Computer modeling of micropile systems with ZSoil

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What is ZSoil?

- FEM software for solving 2D/3D static/dynamic soil-structure interaction problems
Main ZSoil capabilities

- Statics (short/long term) and transient dynamics for single and two-phase (partially saturated) media + structures

- Stage construction and excavation analysis is allowed in the real time scale (including consolidation and/or creep effects)

- Strong deformation discontinuities between the structure-subsoil or structure-structure can be introduced via Coulomb type interfaces

- Small strain stiffness of soils can be represented by a complex but easily calibrated nonlinear constitutive models (Hardening Soil-small (HSs) model for instance)
Why do we need FEM modeling of micropile systems?

- FEM models allow to analyze coupled micropile-foundation-subsoil systems (rehabilitation of foundation of an existing building)
- Serviceability and ultimate limit states can be analyzed
- FEM modeling helps to understand all interactions between the micropile-foundation-subsoil components
- All kind of nonlinearities can be included (in micropile itself, subsoil, interfaces)
Sources of nonlinearities in micropile-subsoil-structure system

- Subsoil behaves in a nonlinear manner
- Interface micropile-subsoil is probably the source of strongest nonlinearity
- In some cases reinforcement-concrete interface can be activated
- Concrete can crack (if bending is activated)
- Other?
Sources of uncertainties in FEM models of micropile-subsoil-structure system

**Subsoil**: stress history (overconsolidation), initial pore pressures, stiffness

1. Geostatic conditions ($K_o$ in situ)
2. Level of saturation
3. Dilatancy (usually $\psi = \frac{1}{6} \div \frac{1}{4} \phi'$ in triaxial tests)

**Micropile-subsoil interface**: effect of micropile installation and dilatancy

1. During installation radial stresses increase locally near the micropile (we add an axisymmetric stress field into the general 3D state) $\rightarrow$ **$K$ effect**
2. Friction angle in the interface depends strongly on the technology
3. Strains are large (but only locally)
Effective stress analysis in ZSoil (static case)

- Overall equilibrium: \( \sigma_{ij,j}^\text{tot} + f_i = 0 \)
- Effective stress principle \( \sigma_{ij}^\text{tot} = \sigma_{ij}' + S \rho \delta_{ij} \)
- Fluid flow continuity: \( S \varepsilon_{kk} + v^F_{k,k} - c \rho = 0 \)
- Darcy velocity \( v^F_i = -k_{ij} k_r(S) \left(-\frac{\rho}{\gamma^F} + z\right) \)
- \( k_r(S) \) function \( k_r = \frac{(S - S_r)^3}{(1 - S_r)^3} \)
- \( S(\rho) \) (van Genuchten)
  \[
  S(\rho) = S_r + \frac{1 - S_r}{\left[1 + \left(\frac{\rho}{\alpha \gamma^F}\right)^2\right]^{1/2}}
  \]
- \( c(\rho) \) storage function \( c = c(\rho) = n \left(\frac{S}{K^F} + \frac{dS}{d\rho}\right) \)
Effective stress analysis in ZSoil: possible drivers

- Quasi-undrained analysis → short loading time, low permeability (in statics)

- Steady state drained analysis → long loading time

- Transient case → tracing pore pressure disipation in real time
Consequences of effective stress analysis

- Parameters for soil constitutive model must be effective → $c'$, $\phi'$

- Undrained ($s_u$) or transient values of strength parameters $c$, $\phi$ are naturally embedded in the theory once the consolidation driver is used and proper elasto-plastic model is used

- Cohesion results from suction pressure or effect of cementation
Soil constitutive models: M-C vs HSs

- **Elasto-plastic M-C model**
  (frequently used in practice)
  - Ultimate limit states: 🍎 YES
  - Serviceability limit states: 🍏 NO (most often)

- **Elasto-plastic model HSs**
  (since last few years quite often used in practice)
  - Ultimate limit states: 🍎 YES
  - Serviceability limit states: 🍏 YES

HSs model: 2 plastic mechanisms

Double hardening model
Cap surfaces and failure cone (M-C) in principal stress space

Isotropic hardening mechanism:
cap yield surfaces described with van Ekelens’s formula

