Deep Foundation Selection: Drilled Shafts or Driven Piles?

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USU, Logan, Utah
PDCA Professor’s Driven Pile Institute

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Driven Piles: Foundation support typically using steel or precast concrete elements driven into soil with impact or vibratory methods.

Drilled Shafts: Elements formed by creating a drilled hole into which structural steel and concrete is cast or placed.

Choice of piles vs. shafts may be driven by a wide range of factors-relating- often indirectly- to time and money.
Deep Foundation Overview:

**Shafts**
- Concrete filled, drilled, ‘manufactured’ on-site
- Side and End bearing contributions
- General methods for friction, cohesion, rock
- Exclusion areas
- LRFD factors based on design methods, materials, loading

**Piles**
- Many Types/Materials, prefabricated
- Side and End bearing contributions
- Several design methods (similar to shafts)
- Generally LRFD factors will be based on installation
Foundation Selection Considerations

- Cost (materials/labor/inspection)/ Time
- Structural loading requirements
  - Compression, uplift, deformation, cyclic, redundancy
  - Extreme events (seismic, lateral impact, scour)
- Ease of design/construction/inspection
  - Standard practice & familiarity; codes
- Special site requirements (noise/vibration/clearance)
- Unusual or problematic geological conditions
  - Rock (near surface or sloping), karst, boulders
- Environmental factors (contaminated site?)
- Site footprint, access, congestion
- Availability of materials, equipment, skilled contractors, or local/competitive contractors
Design Methods
Comparing [Driven] Piles and Drilled Shafts

**Similarities**
- α Methods (cohesive soils)
- β Methods (frictional soils)

**Differences**
- Option for ‘belled’ shafts
- Rock Socketed Shafts
- Installation Details
  - Soil Removal/Displacement
  - Frictional/Adhesion properties
- Direct CPT Methods available in pile design software

\[ Q_T = Q_s + Q_b - W_p \]

Unit side shear distribution

\[ Q_T = \int_0^L f_z(z) \cdot p(z) \cdot dz \]

where:
- \( f_z(z) \) = unit side shear stress
- \( p(z) \) = pile perimeter at \( z \)

Axial Load
- Concrete - mix design can vary based on several factors
- Diameter can vary widely
- Depth can vary widely

Lateral Load
- Reinforcing Steel (Typically required by design)
- Bell - May be used or omitted as desired.
- Bell size varies - Not larger than 3 times the shaft diameter at base.

Base Resistance
In friction piles or shaft using predominantly side resistance (skin friction), structural loads are supported by shear resistance along the length of the element.

In an end bearing element, structural loads bear on the end (also base, tip, toe, etc) of element on stiff clays, dense, sandy soils, or solid rock*. (Shafts may extend into rock).

Driven piles typically use both components without much additional consideration. Due to strain compatibility, drilled shafts are often designed as either primarily end bearing or side resistance (skin friction) type shafts or a combination if using base grouting or when field testing is used to evaluate the contributions).
Axial Shaft Capacity

SHAFT CYLINDRICAL PERIMETER AREA

- Concrete mix design can vary based on several factors.
- Diameter can vary widely.
- Reinforcing Steel (Typically required by design).
- Depth can vary widely.
- Side Resistance.
- Bell - May be used or omitted as desired.
- Bell size varies - No larger than 3 times the shaft diameter at base.

