DESIGN AND ANALYSIS OF DRIVEN PILE FOUNDATIONS FOR LATERAL LOADS

Aaron S. Budge, Ph.D., P.E.
Center for Transportation Research and Implementation
Minnesota State University, Mankato

ASCE Structural Conference
Lateral Capacity of Single Piles

- Potential sources of lateral loads include vehicle acceleration & braking, wind loads, wave loading, debris loading, ice forces, vessel impact, lateral earth pressures, slope movements, and seismic events.

- These loads can be of the same magnitude as axial compression loads.
Lateral Capacity of Single Piles

- Historically, prescription values were used for lateral capacity of vertical piles, or battered (inclined) piles were added.

- Modern design methods are readily available which allow load-deflection behavior to be rationally evaluated.
Lateral Capacity of Single Piles

Soil, pile, AND load parameters significantly affect lateral capacity.

- Soil Parameters
  - Soil type & strength
  - Horizontal subgrade reaction

- Pile Parameters
  - Pile properties
  - Pile head condition
  - Method of installation
  - Group action

- Lateral Load Parameters
  - Static or Dynamic
  - Eccentricity
Lateral Capacity of Single Piles

Design Methods

- Lateral load tests
- Analytical methods
  - Broms' method (long pile, short pile)
  - Reese's COM624P method
  - LPILE program
  - More robust/current models (FB-MultiPier)
Long pile - pile fails

Short pile - soil fails
Figure 9.36  Soil Resistance to a Lateral Pile Load (adapted from Smith, 1989)
Fig. 3.1. Graphical definition of $p$ and $y$
(a) view of elevation of section of pile
(b) view A-A - earth pressure distribution prior to lateral loading
(c) view A-A - earth pressure distribution after lateral loading.
Figure 9.45: Typical p-y Curves for Ductile and Brittle Soil (after Coduto, 1994)
Figure LPILE Pile-Soil Model
Development of general equation for laterally loaded pile

\[ y_m = \text{deflection at top} \]
\[ y_{m+1} = \text{deflection at bottom} \]
\[ M_m = \text{moment at top} \]
\[ M_{m+1} = \text{moment at bottom} \]

Take moments about lower left on x axis:

\[ M_{m-1} - M_m + Q(y_{m-1}) - Q(y_m) - V_m(dx) = 0 \]
\[ M_{m-1} - M_m - Q(y_m - y_{m-1}) - V_m(dx) = 0 \]
\[ \Delta M + Q(\Delta y) - Vdx = 0 \]
\[ dM/dx + Q \cdot dy/dx - V = 0 \]

differentiate with respect to x:

\[ d^2M/dx^2 + Q \cdot d^2y/dx^2 - dV/dx = 0 \]
\[ EI \cdot d^4y/dx^4 + Q \cdot d^2y/dx^2 - p = 0 \]

\[ p = \text{soil response (force/length)} \]
\[ Q_m = \text{axial load (top and bottom)} \]
\[ x = \text{direction along pile length} \]
\[ y = \text{deflection at some distance, x} \]

Recall that \( dV/dx = p \) (distributed load)
Recall that \( M = EI \cdot d^2y/dx^2 \)

This is the equation that is solved by means of finite differences in most software packages (COM624P, LPILE etc.)
5.2 RELATIONSHIPS IN DIFFERENCE FORM

Figure 5.1 shows a portion of the elastic curve of a pile. Relationships in difference form are as follows:

\[
\left( \frac{dy}{dx} \right)_{x=m} = \frac{y_{m-1} - y_{m+1}}{2h} \quad (5.2)
\]

\[
\left( \frac{d^2y}{dx^2} \right)_{x=m} = \frac{y_{m-1} - \frac{y_m}{h} - \frac{y_m}{h} + y_{m+1}}{h^2} = \frac{y_{m-1} - 2y_m + y_{m+1}}{h^2} \quad (5.3)
\]

Fig. 5.1. Representation of deflected pile.