Mohr-Coulomb failure surface
HSs model: stiffness representation

- Secant shear modulus
  - $G_0$

- Hardening Soil Small Strain
  - Duncan-Chang

- Hardening Soil Standard
  - Mohr-Coulomb

- Very small strains
- Engineering strains

Shear strain: $\gamma_s$

- $G_{ur}$
- $10^{-7}$
- $\sim 10^{-3}$
- $\sim 10^{-1}$
HSs model: calibration

- (S)CPTU field test
- (S)DMT field test
- Triaxial test (CD) including shear wave velocity measurement as a calibration test for CPTU/DMT correlation formula
- CPTU/DMT serve us stress history parameter OCR and $K_0$ in situ
Micropile-subsoil interaction: fully conforming discretization (A)

- Resulting FE models are huge and extremely time consuming
- Each redesign of piles requires new mesh for whole system
Fully conforming discretization: interface treatment

- Interface thickness is zero

- Contact stress computation
  \[ \sigma_{n,N+1} = k_n \ g_{n,N+1} \]
  \[ \tau_{N+1} = \tau_N + k_s \ \Delta g_s \quad \text{and} \quad |\tau_{N+1}| \leq \sigma'_n \ \tan(\phi) + c' \]

- \( k_n \) and \( k_s \) are penalty factors for rigid plastic interface

- \( k_n \) and \( k_s \) can be related to the shear band thickness \( t \) and its quasi-elastic stiffness:
  \( k_n = E/t \) while \( k_s = G/t \)

- Rigid plastic interface leads to overstiffening of the micropile response
Micropile-subsoil interaction: overlaid mesh approach (B)

- Resulting FE models are smaller than for conforming model
- Relatively coarse mesh for subsoil is used while mesh for micropile+interface+small part of subsoil is dense
Micropile-subsoil interaction:
micropiles as 1D members embedded in 3D
continuum (C)

- Resulting FE models are small
- Special interface must be implemented
- Redesign of micropile system is very easy
Micropiles as 1D members embedded in 3D continuum: interface treatment

Plate/shell element „p”
Top pile node „T”
Master segment „m”
Beam elements
Slave segment „s”
Master node of pile tip
Interface „B”
3D continuum element „c”

NB. Effect of micropile installation will be discussed later
Interface micropile-subsoil in simplified approach

In simplified approach there is no way to recover $\sigma_n$ from the interface.
Hence we have to recover it from the adjacent continuum.
Interface micropile-subsoil in simplified approach

Recovering $\sigma_n$ from adjacent continuum

$$R = \sqrt{\frac{A}{\pi}}$$
Effect of installation: K-pressure method

K-pressure method (PhD by Syawal Satibi, Stuttgart, 2009)

- In situ Ko state
- „excavation“ unloading is delayed
- Add \((K - Ko) \gamma h\)
- Add micropile/unload exc. forces/remove pressure

But how to define K value?
Effect of micropile installation

- Micropile diameter is relatively small → effect on increase of radial stress due to installation is localized in a relatively narrow zone

- This effect can be analyzed in an analytical manner using known solutions for cavity expansion problem

- In methods (A) and (B) we can use K-pressure method (PhD by Syawal Satibi, Stuttgart, 2009)

- In method (C) K-pressure method is applicable but mesh size must be carefully chosen

- Back analysis of load test may yield $K$ value and interface stiffness
Effect of micropile installation in method (C): possible solution

- Stress variation due to installation is neglected in subsoil

- Equivalent interface friction angle $\tan(\phi^*)$ has to be used to reproduce skin friction

- This may lead to overestimation of micropile settlements near the limit state

- K-pressure is recommended (adding axisymmetric stress field) → not available so far
In methods (A) and (B) effect of dilatancy is present.

In simplified approach (C) this effect is missing (so far).
An example: loading test on single micropile

\[ D = 18 \text{cm} \]
An example: micropile foundation system

3x3 and 5x5 micropile foundation system ($D = 20\text{cm}$)
An example: micropile foundation system

a) Detail of conformed FE mesh

b) 3D mesh: overview of the model
d) Piles located at arbitrary points (detail)
e) 3D mesh: overview of simplified model
An example: micropile foundation system

Comparison of displacements:
3D FEM with fully conforming mesh
3D FEM with simplified ZSoil® method of pile modelling

$U_{y,\text{Simpl}} = 2.5\text{mm}$
slightly stiffer (~15%) response

$U_y = 3\text{mm}$

$s = 3\text{ mm}$  $s = 2.5\text{ mm}$ (stiffer response)
Conclusions

- Proposed simplified approach is a very useful tool for solving problems with large number of micropiles/piles

- Standard discretization technique (A) is inefficient for complex 3D problems

- Both approaches (A)/(B) and/or (C) require careful calibration of strength and stiffness parameters (by back analysis)

- Combined standard design methods (for micropile) and numerical modeling of whole system seem to be the most appropriate approach