Micropiles Design 101

Allen Cadden, P.E.
West Chester, PA

Las Vegas, NV 2008

Objective

- Develop a background understanding of the geotechnical and structural design processes for micropiles in structural foundation support applications
1. Background for Engineers

♦ Fundamentals are similar to traditional pile design
♦ However, due to the small structural section, structural design and stiffness can often control
Designers Must Understand Available Tools

- Drilling rigs
- Drilling methods
- Available Structural Materials
- Reasonable Bond Values
- Quality Control

Construction Techniques

“Drill Rig”
Micropile Materials

- **Permanent Steel Pipe**
  - API 5CT & ASTM A252
  - 80 ksi yield
  - Flush joint threads

- **Steel Reinforcement**
  - ASTM A615, Gr. 60 & 75
  - ASTM A722, Gr. 150
  - Mechanical coupling
  - Hollow bars

- **Cement Grout**
  - Neat cement – ASTM C150
  - W/C ratio of 0.45
  - 4000 psi (min)

Design Involves:

- Knowing the site
- Understanding the loads
- Understanding the geology
- Calculations
- Specifications
- Quality Control
A Word on Geology

- Review of Geotechnical Data
  - obtain samples and develop sections
  - estimate design parameters
  - evaluate corrosion potential
  - identify problem areas, if any

Micropile Design Steps

- Internal - Structural
- External - Geotechnical
- Connection of Pile to Structure
2. Structural Design

- Components
  - Cased length
  - Uncased length
  - Grout to steel bond
  - Transitions between reinforcement types
  - Strain compatibility
  - Casing or bar splice and connection
  - Footing connection

Structural Design (internal)

- Grout & steel
- Transfer zone
- Bond zone

IBC 2006 code allowable stresses

- Compression
  - Grout: 0.33 f’c
  - Steel: 0.4 fy
    - max 32ksi

- Tension
  - Grout: 0
  - Steel: 0.6 fy
### Allowable Stresses

<table>
<thead>
<tr>
<th>CODE</th>
<th>Compression</th>
<th>Tension</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CASING BAR</td>
<td>GROUT</td>
</tr>
<tr>
<td>ACI with LF = 1.55</td>
<td>0.45 0.45</td>
<td>0.38</td>
</tr>
<tr>
<td>FHWA Micropiles</td>
<td>0.47 0.47</td>
<td>0.40</td>
</tr>
<tr>
<td>AASHTO Caisson</td>
<td>0.35 0.35</td>
<td>0.30</td>
</tr>
<tr>
<td>AASHTO Driven Unfilled with increase for unlikely damage</td>
<td>0.33 0.33</td>
<td>0.40</td>
</tr>
<tr>
<td>AASHTO Driven Concrete Filled NO increase for unlikely damage</td>
<td>0.25 0.25</td>
<td>0.40</td>
</tr>
<tr>
<td>JAMP</td>
<td>0.59 0.59</td>
<td></td>
</tr>
</tbody>
</table>

2006 IBC: 0.33\(f_c\), 0.4fy (max 32ksi) compression: 0.6fy tension

### AASHTO LRFD Design

Table 10.5.5.2.4-2 - Resistance Factors for Structural Resistance of Axially Loaded Micropiles

<table>
<thead>
<tr>
<th>METHOD/SOIL/CONDITION</th>
<th>RESISTANCE FACTOR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pile Cased Length</td>
<td>Tension, (\phi_{TC})</td>
</tr>
<tr>
<td></td>
<td>Compression, (\phi_{CC})</td>
</tr>
<tr>
<td>Pile Uncased Length</td>
<td>Tension, (\phi_{TU})</td>
</tr>
<tr>
<td></td>
<td>Compression, (\phi_{CU})</td>
</tr>
</tbody>
</table>
Connection Details

- Shear transfer from grout
- Bearing plate
- Shear rings

Connection Strength Research
ISM 2006
Caisson Repair - Connections

♦ Controlling Factors
- Column Loads
- Access

Short Shaft, Very High Load

Caisson Repair

Lower load
Longer shafts
Connection Examples

Do we need plates?

