Computer modeling of micropile systems with ZSoil

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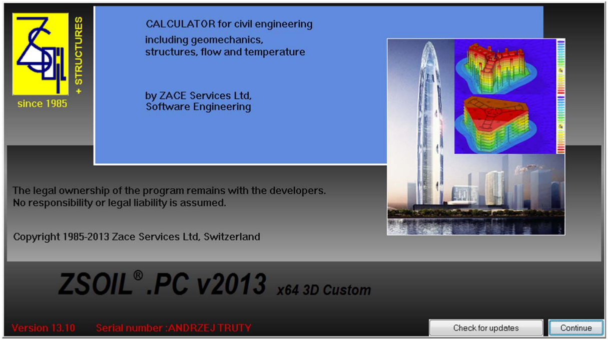
What is ZSoil ?

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



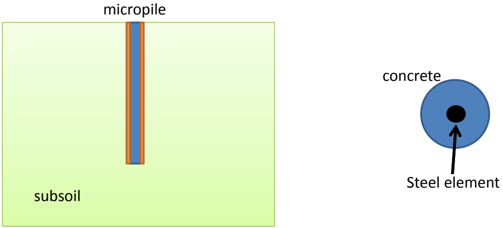
Main ZSoil capabilities

- 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 alow 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:** $\sigma^{\text{tot}}_{ij,j} + f_i = 0$
- **Effective stress principle** $\sigma^{\text{tot}}_{ij} = \sigma^{'}_{ij} + S\, p\, \delta_{ij}$
- **Fluid flow continuity**: $S\, \dot{\varepsilon}_{kk} + v^F_{k,k} - c\, \dot{p} = 0$
- **Darcy velocity** $v^F_i = -k_{ij}\, k_r(S)\, \left(-\dfrac{p}{\gamma^F} + z \right)_{,j}$
- $k_r(S)$ **function** $k_r = \dfrac{(S - S_r)^3}{(1 - S_r)^3}$
- $S(p)$ **(van Genuchten)**

$$S(p) = S_r + \frac{1 - S_r}{\left[1 + \left(\alpha \dfrac{p}{\gamma^{\text{F}}} \right)^2 \right]^{1/2}}$$

- $c(p)$ **storage function** $c = c(p) = n \left(\dfrac{S}{K_{\text{F}}} + \dfrac{\text{d}S}{\text{d}p} \right)$

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

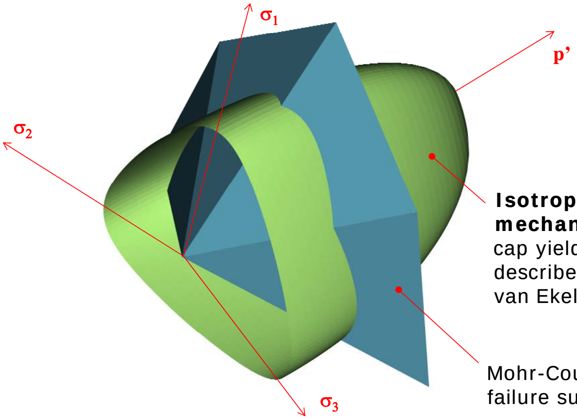
- Parameters for soil constitutive model must be effective $\rightarrow c', \phi'$
- Undrained (s_u) or transient values of strength parameters c, ϕ are naturally embeded in the theory once the consolidation driver is used and proper elasto-plastic model is used
- Cohesion results from suction pressure 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 practise)
  - Ultimate limit states: YES
  - Serviceability limit states: YES

Technical report: R. Obrzud, A. Truty. THE HARDENING SOIL MODEL - A PRACTICAL GUIDEBOOK Z Soil.PC 100701 report

