Determining and Increasing Bearing Capacity

A Seminar Presentation by
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Definition of Bearing Capacity

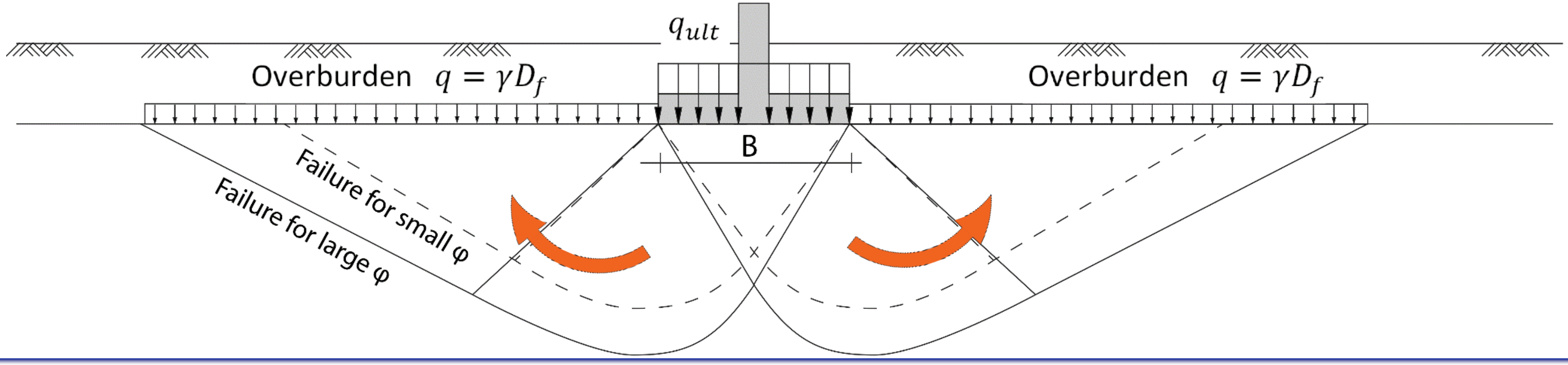
- Bearing capacity is the ability of the ground to support loads that are applied by shallow or deep foundations.
- The **ultimate bearing capacity** q_{ult} is the maximum pressure which can be supported by the soil without failure.
- In the Allowable Stress Design (ASD), which is the common geotechnical engineering approach, the **allowable bearing pressure** q_{all} is calculated as the maximum pressure which the geotechnical engineer considers safe. It is typically calculated as $q_{all} = q_{ult}/FS$ and is designed to reduce the risk of failure and to control undesirable settlements. The design demand is that $q_{all} \geq q_{appl}$, where q_{appl} is the applied pressure based on unfactored loads (e.g., $P_{appl} = DL + LL$), where DL is the dead load and LL is the live load

Definition of Bearing Capacity

- In the Load and Resistance Factor Design (LRFD) approach, the **resisting bearing pressure** q_R is calculated as $q_R = \phi\, q_{ult}$ where, ϕ is the resistance factor, and is less than 1, while the applied loads are magnified by appropriate factors expressing the uncertainty of each component (e.g., $q_u = 1.2DL+1.6LL$) The design demand is that $q_R \geq q_u$.
- The ASD approach is more common in practice, although the LRFD approach may be required some State Departments of Transportation (DOT).

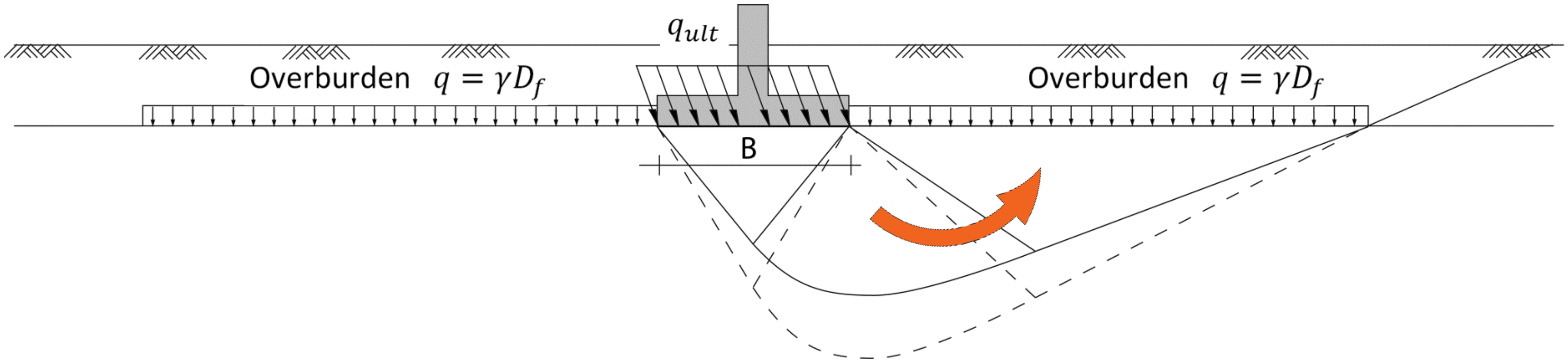
Basic Bearing Capacity Equation

- $q_{ult} = cN_c + qN_q + \frac{1}{2}\gamma B N_\gamma$
  - Term cN_c is the contribution of cohesion c to the bearing capacity.
  - Term qN_q is the contribution of the overburden pressure q to the bearing capacity.
  - Term $\frac{1}{2}\gamma B N_\gamma$ is the contribution of the friction of the weight of the sliding mass



Improved Bearing Capacity Equation

- $q_{ult} = cN_c\, s_c d_c i_c + qN_q s_q d_q i_q + \frac{1}{2}\gamma B N_\gamma s_\gamma d_\gamma i_\gamma$
  - s: Shape factors, which account for the 3-D effects of the shape of the footing (width B, and Length L).
  - d: Depth of embedment factors because the overburden pressure is the result of real soil (rather than just weight), which provides additional resistance to failure.
  - i: Inclination factors, which account for inclined loading.



