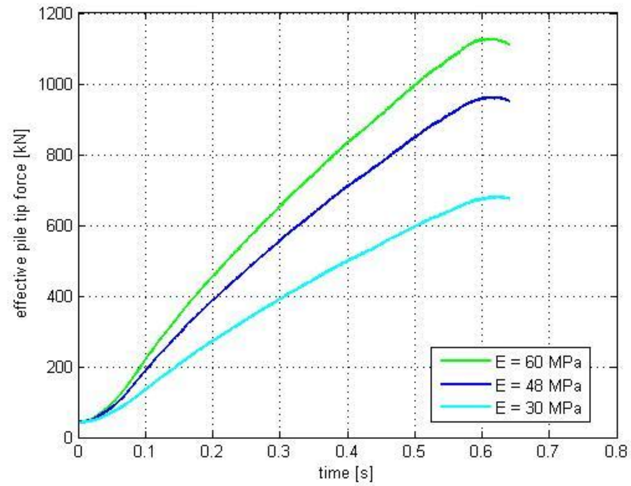
First results

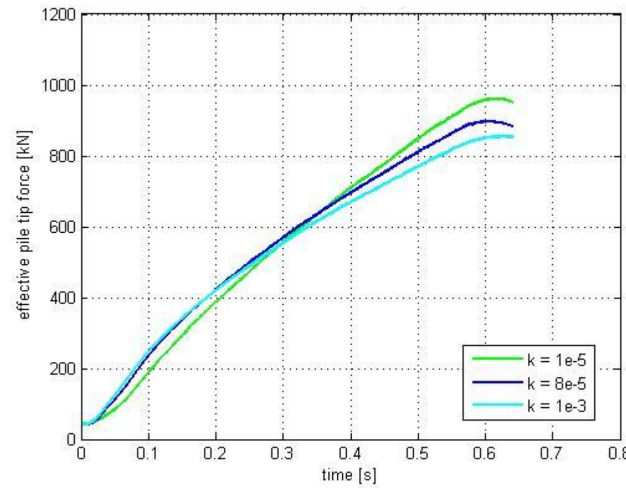


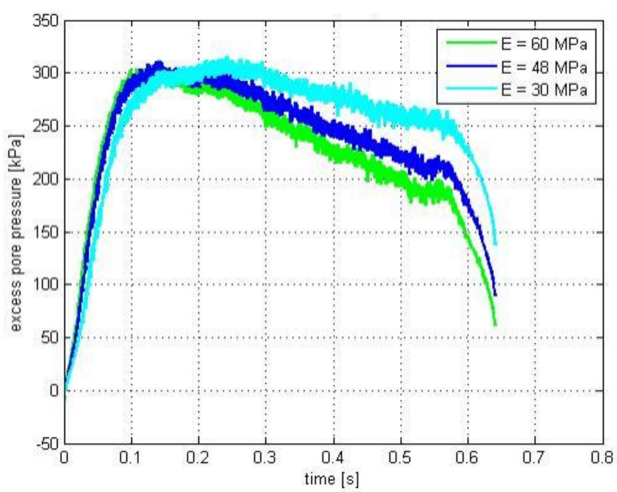


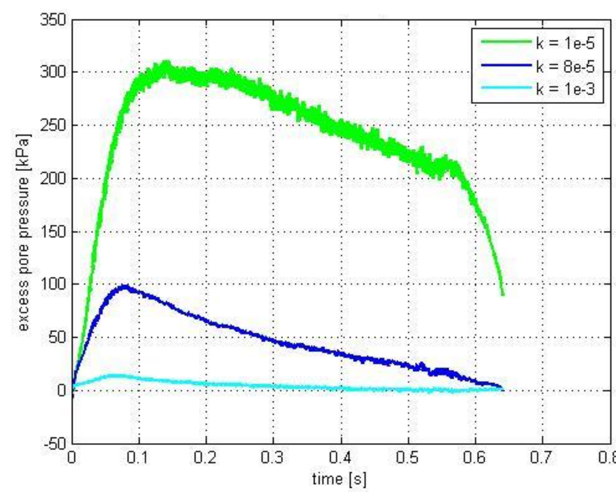
Rapid load test (RLT)

