14.528 Drilled Deep Foundations
Spring 2014

Lecture 1 – Introduction to Deep Foundations

Class Notes

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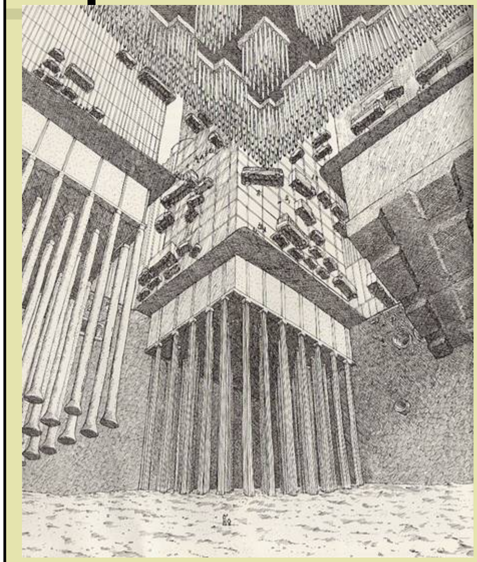
OVERVIEW

- Introduction
- Usage
- Historical Perspective
- Classification
- Design Process
- Economics

INTRODUCTION – Definition

- **PILE**
  - (1) A structural member that is used to transmit surface loads to lower elevations in the soil.
  - (2) Piles are common foundation tools for transferring superstructure through water and/or soft soil deposits. The loads may be distributed through the soils (friction piles) or transferred to firm, underlying soil or rock strata (end bearing piles). Most piles function as a combination of the two.

INTRODUCTION – Definition



- 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

INTRODUCTION

- **Main Problem**
  Limited ability to accurately assess the capacity and integrity state of a pile in the ground. Required to allow safe and optimal design and construction
- **History**
  General
  Man's oldest method of overcoming the difficulties of founding above water and/or on soft soils. The Neolithic inhabitants of Switzerland supported their homes 12,000 years ago on driven wooden poles in shallow lakes. The ancient Egyptians depicted manpower pile driving operations and failures. The Romans supported many of their bridges over the Rhine river with driven timber piles.
  Modern analysis and literature began at the end of the 19th century.
  Diesel hammers were used after the second World War.

Performance

Some work better than others.

Performance

Transcona Grain Elevator
Winnipeg, Manitoba
October 18, 1913
Tilt: 27°
Photograph and Figure from Baracos (1957).

Bridge Abutment on Piles - 30 inches of Settlement over 10 years
Photograph courtesy of FHWA-NHI-132012 Soils and Foundations Workshop Participants Workbook

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Performance

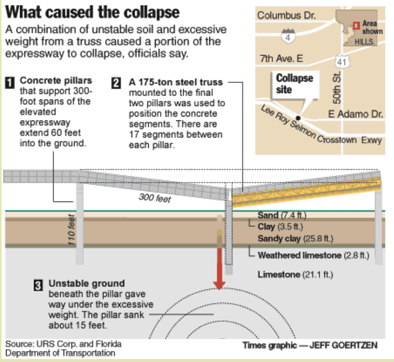
Lee Roy Selmon Expressway, Tampa, FL

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

Source: Tampa Bay Times

Photograph: St. Petersburg Times

Photograph: St. Petersburg 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 60 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.

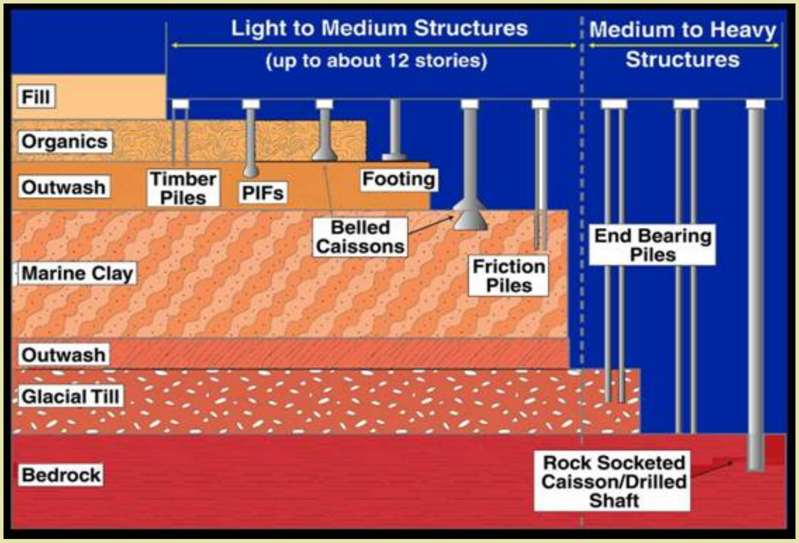
3 **Unstable ground** beneath the pillar gave way under the excessive weight. The pillar sank about 15 feet.

Source: URS Corp. and Florida Department of Transportation

Times graphic — JEFF GOERTZEN

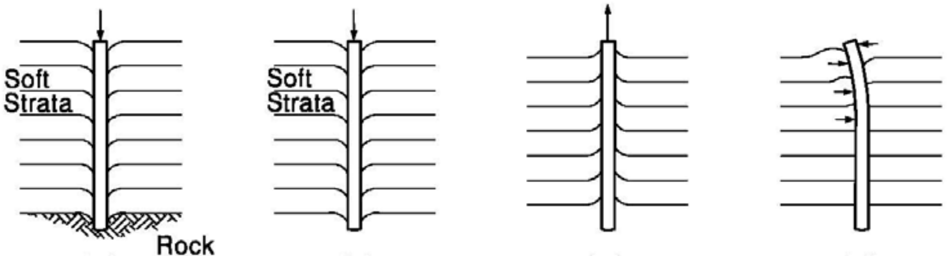
Infographic: St. Petersburg Times

Boston Area Foundation Concepts



Use of Deep Foundations

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



End Bearing Friction

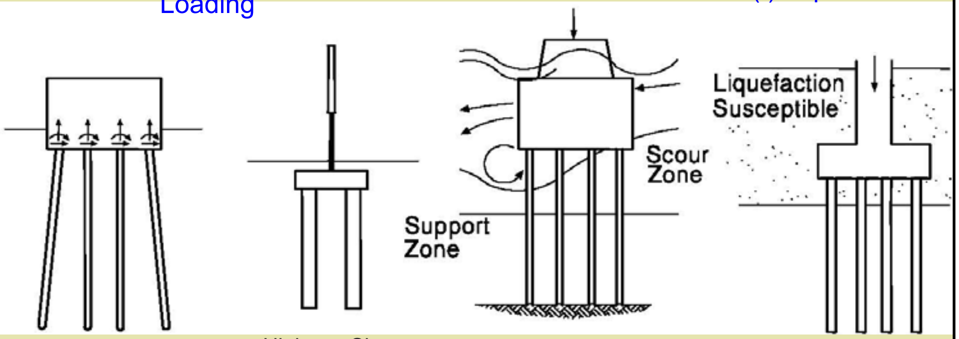
Vesić (1977)

Use of Deep Foundations

(d) Combined Uplift and Lateral Loading

(e) Scour

(f) Liquefaction



Bridge Bent

Highway Signs
Or Noise Barriers

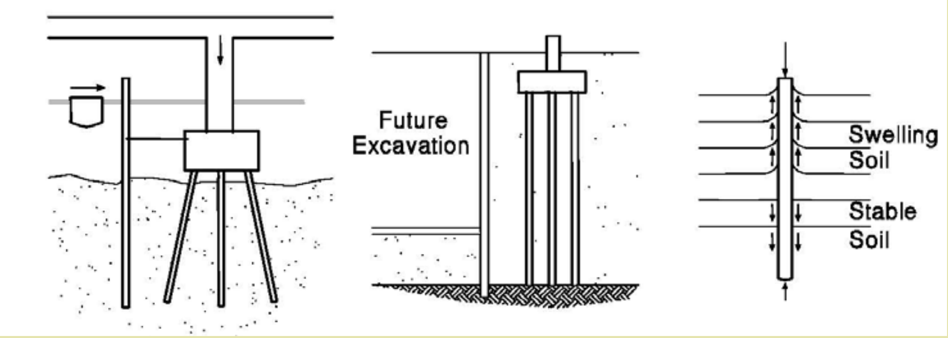
Vesić (1977)

