Schnabel ENGINEERING

Lesson 5

Design of Micropiles for Structural Foundations

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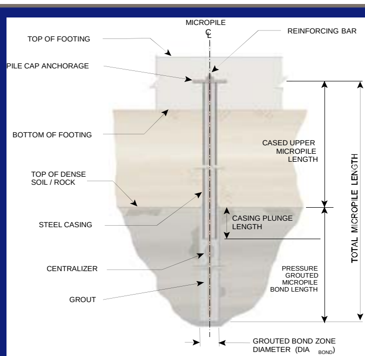
Learning Outcomes

- Evaluate structural and geotechnical capacity of micropiles and micropile groups
- Identify special design considerations for micropiles

Micropile Structural Design Basics

- Fundamentals are similar to traditional pile design
- Due to the small structural section, structural design and stiffness can often control (as compared to geotechnical failure)

Typical Micropile Detail



Design Process

Step 1	Evaluate Feasibility of Micropiles
Step 2	Review Project Information
Step 3	Establish Load and Performance Requirements
Step 4	Preliminary Design Considerations
Step 5	Evaluate Structural Capacity of Cased Length

Design Process

Step 6	Evaluate Structural Capacity of Uncased Length
Step 7	Compare Capacity to Need
Step 8	Evaluate Geotechnical Capacity of Micropile
Step 9	Estimate Micropile Movements
Step 10	Design Micropile/Footing Connection
Step 11	Develop Load Testing Program
Step 12	Drawings and Specifications

Step 1. Evaluate Feasibility

- Subsurface conditions
- Difficult access or limited overhead clearance
- Subsurface voids
- Vibration limits
- Underpinning or retrofitting of existing foundations

Step 2. Review Project Information

- Geologic conditions
- Site history
- Geotechnical data
- Environmental conditions

Review of Geotechnical Data

- Review published information
- Obtain samples
- Develop profiles
- Estimate design parameters
- Evaluate corrosion potential
- Identify problem areas
- Liquefaction

How Many Borings Do I Need ?

Application	Min. No. Exploration Points	Minimum Depth
Deep Foundations	Structure Size <100 ft, one point at each structure >100 ft, min 2 points at each structure	Soils: at least 20 ft below anticipated deep foundation tip grade not less than 2x the maximum group dimension Rock: minimum 10 ft, but below the anticipated tip or 2x group dimension

After FHWA-IF-02-034

Step 3. Establish Applicable Loading Cases

- Battered micropiles required for large lateral loading applications
- For retrofits, need to consider existing foundation loads and whether these loads will be carried solely or shared by micropiles
- Micropile geotechnical capacity will be confirmed via load testing to 2.0 times the design loading
- Establish deflection criteria

Load Cases

- AASHTO Bridge Design Specification load cases will combine items such as:
  - Live
  - Dead
  - Wind
  - Seismic
  - Downdrag
  - Scour…

Step 4. Preliminary Design Considerations

- Micropile spacing
- Micropile length
- Micropile cross section
- Micropile type

Micropile Spacing

- At least 3 micropile diameters or 760 mm
- Depends on condition of existing footing, access to footing, and magnitude of loads

Micropile Length

- Depth to good ground
- Depth to establish fixity for lateral loading application
- Depth to resist downdrag loads
- Depth of significant scour
- Impact of group loads on a compressible layer
- Location of liquefiable layers, karstic features, and other underground anomalies

Micropile Cross Section

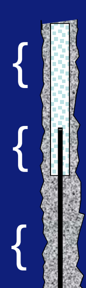
- Typically selected based on rough estimate of required diameter to resist axial design loads
- Use common casing sizes (refers to outside diameter)
  - 5-1/2 in <100 Ton
  - 7 in. 100-150 Ton
  - 9-5/8 in >150 Ton
- Nominal yield stress of 80 ksi

Design Engineers Must Understand Available Tools

- Drilling rigs
- Drilling methods
- Available structural materials
- Reasonable bond values
- Quality control

