Soil-Pile Interaction in FB-MultiPier
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FB-MultiPier
(FB-Pier Version 4)

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Developed by: Florida Bridge Software Institute
Session Outline

• Introduce FB-MultiPier Software
• Identify and Discuss Soil-Pile Interaction Models
  – Precast & Cast Insitu Axial T-Z & Q-Z Models
  – Torsional T-θ Models
  – Lateral P-Y Models
  – Nonlinear Pile Structural Models
• FB-MultiPier Input and Output
  – Example #1 Single Pile
FB-MultiPier

- Nonlinear finite element analysis program capable of analyzing multiple bridge pier structures interconnected by bridge spans.
- The full structure can be subject to a full array AASHTO load types in a static analysis or time varying load functions in a dynamic analysis.
FB-MultiPier

- Each pier structure is composed of pier columns and cap supported on a pile cap and piles/shafts with nonlinear soil.
- FB-Multiplier couples nonlinear structural finite element analysis with nonlinear static soil models for axial, lateral and torsional soil behavior to provide a robust system of analysis for coupled bridge pier structures and foundation systems.
FB-MultiPier

- FB-MultiPier performs the generation of the finite element model internally given the geometric definition of the structure and foundation system as input graphically by the designer.
Coupled Soil-Structure Interaction

Live and Dead Loading

Ship Impact Scour
(Shallow Water)
Plumb Piles/Shafts Earthquake

Ship Impact Scour
(Deep Water)
Battered Piles or Shafts
Coupled Soil-Structure Interaction
Florida Pier
FB-MultiPier
Florida Bride Software Institute

• FB-MultiPier and other software for bridge analysis and design developed and supported by BSI

• http://bsi-web.ce.ufl.edu

• Good *educational* discounts (free)
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Soil-Structure Interaction

Vertical Nonlinear Spring

Torsional Nonlinear Spring

Lateral Nonlinear Spring

Nonlinear Tip Spring
Driven Piles - Axial Side Model

\[ \tau = \frac{\tau_o r_o}{r} \]

(Randolph & Wroth)
Driven Piles - Axial Side Model

\[ \frac{\Delta z}{\Delta r} = \frac{d z}{d r} = \gamma \]

Also:
\[ \tau = \gamma G \]

Substitute:
\[ \tau = \frac{d z}{d r} G \]

Rearrange:
\[ dz = \frac{\tau}{G} dr \]

Previous:
\[ \tau = \frac{\tau_o r_o}{r} \]

Substitute:
\[ dz = \frac{\tau_o r_o}{r G} dr \]

Also:
\[ G = G_i \left[ 1 - \frac{\tau}{\tau_f} \right]^2 \]

Substitute:
\[ z = \int_{r_0}^{r_m} \frac{\tau_o r_o}{r G} \left[ 1 - \frac{\tau}{\tau_f} \right]^2 dr \]
Driven Piles - Axial Side Model

\[ z = \frac{\tau_0}{G_i} \left[ \ln \left( \frac{r_m - \beta}{r_0 - \beta} \right) + \frac{\beta (r_m - r_0)}{(r_m - \beta)(r_0 - \beta)} \right], \quad \beta = \frac{r_0 \tau_0}{\tau_f} \]

\( \tau_f = 1000\text{psf} \)

\( G_i = 3 \text{ ksi} \)
Driven Piles - Axial Tip Model

(Kraft, Wroth, etc.)

Where:

\[ z = \frac{P (1 - \nu)}{4r_0 G_i \left[ 1 - \frac{P}{P_f} \right]^2} \]

- \( P \) = Mobilized Base Load
- \( P_f \) = Failure Tip Load
- \( r_0 \) = effective pile radius
- \( \nu \) = Poisson ratio of Soil
- \( G_i \) = Shear Modulus of Soil

- \( P_f = 250 \text{ kips} \)
- \( G_i = 10 \text{ ksi} \)
- \( \nu = 0.3 \)
- \( r_0 = 12 \text{ inches} \)
Driven Piles - Axial Properties

- Ultimate Skin Friction (stress), $\tau_{uf}$, along side of pile (input in layers).
- Ultimate Tip Resistance (Force), $P_f$, at pile tip.
- Compressibility of individual soil layers, i.e. Shear Modulus, $G_i$, and Poisson’s ratio, $\nu$. 
Driven Piles - Axial Properties

