



Elective Course in Geotechnical Engineering

DESIGN OF PILE FOUNDATION

Civil Engineering Department

Fourth Year

Spring Semester

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Soil Mechanics and Foundations Research Lab

Faculty of Engineering- Cairo University

Lecture I



REVIEW OF PILE DESIGN AND CONSTRUCTION

Acknowledgment

- Prof Dr.Amr Elhakim
- Dr. Omar Ezzeldin

Lecture I Outline

- Piles Application
- Pile Types based on Construction
- Pile Axial Capacity
- Pile Tests

Introduction

Piles are vertical or slightly inclined slender structural elements placed in the ground to transfer the load from the superstructure to soils at some significant depth below the base of the superstructure.



Why use piles?

- The soil close to the base of the superstructure does not have sufficient bearing capacity.
- The soils immediately beneath the foundations are subject to scour/erosion.
- The estimated settlements exceed the allowable limits.
- Excessive differential settlements that are intolerable by the superstructure.

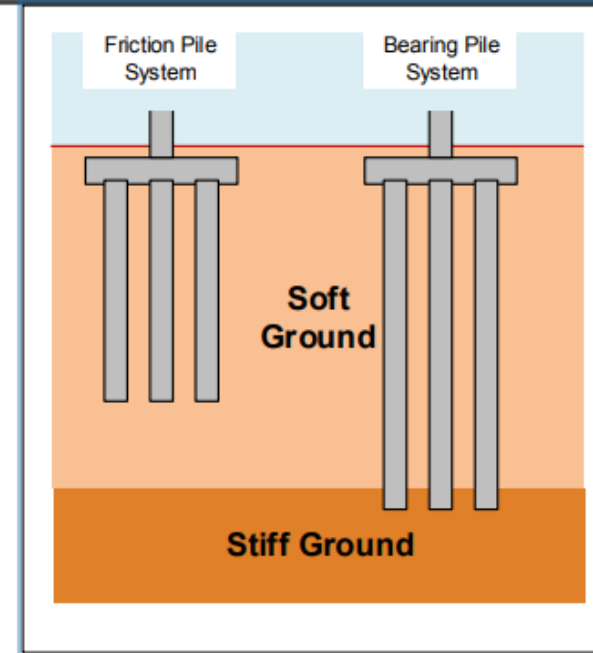
USES OF PILES

- **Foundation System**

- Friction Piles
- Bearing Piles
- Piles connected to pile caps
- Piles connected to raft foundation
- Pile supporting embankment

- **Lateral/Uplift Support**

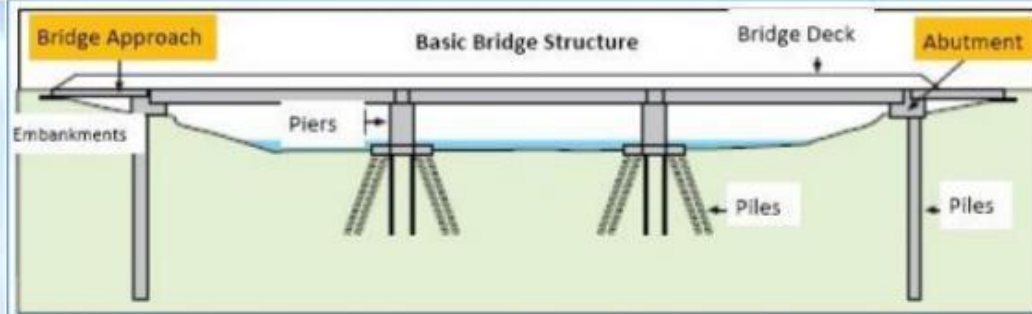
- Temporary System
- Permanent System
- Quay Wall Pile System
- Electric Post Pile Support



USES OF PILES VERTICAL LOADS



Pile Cap and Piled Raft System to support High rise Building



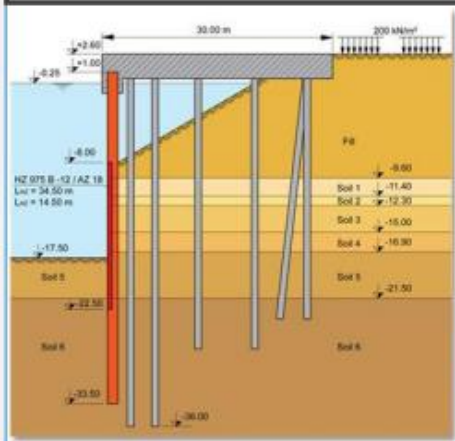
Piles supporting Bridge Piers and Bridge Abutments



CFA to support an Embankment
Square RC Precast Driven Piles to support an embankment



USES OF PILES COMBINED LOADS



Piles under Vertical and Lateral Loads to Support a Quay Wall



Battered Piles to support Lateral Loads of Bridge Piers



Secant Pile Wall to Support Deep Excavation Lateral Load



Contiguous Pile Wall to Support Deep Excavation Lateral Load

Secant Pile Wall

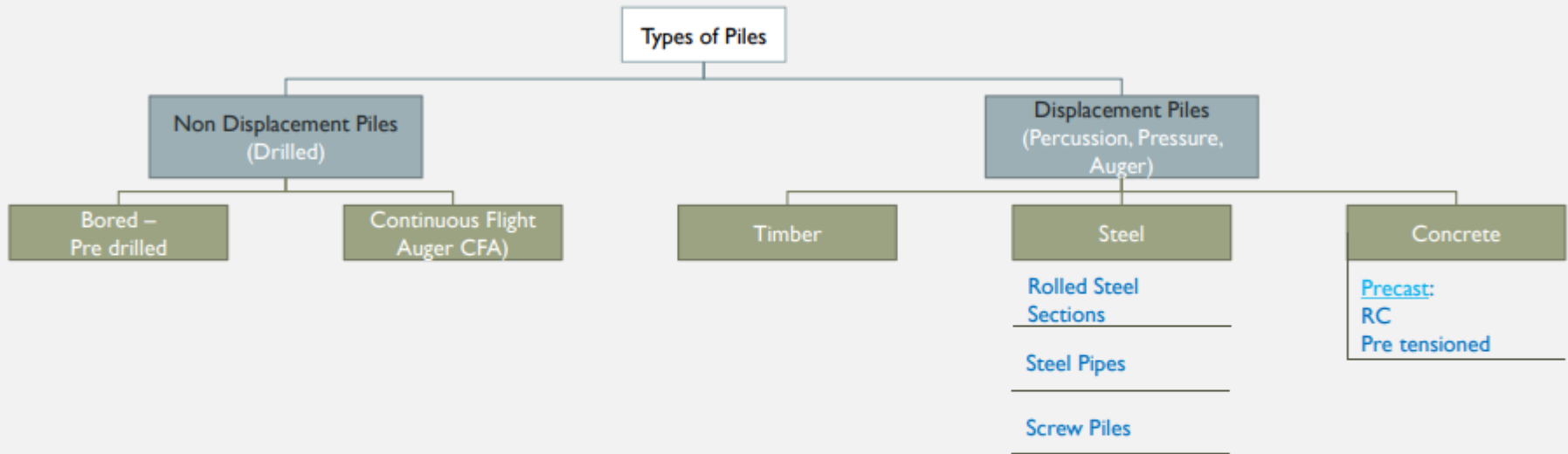


Tangent Pile Wall



Contiguous Pile Wall





Low Displacement



High Displacement



PILE TYPES

Pile Type	Typical Dimensions	Axial Load	Advantages	Disadvantages	Applicability
Bored	Length: 5m to 65 m Diameter: 500 mm to more than 2,000 mm	1,500 kN to 20,000 kN	<ul style="list-style-type: none"> • Length variation easily accommodated • High capacity and bending resistance 	<ul style="list-style-type: none"> • Extensive Inspection Required • Construction critical to quality • Boulders could cause problems 	<ul style="list-style-type: none"> • Construction process should suit existing ground. • Soft soils may cause necking problems
CFA	Length: 5m to 25 m Diameter: 300 mm to 600 mm	200 kN to 800 kN	<ul style="list-style-type: none"> • Economy • Zero Displacement • No vibrations • Visual inspection of excavated material 	<ul style="list-style-type: none"> • Dependence on quality workmanship • Capacity could not be estimated during construction (blow counts) 	<ul style="list-style-type: none"> • Not suitable through peat or highly compressible material

