Deep Foundation Selection: Drilled Shafts or Driven Piles?

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8:15 – 9:15 AM
USU, Logan, Utah
PDCA Professor's Driven Pile Institute

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Deep Foundations

- 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

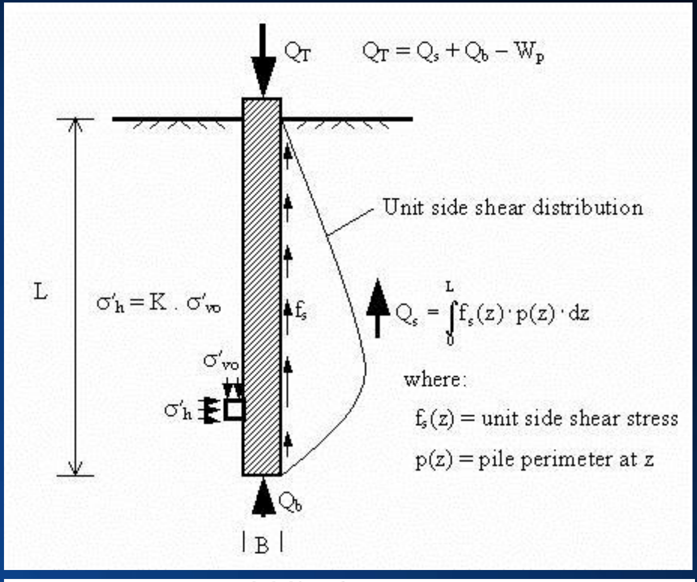
Foundation Selection Considerations

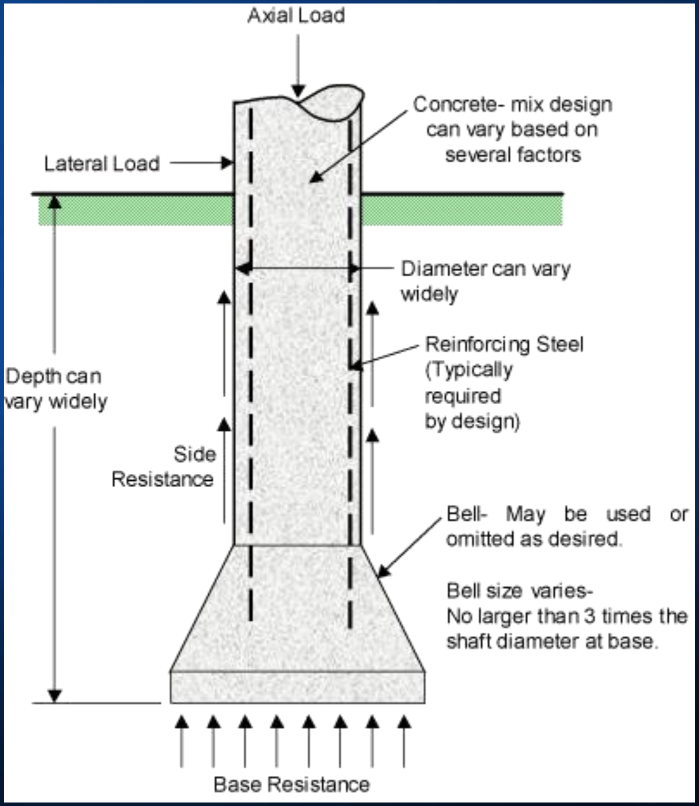
- Cost (materials/labor/inspection)/ Time
- Structural loading requirements
  - Compression, uplift, deformation, cyclic, redundancy
  - Extreme events (seismic, lateral impact, scour)
- Ease of design/construction/inspection
  - Standard practice & familiarity; codes
- Special site requirements (noise/vibration/clearance)
- 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

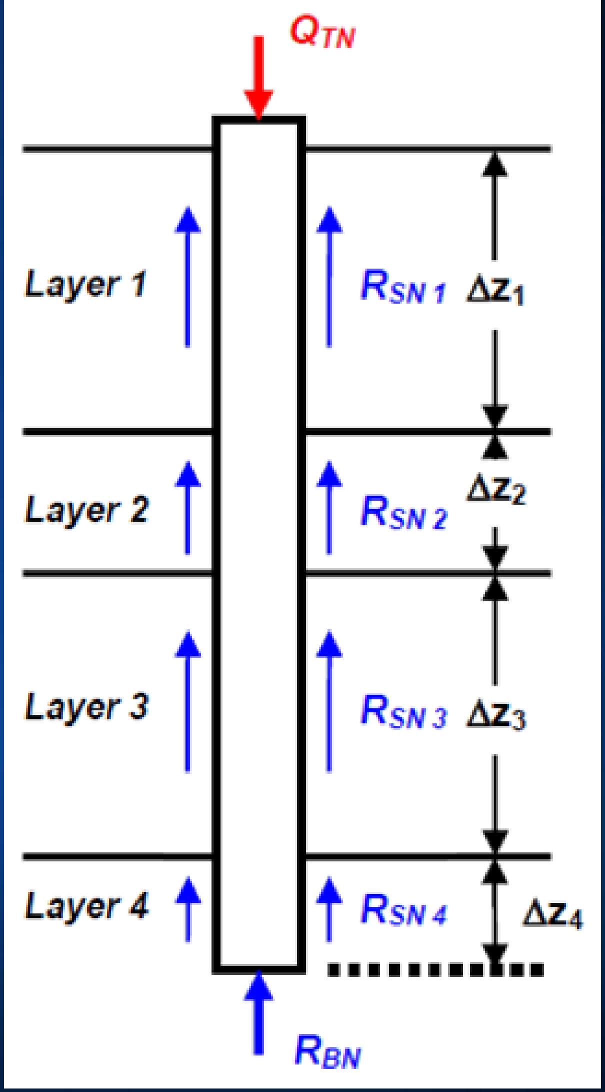
- Similarities
  - α Methods (cohesive soils)
  - β Methods (frictional soils)
- Differences
  - Option for 'belled' shafts
  - Rock Socketed Shafts
  - Installation Details
    - Soil Removal/Displacement
    - Frictional/Adhesion properties
  - Direct CPT Methods available in pile design software





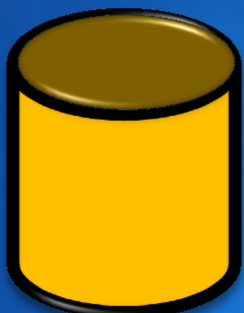
Resistance Contributions

- 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).

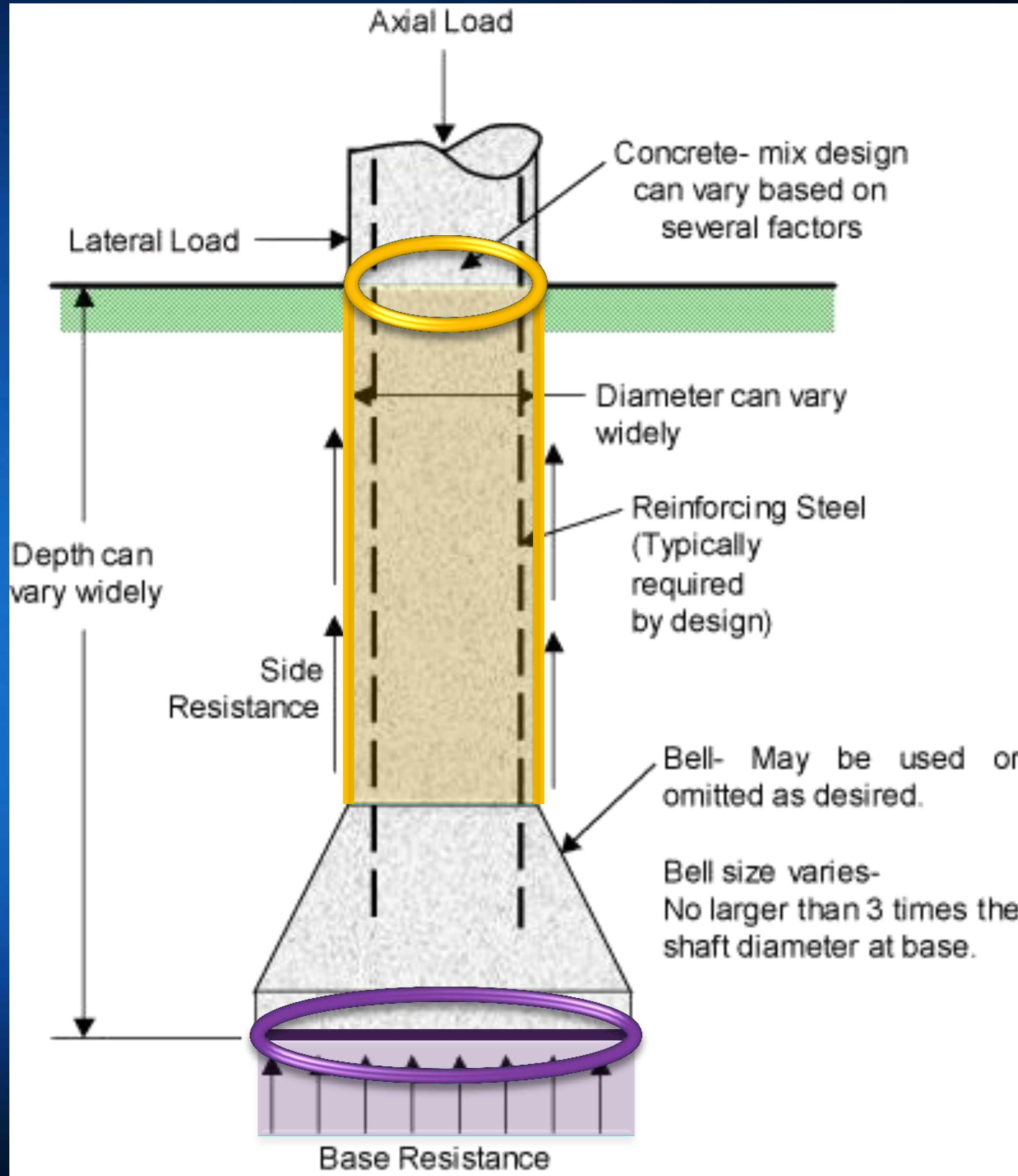


Axial Shaft Capacity

SHAFT CYLINDRICAL PERIMETER AREA



BASE
END AREA



Axial Shaft Non-Contributing Areas (AASHTO)

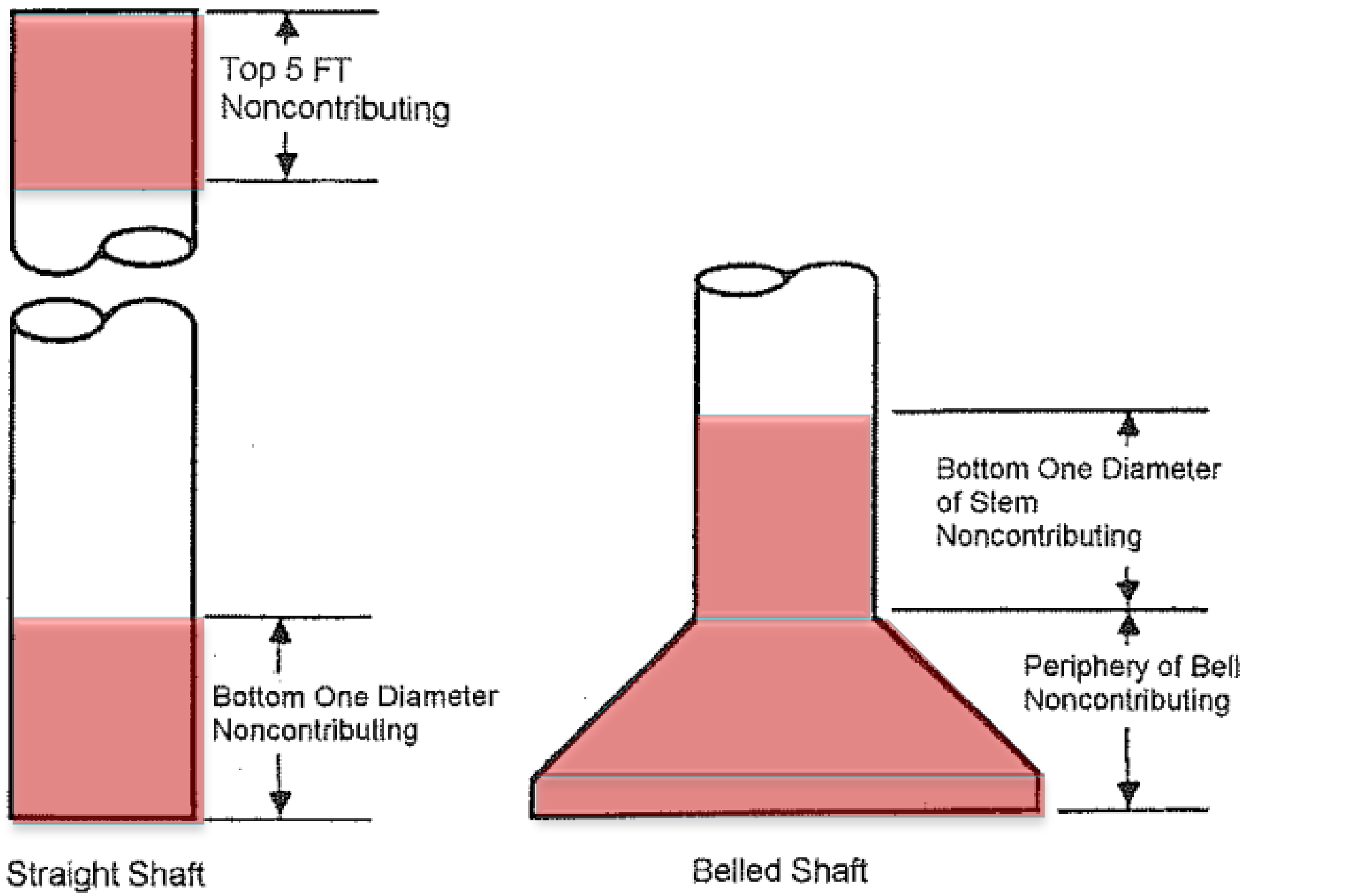
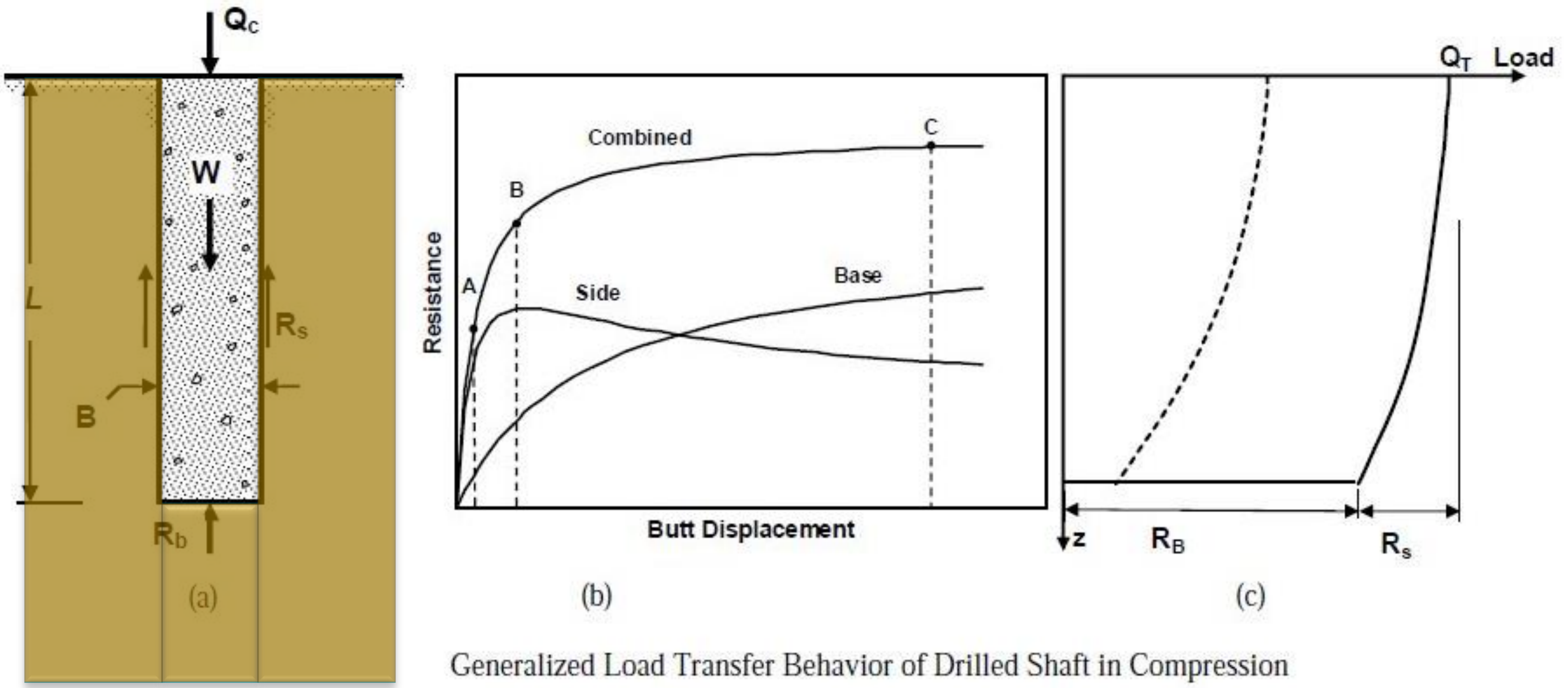