Use of Deep Foundations

(g) Fender Systems

(h) Underpinning

(i) Swelling Soils



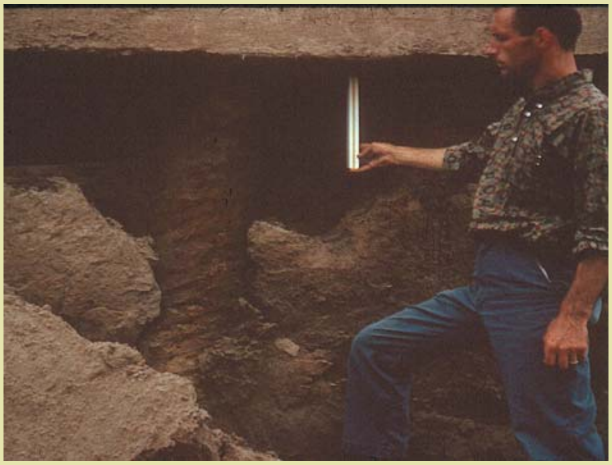
Vesić (1977)

Example – Scour

Bridge Abutment Scour

Photograph courtesy of FHWA-NHI-132012 Soils and Foundations Workshop Participants Workbook

Example – Scour



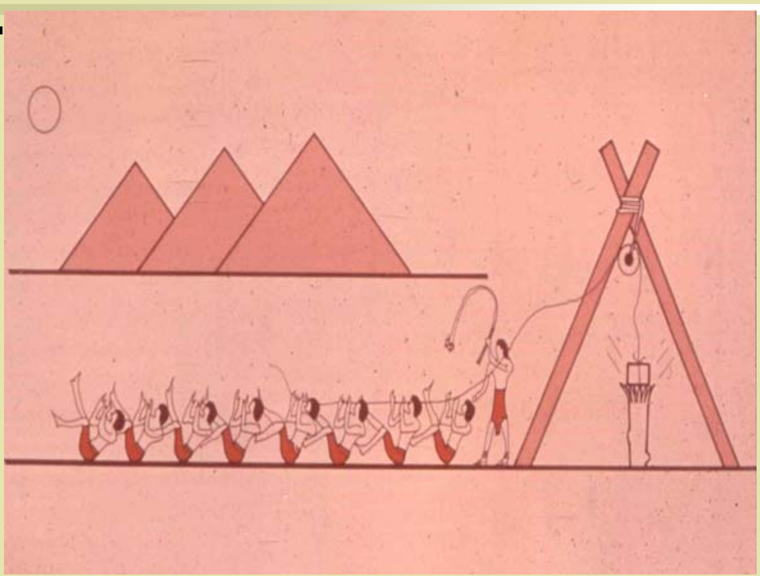
Scour at Bridge Abutment

Photograph courtesy of FHWA-NHI-132012 Soils and Foundations Workshop Participants Workbook

HISTORICAL PERSPECTIVE OF PILE DRIVING

Drilled foundations are a relatively new technique. Pile driving, however, dates back many centuries. Herodotus, the fourth century BC Greek writer ("the father of history"), provides historical documented references to piles. Ancient Egyptians depicted hieroglyphics of pile driving. Romans, Chinese, Mesopotamians and others used driven piles.

Egyptian Hieroglyphs of Pile Driving



HISTORICAL PERSPECTIVE OF PILE DRIVING

Hammer aka Pile Driver – a mechanical device used to drive piles into soil

Historical pile hammers includes a heavy weight placed between guides so that it is able to freely slide up and down vertically or inclined. The hammer is placed upon a pile and the weight is raised -- an operation which may involve the use of manual labor, steam, air, diesel, or hydraulic power. The weight is then released and impacts the pile in order to drive it into the ground.

HISTORICAL PERSPECTIVE OF PILE DRIVING

Reconstructed Crannóg on Loch Tay

There is evidence that a pile driving device was used in the construction of Crannogs (artificial islands) at Oakbank and Loch Tay in Scotland as early as 5000 years ago. (Ref - History Trails: Ancient Crannogs from BBC's Mysterious Ancestors series)

HISTORICAL PERSPECTIVE OF PILE DRIVING

Vitruvius was an architect and engineer under Julius Caesar in the first century B.C. and retired when Augustus died. Under Octavian’s patronage, he wrote a ten-volume account of known technology by the name of *De Re Architectura* (On Architecutre).

HISTORICAL PERSPECTIVE OF PILE DRIVING

“But if a solid foundation is not found, and the site is loose earth right down, or marshy, then it is to be excavated and cleared and remade with piles of alder or of olive or charred oak, and the piles are to be driven close together by machinery, and the intervals between are to be filled with charcoal. Then the foundations are to be filled with very solid structures.”

Ivo Herle, Institute of Geotechnical Engineering, TU Dresden, Germany, 2004

HISTORICAL PERSPECTIVE OF PILE DRIVING

Double timber pilings were rammed into the bottom of the river by winching up a large stone and releasing it, thereby driving the piles into the riverbed. The most upstream and downstream pilings were inclined and secured by a beam, and multiple segments of these then linked up to form the basis of the bridge

Roman Hammer (replica) used at the construction of Caesar's Rhine bridges during the Gallic War (1st bridge 55 BC and 2nd bridge 53 BC)

Roman Bridge on the Mosel- Currently in use in Trier Germany

Porta Nigra Trier Germany

Manual Timber Pile Driving - Holland

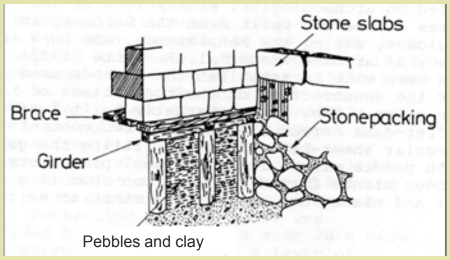
Movie Clip: Manual Timber Pile Driving - Holland

Timber-a & Timber-b

HISTORICAL PERSPECTIVE OF PILE DRIVING

Pile Foundations of Bridges

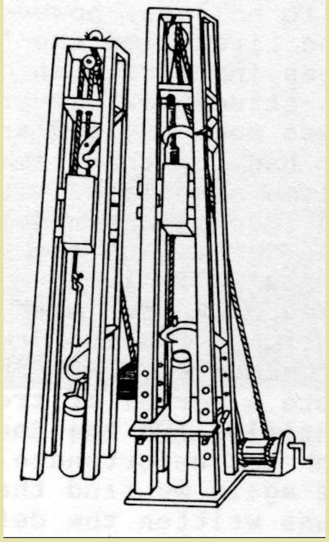
Bridge of Beaugency (central France)
(earlier than 14th century)
– foundations of a pier on sand
– masonry on short wooden piles



(Herle, 2004)

HISTORICAL PERSPECTIVE OF PILE DRIVING

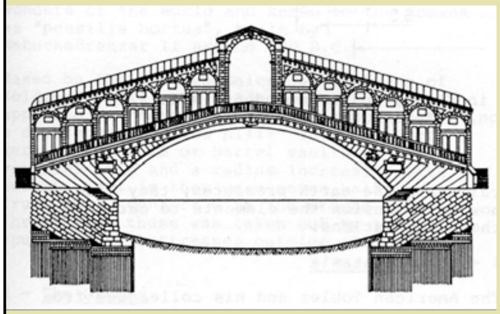
Drop-Hammer Piling Rig, hand operated, designed by Francesco Di Giorgio (around 1450, credited as the first hammer design drawings)



(Herle, 2004)

HISTORICAL PERSPECTIVE OF PILE DRIVING

Rialto Bridge, Venice (1588-92)



- Single span of 26.4m (119.4ft) (designed by Antonio da Ponte)
- Alluvium subsoil
- Beneath each abutment 600 piles – 15 cm diameter, 3.3 m length (3 groups)

