WHAT IS A FOUNDATION?

• The element of a structure that transfers loads to the underlying ground with performance consistent with the design of the structure.

• Loads are a combination of:
  – Static
  – Dynamic
  – Horizontal
  – Vertical

from *Underground* by David Macaulay (1976)
WHAT IS A FOUNDATION?

Transcona Grain Elevator
Winnipeg, Manitoba
October 18, 1913
Tilt: 27°

Bridge Abutment on Piles
- 30 inches of Settlement
over 10 years

Photograph and Figure from Baracos (1957).

Photograph courtesy of FHWA-NHI-132012 Soils and Foundations Workshop Participants Workbook
Lee Roy Selmon Expressway, Tampa, FL

- Drilled Shafts sink 11ft
- Repair Cost: $92,000,000
- 155 of 224 Shafts Strengthened

Source: Tampa Bay Times

What caused the collapse
A combination of unstable soil and excessive weight from a truss caused a portion of the expressway to collapse, officials say.

1. Concrete pillars that support 300-foot spans of the elevated expressway extend 50 feet into the ground.
2. A 175-ton steel truss mounted to the final two pillars was used to position the concrete segments. There are 17 segments between each pillar.

3. Unstable ground beneath the pillar gave way under the excessive weight. The pillar sank about 15 feet.

Source: URS Corp. and Florida Department of Transportation

Infographic: St. Petersburg Times
REASONS FOR DEEP FOUNDATIONS

(a) Upper Strata Weak or Compressible  (b) Uplift  (c) Lateral Loading

Figure 7.1. FHWA NHI-05-042 Design and Construction of Driven Pile Foundations - Volume I.
REASONS FOR DEEP FOUNDATIONS

(d) Combined Uplift and Lateral Loading

(e) Scour

(f) Liquefaction

Figure 7.1. FHWA NHI-05-042 Design and Construction of Driven Pile Foundations - Volume I.
REASONS FOR DEEP FOUNDATIONS

Bridge Abutment Scour

Photograph courtesy of FHWA-NHI-132012 Soils and Foundations Workshop Participants Workbook
REASONS FOR DEEP FOUNDATIONS

Scour at Bridge Abutment

Photograph courtesy of FHWA-NHI-132012 Soils and Foundations Workshop Participants Workbook
REASONS FOR DEEP FOUNDATIONS

Example of Forces on a Bridge
(Lateral – Ice and River, Vertical – Vehicle)

Photograph courtesy of FHWA-NHI-132012 Soils and Foundations Workshop Participants Workbook
REASONS FOR DEEP FOUNDATIONS

(g) Fender Systems  (h) Underpinning  (i) Swelling Soils

Figure 7.1. FHWA NHI-05-042 Design and Construction of Driven Pile Foundations - Volume I.
BOSTON AREA FOUNDATION CONCEPTS
DEEP FOUNDATION CLASSIFICATIONS

Figure 8.1. FHWA HI-97-013 Driven Pile Design and Construction Volume I.
DEEP FOUNDATION CLASSIFICATIONS

Figure 8.1. FHWA NHI-05-042 Design and Construction of Driven Pile Foundations Volume I.
### Table 8-1. FHWA NHI-05-042 (from NAVFAC DM7.02).

<table>
<thead>
<tr>
<th>PILE TYPE</th>
<th>CAST-IN-PLACE (MANDREL DRIVEN SHELL)</th>
<th>CONCRETE</th>
<th>TYPICAL ILLUSTRATION</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>TYPICAL LENGTHS</strong></td>
<td>3 m - 40 m (10 – 130 ft), but typically in the 15 m - 25 m (50 – 80 ft) range.</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>MATERIAL SPECIFICATIONS</strong></td>
<td>ACI 318 - for concrete.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
| **MAXIMUM STRESSES**    | 33% of 28-day strength of concrete, with increase to 40% of 28-day strength provided:  
  - Casing is a minimum of 12 gage thickness.  
  - Casing is seamless or with welded seams.  
  - Ratio of steel yield strength to concrete is not less than 6.  
  - Pile diameter not greater than 450 mm (18 in). |          |                      |
| **TYPICAL AXIAL DESIGN LOADS** | Designed for a wide loading range but generally in the 400-1400 kN (90 – 315 kip) range. |          |                      |
| **DISADVANTAGES**       | Difficult to splice after concreting.  
  - Redriving not recommended.  
  - Thin shell vulnerable during driving to excessive earth pressure or impact.  
  - Considerable displacement. |          |                      |
| **ADVANTAGES**          | Initial economy.  
  - Tapered sections provide higher resistance in granular soil than uniform piles.  
  - Can be inspected after driving.  
  - Relatively less waste of steel.  
  - Can be designed as toe bearing or friction pile. |          |                      |
| **REMARKS**             | Best suited as friction pile in granular materials. |          |                      |
### Table 8-1. FHWA NHI-05-042 (from NAVFAC DM7.02).