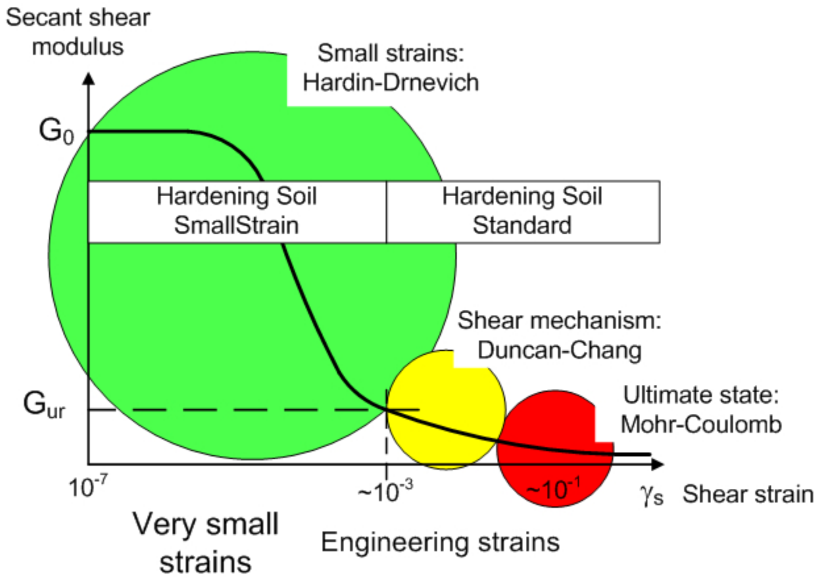
HSs model: 2 plastic mechanisms



Isotropic hardening mechanism:
cap yield surfaces
described with
van Ekelen's formula

Mohr-Coulomb
failure surface

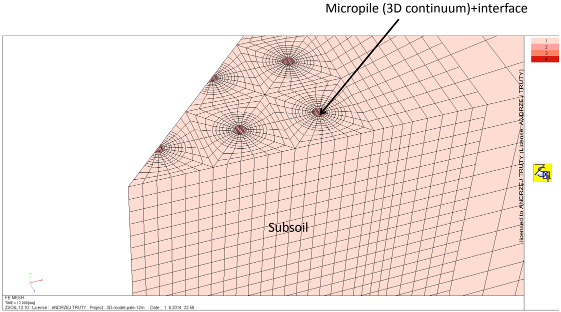
HSs model: stiffness representation



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 formuli
- CPTU/DMT serve us stress history parameter OCR and K_o in situ

Micropile-subsoil interaction: fully conforming discretization (A)

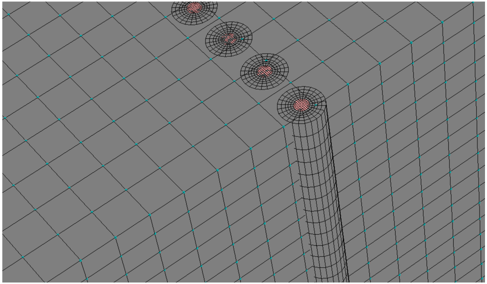


- Resulting FE models are huge and extremely time consuming
- Each redesign of piles requires new mesh for whole system

Fully conforming discretization: interface treatment

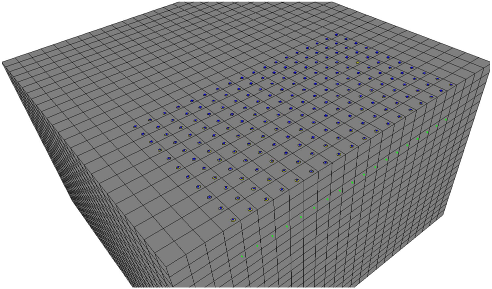
- Interface thickness is zero
- Contact stress computation
  $\sigma_{n,N+1} = k_n \, g_{n,N+1}$
  $\tau_{N+1} = \tau_N + k_s \, \Delta g_s$ and $|\tau_{N+1}| \leqslant \sigma'_n \, \mathrm{tg}(\phi) + c'$
- k_n and k_s are penalty factors for rigid plastic interface
- k_n and k_s can be related to the 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)



