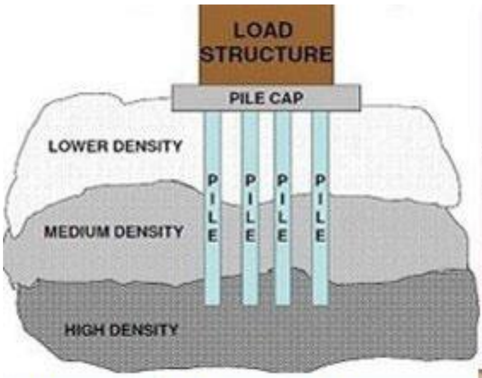
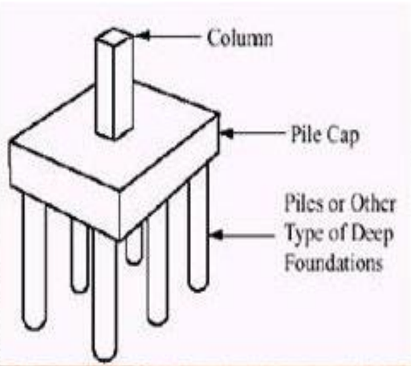
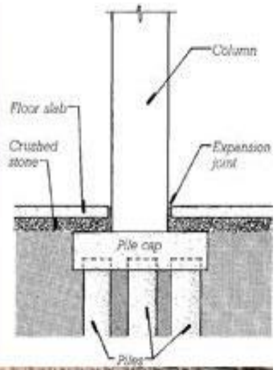
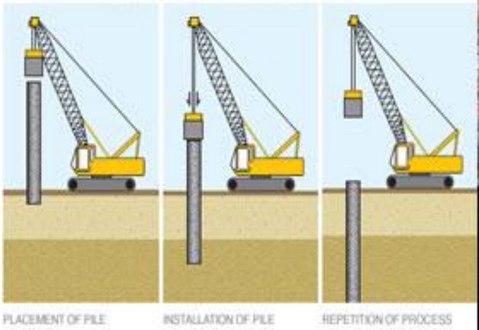
Design of Concrete Pile Foundation









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Abstract :

Deep foundations are employed when the soil stratum beneath the structure is not capable of supporting the load with a tolerable settlement or adequate safety against shear failure. The two common types of deep foundations are well foundations (or caissons) and pile foundations. Piles are relatively long, slender members that are driven into the ground or cast-in-situ. The design of pile foundation involves providing adequate pile type, size, depth, and number to support the superstructure load without excessive settlement and bearing capacity failure. Deep foundations are more expensive and technical than shallow foundations.