BASE END AREA
Axial Shaft Non-Contributing Areas (AASHTO)

Figure 10.8.3.5.1b-1—Explanation of Portions of Drilled Shafts Not Considered in Computing Side Resistance (O’Neill and Reese, 1999)
Axial Shaft Capacity Diagrams

There is similarity to driven pile design: Side (shaft) and Base (point) components.
**Factored Resistance** = \( \phi \times \text{Nominal Resistance} \)

Note that factors are provided based on side/tip, material, and compression/uplift

<table>
<thead>
<tr>
<th>Method/Soil/Condition</th>
<th>Side resistance in clay</th>
<th>Tip resistance in clay</th>
<th>Side resistance in sand</th>
<th>Tip resistance in sand</th>
<th>Side resistance in IGMs</th>
<th>Tip resistance in IGMs</th>
<th>Side resistance in rock</th>
<th>Tip resistance in rock</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resistance Factor</td>
<td>0.45</td>
<td>0.40</td>
<td>0.55</td>
<td>0.50</td>
<td>0.60</td>
<td>0.55</td>
<td>0.55</td>
<td>0.50</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Block Failure, ( \phi_{bl} )</th>
<th>Clay</th>
<th>Clay</th>
<th>Clay</th>
<th>Sand</th>
<th>Rock</th>
<th>Clay and Sand</th>
<th>All materials</th>
<th>All Materials</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resistance Factor</td>
<td>0.55</td>
<td>0.35</td>
<td>0.45</td>
<td>0.40</td>
<td>0.45</td>
<td>0.45</td>
<td>1.0</td>
<td>0.70</td>
</tr>
</tbody>
</table>

| Static Load Test (compression), \( \phi_{load} \) | All Materials | | | | | | | |
| Static Load Test (uplift), \( \phi_{upload} \) | All Materials | | | | | | | |
| Resistance Factor | 0.60 | | | | | | | |
### Table 10.5.5.2.3-1—Resistance Factors for Driven Piles

<table>
<thead>
<tr>
<th>Condition/Resistance Determination Method</th>
<th>Resistance Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Driving criteria established by successful static load test of at least one pile per site condition and dynamic testing* of at least two piles per site condition, but no less than 2% of the production piles</td>
<td>0.80</td>
</tr>
<tr>
<td>Driving criteria established by successful static load test of at least one pile per site condition without dynamic testing</td>
<td>0.75</td>
</tr>
<tr>
<td>Driving criteria established by dynamic testing* conducted on 100% of production piles</td>
<td>0.75</td>
</tr>
<tr>
<td>Driving criteria established by dynamic testing*, quality control by dynamic testing* of at least two piles per site condition, but no less than 2% of the production piles</td>
<td>0.65</td>
</tr>
<tr>
<td>Wave equation analysis, without pile dynamic measurements or load test but with field confirmation of hammer performance</td>
<td>0.50</td>
</tr>
<tr>
<td>FHWA-modified Gates dynamic pile formula (End of Drive condition only)</td>
<td>0.40</td>
</tr>
<tr>
<td>Engineering News (as defined in Article 10.7.3.8.5) dynamic pile formula (End of Drive condition only)</td>
<td>0.10</td>
</tr>
</tbody>
</table>

* Dynamic testing requires signal matching, and best estimates of nominal resistance are made from a restrike. Dynamic tests are calibrated to the static load test, when available.
Pile Installation:

Methods
- Impact/Driven
- Vibratory
- Auger-cast
- Cast-in-place/mandrel
- Helical

Inspection
- Mill certificates
- Visual
- Driving [Dynamic] Performance
- Static Performance
Impact Pile Driving Rigs

- Drop
- Air/Stem
- Diesel
- Hydraulic
Drilled Shaft Rig

- Kelly
- Table
- Power Unit
- Crane
- Tool
Drilled Shafts
Installation:

**Methods**
- Dry
- Cased
  - Temporary
  - Permanent
- Wet/Slurry

**Inspection**
- Materials
- Integrity
- Performance
Drilled Shaft Installation Methods

- Dry
- Cased
  - Temporary
  - Permanent
- Wet or “Slurry”
This method is used when excavations, started as a “dry construction method”, encounter water bearing or caving (loose sands) soil formations.

A temporary casing is then placed through the problematic formation to produce a watertight seal or to restrict the loose material from collapsing into the shaft.

