Selected aspects of designing deep excavations using ZSoil.PC

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Selected aspects of designing deep excavations

- **Goal**
  - recall for less experienced modelers
  - exchange users’ experience

- **Compare different approaches to serviceability state analysis**
  - simplified (wall rigidity arbitrarily reduced to account for cracking in concrete)
  - “true” serviceability control

- **Effect of analysis type in quasi-impermeable soils**
  - steady-state (dissipated excess of pore water pressure)
  - consolidation (real time)
Compare different approaches to serviceability state control

Berlin Sand benchmark

..\ZSoil v2013\Full\HS Model\HS-std-Exc-Berlin-Sand-2phase.inp

Wall
h = 0.8 m

Sand I
\( \phi = 35^\circ \)
\( E_{ur} = 180 \text{ MPa} \)
\( E_{ur}/E_{50} = 4 \)

Sand II
\( \phi = 38^\circ \)
\( E_{ur} = 300 \text{ MPa} \)
\( E_{ur}/E_{50} = 4 \)

Impermeable barrier

- 3.0 m
Simplified serviceability control

Assumptions:
- short term (creep neglected)
- **reduced wall stiffness** to account for concrete cracking

Results:
- intuitively a good approximation of wall deflection and settlements behind the wall
- **pitfall:** results of internal forces \((M_k-N_k-V_k)\) may be carelessly used to design concrete structures

Retaining wall:
*Elastic-beam* \(E = 20\) GPa
(EC2 values \(\approx 34\) GPa)
Compare different approaches to serviceability control

**Simplified approach**

**Single FE run**
- Wall model: *elastic* $E=20$ GPa
- Results:
  1. Wall deflection & soil deformations
  2. $M_k = M_k (E=20 \text{ GPa})$

**Design of concrete structure**
- $M_d = 1.35 \cdot M_k (E=20 \text{ GPa})$
- Reinforcement: $A_d = A_d (M_d)$

**“True” control approach**

**1\text{st} First FE run**
- Wall model: *elastic* $E=34$ GPa
- Results:
  - $M_k = M_k (E=34 \text{ GPa})$

**Design of concrete structure**
- $M_d = 1.35 \cdot M_k (E=34 \text{ GPa})$
- Reinforcement: $A_d = A_d (M_d)$

**2\text{nd} FE run TRUE CONTROL**
- Wall model: layered beam, *elasto-plastic* $E_{\text{init}}=34$ GPa
  - 1. « True » wall deflection & soil deformations
Compare different approaches to serviceability control

Layered beam model used in 2nd FE run

σ-ε relationship according to EC2 for C30

\[ E_{\text{init}} = 34 \text{ GPa} \]
\[ f_{\text{cm}} = 38 \text{ MPa} \]
\[ f_{\text{ctk}} = 0.1 \text{ MPa (neglected)} \]

\[ E_s = 210 \text{ Gpa} \]
\[ f_{\text{sd}} = 500 \text{ MPa} \]
\[ f_{\text{sk}} = 435 \text{ MPa} \]
Compare different approaches to serviceability control

Simplified model

Hypothesis

- Contribution of the compressed rebar is not considered
- Tension in concrete is neglected

Given:
- \( h = 0.8 \text{ m} \)
- \( b = 1.0 \text{ m} \)
- \( e = 55 \text{ mm} \)

Initial choice:
- \( \phi = 30 \text{ mm} \)

\[
N_C = A_c \cdot f_{cd} \quad N_T = A_s \cdot f_{sd}
\]

\[
A_s = \frac{b \cdot x_{pl} \cdot f_{cd}}{f_{sd}}
\]

\[
N_T = - N_C = \frac{M_d}{z}
\]
### Compare different approaches to serviceability control

#### Computation of $A_d$

1. **Start**
   - $d = h - e - \frac{\phi}{2}$
   - $z_0 = 0.9 \cdot d$

2. **Iterate**
   - $x_{pl} = \frac{M_d}{b \cdot z \cdot f_{cd}}$
   - $z = d - \frac{x_{pl}}{2}$

