
بسم الله الرحمن الرحيم

Bearing Capacity of Shallow Foundations

By
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Bearing Capacity of Soils

- The maximum pressure which a soil through foundation can bear /can be allowed without out shear failure and excessive settlement, is called the bearing capacity of soil.
- Basic definitions:

- Gross Ultimate Bearing Capacity

- Net Ultimate Bearing Capacity

- Gross Safe Bearing Capacity

- Net Safe Bearing Capacity

- Safe Settlement Pressure

- Allowable Bearing Capacity

Basic Definitions :

1) Gross Ultimate Bearing Capacity (q_u):

The ultimate bearing capacity is the gross pressure at the base of the foundation at which soil fails in shear.

2) Net Ultimate Bearing Capacity (q_{nu}) :

It is the net increase in pressure at the base of foundation that cause shear failure of the soil.

Thus, $q_{nu} = q_u - \gamma D_f$ (ovrbruden pressure)

Basic Definitions :

3) Gross Safe Bearing Capacity (q_s) :

It is the maximum pressure which the soil can carry safely without shear failure at the base of foundation.

$$q_s = (q_u) / \text{FOS}$$

4) Net Safe Bearing Capacity (q_{ns}) :

It is the net soil pressure which can be safely applied to the soil considering only shear failure.

Thus, $q_{ns} = q_{nu} / \text{FOS}$

FOS - Factor of safety usually taken as 2.0 - 3.0

Basic Definitions :

5) Safe Settlement Pressure (q_{sp}) :

It is the maximum pressure which the soil can carry without exceeding allowable/permissible settlement.

***6)* Allowable Bearing Capacity (qa):**

It is the net bearing pressure which can be used for design of foundation satisfying both bearing capacity and settlement criteria.

Thus,

$$q_a = q_s \quad ; \text{if } q_{sp} > q_s$$

$$q_a = q_{sp} \quad ; \text{if } q_s > q_{sp}$$

It is also known as Allowable Soil Pressure (ASP) or Allowable bearing Capacity (ABC)

ADEQUACY OF FOUNDATIONS

A foundation is considered adequate if it meets the following requirements:

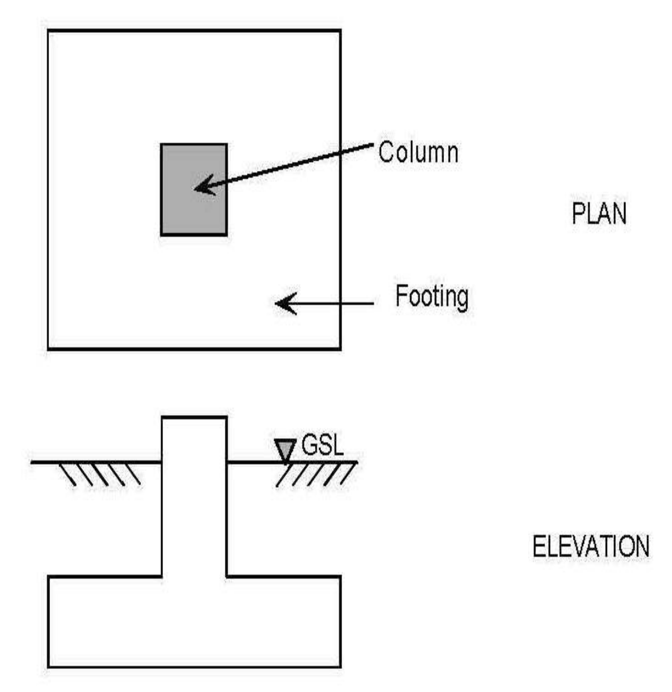
- It should be safe against shear failure of ground (generally known as bearing capacity failure.)
- It should not undergo excessive settlement (both total and differential settlements)
- The foundations must be placed at an adequate depth so as to be safe from erosion, scouring action of water and seasonal variations. The depth must be sufficient to avoid lateral squeezing of material from underneath the foundations, provide adequate resistance to the horizontal forces, and must bear on a stratum of adequate bearing capacity.

- The foundations must be safe against corrosion or deterioration due to harmful materials present in the soil and/or ground water.
- The foundation system should be buildable with local materials and available construction personnel. The foundation system must not excessively degrade the environment.
- The foundation system should be durable and strong to assure safety against overturning, sliding and uplift.

