Tackling liquefaction problems with ZSOIL

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Contents

- Context of the study
- Elementary calibration of Sawicki law
- 1D column coupled transient dynamic analysis
- Pseudo-static approach
- Conclusions and perspectives
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Context

- New hospital construction in Rennaz, Switzerland
  - estimated total cost: 315 mios CHF

- 2012: first geological campaign shows possible liquefaction problems, at depth = 0 to 6 m => fondation system: piles, L = approx. 20 m

- 2014: new geological campaign (CPTU) => other potential liquefaction zone, at depth = 15 to 25 m !!

- Geotechnicians and their expert proposed solutions to the contractor:
  - L(piles) -> 35 m + 6-8 mios
  - Vibratory compaction + 8-10 mios
  - Drainage + 10-12 mios
Context

Influence fondations + structure en cas de liquéfaction en profondeur (15-25m)

- Tassements très importants sous les pieux courts (10cm à >30cm)
- Tassements «limités» sous les pieux longs (<1cm à 10cm)
- Zone très critique pour la structure

Zones liquéfiables + Pieux de diverses longueurs → Tassements différentiels très importants
Problème pour structure + fonctionnalité

Document [K+F SA, 2014]
Context

- People involved for geotechnical problems:
  - Contractor/project director: HRC Vaud-Valais
  - Civil Engineer: Willi SA
  - Geotechnician: Karakas+François SA
  - Expert for geotechnician: Résonance SA
  - Expert for contractor: Bureau Tissières SA
  - Numerical modeling: GeoMod SA

- Goal of numerical model:
  - Help understand if/how liquefaction can happen at 15-25 m under a given seismic loading, for a given stratigraphy and parameters
  - Estimate the settlement induced by liquefaction
  - Evaluate the effect of long piles vs. short piles => choose length
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Elementary tests

- First question: is it possible to reproduce mean effective stress decrease as well as pore pressure increase under cyclic loading with ZSOIL?
- Local seismic demand: $a_{g,d} = 2.14 \text{ m/s}^2$ (for design), $M = 6$
- In situ conditions, at depth of 25 m

\[
\begin{align*}
\Delta &= \text{28 m} \\
\gamma &= 20 \text{ kN/m}^3 \\
\gamma_{o} &= -250 \text{ kPa} \\
\gamma_{v0} &= -500 \text{ kPa} \\
\gamma_{v0}' &= -250 \text{ kPa} \\
\gamma_{v0}' &= \gamma_{v0}' \\
\gamma_{o} &= \gamma_{o}' + p_{w0} \\
\end{align*}
\]
Elementary tests

\[ \sigma'_v = \sigma'_{v0} + \Delta \sigma'_v \]

Conditions initiales

\[ \sigma'_h = K_U \sigma'_{v0} \]
\[ \sigma'_v = \sigma'_{v0} \]
\[ \sigma'_H = K_U \sigma'_{v0} \]

\[ \Delta \sigma'_v \]

\[ \Delta q = 55 \text{ kPa} \]

\[ T \]
Elementary tests

- Determination of cyclic stress amplitude (from Geotechnical earthquake engineering book [Kramer 1996])
Elementary tests

- Densification model (Sawicki approach): accumulated volumetric straining due to cyclic loading:

\[ \varepsilon_{\text{acc}} = e_0 C_1 \ln(1 + C_2 z) \]

\[ z = 0.25 N \gamma_0^2 \]

- Note: for this study, only the densification mechanism was activated at the UI level: no shear plastic mechanism

N = number of cycles = 6 for M = 6 [Boulanger]
Elementary tests

- Densification model (Sawicki approach): estimation of a «reasonable» volumetric deformation, based on [Kramer] and [Tokimatsu & Seed] leads to estimation of C1 and C2 (not unique, but not stress dependent)

\[ \varepsilon^{acc} = e_0 \ C_1 \ \ln(1 + C_2 \ z) \]

Figure 5. Estimation de C1 et C2

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>e0</td>
<td>0.65</td>
</tr>
<tr>
<td>C1</td>
<td>1.00E-02</td>
</tr>
<tr>
<td>C2</td>
<td>2.50E+05</td>
</tr>
<tr>
<td>( z )</td>
<td>7.35E-07</td>
</tr>
<tr>
<td>N</td>
<td>6</td>
</tr>
<tr>
<td>( \gamma_0 )</td>
<td>7.00E-04</td>
</tr>
<tr>
<td>( \varepsilon_{ps} )</td>
<td>0.001096</td>
</tr>
<tr>
<td>( \varepsilon_{ps} [%] )</td>
<td>0.109647</td>
</tr>
<tr>
<td>( \varepsilon_{ps,calc} [%] )</td>
<td>0.1</td>
</tr>
</tbody>
</table>

\[ \varepsilon_{eff} = 0.6 \ (1 + 2 \ \varepsilon_{ps}) \]

\[ \varepsilon_{eff} = 7 - 4 + 7 \times 2 \ % \]

\[ \varepsilon_{eff} = 7 - 4 + 7 \times 2 \ % \]