(Herle, 2004)

HISTORICAL PERSPECTIVE OF PILE DRIVING

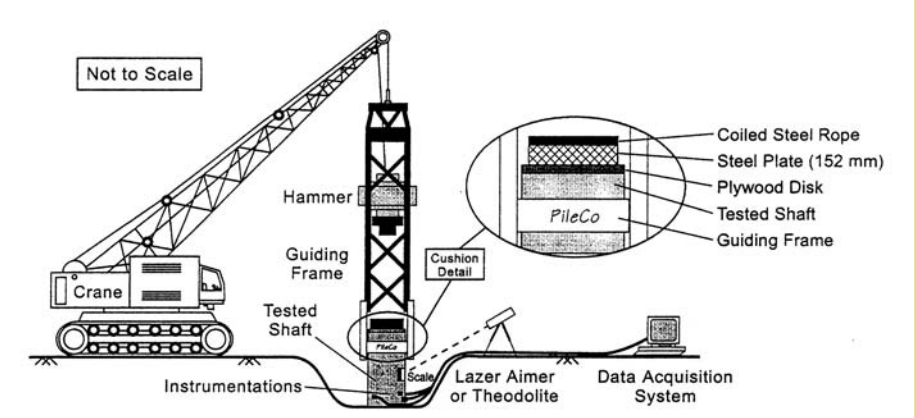
Steam Hammers

- Advanced design of steam engines had become a major source of mechanical power in the 18th century enabling the industrial revolution.
- **Otis Tufts** (1804 - 1869) Massachusetts USA - built the first steam-operated printing press (1837) and invented the steam pile hammer.
- For the first time pile driving was performed utilizing mechanical power produced by a machine.

THE PRINCIPLE OF MODERN PILE HAMMERS

THE PRINCIPLE OF MODERN PILE HAMMERS

Basic System – The Drop Weight Hammer



THE PRINCIPLE OF MODERN PILE HAMMERS
Basic System – The Drop Weight Hammer

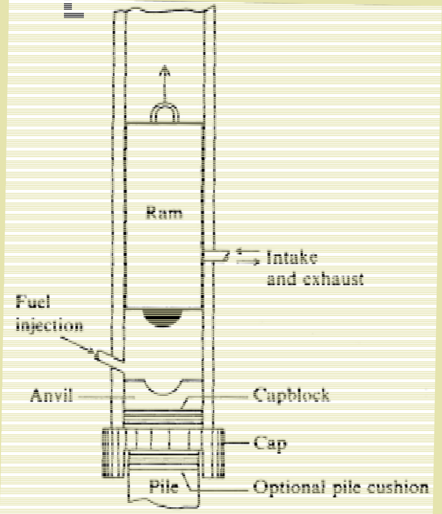
Pileco of Houston. The system having swinging leads operated with a small crane.

THE PRINCIPLE OF MODERN PILE HAMMERS
Modified Drop Weight Hammer - Operation

Drop

Updated Israeli Drop Weight System (2009)

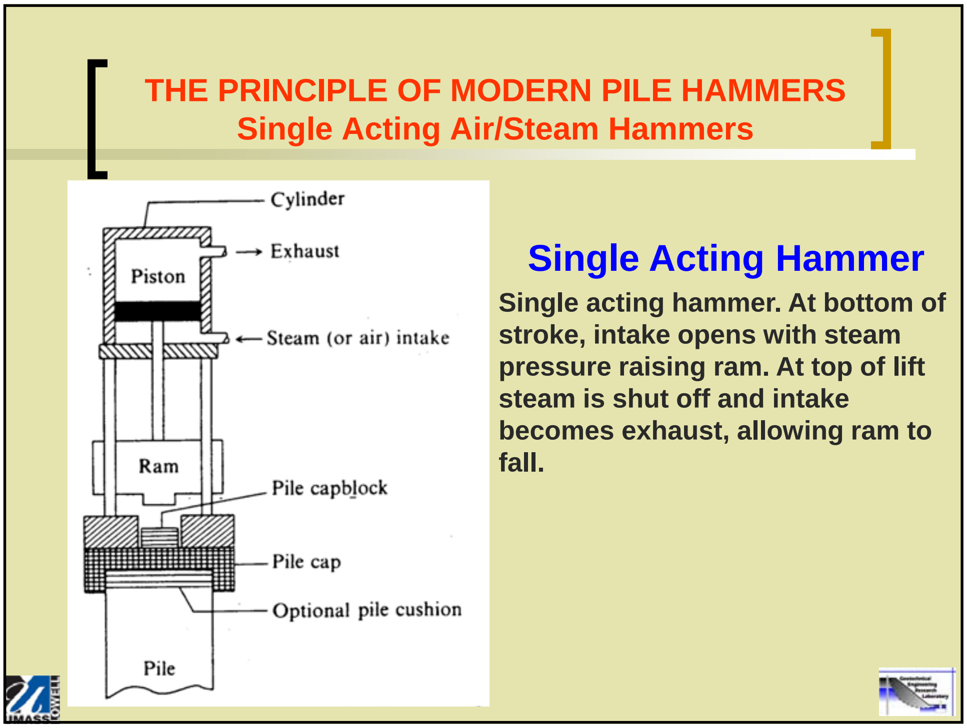
THE PRINCIPLE OF MODERN PILE HAMMERS
Diesel Hammer - Schematics



Diesel hammer – Crane initially lifts ram. Ram is released and falls; at select point fuel is injected. Ram compresses the fuel and ignites it. Resulting explosion drives pile and lifts ram for next cycle.

THE PRINCIPLE OF MODERN PILE HAMMERS
Modern Hammer – Operation Diesel

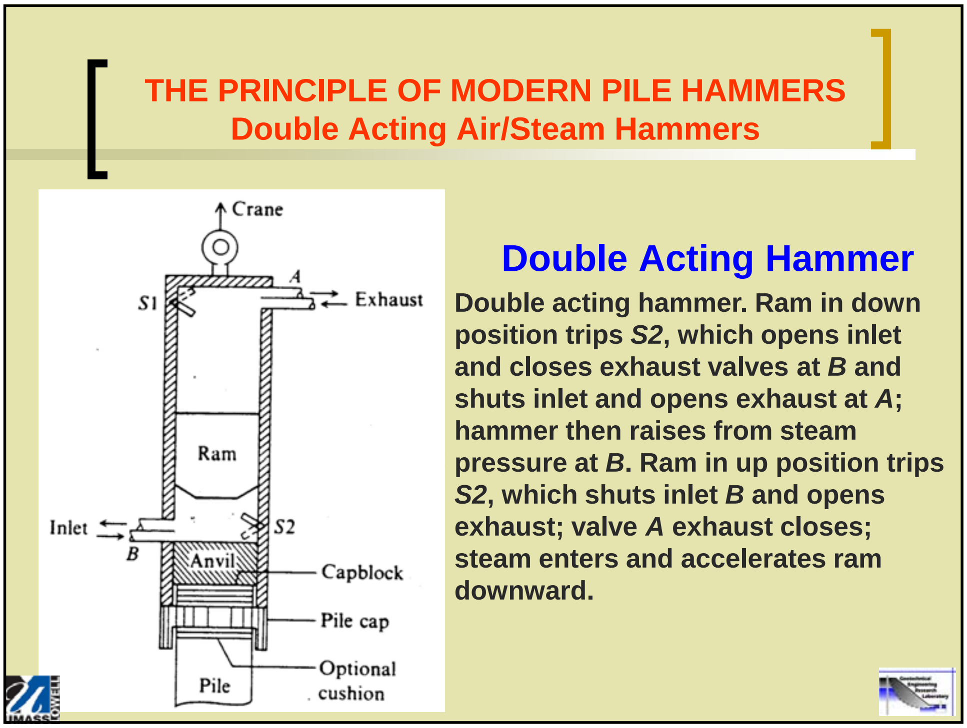
Movie clip:
Diesel and Dynamic Measurements



THE PRINCIPLE OF MODERN PILE HAMMERS
Single Acting Air/Steam Hammers

Single Acting Hammer

Single acting hammer. At bottom of stroke, intake opens with steam pressure raising ram. At top of lift steam is shut off and intake becomes exhaust, allowing ram to fall.

