New developments in numerical modelling of pile installation

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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)

rapid load test (RLT)

lateral load test
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)
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
Mesh distortion in classical FEM

Material Point Method (MPM)
- 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?
Basic concept of MPM

in each calculation step:

- Initial configuration
- Deformation
- After resetting the mesh

Lagrangian | Eulerian
Basic principle of MPM

- Initial position of material points
- Final position of material points

Material points move through mesh

Eulerian background mesh & Lagrangian material points
Example of MPM calculation

collapsing sand column: total displacements in [m]
Modelling saturated soil

Saturated soil

1-phase

Pore pressure dissipation impossible

No excess pore pressure

Drained

E', ν', ρ<sub>dry</sub>', φ', c'

Total stress analysis

σ<sub>tot</sub>

2-phase

Pore pressure dissipation possible

Excess pore pressure generation

Undrained

E', ν', ρ<sub>dry</sub>', φ', c'

Effective stress analysis

σ<sub>tot</sub> = σ' + u

E<sub>u</sub>, ν<sub>u</sub>, ρ<sub>sat</sub>, φ<sub>u</sub>, c<sub>u</sub>

K<sub>w</sub>, n, ρ<sub>w</sub>
Two-phase formulation (v-w-formulation)

\[
\rho_w \dot{w} + \frac{n \gamma_w}{k} (w - v) = \nabla p + \rho_w g
\]

**momentum of fluid**

\[
(1-n) \rho_s \dot{\varepsilon} + n \rho_w \dot{w} = \nabla \cdot (\sigma' + Ip) + \rho_{sat} g
\]

**momentum of fluid and solid**

\[
\frac{n}{K_w} \dot{p} = (1-n) \nabla \cdot v + n \nabla \cdot w
\]

**mass balance**

\[
\dot{\sigma}' = D : \dot{\varepsilon} + \sigma' \cdot \dot{\omega} - \dot{\omega} \cdot \sigma' + (I : \dot{\varepsilon}) \sigma'
\]

**stress-strain equation**

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

stress and strain (rate) dependent, density dependent
\[\Rightarrow \textit{therefore correct handling of state parameters extremely important}\]
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 at Deltares (Huy, 2008) in a steel container (0.6 m diameter and 0.79 m height) filled with sand.

modelling phases:
- preparation at 1g, pile embedded 10D
- spin-up to 40g, pile still embedded 10D
- installation at 40g
  \( v = 10 \text{ mm/min}, \hspace{1cm} \Delta d=10D \)
- static load test (SLT) at 40g
  \( v = 0.00167 \text{ mm/s}, \hspace{1cm} \Delta d=0.1D \)
Modelling approach

numerical model:
- soil wedge of $20^\circ$
- 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, $RD = 36\%$, $e_0 = 0.75$
Results using Mohr-Coulomb model (1)

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

<table>
<thead>
<tr>
<th>sand</th>
<th>RD [%]</th>
<th>E [kPa]</th>
<th>( \phi_{\text{max}} [^\circ] )</th>
<th>( \psi_{\text{max}} [^\circ] )</th>
<th>c [kPa]</th>
<th>( \nu [-] )</th>
</tr>
</thead>
<tbody>
<tr>
<td>medium dense</td>
<td>54</td>
<td>40 000</td>
<td>30</td>
<td>0</td>
<td>1.0</td>
<td>0.3</td>
</tr>
<tr>
<td>loose</td>
<td>36</td>
<td>22 000</td>
<td>30</td>
<td>0</td>
<td>1.0</td>
<td>0.3</td>
</tr>
</tbody>
</table>
horizontal effective stress [kPa] during installation at 40g
Results using Mohr-Coulomb model (3)

loose sand

medium dense sand

installation phase

static load test (SLT)
Results using Mohr-Coulomb model (4)

horizontal effective stress [kPa] after installation

loose sand

medium dense sand
Results using Mohr-Coulomb model (5)

horizontal cross section A-A’

vertical cross section B-B’

- K0-state
- medium dense sand
- loose sand

radial stress [kPa]

Deltabes
Results using hypoplastic model (1)

loose sand  |  medium dense sand

installation phase

static load test (SLT)
void ratio during installation

medium dense sand $e_0 \approx 0.68$

loose sand $e_0 \approx 0.75$
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.
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
  \[ F_{imp} = 1000 \text{ kPa} \]
  \[ t_{imp} = 0.012 \text{ s} \]
  \[ t_{blow} = 0.25 \text{ s} \]

\[ \begin{array}{cccccccccc}
\varphi_c & h_s & n & e_{d0} & e_{c0} & e_0 & \alpha & \beta & e_0 & P_t & \gamma \\
33 & 1600 & 0.19 & 0.44 & 0.85 & 1.00 & 0.25 & 1.00 & 0.645 & 1 & 16 \\
\end{array} \]

\[ \begin{array}{cccc}
m_t & m_t & R_{max} & \beta_t & \gamma \\
2 & 5 & 0.0001 & 0.5 & 6 \\
\end{array} \]
Results for loose sand

RD = 30.4%, $\mu = 0.5$

each step represents one blow
First results
Rapid load test (RLT)
Effect of stiffness and permeability
Comparison with centrifuge test

\[ E = 48 \, 300 \, \text{kPa} \]
\[ \varphi = 40^\circ \]
\[ \psi = 5^\circ \]
\[ k = 2 \cdot 10^{-5} \, \text{m/s} \]

damping 0.05
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
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
Thank you for your attention!