<table>
<thead>
<tr>
<th>PILE TYPE</th>
<th>CAST-IN-PLACE CONCRETE (SHELLS DRIVEN WITHOUT A MANDREL)</th>
<th>TYPICAL ILLUSTRATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>TYPICAL LENGTHS</td>
<td>5 m - 25 m (15 – 80 ft)</td>
<td></td>
</tr>
<tr>
<td>MATERIAL SPECIFICATIONS</td>
<td>ACI 318 - for concrete. ASTM A252 - for steel pipe.</td>
<td></td>
</tr>
<tr>
<td>MAXIMUM STRESSES</td>
<td>See Chapter 10.</td>
<td></td>
</tr>
<tr>
<td>TYPICAL AXIAL DESIGN LOADS</td>
<td>500 kN - 1350 kN (110 – 300 kips)</td>
<td></td>
</tr>
<tr>
<td>DISADVANTAGES</td>
<td>• Difficult to splice after concreting.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Considerable displacement.</td>
<td></td>
</tr>
<tr>
<td>ADVANTAGES</td>
<td>• Can be redriven.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Shell not easily damaged if fluted.</td>
<td></td>
</tr>
<tr>
<td>REMARKS</td>
<td>• Best suited for friction piles of medium length.</td>
<td></td>
</tr>
</tbody>
</table>
### DEEP FOUNDATIONS: CAST-IN-PLACE (CIP) PILES

**Table 8-1.** FHWA NHI-05-042 (from NAVFAC DM7.02).

<table>
<thead>
<tr>
<th>PILE TYPE</th>
<th>AUGER PLACED, PRESSURE INJECTED CONCRETE PILES (CFA PILES)</th>
<th>TYPICAL ILLUSTRATION</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>TYPICAL LENGTHS</strong></td>
<td>5 m - 25 m (15 – 80 ft)</td>
<td></td>
</tr>
<tr>
<td><strong>MATERIAL</strong></td>
<td>ACI 318 - for concrete. ASTM A82, A615, A722, &amp; A884 - for reinforcing steel.</td>
<td></td>
</tr>
<tr>
<td><strong>MAXIMUM STRESSES</strong></td>
<td>33% of 28-day strength of concrete.</td>
<td></td>
</tr>
<tr>
<td><strong>TYPICAL AXIAL</strong></td>
<td>260 kN - 875 kN (60 – 200 kips)</td>
<td></td>
</tr>
<tr>
<td><strong>DISADVANTAGES</strong></td>
<td>• Greater dependence on quality workmanship.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Not suitable through peat or similar highly compressible material.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Requires more extensive subsurface exploration.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• No driving observation (blow count) to aid in assessing capacity.</td>
<td></td>
</tr>
<tr>
<td><strong>ADVANTAGES</strong></td>
<td>• Economy.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Zero displacement.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Minimal vibration to endanger adjacent structures.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• High shaft resistance.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Good contact on rock for end bearing.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Visual inspection of augured material.</td>
<td></td>
</tr>
<tr>
<td><strong>REMARKS</strong></td>
<td>• Best suited as a friction pile in granular material.</td>
<td></td>
</tr>
</tbody>
</table>

*ACIP – Auger Cast In Place DD – Drilled Displacement  
CFA – Continuous Flight Auger APG - Auger Pressure Grouted  
APGD - Auger Pressure Grouted Displacement*
## Table 8-1. FHWA NHI-05-042 (from NAVFAC DM7.02).

<table>
<thead>
<tr>
<th>PILE TYPE</th>
<th>COMPOSITE PILES</th>
<th>TYPICAL ILLUSTRATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>TYPICAL LENGTHS</td>
<td>15 m - 65 m (50 – 210 ft)</td>
<td></td>
</tr>
<tr>
<td>MAXIMUM STRESSES</td>
<td>33% of 28-day strength of concrete. 62 MPa (9 ksi) for structural and pipe sections if thickness is greater than 4 mm (0.16 inches).</td>
<td></td>
</tr>
<tr>
<td>TYPICAL AXIAL DESIGN LOADS</td>
<td>300 kN - 1,800 kN (70 – 400 kips)</td>
<td></td>
</tr>
<tr>
<td>DISADVANTAGES</td>
<td>• Difficult to attain good joints between two materials except for concrete H or pipe composite piles.</td>
<td></td>
</tr>
<tr>
<td>ADVANTAGES</td>
<td>• Considerable length can be provided at comparatively low cost for wood composite piles. • High capacity for some composite piles. • Internal inspection for pipe composite piles.</td>
<td></td>
</tr>
<tr>
<td>REMARKS</td>
<td>• The weakest of any material used shall govern allowable stresses and capacity.</td>
<td></td>
</tr>
</tbody>
</table>
# Deep Foundations: Drilled Shafts