Bearing Capacity Coefficients

- *Equations Proposed by Meyerhof (1963)*
  - $N_q = e^{\pi \cdot \tan\phi} \tan^2\left(45 + \frac{\pi}{2}\right)$
  - $N_c = \left(N_q - 1\right)\cot\phi$
  - $N_\gamma = \left(N_q - 1\right)\tan(1.4\phi)$
- Other notable bearing capacity equations were presented by:
  - Terzaghi (1943)
  - Hansen (1970)
  - Vesić (1973, 1975)
- To avoid making this presentation too long, only Meyerhof's approach will be discussed here.

Bearing Capacity Coefficients (Cont.)

- Shape Factors
  - $s_c = 1 + 0.2K_p\frac{B}{L}$
  - $s_q = s_\gamma = 1 + 0.1K_p\frac{B}{L}$ for $\phi > 10^o$
  - $s_q = s_\gamma = 1$ for $\phi = 0$
- Depth Factors
  - $d_c = 1 + 0.2\sqrt{K_p}\,\frac{D}{B}$
  - $d_q = d_\gamma = 1 + 0.1\sqrt{K_p}\,\frac{D}{B}$ for $\phi > 10^o$
  - $d_q = d_\gamma = 1$ for $\phi = 0$
- Inclination Factors
  - $i_c = i_q = \left(1 - \frac{\theta^o}{90^o}\right)^2$
  - $i_\gamma = \left(1 - \frac{\theta^o}{\phi^o}\right)^2$ for $\phi > 0$
  - $i_\gamma = 0$ for $\theta > 0$ and $\phi = 0$

Definitions

$K_p = \tan^2\left(45 + \frac{\phi^o}{2}\right)$

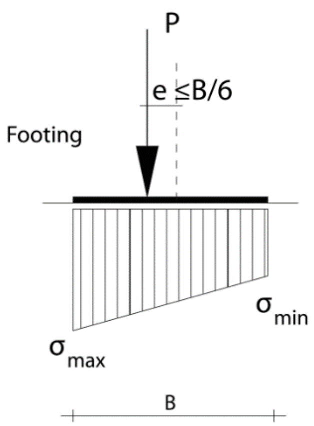
B and L are the dimensions of the footing. $B \leq L$

D is the depth of the footing embedment.

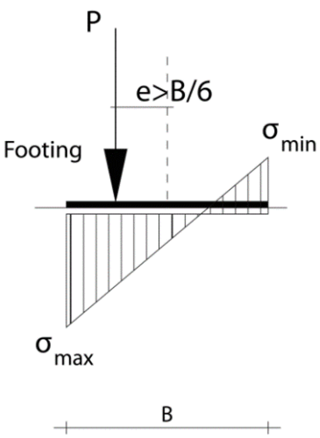
θ = The angle of the resultant force R measured from vertical, without sign. If $\theta = 0$, then all inclination coefficients $(i_c, i_q, and\ i_\gamma)$ are equal to 1.

Bearing Capacity (Load Eccentricity)

- When load is applied eccentrically, the pressure under the footing becomes non-uniform.
  $q = \frac{P}{BL} \pm \frac{6Pe_B}{LB^2} \pm \frac{6Pe_L}{BL^2}$ (+ sign on side of eccentricity) See Figure (a)
- What happens when the eccentricity is large enough to create negative stresses under the footing?
- An interface stress diagram with tensile stresses (Figure b) is not possible, as the footing interface cannot transfer tension.
- Thus, a triangular stress must develop, with a resultant force equal to the applied load P.
- The centroid of the triangle must be aligned vertically with the location of P. See Figure c.



(a)



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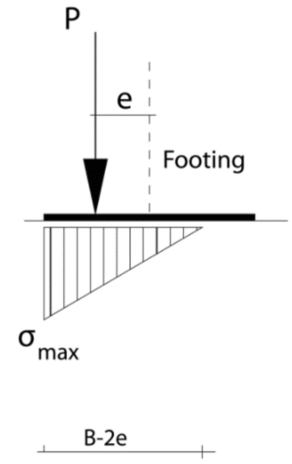
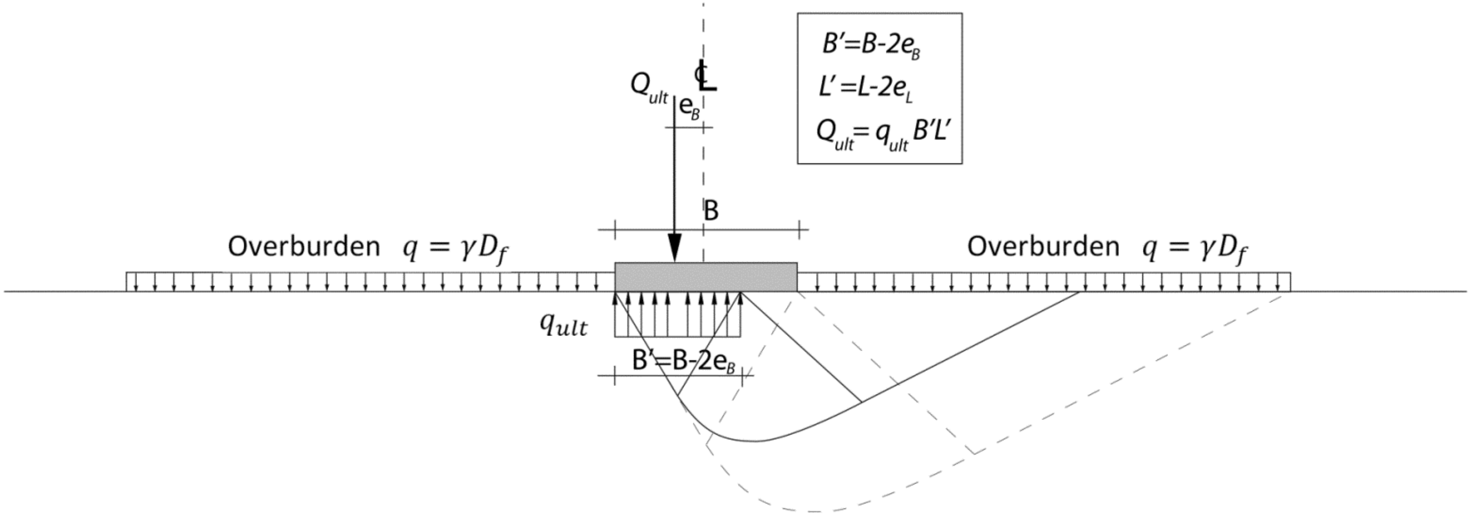


(c)