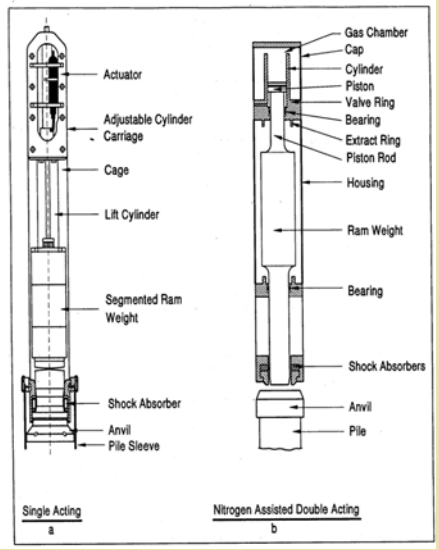


THE PRINCIPLE OF MODERN PILE HAMMERS
Double Acting Air/Steam Hammers

Double Acting Hammer

Double acting hammer. Ram in down position trips *S2*, which opens inlet and closes exhaust valves at *B* and shuts inlet and opens exhaust at *A*; hammer then raises from steam pressure at *B*. Ram in up position trips *S2*, which shuts inlet *B* and opens exhaust; valve *A* exhaust closes; steam enters and accelerates ram downward.

THE PRINCIPLE OF MODERN PILE HAMMERS
Single and Double Acting Hydraulic Hammers



Schematics of Single and Double Acting Hydraulic Hammers (FHWA)

THE PRINCIPLE OF MODERN PILE HAMMERS
Single and Double Acting Hydraulic Hammers

IHC S-600 Hydraulic Hammer: Rated Energy ~440kip-ft (600kN-m)

Different Deep Foundations Classifications

(1) Methods of construction: driven piles
cast in place piles
vibrated piles
jacked piles

DP IPCDF

Broadly categorized as Driven Piles and Drilled Foundations or In-Place Constructed Deep Foundations (IPCDF)

(2) Pile type by material: timber
steel
concrete

(3) By their influence zone: small displacement vs.
large displacement piles

-- Table 16.1 Bowles both classification by pile type & method of construction
-- see handout tables

Deep Foundation Classifications

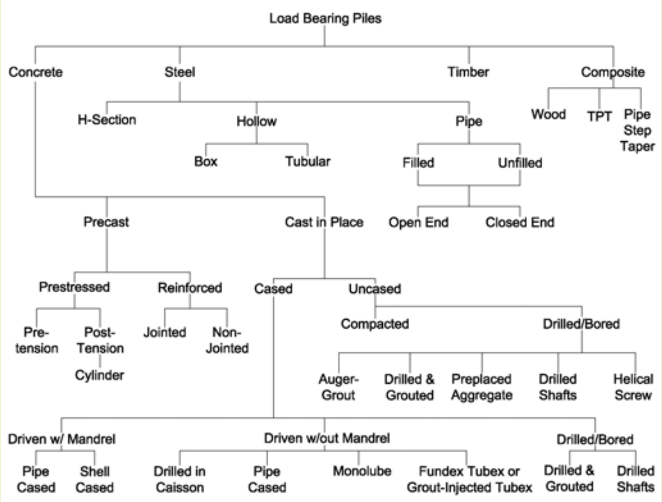


Figure 8.1. FHWA HI-97-013 Driven Pile Design and Construction Volume I.

Deep Foundation Classifications

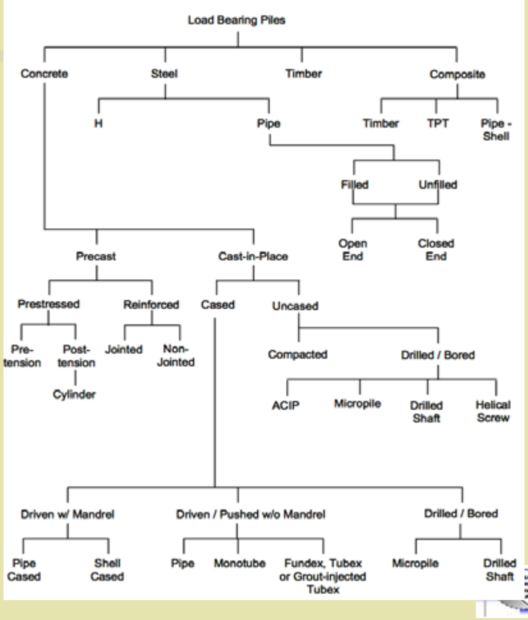


Figure 8.1. FHWA NHI-05-042 Design and Construction of Driven Pile Foundations Volume I.

Use of Foundations in Bridge Construction

(1) **NCHRP 507 Report**:

- Survey in 2000 as part of NCHRP research
  75% Driven Piles 14% Shallow Fnds. **11% DS**

(2) **NCHRP 12-66**:

- Summer 2004 Survey
  62% Driven Piles 17% Shallow Fnds. **21% DS**

Conclusions:

- Reduced use of DP
- Yet 3 times the use of IPCDF

(3) **2000 Study**:

DP → 21% PPC
DP → 52% H
DP → 2% OEP
DP → 25% CEP

IPCDF ⇒ DS no use of CFA (?)

DRILLED DEEP FOUNDATIONS
DRILLED SHAFTS – HISTORY

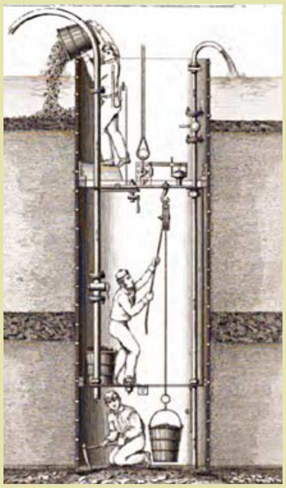
Drilled Shafts: History

- 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.

Drilled Shafts: History

vocabulary:

- **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**



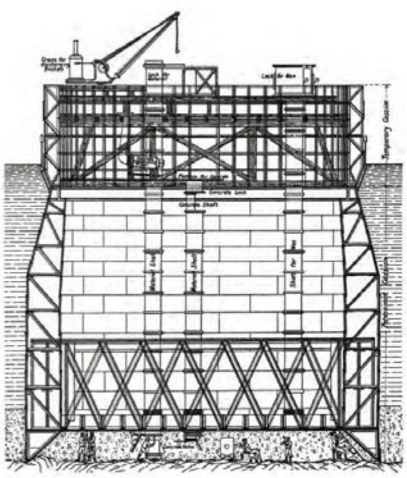
Open Caisson
Jules Triger (1846)

Drilled Shafts: History

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)



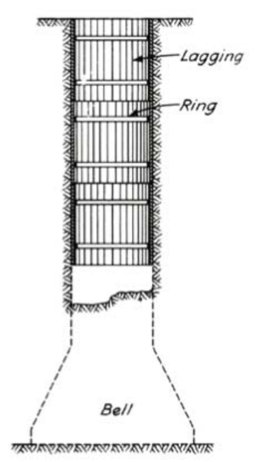
Pneumatic Caisson, Firth of Forth Bridge
(Mackay, 1990)

Drilled Shafts: History

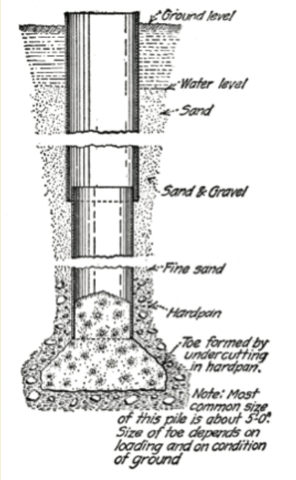
Motivated by large building construction in cities such as Chicago, Detroit, Cleveland and London with a subsurface consisting of thick layers of clay overlying a glacial till or bedrock.

