A macro-element for a shallow foundation to simulate Soil-Structure Interaction

Stéphane Grange\(^{(1)}\), George Nahas\(^{(2)}\), Jean-Mathieu Rambach\(^{(2)}\)

\(^{(1)}\) Laboratoire Sols, Solides, Structures, Risques (3SR), Université Joseph Fourier (UJF), Grenoble, France

\(^{(2)}\) Institut de Radioprotection et de Sûreté Nucléaire (IRSN) Fontenay aux Roses, France
1. Introducing the soil-structure interaction problem

2. Description of 3D macro-element for SSI
   - Description of the model: plasticity & uplift
   - Mechanisms coupling and radiative damping
   - Parameters

3. Results: static, cyclic and dynamic

4. Conclusion and way forward
1. Introducing the SSI problem

Residual displacements can occur

Which can be dramatic in case of:
• Structure where P-δ effect is important
• slender structures and tall structures
• structures lying on soils with very low characteristics ($V_s < 100\text{m/s}$)

Elastic analysis is not sufficient for safety related structures: for SMA and seismic PSA analyses, with beyond design EQ levels, strong non linearities may occur, due to basemat uplift and soil plastification.

⇒ Development of a macro-element for soil-structure interaction
Analysis in term of displacements « Displacement based design »
2. Description of SSI 3D Macro-element

Macro-element concept

- 2 sub-domains: close field and far field
- 2 non linearities: plasticity and uplift
- Non linearities are nevertheless coupled

Global forces  Global displacements

circular, rectangular or strip foundations

[Nova et al.1991]
[Pedretti, 1998]
[Crémer, 2001]
[di Prisco, Galli, 2006]
[Chatzigogos, Pecker, 2008]
2. Description of the model: Plasticity

- Failure criterion (developed by C. Crémer and A. Pecker for plasticity with rocking)

\[
J_{\infty} \equiv \left( \frac{H'_x}{a V'^c (1 - V'/f)} \right)^2 + \left( \frac{M'_y}{b V'^c (1 - V'/f)} \right)^2 + \left( \frac{H'_y}{a V'^c (1 - V'/f)} \right)^2 + \left( \frac{M'_x}{b V'^c (1 - V'/f)} \right)^2 - 1 = 0
\]

- Loading surface

\[
f_c (F, \tau, \rho, \gamma) \equiv \left( \frac{H'_x}{\rho a V'^c (\gamma - V'/f)} - \frac{\alpha}{\rho} \right)^2 + \left( \frac{M'_y}{\rho b V'^c (\gamma - V'/f)} - \frac{\beta}{\rho} \right)^2 + \left( \frac{H'_y}{\rho a V'^c (\gamma - V'/f)} - \frac{\delta}{\rho} \right)^2 + \left( \frac{M'_x}{\rho b V'^c (\gamma - V'/f)} - \frac{\eta}{\rho} \right)^2 - 1 = 0
\]

Interaction in the \( H'x_H'y \) and \( M'x_M'y \) planes: circles

Dimensionless variables \( \rightarrow \) axial symmetry
2. Description of the model: Uplift

Even with a plastic soil, we can assume a non-linear but reversible uplift behavior.

On a plastic soil:
- Overturning moment
- Uplift initiation moment

(rectangular-strip):
(circular):

δ percentage of uplift → state variable for the uplift mechanism.
2. Description: Coupling, Radiative damping

**Coupling between the two mechanisms**

**Space M-H-V**

**Space M-M-V**

**Radiative damping**

A dashpot is added in parallel of the plasticity model and uplift.

Effect of the dashpot during a step time.
2. Description: Parameters of the macro-element

Foundation impedance [G. Gazetas]

CAST3M
FedelasLab

\[ \eta_v = \frac{C_z}{K_{elz}} \]

Most of theses parameters keep unchanged
3. Results: Static tests

3.1 Results: Swipe tests

Displacements imposed tests ⇒ allow determining the failure criteria of plasticity and uplift mechanisms
3. Results: Static tests

3.1 Results: Swipe tests

Numerical response of the macro-element submitted to cyclic displacements (swipe test)

→ The response path follows the bounds of the failure criteria of plasticity and uplift mechanisms
3. Results: dynamic tests

3.2 Dynamic behavior on sand: Camus IV tests (CEA Saclay)

Lumped mass modeling

<table>
<thead>
<tr>
<th>Mode</th>
<th>Frequency Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (bending)</td>
<td>3.5</td>
</tr>
<tr>
<td>2 (pump)</td>
<td>13</td>
</tr>
</tbody>
</table>

Numerical vs experimental results
3. Results: dynamic tests

3.3 Dynamic behavior: NEES test (UC San Diego), effect of the characteristics of the soil
3. Results: dynamic tests

3.4 Study of a Reactor building.  

Influence of the bearing capacity of the soil

Lumped mass modeling

Modal analysis taking into account the softness of the soil

<table>
<thead>
<tr>
<th></th>
<th>frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rocking</td>
<td>1.89Hz</td>
</tr>
<tr>
<td>Pumping</td>
<td>4.48Hz</td>
</tr>
</tbody>
</table>

Accelerogram: NUREG 0.3 g
3.4 Study of a Reactor building

With the actual soil

The soil under the building behaves quasi elastically.
3. Results: dynamic tests

3.4 Study of a Reactor building

Influence of the bearing capacity of the soil

\( q_{\text{max}} = 11546 \text{ kPa} \) is decreased to \( q_{\text{max}} = 600 \text{ kPa} \)

For:  
- an elastic soil
- a plastic soil

In this case, taking into account non-linearities into the soil allows better estimating of the internal forces and also the floor response spectra.
3. Results: dynamic tests

3.4 Study of a Reactor building

Parametrical study
- Decreasing the bearing capacity
- Increasing the seismic level

Increasing the seismic level
4. Conclusion and way forward

- The 3D SSI macro element gives good trends for **monotonic**, **cyclic and dynamic** behavior.

- Low computational costs allow to perform parametrical studies to investigate a wide range of boundary conditions.

- Adaptation of the model to simulate **base-isolators** have been computed.

- It takes into account, plasticity, uplift, radiative damping and allows determining residual displacements.

Nevertheless, various improvements could be made concerning:

- the fitting of the parameters (stiffness, shape of the loading surface, radiation damping)

- development of macro-element for deep foundations or improved ground with deep piles or mixed columns.
Thank you for your attention