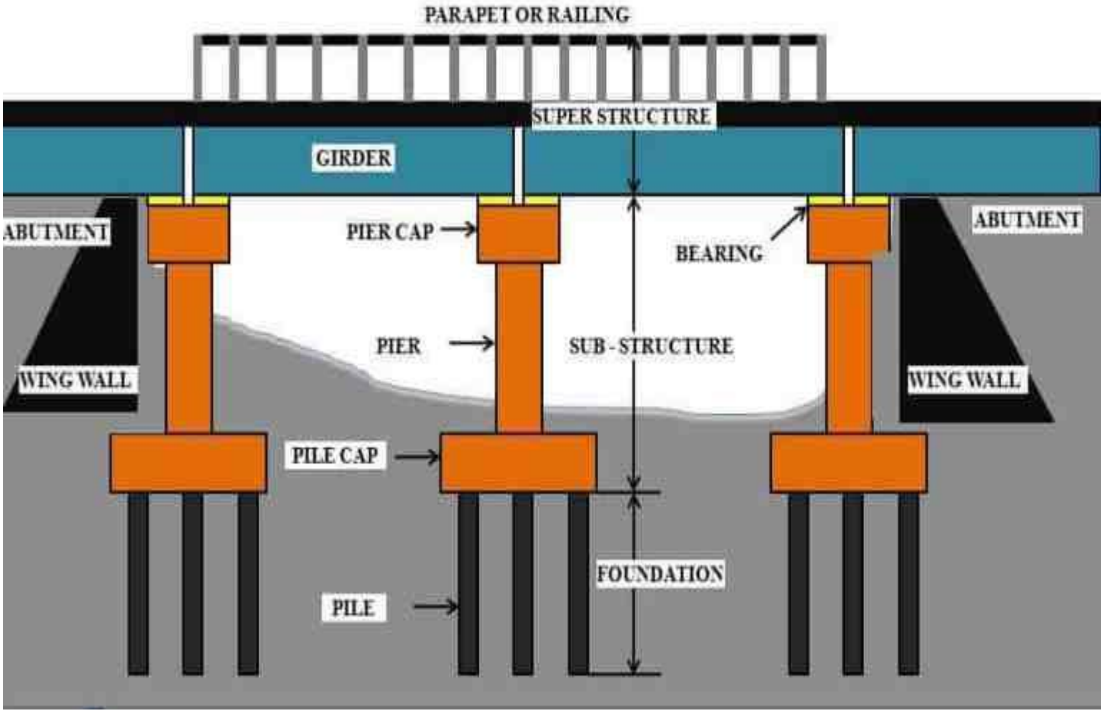

Figure 1: Bridge pile

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1- Introduction

A concrete pile is a foundation driven deep into the ground to support the structure, unlike shallow or wide foundations such as Isolated Footings or Combined Footings. They are usually much thinner in diameter or width than in length. Due to their sometimes incredible length/depth, piles typically carry a higher load capacity than the aforementioned shallow footings.

With most structures, concrete piles are more common than the other piles. The earliest form of the concrete pile is a cast-in-place pile. Further advancement in construction technology led to the creation and adoption of precast piles and, eventually, prestressed piles. All three concrete piles are viable options in today’s construction.

Pile Foundations can be used in the following cases;

1. When the upper soil layer(s) is (are) highly compressible and too weak to support the load transmitted by the superstructure, piles are used to transmit the load to underlying bedrock or a stronger soil layer. When bedrock is not encountered at a reasonable depth below the ground surface, piles are used to transmit the structural load to the soil gradually. The resistance to the applied structural load is derived mainly from the frictional resistance developed at the soil–pile interface.
2. When subjected to horizontal forces, pile foundations resist by bending while still supporting the vertical load transmitted by the superstructure. This situation is generally encountered in the design and construction of earth-retaining structures and foundations of tall structures that are subjected to strong wind and/or earthquake forces.
3. In many cases, the soils at the site of a proposed structure may be expansive and collapsible. These soils may extend to a great depth below the ground surface. Expansive soils swell and shrink as the moisture content increases and decreases, and the swelling pressure of such soils can be considerable. If shallow foundations are used, the structure may suffer considerable damage.
4. The foundations of some structures, such as transmission towers, offshore platforms, and basement mats below the water table, are subjected to uplifting forces. Piles are sometimes used for these foundations to resist the uplifting force.
5. Bridge abutments and piers are usually constructed over pile foundations to avoid the possible loss of bearing capacity that a shallow foundation might suffer because of soil erosion at the ground surface

2- Types of Pile Foundation :

What are other types of piles?

Traditionally, timber or wood can be used as piles and are commonly used to support small structures or bridges in weak soils. Some larger structures still use timber piles, such as jetties, but timber piles bear some limitations. First, timber is prone to deterioration or decay over time, increasing the uncertainty in its lifespan. Another drawback is the limited available length of timber that can be produced from the tree being cut down due to its actual length. Subsequently, it is not advisable to join two timber trunks together to combat this length issue.

Steel H-piles became a common substitute for concrete piles. They can withstand heavier loads and may eliminate some installation issues compared to concrete piles. The process of importing and pouring concrete may not be doable in some environments, so the steel pile is used. However, concrete piles are preferred to use in locations with corrosive soils than steel piles.

A composite pile may be a combination of two different materials, most commonly steel and concrete. This type of pile is usually used when the required length for bearing capacity exceeds the capacity of a simple concrete pile. Composite piles are rarely used as the installation is complex, and it is challenging to provide a proper joint between the materials.

https://skyciv.com/wp-content/uploads/2020/03/piles_types-e1584599703791.png.webp