Structural Design – Compression/Tension Only

- Grout & steel
- Transfer zone (plunge)
- Bond zone



Step 5. Structural Design of Cased Length - Compression

$$P_{c\text{-allowable}} = [\,0.4\, f'_{c\ grout} \times A_{grout} + 0.47 F_{y\text{-steel}} (A_{bar} + A_{casing})]$$

(Eq. 5-1)

$P_{c\text{-allowable}}$	= allowable compression load;
$f'_{c\ grout}$	= unconfined compressive strength of grout (typically a 28-day strength);
A_{grout}	= area of grout in micropile cross section;
$F_{y\text{-steel}}$	= yield stress of steel;
A_{bar}	= cross sectional area of steel reinforcement bar (if used);
A_{casing}	= cross sectional area of steel casing (adjusted for assumed steel section losses due to corrosion).

Step 5. Structural Design of Cased Length - Tension

$$P_{t\text{-allowable}} = [0.55 F_{y\text{-steel}} (A_{bar} + A_{casing})]$$

(Eq. 5-2)

- Do not consider grout in this calculation
- Assume zero (or small) tension load carried by casing if threaded joints on casing and no lab data available

Step 6. Structural Design of Uncased Length

Compression

$$P_{c\text{-allowable}} = [\,0.4\, f'_{c\ grout} \times A_{grout} + 0.47 F_{y\text{-steel}} \times A_{bar}\,]$$

(Eq. 5-7)

Tension

$$P_{t\text{-allowable}} = [0.55 F_{y\text{-steel}} (A_{ba} + A_{casing})]$$

(Eq. 5-8)

Step 11: Load Test Structural Capacity

- Check whether micropile design will be overstressed during load testing
- Upgrade design section, if necessary, to allow safe load testing
- Allowable stress of 80 percent of ultimate is typical

$$P_{ult-compression} = \left[0.85\, f'_{c-grout} \times A_{grout} + f_{y-casing} \times A_{casing} + f_{y-bar} \times A_{bar}\right]$$

$$P_{ult-tension} = \left[f_{y-casing} \times A_{casing} + f_{y-bar} \times A_{bar}\right]$$

Step 7: Compare Design Loads

- Micropile Capacity > Required Design

If not, Back to Step 4

Step 8. Geotechnical Capacity of Micropile

- Consider load transfer parameters
  - Grout to ground average bond values
  - Identify variations throughout profile and across the site
  - Define the required minimum bond length
  - Define testing required to confirm this
- Evaluate pile spacing
  - Impact from group effects

Allowable Geotechnical Bond Capacity

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

(Eq. 5-9)

α_{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

Grout-to-Ground Bond Values

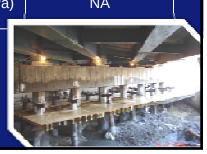
SEE TABLE 5-3 IN MANUAL

Page

5-21

Hollow Bar Bond Values

Soil Type	Mobilized Bond Strength in Proof Tests	Bond Strength Suggested By FHWA Type B Micropile
Sand (some silt) (fine, loose-medium dense	27-53 psi (186.2-365.4 kPa)	10-28 psi (68.9-193.1 kPa)
Silt & Clay (some sand) (stiff, dense to very dense)	7-28 psi (50.6-193.1 kPa)	10-28 psi (68.9-193.1 kPa)
Combined Soil (approximately ½ bond length in stiff clay and ½ in medium density sand)	11-35 psi (72.4-241.3 kPa)	NA



Factor of Safety on Bond

- With load testing requirements provided (Chapter 7 of Manual), use FS = 2.0
- Use FS = 2.5 if,
  - Bond length in soil susceptible to creep
  - Other marginal ground
  - Previous experience in similar ground is limited

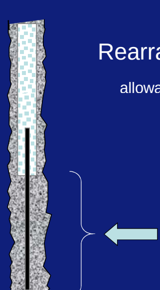
Geotechnical Design – Empirical

Average Bond Values (allowable loads)