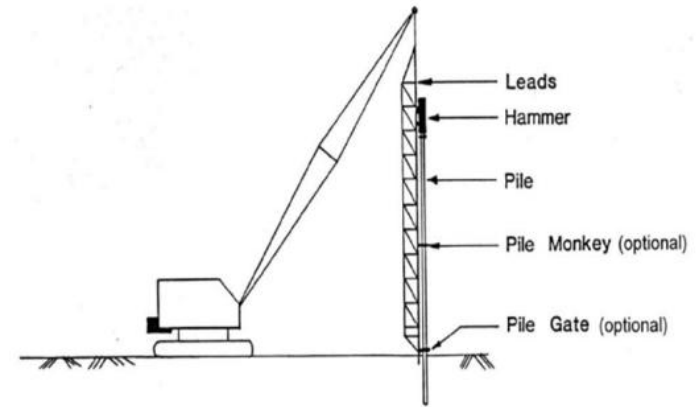
PILE TYPES

Pile Type	Typical Dimensions	Axial Load	Advantages	Disadvantages	Applicability
Timber (Driven)	Length: 5m to 37 m Diameter: 300 mm to 550 mm	100 kN to 500 kN	<ul style="list-style-type: none"> • Low Cost • Easy to Handle 	<ul style="list-style-type: none"> • Difficult to Splice • May be damages due to driving • Long term deterioration 	<ul style="list-style-type: none"> • Best suited for friction piles in granular material
Steel H Section (Driven)	Length: 5m to 40 m Size: Variable	600 kN to 2,500 kN	<ul style="list-style-type: none"> • Available in various lengths and sizes • High capacity • Small soil displacement • Easy to splice • Can penetrate light obstructions 	<ul style="list-style-type: none"> • Corrosion • May be deflected due to hard obstructions 	<ul style="list-style-type: none"> • Best suited for toe bearing rock
Steel Pipe Piles (Driven)	Length: 5m to 40 m Diameter: 200 mm to 1220 mm Without core 300 mm to 900 mm With core	800 kN to 2,500 kN Without core 2,500 kN to 15,000 kN With core	<ul style="list-style-type: none"> • Closed pipe can be inspected after driving • Open end pipe with cutting shoe can be used against obstructions • Open end pipes can be cleaned and driven further • High load capacity • Easy to splice 	<ul style="list-style-type: none"> • Soil displacement for closed end pipe 	<ul style="list-style-type: none"> • High bending resistance (lateral load resistance) • Open end not recommended for friction pile in granular material
Precast Concrete Piles	Length: 15m to 40 m (Pre stressed) 10m to 15 m (Reinforced) Diameter: 900 mm to 1600 mm	400 kN to 4,500 kN (Pre stressed) 400 kN to 1,000 kN (Reinforced)	<ul style="list-style-type: none"> • High load capacity • High corrosion resistance • Hard driving possible 	<ul style="list-style-type: none"> • Handling damage • High breakage rate especially with splicing • High displacement • Difficult to splice 	<ul style="list-style-type: none"> • High bending resistance for cylindrical piles

Types of piles - installation

- Piles can be installed by:

- Driving.
- Boring.
- Jetting.
- Jacking.



Precast Piles



H Piles



Steel or Pipe Piles



Continuous Flight Auger Piles

- **Ultimate Pile Vertical Resistance:**

- $Q_{ult} = Q_f + Q_b - W$
 - W : Pile Weight (extracted soil weight could be taken into consideration)

- **Allowable Pile Vertical Resistance**

- $Q_{all} = \frac{Q_f}{FS} + \frac{Q_b}{FS}$
 - $FS=3.0$, $FS=2.5$ if wind loads are taken into consideration, $FS=2.0$ if seismic loads are considered.

- **Using SPT (N) Results:**

- $Q_{all} = \alpha \left[\bar{N}(\pi DL) + 90N \left(\frac{\pi D^2}{4} \right) \right] \quad (kN) \quad \alpha = 0.5 \text{ to } 1.0$
 - D : pile diameter
 - \bar{N} : average SPT (N) over the sub-segments constituting the total length of the pile (L)
 - Q_{all} includes $FS=2.5$ for end bearing and $FS=2.0$ for friction.

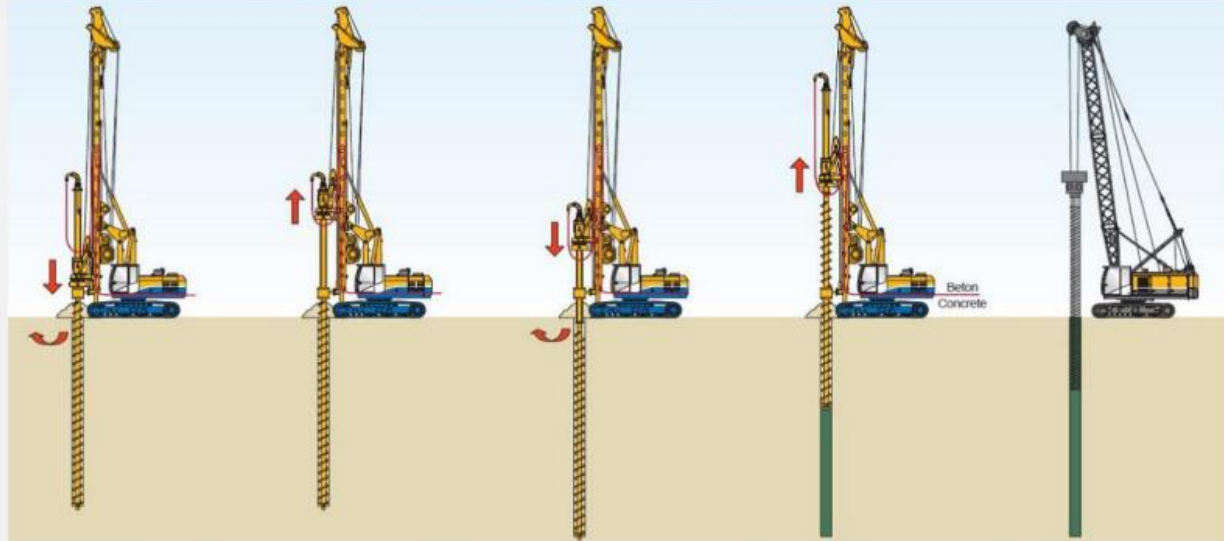
- **Using Cone Penetration Results**

- $Q_{all} = \alpha \left[\frac{f_c}{2}(\pi DL) + \frac{q_c}{3} \left(\frac{\pi D^2}{4} \right) \right] \quad \alpha = 0.5 \text{ to } 1.0$
 - f_c : sleeve friction of the cone
 - q_c : cone resistance
 - Q_{all} includes $FS=3.0$ for end bearing and $FS=2.0$ for friction.

CONTINUOUS FLIGHT AUGER PILES CONSTRUCTION SEQUENCE

1. Drilling

- An Auger penetrates the ground with a rotary speed and a penetration rate that should be adjusted to ensure the preservation of the sides of excavation.
- The auger should penetrate to the full design length of the pile. Hence, **pile length restriction** and **Headroom** requirement according to existing auger splicing.
- Some construction techniques result in creating displacement to the ground (partial or full displacement) which should increase pile capacity.



2. Concreting

- Once the auger reaches the intended bottom of excavation, concreting starts **immediately** from a pipe inside the auger.
- Concrete dispensing is synchronized with auger withdrawal rate in order to ensure that fresh concrete is always under pressure and soil is prevented from precipitating into the hole.
- The auger normally does not rotate at the withdrawal stage. Sometimes very slow rotation of the auger is permitted at the drilling direction to facilitate auger extraction.

3. Installing Steel Cage

- Once the auger is fully withdrawn from the ground, the steel concrete should be placed **immediately** while concrete is still fresh.