### Table 8-1. FHWA NHI-05-042 (from NAVFAC DM7.02).

<table>
<thead>
<tr>
<th>PILE TYPE</th>
<th>DRILLED SHAFTS</th>
<th>TYPICAL ILLUSTRATION</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Typical Lengths</strong></td>
<td>5 m to 65 m or more (15 – 200 ft)</td>
<td></td>
</tr>
<tr>
<td><strong>Maximum Stresses</strong></td>
<td>33% of 28-day strength of concrete.</td>
<td></td>
</tr>
<tr>
<td><strong>Typical Axial Design Loads</strong></td>
<td>1,500 kN - 20,000 kN (330 – 4500 kips) or more.</td>
<td></td>
</tr>
<tr>
<td><strong>Disadvantages</strong></td>
<td>Requires relatively more extensive inspection.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Construction procedures are critical to quality.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Boulders can be a serious problem, especially in small diameter shafts.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mobilization of end bearing on a long shaft can require substantial displacement of shaft head.</td>
<td></td>
</tr>
<tr>
<td><strong>Advantages</strong></td>
<td>Length variations easily accommodated.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>High bearing capacity and bending resistance.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Availability of several construction methods.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Can be continued above ground as a column.</td>
<td></td>
</tr>
<tr>
<td><strong>Remarks</strong></td>
<td>No driving observations (blow count) available to aid in assessing capacity.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Not recommended in soft clays and loose sands.</td>
<td></td>
</tr>
</tbody>
</table>
# Deep Foundations: Micropiles (A.K.A. Mini, Pin)

Table 8-1. FHWA NHI-05-042 (from NAVFAC DM7.02).

<table>
<thead>
<tr>
<th>PILE TYPE</th>
<th>MICROPILES</th>
<th>TYPICAL ILLUSTRATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>TYPICAL LENGTHS</td>
<td>12 m - 25 m (40 – 100 ft)</td>
<td></td>
</tr>
<tr>
<td>MATERIAL SPECIFICATIONS</td>
<td>ASTM C150 - for Portland cement.</td>
<td>![Micropile Diagram]</td>
</tr>
<tr>
<td></td>
<td>ASTM C595 - for blended hydraulic cement.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>ASTM A615 - for reinforcing steel.</td>
<td></td>
</tr>
<tr>
<td>TYPICAL AXIAL DESIGN LOADS</td>
<td>300 kN - 1100 kN (70 – 250 kips)</td>
<td></td>
</tr>
<tr>
<td>DISADVANTAGES</td>
<td>• Cost</td>
<td></td>
</tr>
<tr>
<td>ADVANTAGES</td>
<td>• Low noise and vibrations.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Small amount of spoil.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Excellent for sites with low headroom and restricted access.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Applicability to soil containing rubble and boulders, karstic areas.</td>
<td></td>
</tr>
<tr>
<td>REMARKS</td>
<td>• Can be used for any soil, rock or fill condition.</td>
<td></td>
</tr>
</tbody>
</table>
**Table 8-1. FHWA NHI-05-042 (from NAVFAC DM7.02).**

<table>
<thead>
<tr>
<th>PILE TYPE</th>
<th>PRESSURE INJECTED FOOTINGS</th>
<th>TYPICAL ILLUSTRATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>TYPICAL LENGTHS</td>
<td>3 m - 15 m (10 – 50 ft)</td>
<td></td>
</tr>
<tr>
<td>MATERIAL SPECIFICATIONS</td>
<td>ACI 318 - for concrete.</td>
<td><img src="image1" alt="Concrete Compacted by Ramming" /></td>
</tr>
<tr>
<td></td>
<td>ASTM A252 for steel pipe.</td>
<td><img src="image2" alt="Casing Corrugated Shell or Pipe" /></td>
</tr>
<tr>
<td>MAXIMUM STRESSES</td>
<td>33% of 28-day strength of concrete. 62 MPa (9 ksi) for pipe shell if thickness is greater than 4 mm (0.16 inches).</td>
<td></td>
</tr>
<tr>
<td>TYPICAL AXIAL DESIGN LOADS</td>
<td>600 kN - 1,200 kN (135 – 270 kips)</td>
<td></td>
</tr>
<tr>
<td>DISADVANTAGES</td>
<td></td>
<td><img src="image3" alt="Uncased Shaft" /></td>
</tr>
<tr>
<td></td>
<td>Base of footing cannot be made in clay or when hard spots (e.g., rock ledges) are present in soil.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>When clay layers must be penetrated to reach suitable material, special precautions are required for shafts in groups.</td>
<td></td>
</tr>
<tr>
<td>ADVANTAGES</td>
<td></td>
<td><img src="image4" alt="Cased Shaft" /></td>
</tr>
<tr>
<td></td>
<td>Provides means for placing high capacity footings on bearing stratum without necessity for excavation or dewatering.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>High blow energy available for overcoming obstructions.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Great uplift resistance if suitably reinforced.</td>
<td></td>
</tr>
<tr>
<td>REMARKS</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Best suited for granular soils where bearing is achieved through compaction around base.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Minimum spacing 1.5 m (5 ft) on center.</td>
<td></td>
</tr>
</tbody>
</table>