3. Geotechnical Design

- Evaluate Load Transfer Parameters
  - grout to ground average bond values
  - identify variations throughout profile and across the site
  - define the required minimum bond length
- Evaluate pile spacing
  - impact from group effects
Geotechnical Design - Rational (external)

- FHWA
  - β method - cohesionless
  - α method - cohesive
  - grout pressure increases bond

- Rock
  - Bruce, FHWA, PTI
  - Based on $q_a$
  - local bldg. code limits

PTI bond values for gravity and pressure grouted (>50psi) anchors

Geotechnical Capacity (ASD)

\[ P_{G\text{-allowable}} = \frac{\alpha_{\text{bond}}}{FS} \times \pi \times D_b \times L_b \]

- $\alpha_{\text{bond}}$ = grout to ground ultimate bond strength
- FS = factor of safety applied to the ultimate bond strength
- $D_b$ = diameter of the drill hole
- $L_b$ = bond length
Calculate Bond Length

Rearranging this a bit

\[ L_b = \frac{P_{G - allowable} \times FS}{\alpha_{bond} \times \pi \times D_b} \]

### AASHTO LRFD Design

Table 10.5.2.4-1 - Resistance Factors for Geotechnical Resistance of Axially Loaded Micropiles

<table>
<thead>
<tr>
<th>METHOD/SOIL/CONDITION</th>
<th>RESISTANCE FACTOR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compression Resistance of Single Micropile, ( \phi_{\text{incl}} )</td>
<td>Side Resistance (Bond Resistance): Presumptive Values 0.55 (^{(1)} )</td>
</tr>
<tr>
<td></td>
<td>Tip Resistance on Rock O'Neill and Reese (1999) 0.50</td>
</tr>
<tr>
<td></td>
<td>Side Resistance and Tip Resistance Load Test Values in Table 10.5.5.2.2-2, but no greater than 0.70</td>
</tr>
<tr>
<td>Block Failure, ( \phi_{\text{bl}} )</td>
<td>Clay 0.60</td>
</tr>
<tr>
<td>Uplift Resistance of Single Micropile, ( \phi_{\text{up}} )</td>
<td>Presumptive Values 0.55 (^{(1)} )</td>
</tr>
<tr>
<td></td>
<td>Load Test (Type A micropile) Values in Table 10.5.5.2.2-2, but no greater than 0.70</td>
</tr>
<tr>
<td></td>
<td>Load Test (Types B, C, D &amp; E micropiles)</td>
</tr>
<tr>
<td>Group Uplift Resistance, ( \phi_{\text{ug}} )</td>
<td>Sand &amp; Clay 0.50</td>
</tr>
</tbody>
</table>

\(^{(1)}\) For Group Uplift Resistance, use 0.80.
AASHTO LRFD Design

Table 10.5.5.2.4-1 - Resistance Factors for Geotechnical Resistance of Axially Loaded Micropiles

<table>
<thead>
<tr>
<th>METHOD/SOIL/CONDITION</th>
<th>RESISTANCE FACTOR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compression Resistance of Single Micropile, $\phi_{s}$</td>
<td>Side Resistance (Bond Resistance): Presumptive Values</td>
</tr>
<tr>
<td></td>
<td>Tip Resistance on Rock O'Neill and Reese (1999)</td>
</tr>
<tr>
<td></td>
<td>Side Resistance and Tip Resistance Load Test</td>
</tr>
<tr>
<td>Block Failure, $\phi_{b}$</td>
<td>Clay</td>
</tr>
<tr>
<td></td>
<td>Presumptive Values</td>
</tr>
</tbody>
</table>

Additional reduction in resistance factors for marginal ground or lack of redundancy

LRFD Geotechnical Design

$$R_R = \phi R_s = \phi_{q_p} R_p + \phi_{d_p} R_s$$

in which:

$$R_p = q_p A_p$$

$$R_s = q_s A_s$$

where:

- $R_R$ = nominal tip resistance (KIPS)
- $R_p$ = nominal grout-to-ground bond resistance (KIPS)
- $\phi_{q_p}$ = resistance factor for tip resistance specified in Table 10.5.5.2.4-1
- $\phi_{d_p}$ = resistance factor for grout-to-bond bond resistance specified in Table 10.5.5.2.4-1
- $q_p$ = unit tip resistance (KSF)
- $q_s$ = unit grout-to-ground bond resistance (KSF)
- $A_p$ = area of micropile tip (FT<sup>2</sup>)
- $A_s$ = area of grout-to-ground bond surface (FT<sup>2</sup>)
Geotechnical Design – Empirical

Average Bond Values (allowable loads)
- Clay: 15-30 kN/m (1-2 k/ft)
- Loose sands: 30-60 kN/m (2-4 k/ft)
- Compact sand: 60-120 kN/m (5-10 k/ft)
- Rock: 60-240+ kN/m (5-20+ k/ft)