CONTINUOUS FLIGHT AUGER PILES GENERAL



Auger Withdrawal



Auger Requires High Headroom to limit Auger Splicing



CFA could be used for Secant Pile Walls

Diameter ranges between 0.3 m to 0.6 m
Pile Length should be less than 30 m

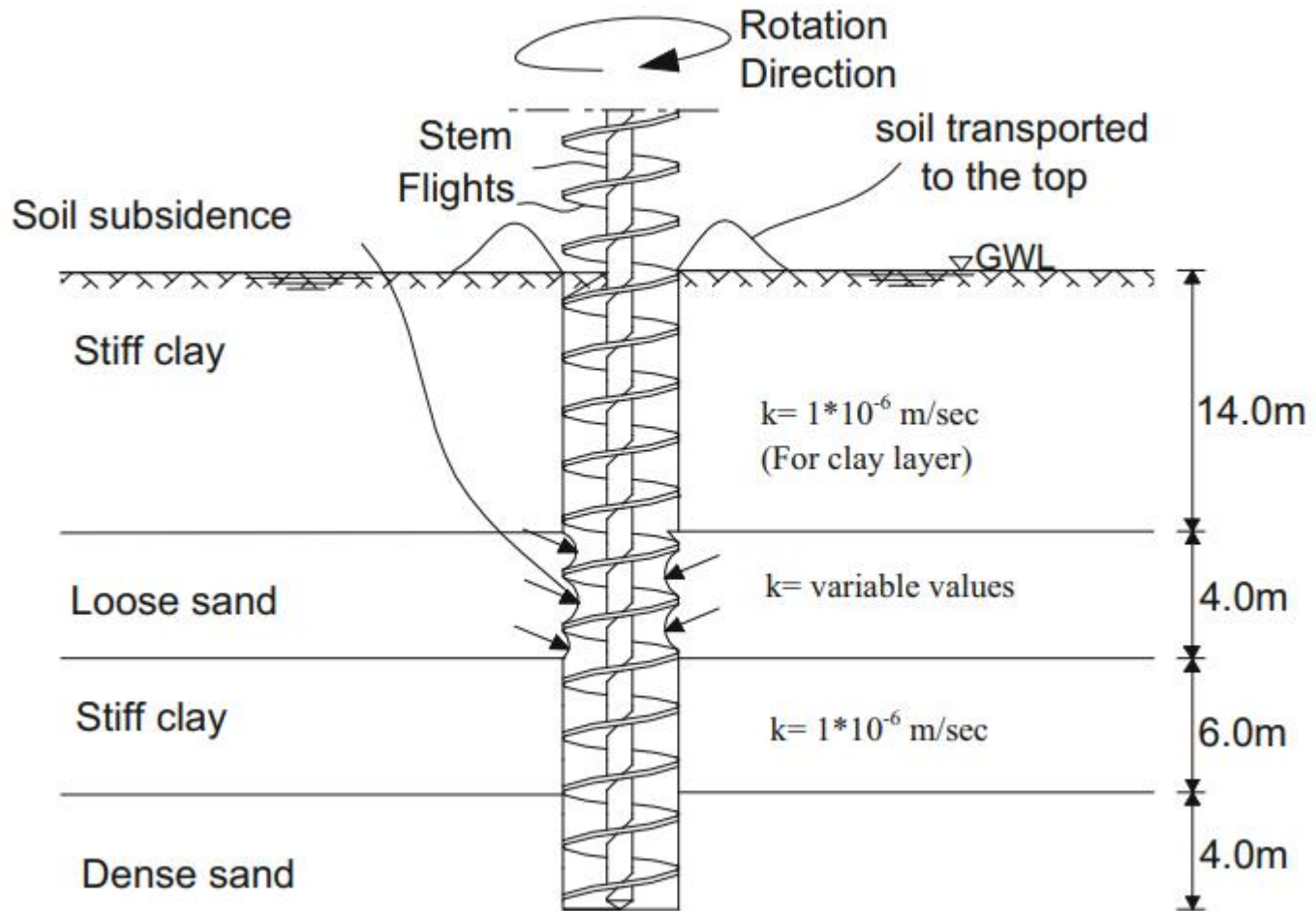


CONTINUOUS FLIGHT AUGER PILES ADVANTAGES / DISADVANTAGES

- Diameter ranges between 0.3 m to 0.6 m. In some extreme case, the diameter could reach 0.9 m .
- Pile Length should be less than 30 m.
- Pile vertical load capacity ranges between 50 kN to 2 000 kN (5 ton to 200 ton).
- Applications:
 - Buildings
 - Transportation Structures
 - Earth Retention Walls
 - Ground Improvement
- Advantages:
 - No vibration,
 - Low noise levels,
 - No temporary casing required,
 - Speed of installation, and
 - Lower unit cost
 - Ideal for projects requiring large number of piles (embankment support, ground improvement, etc.)

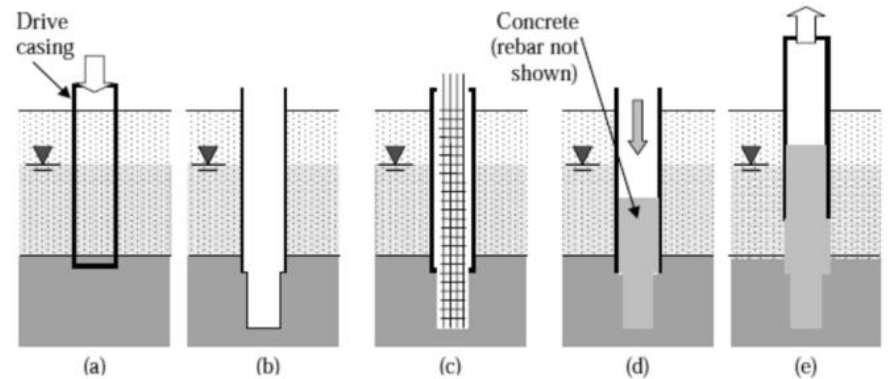
- Disadvantages:
 - Quality Control and Structural Integrity are questionable.
 - Low vertical capacity, limited ability to resist lateral or tensile loads
- Favorable Ground Conditions:
 - Medium to very stiff cohesive Soil,
 - Cemented Sand or weak limestone,
 - Medium dense to dense silty sands and well-graded sands,
 - Rock overlain by stiff or cemented deposits.
- Unfavorable Ground Conditions:
 - Very soft soils
 - Loose sands or very clean uniformly graded sands under groundwater
 - Geologic formations containing voids, pockets of water, lenses of very soft soils, and/or flowing water
 - Obstacles
 - Highly variable ground conditions