• From Insitu Data:
  – Using SPT “N” Values run SPT97, DRIVEN, UNIPILE, etc. to Obtain: $\tau_f$ , and $P_f$
  – Using Electric Cone Data run PL-AID, LPC, FHWA etc. to Obtain: $\tau_f$ , and $P_f$
  – Determine G or E from SPT correlations, i.e. Mayne, O’Neill, etc.
Florida: SPT 97 Concrete Piles

Skin Friction, $\tau_f$ (TSF)
- Plastic Clay:
  - $\tau_f = 2N(110-N)/4006$
- Sand, Silt Clay Mix:
  - $\tau_f = 2N(110-N)/4583$
- Clean Sand:
  - $\tau_f = 0.019N$
- Soft Limestone:
  - $\tau_f = 0.01N$

Ultimate Tip, $P_f/\text{Area(tsf)}$
- Plastic Clay:
  - $q = 0.7 \text{ N}$
- Sand, Silt Clay Mix:
  - $q = 1.6 \text{ N}$
- Clean Sand:
  - $q = 3.2 \text{ N}$
- Soft Limestone:
  - $q = 3.6 \text{ N}$
API Side Friction Model - Sand

\[ \tau_f = K p'_0 \tan \delta \]

where

- \( k \) = dimensionless coefficient of lateral earth pressure (ratio of horizontal to vertical normal effective stress (for unplugged \( K=0.8 \) and for plugged \( K=1.0 \))

- \( p'_0 \) = effective overburden pressure in stress units

- \( \delta \) = friction angle between the soil and pile wall, which is defined as \( \delta = \phi - 5^\circ \)
API Side Friction Model - Sand
API Side Friction Model - Clay

- \( \tau_f = \alpha c_u \)

where

- \( c_u = \) undrained shear strength
- \( \alpha = \) a dimensionless factor, which is defined as
  - \( \alpha = 0.5 \Psi^{-0.5} \leq 1.0 \) for \( \Psi \leq 1.0 \)
  - \( \alpha = 0.5 \Psi^{-0.25} \leq 1.0 \) for \( \Psi > 1.0 \)

\( \Psi = \frac{c_u}{p'_0} \)
API Side Friction Model - Clay

Graph showing the relationship between $v/v_{max}$ and $z/D$ with corresponding values for $z/D$ and $t/t_{max}$.

<table>
<thead>
<tr>
<th>$z/D$</th>
<th>$t/t_{max}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0016</td>
<td>0.30</td>
</tr>
<tr>
<td>0.0031</td>
<td>0.50</td>
</tr>
<tr>
<td>0.0057</td>
<td>0.75</td>
</tr>
<tr>
<td>0.0080</td>
<td>0.90</td>
</tr>
<tr>
<td>0.0100</td>
<td>1.00</td>
</tr>
<tr>
<td>0.0200</td>
<td>0.90</td>
</tr>
<tr>
<td>$\infty$</td>
<td>0.90</td>
</tr>
</tbody>
</table>
API Tip Model - Sand

- \( q = p'_0 N_q \)

where

- \( p'_0 \) = effective overburden pressure in stress units
- \( N_q = e^{\pi \tan(\phi')} \tan^2(45 + \phi'/2) \)

- \( Q_p = qA \)

- Where
  - \( Q_p \) is the total end bearing capacity
  - \( A \) is the cross sectional area
API Tip Model Sand

\[
\begin{array}{cc}
\frac{z}{D} & \frac{Q}{Q_p} \\
0.002 & 0.25 \\
0.013 & 0.50 \\
0.042 & 0.75 \\
0.073 & 0.90 \\
0.100 & 1.00 \\
\infty & 1.00 \\
\end{array}
\]
API Tip Model - Clay

- $q = 9c_u$

where

- $c_u =$ undrained shear strength

- $Q_p = qA$

where

- $Q_p$ is the total end bearing capacity
- $A$ is the cross sectional area
API Tip Model Clay
Cast Insitu Axial Side and Tip Models

- For soil (sands and clays)
  - Follow FHWA Drilled Shaft Manual For Sands and Clays to Obtain $\tau_f$ and $P_f$ ($\gamma$ and $c_u$)
  - Shape of $T-Z$ curve is given by FHWA’s Trend Lines.

