ASSESSMENT AND MITIGATION OF LIQUEFACTION POTENTIAL ACROSS EUROPE

A holistic approach to protect structures / infrastructures for improved resilience to earthquake-induced liquefaction disasters

INNOVATIVE GROUND IMPROVEMENT FOR LIQUEFACTION MITIGATION: FROM EXPERIMENTAL EVIDENCES TO DESIGN APPROACHES

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PRESENTATION OUTLINE

1. Activities of the UNINA team in the Liquefact project
2. An insight on the cyclic behaviour of unsaturated soils
3. Ground Improvement design goals
4. Design procedure for (horizontal) drains and Induced Partial Saturation (IPS)
5. Concluding remarks
1. Activities of the UNINA team in the Liquefact project (WP4)

- Experimental evidences for some innovative ground improvement technologies
- Theoretical interpretation
- Design procedure

Exposure

+ Assessment of vulnerability of structures to liquefaction
+ Assessment of liquefaction hazard

Liquefaction RISK assessment
1. Activities of the UNINA team in the Liquefact project (WP4)

- Experimental evidences for some innovative ground improvement technologies
- Theoretical interpretation
- Design procedure

Exposure

+ Assessment of vulnerability of structures

Liquefaction RISK assessment

WP3

WP2

WP4

Numerical analyses

- Laboratory testing
- Centrifuge testing
- Field testing

• Induced Partial Saturation (IPS)
• Horizontal Drains (HD)

MITIGATION
An insight on the cyclic behaviour of unsaturated soils
INDUCED PARTIAL SATURATION (IPS)

1. High desaturation

2. Limited desaturation

Why is it effective?

For limited desaturation, the compressibility \( \beta_f \) of the equivalent fluid \( f \) can be written as follows (Mihalache and Buscarnera, 2016):

\[
\beta_f = \frac{1-S_r}{u + p_a} + \beta_w \cdot S_r
\]
UNDRAINED CYCLIC BEHAVIOUR OF UNSATURATED SANDS

Some experimental evidences

Sands tested in CSS and CTX

<table>
<thead>
<tr>
<th>Physical Properties</th>
<th>SAS</th>
<th>Bauxite</th>
<th>Inagi</th>
</tr>
</thead>
<tbody>
<tr>
<td>FC (&lt;0.075 mm) (%)</td>
<td>20.0</td>
<td>40.6</td>
<td>29.5</td>
</tr>
<tr>
<td>Gs</td>
<td>2.674</td>
<td>2.642</td>
<td>2.656</td>
</tr>
<tr>
<td>Ds0 (mm)</td>
<td>0.200</td>
<td>0.200</td>
<td>0.115</td>
</tr>
<tr>
<td>e_max</td>
<td>1.01</td>
<td>-</td>
<td>1.645</td>
</tr>
<tr>
<td>e_min</td>
<td>0.37</td>
<td>-</td>
<td>0.907</td>
</tr>
</tbody>
</table>
UNDRAINED CYCLIC BEHAVIOUR OF UNSATURATED SANDS

Some experimental evidences

Liquefaction triggering mechanism at the lab scale

- Stress based criterion ($r_u = \Delta u / \sigma'_v$)
- Strain based criterion ($\varepsilon_{DA}, \gamma_{DA}$)

Difference increases as $S_r$ decreases

(Mele et al. 2018)

Sant’Agostino sand, $S_r=56%$

<table>
<thead>
<tr>
<th>CSR</th>
<th>$N_{cyc}$</th>
<th>$\Delta u$ (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>-0.1</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>-0.2</td>
<td>20</td>
<td>10</td>
</tr>
<tr>
<td>-0.3</td>
<td>30</td>
<td>15</td>
</tr>
<tr>
<td>-0.4</td>
<td>40</td>
<td>20</td>
</tr>
</tbody>
</table>