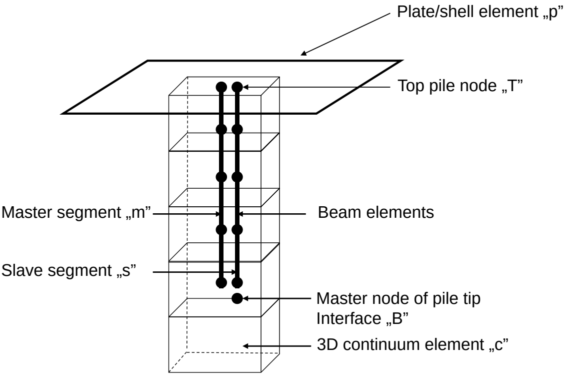
- Resulting FE models are smaller than for conforming model
- Relatively coarse mesh for subsoil is used while mesh for micropile+interface+small part of subsoil is dense

Micropile-subsoil interaction: micropiles as 1D members embedded in 3D continuum (C)



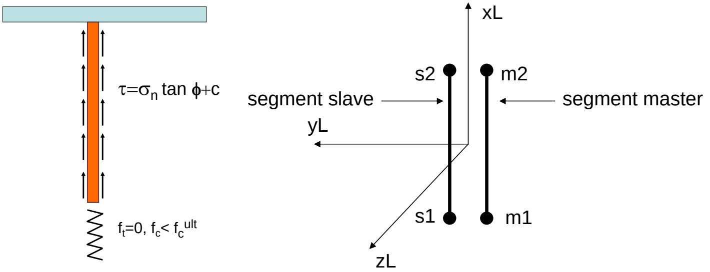
- Resulting FE models are small
- Special interface must be implemented
- Redesign of micropile system is very easy

Micropiles as 1D members embedded in 3D continuum: interface treatment



NB. Effect of micropile installation will be discussed later

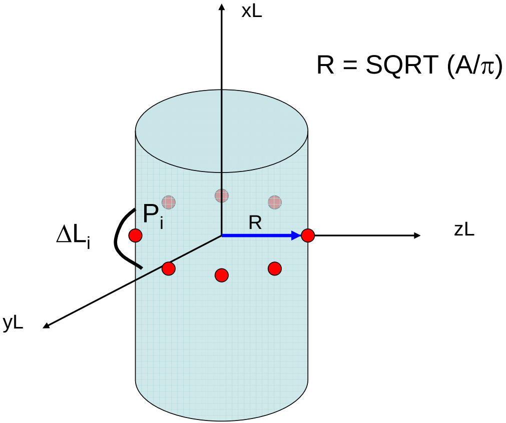
Interface micropile-subsoil in simplified approach



- In simplified approach there is no way to recover σ_n from the interface
- Hence we have to recover it from the adjacent continuum

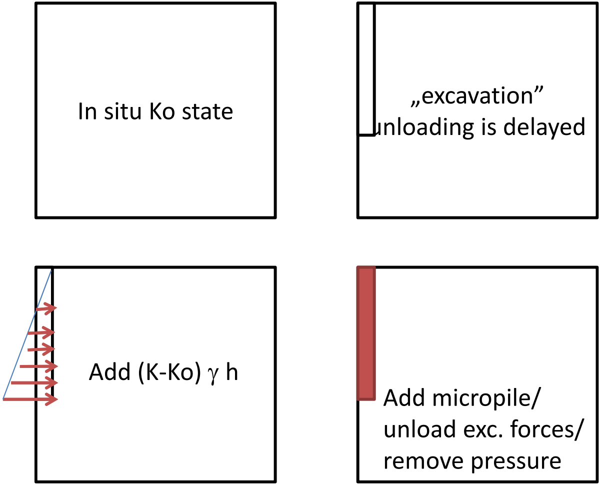
Interface micropile-subsoil in simplified approach

Recovering σ_n from adjacent continuum



Effect of installation: K-pressure method

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



Effect of micropile installation

- Micropile diameter is relatively small $\rightarrow$ 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 choosen
- Back analysis of load test may yield $\rightarrow$ K value and interface stiffness

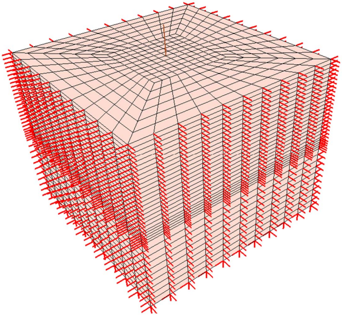
Effect of micropile installation in method (C): possible solution