- **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

Drilled Shafts: History

- **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).**

Drilled Shafts: History

- **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.**

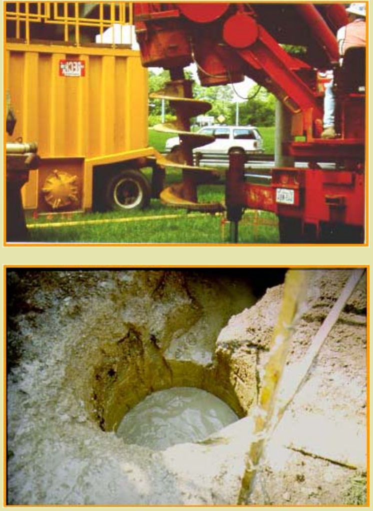
Drilled Shafts

Terminology

- Barrette Foundations
- Different shaped cast in place elements (e.g., rectangle, round, H, etc.) usually associated with slurry wall construction.
- Other types of constructed in place deep foundations. Geojet, soil-cement mix, mini or micro-piles, pin-piles and more are available but are not drilled shafts.
- PIF (Pressure Injected Footings) are also concrete constructed in place deep foundations but due to the construction method, they also are not considered drilled shafts.

DRILLED DEEP FOUNDATIONS

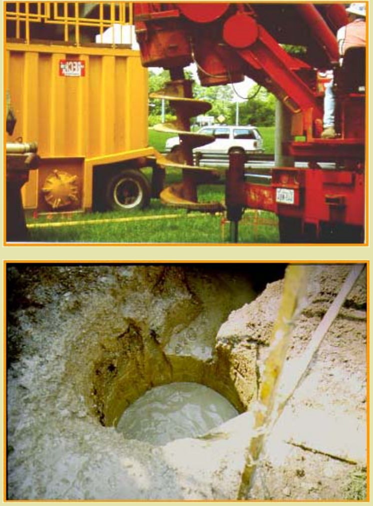
Dry and Slurry Methods of Construction

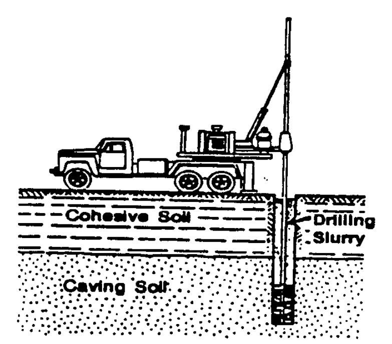


LADOTD Drilled Shaft Inspection Manual, January 2002

DRILLED DEEP FOUNDATIONS

Slurry Method of Construction

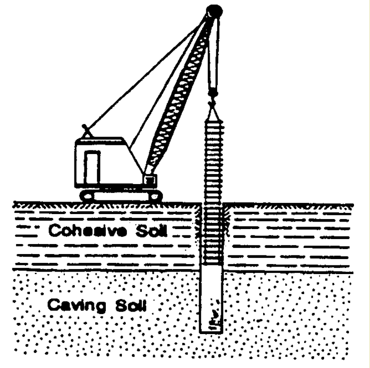




Drilling to full depth (bucket or flight auger) with Slurry

DRILLED DEEP FOUNDATIONS

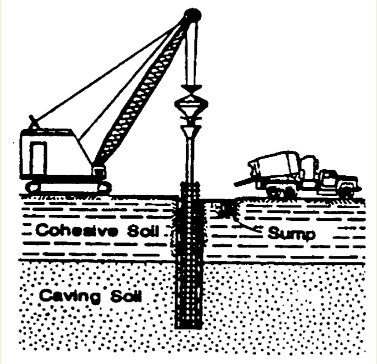
Slurry Method of Construction



Placing the Rebar Cage

DRILLED DEEP FOUNDATIONS

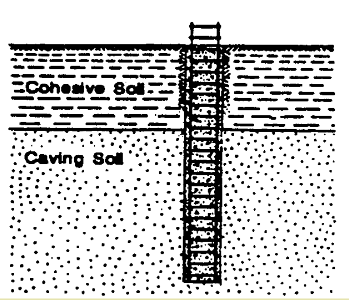
Slurry Method of Construction



Placing Concrete using Tremy

DRILLED DEEP FOUNDATIONS

Slurry Method of Construction



Completed Shaft

Deep Foundation Examples: Drilled Shafts

Town Creek

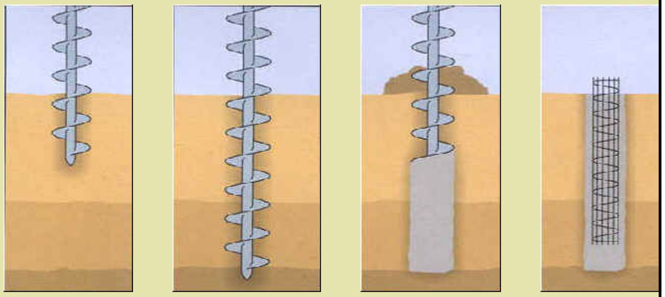
West Tower

Arthur Ravenel Jr. Bridge

Photograph courtesy of WPC Inc. and Marvin Tallent, Palmetto Bridge Constructors

DRILLED DEEP FOUNDATIONS

Continuous Flight Auger (CFA) Construction



pilingequipment.com

Cast in Place Concrete Piles

(Mandrel Driven)

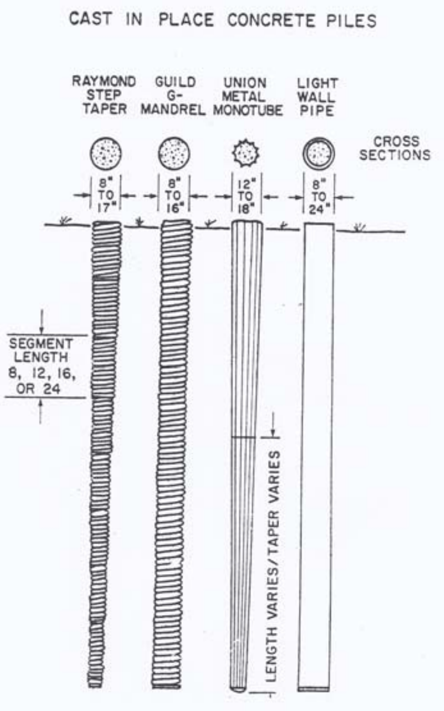
Design Capacity Range	**50 to 120 tons**
Length Range	Up to 100 ft (check manufacturer)
Application	Friction or Bearing
Typical Building Code Allowable Stresses	$f_c \le 33\% f'_c$ ($f_c \le 1600$ psi)
Pile Deterioration	High sulfate soils or groundwater, exposure to freeze/thaw may require special concrete mix.
Applicable Material Specifications	ACI-318-2011 "Building Code Requirement for Structural Concrete and Commentary ACI 543R-00

Design Considerations:

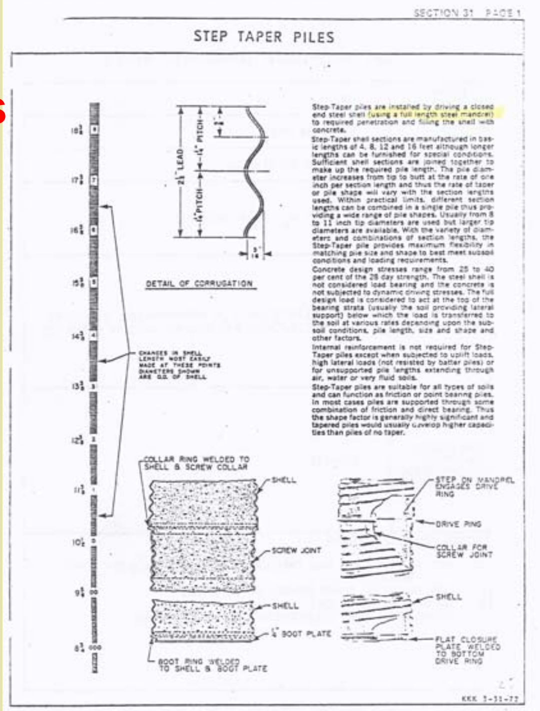
1. **Corrugated metal shell piles (Raymond, Guild, etc.) may be used as friction or bearing piles. Smooth steel piles (pipe, monotube, etc.) usually not as efficient as friction piles.**
2. **Must be able to predict maximum length for mandrel driven piles since splicing is not possible.**
3. **Shells susceptible to collapse after driving and prior to concreting.**
4. **Piles can be inspected internally after driving.**
5. **Mandrel increases driveability considerably.**
6. **Reinforcement must be added for lateral and uplift loads.**

See NHI publication Table 8-1, p.8-7

Cast in Place Concrete Piles



Cast in Place Concrete Piles



STEP TAPER PILES

Step-Taper piles are installed by driving a closed end steel shell (using a full length steel mandrel) to required penetration and filling the shell with concrete.