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Elementary tests

\[ \sigma'_v = \sigma'_{v0} + \Delta \sigma'_v \]

\[ \sigma'_h = \sigma'_{v0} = -250 \text{ kPa} \]

\[ \Delta q = 55 \text{ kPa} \]
Elementary tests

![Graph showing deviatoric stress vs mean effective stress with lines for Cyclic and M-C]
Elementary tests
Elementary tests

\[ \sigma'_v = \sigma'_{v0} + \Delta \sigma'_v \]

\[ \sigma'_h = \sigma'_{h0} = K_0 \sigma'_{v0} \]

\[ \Delta \sigma'_v \]

\[ \Delta q = 55 \text{kPa} \]
Elementary tests

\[ N = \text{number of cycles depends on } C_1, C_2! \]
Elementary tests
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déconvolution + scaling
1D column coupled transient dynamic analysis

2-phase nonlinear dynamics consolidation
\[ \Delta t = 0.02 \text{ s, HHT scheme} \]
Damping: plastic, hysteretic \( (E_p) \), Rayleigh
Rayleigh: \( \alpha = 0, \beta = 0.0006 \) (5% on \( f = 25 \text{ Hz} \))

- Palustre
  - Densification model
  - \( (C1, C2 = 0) \)
- Graviers
  - Densification model
  - \( (C1, C2 = 0) \)
- Sables
  - Densification model
  - \( (C1, C2) \)

```
acc1 déconvolué et amplifié x 2.33
```

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1D column coupled transient dynamic analysis
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1D column coupled transient dynamic analysis
1D column coupled transient dynamic analysis

Conclusions

- 1D column subjected to an earthquake compatible with the local design spectrum leads to liquefaction in the 15m-25m depth zone (no surprise as we calibrated the model for that)

- Visualization of pore pressure >> and mean effective stress <<

- Estimation of induced settlement post-earthquake = 20 cm
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Pseudo-static approach

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Pseudo-static approach

- 5 x 5 3D cell with pile element at center
- Mesh refinement in the vicinity of the pile element
- Hospital g+q load applied on top shell
- E << for top layer => everything goes into pile
- Pile interface with \( \tau = c_{\text{soil}} + \sigma_n \tan \phi \)
  \( \phi = \phi_{\text{soil}} \) in gravel, \( \phi = 0.7 \phi_{\text{soil}} \) in sand

- Post-liquefaction strength: 2 approaches
  - \( \phi = 0^\circ, c = 20 \text{ kPa} \) (9% \( \sigma'_{v0} \) at -20 m, [1] et [2])
  - \( \phi = 0^\circ, c = 1 \text{ kPa} \) (almost zero)

## Pseudo-static approach

<table>
<thead>
<tr>
<th>Lpieu [m]</th>
<th>calc 2014</th>
<th>c(liq) = 20 kPa</th>
<th>c(liq) = 10 kPa</th>
<th>c(liq) = 1 kPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>dyn 2D</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>-18.6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3D pseudostat</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DT = T6-T3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>-16.5</td>
<td>non significatif (vide sous radier)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>-15.3</td>
<td>-16.2</td>
<td>-18.7</td>
<td>fails at 80%</td>
</tr>
<tr>
<td>25</td>
<td>-11.5</td>
<td>-15.0</td>
<td>-17.9</td>
<td>fails at 80%</td>
</tr>
<tr>
<td>30</td>
<td>-6.8</td>
<td>-9.6</td>
<td>-12.6</td>
<td>-15.5</td>
</tr>
<tr>
<td>35</td>
<td>-3.6</td>
<td>-2.5</td>
<td>-4.3</td>
<td>-5.1</td>
</tr>
</tbody>
</table>
Pseudo-static approach
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\[ \phi = 0^\circ, \ c = 20 \text{ kPa} \]
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\[ \phi = 0^\circ, c = 20 \text{ kPa} \]

-28 m

-15 m

-5 m

-2.500e+003
-2.250e+003
-2.000e+003
-1.750e+003
-1.500e+003
-1.250e+003
-1.000e+003
-7.500e+002
-5.000e+002
-2.500e+002

**PALUSTRE**

**GRAVIER**

**SABLES LIQUEFIES**

**SABLES**

---

**SECTIONAL FORCES [N·X]**

**TIME = 0.000 s**

**ZSOIL 13.11 License: GEOMOD 2014 Project: PSEUDOSTAT_strut1_pile39_c20 Date: 18.1.2015 18:21**

**GEOMOD**
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\[ \phi = 0^\circ, \ c = 20 \text{ kPa} \]
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\( \phi = 0^\circ, c = 1 \text{ kPa} \)

PALUSTRE
-5 m

GRAVIERS
-15 m

SABLES LIQUEFIES
-28 m

SABLES

\[ \text{SECTIONAL FORCES [N:x]} \]
TIME = 0.000s
ZSOIL 13.11 License : GEOMOD 2014 Project: PSEUDOGSTAT_strat1_pile39_c1 Date : 19.1.2015 6:14

Licensed to GEOMOD (License: GEOMOD 2014)

9.663e-013

UNIT
[kN]
\( \phi = 0^\circ, c = 1 \text{ kPa} \)
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$\phi = 0^\circ, c = 1 \text{ kPa}$
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Conclusions

- Possibility of representing liquefaction phenomenon with ZSOIL: YES

- Calibration of Sawicki law: not straightforward, but possible

- 3D soil-structure interaction transient dynamic analysis with densification model: still needs to be benchmarked?

- On the project itself: difficult for all experts to agree on an optimal length (statically/economically)
Conclusions

- Final decision... Vibratory compaction => liquefaction