   ![Diagram](image)

#### Results

| $A_{sd}$ [mm$^2$]   | E20  | E34  | RE
|---------------------|------|------|----
| $A_{sd+}$ [mm$^2$]  | 3339 | 4016 | $-17\%$
| $A_{sd-}$ [mm$^2$]  | 1690 | 1792 | $-5.7\%$ |
Compare different approaches to serviceability control

Simplified approach
Beam elastic $E=20\text{GPa}$

$M_{\text{max}} = 757 \text{kNm}$

$M_{\text{min}} = 393 \text{kNm}$

$M_{\text{max}} \text{ RE} = -16\%$

$M_{\text{min}} \text{ RE} = -5.5\%$

1st run of “true” control
Beam elastic $E=34\text{GPa}$

$M_{\text{max}} = 901 \text{kNm}$

$M_{\text{min}} = 416 \text{kNm}$
Compare different approaches to serviceability control

**Simplified approach**
Beam elastic $E=20 \text{GPa}$

- $u_x = 3.88 \text{ cm}$
- $u_y = 1.89 \text{ cm}$
- $u_x \text{ RE} = -5 \%$
- $u_y \text{ RE} = -5.5 \%$

**2nd run of “true” control**
Beam elasto-plastic $E_{\text{init}}=34 \text{GPa}$

- $u_x = 4.09 \text{ cm}$
- $u_y = 1.95 \text{ cm}$

1st run for elastic beam $E=34 \text{ GPa}$
- $u_x = 3.52 \text{ cm}$
- $u_y = 1.75 \text{ cm}$
- ARE = 14 \%
- ARE = 10 \%
Compare different approaches to serviceability control

- Discrepancies might increase with increasing amplitude of deformations …

- Is the careless use of internal efforts for wall designing based on the simplified approach consistent with design codes?
Effective stress in ZSoil

Fluid is considered as a mixture of air and water (single-phase model of fluid)

\[
\sigma_{ij}^{\text{tot}} = \sigma_{ij}' + S \, p \, \delta_{ij}
\]

suction stress
if \( p > 0 \) (above GWT)

\( p \) – pore water pressure

\( S = S(p) \) – degree of saturation depending on pore water pressure
Deformation + flow analysis (soil water retention curve)

- Effect of an apparent cohesion can be easily reproduced by coupling:
  - constitutive model described by effective parameters
  - Darcy’s flow in consolidation analysis
  - Soil water retention curve model (van Genuchten’s model)

\[ S = S(p) = \begin{cases} 
    S_r + \frac{1 - S_r}{1 + \left( \frac{p}{\alpha \gamma_F} \right)^2}^{1/2} & \text{if } p > 0 \\
    1 & \text{if } p \leq 0 
\end{cases} \]
Effect of analysis type in quasi-impermeable soils

Berlin Sand benchmark reused
Sand replaced with impervious clay

Clay I
- $\phi = 30^\circ$
- $E_{ur} = 90\,\text{MPa}$
- $E_{ur}/E_{50} = 4$
- $k = 10^{-9}\,\text{m/s}$
- $\alpha = 0.1$

Clay II
- $\phi = 32^\circ$
- $E_{ur} = 150\,\text{MPa}$
- $E_{ur}/E_{50} = 4$
- $k = 10^{-9}\,\text{m/s}$
- $\alpha = 0.1$

Wall
$h = 0.8\,\text{m}$

Impermeable barrier REMOVED
Effect of analysis type in quasi-impermeable soils

**ANALYSIS TYPE**

**Steady – state**
- excess of excess pore water pressure is dissipated at each state (full drainage)

**Consolidation**
- real time analysis
- development of partially saturated zones due to undrained and partially-drained conditions

False GWT lowering when in equilibrium in the case of homogenous hydraulic conductivity