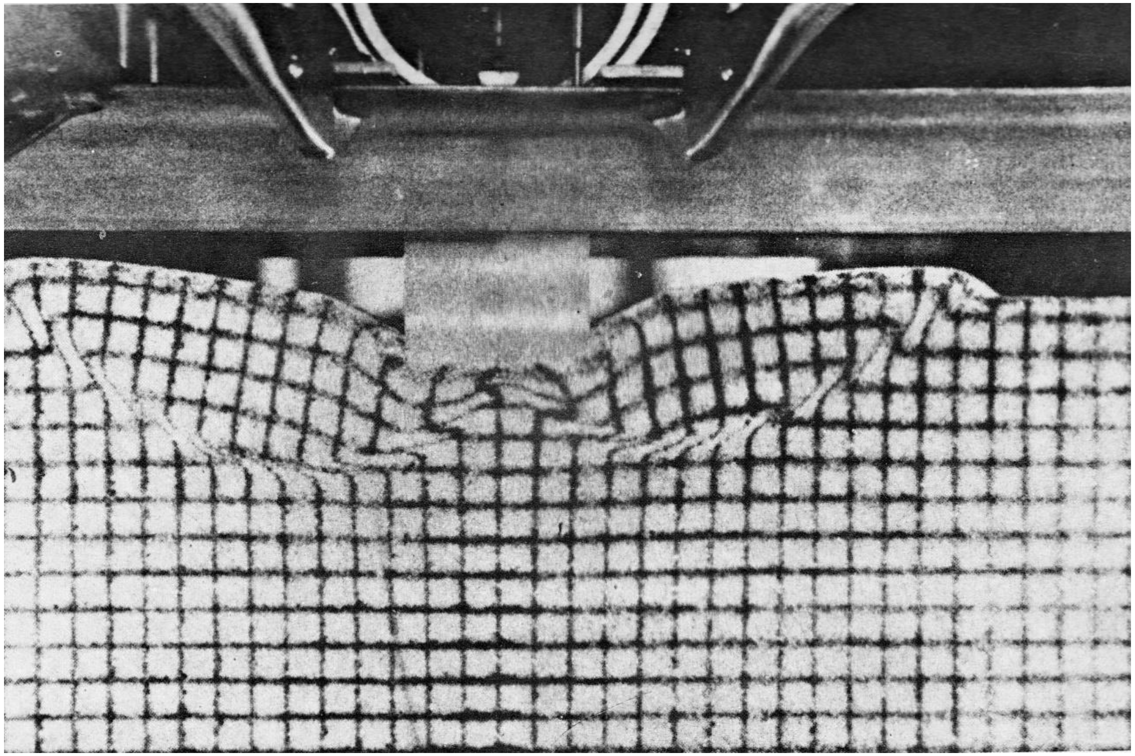
Bearing Capacity (Load Eccentricity)

- The approach described in the previous slide is more commonly used on foundations on rock, due to the required linear response of the foundation, which is uncommon in most soils.
- An alternative approach to account for eccentric loads on footings on subgrade is to consider a uniform load on reduced footing area to allow for equilibrium with the applied load. This approach is more suitable for soil subgrades.
- Each side of the footing is reduced in size to account for the corresponding eccentricity.
- The new effective size of the footing is $B' \times L'$, where $B' = B - 2e_B$ and $L' = L - 2e_L$ ($e_B =$ eccentricity in B direction, $e_L =$ eccentricity in L direction).



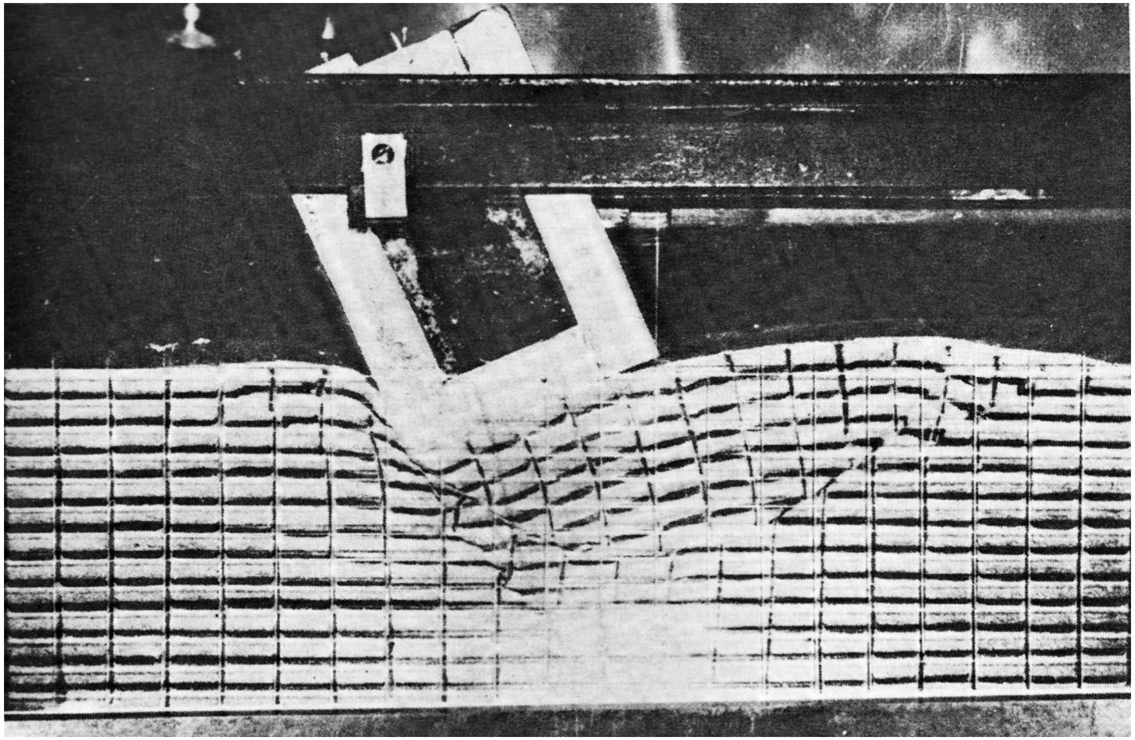
Centrally Loaded Failure

When the load is central AND the soil is uniform horizontally, a two-sided symmetric failure is possible (Selig and McKee (1961 "Static and Dynamic Behavior of Small Footings" ASCE J. of Soil Mechanics and Foundation Division)