Figure 10.8.3.5.1b-1—Explanation of Portions of Drilled Shafts Not Considered in Computing Side Resistance (O'Neill and Reese, 1999)

Axial Shaft Capacity Diagrams



Generalized Load Transfer Behavior of Drilled Shaft in Compression

There is similarity to driven pile design: Side (shaft) and Base (point) components

Drilled Shaft LRFD Resistance Factors, ϕ

Factored Resistance = ϕ * Nominal Resistance

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

Table 10.5.5.2.4-1—Resistance Factors for Geotechnical Resistance of Drilled Shafts

Method/Soil/Condition			Resistance Factor
Nominal Axial Compressive Resistance of Single-Drilled Shafts, φ_{stat}	Side resistance in clay	α-method (O'Neill and Reese, 1999)	0.45
	Tip resistance in clay	Total Stress (O'Neill and Reese, 1999)	0.40
	Side resistance in sand	β-method (O'Neill and Reese, 1999)	0.55
	Tip resistance in sand	O'Neill and Reese (1999)	0.50
	Side resistance in IGMs	O'Neill and Reese (1999)	0.60
	Tip resistance in IGMs	O'Neill and Reese (1999)	0.55
	Side resistance in rock	Horvath and Kenney (1979) O'Neill and Reese (1999)	0.55
	Side resistance in rock	Carter and Kulhawy (1988)	0.50
	Tip resistance in rock	Canadian Geotechnical Society (1985) Pressuremeter Method (Canadian Geotechnical Society, 1985) O'Neill and Reese (1999)	0.50
Block Failure, φ_{b1}	Clay		0.55
Uplift Resistance of Single-Drilled Shafts, φ_{up}	Clay	α-method (O'Neill and Reese, 1999)	0.35
	Sand	β-method (O'Neill and Reese, 1999)	0.45
	Rock	Horvath and Kenney (1979) Carter and Kulhawy (1988)	0.40
Group Uplift Resistance, φ_{ug}	Sand and clay		0.45
Horizontal Geotechnical Resistance of Single Shaft or Shaft Group	All materials		1.0
Static Load Test (compression), φ_{load}	All Materials		0.70
Static Load Test (uplift), φ_{upload}	All Materials		0.60

Driven Pile LRFD Resistance Factors ϕ_{dyn}: Construction

Table 10.5.5.2.3-1—Resistance Factors for Driven Piles

Condition/Resistance Determination Method		Resistance Factor
Nominal Bearing Resistance of Single Pile—Dynamic Analysis and Static Load Test Methods, φ_{dyn}	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	0.80
	Driving criteria established by successful static load test of at least one pile per site condition without dynamic testing	0.75
	Driving criteria established by dynamic testing* conducted on 100% of production piles	0.75
	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	0.65
	Wave equation analysis, without pile dynamic measurements or load test but with field confirmation of hammer performance	0.50
	FHWA-modified Gates dynamic pile formula (End of Drive condition only)	0.40
	Engineering News (as defined in Article 10.7.3.8.5) dynamic pile formula (End of Drive condition only)	0.10

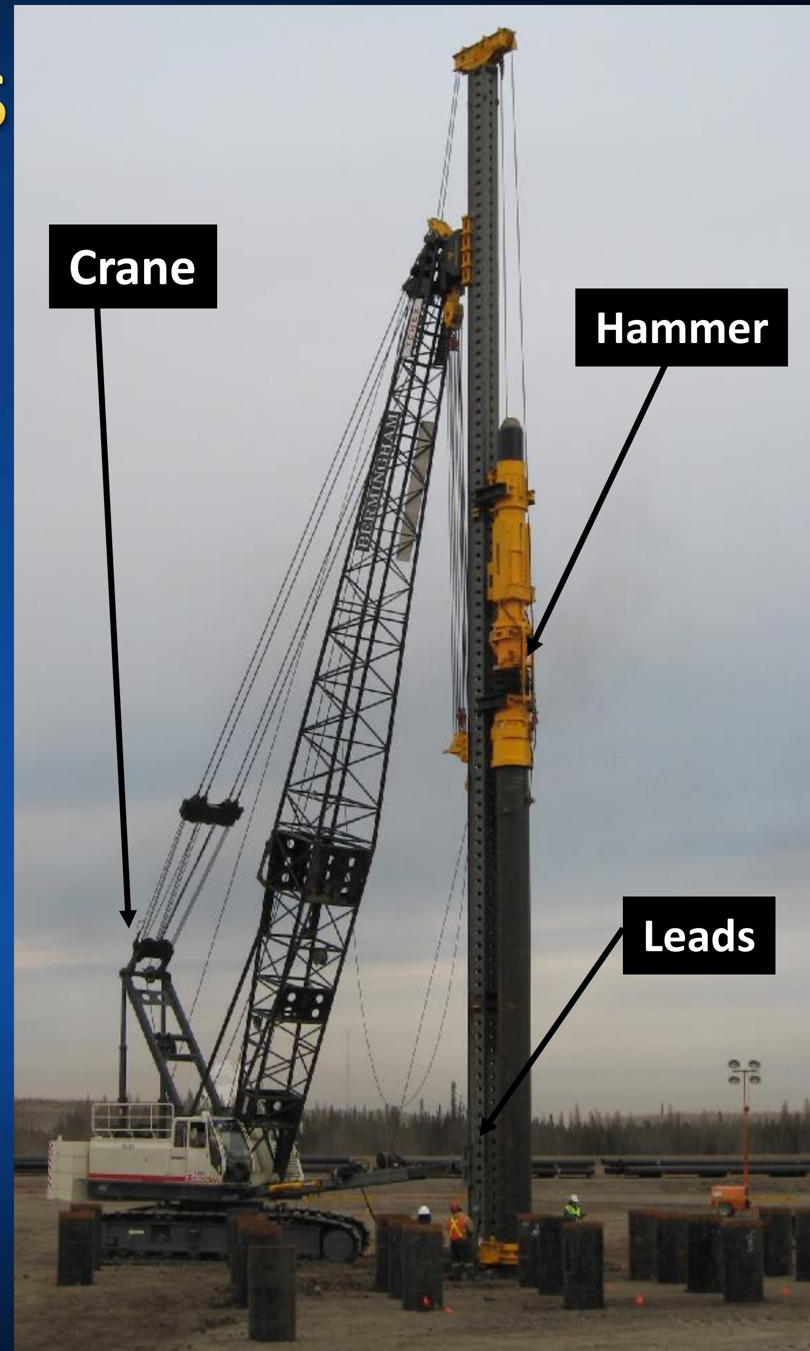
* Dynamic testing requires signal matching, and best estimates of nominal resistance are made from a restrike. Dynamic tests are calibrated to the static load test, when available.

Pile Installation:

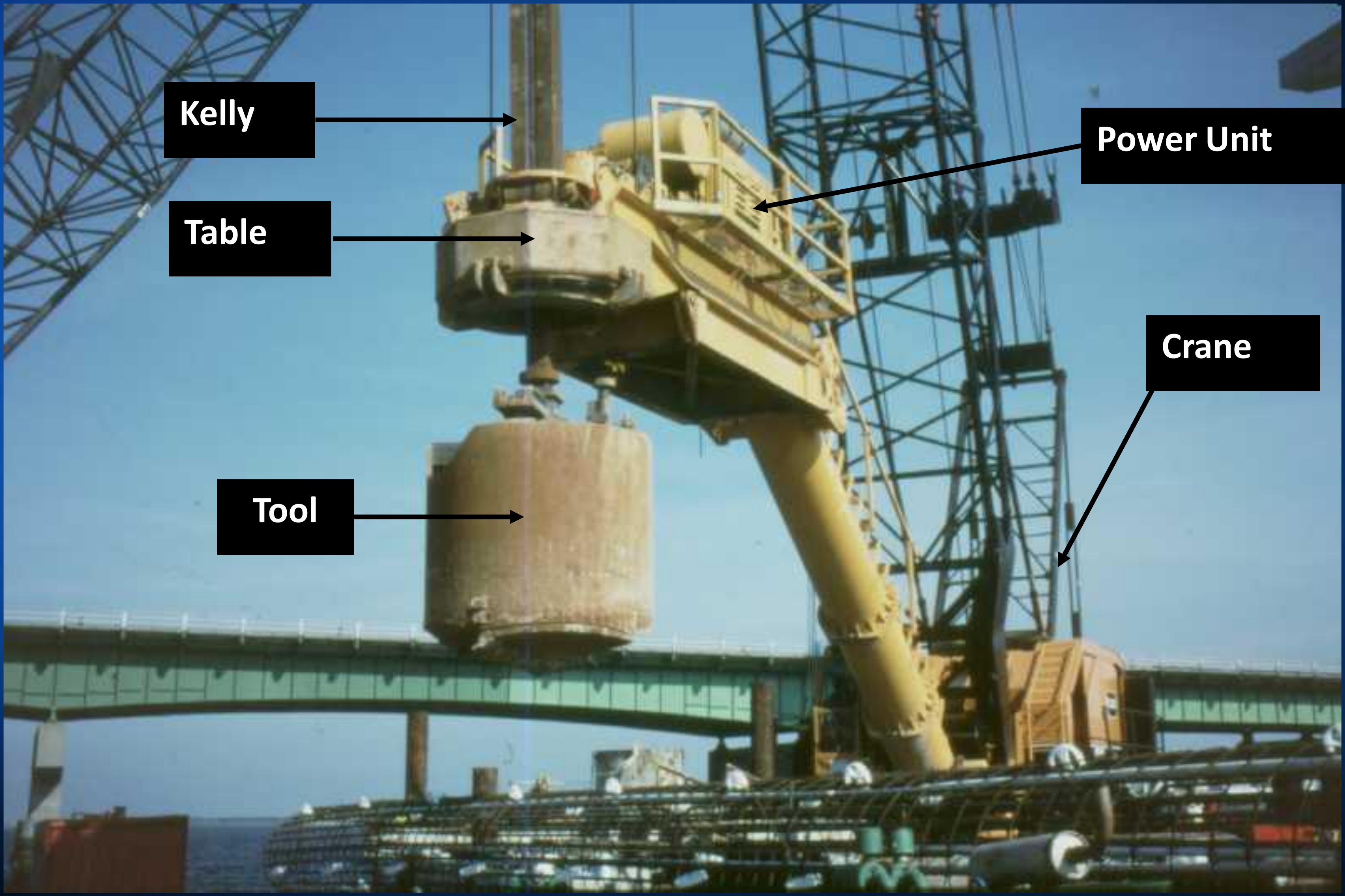
- Methods
  - Impact/Driven
  - Vibratory
  - Auger-cast
  - Cast-in-place/mandrel
  - Helical
- Inspection
  - Mill certificates
  - Visual
  - Driving [Dynamic] Performance
  - Static Performance