Affecting Neighboring structures

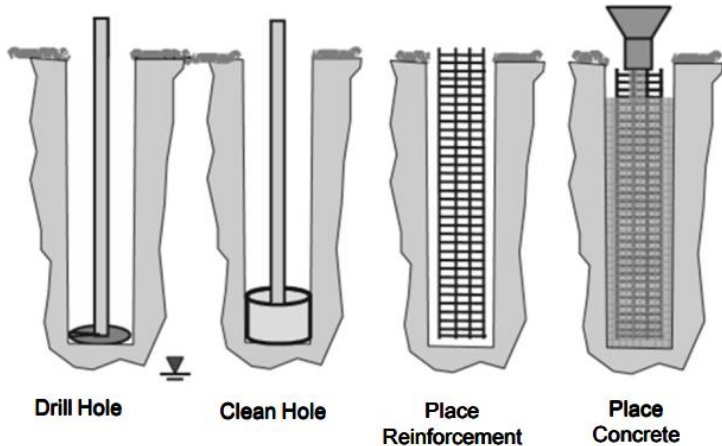


Boring Methods

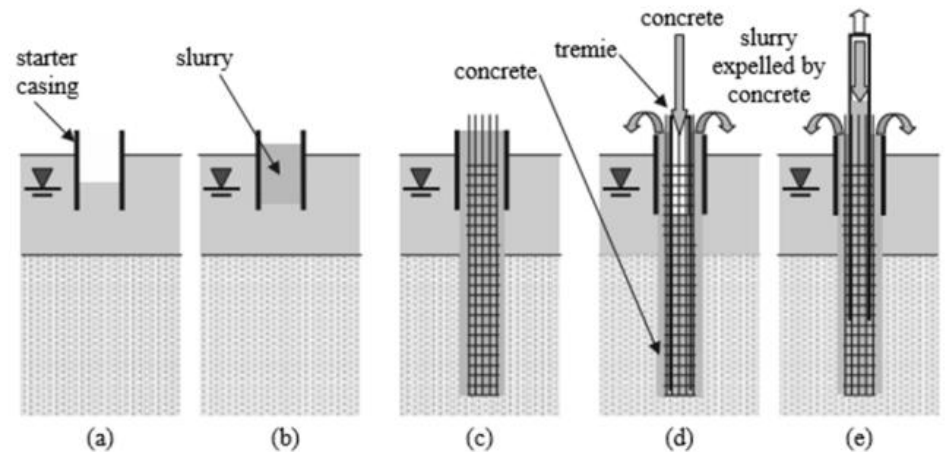
Casing Method



Dry Method



Wet Method



BORED PILES CONSTRUCTION

- Drilling should be able to advance through potentially difficult ground conditions such as rock, boulders, etc.
- Drilling should be able to advance through weak soil layers, especially below the ground water table, without allowing the boundary of excavation to cave into the drilled void.
- The boundaries of the drilled hole must be kept stable to ensure good contact between pile material and the surrounding soil layers and to ensure that the bearing stratum is intact.
- Pile material (concrete and steel cage) should be placed such that it will produce the structural capacity as per pile design. Structural strength of pile material in compression, tension, and flexure should be sufficient to transfer all loading conditions as per pile design.
- Construction methods of bored piles are classified into the following three groups:
 1. The dry method.
 2. The casing method.
 3. The wet method.

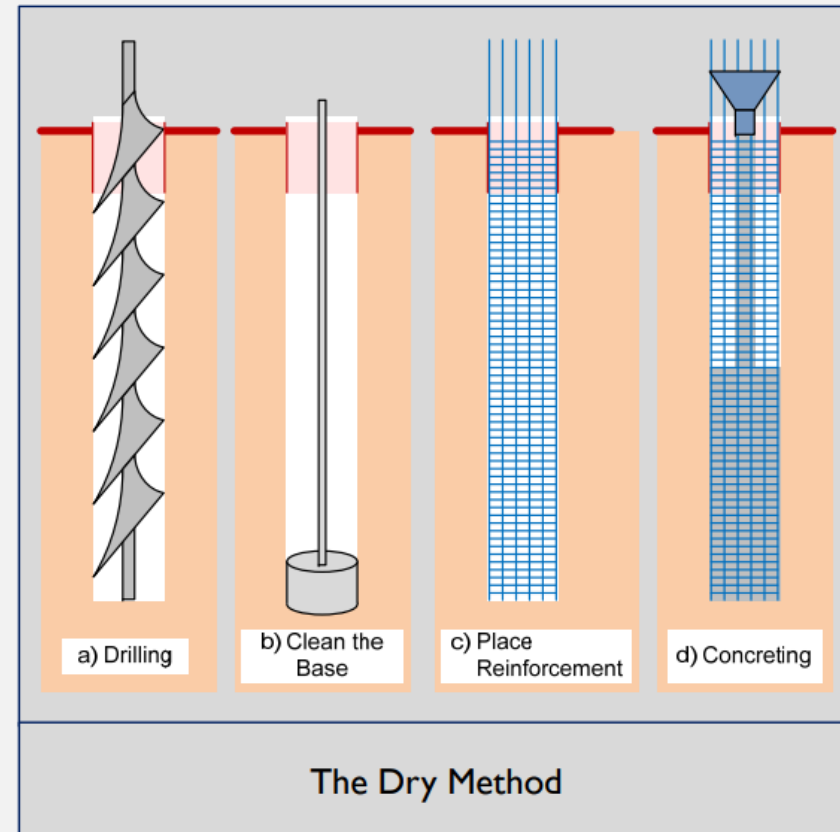
BORED PILES CONSTRUCTION METHOD I: THE DRY METHOD

- **Applicability:** Dry hole method of construction is applicable in the following conditions:

1. Competent soil and rock that is above the water table. There is no concern that the ground will cave or slump when the hole is drilled to its full depth during the period required for installation of the drilled shaft.
2. Homogeneous stiff clay where drilling is undertaken down to moderate depth (about 15 m) even below the ground water table where low permeability can sustain the excavation boundaries until pile installation is achieved.
3. Sands above the water table if the sands contain some cementation that will provide sufficient apparent cohesion after drilling is finished.

- **Four steps are made during the construction:**

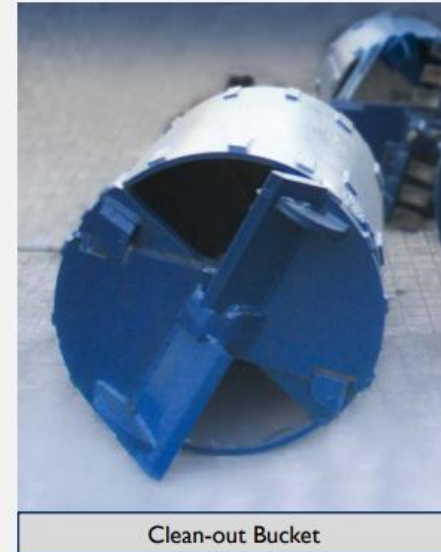
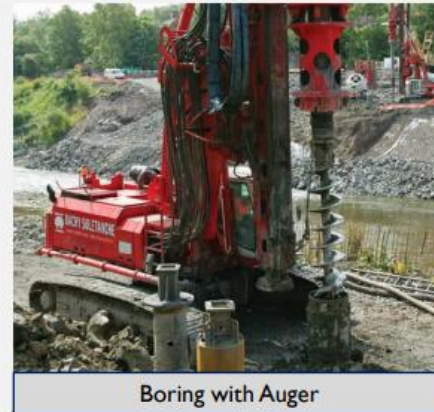
1. Drilling: The shaft is excavated using augers which should be capable to break through the soil.
2. Cleaning and inspection of bottom of excavation: The base is cleaned using a bucket or flat bottom tool to remove loose debris and possibly any small amount of water
3. Placing the steel reinforcement cage, and
4. Concreting.



BORED PILES CONSTRUCTION METHOD 1: THE DRY METHOD

- **Construction Steps:**

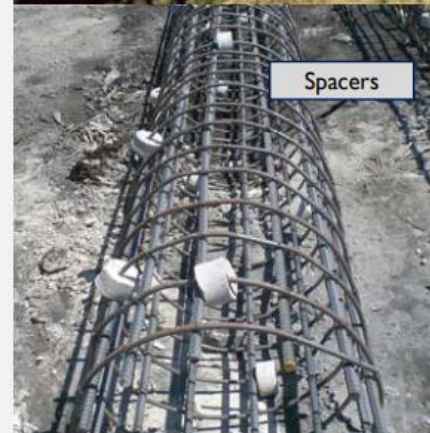
1. A **Surface casing** is to be installed at the top of drilling hole. This casing is supplied because, typically, soil near the surface tends to cave in. The casing supports surface ground layers and protects the excavation especially if the drilling rig is close to the hole. In practice, it serves as a tool guide and safety barrier. This casing could be removed after construction completion or could be left permanently.
2. **Rotary auger** is normally used for dry excavation method. The auger is required to extract as much spoil in every pass until it reaches the full excavation depth. Spoil material is removed from the site by loaders or other equipment.
3. After the excavation has been carried to its full depth, a different tool such as a special **clean-out bucket** is often used to clean the base of the excavation of loose material. Sometimes, hand cleaning could be used provided safety requirements are fulfilled.