- User has Option of inputting custom $T-z$ / $Q-z$ curves
Cast Insitu - Sand (FHWA):

\[
Q_s = \pi D L \beta \sigma_v'
\]

\[
Q_t = 0.6 N_{SPT} \pi D^2 / 4 \quad \text{if} \quad N_{SPT} < 75
\]

\[
\beta = 1.5 - 0.135 (L/2)^{0.5} \quad \text{if} \quad 1.2 > \beta > 0.25
\]

\[
\sigma_v' = \gamma L/2
\]
Cast Insitu - Clay (FHWA):

\[ Q_s = 0.55 \, Cu \, \pi \, D \, (L-5'-D) \]

\[ Q_t = 6 \, [1+0.2(L/D)] \, Cu \left( \frac{\pi \, D^2}{4} \right) \]
Cast Insitu trend line for Sand

Settlement / Diameter (%) vs. Mobilized Stress / Ultimate Stress

- End Bearing
- Side Friction

CIVIL ENGINEERING
Cast Insitu trend line for Clay
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Torsional Model (Pile/Shaft)

• Hyperbolic Model
  – $G$ and $\tau_f$

• Custom T-$\theta$
Torsional Model (Pile/Shaft)

\[ T_{\text{ult}} = \frac{1}{b} \]

\[ (dT/d\theta) = \frac{1}{a} \approx G_i \]

\[ T_{\text{ult}} = \tau_i A_{\text{surf}} r \]

\[ T_{\text{ult}} = 2\pi r^2 \Delta L \tau_{\text{ult}} \]

\[ \tau_{\text{ult}} = \text{Ultimate Axial Skin Friction (stress)} \]

\[ T = \theta / (a + b \theta) \]
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Lateral Soil-Structure Interaction

Active State

Passive State
Near Field: Lateral (Piles/Shafts)

\[ P \left( \frac{F}{L} \right) = \frac{2\pi}{0} \sigma_r \, r \, d\theta \]

\[ Y = 0 \]

\[ Y = 5'' \]

\[ P = 0 \]

Stiff Clay

Sand & Soft Clay
P-y Curves - Reese’s Sand

Pu is a function of \( \phi, \gamma, \) and \( b \)

Y is a function of \( b \) (pile diameter)
Matlock’s Soft Clay

Pu is a function of $C_u$, $\gamma$, and $b$

$Y$ is a function of $y_{50}$ ($\varepsilon_{50}$)

\[
\left( \frac{p}{p_u} \right) = 0.5 \left( \frac{y}{y_{50}} \right)^{1/3}
\]
Reese’s Stiff Clay Below Water

Pc is a function of C, γ, ks and b

Y is a function of

$y_{50}$ ($\varepsilon_{50}$)

$E_{ss} = -\frac{0.0625P_c}{y_{50}}$

$P_{offset} = 0.055P_c \left( \frac{y-A_s y_{50}}{A_s y_{50}} \right)^{1.25}$
Pu is a function of c, and b

\[ \frac{P}{P_U} = 0.5\left(\frac{Y}{Y_c}\right)^{0.387} \]

\[ \frac{P}{P_U} = F_S + (1 - F_S) \frac{X}{X_{cr}} \]

\( F_S \) is a function

\( Y_c \) is a function of b and \( \varepsilon_{50} \)
Soil Properties for Standard Curves

- **Sand:**
  - Angle of internal friction, $\phi$
  - Total unit weight, $\gamma$
  - Modulus of Subgrade Reaction, $k$

- **Clay or Rock:**
  - Undrained Strength, $Cu$
  - Total Unit Weight, $\gamma$
  - Strain at 50% of Failure Stress, $\varepsilon_{50}$
  - Optional: $k$, and $\varepsilon_{100}$
Soil Information

Help Menu

EPRI (Kulhawy & Mayne)

Manual on Estimating Soil Properties for Foundation Design
P-y Curves from Insitu Tests

- Cone Pressuremeter
- Marchetti Dilatometer
Insitu PMT & DMT Testing
Cone Pressuremeter

\[ P^* = P - P_{oh} \]

\[ \frac{\Delta R_c}{R_c} \]

\[ \frac{\Delta R}{R_0} \]
Cone Pressuremeter

(Robertson, Briaud, etc.)
Marchetti Dilatometer
PMT P-y Curves - Auburn
DMT P-y Curves - Auburn
Auburn Predictions

![Graph showing lateral deflections and loads for different shafts and methods.](image-url)
DMT P-y Curves Pascagoula
Pascagoula Predictions

![Graph showing load versus deflection with DMT, PMT, and Actual data points and curves.](image-url)
Instrumentation & Measurements

- **Strain gages**
  - Measure strain
  - Calculate bending moment, $M = \varepsilon (EI/c)$, if $EI$ of section known
  - "high tech"

- **Slope inclinometer**
  - Measures slope
  - Relatively "low tech"
Theoretical Pile Behavior