Impact Pile Driving Rigs

- Drop
- Air/Stem
- Diesel
- Hydraulic

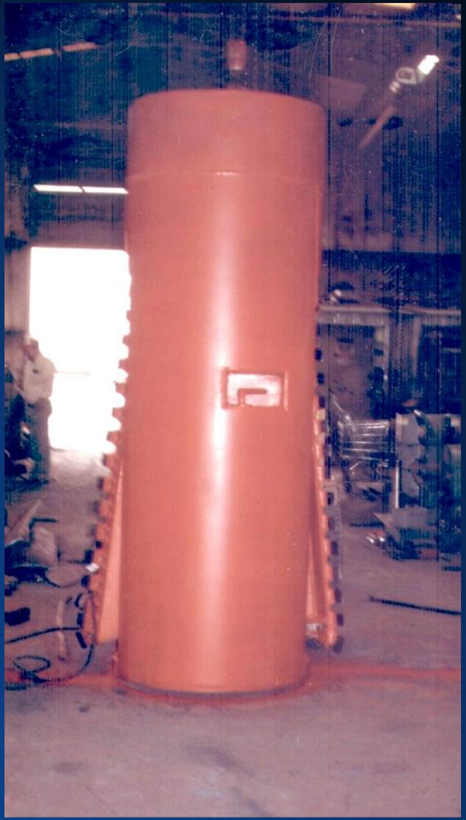


Drilled Shaft Rig



Tools

Belling Tool

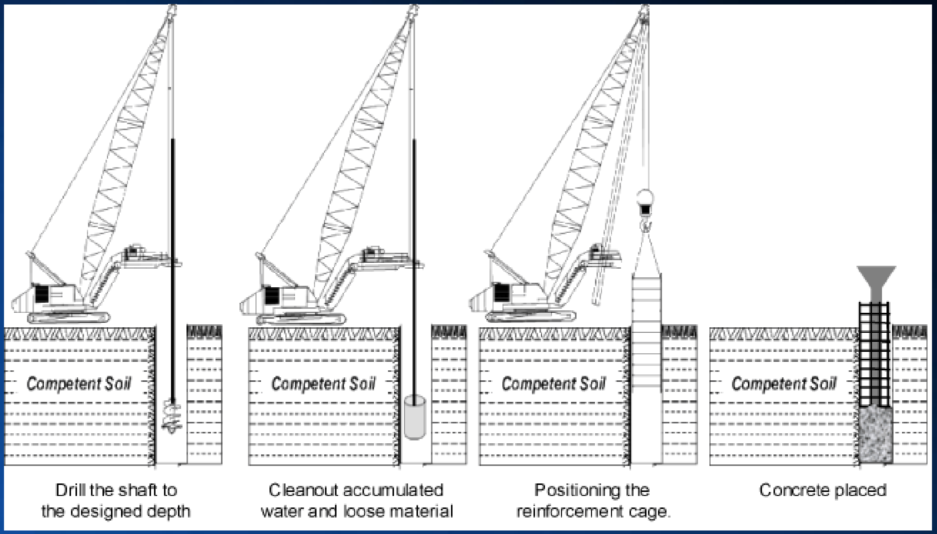


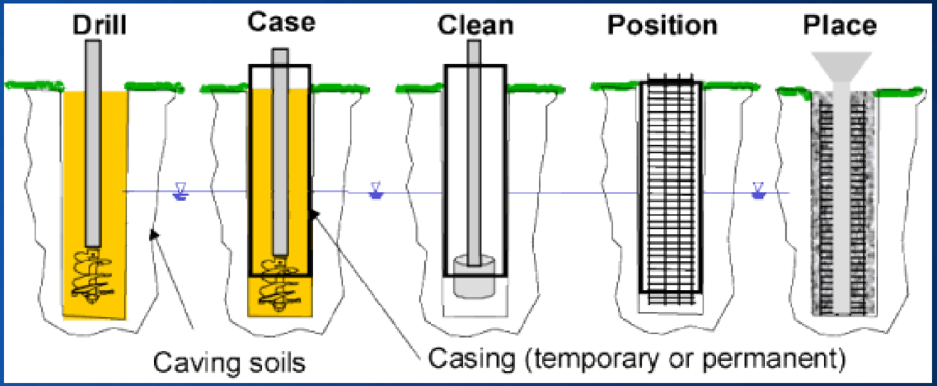
Earth Auger

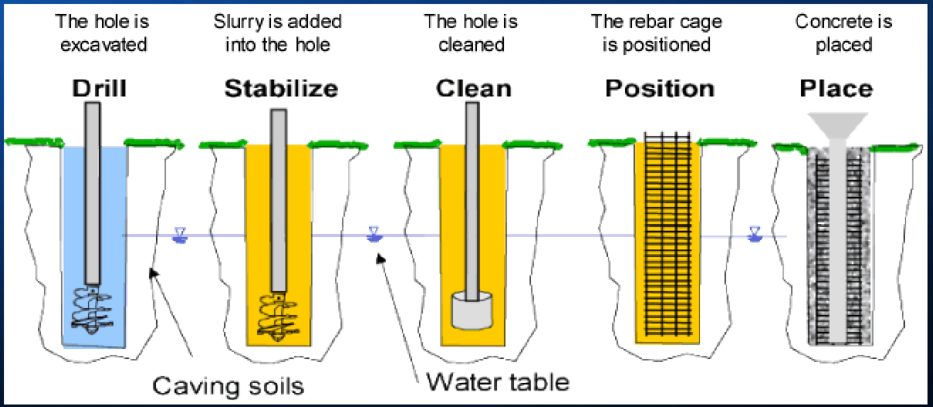
Rock Auger

Drilled Shafts Installation:

- Methods
  - Dry
  - Cased
    - Temporary
    - Permanent
  - Wet/Slurry
- Inspection
  - Materials
  - Integrity
  - Performance

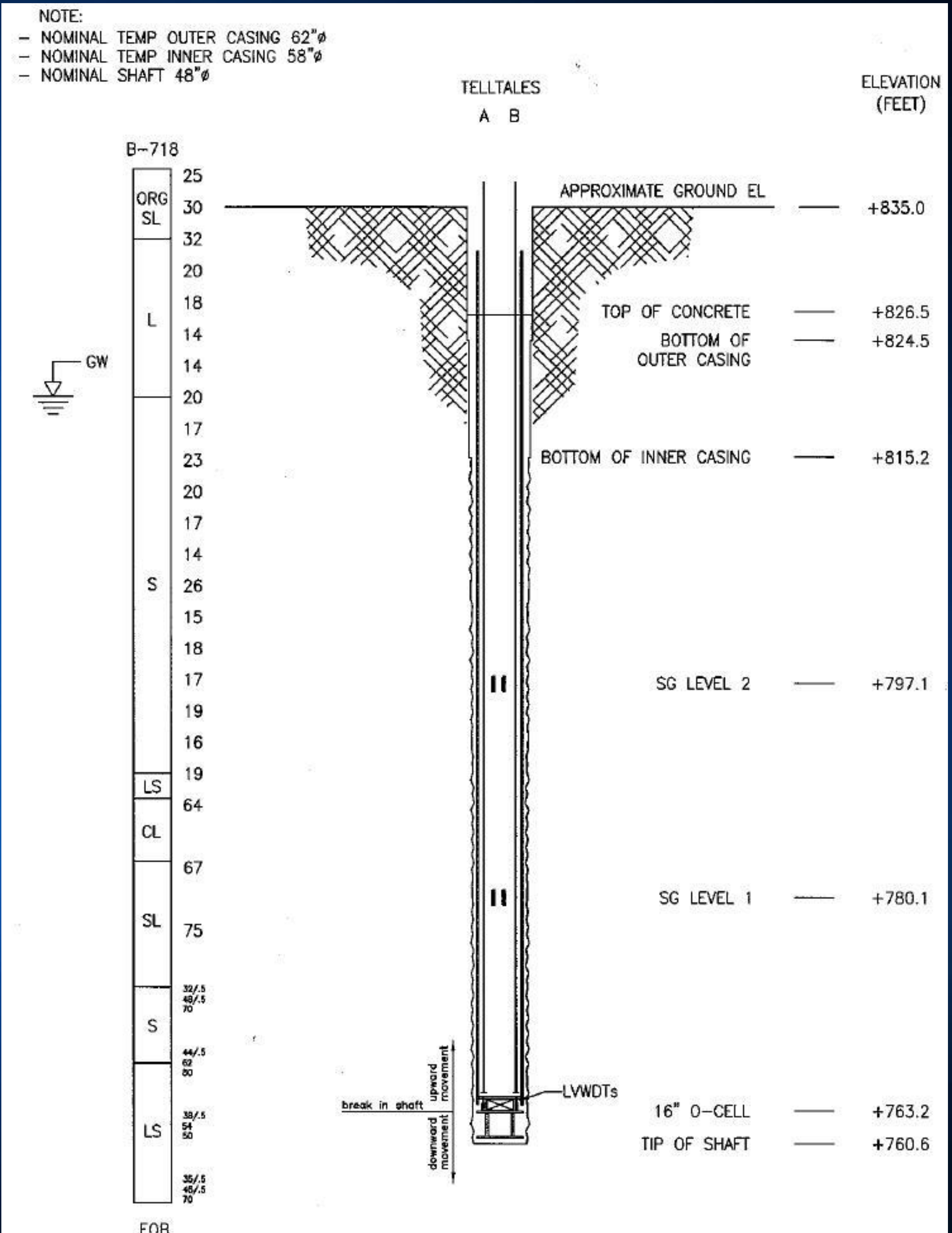






Drilled Shaft Installation Methods

- Dry
- Cased
  - Temporary
  - Permanent
- Wet or “Slurry”



Temporary Casing Installation

- 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

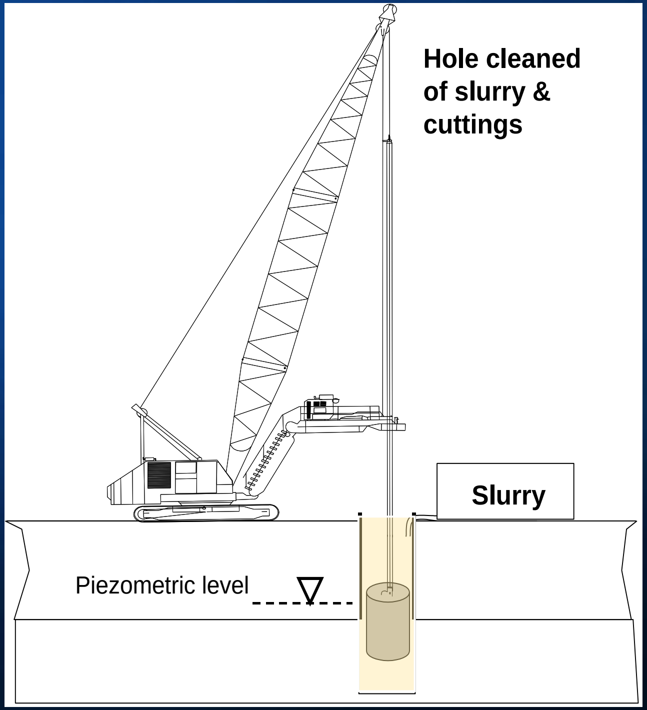
- This method consists of placing a steel casing to a prescribed depth before excavation begins.
- This method is frequently used where extracting a temporary casing is judged to be too expensive, problematic, or ‘risky’ due to the potential loss of ground or concrete contamination.

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

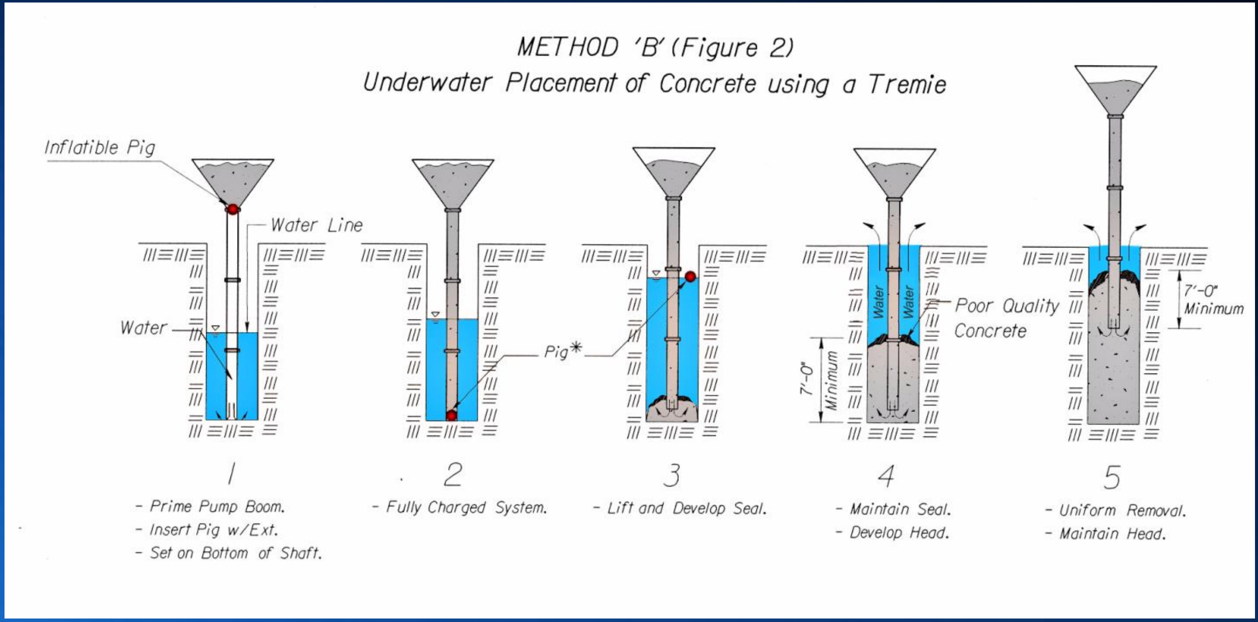
Wet Installation

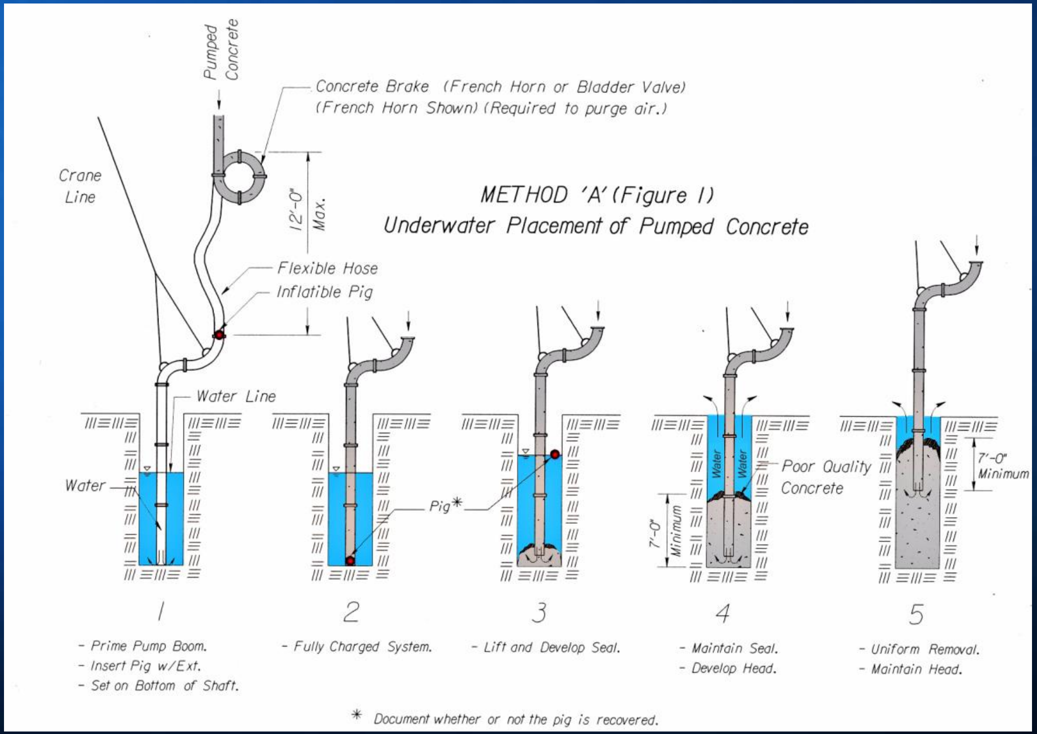
- Shafts are installed either with ground water or under water using tremie concrete.