Typical for approximately 5-7 inch pile

Rock Bond Values

Average Rock Bond Stress (allowable)
- Shale 100-600 kPa (15-85 psi)
- Limestone 275-1000 kPa (40-150 psi)
- Granite/schist 300-1000 kPa (45-150 psi)
- Basalt 1000-1400 kPa (150-200 psi)
4. Additional Considerations

♦ Combined Geotechnical and Structural
  – Settlement/Stiffness of the System
  – Lateral Capacity
    • deflection
    • combined stress
    • group effect
  – Buckling

Axial Displacement

*a few reminders*

♦ Consider compatibility with existing foundation
♦ Elastic shortening of the pile
  – Length (elastic) is not the total length installed
♦ Creep – Structural not an issue, cohesive soils may be an issue
♦ Group Settlement
Elastic Shortening Estimate

\[ \Delta_{\text{elastic}} = \frac{PL}{AE} \]

- For micropiles in competent soil, \( L = \) length above bond length plus \( \frac{1}{2} \) bond length
- For micropiles in rock, \( L = \) full length of micropile above bond length
- Axial stiffness, \( AE \), considers steel and concrete if compression loading and steel only if tension loading

AE ?

\[ \Delta_{\text{elastic}} \frac{H}{AE} \]

- Evaluate for each section of pile
- \( E_{\text{grout}} = 1500-2500 \) ksi
- \( E_{\text{steel}} = 29000 \) ksi
Lateral Capacity

**general thoughts**

- Micropiles do not have large lateral capacities
- Design is similar to drilled shafts and driven piles
- Consider combined stress effect, particularly at the threads

---

Combined Axial Compression and Bending Stress

\[
\frac{P_c}{M_{\text{allowable}}} = \frac{P_{c\text{-allowable}} \times M_{\text{allowable}}} {P_{\text{c allowable}}} = \frac{P_{\text{c allowable}} \times M_{\text{allowable}}} {P_{c\text{-allowable}}}
\]

- \( P_c \) = maximum axial compression load
- \( P_{c\text{-allowable}} \) = allowable compression load
- \( M_{\text{max}} \) = maximum bending moment
- \( M_{\text{allowable}} = (0.55 \times F_y \times S) \)
LPILE Analysis

Stiff Clay Profile
Axial Load = 1,335 kN
Shear Load = 54 kN

Bending Moment Capacity at Threaded Connection

♦ For compression only, capacity is not affected by threaded connections
♦ For tension/bending, no codified testing procedure is available to evaluate strength at connection

Casing with $t_w$  Casing thread with $t_w/2$
Analysis of Threaded Connection

♦ Use steel yield stress (no need to limit based on strain compatibility)
♦ Assume casing wall thickness, $t_w$, is reduced by 50 percent along the length of the casing joint
♦ Calculate section modulus of joint, $S_{\text{joint}}$

A Few Final Considerations

♦ Corrosion Protection
♦ Load Testing
♦ Quality Control Procedures
♦ Constructability
♦ Cost Effectiveness of Design
5. Design Example

♦ FHWA Design and Construction Manual, 2005
♦ Micropiles for support of a bridge abutment
♦ Sample Problem 1, Appendix D

Design Process

<table>
<thead>
<tr>
<th>Step</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Step 1</td>
<td>Evaluate Feasibility of Micropiles</td>
</tr>
<tr>
<td>Step 2</td>
<td>Review Project Information</td>
</tr>
<tr>
<td>Step 3</td>
<td>Establish Load and Performance Requirements</td>
</tr>
<tr>
<td>Step 4</td>
<td>Preliminary Design Considerations</td>
</tr>
<tr>
<td>Step 5</td>
<td>Evaluate Structural Capacity of Cased Length</td>
</tr>
</tbody>
</table>
## Design Process

<table>
<thead>
<tr>
<th>Step</th>
<th>Activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>Evaluate Structural Capacity of Uncased Length</td>
</tr>
<tr>
<td>7</td>
<td>Compare Capacity to Need</td>
</tr>
<tr>
<td>8</td>
<td>Evaluate Geotechnical Capacity of Micropile</td>
</tr>
<tr>
<td>9</td>
<td>Estimate Micropile Movements</td>
</tr>
<tr>
<td>10</td>
<td>Design Micropile/Footing Connection</td>
</tr>
<tr>
<td>11</td>
<td>Develop Load Testing Program</td>
</tr>
<tr>
<td>12</td>
<td>Drawings and Specifications</td>
</tr>
</tbody>
</table>

## Design Example – Service Load Design Method

### Overview – Step 1 and 2

![Diagram of design example](image-url)
Bridge Abutment Loading
Step 3

30 m long single span, AASHTO Type IV precast – prestressed concrete girders with concrete deck.