BORED PILES CONSTRUCTION METHOD I: THE DRY METHOD

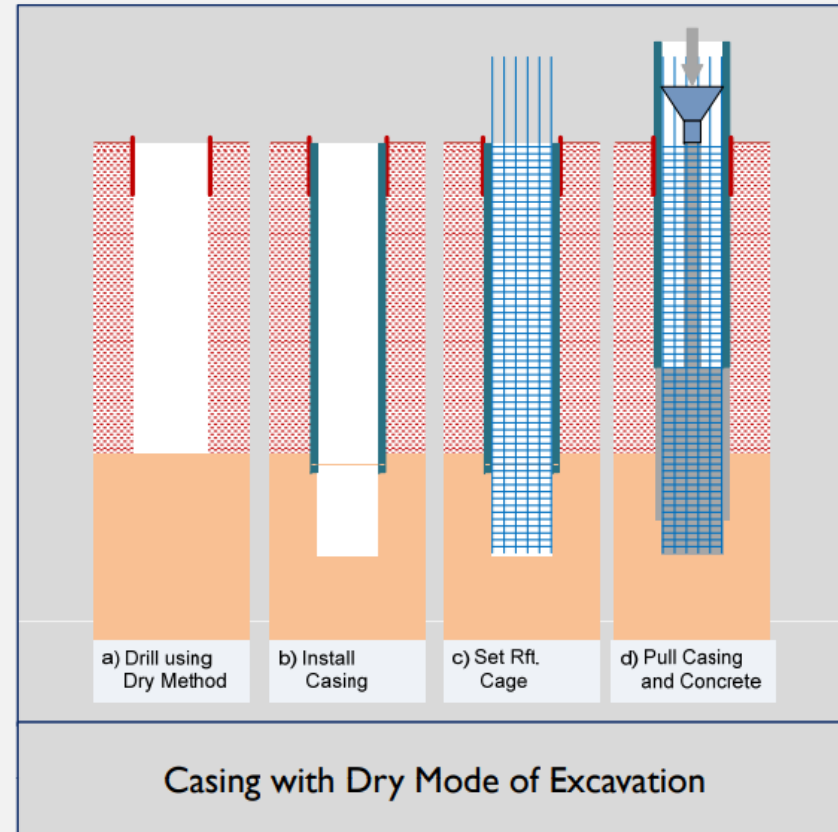
• Construction Steps:

4. The base of excavation should be **inspected** after cleaning and should be approved before moving to the next step of installing the steel cage.
5. **Feet Chairs** are used at the end of the steel cage in the case the cage extends to the full length of the pile. These spacers ensure that the cage is uniformly resting at the bottom of excavation.
6. Along the pile shaft, **spacers and centralizers** are normally installed with the reinforcement cage to ensure that the cage is well centralized and to guarantee a uniform concrete cover as per design.
7. **Concreting** should be carried out such that the flow of concrete should be directed to the center of the shaft and thus avoiding dislocating the steel cage. Tremie pipe is commonly used to direct concrete to the center of the shaft.
8. Construction of a shaft using the dry method and open holes should generally be completed in one continuous operation without stopping.

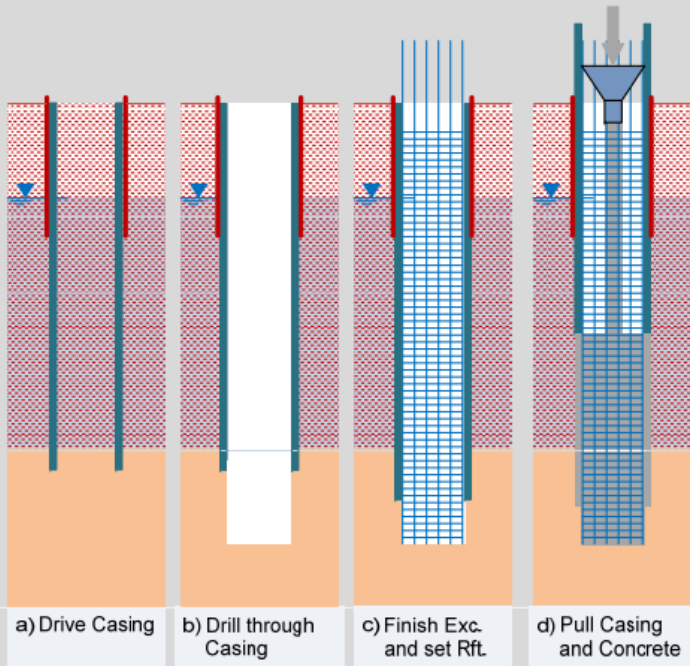


BORED PILES CONSTRUCTION METHOD 2: THE CASING METHOD OF CONSTRUCTION

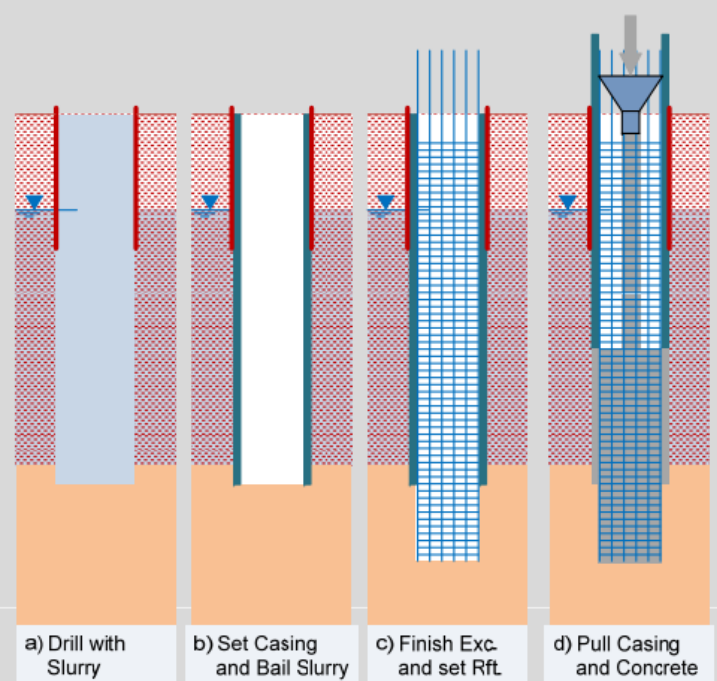
- **Applicability:** Casing method of construction is applicable in the following conditions:
 1. To protect the pile shaft excavation from caving or excessive deformation of the ground material at the perimeter of the excavation.
 2. In the case drilling is required to be advanced through permeable soil below the ground water table.
 3. Casing should be extended to reach a dry stable ground formation, otherwise drilling fluid should be used.
- **Three sub-categories of Casing Methods are used:**
 1. Casing is associated with dry mode of Excavation.
 2. Casing pushed into the ground.
 3. Casing is associated with drilling fluid.



BORED PILES CONSTRUCTION METHOD 2: THE CASING METHOD OF CONSTRUCTION



Casing pushed into the ground



Casing with Drilling Fluid

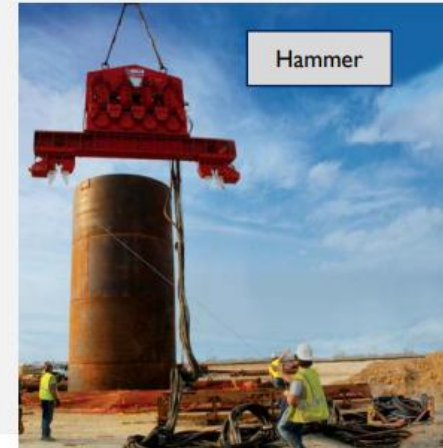
BORED PILES CONSTRUCTION METHOD 2: THE CASING METHOD OF CONSTRUCTION

Notes

1. Typically, casings are made of steel and are recovered as concreting takes place. In some instances, casings are left in place and are considered as **permanent casing**. In this case, they are either used as a form or they are used as a structural element in the bored pile design.
2. Sometimes casings are equipped with **cutting teeth** or **cutting bits** to assist they advance through rock material.
3. Care should be taken to ensure that the casing is well sealed inside the bearing strata to avoid caving or seepage from underneath the casing.
4. Casings are normally driven using **hammer** or **oscillators** that should be capable to achieve acceptable advance rate without damaging the casing itself.
5. Care should be taken during lifting the casing in order to preserve always the sealing effect between the casing and the concrete. Failure to do so, will result in ground water flowing into the pile shaft and hence, contaminating the concrete.
6. The reinforcement cage usually extends to the full depth of the pile in order to preserve its position during lifting the casing. The steel cage should be stable under its own weight.
7. The concrete used with the casing method must have good flow characteristics in order to flow easily through the reinforcing cage.
8. Downward movement of the cage upon casing withdrawal could indicate that the concrete is pulling the cage laterally toward a void or that the cage is dragged downward into a distorted position.
9. Casing sometimes needs to be used to stabilize very deep shafts and/or into very strong soil or rock which may make it difficult to remove the casings. In such instances, contractors may choose to "telescope" the casing. With this approach, the upper portion of the shaft is excavated and a large-diameter casing sealed into a suitable stratum. A smaller-diameter shaft will then be excavated below the bottom of the casing and a second casing, of smaller diameter than the first casing will be sealed into another suitable stratum at the bottom of the second-stage of excavation.