- 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



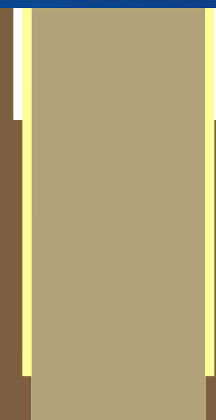


Drilled Shaft Construction

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.

Drilled Shaft Construction

Casing may be used, but is not necessary in either the basic dry or wet methods



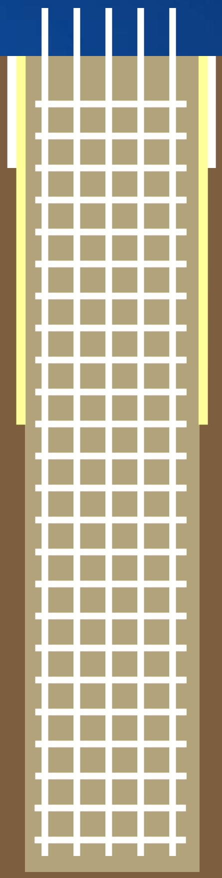
Dry shafts are a popular construction technique particularly in areas with "hardpan" clays that are dry and cohesive.

Drilled Shaft Construction

A steel reinforcing cage is always installed as part of the construction.

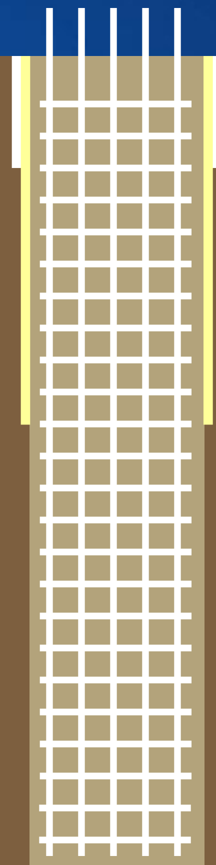
The amount of steel varies depending on the type of loading the shaft is expected to experience.

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

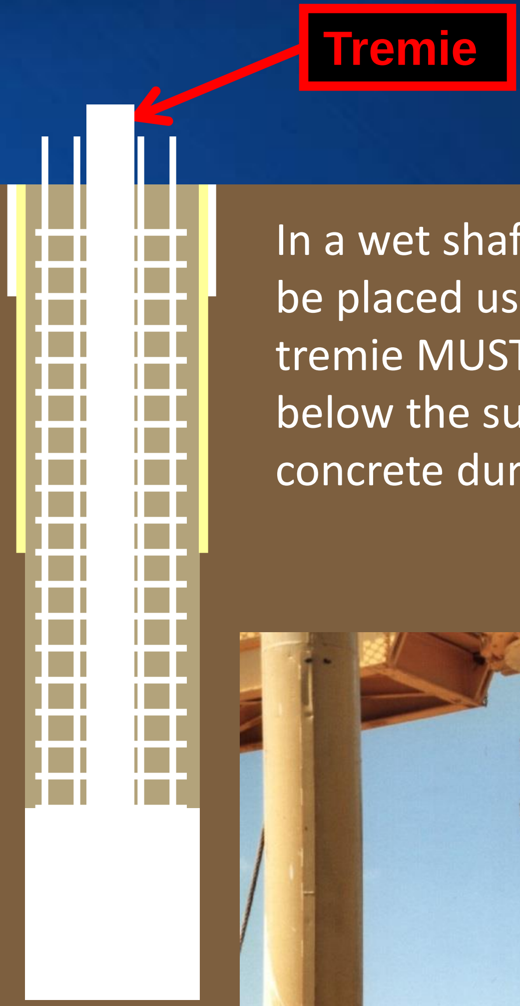


Drilled Shaft Construction

PVC or Steel tubes are attached to the rebar cage

Integrity testing is almost universal for WET shaft construction: CSL, γ - γ, or thermal integrity

Drilled Shaft Construction

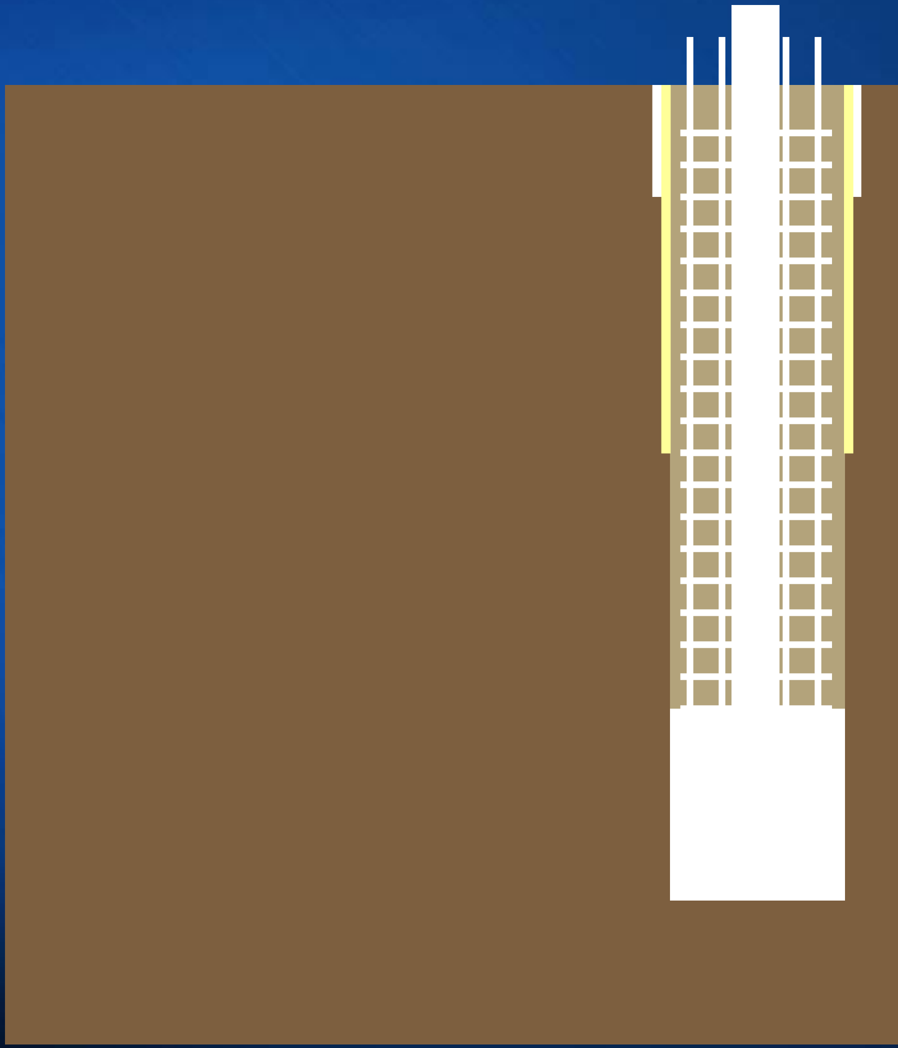


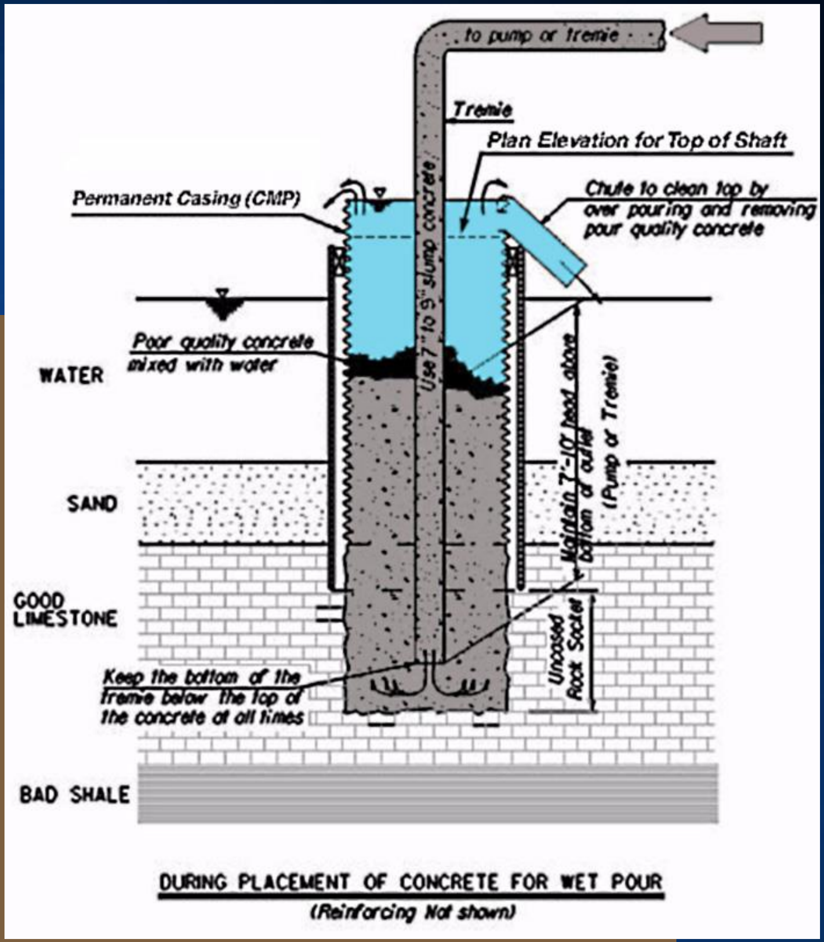
In a dry shaft, "self compacting" concrete may be "free dropped" in the center of the shaft.

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.

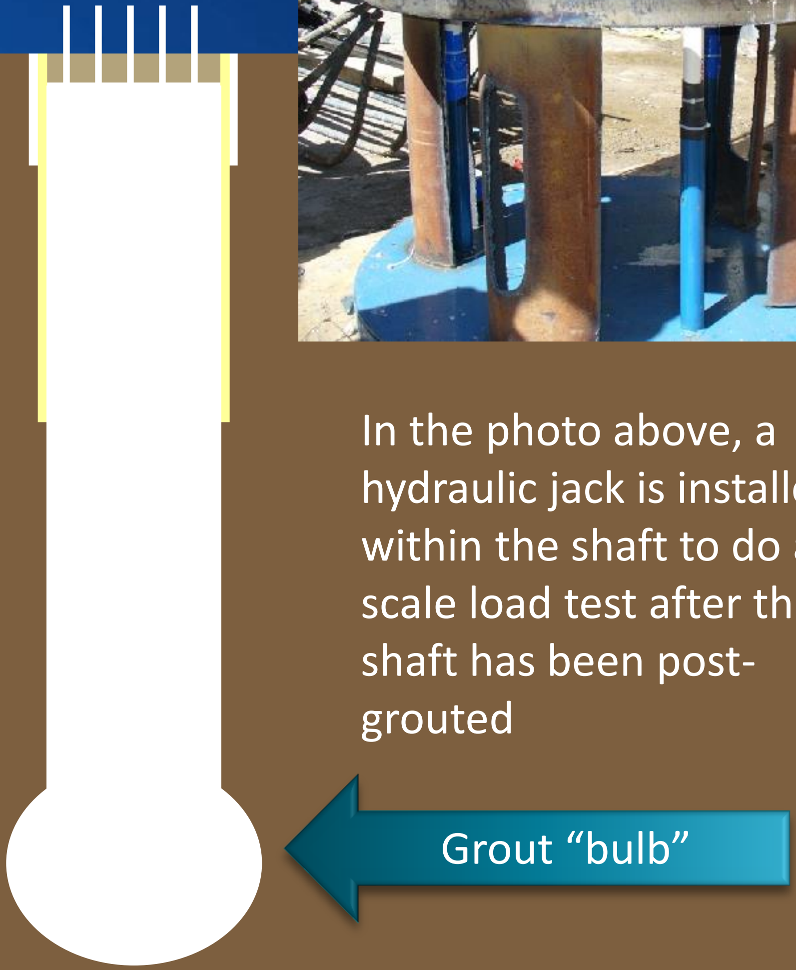
In a wet shaft, concrete must be placed using the tremie; the tremie MUST ALWAYS be kept below the surface of the fresh concrete during the pour.

Drilled Shaft Construction





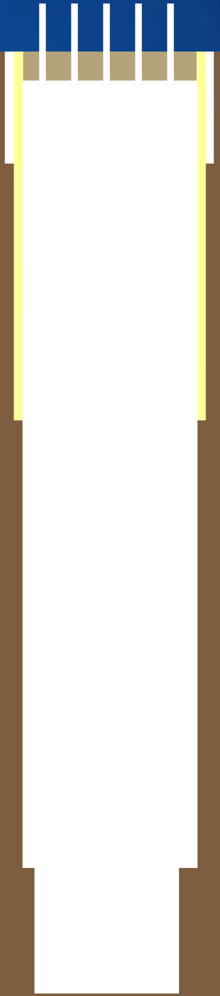
Drilled Shaft Construction



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

Drilled Shaft Construction



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.