Clay:	1-2 k/ft
Loose sands:	2-4 k/ft
Compact sand:	5-10 k/ft
Rock:	5-20+ k/ft

Typical for approximately 5 ½ to 7 inch diameter micropile

Calculate Bond Length



Rearrange Eq. 5-9 and set $P_{G-allowable}$ equal to design load

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

Micropile Group Capacity

- Pressure grouting results in increase in confining pressure in the ground (like driven piles)
- Gravity grouted micropiles result in stress relief in the ground (like drilled shafts)
- Gravity grouted micropiles, however, are only used in rocks where group effects are perceived to be negligible

Group Effects

- If in cohesionless soils, assume no group effects
  - (where minimum spacing is satisfied)

Group Effects

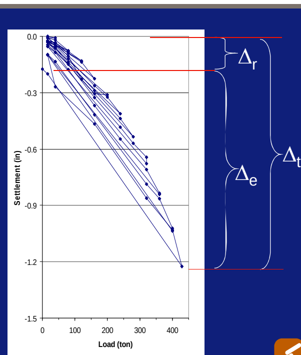
- For cohesive soils:
  - Consider contact condition of cap and shear strength of soil and adjust efficiency between 0.65 and 1.0
  - For close spacing (less than 3 micropile diameters between micropiles), consider block failure and compare to the sum of individual pile capacities

Step 9. Estimate Micropile Movements

- Individual micropile vertical movement
- Micropile group settlement
- Lateral movement

Micropile Axial Deflection

- Elastic shortening
- Residual movement
- Creep movement



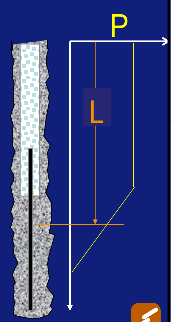
Elastic Movement

- Vertical movements (at design load) must be less than tolerable for the structure
- Since micropiles have small cross sections, they may have relatively significant elastic movements
- Length (for elastic estimate) is not the total length installed

Elastic Shortening Estimate

$\Delta elastic = PL / AE$

- For micropiles in competent soil, L = length above bond length plus ½ 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 ?

$$\Delta_{elastic} = \sum_i \frac{P_i L_i}{A_i E_i}$$

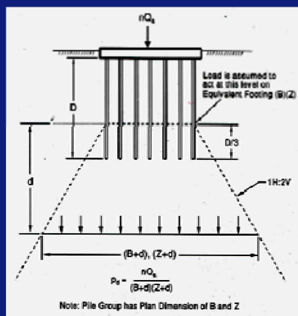
$$EA_{pile} = \left[A_{grout} \times E_{grout}\right] + \left[A_{steel} \times E_{steel}\right]$$

- Evaluate for each section of pile
  - E_{grout} = 1500 ksi
  - E_{steel} = 29000 ksi

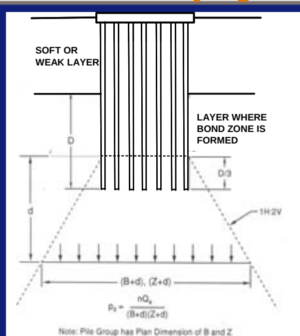
Creep Movements

- Creep movements concern for clayey soils with LL > 50 and PI > 20
- Where bond length to be established in potentially creep-sensitive ground, consider preproduction load test program and verify creep movements via extended load testing

Group Settlement
Uniform Soil

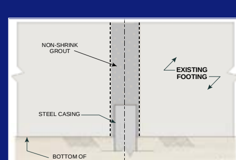


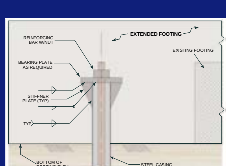
Group Settlement
Underlying Soft Soil

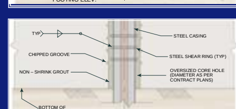


Step 10. Design Footing Connection Details

- Shear transfer from grout
- Bearing plate
- Shear rings







Connection Examples

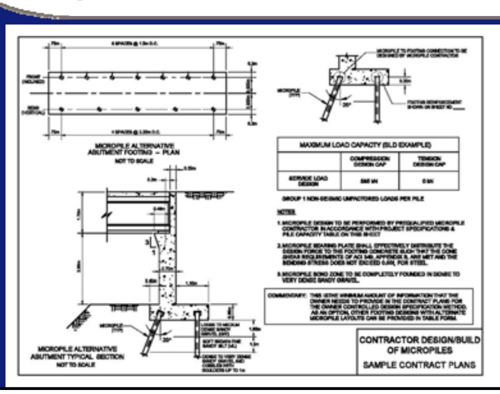
Step 11: Develop Load Testing Program

- Chapter 7
- Basis
  - Factor of Safety
  - Structural Capacity of Pile
  - Schedule