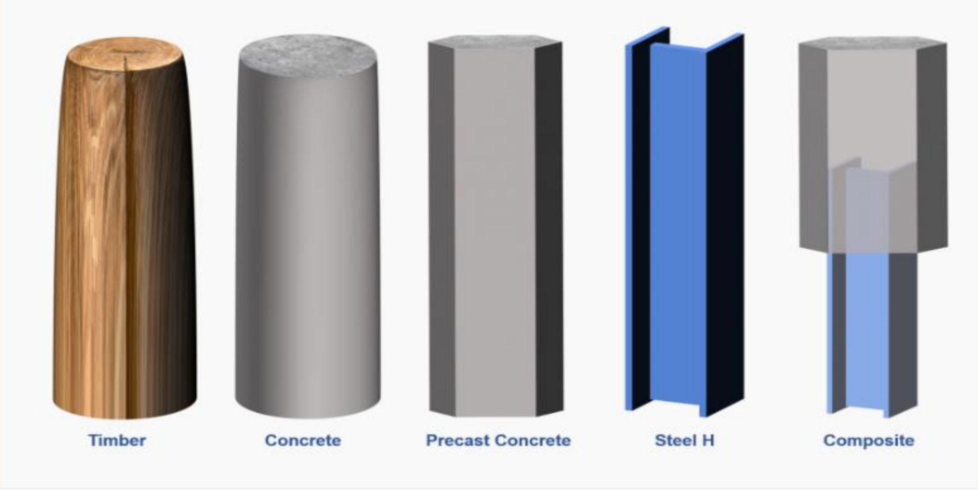


Figure 2: Types of piles

One of the most common situations in which concrete piles are used is when the top layers of the site's soil are very weak and cannot support the structure, usually characterized by wet, clay-like soil. In this case, piles bypass these weak ground conditions and transfer the building loads to a more stable layer of soil beneath, like bedrock. Another reason to use concrete piles is when the building loads are large and cover a small footprint. Examples include high-rise structures or skyscrapers, large bridges, and water tanks.

In terms of material and mechanical properties, concrete piles provide high structural capacity and more durability, especially in corrosive and marine environments, than steel piles. However, concrete is not as flexible as steel. It can be easily be damaged during driving and requires larger lifting equipment. Despite this issue, concrete piles remain the most common type.

3- Types of Piles in Construction:

Piles can be classified into many types based on their load transfer mechanism.

- Friction piles
- Bearing piles
- Friction-cum-bearing piles.
- Guide piles
- Batter piles
- sheet piles.

Source:

Piling Construction: What is it, Types, Design, Problems
machinesl.com
https://www.machinesl.com/piling-constructi…

4- Types of concrete piles :

Concrete piles are categorized into two types: cast-in-place piles and precast piles. Cast-in-place piles can be further identified as cased or uncased piles. Conversely, precast piles can either be a typical reinforced concrete pile or a prestressed pile.

Cast-in-place piles

Generally, cast-in-place piles are more commonly used than precast piles. This type of pile is more advantageous than precast piles due to ease of handling and the elimination of any storage requirements. There is a chance for damage upon handling when moving precast piles, and they need to be stored on site. Uncased piles offer a more economical cast-in-place pile, while cased piles offer a more secure and accurate concrete placement.

Cased cast-in-place piles use a cylindrical or tapered thin-walled steel tube that serves as the form or mold for the concrete, which lines the bored hole where the pile is housed. This type of pile is more desirable as it allows inspection of the pile before the pouring of concrete. The casing leads to a cleaner and more dependable pour, without irregularities. Cased cast-in-place piles are better in nearly every soil condition. Some common examples of cased cast-in-place piles include:

- Raymond piles
- Mac-Arthur piles
- Union metal monotube pile
- Swage pile
- Western button bottom pile