Eccentrically Loaded Failure

However, real-life loads are typically eccentric, and often inclined. Also, the soil is rarely uniform horizontally. As a result, a one-sided failure is more common (Selig and McKee (1961 "Static and Dynamic Behavior of Small Footings" ASCE J. of Soil Mechanics and Foundation Division)



Transcona Elevator Failure

Here is a real-life example of the Transcona Elevator (1913)

Bearing Capacity – Influence of Water Table

- The depth of the wedge zone under the footing is approximately equal to $\mathrm{H} = 0.5B \tan\left(45 + \frac{\phi^o}{2}\right) \approx B$ *for the most common range of friction angles*
- If the water table is below the depth of the wedge, then the water table can be reasonably ignored in computing the bearing capacity.
- If the water table is within the range of the wedge, then:
  - The contribution of the term $\frac{1}{2}\gamma B N_\gamma$ can be conservatively ignored.
  - An average effective γ_e can be calculated as: $\gamma_e = \gamma' + \frac{D_{GWT} - D_f}{H}\,\gamma_w$

    where D_{GWT} = depth of water table below the footing base.

    γ_{sat}= saturated unit weight of the soil in depth D_{GWT}.

    γ' = submerged unit weight below water table=$\gamma_{sat} - \gamma_w$.
- One must remember, especially for varying groundwater table, that wet soils are weaker than dry soils (clays more so than granular material).
- Also be aware, that the water table may have an influence on the settlement for depths up to approximately 2B (square footings) to 3B (long footings) below the footing base.

Factor of Safety

- The factor of safety serves two purposes:
  - Account for uncertainties (The bigger the uncertainty, the bigger the required FS):
    - Knowledge of material parameters: c, ϕ, γ.
    - Confidence in bearing capacity equation.
    - Confidence in loads.
  - Control settlements (The smaller the required settlement, the bigger the required FS).
  - Importance of structure (The higher the significance of the structure, the bigger the required FS).
  - ***It is important to remember: Bigger factor of safety does not necessarily mean a safer design. Instead, it signifies the engineer's concern due to bigger uncertainty, which necessitates larger FS to maintain the same level of risk.***
- Common FS for structures without any special restrictions is 3.
  - When a structure is founded on different types of bearing material (e.g., part on rock and part on soil) or if a structure is founded part on shallow and part on deep foundations), larger factors of safety (as high as 4 or 5) may be appropriate to control excessive differential settlements.

Bearing Capacity Example

- Evaluate allowed bearing capacity q_{all} for a square footing, with width B, a depth of embedment $D_f = 4'$. FS=3
- Soil Data: $c = 0; \phi = 32^o; \gamma = 110\, pcf$.
- Load inclination angle $\theta = 10^o$
- Note: Despite the common approach of geotechnical reports, where a *general* allowed bearing capacity is presented, the bearing capacity equation clearly depends on the Depth of embedment D_f and the size B, and the shape B/L of the footing.
- Implicitly, the bearing capacity is also limited based on allowed settlement.
- In our example, the depth of embedment is selected, possibly based on frost depth restrictions.
- The footing size, however, is yet to be determined.

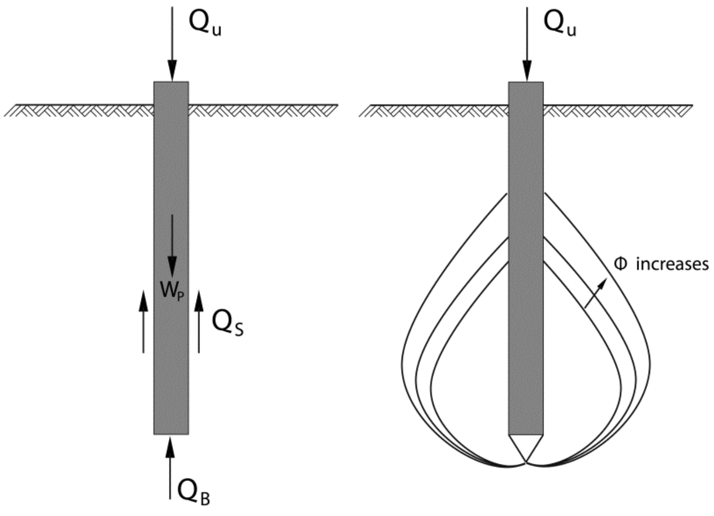
Bearing Capacity Example (Continued)

- $N_q = 23.18;\ N_\gamma = 22.02$
- $s_q = s_\gamma = 1.33$
- $d_q = d_\gamma = 1.18$
- $i_q = 0.79;\ i_\gamma = 0.47$
- $q_{ult} = \gamma D_f N_q s_q d_q i_q + \frac{1}{2}\gamma B N_\gamma s_\gamma d_\gamma i_\gamma$

B(ft)	$q_{ult}\ (psf)$	$q_{all}\ (psf)$	$Q_{all}\ (kips)$
4	16190	5390	86
5	16560	5520	138
6	17060	5680	205
8	18260	6080	390

Bearing Capacity of Piles and Drilled Shafts

- The bearing resistance of piles and shafts is contributed by
  - The tip resistance Q_P
  - Side resistance Q_s
- $Q_u = Q_{PU} + Q_{SU} - W_P$
- Q_U = Ultimate resistance
- Q_{PU} =Ultimate tip resistance
- Q_{SU} =Ultimate side resistance
- W_P = Weight of pile or shaft