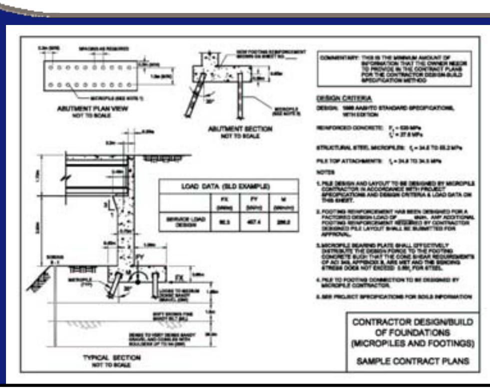
Step 12: Drawings, Specifications, Contracting

- See the Manual.
- Be clear and complete
- Submittals are not just a paper chase

Sample Contract Plans



Sample Contract Plans



Other Design Considerations

- Corrosion Protection
- Plunge Length
- Lateral Loads
- Buckling
- Seismic

Corrosion Protection

- The degree and extent of corrosion protection is a function of
  - loading condition
  - expected service life of the micropile
  - aggressiveness of the ground
  - perceived importance of the structure
  - consequences of failure

Corrosion Potential Evaluation

Test	Units	Strong Corrosion Potential - Aggressive	AASHTO Test Method
pH	–	<5, >10	T 289-91
Resistivity	ohm-cm	<3,000	T 288-91
Sulfates	ppm	>200	T 290-91
Chlorides	ppm	>100	T 291-91

If one or more criteria is met, assume strong corrosion potential

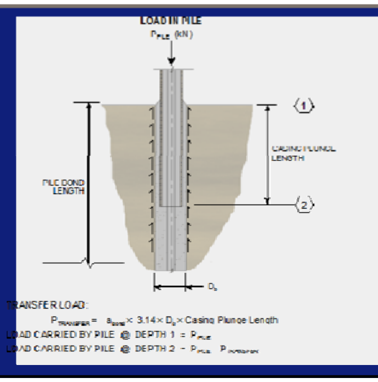
Corrosion Protection

Corrosion Protection				
Loading	Tension[1]		Compression	
Ground	Aggressive[2]	Non aggressive	Aggressive[2]	Non-aggressive
Casing	a. Do not rely on casing for load capacity	a. None required if tension load on casing is less than 20% of casing [illegible]	a. Min.1.6 mm (0.063 in.) corrosion loss on outside The Specifier may use [illegible]	a. None The Specifier may use different corrosion loss [illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Core steel (reinforcing bar)[1]	a. epoxy coating[3] OR a. galvanization[3] OR a. encapsulation in plastic sheath[3] AND Grout cover[4]	a. bare steel[5] OR a. epoxy coating[3] OR a. galvanization[3] OR a. encapsulation in plastic sheath[3] AND Grout cover[4]	a. Grout cover[4] AND The Specifier may desire to add other options listed for tension.	a. Grout cover[4]

SEE TABLE 5-6 IN MANUAL

Page 5-50

Casing Plunge Length - Ptransfer



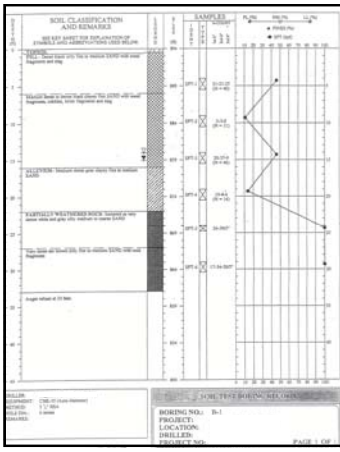
WORKSHOP PROBLEM 1

Problem Statement

- Deep foundations are required to support column loads for bridge.
- Micropiles have been selected for the project: (1) a 320-kip design load micropile; and (2) a 200-kip design load micropile