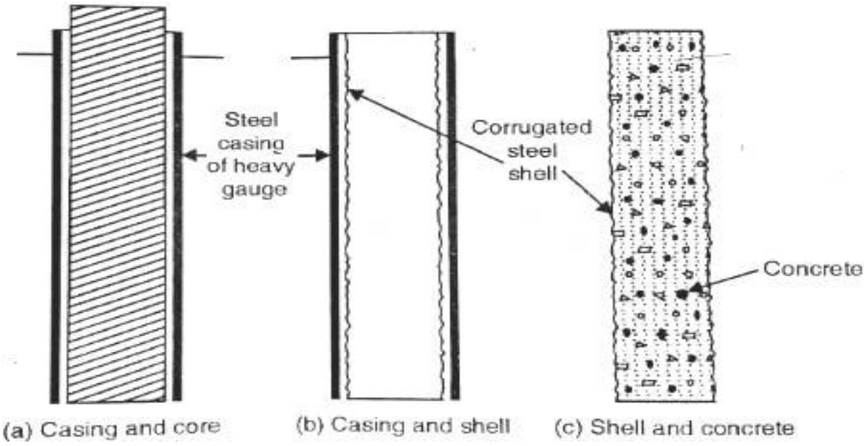


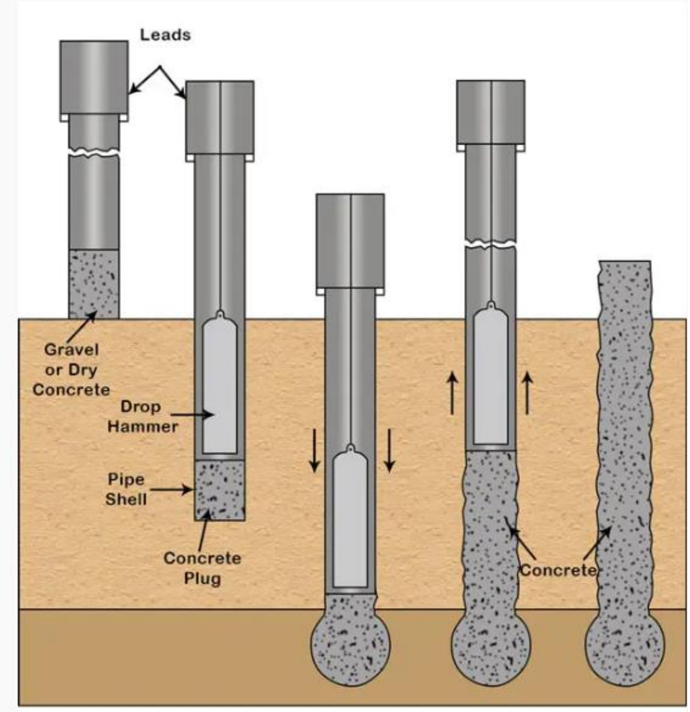
Figure 3 : Breakdown of a **Mac-Arthur** pile

Source: theconstructor.org

Uncased cast-in-place piles are more economical and practical than cased piles. However, caution and inspection are required during installation because of the direct contact with soil. It is recommended to use only on highly cohesive soils. With non-cohesive soils, there is a risk that the soil or water breaks into the pile. Water could seep through the concrete cracks and degrade the reinforcement. The following are the different types of uncased cast-in-place piles:

- Simplex pile
- Frankie pile
- Vibro pile
- Pedestal pile

Figure 4 :



STAGES IN THE FORMATION OF FRANKI PILE

Concrete piles share the same pros and cons as other concrete structural members. The following advantages and disadvantages mainly focus on the installation of cast-in-place piles and differences with the precast piles:

Advantages of cast-in-place piles:

- Creates less vibration during installation
- Piles of any size and length can be fabricated on site
- Requires less or no large equipment as compared with precast piles
- It does not significantly disturb the surrounding soil

Disadvantages of cast-in-place piles:

- Installation time is often longer due to the setting up and removal of forms and concrete curing time.
- Installation requires intensive labor.
- Careful supervision is needed to maintain good workmanship and quality control.
- Requires storage for the equipment or the materials to be used
- Weather and site conditions are evaluated before installation

Precast piles

Precast piles are constructed by hammering or driving the pile into the soil using large driving equipment, as shown in figure 5. They are more versatile and suitable to use in most soil conditions. These are also used where the foundations need to extend above water or ground level. Precast piles are manufactured off-site in a controlled environment with uniform or tapered cross-sections and may be cast in circular, square, or octagonal shapes. The deep end of uniform cross-section piles is sharply tapered and secured with a cast steel shoe to protect the pile and help penetrate hard strata during driving. Precast piles with larger widths are usually manufactured with hollow cross-sections to reduce their weight and increase the effectiveness of the driving of the pile.