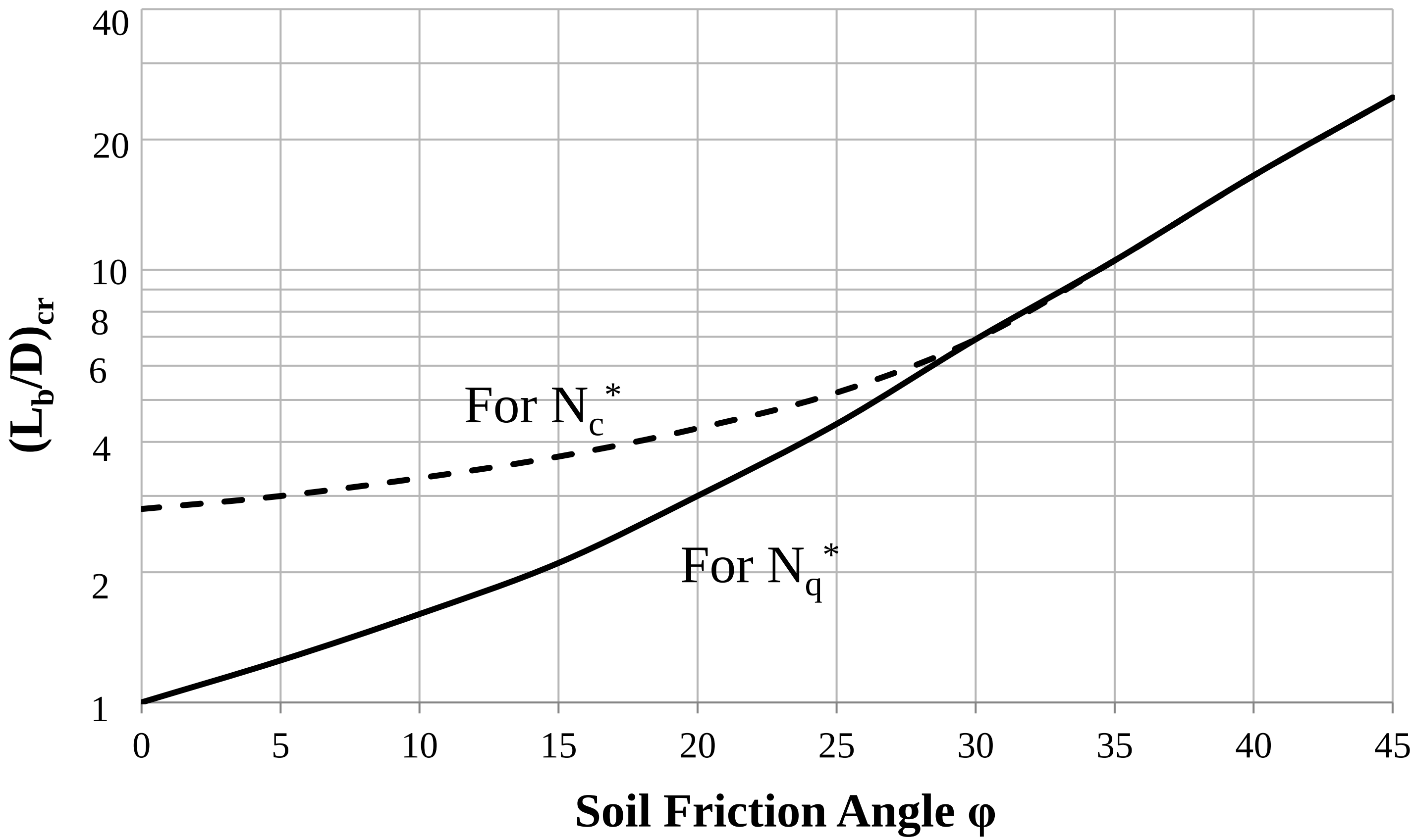
(A) Resisting Forces (B) Tip Resistance Failure Mechanism

Tip Resistance of Piles and Drilled Shafts

- $q_{PU} = cN_c^* + q_L' N_q^*$
- c =cohesion of soil under the tip
- q_L' =effective overburden pressure at pile tip level
- N_c^*, N_q^* = bearing capacity factors
- $q_L' = \gamma_L' L \leq \gamma_L' L_c$
- L_c =Critical depth
  - This is an important parameter in the evaluation of tip resistance. The term $q_L' N_q$ does not increase infinitely with depth!