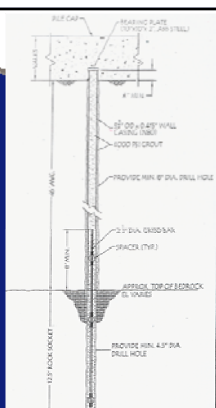
Subsurface Conditions

- Site is underlain by approximately 20 ft of undocumented and variable fill overlying partially weathered rock. The soil matrix of the fill is characterized as loose to very dense silty to clayey sand.
- The groundwater table is located 15 ft below the current ground surface.
- Approximately 10 ft of new fill will be placed over the existing fill to establish foundation grades.

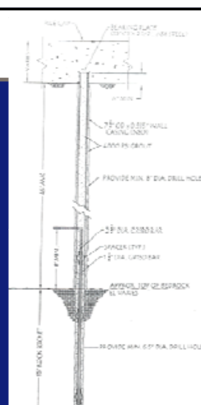


Soil/Rock Data

- RQD values for the bedrock greater than 85 percent
- Minimum unconfined compressive strength of rock is 5 ksi



200 Kip Micropile Detail



320 Kip Micropile Detail

Required

- Evaluate the Contractor-provided design
  - Structural capacity of uncased length (also referred to as socketed length)
  - Structural capacity of cased length
  - Adequacy of proposed bond length

Manual References

- Structural Capacity of Uncased Length
  - Section 5.7 of Manual (page 5-17, Eq. 5-7)
- Structural Capacity of Cased Length
  - Section 5.6 of Manual (page 5-10, Eq. 5-1)
- Adequacy of Bond Length
  - Section 5.9.2 of Manual (page 5-19, Eq. 5-10 and Page 5-21, Table 5-3)

200 Kip Micropile Material Parameters

Portion of Micropile	Property	Value
Cased Length	Casing Outside Diameter	5.5 in.
	Casing Wall Thickness	0.415 in.
	Casing Yield Strength	80 ksi
	Compressive Strength of Grout	4 ksi
Socketed Length	Reinforcing Bar Diameter	2.5 in.
	Reinforcing Bar Yield Strength	150 ksi
	Compressive Strength of Grout	4 ksi

320 Kip Micropile Material Parameters

Portion of Micropile	Property	Value
Cased Length	Casing Outside Diameter	7.75 in.
	Casing Wall Thickness	0.595 in.
	Casing Yield Strength	80 ksi
	Compressive Strength of Grout	4 ksi
Socketed Length	Reinforcing Bar Diameter	2.5 in. / 1.75 in.
	Reinforcing Bar Yield Strength	150 ksi / 150 ksi
	Compressive Strength of Grout	4 ksi

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Lesson 5, Part II

Design of Micropiles for Structural Foundations

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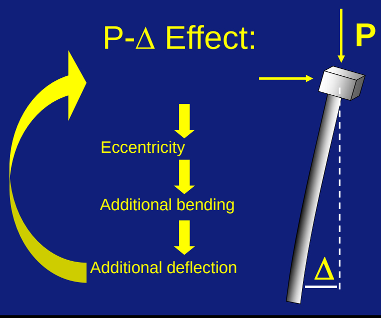
Lateral Loads on Micropiles

What controls lateral strength of a pile?

And what's special about a micropile?

Lateral Stability Under Combined Loads

- Lateral deflection



Do We Have Time?

- For Lateral Loading and Buckling…

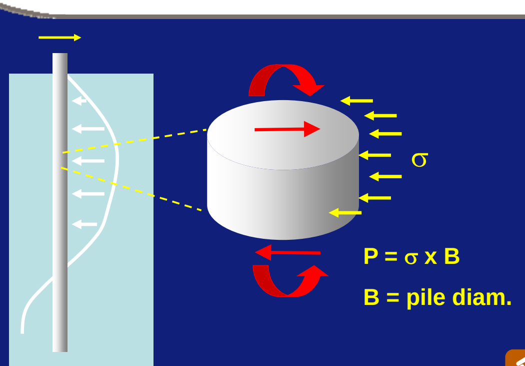
LPILE

- Use for single micropiles
- Nonlinear soil response modeled through p-y curves
- Linear or nonlinear pile response
- Define free head, fixed head, or rotation magnitude
- Multiple load combinations and boundary conditions
- Group effects not considered. Need to do manually