Rock Socket

Generalized Deep Foundation Advantages and Disadvantages Drilled Shafts vs. Driven Piles

Notes:

- 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 trough 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

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Drilled Shafts:

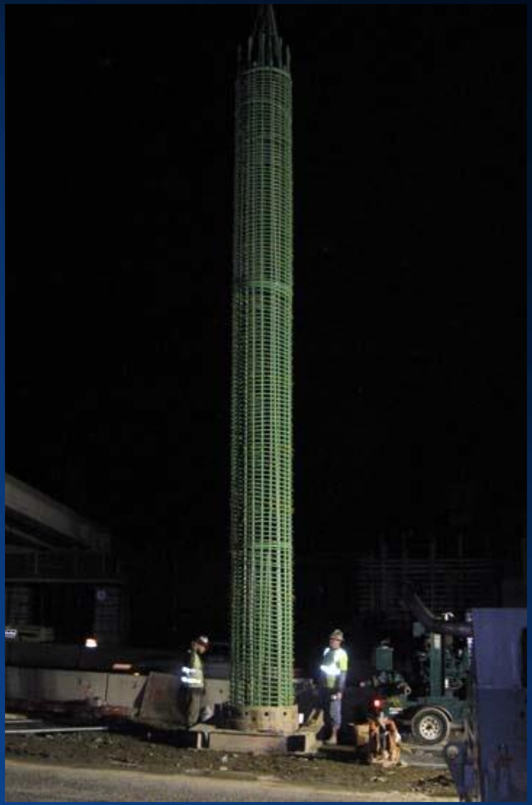
- Advantages
  - Economics
  - Minimizes pile cap dimensions
  - May be able to eliminate cofffferdams using a floating cap
  - May be able to have integral shaft/column design eliminating costs

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:

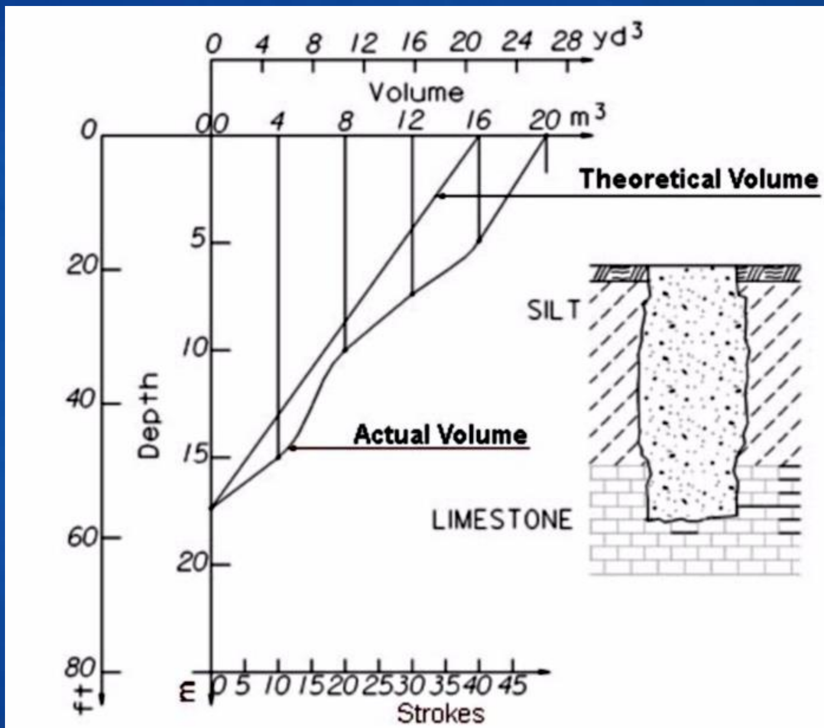
- Disadvantages
  - Requires care when artesian pressures exist in soil strata
  - If lengths are changed in field, cages take time to extend/splice
  - Not good for contaminated sites
    - Retention of spoil/slurry
    - Disposal of soil/slurry
  - Often requires specialty
    - Inspection
    - Integrity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

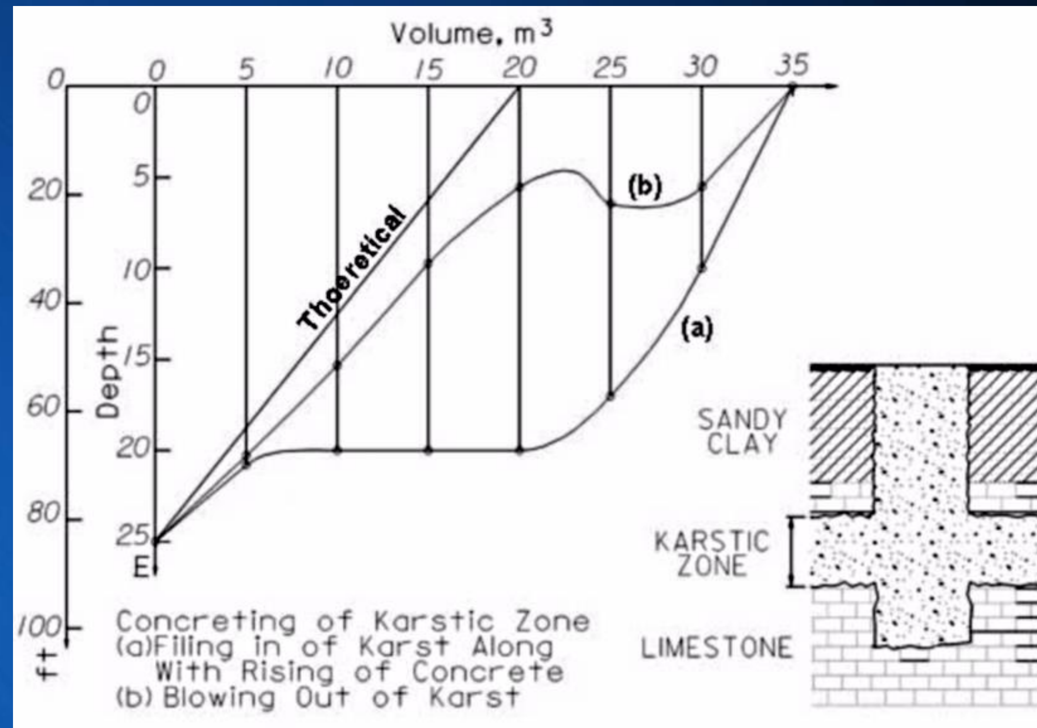


Drilled Shafts:

- 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

Drilled Shaft QC: Volume Measures

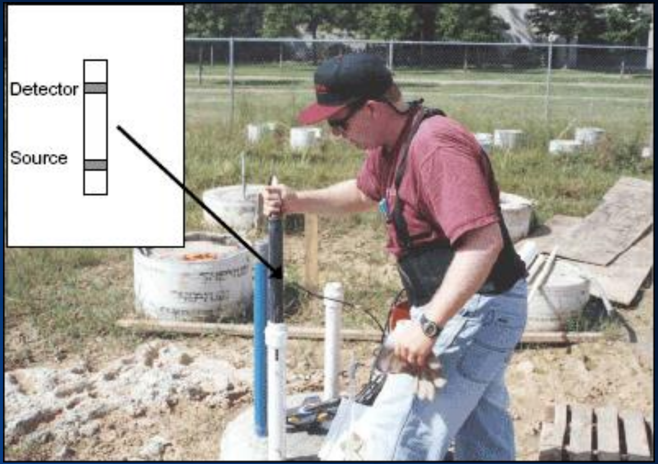




Relatively simple real-time calculations (volume of a cylinder) can be used to assess the theoretical height to which a certain volume of placed concrete should correlate. If the height of the concrete is less- there may be shaft over-reaming. If there is a large discrepancy, voids due to karst, utility 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.**

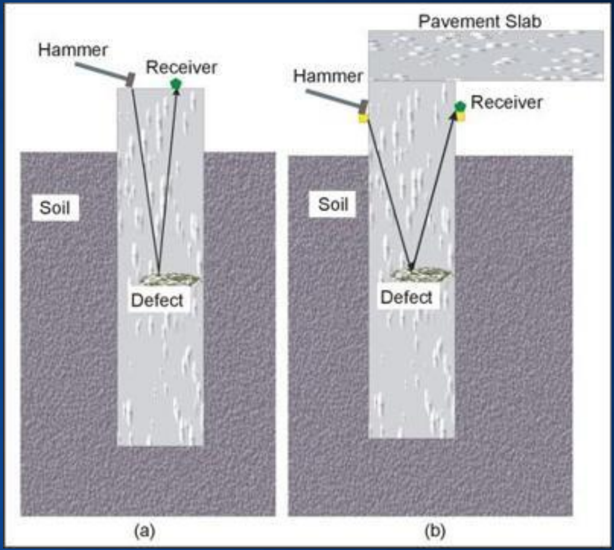
Drilled Shaft Inspection and QC/QA

Integrity testing is almost universal for wet and temporary casing shaft construction

PVC or Steel tubes are attached to the rebar cage

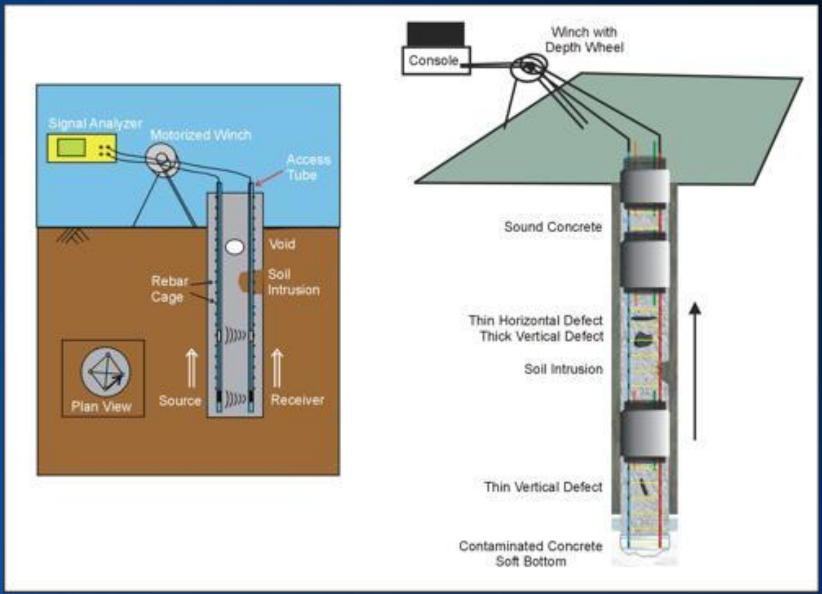
Sonic Echo/Impulse Response

- 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.

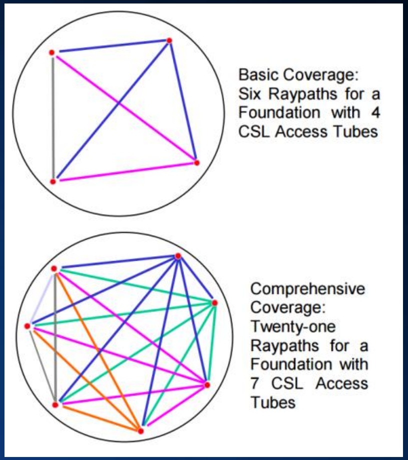


Crosshole Sonic Logging

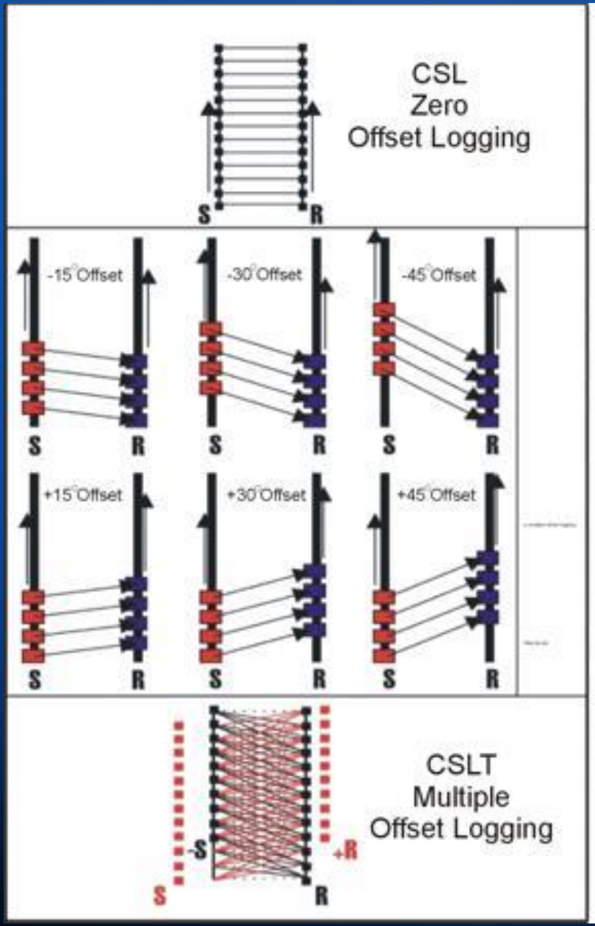
- Cross-hole test: separate emitter and receiver
- Information on shaft interior
- CSL allows for accurate characterization of soil intrusions or other anomalies throughout the shaft inside the rebar cage (between the tubes). Several levels of defects can be detected by this method with high precision.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

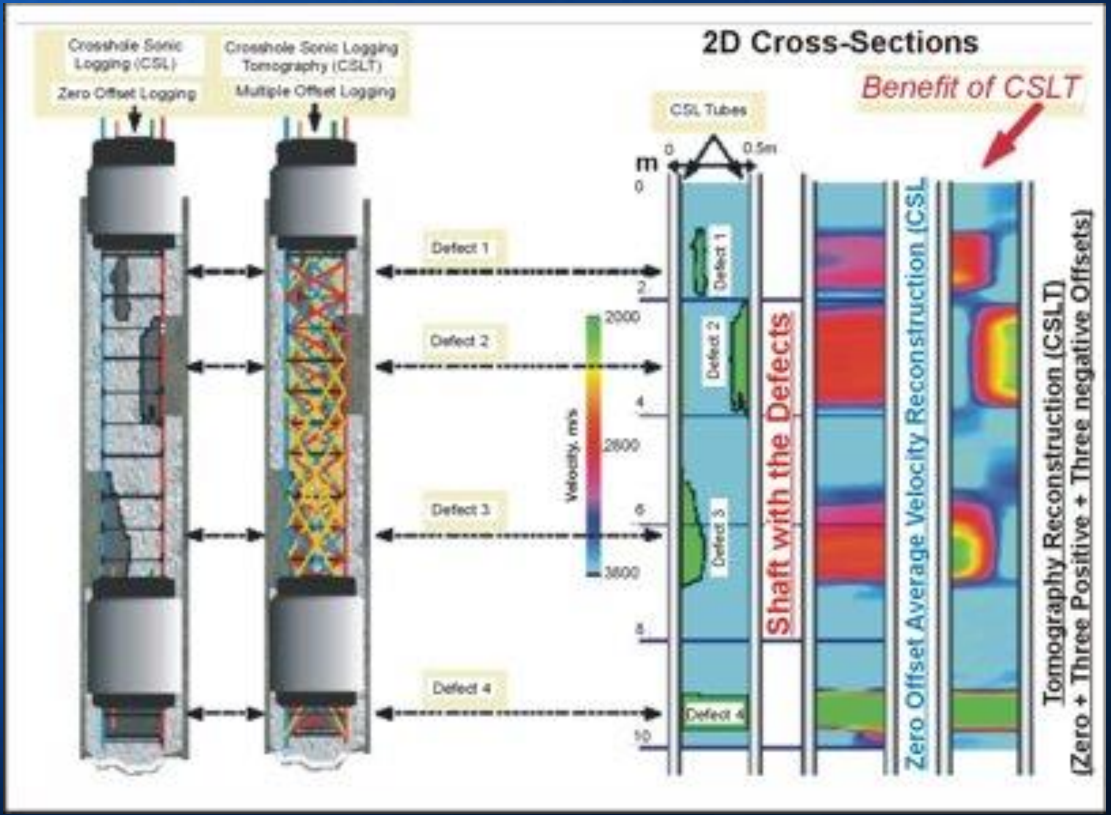


Crosshole Sonic Logging Tomography



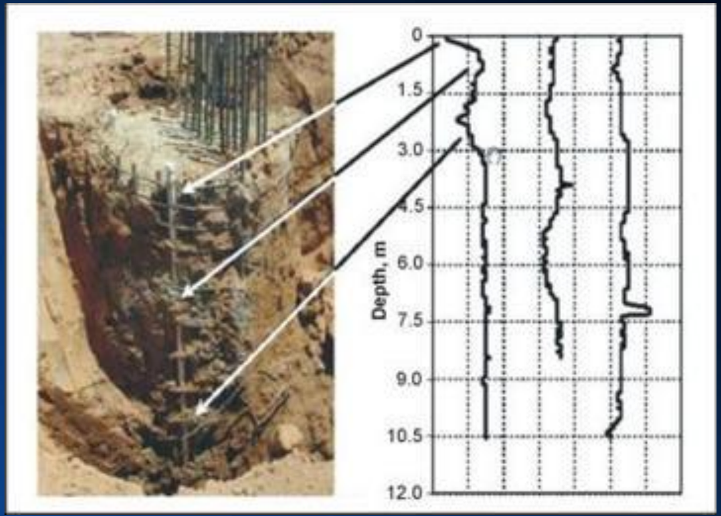
http://www.wa4bpj.com/Construction/64_bypass/bridge/csl_contractor_guidelines.pdf





http://www.cflhd.gov/resources/agm/engApplications/BridgeSystemSubstructure/221IntegrityTestingofFoundation.cfm