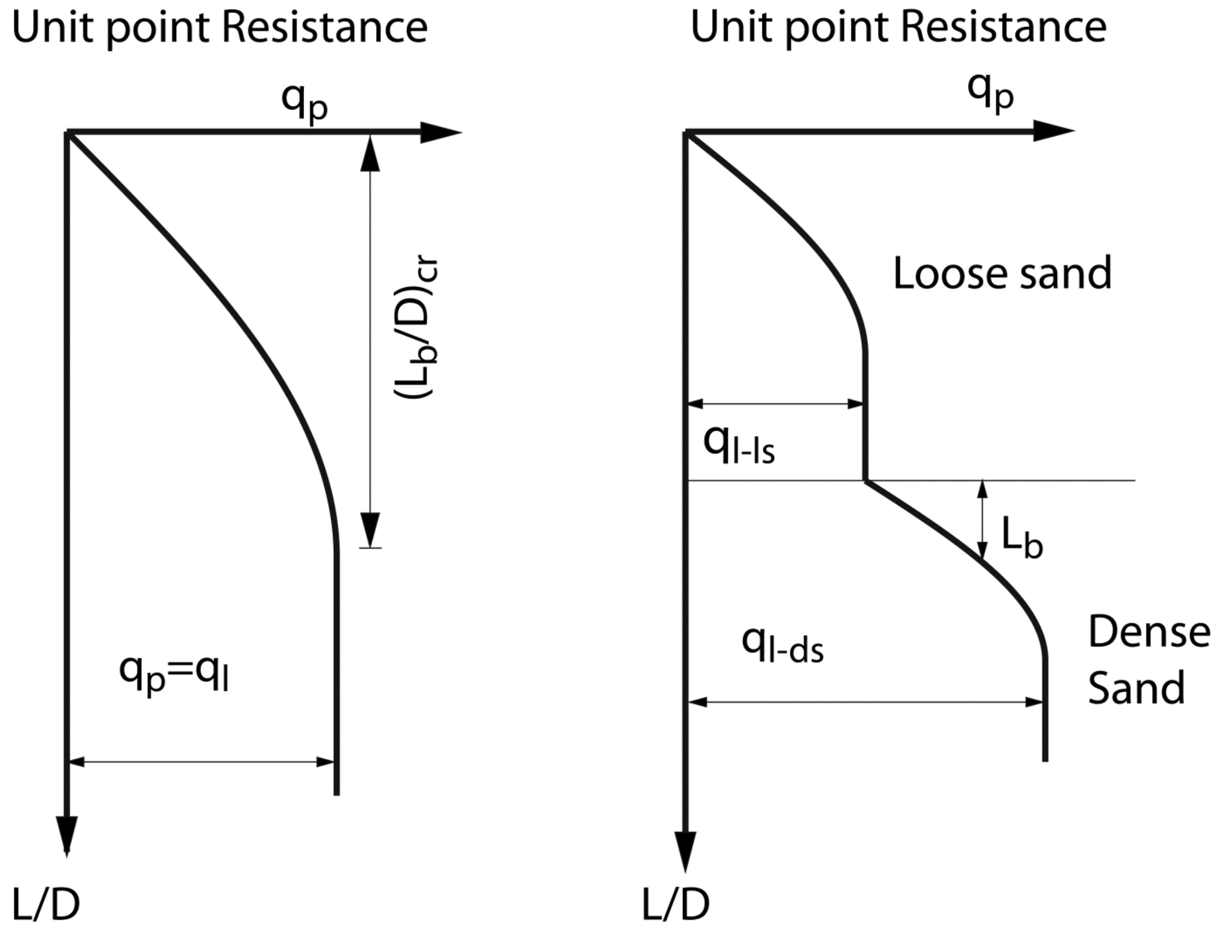
Pile Tip Resistance – Critical Depth

- From Meyerhof (1976)



Pile Tip Resistance – Critical Depth

- Critical Depth of uniform and multilayer embedment



Tip Resistance of Piles and Drilled Shafts – Bearing Capacity Factors

- $N_c^*, and\ N_q^*$ by Meyerhof (1976)
- Ultimate tip capacity:

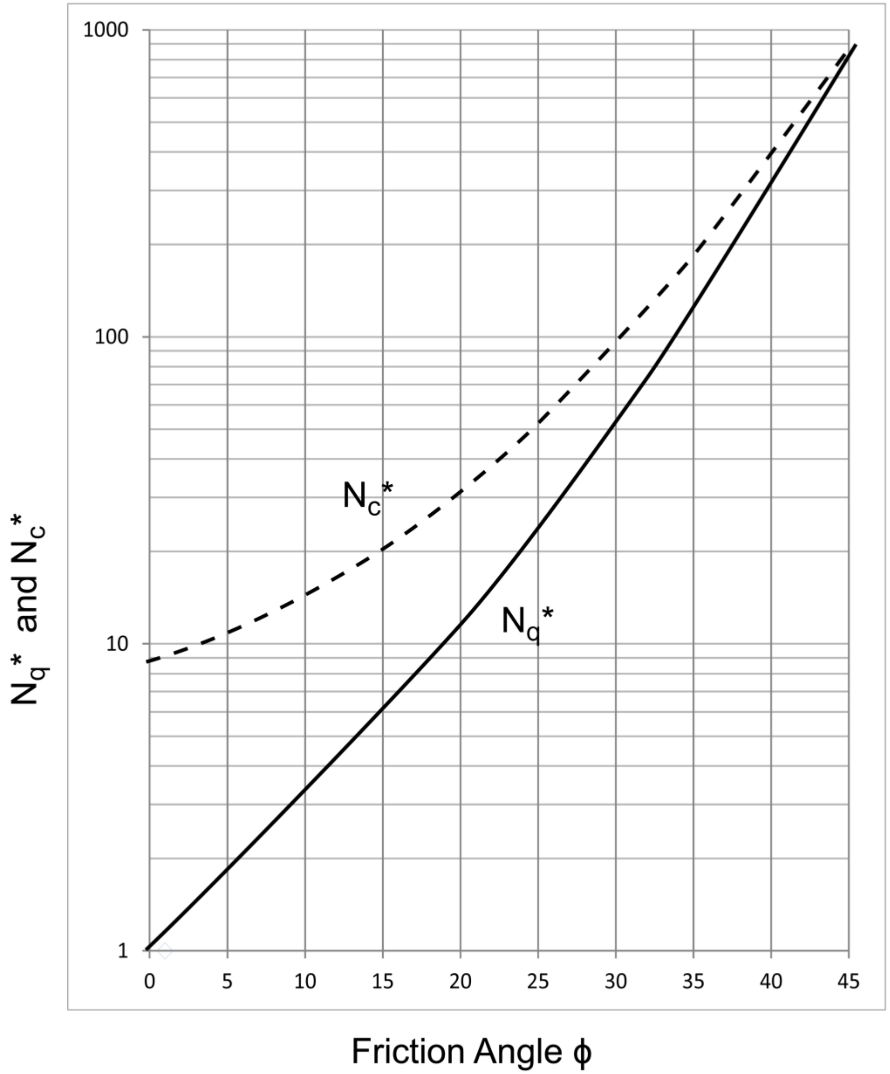
  $$q_{PU} = cN_c^* + q_L' N_q^*$$

- The allowed tip capacity can be evaluated based on:
  - General factor of safety:

    $$q_{PA} = q_{PU}/FS$$

  - Partial factors of safety:

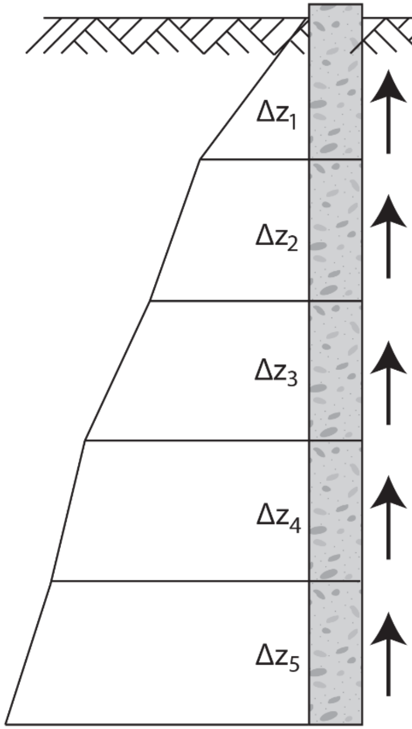
    $$q_{PA} = \frac{cN_c^*}{FS_c} + \frac{q_L' N_q^*}{FS_q}$$