Step-Taper shell sections are manufactured in basic lengths of 4, 8, 12 and 16 feet although longer lengths can be furnished for special conditions. Sufficient shell sections are joined together to make up the required pile length. The pile diameter increases from tip to butt at the rate of one inch per section length and thus the rate of taper or pile shape will vary with the section lengths used. Within practical limits, different section lengths can be combined in a single pile thus providing a wide range of pile shapes. Usually from 8 to 11 inch tip diameters are used but larger tip diameters are available. With the variety of diameters and combinations of section lengths, the Step-Taper pile provides maximum flexibility in matching pile size and shape to best meet subsoil conditions and loading requirements.

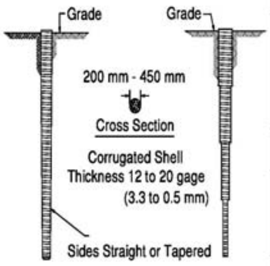
Concrete design stresses range from 25 to 40 per cent of the 28 day strength. The steel shell is not considered load bearing and the concrete is not subjected to dynamic driving stresses. The full design load is considered to act at the top of the bearing strata (usually the soil providing lateral support) below which the load is transferred to the soil at various rates depending upon the subsoil conditions, pile length, size and shape and other factors.

Internal reinforcement is not required for Step-Taper piles except when subjected to uplift loads, high lateral loads (not resisted by batter piles) or for unsupported pile lengths extending through air, water or very fluid soils.

Step-Taper piles are suitable for all types of soils and can function as friction or point bearing piles. In most cases piles are supported through some combination of friction and direct bearing. Thus the shape factor is generally highly significant and tapered piles would usually develop higher capacities than piles of no taper.

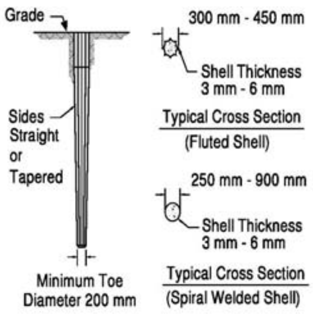
Deep Foundations: Cast-In-Place (CIP) Piles

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

PILE TYPE	CAST-IN-PLACE CONCRETE (MANDREL DRIVEN SHELL)	TYPICAL ILLUSTRATION
TYPICAL LENGTHS	3 m - 40 m (10 – 130 ft), but typically in the 15 m - 25 m (50 – 80 ft) range.	
MATERIAL SPECIFICATIONS	ACI 318 - for concrete.	
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.	

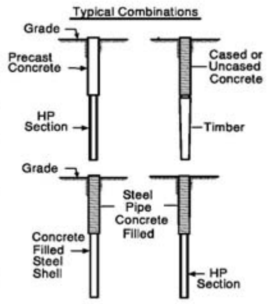
Deep Foundations: Cast-In-Place (CIP) Piles

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

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

Deep Foundations: Composite Piles

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

PILE TYPE	COMPOSITE PILES	TYPICAL ILLUSTRATION
TYPICAL LENGTHS	15 m - 65 m (50 – 210 ft)	
MATERIAL SPECIFICATIONS	ASTM A572 - for HP section. ASTM A252 - for steel pipe. ASTM D25 - for timber. ACI 318 - for concrete.	
MAXIMUM STRESSES	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).	
TYPICAL AXIAL DESIGN LOADS	300 kN - 1,800 kN (70 – 400 kips)	
DISADVANTAGES	• Difficult to attain good joints between two materials except for concrete H or pipe composite piles.	
ADVANTAGES	• 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.	
REMARKS	• The weakest of any material used shall govern allowable stresses and capacity.	

Cast in Place (Uncased) Piles

(Drilled Shafts Caissons)

Design Capacity Range	Up to 1000's tons
Length Range	Up to 100's ft
Application	Friction or Bearing
Typical Building Code Allowable Stresses	$f_c \leq 33\% f'_c$ $f_c \leq 1600$ PSI
Pile Deterioration	High sulfate soils or groundwater, exposure to freeze/thaw may require special concrete mix.
Applicable Material Specifications	ACI-318-2011 "Building Code Requirement for Structural Concrete and Commentary

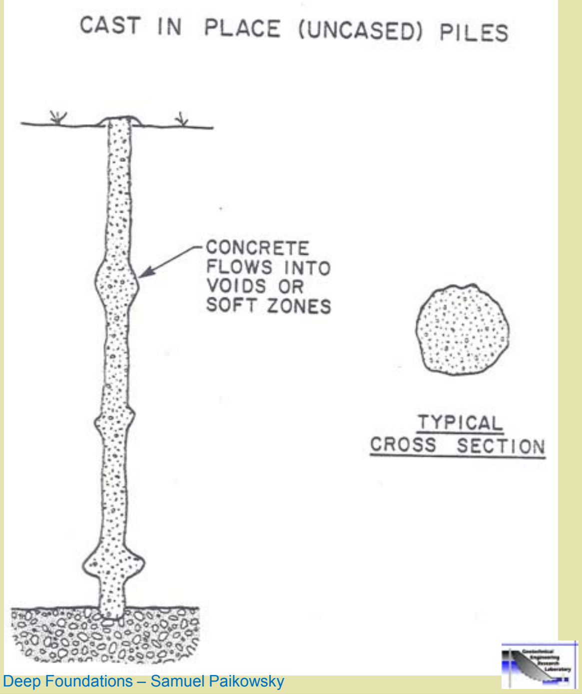
Design Considerations:

1. Not suitable for use through peat or similar very soft soils.
2. Continuity of shaft cannot be verified.
3. No driving vibrations.
4. Completely nondisplacement (except interpile).

See NHI publication Table 8-1, p.8-11

Cast in Place (Uncased) Piles

(caissons)

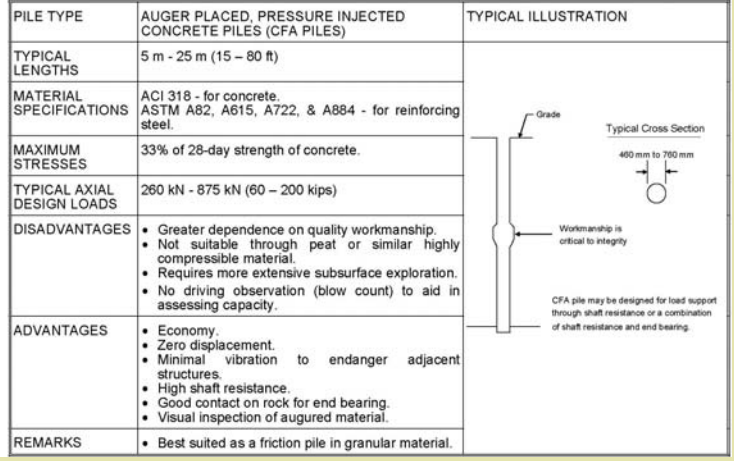


Cast in Place (Uncased) Piles

Cambridge Water Treatment Facilities

Deep Foundations: Cast-In-Place (CIP) Piles

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



PILE TYPE	AUGER PLACED, PRESSURE INJECTED CONCRETE PILES (CFA PILES)	TYPICAL ILLUSTRATION
TYPICAL LENGTHS	5 m - 25 m (15 – 80 ft)	Grade Typical Cross Section 460 mm to 760 mm Workmanship is critical to integrity CFA pile may be designed for load support through shaft resistance or a combination of shaft resistance and end bearing.
MATERIAL SPECIFICATIONS	ACI 318 - for concrete. ASTM A82, A615, A722, & A884 - for reinforcing steel.	
MAXIMUM STRESSES	33% of 28-day strength of concrete.	
TYPICAL AXIAL DESIGN LOADS	260 kN - 875 kN (60 – 200 kips)	
DISADVANTAGES	• Greater dependence on quality workmanship. • Not suitable through peat or similar highly compressible material. • Requires more extensive subsurface exploration. • No driving observation (blow count) to aid in assessing capacity.	
ADVANTAGES	• Economy. • Zero displacement. • Minimal vibration to endanger adjacent structures. • High shaft resistance. • Good contact on rock for end bearing. • Visual inspection of augured material.	
REMARKS	• Best suited as a friction pile in granular material.	