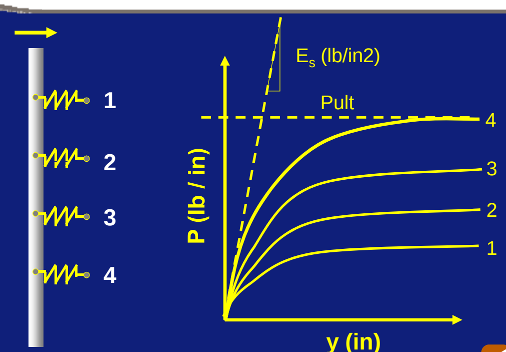
FB-Pier and GROUP

- Best for pile group analysis
- Nonlinear soil response modeled through p-y curves and response curves for axial load transfer (side and end bearing)
- Linear or nonlinear pile response
- Define rotational stiffness of superstructure
- May introduce batter
- Very powerful

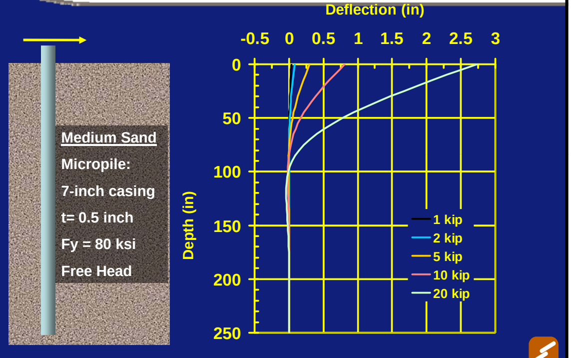
P-y Curves



P-y Curves



Example



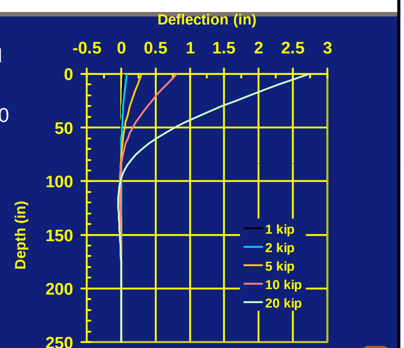
Example

First 5-10 ft critical

Acceptable deflection under 10 kip (~3/4 inch)

20 kip is close to ultimate

For fixed head, deflection <1 inch under 20 kip



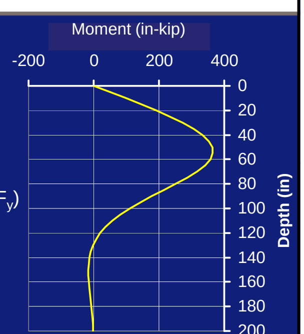
Example – 10 kip Case

Max Moment ~ 400 in-kip at ~5ft

Section Modulus of Casing S = 15.5 in^3

Maximum Bending Stress = 400 in-kip / 15.5 = 26 ksi (0.32 F_y) OK

Usually, deflection controls for free head condition. Moment often controls for fixed head condition



Combined Axial Compression and Bending Stress

$$\frac{f_a}{F_a} + \frac{f_b}{\left(1 - \frac{f_a}{F_e'}\right) F_b} \le 1.0$$

(Eq. 5-3)

f_a = axial stress (assumes all load carried by steel)
f_b = bending stress (=Mmax/S)
F_a = allowable axial stress in steel (0.47 Fy)
F_b = allowable bending stress (0.55 Fy)
F'_e = Euler buckling stress (a function of unbraced length)

Combined Axial Compression and Bending Stress – Alternate Evaluation

$$\frac{P_c}{P_{c-allowable}} + \frac{M_{max}}{M_{allowable}} \le 1.0$$

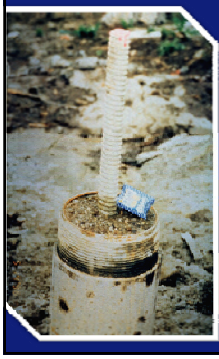
(Eq. 5-6)