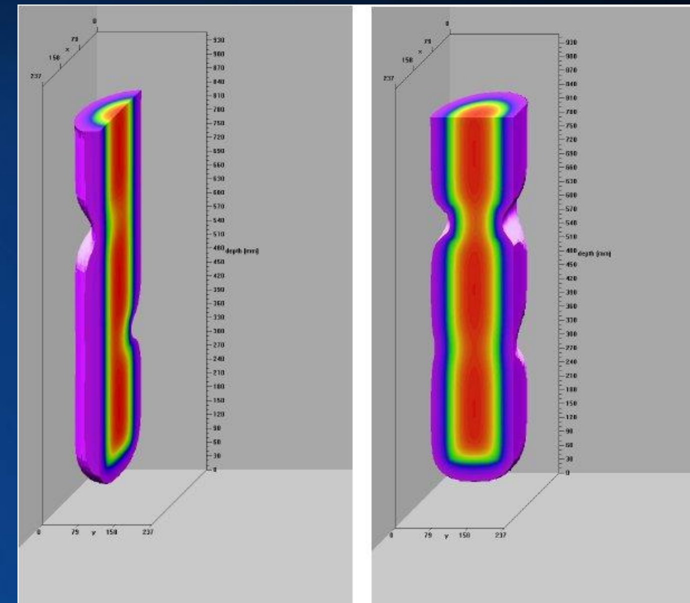
γ-γ Logging Gamma Density Logging

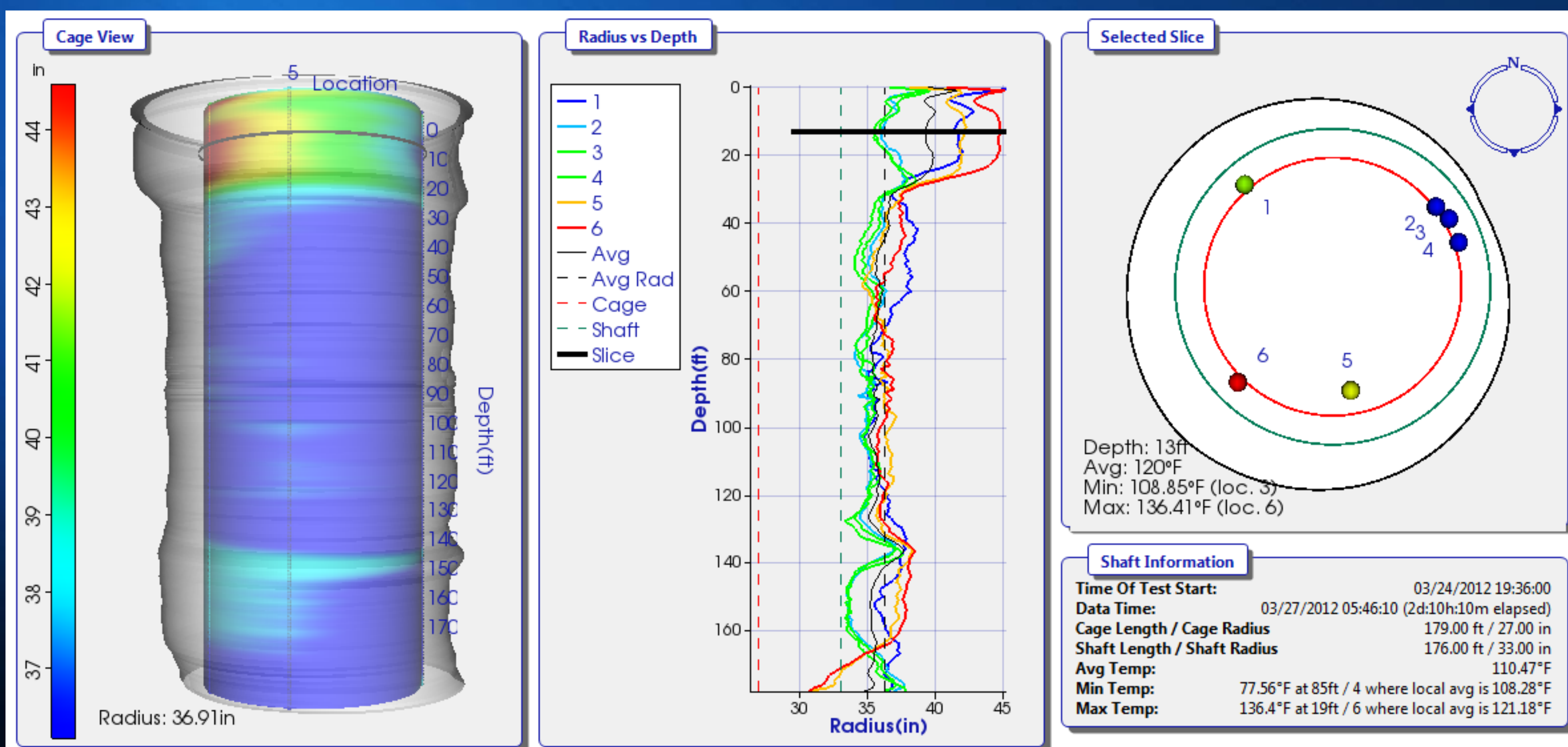


- Provides near probe information
- Cesium 137 Source
- Single-hole logging technique
- Typically used to determine rebar “cover”
- Air or water-filled PVC or steel access tubes
- GDL allows for precise Characterization of soil intrusions or other anomalies at a radius of about 8 inches both inside and 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.

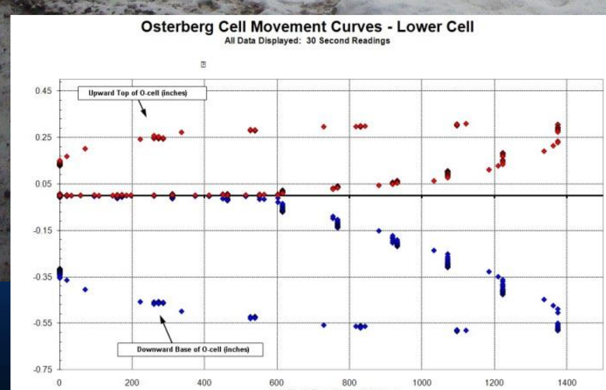
Thermal Imaging

- Newer Technique
- Uses CSL tubes
- Inside and Outside Rebar Cage



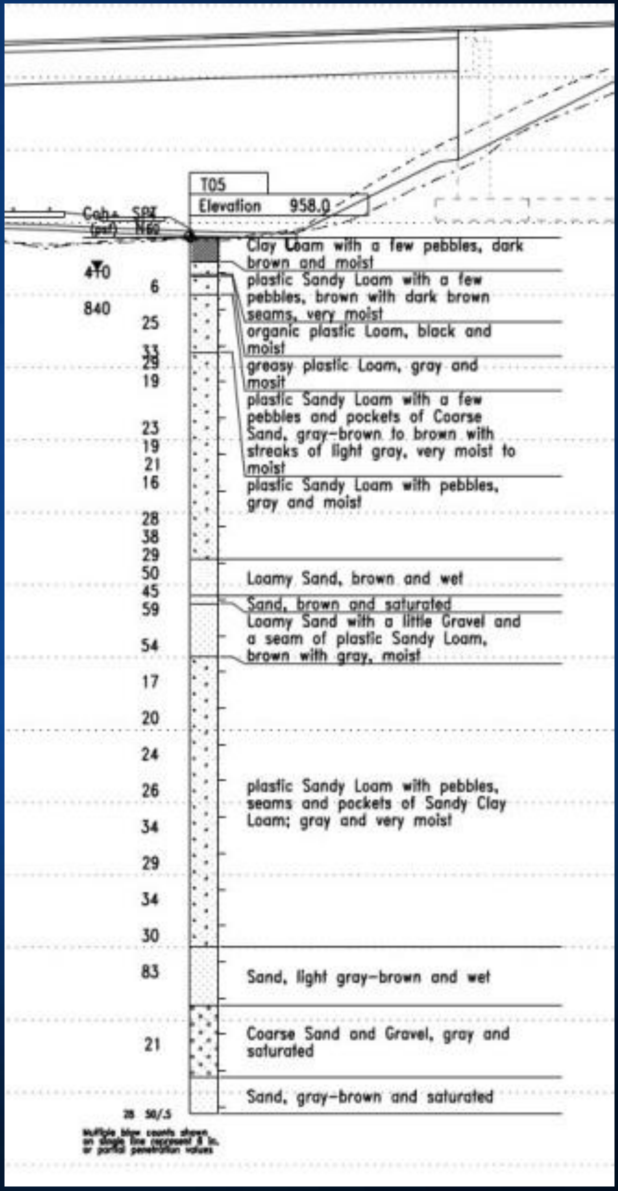


Performane QC/QA Testing: O-cell



Pile* Driving Construction Control

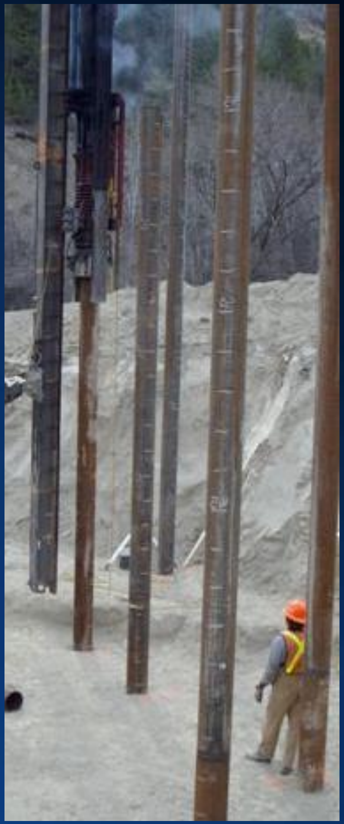
- Static Prediction Methods
  - Usually used to estimate pile quantities
- *WEAP (Wave Equation Analysis)
- *Dynamic Formulas
  - Most Common Field Practice
  - Inexpensive/perform well
- *High Strain Dynamic Monitoring (PDA/CAPWAP)
- Static Load Testing (SLT)



"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

Driven Piles:

- 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)

Driven Piles:

- 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 asses damage for other pile types (H-pile, concrete)
  - Soil is not removed*
    - No spoil
    - No caving, heave, or loss of support

*(unless open-ended)

Driven Piles:

- 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:

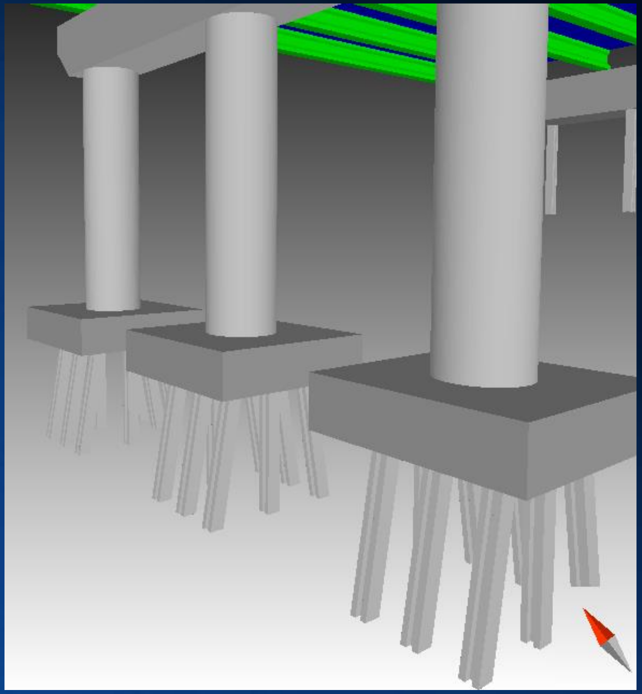
- Disadvantages
  - Perception of noise and vibration may limit foundation choices depending on project location
  - Impact driving may be restricted (particularly with displacement piles) near other foundations or older utilities due to concerns with damage
  - Displacement may cause heave
  - Driven 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).