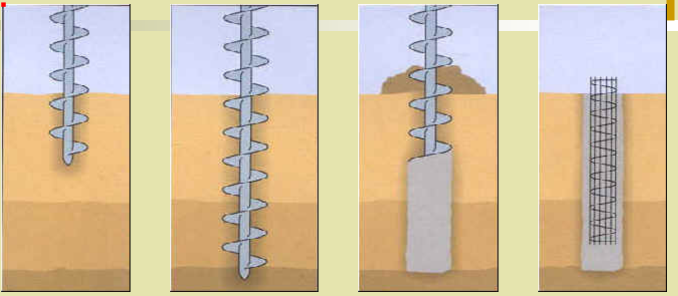
ACIP – Auger Cast In Place DD – Drilled Displacement
CFA – Continuous Flight Auger APG - Auger Pressure Grouted
APGD - Auger Pressure Grouted Displacement

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

The Continuous Flight Auger (CFA) Construction Sequence is comprised of four stages:



1. The digging head of the auger is fitted with an expendable cap.
2. The auger is screwed into the ground to the required depth.
3. Concrete is pumped through the hollow stem, blowing off the expendable cap under pressure, and
4. Maintaining positive concrete pressure the auger is withdrawn and the reinforcement is placed into the pile up to the required depth.

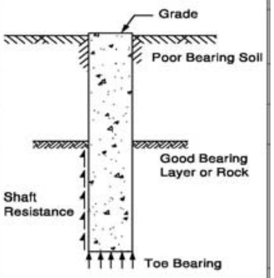
pilingequipment.com

GeoForum.com

Continuous Flight Auger Drilling Rig

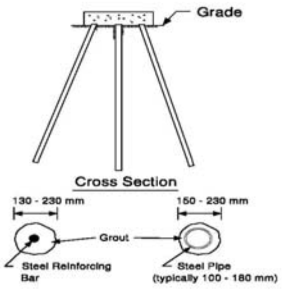
Deep Foundations: Drilled Shafts

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

PILE TYPE	DRILLED SHAFTS	TYPICAL ILLUSTRATION
TYPICAL LENGTHS	5 m to 65 m or more (15 – 200 ft)	
MATERIAL SPECIFICATIONS	ACI 318 - for concrete. ASTM A82, A615, A722, and A884 for reinforcing steel.	
MAXIMUM STRESSES	33% of 28-day strength of concrete.	
TYPICAL AXIAL DESIGN LOADS	1,500 kN - 20,000 kN (330 – 4500 kips) or more.	
DISADVANTAGES	• Requires relatively more extensive inspection. • Construction procedures are critical to quality. • Boulders can be a serious problem, especially in small diameter shafts. • Mobilization of end bearing on a long shaft can require substantial displacement of shaft head.	
ADVANTAGES	• Length variations easily accommodated. • High bearing capacity and bending resistance. • Availability of several construction methods. • Can be continued above ground as a column.	
REMARKS	• No driving observations (blow count) available to aid in assessing capacity. • Not recommended in soft clays and loose sands.	

Deep Foundations: Micropiles (a.k.a. Mini, Pin)

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

PILE TYPE	MICROPILES	TYPICAL ILLUSTRATION
TYPICAL LENGTHS	12 m - 25 m (40 – 100 ft)	
MATERIAL SPECIFICATIONS	ASTM C150 - for Portland cement. ASTM C595 - for blended hydraulic cement. ASTM A615 - for reinforcing steel.	
TYPICAL AXIAL DESIGN LOADS	300 kN - 1100 kN (70 – 250 kips)	
DISADVANTAGES	• Cost	
ADVANTAGES	• Low noise and vibrations. • Small amount of spoil. • Excellent for sites with low headroom and restricted access. • Applicability to soil containing rubble and boulders, karstic areas.	
REMARKS	• Can be used for any soil, rock or fill condition.	

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).

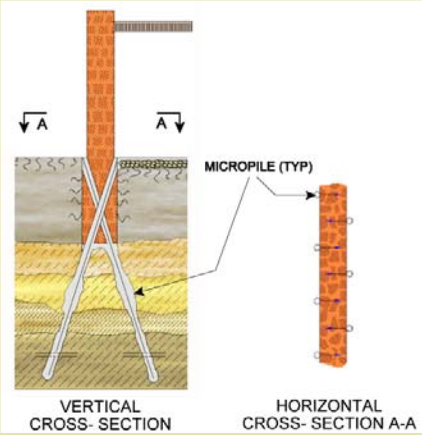


Figure 1-2. Classical Arrangement of Root Piles for Underpinning. (FHWA SA-97-070)

From FHWA SA-97-020, Bruce (2008), and Bennett (2010)

Micropiles: History

- 1970 – Fondedile Corp. established in US.
- 1972 – First use of Root Piles in US (Illinois).
- 1980 to 90 – Decline and Closure of Fondedile in US.
- Early 1980’s - Big “Push” by East Coast Contractors.

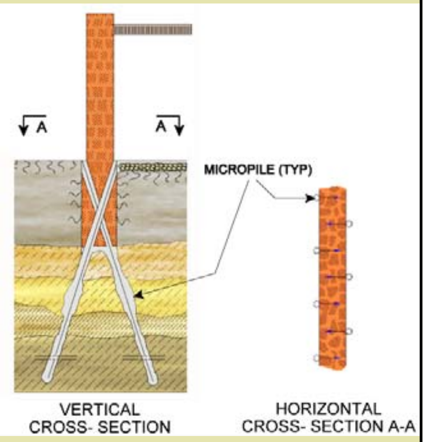


Figure 1-2. Classical Arrangement of Root Piles for Underpinning. (FHWA SA-97-070)

From FHWA SA-97-020, Bruce (2008), and Bennett (2010)

Micropiles: History

- 1989 – Loma Prieta & Start of Micropile Seismic Retrofits on West Coast.
- 1996 to 1998 – Williamsburg Bridge Retrofit (NYC).
- 1993 to 1997 – “FHWA State of the Practice” Report.

Micropile Seismic Retrofit
(Photograph courtesy of Palmetto Gunite)

From FHWA SA-97-020, Bruce (2008), and Bennett (2010)

Micropiles: History

- 1996 to 1999 – FHWA Implementation Manual
- 1997 – International Workshop on Micropiles (IWM) Founded
- 2002 – ADSC develops FHWA/NHI Course
- 2005 – International Society of Micropiles (ISM) Founded

Micropile Seismic Retrofit
(Photograph courtesy of Palmetto Gunite)

From FHWA SA-97-020, Bruce (2008), and Bennett (2010)

Deep Foundation Examples: Micropiles

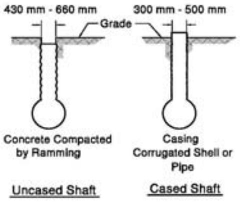
Static Load Test
50 Broad St., Charleston, SC

Dynamic Load Test
Hajduk et al. (2004)

Photographs courtesy of WPC Inc.