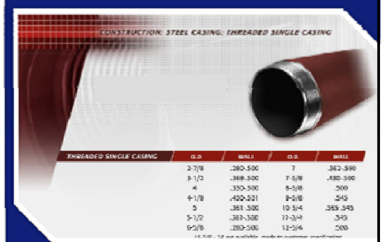
- P_c = maximum axial compression load
- $P_{c\text{-}allowable}$ = allowable compression load (Eq. 5-1)
- M_{max} = maximum bending moment
- $M_{allowable}$ = $(0.55 \times F_y \times S)$

Lateral Loading Analysis - Summary

- Good subsurface data near surface is critical
- p-y curves in computer programs developed for larger diameter drilled shafts so it is conservative
- Use appropriate level of fixity to model ground line boundary condition
- Use available lateral load test data

Threaded Casing Connections





Structural 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
- Qualified Engineer to evaluate supplier-provided data
- Conservative method provided herein\

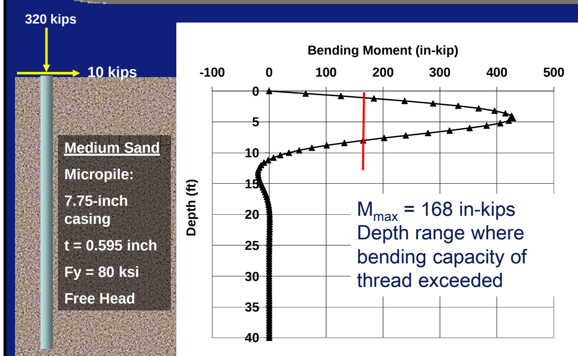
Analysis of Threaded Connection for Bending

- Assume casing wall thickness, tw, is equal to ½ of the thickness of the intact casing
- Calculate casing area and section modulus based on this reduced thickness

Four Point Bending Test Data (at Threaded Joints)

Casing	Maximum Moment (Kip-in)
7" – ½" wall (N80)	1120
7" – ½" wall (N80)	1200
9 $^5/_8$" – ½" wall w/ 7"- ½" wall inside (N80)	3000

Example



Buckling may control if…

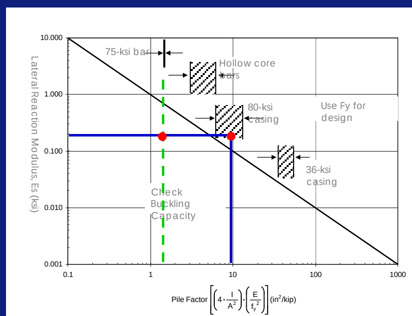
$$P_{cr} = \frac{\pi^2 EI}{l^2} + \frac{E_s l^2}{\pi^2}$$

(Eq. 5-28)

45mm (1 ¾") bar - Es <~ 4.8 MPa (700 psi)
178mm (7") - N80 Casing - Es <~ 690 kPa (100 psi)
248MPa (36 ksi) pipe - Es <~ 200 kPa (30 psi)

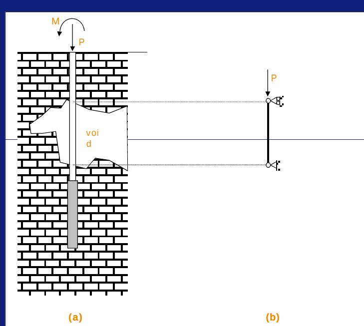
E_s = lateral soil reaction (~ 100 s_u for soft clays)
l = the unbraced length