Design Example - Step 4

Preliminary Pile Detail

Case 1
Type B

Casing
5.5 in diam. .375 in wall

Centralizer

Top of Dense Gravel

Reinforcing Bar
2.25 in Grade 520

Neat Cement Grout
### Design Example

#### Design Parameters

- **Required Compression Load**
  - 133 kip (assume vertical)
- **Casing** 
  - $f_y = 36$ ksi
- **Bar** 
  - $f_y = 75$ ksi *
  - * limit $f_y$ bar to 36 ksi for Strain Compatibility
- **Grout** 
  - $f'_c = 5$ ksi
- **Abutment Concrete** 
  - $f'_c = 4$ ksi

### Design Example

#### Geometry

- **Reduce Steel Casing Thickness by 16$^{th}$ in.**
  - Old Manual Section 4.D.3 - 50 yr design, barely aggressive
- **Casing OD =**
  - 5.5 in – 2 x 1/16 in = 5.375 in
- **Casing ID =**
  - 5.5 in – 2 x 3/8 in = 4.8 in
- **Casing Area =**
  - 5 in$^2$
Design Example

*Geometry*

- Bar Area = 2.25 in²
- Grout Area
  - Cased Length Area = ID - Bar = 15.9 in²
  - Uncased Zone
    - Drill Diameter = 5.5 in + ~2 in = 7.5 in
    - Area = Drill - Bar = 42 in²

Design Example – Step 5

*Structural Capacity - Cased Length*

\[ P_{c-all} = [0.4f'cA_g + 0.47F_y\text{steel}(A_{bar} + A_{casing})] \]

\[ P_{c-all} = 151 \text{ kip} \]
Design Example - Step 6

*Structural Capacity – Uncased Zone*

\[ P_{c-all} = 0.4f'_{c}A_g + 0.47F_{y-steel}A_{bar} + P_{Transfer} \]

Assume \( P_{Transfer} = 11 \) kip

\[ P_{c-all} = 175 \text{ kip} \]

Design Example

*\( P_{Transfer} - Plunge Length *\)

- Reduction of load over the length of the casing “Plunged” back into the grouted bond zone material.
- Resulting required structural capacity in bond zone is therefore reduced.
Design Example – Step 7

Comparison

♦ Cased Length Structural Capacity  =  151 kip
♦ Uncased Length Structural Capacity  =  175 kip
♦ Geotechnical Bond Capacity  =  ?
♦ Required = 134 kip  So far OK!

Design Example – Step 8

Geotechnical Capacity - Uncased Zone

♦ Type B pile - Pressure through casing
♦ Very Dense Gravel w/ Cobbles
♦ Table 5-3
  - PTI Rock and Soil Anchors - 1996
  - Ostermayer, Construction, Carrying Behavior and Creep Characteristics of Ground Anchors - 1975
  - Xanthakos et al., Ground Control and Improvement - 1994
  - FHWA Micropile State of Practice Review - 1996
  - FHWA Drilled Shafts - 1988

Reference
page 5-21
### Design Example

#### Geotechnical Capacity - Bond Values

**Table 5.3**

<table>
<thead>
<tr>
<th>Soil/Rock Description</th>
<th>Typical Grout to Ground Bond Strength (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Type A</td>
</tr>
<tr>
<td>soft Silt and Clay some Sand</td>
<td>35-70</td>
</tr>
<tr>
<td>Sand, some Silt med-very dense</td>
<td>95-215</td>
</tr>
<tr>
<td>Gravel med-very dense</td>
<td>95-265</td>
</tr>
<tr>
<td>Soft Shale</td>
<td>205-550</td>
</tr>
<tr>
<td>Limestone Fresh hard</td>
<td>520-1725</td>
</tr>
</tbody>
</table>

#### Design Example

**Geotechnical Capacity - Uncased Zone**

\[
\alpha_{bond} = 48 \text{ psi} \\
PG\text{-all} = \frac{\alpha_{bond} \cdot 3.14 \cdot d_{bond} \cdot L}{FS} \\
FS = 2.5 \quad \text{Design Load} = 134 \text{ kip} \quad L = 24 \text{ ft} \\
\]

Use \( L = 25 \text{ ft} \)  \quad PG\text{-all} = 135 \text{ kip}

Note: this is a preliminary length, final length is dependent on the contractors methods and field testing to confirm capacities.
Design Example

Summary

♦ Cased Length Structural Capacity = 151 kip
♦ Uncased Length Structural Capacity = 175 kip
♦ Geotechnical Bond Capacity = 135 kip

♦ Required = 134 kip  OK!