$N_{cyc,ru} = 34$

<table>
<thead>
<tr>
<th>CSR</th>
<th>$\varepsilon_{DA}$, $\gamma_{DA}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>-0.1</td>
<td>5</td>
</tr>
<tr>
<td>-0.2</td>
<td>10</td>
</tr>
<tr>
<td>-0.3</td>
<td>15</td>
</tr>
<tr>
<td>-0.4</td>
<td>20</td>
</tr>
<tr>
<td>-0.5</td>
<td>25</td>
</tr>
</tbody>
</table>

$N_{cyc,5%} = 26$

A. Flora - Innovative ground improvement for liquefaction mitigation: from experimental evidences to design approaches
UNDRAINED CYCLIC BEHAVIOUR OF UNSATURATED SANDS

Some experimental evidences

Sant’Agostino sand

For \( S_r < 100\% \), liquefaction takes place at \( r_u < 0.9 \).

Pore pressure keeps increasing in subsequent cycles.
UNDRAINED CYCLIC BEHAVIOUR OF UNSATURATED SANDS

Some experimental evidences

**Sant’Agostino sand**
- Dr = 51% - Sr = 55%
- Dr = 45% - Sr = 100%

**Bauxite**
- Dc = 78,5% - Sr = 57%
- Dc = 86,5% - Sr = 84,5%
- Dc = 83,5% - Sr = 100%

**Inagi sand**
- Dr = 63,5% - Sr = 50%
- Dr = 63% - Sr = 100%

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A. Flora - Innovative ground improvement for liquefaction mitigation: from experimental evidences to design approaches
**UNDRAINED CYCLIC BEHAVIOUR OF UNSATURATED SANDS**

Some experimental evidences

A. Flora - Innovative ground improvement for liquefaction mitigation: from experimental evidences to design approaches
The total specific energy of deformation $E_{\text{tot}}$ needed to reach liquefaction can be expressed as the sum of two components:

$$E_{\text{tot,liq}} = E_{\text{v,liq}} + E_{\text{s,liq}}$$

The energetic interpretation of the undrained cyclic behaviour of unsaturated sands can be expressed as:

$$E_{\text{v,liq}} = E_{\text{v,sk,liq}} + E_{\text{w,liq}} + E_{\text{air,liq}}$$

- $E_{\text{v,sk,liq}} = \int_{0}^{\varepsilon_{\text{v,liq}}} [(\sigma - u_a + sS_r)] \cdot d\varepsilon_v$ → Soil
- $E_{\text{w}} = -\int_{S_{\text{r,liq}}}^{s} \frac{e}{1+e} sS_r$ → Water
- $E_{\text{air}} = \frac{e_0}{1+e_0} (1-S_{\text{r,0}}) \mu_{\text{a,liq}} d(\ln \rho_{\text{a,liq}})$ → Air

For $S_r = 100\%$, $E_{\text{v,liq}} = 0$
UNDRAINED CYCLIC BEHAVIOUR OF UNSATURATED SANDS

Volumetric specific energy

\[ E_{v,liq} = f(\sigma'_{un}, e, S_r) \]

Identifies univocally the CRR-N_{liq} curve

\[ CRR_{unsat}(N) = CRR_{sat}(N) + \Delta CRR(E_{v,liq}) \]

First possible approach

Once CRR=CRR(N) is known for \( S_r=1 \), with this approach it is possible to plot \( CRR_{un}=CRR(N, S_r) \) for any value of \( S_r \) just by calculating the corresponding value of \( E_{v,liq} \).
UNDRAINED CYCLIC BEHAVIOUR OF UNSATURATED SANDS

Volumetric specific energy

\[ CRR_{\text{unsat}} \] – practitioners approach

\[ q_{c1Ncs} \]

simple safety check design tool for \( S_r < 100\% \)
UNDRAINED CYCLIC BEHAVIOUR OF UNSATURATED SANDS