Buckling Potential - Example



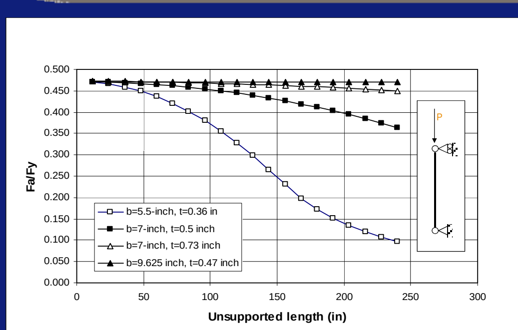
Cadden and Gómez, 2002

Analysis for Voids



Use combined stress check with unbraced length as height of void

Theoretical Effect of Voids



Seismic Design Considerations

- Vertical micropiles are ineffective in resisting seismic deformations and/or lateral spreading
- Use battered micropiles to resist lateral seismic forces
- Consider development of large bending moments in pile cap
- With sufficient flexural reinforcement in pile cap, failure (yielding or pullout) of the micropile will occur before yielding of connection (CALTRANS desire)
- Mitigate cracking of cap (due to tensile forces in micropiles) by increasing vertical shear reinforcement

Learning Outcomes

- Evaluate structural and geotechnical capacity of micropiles and micropile groups
- Identify special design considerations for micropiles

Evaluation of Micropile for Foundation Support – Combined Axial and Bending Stress

WORKSHOP PROBLEM 2

Problem Statement

- Deep foundations are required to support column loads for an Bridge
- Micropiles have been selected for the project: (1) a 320-kip design load micropile; and (2) a 200-kip design load micropile
- Micropiles also need to carry a groundline shear load of 10 kips
- See Workshop Problem 2 for soil/rock data

Required

- Evaluate the Contractor-provided design
  - Evaluate combined stress criterion
  - If not adequate, what is maximum shear load that micropile can support
  - If adequate, what is maximum shear load that micropile can support

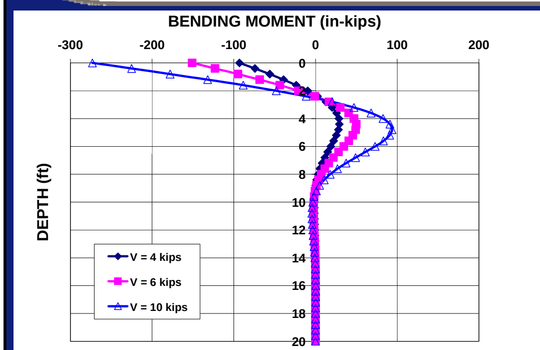
Manual References

- Combined Stress Criterion
  - Section 5.6 (3) of Manual (page 5-14, Eq. 5-6)
  - Calculations for Moment of Inertia, I, and Section Modulus, S (page 5-15)

200 Kip Micropile Material Parameters

Portion of Micropile	Property	Value
Cased Length	Casing Outside Diameter	5.5 in.
	Casing Wall Thickness	0.415 in.
	Casing Yield Strength	80 ksi
	Compressive Strength of Grout	4 ksi
Socketed Length	Reinforcing Bar Diameter	2.5 in.
	Reinforcing Bar Yield Strength	150 ksi
	Compressive Strength of Grout	4 ksi

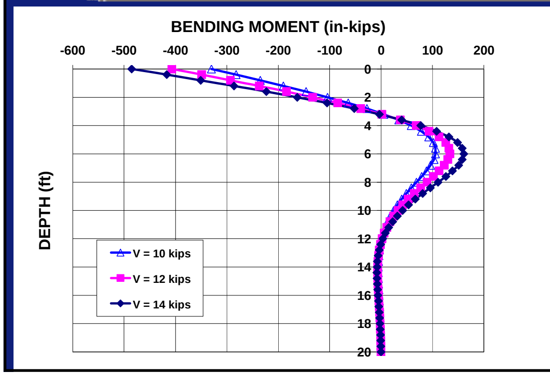
LPILE Analysis Results – 200 Kip Micropile



320 Kip Micropile Material Parameters

Portion of Micropile	Property	Value
Cased Length	Casing Outside Diameter	7.75 in.
	Casing Wall Thickness	0.595 in.
	Casing Yield Strength	80 ksi
	Compressive Strength of Grout	4 ksi
Socketed Length	Reinforcing Bar Diameter	2.5 in. / 1.75 in.
	Reinforcing Bar Yield Strength	150 ksi / 150 ksi
	Compressive Strength of Grout	4 ksi

LPILE Analysis Results – 320 Kip Micropile



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Questions?

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