Pile | Deflection | Slope | Moment | Shear | Soil Reaction
--- | --- | --- | --- | --- | ---
P | Y(z) | Y'(z) | M(z) | M'(z) | P(z)
Strain Gages → Bending Moment
Bending Moment versus Depth

Bending Moment (kN*m)

Depth (m)

Lateral Load in Kilonewtons

36
62
93
121
153
182
211
258

CIVIL ENGINEERING
Two Integrals to Deflection
Two Derivatives to Load

- Pile
- Deflection
- Slope
- Moment
- Shear
- Soil Reaction
Non-linear Concrete Model

Test Pile T1

Curvature, $\phi$ (1/m)

EI (kN-m$^2$)

0.0E+00 2.0E-03 4.0E-03 6.0E-03 8.0E-03 1.0E-02
P-y Curves from Strain Gages

Displacement, y (mm)

p (kN/m)

D. to G.S. (m)

0 5 10 15 20 25 30 35

0 20 40 60 80 100 120 140

P (kN/m)

1.0

2.0

3.0

4.1

Civil Engineering
Slope Inclinometer → Slope
Deflection versus Depth

Horizontal Displacement (m)

Lateral Load in Kilonewtons

Depth (m)

-0.01 0.00 0.01 0.02 0.03 0.04 0.05 0.06 0.07

-2 0 2 4 6 8 10

36 62 90 122 153 183 208 243

Civil Engineering
Slope Inclinometer → Slope vs. Depth

- Pile
- Deflection
- Slope
- Moment
- Shear
- Soil Reaction

Civil Engineering
One Integral to Deflection

Pile  Deflection  Slope  Moment  Shear  Soil Reaction

\[
\int P(z) \, dz = Y(z) + Y'(z) = M(z) + M'(z) = P(z)
\]
Three Derivatives to Load

Pile, Deflection, Slope, Moment, Shear, Soil Reaction
P-y Curves from Slope Inclinometer
Comparison of P-y Curves

Displacement, \( y \) (mm) vs. \( p \) (kN/m)

- **SG**
- **inc**
- **PMT/DMT**
- **SPT**

Legend:
- SG (green)
- inc (pink)
- PMT/DMT (yellow)
- SPT (blue)

**Civil Engineering**
Prediction of Pile Top Deflection
P-y Curves Available in FB-Pier

• Standard
  – Sand
    • O’Neill
    • Reese, Cox, & Koop
  – Clay
    • O’Neill
    • Matlock Soft Clay Below Water Table
    • Reese Stiff Clay Below Water Table
    • Reese & Welch Stiff Clay Above Water Table
P-y Curves Available in FB-Pier

• User Defined
  – Pressuremeter
  – Dilatometer
  – Instrumentation
    • Strain Gages
    • Slope Inclinometer
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Pile Element Model

Universal Joint

Rigid center-blocks

Spring

Rigid end Block

(Cap View)

(Cap View)
Curvature-Strain-Stress-Moment

a) Strain due to z-axis bending

b) Strain due to y-axis bending

c) Strain due to axial thrust

N
N
F
,
F
,
i
i
1
2
x
y
z
dF
dA
i
i
e) Stress-strain relationship
d) Combined strains

CIVIL ENGINEERING
Stress-Strain Curves for Concrete & Steel

\[ \varepsilon_s = 0.0038 \]

\[ s_0 = \frac{2E_s f_s}{E_c} \]

Straight Line

\[ 0.85f_s' \]

\[ f_s' = 0.85f_s \]

\[ f_c = f_s' \left[ 2 \left( \frac{\sigma}{\varepsilon_s} \right) - \left( \frac{\sigma}{\varepsilon_s} \right)^2 \right] \]

\[ \varepsilon_1 = (7.5/57.000) = 0.000131578 \]

\[ \varepsilon_{rel} = 0.0003 \]
Strains $\rightarrow$ Stress $\rightarrow$ Moments

$$dF_i = \sigma_i \times dA_i$$

$$M_x = \sum_{\text{Integration Points}} dF^*y$$
Stiffness of Cross-Section: Flexure, Axial

\[ M_x = \sum_{\text{Integration Points}} dF^* y \]

\( dF \)
\( dA \)
\( dF_i \)
\( dA_i \)

\( \sum \)
\( n_{\text{Points}} \)

\( x \)
\( y \)
\( z \)
Failure Ratio Calculation

\[ \text{Failure Ratio} = \frac{\text{Actual Length}}{\text{Surface Length}} \]

\[ P \]

\[ P_{\text{actual}} \]

\[ M_{x_0} \]

\[ M_{y_0} \]

\[ M_x \]

\[ M_y \]
Pile Material Properties
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