Side Resistance of Piles and Drilled Shafts

- Sands
  - Side resistance is frictional
  - For soil layers *i* with different material properties (φ, γ’, μ)
  - $Q_{su} \approx \sum_{i=1}^{n}(\sigma_{vi}{}' K_i \mu_i P_i \Delta z_i) \sum_{i=1}^{n}\left(\left(\sum_{j=1}^{i-1}(\gamma_j \Delta z_j) - \gamma_i \frac{\Delta z_i}{2}\right) K_i \mu_i P_i \Delta z_i\right)$
  - Example for n=3: $Q_{su} = \frac{\gamma_1 \Delta z_1}{2} K_1 \mu_1 P_1 \Delta z_1 + \left(\gamma_1 \Delta z_1 + \frac{\gamma_2 \Delta z_2}{2}\right) K_2 \mu_2 P_2 \Delta z_2 + \left(\gamma_1 \Delta z_1 + \gamma_2 \Delta z_2 + \frac{\gamma_3 \Delta z_3}{2}\right) K_3 \mu_3 P_3 \Delta z_3$
  - The length of the pile is divided into smaller intervals Δz_i
    - μ_i = coefficient of friction between sand and pile/shaft for interval *i*
    - γ_i' = effective unit weight of soil along the shaft length for interval *i*
    - Δz_i = thickness of layer i
    - P_i =The perimeter of the pile shaft for interval *i*
    - K_i= effective earth pressure coefficient *i*, with recommended values as follows:
      - ✓ = $K_o = 1 - sin\phi$ (bored pile)
      - ✓ = $K_o\ to\ 1.4K_o$ (low displacement driven pile)
      - ✓ = $K_o\ to\ 1.8K_o$ (high displacement driven pile)

Size Resistance of Piles and Drilled Shafts in Frictional Soils



$$\frac{\gamma_1 \Delta z_1}{2} K_1 \mu_1 P_1 \Delta z_1$$

$$\left(\gamma_1 \Delta z_1 + \frac{\gamma_2 \Delta z_2}{2}\right) K_2 \mu_2 P_2 \Delta z_2$$

$$\left(\gamma_1 \Delta z_1 + \gamma_2 \Delta z_2 + \frac{\gamma_3 \Delta z_3}{2}\right) K_3 \mu_3 P_3 \Delta z_3$$

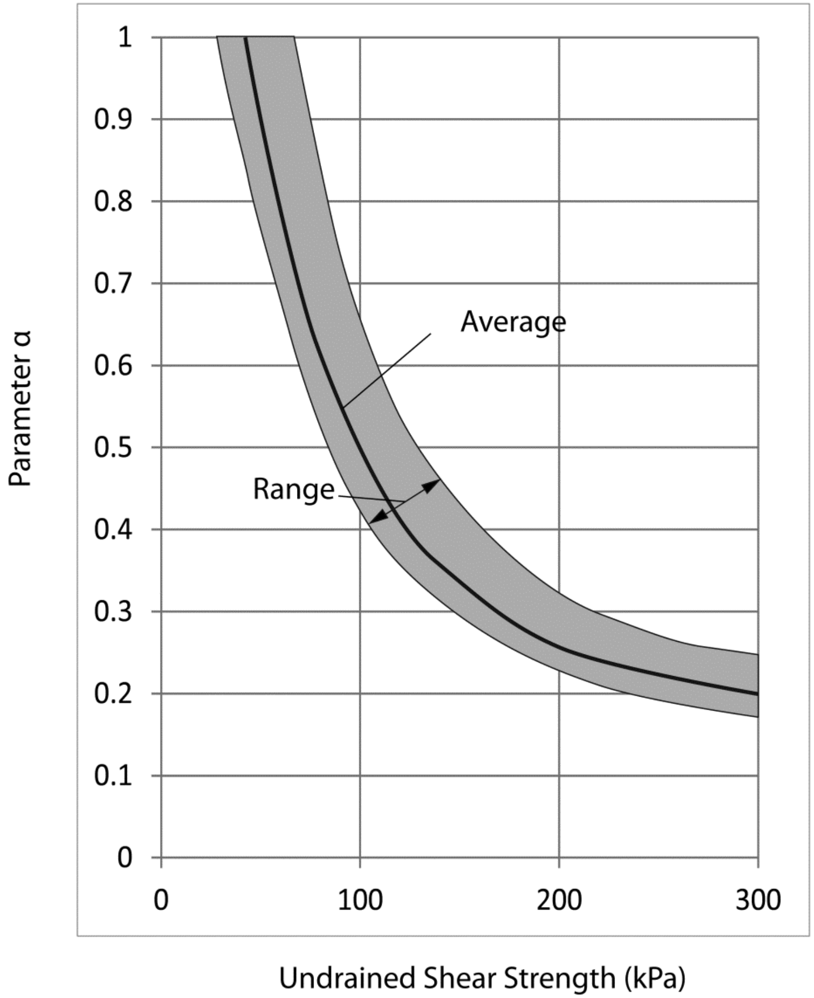
$$\left(\gamma_1 \Delta z_1 + \gamma_2 \Delta z_2 + \gamma_3 \Delta z_3 + \frac{\gamma_4 \Delta z_4}{2}\right) K_4 \mu_4 P_4 \Delta z_4$$

$$\left(\gamma_1 \Delta z_1 + \gamma_2 \Delta z_2 + \gamma_3 \Delta z_3 + \gamma_4 \Delta z_4 + \frac{\gamma_5 \Delta z_5}{2}\right) K_5 \mu_5 P_5 \Delta z_5$$

1. In this example, the pile is divided in 5 intervals of length Δz_i, not necessarily equal.
2. For each interval we calculate the side resistance as shown.
3. **The total side resistance is the sum of all the interval resistances.**

Side Resistance of Piles and Drilled Shafts in Clays (undrained)

- Side Resistance is due to adhesion
- Total stress method. Undrained conditions. **α – method**.
- $Q_{su} = \approx \sum_i f_u P \Delta z_i$
  - $f_u = \alpha c_u$
  - For $c_u < 50\ kPa \rightarrow \alpha = 1$



Side Resistance of Piles and Drilled Shafts in clays (Drained)

- Side Resistance is due to friction
- Effective stress method. Drained conditions. β – method.
- $Q_{su} = \approx \sum_i f_{u_i} P \Delta z_i$
  - $f_{u_i} = \beta_i \sigma'_{V_i}$
  - $\beta_i = K_i \, tan\phi'_{R_i}$
  - σ'_{V_i} = effective overburden pressure at the depth of interval *i*
  - ϕ'_{R_i} =Drained friction angle of remolded clay
  - K_i = earth pressure coefficient at rest at interval *i*
    - =$1 - sin\phi'_R$ for normally consolidated clays
    - $(1 - sin\phi'_R)\sqrt{OCR}$ for overconsolidated clays