PIF – Pressure Injected Footings; a.k.a. Franki Piles
Deep Foundations: Pressure Injected Footing

PIF – Pressure Injected Footings; a.k.a. Franki Piles

Figure courtesy of Franki GRUNDAU.
Deep Foundation Examples: Cast-In-Place (CIP) Piles

Static Load Test on DD Pile
Photograph courtesy of WPC Inc.

CFA Rig
Photograph courtesy of www.skanska.co.uk
Deep Foundation Examples:
Drilled Shafts

Town Creek
West Tower

Arthur Ravenel Jr. Bridge

Photograph courtesy of WPC Inc. and Marvin Tallent, Palmetto Bridge Constructors
Deep Foundation Examples: MICROPILES

Static Load Test
50 Broad St., Charleston, SC

Dynamic Load Test
Hajduk et al. (2004)

Photographs courtesy of WPC Inc.
DEEP FOUNDATION EXAMPLES: PIF

Excavated

Photograph courtesy of www.geoforum.com

LeLachuer Park, Lowell, MA

Photograph courtesy of www.peeepl.com

PIF – Pressure Injected Footings; a.k.a. Franki Piles
Drilled Shafts: History

- Development progressed by and large independently worldwide.

- Different names are therefore associated with different construction methods or different geographical zones. All the names relate essentially to deep foundation elements constructed in place, differing from the prefabricated piles used in driving.
**NRAMES:**

- Caissons ("Old Timers", Midwestern US)
- Cast in Drilled Hole Pile (California by Caltrans)
- Drilled Piers (NCDOT, Midwestern US)
- (Drilled) Shafts (Texas)
- Bored Piles (outside the US)
- Rock Sockets

Open Caisson
Jules Triger (1846)
CAISSONS: Very large footings which are sunk into position by excavation through or beneath the caisson structure. Used for hundreds of years.

**Notable Examples:**
- Firth of Forth Bridge (Scotland)
- Brooklyn Bridge (1870’s)
- Eads Bridge (1870’s)
Motivated by large building construction in cities such as Chicago, Detroit, Cleveland and London with a subsurface consisting of thick layers of clay overlying a glacial till or bedrock.

- Late 1800, hand dug “Chicago” and “Gow” caissons were excavated to a hardpan layer to act like a deep footing. Sections of permanent liners were placed to retain the soil. Usually very conservative design of about 380kPa (4tsf).
HISTORY: CAISSONS (ROGERS, 2006)

Chicago Method

Gow Method
1908 – Early power driven auger, 0.3m diameter to a depth of 6 to 12m.

1920 – Horse driven rotary machines in Texas (swelling conditions).

1931 – Hough Williams of Dallas built small machines for shallow hole excavation followed by truck mounted machines.

1932 – A.H. Beck Company (Texas) begins constructing drilled shafts.
DRILLED SHAFTS: HISTORY

• 1937 - McKinney Drilling founded in Texas.

• Before WW II – development of large scale, mobile, auger-type, earth-drilling equipment allowing for a more economical and faster construction of drilled shafts.

• Late 1940’s and 1950’s – techniques for larger underreams, cutting in rock, casing and drilled mud (a process established by the oil industry).
1960’s to Today - The development of theories for design and analytical techniques lagged behind the developments in the construction methods. The marked differences between driven piles and drilled shafts as well as the importance of quality control and inspection were realized.
MICROPILES: HISTORY

- Early 1950’s in Italy – Conceived to underpin historic structures and monuments damaged in WW II.
- 1952 - Palo Radice (Root Pile) patented by Fondedile (Dr. Fernando Lizzi).