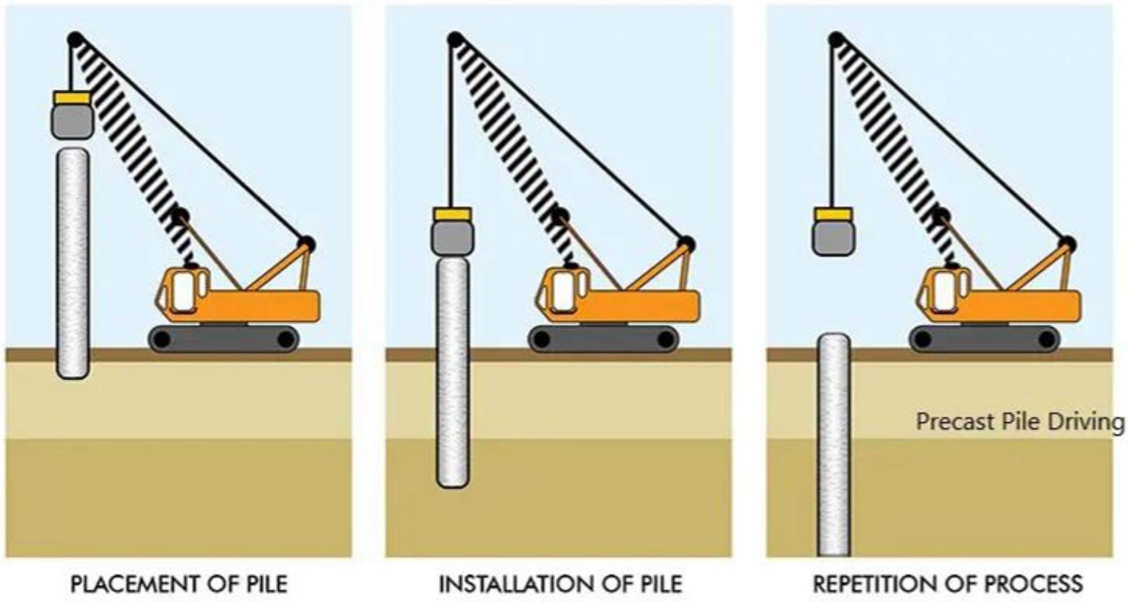


Figure 5: Pile driving of Precast Pile using a vibrating piling machine

Source: structuralguide.com

Advantages of precast piles:

- Can carry relatively higher working loads
- Well suitable for marine installations
- Can extend above ground or water
- Manufactured in a controlled environment — more certainty on overall quality.
- Highly resistant to biological and chemical actions of subsoil

Disadvantages of precast piles:

- Requires special equipment for handling and transporting
- Precast piles are heavy and need machinery to transport and move around the site
- Challenging to increase or excessive cut-off length
- The length of the pile may be limited due to storage or transportation
- High initial cost

5- Design of Concrete pile :

- **ACI 318 Concrete Pile Design**
- **https://skyciv.com/docs/skyciv-foundation/**
- **Single pile design in accordance with ACI 318 (2014)**

Piles are long and slender members which transfer the loads from the superstructure to deeper soil or onto a rock with adequate bearing capacity. Materials used for piles may include wood, steel, and concrete. Installation of the pile into the ground may be driven, drilled, or jacked which are then connected to pile caps. A lot of factors, such as site conditions, soil type, the transmission of loads, are considered to classify the type and installation of piles. This article shall focus on designing a concrete pile in accordance with the American Concrete Institute (ACI) 318 – 2014.

SkyCiv Foundation Design module includes the design of piles conforming to the American Concrete Institute (ACI 318) and Australian Standards (AS 2159 & 3600). FOUNDATION DESIGN CALCULATOR

A- Load carrying capacity of a pile

Generally, vertical loads applied on piles are carried by the end-bearing of the pile, and the skin-frictional resistance developed along its length. The ultimate load carrying capacity (Q_U) shall be represented by equation (1). A factor of safety is applied to compute for the allowable load-carrying capacity (Q_A).

Qu=Qp+Qs��=��+�� **(1)**

Q_U = Ultimate load-carrying capacity

Q_P = End-bearing Resistance

Q_S = Skin-frictional Resistance

QA=QUFOS��=����� **(2)**

Q_A = Allowable load-carrying capacity

FOS = Factor of safety

For a more detailed guide, check out our article on calculating the skin-frictional resistance and end-bearing capacity.

Structural strength of a single pile

Piles are also subjected to axial forces, shear force, and bending moment, which is why they are structurally designed similar to columns. Section 10.5.1.1 states that all factored load shall not exceed its corresponding design strengths.