During concrete placement, the casing is withdrawn. Attention to proper removal of the casing is critical.
Permanent Casing Installation

This method consists of placing a steel casing to a prescribed depth before excavation begins.

This method is frequently used where extracting a temporary casing is judged to be too expensive, problematic, or ‘risky’ due to the potential loss of ground or concrete contamination.

Casing may be installed in one single diameter for short holes, or in multiple stages with reducing diameters for deep holes using - “telescoping casing”
Wet Installation

Shafts are installed either with ground water or under water using tremie concrete.

In this type of operation, drilling fluids, mineral slurry (typically commercial bentonite clay mixed with water) or polymer slurry is used to stabilize the excavation or when ground water is encountered in the excavation that cannot be efficiently sealed or dewatered.
Wet Tremie and Pumping Installation
A very short casing may be used to help support the hole at the ground surface (usually for safety) even if it is not otherwise required.
Casing may be used, but is not necessary in either the basic dry or wet methods.

Dry shafts are a popular construction technique particularly in areas with "hardpan" clays that are dry and cohesive.
A steel reinforcing cage is always installed as part of the construction.

The amount of steel varies depending on the type of loading the shaft is expected to experience.

Shafts are frequently reinforced more near the ground surface where lateral loads and moment forces are larger.

The amount of reinforcement may be very large for shafts in seismic zones.
Drilled Shaft Construction
Integrity testing is almost universal for WET shaft construction: CSL, $\gamma - \gamma$, or thermal integrity.
In a dry shaft, “self compacting” concrete may be “free dropped” in the center of the shaft.

Drilled shaft concrete usually has a very high slump to ensure that it can efficiently migrate through the rebar cage to the exterior of the shaft.

In a wet shaft, concrete must be placed using the tremie; the tremie MUST ALWAYS be kept below the surface of the fresh concrete during the pour.
Drilled Shaft Construction
Some shafts may be “post grouted,” a process where pressurized grout is injected at the base of the shaft to increase the end bearing capacity and the base stiffness.

In the photo above, a hydraulic jack is installed within the shaft to do a full scale load test after the shaft has been post-grouted.

Grout “bulb”
Some shafts may be designed to transfer load to rock, if loads are heavy, lateral loads are high, or rock is relatively shallow.

In the photo above, the reinforcing cage is slightly smaller at the base. Rock sockets are usually advanced with a slightly smaller diameter tool.
Regional considerations have significant impacts on deep foundation type selection both from a geological standpoint and from other business factors.

In general, foundation investigation and geotechnical exploration is similar among deep foundation types.

Design (loading) requirements play a major role.
Drilled Shafts:

Advantages

- Exploration
  - Excavated soils can be examined
  - Pilot holes can be drilled beyond base

- Easily adaptable to varying site conditions
  - Can drill through hard layers to meet scour requirements
  - Can penetrate cobbles/boulders
  - Know where shaft is going
  - Shafts tend not to go out of alignment/wander
Drilled Shafts:

Advantages

- Can advance into rock
- High axial/lateral/moment loading capacity
  - Tend to be economical for large diameter foundations
- Integrity can be economically verified by NDT methods
- Less noise and reduced vibrations
- May have less impact on adjacent infrastructure compared to other methods

www.haywardbaker.com
Drilled Shafts:

Advantages

- Economics
- Minimizes pile cap dimensions
- May be able to eliminate cofferdams using a floating cap
- May be able to have integral shaft/column design eliminating costs
Drilled Shafts:

Disadvantages

- Requires construction expertise
- Quality (and resistance) is sensitive to construction procedures
- Often requires large specialty equipment
  - Specialty subcontractors
  - Cleanout tools
  - Rotators & oscillators
- Requires inspection/acceptance
Drilled Shafts:

Disadvantages

- Requires care when artesian pressures exist in soil strata
- If lengths are changed in field, cages take time to extend/splice
- Not good for contaminated sites
  - Retention of spoil/slurry
  - Disposal of soil/slurry
- Often requires specialty
  - Inspection
  - Integrity Testing
  - Performance Testing
Drilled Shafts:

Disadvantages

- Fewer high capacity elements afford less redundancy
- Large shafts require specialty tests to prove capacity
- May require comparatively high deflection to mobilize shaft resistance
Relatively simple real-time calculations (volume of a cylinder) can be used to assess the theoretical height to which a certain volume of placed concrete should correlate. If the height of the concrete is less—there may be shaft overreaming. If there is a large discrepancy, voids due to karst, utility tunnels, or similar features may be present.
Drilled Shafts:

Testing

- Often requires specialty:
  - Inspection
  - Concrete samples
  - Volume plots
  - Integrity Testing*
  - Performance Testing

*Integrity testing is generally NOT used for DRY of FULLY CASED shafts where visual inspection is possible and the risk of defects or anomalies is greatly minimized.
Integrity testing is almost universal for wet and temporary casing shaft construction.
Conducted at top of shaft
Quick and economical test method used mostly in columnar shaped foundations without access tubes. Defects can be found early with minimal delays to construction.

Limitations: The SE/IR method works best for free-standing columnar-shaped foundations, such drilled shafts, without any structure on top.
Crosshole Sonic Logging

- Cross-hole test: separate emitter and receiver
- Information on shaft interior
- CSL allows for accurate characterization of soil intrusions or other anomalies throughout the shaft inside the rebar cage (between the tubes). Several levels of defects can be detected by this method with high precision. It can be used to identify young (heavy retarded) un-cured concrete.
Crosshole Sonic Logging Tomography

http://www.cflhd.gov/resources/agm/engApplications/BridgeSystemSubstructure/221IntegrityTestingofFoundation.cfm
Provides near probe information
Cesium 137 Source
Single-hole logging technique
Typically used to determine rebar “cover”
Air or water-filled PVC or steel access tubes
GDL allows for precise Characterization of soil intrusions or other anomalies at a radius of about 8 inches both inside and outside of the rebar cage.
Can be used in fresh concrete while restoration is still feasible as the density of concrete changes minimally as it sets. GDL can provide information related to the quality of the concrete.
Tube debonding condition minimally affects the GDL data.
Nuclear source with special operation and storage requirements.
Thermal Imaging

- Newer Technique
- Uses CSL tubes
- Inside and Outside Rebar Cage
Performance QC/QA Testing: O-cell
Pile* Driving Construction Control

- **Static Prediction Methods**
  - Usually used to estimate pile quantities
  - *WEAP (Wave Equation Analysis)*
  - *Dynamic Formulas*
    - Most Common Field Practice
    - Inexpensive/perform well
  - *High Strain Dynamic Monitoring (PDA/CAPWAP)*
- **Static Load Testing (SLT)**
“Right Sizing” of Construction Control

Project Scope
  - Size/Location
  - Cost/Benefit

Factors:
  - # of Piles, Lengths
  - Needed Capacity
Time, Cost, and Project Value

- **Dynamic formula**
  - Shallow bearing layers (common)
  - Small # of Piles
  - Dynamic formula is sufficient in most cases
  - Inexpensive; can be done by field inspectors
  - No special equipment is required
  - Fast- no project delay

- **PDA/CAPWAP**
  - Friction piles
  - Soil set-up
  - Pile damage possible
  - High capacity piles/large # of piles
  - Requires specialty equipment, training, analysis time

- **Static Load Test (SLT)**
  - High value projects; expensive foundations; complex; high $
  - LRFD calibration- tests to geotechnical failure
  - Highest reliability; highest resistance factor
Advantages

Economics:
- Variety of materials/shapes
- Common pile sizes are readily available; few material delays
- Installation systems are common
- Uses contractor’s crane and forces
- Good bid prices as many contractors are generally capable of doing good work
- In many cases a bridge or building contractor will self perform the work (no specialty subcontractor)
Advantages