Design Example

Summary

♦ Need minimum 25 ft uncased length
♦ Final length to be confirmed or modified by the testing program
♦ Pile performance requirement should be clearly stated in the contract and tied back to the contractors installation methods.
Design Example – Step 9

Elastic Shortening

Shortening = \( \frac{PL}{AE} \)

For Compression

\( AE = [Ag*Eg] + [As*Es] \)

\( L \)- above bond zone = 15 ft

Elastic Shortening = 0.1 in

(L includes transition length)

Design Example

Settlement

♦ Minimum Settlement = Elastic Shortening
♦ Actual Settlement = Elastic Shortening + Geotechnical Settlement (permanent)
♦ Geotechnical Settlement Calculated Like Typical Friction Pile
♦ Consider Group Effects if there is tight pile spacing
Design Example – Step 10

Connection Details

♦ New Pile Cap
♦ Existing Structures

Design Example

Connection - New Pile Cap

♦ Assuming 254 mm Square Bearing Plate
♦ Plate Area = 64,516 mm²
♦ Equivalent Diameter = 286 mm
♦ $P_{cone-all} = \frac{4 \left(f'_c\right)^{\frac{1}{2}} A_{cp}}{FS}$

$FS = 2.35 \quad A_{cp} = 862,053 \text{ mm}^2$

$P_{cone-all} = 640 \text{ kN} > 595 \text{ kN} \quad \text{OK!}$
Design Example
Connection - New Pile Cap

♦ Plate Thickness

Bearing Compression

\[ B_c = \frac{P_{c-service}}{A_{plate}} = 9.22 \text{ MPa} \]

\[ M_{max} = B_c \times R^2 \times 0.5 = 0.147 \text{ kNm} \]

\[ F_{y-plate} = 345 \text{ MPa} \]

\[ t_{req} = \left( \frac{6 \times M_{max}}{0.55 F_{y-plate}} \right)^{1/2} = 21.6 \text{ mm} \]

Use 25 mm Thick Plate

Industrial Facility Connections
Hewlett Packard “Corvallis, OR.”
Seismic Upgrade Connection

Screw Top Connections
Design Example

Connection - Existing Structures

- Assuming Shear Rings 24.5 mm Wide and 12 mm Thick
- Ring Area ($A_R$) = 3871 mm$^2$
- Minimum Shear Ring Spacing
  $S_R = 4(W_R) + t_R = 114.3$ mm
- Number of Shear Rings
  
  $$N_R = \frac{P_{c-service} \times LF \times A_R \times f \times 0.85f_c'}{f}$$

  \[f = 0.7, \quad LF = 1.53\]

  \[N_R = 2.11 \quad \text{Use 3 Shear Rings}\]

Reference page 5-37

Design Example – Step 11

Load Test

- Required Load
  Verification $2.5 \times$ Design Load = 337 kip

- Structural Capacity - Casing
  
  \[P_{c-all} = (0.68f_c'Ag + 0.8Fy-steel(A_{bar} + A_{casing}))\]

  \[P_{c-all} = 287 \text{ kip}\]

- Casing not reduced for corrosion
Design Example

Load Test

Structural Capacity - Bond Zone

\[ P_{c-all} = 0.68f_c'A_g + 0.8F_y\text{steel}A_{bar} + P_{\text{Trans All}} \]

\[ P_{\text{Trans All}} = \alpha \times 3.14 \times d \times PL = 36 \text{ kip} \]

\[ \frac{1.25}{P_{c-all} = 315 \text{ kip} < 337 \text{ kip}} \]

Pile not suitable for verification load test increase casing thickness and bar diameter

Final Drawings - Step 12

Reference page 5-104
Specifications

♦ Private Projects
  – DFI/ADSC Guide Spec
  – IBC 2006
♦ Public Work
  – FHWA Manual
  – AASHTO (2008 interim)
♦ International
  – JAMP
  – Eurocode

Summary

♦ Understanding goals and constraints
♦ Know the available tools
♦ Engineering design
♦ Construction verification
Summary

- Most effective designs are tailored to the contractor doing the installation
- Field verification and experience are imperative to success

“Problems may occur if the designer lacks the expertise in micropile design and construction techniques or lacks the control of construction on site to avoid methods that may be detrimental to the pile’s capacity” (FHWA 2000)
Project Sizes

Survey Says
Thank You!

Allen Cadden, P.E.
Schnabel Engineering
acadden@schnabel-eng.com
610-696-6066