øPN≤PUø��≤�� **(3a)**

øMN≤MUø��≤�� **(3b)**

øVN≤VUø��≤�� **(3c)**

P_U, M_U, V_U = *Factored axial, bending moment, shear loads*

P_N, M_N, V_N = *Nominal axial, bending moment, shear loads*

ø = Strength reduction factors (Table 1)

STRENGTH REDUCTION FACTORS(Φ)

Axial	0.65-0.90
Flexural	0.65-0.90
Shear	0.75

Table 1: Strength Reduction Factors (Table 21.2.1, ACI 318-14)

B - Shear capacity of a single pile (øV_N)

Nominal shear strength shall be equivalent to combined contributions of the shear capacities of concrete and steel reinforcement.

Shear strength of concrete (V_c)

The contribution of concrete to the shear capacity is computed as shown on equation (4) which is defined on Section 22.5.5.1 of ACI 318-14.

Vc=0.17×λ×fc′−−−√×b×d��=0.17×λ×��′×�×� **(4)**

λ = Concrete modification factor = 1 (Normal weight concrete, Table 19.2.4.2)

fc' = Strength of concrete

b = Pile width or diameter

d = 0.80 × pile depth (Section 22.5.2.2)

Shear strength of steel bars (V_s)

Lateral shear reinforcement’s contribution to the shear capacity is computed as the minimum between equations (5) and (6).

$V_s = 0.066 \times \sqrt{f_c'} \times b \times d$��=0.066×��′×�×� **(5)**

$V_s = \frac{A_v \times f_{yt} \times d}{s}$��=��×���×�� **(6)**

A_V = Area of the shear reinforcing bars

f_{yt} = Yield strength of the shear reinforcing bars

s = Center-to-center spacing of shear reinforcing bars

Nominal shear strength ($øV_N$)

Summing up the output of equation 4-6 shall result to the nominal shear strength of the pile. Strength reduction factor (ø) shall be equal to 0.75 as defined in Table 22.2.1 of ACI 318-14.

$øV_N = ø \times (V_c + V_s) \le øV_U$ø��=ø×(��+��)≤ø�� **(7)**

C - Axial and flexural capacities of a single pile ($øP_N$, $øM_N$)

Axial and flexural capacities are checked using an interaction diagram. This diagram is a visual representation of the behaviour of the bending and axial capacities caused by an increase in load from puding point until a balanced point is reached.

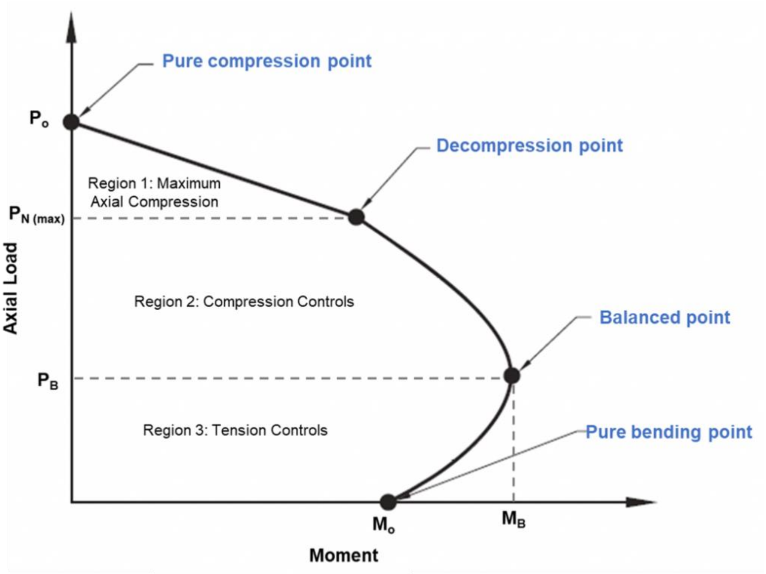


Figure 1: Column Interaction Diagram

D - Column interaction diagram

The pure compression point on the diagram is where the pile will fail compression purely. At this point, the axial load is applied to the plastic centroid of the section to remain in compression without bending. Strength of the pile between the pure compression point until decompression points can be calculated by linear interpolation. The decompression point is where the concrete strain at the extreme compressive fibre is equal to 0.003, and the strain in the extreme tensile fibre is zero. Pure bending point is where the axial load capacity is zero. Between the transition from decompression point to pure bending point, a balanced condition is achieved. At this point, the concrete strain is at its limit (ε_c=0.003), and the outer steel strain reaches yield (ε_s=0.0025). Any combination of axial load and bending moment outside the diagram will cause failure.

