Overview

- **Introduction**
  - Background & Common Practice

- **3D Analysis of Soil-Pile Interaction**
  - Beam-Solid Approach
  - Contact Formulation & Implementation
  - Practical Applications

- **Summary and Conclusions**
Problem Description

Kinematic loading on the pile from the upper liquefied soil mass displacing relative to the underlying stable lower soil mass.

Slippage displacement concentrated on a usually thin liquefied soil layer between the two stiffer soil masses.

Common Solution strategies

- Fixed-fixed beam
- Uncoupled free-field displacement
- Uncoupled displacement considering pile pinning
- 2-D FEM analysis
- 3-D FEM analysis
Fixed-fixed approach

Uncoupled free-field displacement
(with and without pinning effect)
2-D FEM analysis

3D FEM Analysis

Solid-Solid Model
New approach: Beam-Solid Contact Element

Soil: solid elements

Pile: beam elements

Pile-Soil Interface: Beam-Solid Contact Element

Laterally Loaded Piles (comparison with LPILE)

- Perform numerical load test
- Compare results

3x Magnification
Laterally Loaded Piles

- Numerical $p$-$y$ curves:
  - Obtained by differentiation of pile bending moments
  - Obtained directly from contact element force output

Solid pile: Beam pile:

Discretized beam Deformed beam Deformed beam with interface forces, $f(z, \theta)$ Deformed beam with interface forces, $p_i = \sum f_i (z, \theta)$ def and displacement, $y_i$

Laterally Loaded Piles

- Normal interface stresses and radial soil stresses
Laterally Loaded Piles

- **Evaluation of beam response**

- **GiD Visualization of pile and soil deformation with interface forces**
Back to our problem…

Undeformed mesh

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Base Soil & Pile Properties

Elastic isotropic soil properties

<table>
<thead>
<tr>
<th>Soil profile</th>
<th>E [kPa]</th>
<th>Poisson’s ratio</th>
<th>Unit weight [kN/m$^3$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top strong layer (brown)</td>
<td>25,000</td>
<td>0.35</td>
<td>17.0</td>
</tr>
<tr>
<td>Middle soft layer (white)</td>
<td>2,500</td>
<td>0.47</td>
<td>17.0</td>
</tr>
<tr>
<td>Bottom strong layer (brown)</td>
<td>25,000</td>
<td>0.35</td>
<td>17.0</td>
</tr>
</tbody>
</table>

Elasto-plastic (Drucker Prager) soil properties

<table>
<thead>
<tr>
<th>Soil profile</th>
<th>K [kPa]</th>
<th>G [kPa]</th>
<th>Friction angle $\phi$ [degrees]</th>
<th>Cohesion c [kPa]</th>
<th>Unit weight [kN/m$^3$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top strong layer (brown)</td>
<td>27778.0</td>
<td>9259.3</td>
<td>32</td>
<td>5</td>
<td>17.0</td>
</tr>
<tr>
<td>Middle soft layer (white)</td>
<td>13888.0</td>
<td>862.0</td>
<td>0</td>
<td>10</td>
<td>17.0</td>
</tr>
<tr>
<td>Bottom strong layer (brown)</td>
<td>27778.0</td>
<td>9259.3</td>
<td>325</td>
<td>5</td>
<td>17.0</td>
</tr>
</tbody>
</table>
### Base Soil & Pile properties

#### Pile elastic properties

<table>
<thead>
<tr>
<th>Beam material</th>
<th>Diam [m]</th>
<th>Area [m²]</th>
<th>I [m⁴]</th>
<th>E [kPa]</th>
<th>G [kPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>RC Concrete beam</td>
<td>2.5</td>
<td>2.4544</td>
<td>1.7854</td>
<td>25,000,000</td>
<td>12,500,000</td>
</tr>
<tr>
<td>RC Concrete beam</td>
<td>54&quot;</td>
<td>0.73879</td>
<td>0.04780</td>
<td>25,000,000</td>
<td>12,500,000</td>
</tr>
<tr>
<td>RC Concrete beam</td>
<td>24&quot;</td>
<td>0.146</td>
<td>0.004680</td>
<td>25,000,000</td>
<td>12,500,000</td>
</tr>
</tbody>
</table>

#### Contact element material properties

<table>
<thead>
<tr>
<th>Interface</th>
<th>Friction coefficient (µ=\tan(\phi))</th>
<th>Stiffness (for sticking) [kPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam-solid contact</td>
<td>0.1</td>
<td>1000</td>
</tr>
</tbody>
</table>