D. Flora - Innovative ground improvement for liquefaction mitigation: from experimental evidences to design approaches

(Mele and Flora 2019)
A. Flora - Innovative ground improvement for liquefaction mitigation: from experimental evidences to design approaches

**UNDRAINED CYCLIC BEHAVIOUR OF UNSATURATED SANDS**

Total specific energy

\[ E_{\text{tot,liq}} = E_{v,\text{liq}} + E_{s,\text{liq}} \]

\[ \text{CRR}_{\text{unsat}}(N) = \text{CRR}_{\text{unsat}}(N, E_{\text{tot,liq}}) \]

*Second possible approach*

(Mele and Flora 2019)
UNDRAINED CYCLIC BEHAVIOUR OF UNSATURATED SANDS

Prediction of independent data with \( \text{CRR}_{\text{unsat}}(N) = \text{CRR}_{\text{sat}}(N) + \Delta \text{CRR}(E_v,\text{liq}) \)

- Inagi sand, Dr=72%
- Toyoura sand, Dr=6%
- Kochi sand

\( \text{CRR} \) vs \( N_{iq} \)

Wang et al., 2016

Okamura et al., 2011
UNDRAINED CYCLIC BEHAVIOUR OF UNSATURATED SANDS

Prediction of independent data with \( \text{CRR}_{\text{unsat}}(N) = \text{CRR}_{\text{unsat}}(N, E_{\text{tot,liq}}) \)

Wang et al., 2016

Okamura et al., 2011
3

Ground improvement design goals
GOALS OF GROUND IMPROVEMENT

no liquefaction (case 1)

\[ FS_{liq}(z) > FS_{liq,min} \]
\[ r_u \geq r_{u,max} \]
reduce \( r_u(z) \)

liquefaction (case 2)

\[ FS_{liq}(z) < FS_{liq,min} \]
LPI, LSN, ... too high
increase \( FS_{liq}(z) \)

Do we have everything we need to design HD and IPS?

A. Flora - Innovative ground improvement for liquefaction mitigation: from experimental evidences to design approaches
DESIGN NEEDS

Initial checks

With the free field safety check ($FS_{liq,ff}=CRR/CSR$) we know how far we are from liquefaction.

1. What is the pore pressure ratio $r_{u,ff}$ for $FS_{liq,ff}>1$ ($S_r=1$)?

Ground improvement checks

We need tools for case 1 ($FS_{liq} \geq FS_{liq,min}$ and $r_u \geq r_{u,max}$) and case 2 ($FS_{liq} < FS_{liq,min}$) design checks.

**Horizontal drains** are designed with a target maximum value of $\Delta u$ (or $r_u$).

1. What is the effect in terms of $FS_{liq,ff}$?

**IPS** reduces the tendency to accumulate positive pore pressure increments.

1. What is the effect of $S_r<1$ on $FS_{liq,ff}$?

2. What is the pore pressure ratio $r_{u,ff}$ for $FS_{liq,ff}>1$ and $S_r<1$?
ISSUES RELATED TO SAFETY CHECKS

Need to link $r_u$ to $FS$ ($S_r=100\%$)

$$r_u = \frac{2}{\pi} \arcsin \left[ \left( FS \right)^{-\frac{1}{2b\beta}} \right] \quad FS \geq 1, \quad S_r = 100\%$$

$$b = -1.487 \cdot 10^{-8} \cdot q_{clNcs}^3 + 1.291 \cdot 10^{-5} \cdot q_{clNcs}^2 - 5.722 \cdot 10^{-4} \cdot q_{clNcs} + 0.163$$

$$b = -1.000 \cdot 10^{-6} \cdot (N_1)^3_{60cs} + 2.216 \cdot 10^{-4} \cdot (N_1)^2_{60cs} + 1.727 \cdot 10^{-3} \cdot (N_1)_{60cs} + 0.1557$$

$$\beta = 0.01166 \cdot FC + 0.3536 \cdot (q_{clNcs} - \Delta q_{clN})^{0.264} - 0.2805$$

$$\beta = 0.01166 \cdot FC + 0.1091 \cdot ((N_1)_{60cs} - \Delta(N_1)_{60})^{0.5} + 0.5058$$
ISSUES RELATED TO SAFETY CHECKS