In a similar manner

\[
\left( \frac{d^3y}{dx^3} \right)_{x=m} = \frac{y_{m-2} - 2y_{m-1} + 2y_{m+1} - y_{m+2}}{2h^3} \quad (5.4)
\]

\[
\left( \frac{d^4y}{dx^4} \right)_{x=m} = \frac{y_{m-2} - 4y_{m-1} + 6y_m - 4y_{m+1} + y_{m+2}}{h^4} \quad (5.5)
\]
We have $n$ equations and $(n+4)$ unknowns

**BOUNDARY CONDITIONS** *(long pile)*

@ Pile Bottom

Moment = 0

Shear = 0

@ Pile Top

??
Figure 9.47: Comparison of Measured and COM624P Predicted Load-Deflection Behavior with Depth (after Kyfor et al. 1992)
Figure Graphical Presentation of LPYLE Results (Reese, et al. 2000)
Lateral Capacity of Pile Groups
LATERAL CAPACITY OF PILE GROUPS

The lateral deflection of a pile group is typically 2 to 3 times larger than the deflection of a single pile.

Piles in trailing rows of pile groups have significantly less lateral load resistance than piles in the lead row.

Laterally loaded pile groups have a group efficiency less than 1.
LATERAL CAPACITY OF PILE GROUPS

The lateral capacity of an individual pile in a group is a function of its position (row) in the group, and the c-t-c pile spacing.

A p-multiplier, is used to modify p-y curve

Laterally loaded pile groups have a group efficiency less than 1.
The lateral capacity of an individual pile in a group is a function of its position (row) in the group, and the c-t-c pile spacing.

A $p$-multiplier: 0.8, 0.4, & 0.3 (thereafter)
<table>
<thead>
<tr>
<th>Soil Type</th>
<th>Test Type</th>
<th>Center to Center Pile Spacing</th>
<th>Calculated p-Multipliers, $P_m$ For Rows 1, 2, &amp; 3+</th>
<th>Deflection in mm (in)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stiff Clay</td>
<td>Field Study</td>
<td>3b</td>
<td>.70, .50, .40</td>
<td>51 (2)</td>
<td>Brown et al, (1987)</td>
</tr>
<tr>
<td>Stiff Clay</td>
<td>Field Study</td>
<td>3b</td>
<td>.70, .60, .50</td>
<td>30 (1.2)</td>
<td>Brown et al, (1987)</td>
</tr>
<tr>
<td>Medium Clay</td>
<td>Scale Model- Cyclic Load</td>
<td>3b</td>
<td>.60, .45, .40</td>
<td>600 at 50 cycles (2.4)</td>
<td>Moss (1997)</td>
</tr>
<tr>
<td>Clayey Silt</td>
<td>Field Study</td>
<td>3b</td>
<td>.60, .40, .40</td>
<td>25-60 (1.0 - 2.4)</td>
<td>Rollins et al, (1998)</td>
</tr>
<tr>
<td>V. Dense Sand</td>
<td>Field Study</td>
<td>3b</td>
<td>.80, .40, .30</td>
<td>25 (1)</td>
<td>Brown et al, (1988)</td>
</tr>
<tr>
<td>M. Dense Sand</td>
<td>Centrifuge Model</td>
<td>5b</td>
<td>1.0, .85, .70</td>
<td>76 (3)</td>
<td>McVay et al, (1995)</td>
</tr>
<tr>
<td>Loose F. Sand</td>
<td>Field Study</td>
<td>3b</td>
<td>.80, .70, .30</td>
<td>25-75 (1-3)</td>
<td>Ruesta et al, (1997)</td>
</tr>
</tbody>
</table>
Lateral Load

Single Pile Model

Lateral Load

Third & Subsequent Rows
Second Row
Front Row

$p$  $P_m p_s$

$p_y$ Curves for Group
$\Delta x =$ DEFLECTION OF PILE TOPS (SAME)

MINIMUM CURVATURE

MAXIMUM CURVATURE

POINTS OF FIXITY
STEP BY STEP DESIGN PROCEDURE
FOR LATERALLY LOADED PILE GROUPS

STEP 1 : Obtain Lateral Loads.