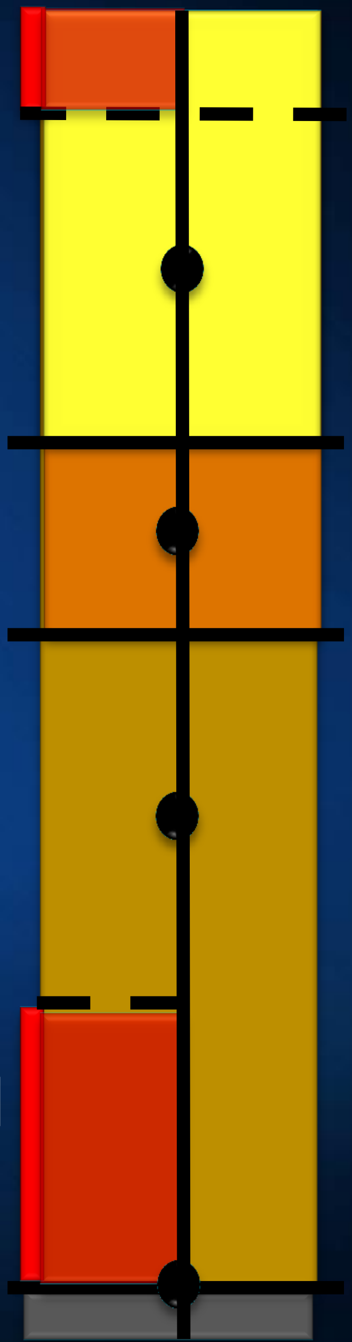


Driven Piles:

- 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)

Design Overview

- Total Resistance has 2 components:
  - Side
  - Base† †(compression)
- Total Resistance will depend on:
  - Geometry
  - Material Properties (α, β, empirical, rock)
  - Stratigraphy
  - Shaft Exclusion Areas (top and base)
- Apply LRFD Factors based on:
  - Pile: Static Methods/Construction Control
  - Shaft: Soil (c-φ)/IGM/Rock & (Shaft,Base)

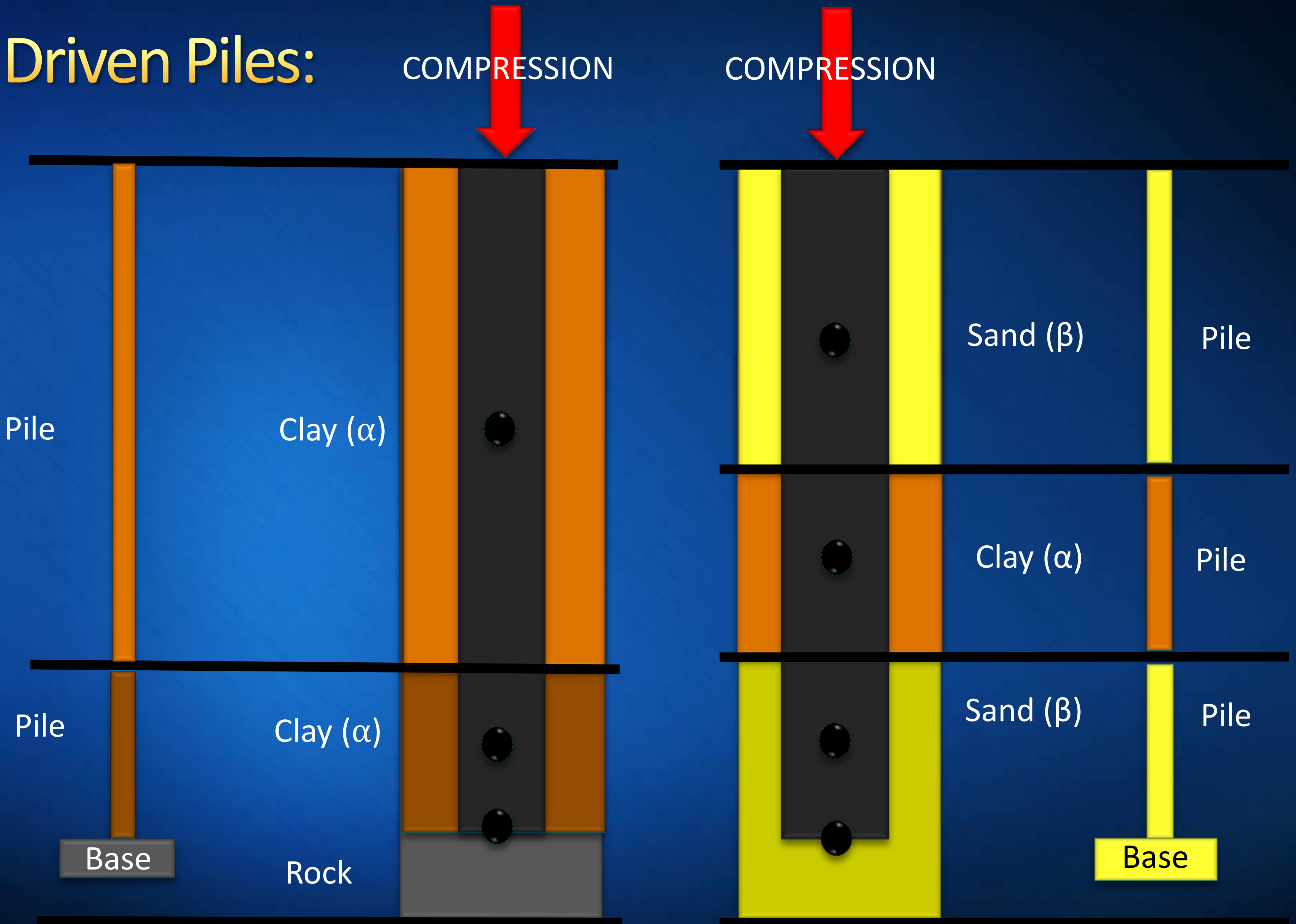


Pile Design Methods (Continued)

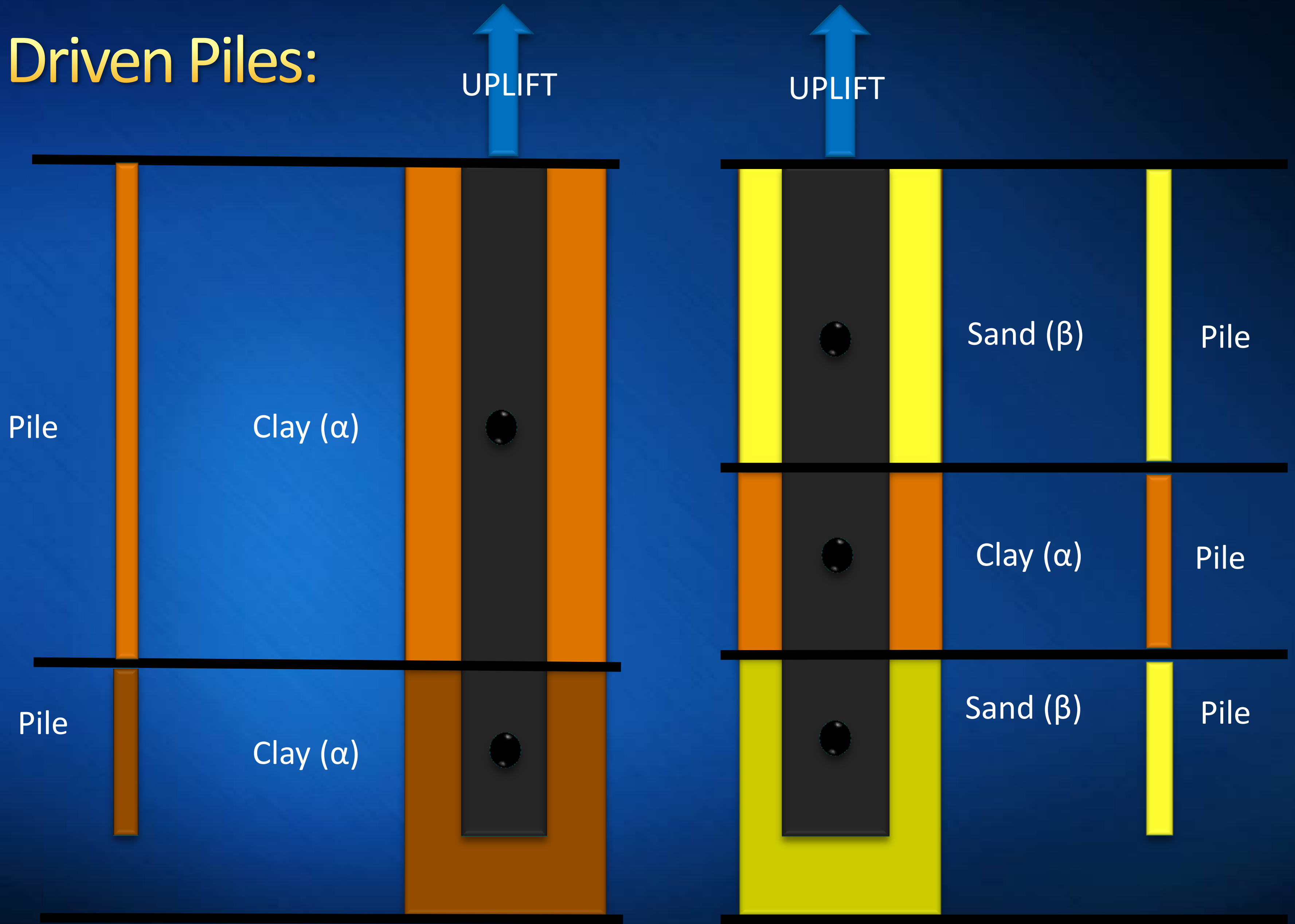
- α Method (Tomlinson), FHWA cohesive
- β Method (Nordlund), FHWA frictional
- USACE Method (α, β elements)
- Revised λ Method
- API (Method 2A Revised) (cohesive + frictional)
- **Representative DIRECT CPT Methods**:
  - NGI, MTD [available in APILE 5.0]
  - Schmertmann and Nottingham (1975,1978)
  - deRuiter and Beringen (1979)
  - LCPC, Bustamante and Gianeselli (1982)
  - Myerhof (1956, 1976, 1983)
  - Tumay and Fakhroo (1981)
  - Eslami Fellenius (1996)

There are more CPT methods (not shown)

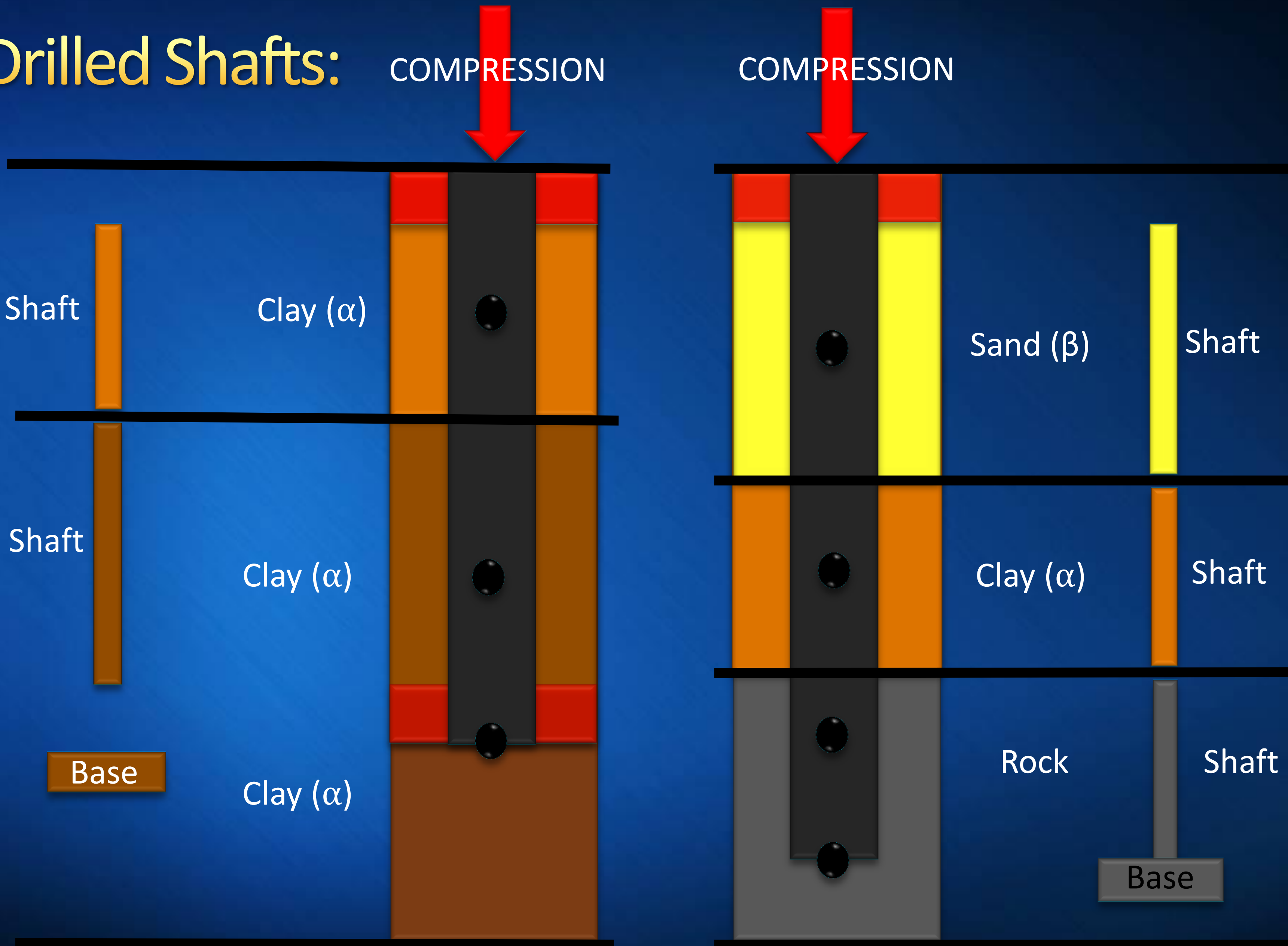
Driven Piles:



Driven Piles:

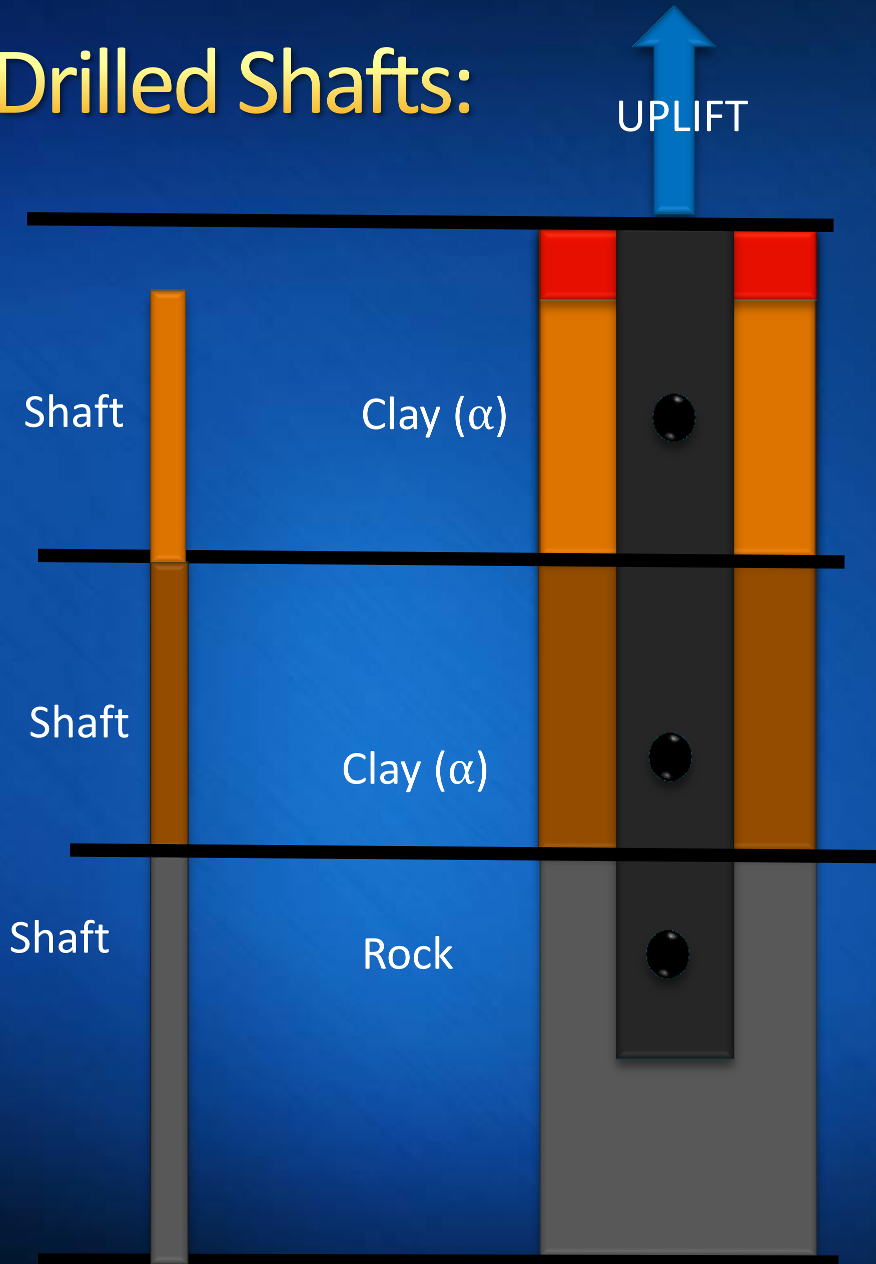


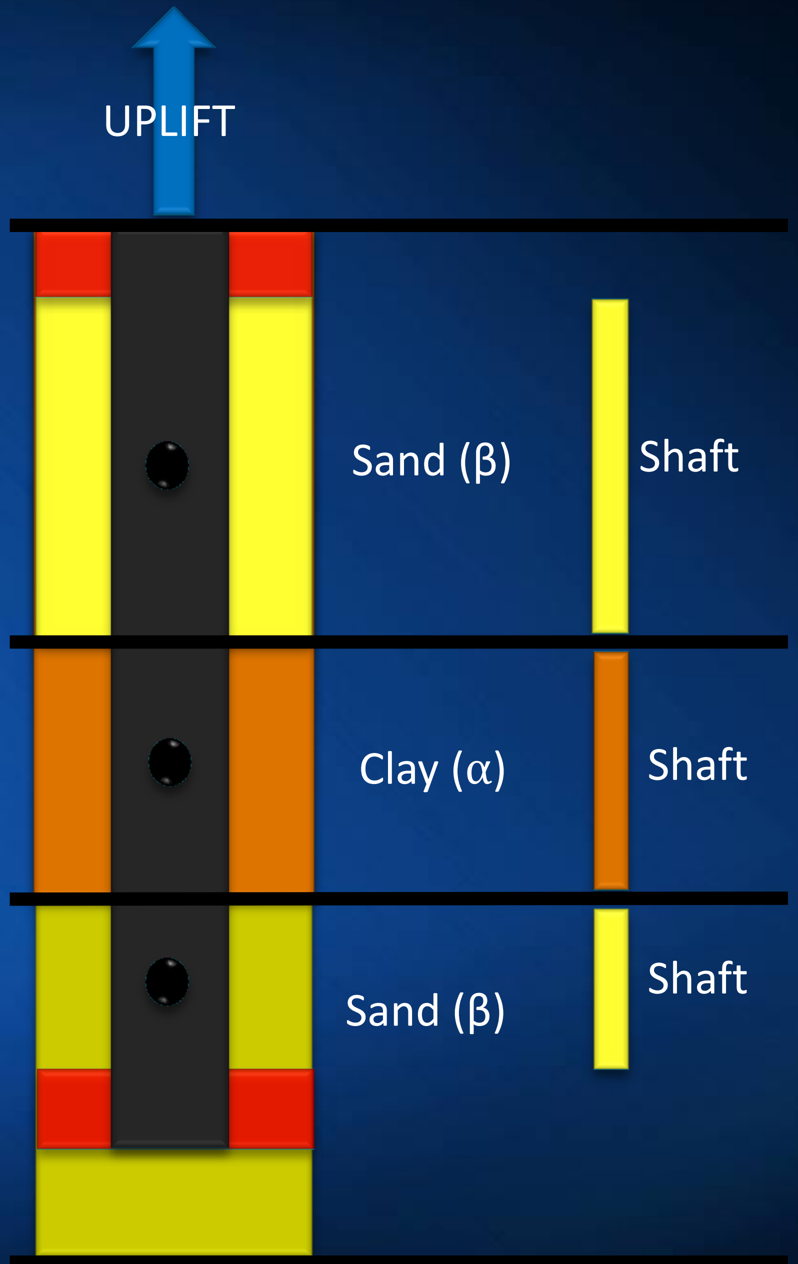
Drilled Shafts:



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

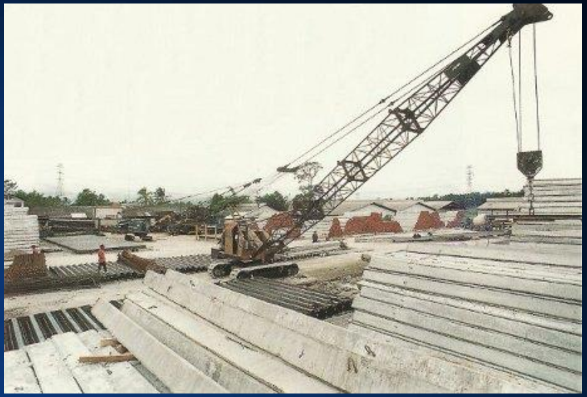
Foundation Costs

- 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


27 July 2004

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





Loading and Redundancy (Generalized)

Driven Piles

- Smaller elements
- Lower capacity
- Lower cost
- More elements used
- Highly redundant
- Simple field inspection

Drilled Shafts

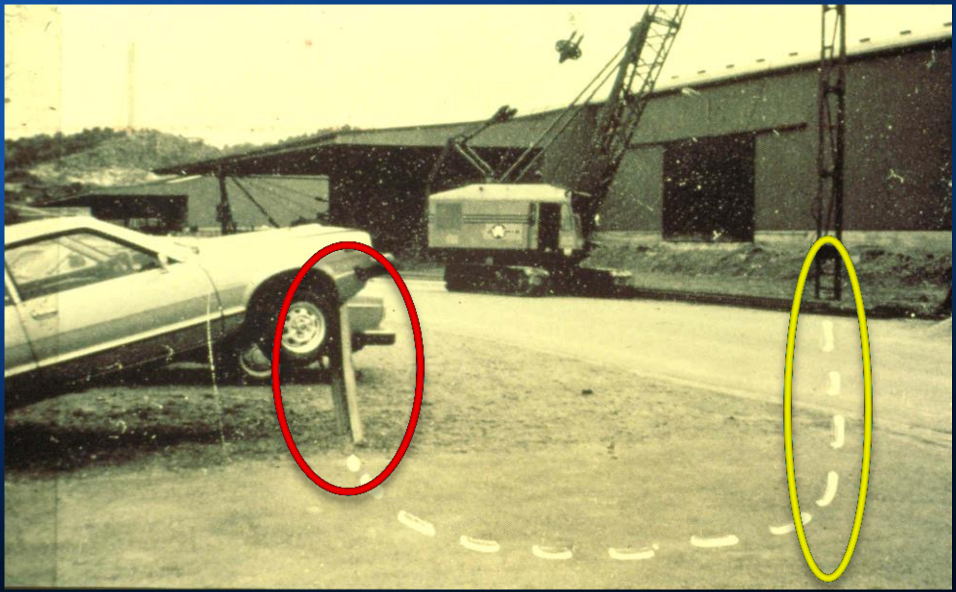
- Bigger elements
- Higher capacity
- Higher cost
- Fewer elements used
- Little to no redundancy
- More complex field inspection

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 traveller)
  - $75 million settlement

WEDNESDAY APRIL 14, 2004 • TAMPA, FLORIDA • TBO.com LIFE. PRINTED DAILY.

THE TAMPA TRIBUNE

CROSSTOWN COLLAPSE 4-PAGE SPECIAL REPORT

COMMUTING SINKS

WHAT HAPPENED: A section of the elevated road being built over the Lee Roy Selmon Expressway caved in Tuesday.

WHAT IT MEANS: Traffic will be a nightmare as the Selmon remains open but lanes are restricted near the collapse.

WHAT'S NEXT: The collapsed decks will be dismantled, but the contractor says the new road will still open on schedule in July 2005.

The partial collapse of the Lee Roy Selmon Expressway's elevated portion is thought to have been caused by a sinkhole deep underground.

Soil-Testing Methods Under Scrutiny

By TOM BRENNAN

TAMPA — It started with a slight tremble, quickly sent a major tremor through workday commutes and undermined some motorists' confidence in the high-tech highway being erected in the median of the Lee Roy Selmon Expressway.

A concrete pier sank 20 feet just west of 50th Street about 7 a.m. Tuesday, bringing down the two spans of the new elevated road deck it was supporting along with it. The collapse injured two workers, cracked windshields of vehicles traveling on the expressway below and brought traffic nearly to a standstill for tens of thousands of commuters.

No cars were on the deck because the road isn't open yet.

Authorities shut down the expressway from U.S. 301 to 22nd Street and kept it closed between 50th and 39th streets until 3 p.m., when a single lane was opened in each direction.

Officials with the Tampa-Hillsborough County Expressway Authority, which oversees the expressway and construction of the elevated, reversible road being built above its median, blamed the collapse on a sinkhole that opened beneath the pier.

"As far as we know, it wasn't a design problem or a construction problem," said Pat McCue, the authority's executive director. "It is a natural occurrence that was impossible to predict."

The estimated 52,700 motorists

SOME SAY NEW TECHNOLOGY MIGHT HAVE DETECTED HOLE

CLOSEST KNOWN SINKHOLES

ALTERNATE ROUTES

- Adamo Drive
- Causeway Boulevard/22nd Street
- Interstate 4

TRAFFIC UPDATES

INSIDE

Case Studies-

- 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.

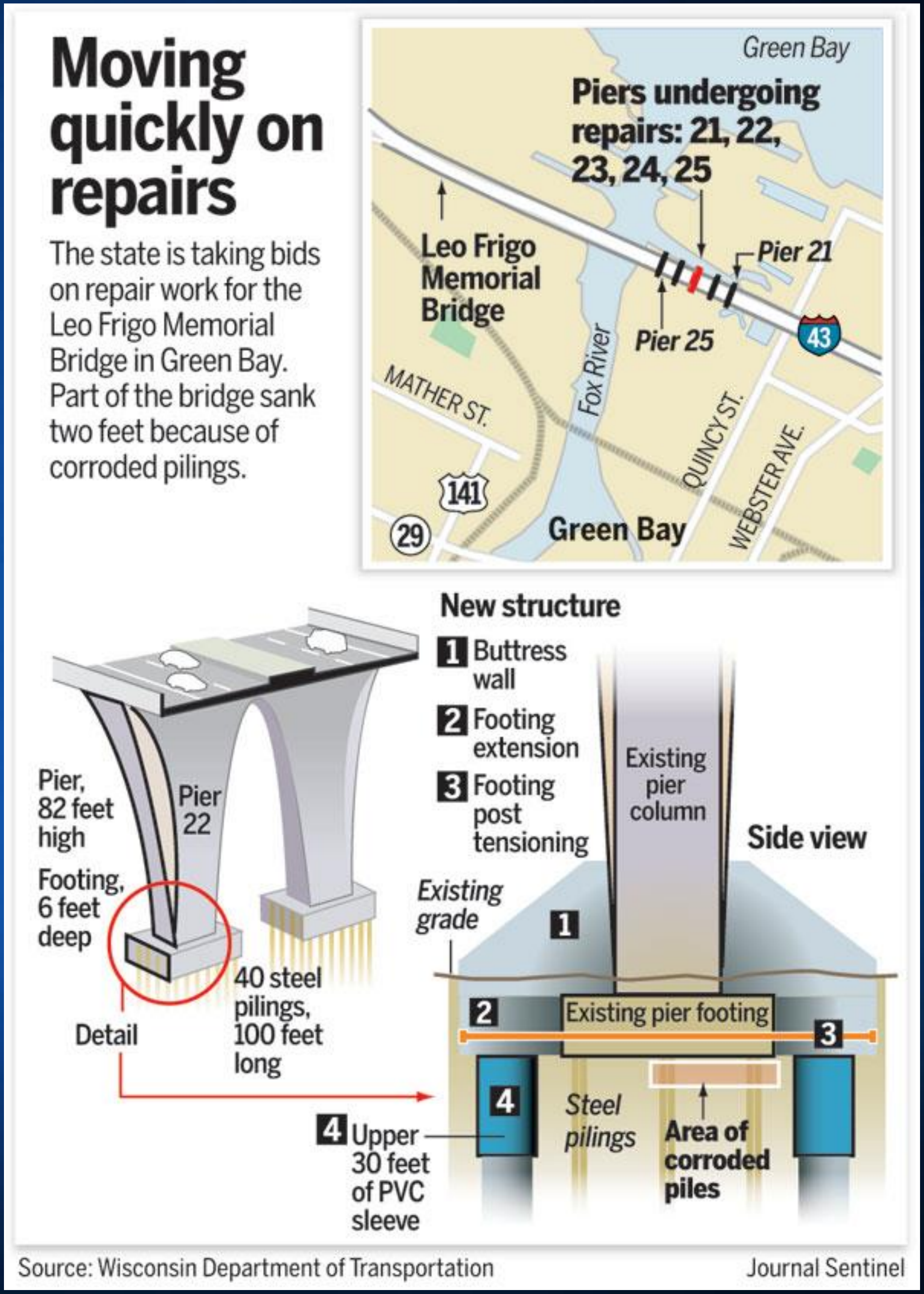
  Heavy rainfall may also have contributed to the collapse

  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

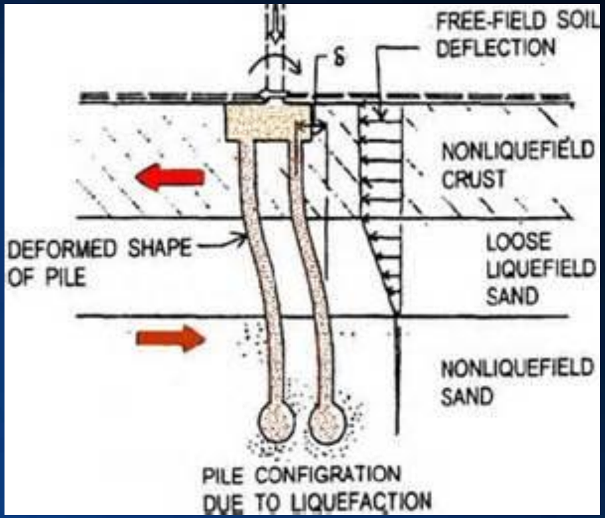
Case Studies-

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



Severe Foundation Failures are Rare

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



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