Maximum nominal axial compressive strength for design (øP_N)

The design axial strength of a section shall only be limited to 80-85% of the nominal axial strength to account for accidental eccentricity.

øPN=ø×Poø��=ø×�� **(8a)**

Po=F×[0.85×fc×(Ag–Ast)+(fy×Ast)]��=�×[0.85×��×(��–���)+(��×���)] **(8b)**

F = 0.80 (Ties)

F = 0.85 (Spiral)

A_G = *Gross area of the pile cross-section*

A_{st} = *Total area of the longitudinal steel bars*

f_y = *Yield strength of steel bars*

Nominal flexural strength ($øM_N$)

Construction of the interaction diagram for the column involves plotting a series of values of P_N and M_N. Values for P_N shall be equivalent to the sum of the tensile and compressive forces, as shown in Figures 2a and 2b, while the corresponding M_N is calculated by resolving these forces about the neutral axis. These forces include the compressive force acting on the compressive area and the forces exerted by each of the reinforcing bars which could either be compressive or tensile. A general procedure is suggested below to construct an interaction diagram using the equations presented.

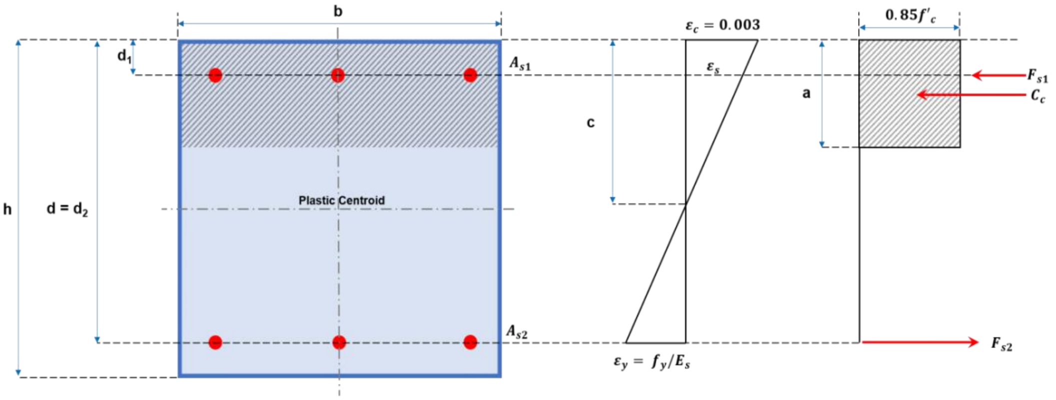


Figure 2a: Rectangular column cross-section

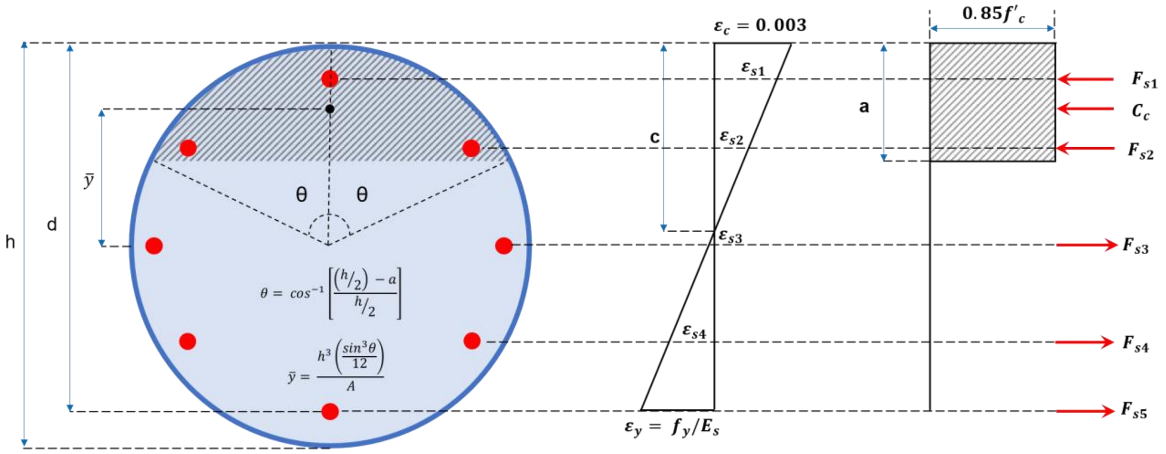


Figure 2b: Circular column cross-section

E - General procedure for interaction diagram of a column

(1) Compute for the value of P_o and P_N (equations 8a and 8b).