Allowed Bearing Load of Piles and Drilled Shafts

- **Driven Piles**
  - $Q_U = Q_{PU} + Q_{SU}$
  - $Q_{all} = \frac{Q_U}{FS}$
    - $FS = 2\ to\ 4$
  - $Q_{all} = \frac{Q_{PU}}{3} + \frac{Q_{SU}}{1.5}$
- **Drilled Shafts**
  - $Q_{all} = \frac{Q_U}{2.5}$ for shaft diameter < 2.0m AND bell-shaped tip
  - $Q_{all} = \frac{Q_U}{2}$ Straight drilled shaft

Improving the Bearing Capacity

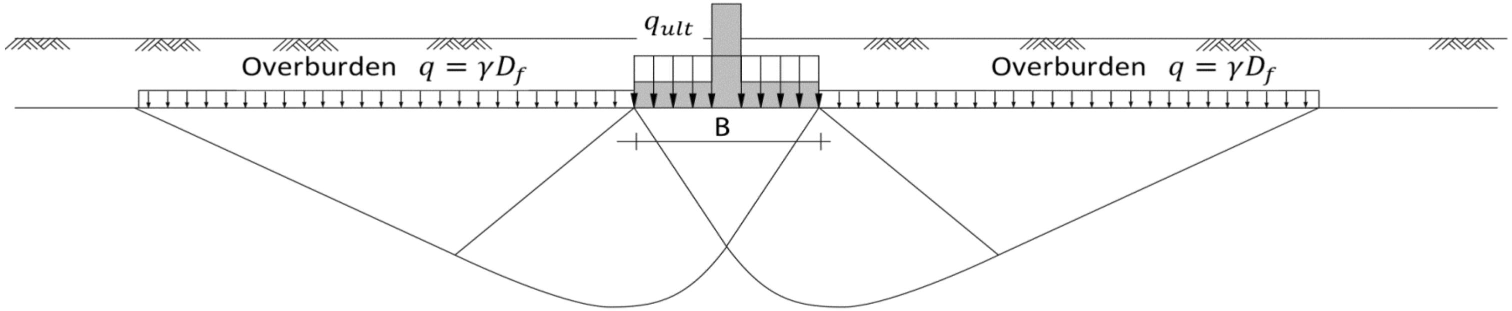
- A quick review of the bearing capacity equation reveals that the bearing capacity increases as
  - 1) the cohesion c increases (cN_c),
  - 2) the effective friction angle ϕ' increases ($N_c, N_q, and\ N_\gamma$),
  - 3) as the overburden gravity q $= \gamma' D_f$ increases (qN_q),
  - 4) as the gravity of the soils under the foundation γ' increases ($\frac{1}{2}\gamma' B N_\gamma$), and
  - 5) as the foundation size B increases ($\frac{1}{2}\gamma' B N_\gamma$).
- One of the simplest methods to increase bearing capacity is to improve the second term of the bearing capacity equation qN_q. That is, to increase the **depth of the embedment of the footing.** This approach is restricted to sites where the sub-soil water level is low enough to not interfere with the foundation excavation and the equation of bearing capacity. Existing underground utilities may also be a restricting factor. Attention should also be paid at the soil conditions, as sometimes going deeper may activate weaker underlying soil layers.

Improving the Bearing Capacity

- Drainage is also an efficient approach to improve the bearing capacity of some soils. Lowering the water table has multiple benefits:
  - *It improves the friction* ϕ'.
  - *It improves the cohesion c for soils with fines.*
  - *It increases the effective gravity*.
- All of the above have beneficial effects on the bearing capacity. Drains are typically laid in trenches at the footing base. The sub-soil water is collected and drained out through a system of pipe drains which is typically installed outside the external walls of the building.

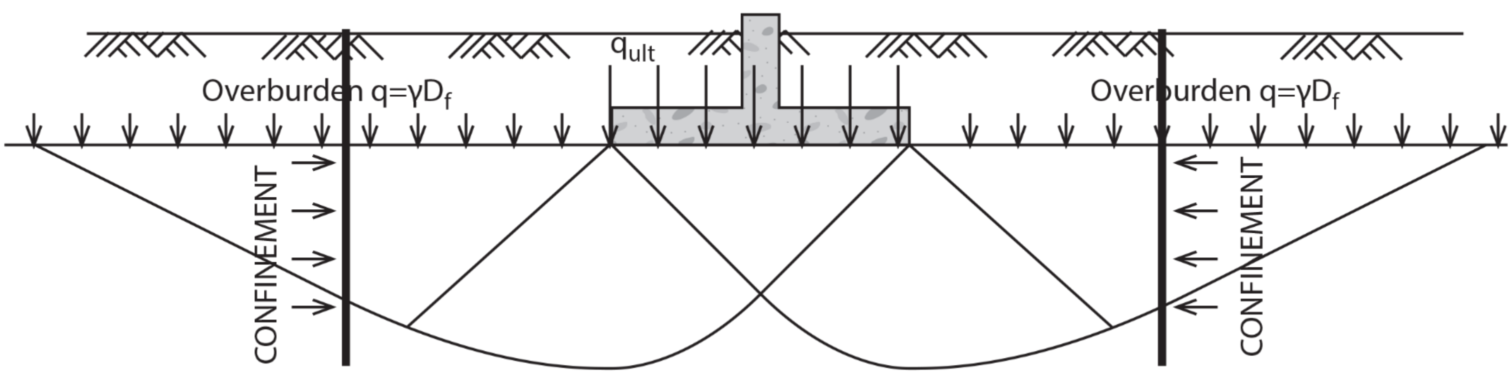
Improving the Bearing Capacity

- Improving the bearing soil results in improved bearing capacity. Blending granular materials, such as gravel or crushed stone into the natural soil results in a stronger soil, thus improving its bearing capacity.
- Bearing Capacity may also be improved by compaction of the bearing soil. Compaction improves the material parameters (c, c', ϕ', and γ) of the compacted soil, thus naturally improving the bearing capacity of the soil.



Improving the Bearing Capacity

- Preventing a complete development of the failure pattern is also beneficial to the bearing capacity. This can be achieved by confining the soil in an enclosed area with the help of sheet piles. This method works well in shallow foundations in sandy soils of medium to high density.



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