Cutting
Teeth



Hammer



Oscillators

BORED PILES CONSTRUCTION METHOD 3: THE WET METHOD

The wet method is used in the case it is viewed that **dewatering is not recommended** either because it may have detrimental effect on pile behavior or because it is difficult to achieve. In this case, the entire piling operation including drilling, cleaning, setting reinforcement, and concreting is carried out in a wet condition. Drilling fluid could consist of water in the case the soil is stable against collapse or of slurry that will improve the stability of the hole.

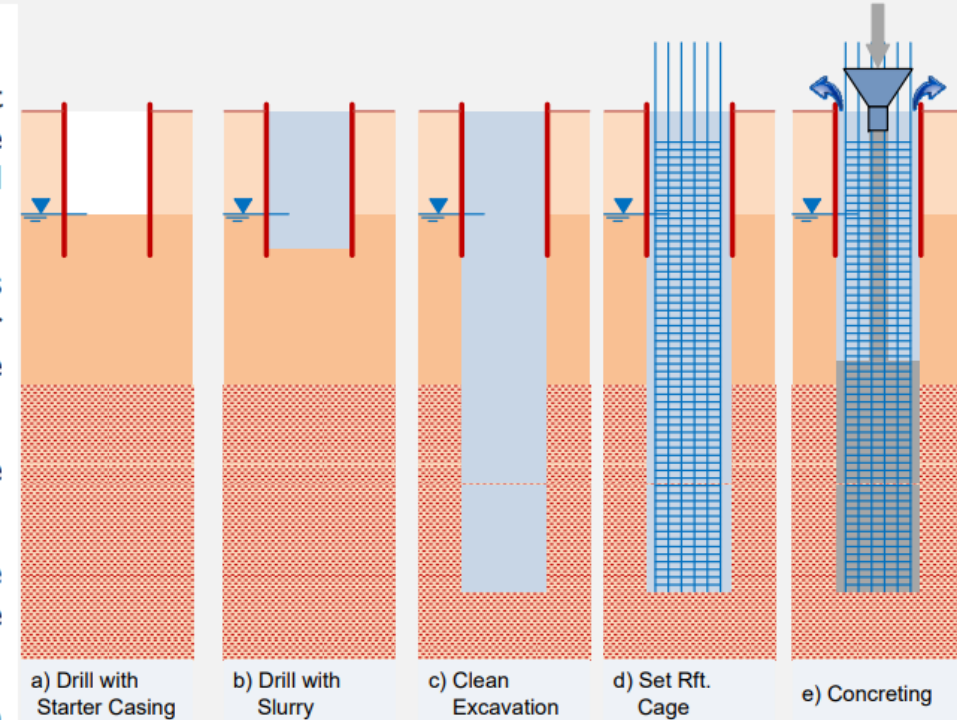
- **Applicability**

1. The pile is resting in **cohesionless material or other permeable layer**. The bottom of excavation could become unstable or severely disturbed there is water flow into the excavation. A drilling slurry will act to preserve the integrity of the excavation boundary as well as that of the bottom of excavation by stabilizing them and preventing water inflow.
2. The pile length passes through a **caving or permeable soils** at a depth and thickness that would not allow for a casing to be installed. In this case, drilling slurry will be used.
3. The **bearing strata is permeable** and dewatering will cause disturbance at the pile base. In this case, the pile could be cased before excavation and water is added into the casing to maintain a suitable hydraulic pressure at the base.
4. The bearing strata is stable but **water inflow through the base is too high to handle** (more than 0.3 m/hour) which will affect concrete placement.

BORED PILES CONSTRUCTION METHOD 3: THE WET METHOD

• Construction Method

1. A surface casing is installed as deep as necessary to prevent caving of surface layer. The casing could protrude above the ground surface if necessary to maintain an inside fluid level higher than 1.50 m above the existing ground water level.
2. Proceed with the excavation of the hole while always maintaining the fluid head above the existing ground water level by adding fluid as necessary to compensate losses due outflow. After cleaning the base, the reinforcing cage is placed.
3. Concrete is placed using tremie which will dispense concrete at the base of the shaft and displaces the slurry upward.
4. The slurry is pumped out of the hole and the pumping rate depends on the quantity of concrete dispensed into the hole in order to maintain the slurry level inside the hole.
5. The bottom of the tremie should always be at least 3.0 m below the surface of the fresh concrete in order to prevent contaminating the concrete with the slurry.