STEP 2 : Develop p-y curves for single pile.

a. Obtain site specific single pile p-y curves from instrumented lateral pile load test at site.

b. Use p-y curves based on published correlations with soil properties.

c. Develop site specific p-y curves based on in-situ test data.
STEP 3 : Perform LPILE (or Other) Analyses

a. Perform LPILE analyses using the $P_m$ value for each row position to develop load-deflection and load-moment data.

b. Based on current data, it is suggested that $P_m$ values of 0.8 be used for the lead row, 0.4 for the second row, and 0.3 for the third and subsequent rows. These recommendations are considered reasonable for center to center pile spacing of 3b and pile deflections at the ground surface of .10 to .15b. For larger c-t-c spacings or smaller deflections, these $P_m$ values should be conservative.

c. Determine shear load versus deflection behavior for piles in each row. Plot load versus pile head deflection results similar to what is shown in the following figure.
STEP 4: Estimate group deflection under lateral load.

a. Average the load for a given deflection from all piles in the group (i.e., each of the four rows) to determine the average group response to a lateral load as shown in the subsequent figure.

b. Divide the lateral load to be resisted by the pile group by the number of piles in the group to determine the average lateral load resisted per pile.

c. Enter load-deflection graph (as follows) with the average load per pile to estimate group deflection using the group average load deflection curve.
Maximum Bending Moment Per Pile, (kN-m)

Front Row
2nd Row
3rd - 4th Rows

Estimated Pile Group Deflection

Pile Head Deflection (mm)
STEP 5: Evaluate pile structural acceptability.

a. Plot the maximum bending moment determined from LPILE analyses versus deflection for each row of piles.

b. Check the pile structural adequacy for each row of piles. Use the estimated group deflection under the lateral load per pile to determine the maximum bending moment for an individual pile in each row.

c. Determine maximum pile stress from LPILE output associated with the maximum bending moment.

d. Compare maximum pile stress with pile yield stress.
STEP 6: Perform refined pile group evaluation that considers superstructure-substructure interaction.

SEEMS LIKE A LOT OF WORK, DOESN’T IT?
A Modern Tool: FB-MultiPier
Soil Pile Group Interaction in FB-MultiPier

Dr. J. Brian Anderson, P.E.

Developed by: Florida Bridge Software Institute
Coupled Soil-Structure Interaction

Live and Dead Loading

- Debris Impact
- Scour
- Plumb Piles/Shafts
- Earthquake
- Ship Impact
- Scour
- Battered Piles

Civil Engineering
Soil-Structure Interaction

- Vertical Nonlinear Spring
- Torsional Nonlinear Spring
- Lateral Nonlinear Spring
- Nonlinear Tip Spring
Pile Groups
How Do We Know We Are Going in the Right Direction?
Lateral Testing

Useful where lateral loads may control design

Main Objective: measure soil resistance of critical strata

Zone of most influence
Approx top 5 d
Lateral - Pull
Lateral - Push
TWO-PILE TEST ARRANGEMENT FOR TWO-WAY LOADING

- Load Cell
- Strut
- Three-Dimensional Swivel
- Hydraulic Ram
Conventional Arrangement

- Reaction Shaft
- Reaction Beam
- Inclinometer and Deflection Gauge
- Test Shaft
- Jack and Load Cell
- Hand pump
Lateral Load Test Setup

16 in. x 0.5 in wall CEP

14 in. x 0.375 in wall CEP

Load Cell and Spherical Bearing Plates

Hydraulic Jack
Load Cell and Spherical Bearing Plates

Hydraulic Jack
Pile Head Movement Versus Lateral Load

Lateral Load, (kN)

Movement of Pile Head, (mm)
Lateral – Additional Measurements

• In addition to lateral movement, measurement of test pile head rotation, or deflected shape, can be used to calibrate soil properties in design software
Lateral – Head Rotation
Lateral – Deflected Shape
Strain Gages $\rightarrow$ Bending Moment
Lateral Load Test Measured Deflected Shape

![Graph showing depth below ground surface versus horizontal displacement in direction of applied load for Marquette Interchange - Lateral Load Test - Site A - Pile SLT-A-14-2. The graph includes lines for different load readings: Last 11.25-Ton Reading, Last 22.5-Ton Reading, Last 33.75-Ton Reading, Last 45-Ton Reading. The soil types indicated are Soft to Very Stiff Silty Clay and Stiff Silty Clay Fill.]
QUESTIONS???