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.
SOURCES of LATERAL LOADS

- Ship Impact
- Ice
- Debris
- Earthquake
- Traffic Loads
Lateral Capacity of Single Piles

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 9-86 (long pile, short pile)
  - Reese’s COM624P method
  - LPILE program 9-100
Long pile – pile fails

Short pile - soil fails

Long pile - pile 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)
9.44 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:

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

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 = soil response (force/length)
Q_m = axial load (top and bottom)
x = direction along pile length
y = 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:

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

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

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

\[
\frac{d^4y}{dx^4}_{x=m} = \frac{y_{m-2} - 4y_{m-1} + 6y_m - 4y_{m+1} + y_{m+2}}{h^4}. \quad (5.5)
\]

Fig. 5.1. Representation of deflected pile.

In a similar manner.
We have \( n \) equations and \((n+4)\) unknowns

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

@ Pile Bottom

Moment = 0
Shear = 0

@ Pile Top

??
9.46 Graphical Presentation of LPILE Results (Reese, et al. 2000)
Lateral Capacity of Pile Groups
Why Worry?
Sunshine Skyway bridge disaster, May 1980

• 35 souls plunged to their deaths
• Including Greyhound bus - 26 deaths
• Summit Venture – 20,000 ton barge riding high in the water
• Winds of 60 mph
Laterally Loaded Deep Foundations
Old Sunshine Skyway Bridge, Tampa Bay
New Sunshine Skyway Bridge
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.
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: 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

\( p \)
\( p_s \)
\( P_m p_s \)

p-y Curves for Group

9-151
Where is maximum moment?

Where is maximum Load?
Δx = 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 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 0.10 to 0.15b. For larger c-t-c spacings or smaller deflections, these Pm 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 as shown in Figure 9.69(a).
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 Figure 9.69(a).

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 similar to Figure 9.69(a) with the average load per pile to estimate group deflection using the group average load deflection curve.
Maximum Bending Moment Per Pile, (kN-m)

Pile Head Deflection (mm)

Front Row
2nd Row
3rd - 4th Rows

Estimated Pile Group Deflection
STEP 5: Evaluate pile structural acceptability.

a. Plot the maximum bending moment determined from LPILE analyses versus deflection for each row of piles as illustrated in Figure 9.69(b).

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.
SEE HANDOUT FOR USU HW PROBLEM
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
- 19-24
Load Cell and Spherical Bearing Plates

Hydraulic Jack
Pile Head Movement Versus Lateral Load

Lateral Load, (kN)

Movement of Pile Head, (mm)
Figure 9.47  Comparison of Measured and COM624P Predicted Load-Deflection Behavior versus Depth (after Kyfor et al. 1992)

Depth (m)

Deflection (mm)

Depth (after Kyfor et al. 1992)
Inclinometers

Extensions

Wheel Assembly

19-26
Lateral Load Test Measured Deflected Shape

Depth Below Ground Surface, feet

Horizontal Displacement vs. Depth

A Direction Change From Initial, inches

Marquette Interchange - Lateral Load Test - Site A - Pile SLT - A - 14 - 2 - Horizontal Displacement vs. Depth

Soft to Very Stiff Silty Clay

Stiff Silty Clay Fill

Depth Below Ground Surface (ft)

Horizontal Displacement in Direction of Applied Load (in)

Last 11.25-Ton Reading

Last 22.5-Ton Reading

Last 33.75-Ton Reading

Last 45-Ton Reading
ANY QUESTIONS?