No suction effect

Null pore pressure line

Positive pore pressures
Effect of analysis type in quasi-impermeable soils

Construction stages

4 excavation steps, each includes:

I. Excavation N - N+20 days (unloading over 5 days); accounting for 3D effect

II. Realisation of prestressed anchors N+20 - N+30
Effect of analysis type in quasi-impermeable soils

Analysis type: Consolidation
Maps: S*p

\[ \sigma^\text{tot}_{ij} = 0 \]
\[ \sigma^\prime_{ij} = -S(p) \cdot p = 20 \text{kPa} \]

Thickness of unsaturated zone: 4 m
Effect of analysis type in quasi-impermeable soils

**Steady-state**
Beam elastic $E=34$ GPa

- Assumed horizontal GWT (auxiliary superficial permeable layer)

**Consolidation**
Beam elastic $E=34$ GPa

Comparison in terms of J2 Strain
Effect of analysis type in quasi-impermeable soils

**Steady - state**
Beam elastic $E=34\text{GPa}$

- $u_y^- = 7.8 \text{ cm}$
- $u_y^+ = 9.6 \text{ cm}$
- $u_x = 11.0 \text{ cm}$

**Consolidation**
Beam elastic $E=34\text{GPa}$

- $u_y^- = 4.6 \text{ cm}$
- $u_y^+ = 4.3 \text{ cm}$
- $u_x = 6.6 \text{ cm}$

### Instantaneous

- $u_y^- = 4.6 \text{ cm}$
- $u_y^+ = 4.3 \text{ cm}$

### After 25 days

- $u_y^- = 5.1 \text{ cm}$
- $u_y^+ = 4.8 \text{ cm}$
- $u_x = 7.2 \text{ cm}$

<table>
<thead>
<tr>
<th>Result</th>
<th>RE</th>
</tr>
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<tbody>
<tr>
<td>$u_y^+$</td>
<td>+ 100 %</td>
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<tr>
<td>$u_y^-$</td>
<td>+ 70 %</td>
</tr>
<tr>
<td>$u_x$</td>
<td>+ 66 %</td>
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Effect of analysis type in quasi-impermeable soils

Steady-state
Beam elastic $E = 34\text{GPa}$

Consolidation
Beam elastic $E = 34\text{GPa}$

$M_{\text{max}} = 1403\ \text{kNm}$

$M_{\text{max}} = 919\ \text{kNm}$

$M_{\text{max}} \ \text{RE} = +52\ %$
Effect of analysis type in quasi-impermeable soils

**SERVICABILITY CONTROL**

**Steady-state + simplified approach**
Beam elastic $E=20\text{ GPa}$

**Consolidation + “true“ control**
Beam elasto-plastic $E=34\text{ GPa}$
$A_d = A_d(M_{\text{max}})$

<table>
<thead>
<tr>
<th></th>
<th>$u_x$</th>
<th>$u_y^-$</th>
<th>$u_y^+$</th>
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<tbody>
<tr>
<td>Steady-state</td>
<td>11.8 cm</td>
<td>8.2 cm</td>
<td>10. cm</td>
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<tr>
<td>Consolidation</td>
<td>7.6 cm</td>
<td>5.3 cm</td>
<td>4.9 cm</td>
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</table>

Result

<table>
<thead>
<tr>
<th></th>
<th>$u_y^+$</th>
<th>$u_y^-$</th>
<th>$u_x$</th>
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<tbody>
<tr>
<td>$u_y^+$</td>
<td>+104%</td>
<td></td>
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</tr>
<tr>
<td>$u_y^-$</td>
<td>+55%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$u_x$</td>
<td></td>
<td>+55%</td>
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Effect of analysis type in quasi-impermeable soils

- Discrepancies are difficult to foresee due to a highly nonlinear nature of the problem.

- In this example, the steady-state approach gives a superior confidence limit for internal efforts with respect to consolidation analysis.

- Is the “steady-state shortcut” profitable in the light of an optimal design?
Thank you for your attention