Effect of stiffness and permeability



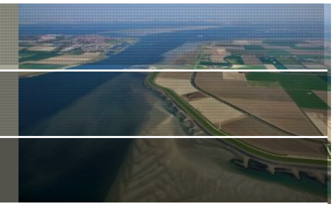


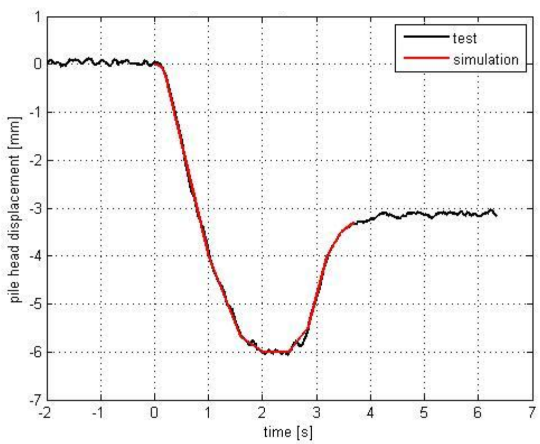


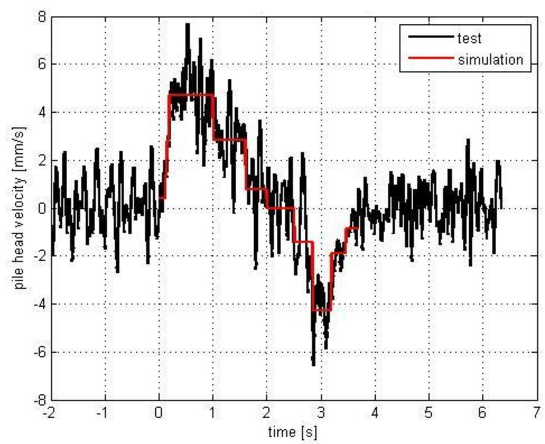


Deltares

Comparison with centrifuge test







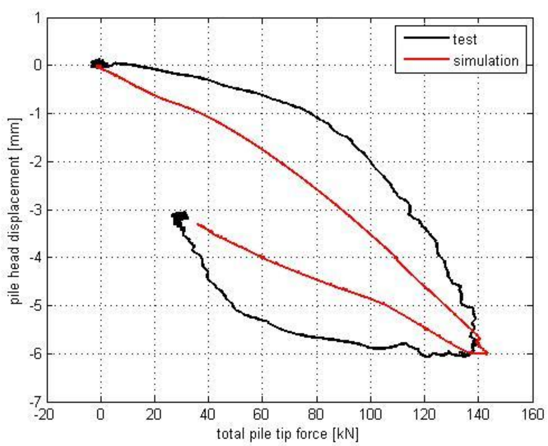
E = 48 300 kPa

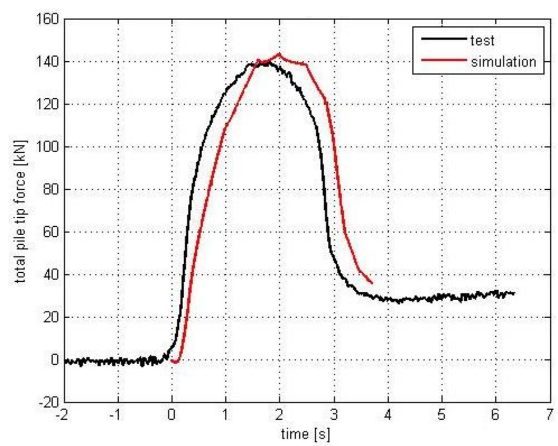
φ = 40°

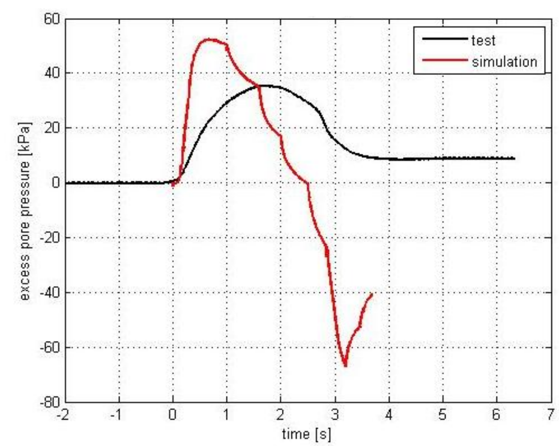
ψ = 5°

k = $2 \cdot 10^{-5}$ m/s

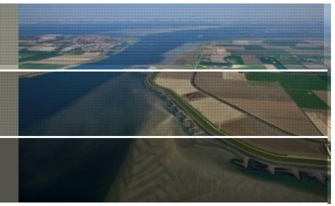
damping 0.05







Deltares

Conclusions

- numerical method (MPM) presented, which is able to model
  - large deformations and strains
  - coupled two-phase behaviour (consolidation)
  - (quasi-)static and dynamic loading conditions
  - liquefying soil and material softening
  - advanced material behaviour (constitutive models)
- validation of MPM for jacked piles and static load tests with centrifuge experiments
- verification of MPM for impact driven piles and rapid load tests
- extension of MPM for vibratory driven piles is ongoing
- bearing capacity of displacement piles can be numerically determined depending on installation method, soil conditions, pile specifications

Deltares

Outlook

Practical use for foundation engineering :

- simulate installation of each pile?
  - computational time
  - numerical experience
- impose stress and density state on mesh?
  - equilibrium state
  - flexibility and variation

Deltares

Thank you for your attention!