Need to link $r_u$ to FS ($S_r=100\%$)

(a) $FC = 0\%$

\[ q_{c1NCS} ; (N_1)_{50CS} (Dr (\%)) \]
- 39.7 : 1.8 (20)
- 69.2 : 7.4 (40)
- 100.2 : 13.9 (55)
- 125.8 : 19.4 (65)
- 156.0 : 25.9 (75)

(b) $FC = 10\%$

\[ q_{c1NCS} (Dr (\%)) ; (N_1)_{50CS} (Dr (\%)) \]
- 45.7 (20)
- 76.1 (40)
- 107.9 (55)
- 134.2 (65)
- 165.3 (75)

(c) $FC = 20\%$

\[ q_{c1NCS} (Dr (\%)) ; (N_1)_{50CS} (Dr (\%)) \]
- 68.5 (20)
- 102.1 (40)
- 137.2 (55)
- 166.3 (65)
- 200.5 (75)

(d) $FC = 30\%$

\[ q_{c1NCS} (Dr (\%)) ; (N_1)_{50CS} (Dr (\%)) \]
- 83 (20)
- 118.5 (40)
- 155.8 (55)
- 186.6 (65)
- 222.9 (75)

Chiaradonna and Flora (2019)
ISSUES RELATED TO SAFETY CHECKS
Need to link $r_u$ to FS ($S_r=100\%$)

Experimental verification

Chiaradonna and Flora (2019)
ISSUES RELATED TO SAFETY CHECKS
Need to link \( r_u \) to FS \( (S_r < 100\%) \)

\[
r_u = \frac{2}{\pi} \arcsin \left( (FS)^{-\frac{1}{2b\beta}} \right)
\]

\( FS \geq 1, \ S_r = 100\% \)

What happens if \( S_r < 100\% \)? Our new proposal:

\[
r_u = r_{u,FS=1}(S_r) \frac{2}{\pi} \arcsin \left( (FS)^{-\frac{1}{2b\beta}} \right)
\]

\( FS \geq 1, \ S_r \leq 100\% \)

- \( r_{u,FS=1}(S_r) \) is the value of \( r_u \) at liquefaction

- \( f_1(S_r) \) takes into account that the slope of the \( CRR_{unsat}(N) \) curve can differ from that of the \( CRR_{sat}(N) \) one

\( r_{u,FS=1}(S_r) \) and \( f_1(S_r) \) can be obtained theoretically using the energetic interpretation (Mele et al. 2108) or can be calibrated experimentally
4

Design procedures
DESIGN OF HORIZONTAL DRAINS (HD)

Horizontal drains are designed with a target maximum value of \( \Delta u \) (or \( r_u \)).

(Fasano et al. 2019)

How to assign spacing and depth if \( FS_{\text{liq}} < FS_{\text{liq,min}} \), having \( FS_{\text{liq,min}} \) as a goal?

\[ Design \ value \ of \ r_{u,ff} \]
CONCLUDING REMARKS …

- HD and IPS are innovative technologies that can be of extreme interest in urbanized areas.
- Experimental evidences indicate that IPS is very effective even at high $S_r$.
- Design procedures are available for the two technologies (HD and IPS) in the case of full liquefaction or just critical pore pressure increments and no liquefaction.

... AND THINGS STILL TO DO

**Experimental**
- IPS generation? Duration?
- Reliable in situ estimate of $S_r$
- New field trials

**Theoretical**
- Link between $r_{u,ff}$ and $r_{u,str}$
- Definition of the critical value $r_{u,max}$ for different mechanisms
Thank you