Economics:

- Pile groups provide design redundancy
- Relatively easy to add piles to foundation footprints (piles are relatively small and there is usually space to install additional elements, if needed.
- Additional pile length relatively easy to add to production piles by splicing additional pile sections
  - Welding (steel)
  - Mechanical coupling; drive splices, sleeves, and similar (for steel and concrete)
Driven Piles:

Advantages

- Inspection is relatively easy
- Dynamic driving formulas are straightforward
- “A driven pile is a tested pile”
- CIP pipes can be visually inspected
- PDA/CAPWAP can be used to assess damage for other pile types (H-pile, concrete)

Soil is not removed*

- No spoil
- No caving, heave, or loss of support

*(unless open-ended)
Advantages

- Tend to be favored in marine environments or where pile bent piers can be used
- Pile sizes and loads are usually light enough to perform ‘traditional’ static load testing to failure
Driven Piles:

**Advantages**
- Specifications generally straightforward
- Often there is institutional familiarity with process if foundations are regularly constructed
- Comparable to dry drilled shaft effort
- Less complicated than shafts requiring casing/wet shafts
- Speed (prefabricated elements)
- Work area is generally neat/clean; no spoil and extracted soil
- Practical when artesian pressures exist
Driven Piles:

Disadvantages

- Perception of noise and vibration may limit foundation choices depending on project location
- Impact driving may be restricted (particularly with displacement piles) near other foundations or older utilities due to concerns with damage
- Displacement may cause heave
- Driven piles can’t penetrate rock
- Cobbles and boulders can damage piles, making drilled shafts preferable
Driven Piles:

Disadvantages

- Material costs for thick walled large diameter piles can be large
- Concrete piles can suffer pile damage during driving
- Design may not be economical if piles need to be designed to withstand driving/installation and these requirements are much larger than structural loading requirements
- Can’t be driven closed-end in large diameters
Driven Piles:

Disadvantages

- Elements are often more limited in diameter (size)- usually by contractor’s equipment
- Requirements for uplift or fixity may be difficult to meet
- Penetrating hard materials may be difficult without pile damage. This could require pre-boring or jetting, reducing pile economy
- Larger lateral loads may require many elements or battered (inclined piles).
Driven Piles:

Disadvantages

- Difficult in low-headroom conditions
- Pile driving dynamic formulas are related to blow count and penetration; they may not be appropriate if the hammer is not working properly (if a standard efficiency is assumed)
Total Resistance has 2 components:

- Side
- Base†

Total Resistance will depend on:

- Geometry
- Material Properties ($\alpha, \beta, \text{empirical, rock}$)
- Stratigraphy
- Shaft Exclusion Areas (top and base)

Apply LRFD Factors based on:

- Pile: Static Methods/Construction Control
- Shaft: Soil ($c-\varphi$)/IGM/Rock & (Shaft, Base)
Pile Design Methods (Continued)

- α Method (Tomlinson), FHWA cohesive
- β Method (Nordlund), FHWA frictional
- USACE Method (α, β elements)
- Revised λ Method
- API (Method 2A Revised) (cohesive + frictional)

Representative DIRECT CPT Methods:
- NGI, MTD [available in APILE 5.0]
- Schmertmann and Nottingham (1975, 1978)
- deRuiter and Beringen (1979)
- LCPC, Bustamante and Gianeselli (1982)
- Tumay and Fakhroo (1981)
- Eslami Fellenius (1996)

There are more CPT methods (not shown)
Driven Piles:

- Sand ($\beta$)
- Clay ($\alpha$)
- Pile
- Base
- Clay ($\alpha$)
- Rock

Compression

- Sand ($\beta$)
- Clay ($\alpha$)
- Pile
- Base
- Rock
Driven Piles:

- Clay (α)
- Sand (β)

UPLIFT
Drilled Shafts:

- Clay (α)
- Rock

Use LRFD factors for single shafts: side and base resistance for sands and clays in compression.
Drilled Shafts:

Use LRFD factors for single shafts: side and base resistance for sands and clays in uplift
Real-Time Construction Feedback

Driven Piles
- Driving resistance
- Transferred hammer energy/hammer performance
- Driving stresses
- Pile integrity
- Capacity

Drilled Shafts
- Auger cuttings
- Observation of bottom cleanliness (sometimes)
- Concrete volume
- Shaft profile/geometry (possible but not widely done)

http://www.mancinicompanies.com/construction
Different foundation types will have different economics

- Mobilization + Equipment
- Material + Shipping Cost
- Design
  - Foundation Footprint
  - Cofferdams
  - Number of Elements
  - Depth of Elements
  - Reliability/Testing
- Construction
Reliability and Risk Factors

Point of Manufacture
- **Driven Piles**
  - Steel mill; casting yard; wood yard
  - Uniform consistent product delivered to site
- **Drilled Shafts**
  - On-site; In-place
  - Complex process
  - Significant QC/QA needed

Installation Distress
Redundancy (# elements)
Inspection/Testing
Proper Design Considerations
Driven Piles
- Smaller elements
- Lower capacity
- Lower cost
- More elements used
- Highly redundant
- Simple field inspection

Drilled Shafts
- Bigger elements
- Higher capacity
- Higher cost
- Fewer elements used
- Little to no redundancy
- More complex field inspection
Foundation Selection

Consider:

- Economics: Time, Risk, Reliability,
- Design Needs: Axial, Lateral, Moment, Extreme Event
- Material, Labor, Construction Cost
- Site access (congested site/over water)
- Impact on Pile/Shaft Cap and Structural Design
- Noise/Vibration/spoil/pollution
- Adaptability; ability to change/retrofit
- Sensitivity to construction procedures/site conditions
- Specifications, regulations
- Construction/inspection/acceptance expertise
- Weather, groundwater, and other impacts
Case Studies -

Piles and Shafts can fail (service/strength)

Extreme Examples:
- Poor Shaft Integrity
  - Concrete up pulled with cage?
  - Mix design wrong?
  - Pulled tremie?

- Poor Pile Alignment
  - Obstruction?
  - Capacity?
Case Studies -

- Shaft Plunging
- Lee Roy Selmon Expressway
  - Tampa, Fl, 2004
  - Pier 97 sank 20 feet
  - 735 tons of load (form travellers)
  - $75 million settlement
Lotus Waterside 7

2009: According to Shanghai Daily, initial investigations attribute the accident to the excavations for the construction of a garage under the collapsed building.

Large quantities of earth were removed (4.6 m) in an unbraced excavation and piled to a height of 10 m on the other side of the building. Heavy rainfall may also have contributed to the collapse. Precast Concrete Shell piles may not have been able to resist the large shear forces.

http://www.telegraph.co.uk/news/worldnews/asia/china/5685963/Nine-held-over-Shanghai-building-collapse.html
Case Studies -

- Pile Group Plunging
- Leo Frigo Expressway
  - Green Bay, WI, 2013
- Pile Corrosion
- Settlement of 2 feet

Moving quickly on repairs

The state is taking bids on repair work for the Leo Frigo Memorial Bridge in Green Bay. Part of the bridge sank two feet because of corroded pilings.

New structure:
1. Buttress wall
2. Footing extension
3. Footing post tensioning

Existing pier column

Detail:
- Pier: 82 feet high
- Footing: 6 feet deep
- 40 steel pilings, 100 feet long

Source: Wisconsin Department of Transportation

Journal Sentinel
Severe Foundation Failures are Rare

- Earthquake
- Landslide
- Vessel Impact/Collision
- Liquefaction
- Coastal Erosion/Storms
- Extreme Construction Loading
- Corrosion
- Differential Settlement