(2) Determine c and the strains in the reinforcements.

c=0.003×d10.003+(Z+εy)�=0.003×�10.003+(�+ε�) ***(9)***

c = Neutral axis depth

ε_y = Strain of steel = f_y/E_s

Z = Arbitrary value (0, -0.5, -1.0, -2.5)

A series of cases shall be considered by selecting various locations of the neutral axis, c. To set the locations of the neutral axis, different steel strains shall be selected by multiplying an arbitrary value Z to the yield strength of the steel. There is a wide range of values for Z. However, there are only four mandatory points to use for the interaction diagram.

- Z = 0: at this point, the strain at the extreme layer in tension is zero. This point marks the change from compression lap splice being allowed on all longitudinal bars to a tension lap splice.
- Z = -0.5: this strain distribution affects the length of tension lap splice in a column & is customarily plotted on an interaction diagram.
- Z = -1: this marks the point of a balanced condition. This strain distribution marks the change from compression failures originating by crushing of the compression surface of the section to tension failures initiated by the yield of the longitudinal reinforcement.
- Z = -2.5: this point corresponds to the tension controlled strain limit of 0.005.

(3) Compute for the stresses in the reinforcement layers.

fsi=εsi×Es���=ε��×�� ***(10)***

f_{si} = Stress in steel

ε_{si} = Strain in steel

εsi=c−dic×0.003ε��=�−���×0.003 ***(11)***

E_s = Modulus of elasticity of steel

(4) Determine the height of the compression stress block, a.

a=β1×c�=β1×� *(a ≤ h)****(12)***

For f’c ≤ 4000 psi (28 MPa):

$$\beta_1 = 0.85$$

For f’c > 4000 psi (28 MPa):

β1=0.85–0.05×(f′c–4000)1000β1=0.85–0.05×(�′�–4000)1000 *(Imperial)*

β1=0.85–0.05×(f′c–28)7β1=0.85–0.05×(�′�–28)7 *(Metric)*

(5) Compute for the forces in concrete and steel.

Area of the compressive stress block:

Ac=a×b��=�×� *(Rectangular cross-section)*

Ac=h2×θ–sinθcosθ4��=*h*2×θ–���θ���θ4 *(Circular cross-section)*

Compressive force in concrete:

Cc=(0.85×f′c)×Ac��=(0.85×�′�)×�� ***(14)***

Tensile force in steel ($d_i \leq a$):

Fsi=fsi×Asi���=���×��� ***(15)***

Compressive force in steel ($d_i > a$):

Fsi=[fsi–(0.85×f′c)]×Asi���=[���–(0.85×�′�)]×��� ***(16)***

(6) Calculate for the axial capacity (P_N).

PN=Cc+ΣFsi��=��+Σ��� ***(17)***

(7) Calculate for the flexural capacity (M_N).

MN=[Cc×(h2–a2)]+Σ[Fsi×(h2–di)��=[��×(*h*2–�2)]+Σ[���×(*h*2–��) ***(18)***

(8) Compute for the value of the strength reduction factor (ø).

As shown in Table 1, the strength reduction factor for both axial and flexure varies from 0.60 to 0.90. Section 21.2 of ACI 318-14 demonstrates its value for the moment, axial force, or combined moment and axial force, as shown in Table 2 below.

CLASSIFICATION	SPIRAL	TIED
Compression controlled	0.75	0.65
Transition from compression to tension	0.75 + [50 × (ε_t – 0.003)]	0.65 + [(250/3) × (ε_t – 0.003)]
Tension controlled	0.90	0.90

Table 2: Strength Reduction Factors for Axial, moment or combine axial and moment (Table 21.2.2, ACI 318-14)

(9) Repeat steps 2-8 with various values for Z.

(10) Plot into the diagram the values of $øP_N$ and $øM_N$.

Concrete Pile Design with SkyCiv Free Foundation Calculator

SkyCiv Free Foundation Calculator helps you with concrete pile design and other tasks such as footing and concrete piles design. Check it out now to explore how our calculator can help you with your concrete pile project!

FOUNDATION DESIGN CALCULATOR

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