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### GiD post processing

**Self Weight - Vertical and Horizontal stresses due to self weight (notice near isotropic condition in liquefied layer)**

Notice horizontal and vertical stresses are similar (fluid) in the liquefiable layer

![Vertical Stress](image1.png)

![Horizontal Stress](image2.png)
GiD post processing
Initial Conditions OpenSees

Push-over deformation pattern
**GiD post processing**

\( \sigma_{xx} \) stresses after displacement

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**GiD post processing**

Contact Forces at the end of displacement

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**Perspective View**

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**XZ Plane View**

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**GiD post processing**

Contours of Contact Forces at the end of Displacement

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**GiD post processing**

Forces in the Beam at the End of Displacement

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(a) Contact forces at soil-pile interface and  
(b) Horizontal pile forces at the end of loading
Parametric Study

- **Pile diameters**
  - D1=2.50 m, D2=54in., and D3=24in.

- **Soft Layer Thicknesses**
  - T1=1D, T2 = 2D, and T4=4D.

- **Piles stiffness, EI**
  - (scale factors for base EI values)
  - “E-3”=0.125, “E-2”=0.25, “E-1”=0.50, “E0”=1.0, “E1”=2.0, “E2”=4.0, and “E3”=8.0.

- **Total cases = 84 cases**

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Final OpenSees Meshes

Finite element meshes for different soft layer thickness. (a)T=1D, (b)T=2D, and (c)T=4D
Characteristic Results of Parametric study
Effect of soil displacement

Shear diagrams

Bending Moment diagrams

Location and value of maxV and maxM changes with soil displacement

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Kinematic Analysis of Piles using OpenSees

Characteristic Results of Parametric study
Effect of pile stiffness EI

EI<sub>1</sub> less stiff

EI<sub>2</sub> stiffer

Location and value of maxV and maxM varies for different EI

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Characteristic Results of Parametric study

Basic definitions

\[ T_{10D} \]

\[ L_{\text{eff}}/D \]

Characteristics Results of Parametric study

maxM and location

Moment M in (kNm)

\[ \text{extreme values for moment } M \text{ for } EI = 2390.00 \text{ MNm}^2 \]

\[ \text{abs(max } M) \text{ in top layer} \]

\[ \text{abs(max } M) \text{ in bottom layer} \]

\[ L_{\text{eff}} \]

\[ \text{position of max } M \text{ in top layer} \]

\[ \text{position of max } M \text{ in bottom layer} \]

\[ L_{\text{eff}}/D \]
Characteristic Results of Parametric study
Pile deformation

Non-dimensional characteristic parameter

\[ \beta = \frac{E_s T^2 D^2}{EI} \]

- \( E_s \) modulus of elasticity of stiff soil layer
- \( EI \) stiffness of pile
- \( T \) thickness of liquefiable layer
- \( D \) outer diameter of pile
Embedment length in stiff soil layer (approximated as average of top and bottom layer)

Dimensionless shear force demand. Maximum shear occurs within the liquefied layer

Results encourage the use of a linear regression for most of the parameter space.
Dimensionless **bending moment** (or curvature demand). Max M occurs at \( \gamma \) from the layer interface within the stiff layer.

![Graph showing dimensionless bending moment](image)

**Design Procedure**

\[
\begin{align*}
\max V &= \gamma_V \frac{EI}{T^2} \frac{\Delta}{D} \\
\max M &= \gamma_M \frac{EI}{T} \frac{\Delta}{D} \\
L_{\text{embed}} &= \gamma_L D 
\end{align*}
\]

- Maximum shear force in the pile
- Maximum moment in the pile
- Location of maximum moment

\[
\begin{align*}
\gamma_L &= 0.5 - \log_{10} \beta \\
\gamma_V &= 0.17 \beta^{0.68} \\
\gamma_M &= 0.09 \beta^{0.45} \\
\beta &= \frac{E_s T^2 D^2}{EI}
\end{align*}
\]

- Non-dimensional coefficients
- Dimensionless characteristic parameter
Dimensionless shear force demand. Maximum shear occurs within the liquefied layer.

Dimensionless bending moment (or curvature demand). Max M occurs at \( L_{\text{embed}} \) from the layer interface within the stiff layer.
Comparison of fixed-fixed vs. OpenSees

Questions?