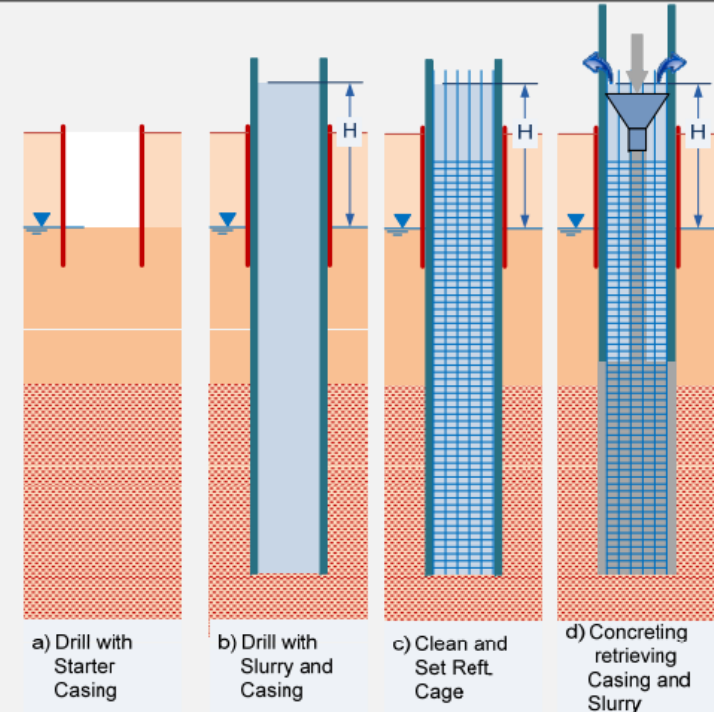


Wet method without Casing

BORED PILES CONSTRUCTION METHOD 3: THE WET METHOD

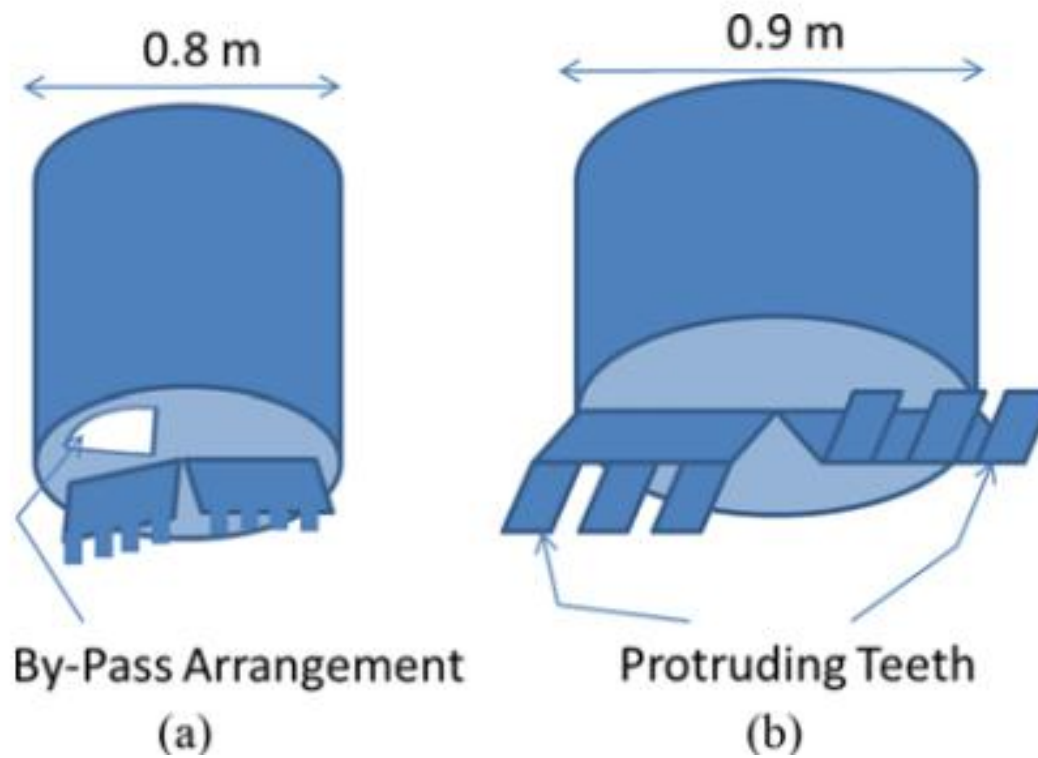
- Notes

1. Artesian groundwater may require that the starter casing be protruded too high above the ground surface. Dewatering outside the pile could be resorted to to reduce this pressure. Dewatering well should be operated without interruptions during the entire pile construction process.
2. It is important to ensure that drilling operation should not cause disturbance to the slurry inside the pile. If the drilling tool, when lifted to extract the cuttings, moved too rapidly, then, it would create suction pressure at the level of excavation and could cause caving and could produce water inflow. Severe disturbances could result at the perimeter of excavation as well as at the bottom of excavation due to this condition.
3. If a casing is used, drilling inside the casing should be such that a sufficient plug is left between the bottom of the casing and the drilled level above it. This condition should be maintained until a stable bearing strata is reached or the design bottom level of the pile is reached.



Wet method with Casing

Piston Effect



Load Capacity of a Single Pile

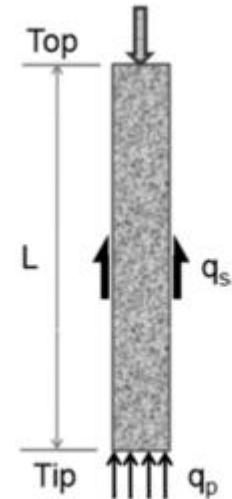
- All calculations of pile capacity are approximate because it is almost impossible to account for the variability of soil types and the differences in the quality of construction practice.
- The ultimate pile capacity Q_{ult} consists of two components: skin/shaft friction or side shear Q_f and end bearing at the pile tip or base Q_b .

$$Q_{ult} = Q_f + Q_b$$

- The allowable pile capacity is expressed as:

$$Q_{all} = Q_{ult} / \text{factor of safety}$$

A minimum factor of safety of 2.5 is typically maintained.



Load Capacity of a Single Pile

- Some pile movement is needed to mobilize skin friction and end bearing.
- Pile load tests on driven piles have shown that a vertical pile movement of 2.5 mm to 10 mm is needed to fully mobilize skin friction.
- For driven piles, end bearing resistance is fully mobilized when the vertical pile displacement is about 8-10% of the pile tip diameter (for diameters 40-120 cm in diameter, movements between 32 mm to 120 mm).



Methods for evaluating capacity of deep foundations

1. Full-scale load tests on prototype foundations.
2. Analytical methods based on soil properties obtained from laboratory and/or insitu tests.
3. Dynamic methods based on pile driving data or wave propagation.

Capacity of Piles in Clay

- **Ultimate Side Resistance in Cohesive Soil:**

- $Q_f = c_a(\pi D \Delta L)$
- $c_a = \alpha c$
- $\alpha = 0.3 \text{ to } 0.4$ *Bored Piles*
- $c_a \leq 100 \text{ kPa}$ (1 kg/cm^2)

- **Ultimate Base Resistance in Cohesive Soil:**

- $Q_b = cN_c \left(\frac{\pi D^2}{4} \right)$
- $N_c = 9$

ECP 202

Displacement Piles

نوع الخازوق	قوام التربة	إجهاد التماسك c kN/m ²	إجهاد التلاصق C_a kN/m ² الأقصى
خشب أو خرسانة	ضعيف التماسك جدا	١٢,٥ - ٠,٠	١٢,٥ - ٠,٠
	ضعيف التماسك	٢٥,٠ - ١٢,٥	٢٤,٠ - ١٢,٥
	متوسط التماسك	٥٠,٠ - ٢٥,٠	٣٧,٥ - ٢٤,٠
	متماسك	١٠٠,٠ - ٥٠,٠	٤٧,٥ - ٣٧,٥
	شديد التماسك	٢٠٠,٠ - ١٠٠,٠	٦٥,٠ - ٤٧,٥
صلب	ضعيف التماسك جدا	١٢,٥ - ٠,٠	١٢,٥ - ٠,٠
	ضعيف التماسك	٢٥,٠ - ١٢,٥	٢٣,٠ - ١٢,٥
	متوسط التماسك	٥٠,٠ - ٢٥,٠	٣٥,٠ - ٢٣,٠
	متماسك	١٠٠,٠ - ٥٠,٠	٣٦,٠ - ٣٥,٠
	شديد التماسك	٢٠٠,٠ - ١٠٠,٠	٣٧,٥ - ٣٦,٠

القيم الصغرى والعليا لإجهاد التلاصق C_a تتناظر القيم الصغرى والعليا لإجهاد التماسك c

١ كجم / سم^٢ = ١٠٠ ك . نيوتن / م^٢

Capacity of Piles in Sand

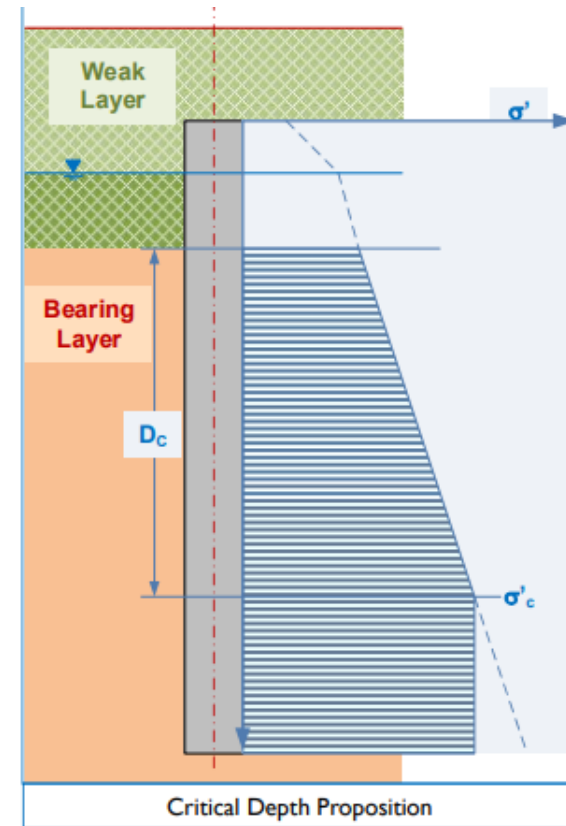
• Ultimate Side Resistance in Cohesionless Soil:

- $Q_f = K_{HC} p_o \tan \delta (\pi D \Delta L)$
- $K_{HC} = 0.7 \text{ to } 1.5$
- $\delta = 0.75\phi$ for R.C. Piles
- p_o is calculated considering the Critical Depth Proposition