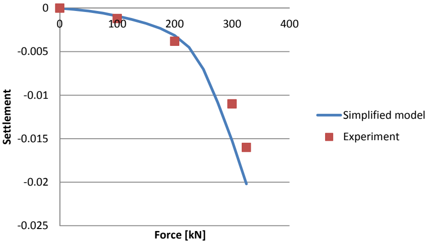
- Stress variation due to installation is neglected in subsoil
- Equivalent interface friction angle $tan\,(\phi^*)$ has to be used to reproduce skin friction
- This may lead to overestimation of micropile settlements near the limit state
- K-pressure is recommended (adding axisymmetric stress field)$\rightarrow$ not available so far

Effect of dilatancy in the interface zone

- In methods (A) and (B) effect of dilatancy is present
- In simplified approach (C) this effect is missing (so far)

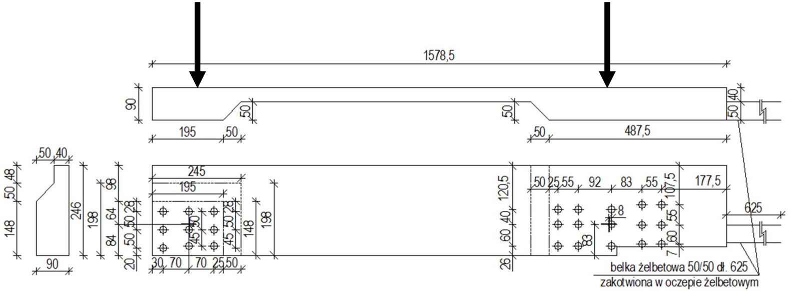
An example: loading test on single micropile $D = 18cm$



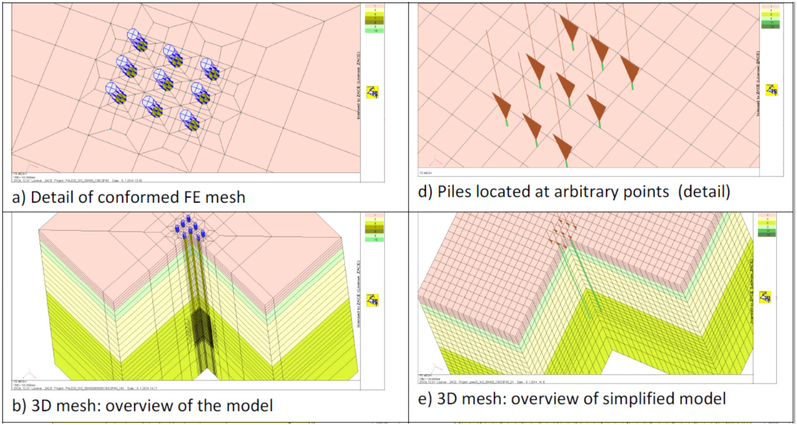


An example: micropile foundation system

3x3 and 5x5 micropile foundation system ($D = 20$cm)



An example: micropile foundation system



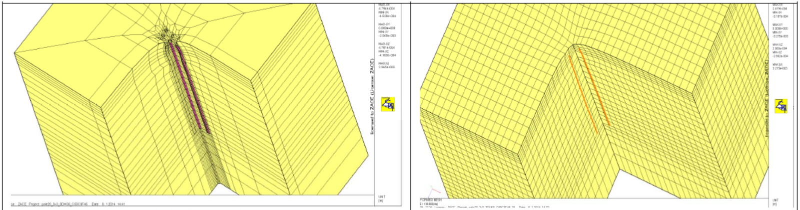
a) Detail of conformed FE mesh

d) Piles located at arbitrary points (detail)

b) 3D mesh: overview of the model

e) 3D mesh: overview of simplified model

An example: micropile foundation system



c) Deformation for full 3D model f) Deformation for simplified model

$s = 3$ mm $s = 2.5$ 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