Figure 1-2. Classical Arrangement of Root Piles for Underpinning. (FHWA SA-97-070)
MICROPILES: HISTORY

- 1970 – Fondedile Corp. established in US.
- 1980 to 90 – Decline and Closure of Fondedile in US.
- Early 1980’s - Big “Push” by East Coast Contractors.

Figure 1-2. Classical Arrangement of Root Piles for Underpinning. (FHWA SA-97-070)
MICROPILES: HISTORY

• 1989 – Loma Prieta & Start of Micropile Seismic Retrofits on West Coast.


MICROPILES: HISTORY

- 1997 – International Workshop on Micropiles (IWM) Founded
- 2002 – ADSC develops FHWA/NHI Course
- 2005 – International Society of Micropiles (ISM) Founded

From FHWA SA-97-020, Bruce (2008), and Bennett (2010)
Deep Foundation Design Process

1. Establish Global Project Performance Requirements
2. Define Project Geotechnical Site Conditions
3. Determine Preliminary Substructure Loads and Load Combinations at Foundation Level
4. Develop and Execute Subsurface Exploration and Laboratory Testing Program for Feasible Foundation Systems
5. Evaluate Information and Determine Foundation Systems for Further Evaluation
6. Select Candidate Driven Pile Foundations Types and Sections for Further Evaluation
7. Evaluate Other Deep Foundation Systems
8. Select Static Analysis Method and Calculate Ultimate Axial Capacity vs Depth
9. Identify Most Economical Candidate Pile Types from Pile of Ultimate Capacity vs Depth and Cost per MPH (ton) vs Depth
10. Driveability of Candidate Pile Types to Penetration Depth(s) and Ultimate Capacity Sufficient?
11. Select 1 to 2 Candidate Pile Types, Ultimate Capacities and Pile Penetration Depths for Trial Pile Group Boring
12. Evaluate Group Axial, Lateral, and Rotational Capacities, Settlement, and Performance of Trial Pile Group Configurations
13. Size and Estimate Cost of Pile Cap for Trial Groups
14. Summarize Total Cost of Candidate Pile Types, Group Configurations and Pile Caps
15. Select and Optimize Final Pile Type, Ultimate Capacity, Group Configuration, and Construction Control Method
16. Does Optimized Design Meet Performance, Constructability and Drivability Requirements?
17. Prepare Plan and Specifications Including Field Capacity Determination Procedure
18. Contractor Selected
19. Perform Wave Equation Analysis of Contractor’s Equipment Submission, Accept or Reject
20. Set Preliminary Driving Criteria
21. Drive Test Piles and Evaluate Capacity
22. Adjust Driving Criteria or Design
23. Construction Control, Drive Production Piles, Resolve Any Pile Installation Problems

Figure 2.1. FHWA NHI-05-042 Design and Construction of Driven Pile Foundations - Volume I.
14.528 DRILLED DEEP FOUNDATIONS
Definitions, Classifications, General Principles

DEEP FOUNDATION DESIGN PROCESS

Field Exploration & Testing

Geomaterial Strength & Deformation Parameters

Laboratory Testing

Static Analysis of Deep Foundation

Deformation and Settlement

Bearing Capacity Vertical and Lateral Resistance Single/Group

Dynamic Analysis of Driven Piles

Deep Foundation Type/Construction Method

Design
- Geometry
- Configuration
- Installation Criteria

Superstructure Loading Evaluation

Superstructure Loading Requirement

Testing
- material
- performance
- driving
- integrity

Design Verification/Modification
- dynamic testing
- static testing

QC Monitoring

Construction

Completed Substructure

Figure 3. NCHRP Report 507 (Paikowsky et al., 2004).
DEEP FOUNDATION DESIGN

AXIAL CAPACITY

\[ Q_{\text{total}} = \sum Q_{\text{skin}} + Q_{\text{tip}} \]

Where:

- \( Q_{\text{total}} \) = Ultimate Pile Capacity
- \( Q_{\text{skin}} \) = Skin Friction (i.e. Side) Capacity
- \( Q_{\text{tip}} \) = Tip (i.e. Toe) Capacity
**Deep Foundation Design**

**Axial Capacity**

\[ Q_{\text{skin}} = f_s A_{\text{skin}} \]

Where:
- \( f_s \) = Unit Skin Friction
- \( A_{\text{skin}} \) = Pile Skin Area

\[ Q_{\text{toe}} = q_p A_{\text{toe}} \]

Where:
- \( q_p \) = Unit End Bearing
- \( A_{\text{toe}} \) = Pile Toe (i.e. Tip) Area
DEEP FOUNDATIONS: EFFECTS OF PILE INSTALLATION