Deep Foundations: Pressure Injected Footing

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

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

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

Compacted Concrete Piles

(Pressure Injected Footing, PIF) (FRANKI piles)

Design Capacity Range	**50 to 150 tons**
Length Range	Up to 60 ft
Application	Bearing
Typical Building Code Allowable Stresses	$f_c \leq 0.33\, f'_c$ $f_c \leq 1600$ PSI
Pile Deterioration	High sulfate soils or groundwater, exposure to freeze/thaw may require special concrete mix.
Applicable Material Specifications	ACI-318-2011 "Building Code Requirement for Structural Concrete and Commentary

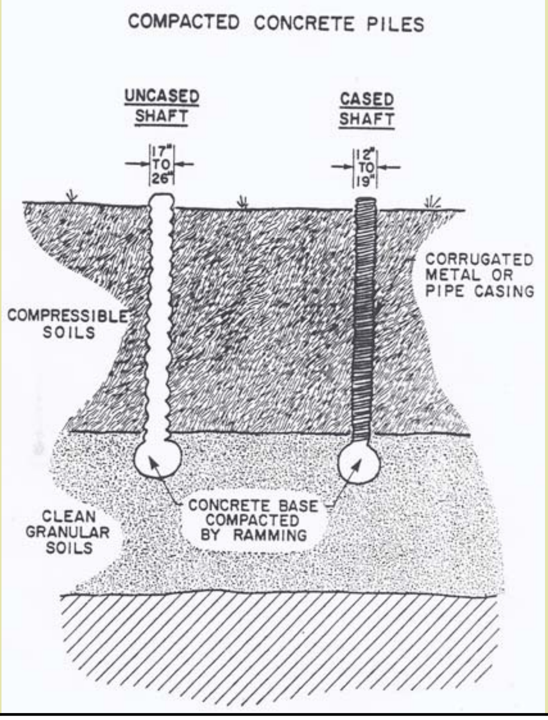
Design Considerations:

1. **Suitable only for use as bearing piles in clean granular soils.**
2. **Very economical for use in sand stratum overlying thick clay stratum.**
3. **Designer must know depth and thickness of bearing stratum.**
4. **High energy drop hammer with bottom driven tube well suited to overcoming obstructions.**
5. **Shafts should be cased in organic soils.**

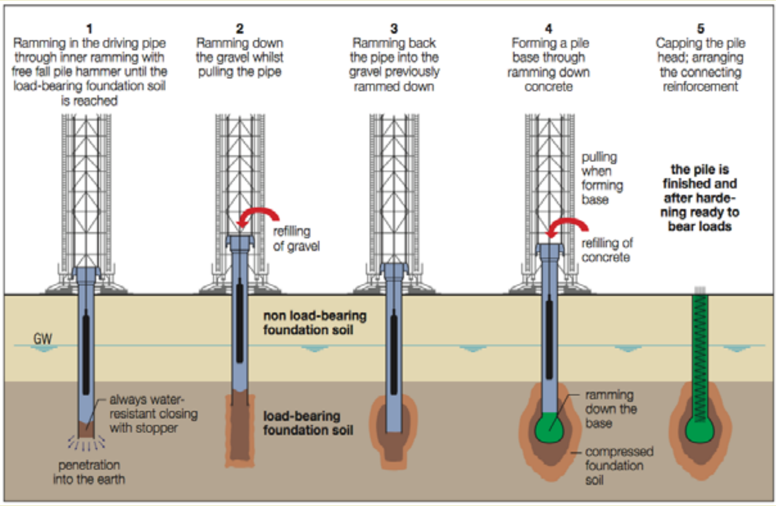
See NHI publication Table 8-1, p.8-12

Compacted Concrete Piles

(Pressure Injected Footing, PIF) (FRANKI piles)



Deep Foundations: Pressure Injected Footing

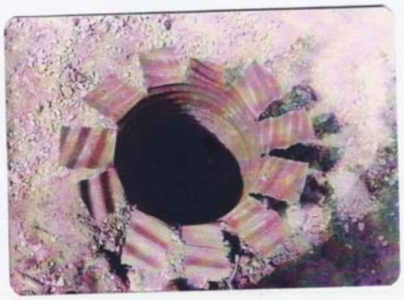


PIF – Pressure Injected Footings ; a.k.a. Franki Piles

Figure courtesy of Franki GRUNDAU.

Compacted Concrete Piles

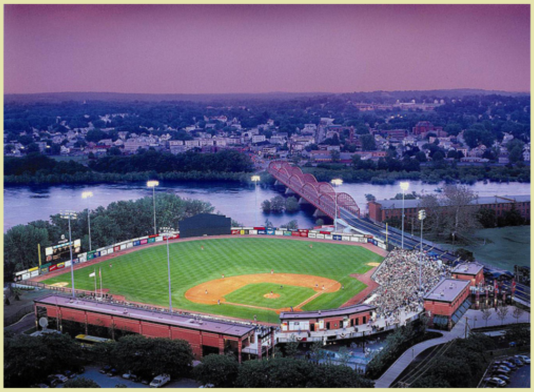
(Pressure Injected Footing, PIF) (FRANKI piles)



Deep Foundation Examples: PIF

Excavated

Photograph courtesy of www.geoforum.com



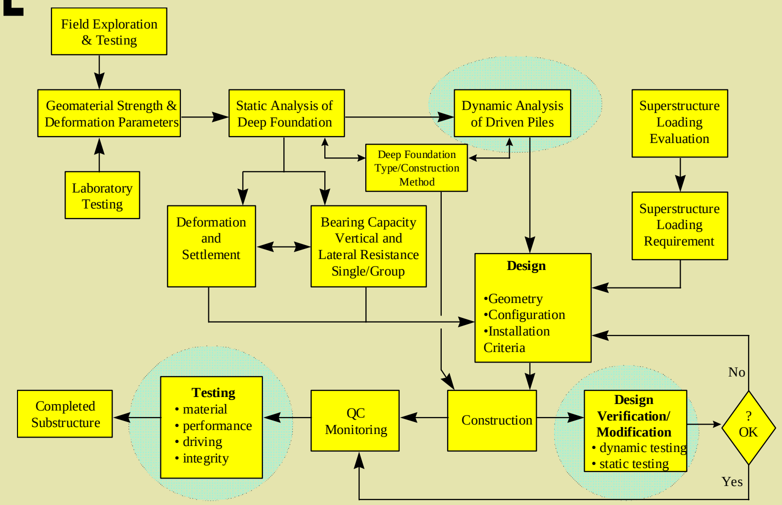
LeLachuer Park, Lowell, MA

Photograph courtesy of www.peeepl.com

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

DEEP FOUNDATION DESIGN PROCESS

DEEP FOUNDATION DESIGN PROCESS



Field Exploration & Testing

Geomaterial Strength & Deformation Parameters

Laboratory Testing

Static Analysis of Deep Foundation

Dynamic Analysis of Driven Piles

Deep Foundation Type/Construction Method

Superstructure Loading Evaluation

Superstructure Loading Requirement

Deformation and Settlement

Bearing Capacity Vertical and Lateral Resistance Single/Group

Design

- Geometry
- Configuration
- Installation Criteria

No

? OK

Yes

Completed Substructure

Testing

- material
- performance
- driving
- integrity

QC Monitoring

Construction

Design Verification/ Modification

- dynamic testing
- static testing

Figure 1 : Deep Foundation Design Process

Deep Foundation Design Axial Capacity

$$Q_{total} = \Sigma Q_{skin} + Q_{tip}$$

Where:

Q_{total} = Ultimate Pile Capacity

Q_{skin} = Skin Friction (i.e. Side) Capacity

Q_{tip} = Tip (i.e. Toe) Capacity

Deep Foundation Design
Axial Capacity

$$Q_{skin} = f_s A_{skin} \qquad Q_{toe} = q_p A_{toe}$$

Where:
f_s = Unit Skin Friction
A_{skin} = Pile Skin Area

Where:
q_p = Unit End Bearing
A_{toe} = Pile Toe (i.e. Tip) Area

Deep Foundations:
Effects of Pile Installation