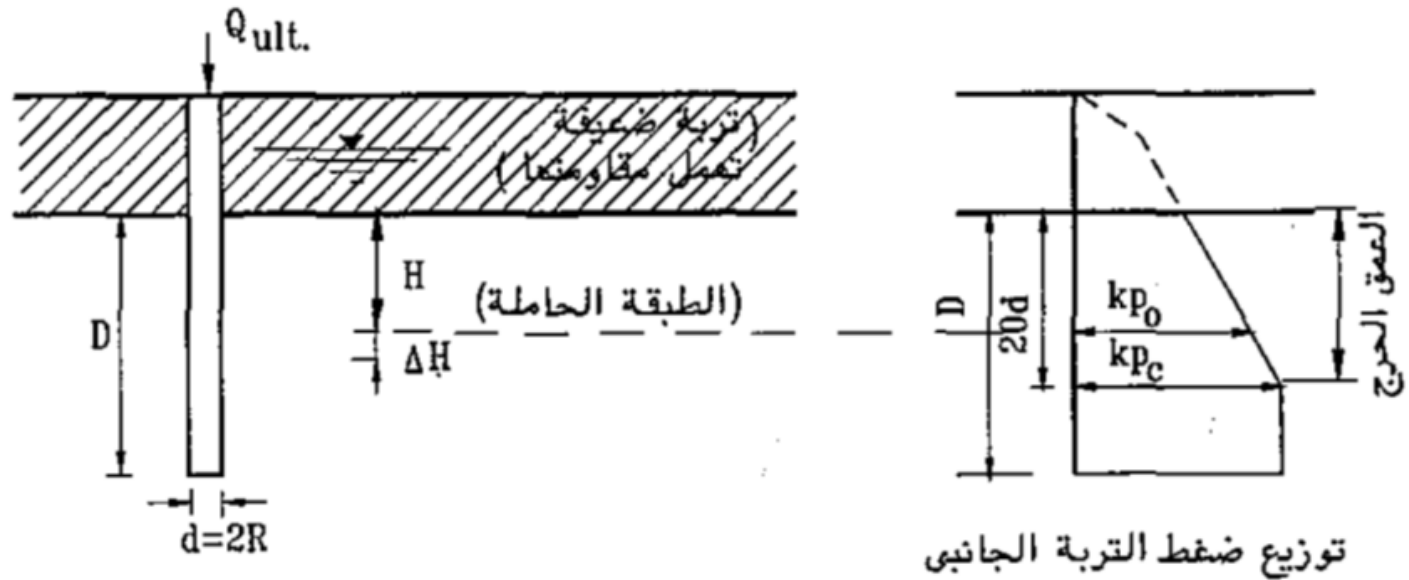
• Ultimate Base Resistance in Cohesionless Soil:

- $Q_b = p_b N_q \left(\frac{\pi D^2}{4} \right)$
- $\phi_{CFA} = (\phi - 3)$ for Non Displacement Piles
- p_b is calculated considering the Critical Depth Proposition

ϕ (Degrees)	25	30	35	40
N_q	15	30	75	150



ECP202



P_C هو ضغط التربة الرأسى عند العمق الحرج

$$k_{HT} \text{ او } k_{HC} = k$$

ECP 202

جدول رقم (٤-٦): قيم المعاملات (K_{HT}) و (K_{HC})

K_{HT}	K_{HC}	نوع الخازوق
٠,٥-٠,٣	١,٠-٠,٥	خازوق ذو قطاع H
١,٠-٠,٦	١,٥-١,٠	خازوق ازاحة
١,٣-١,٠	٢,٠-١,٥	خازوق ازاحة متغير القطاع
٠,٦-٠,٣	٠,٩-٠,٤	خازوق ازاحة باستخدام النفائات
١,٠-٠,٤	١,٥-٠,٧	خازوق تنقيب اعتيادي (قطر اقل من ٠,٦٠ متر)

جدول رقم (٤-٧): قيم زاوية الإحتكاك بين التربة وجزع الخازوق (δ)

δ (درجة)	نوع الخازوق
٢٠	حديد
ϕ ٠,٧٥	خرسانة
ϕ ٠,٧٥	خشب

ϕ زاوية الاحتكاك الداخلي للتربة

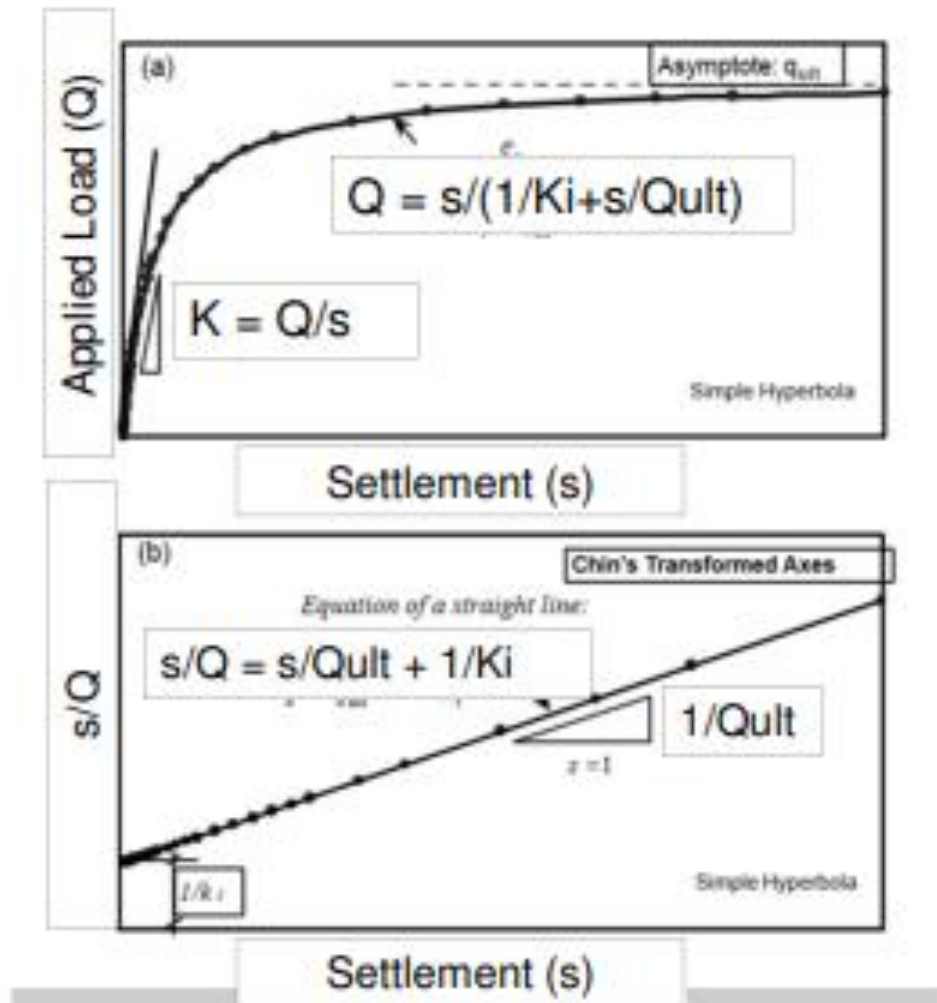
Pile Load Test

Interpretation of Pile Load Modified Chin's Method - Hyperbolic Asymptote

- One of the simplest forms to represent non-linear curves is the hyperbola as only two constants are required.
- Fitting a simple hyperbola to load-displacement test data has been used for evaluating the bearing capacity of piles (Chin, 1971).
- The simple hyperbolic relationship between Load (Q) and settlement (s) is:

$$Q = s / (1/K_i + s/Q_{ult})$$

Interpretation of Pile Load Modified Chin's Method - Hyperbolic Asymptote



Interpretation of Pile Load Modified Chin's Method - Hyperbolic Asymptote

- According to ECP, the ultimate axial pile capacity is:

$$Q_{ult} = 1/1.2 \text{ slope of straight line}$$

- The ultimate pile is not less than 2 times the design load considering dead and live load, 1.75 times the design load considering also wind loads and 1.5 times the design load taking earthquake loading into consideration.
- Additionally, a pile load test is considered satisfactory if the measured pile settlement after 12 hours under 1.5 times the design load does not exceed the following equation:

$$s = 0.02 d + 0.5QL/AE$$

d=pile diameter, Q =1.5 design pile load, L = pile length, A = pile cross sectional area, E = pile material modulus of elasticity.



Thank you