TYPES OF SHALLOW FOUNDATIONS

1) **Spread Foundation**

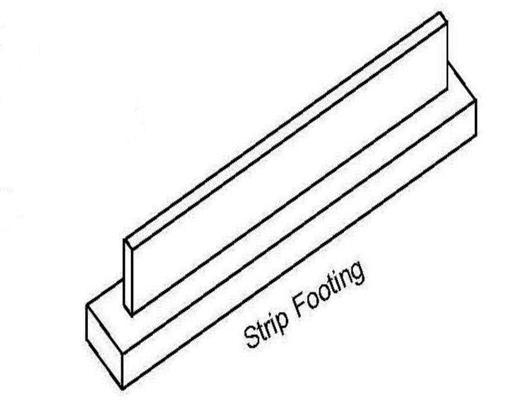
- ❑ This foundation is also called as Pad, Single or Isolated foundation.
- ❑ It supports one column only.
- ❑ It can be of square, circular, rectangular or any other shape.
- ❑ Its function is to spread the column load laterally to the soil so that the stress intensity is reduced to a value that the soil can safely carry.



ISOLATED FOOTING

2) **Continuous Foundation**

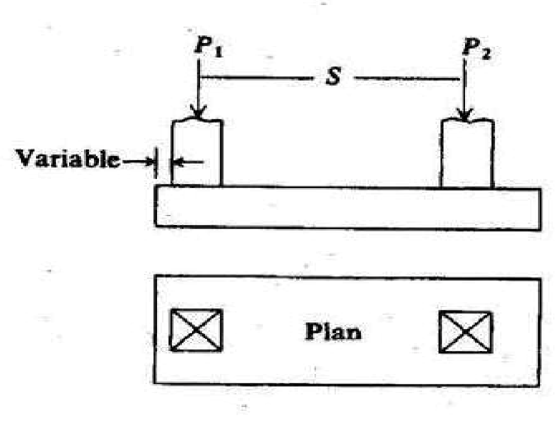
- ☐ If a footing is extended in one direction to support a long structure such as a wall, it is called a continuous footing or a wall footing or a strip footing.
- ☐ Loads are usually expressed in force per unit length of the footing.
- ☐ A strip footing is also provided for a row of columns which are so closely spaced that their spread footings overlap or nearly touch each other.



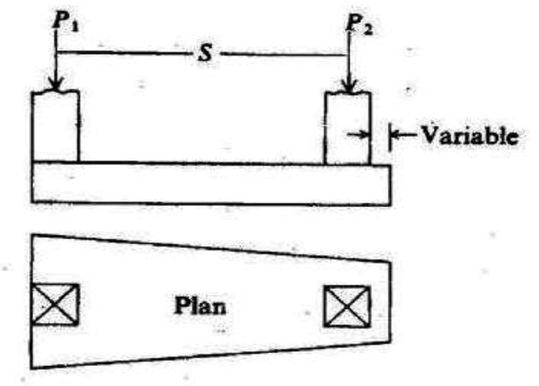
RC WALL FOOTING

3) Combined Foundation

- A combined footing is a larger footing supporting two or more columns in one row.
- This results in a more even load distribution in the underlying soil or rock, and consequently there is less chance for differential settlement to occur.
- While these footings are usually rectangular in shape, these can be trapezoidal (to accommodate unequal column loadings or close property lines).



(*a*) Rectangular

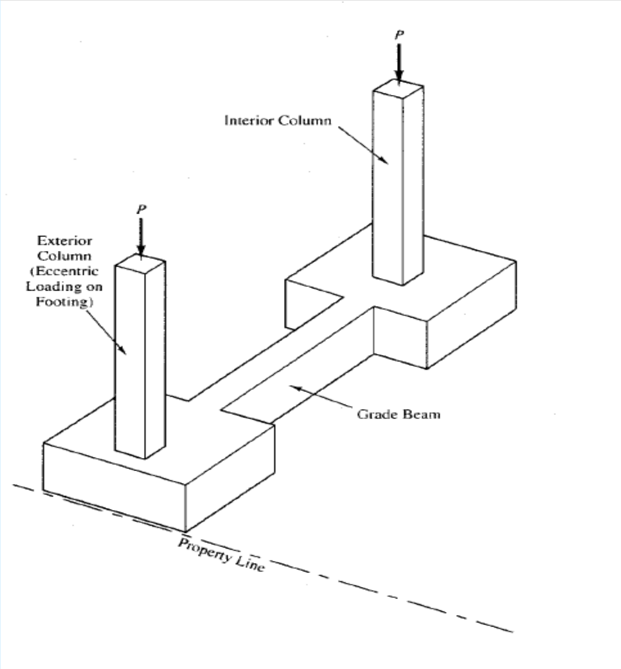


(*b*) Trapezoid

Combined Footing

4) Strap Foundation

- Two or more footings joined by a beam (called a strap) is called a strap footing.
- Strap is designed as a rigid beam to withstand bending moments, shear stresses. The strap simply acts as a connecting beam and does not take any soil reaction. To make this sure, soil below it is dug and made loose.

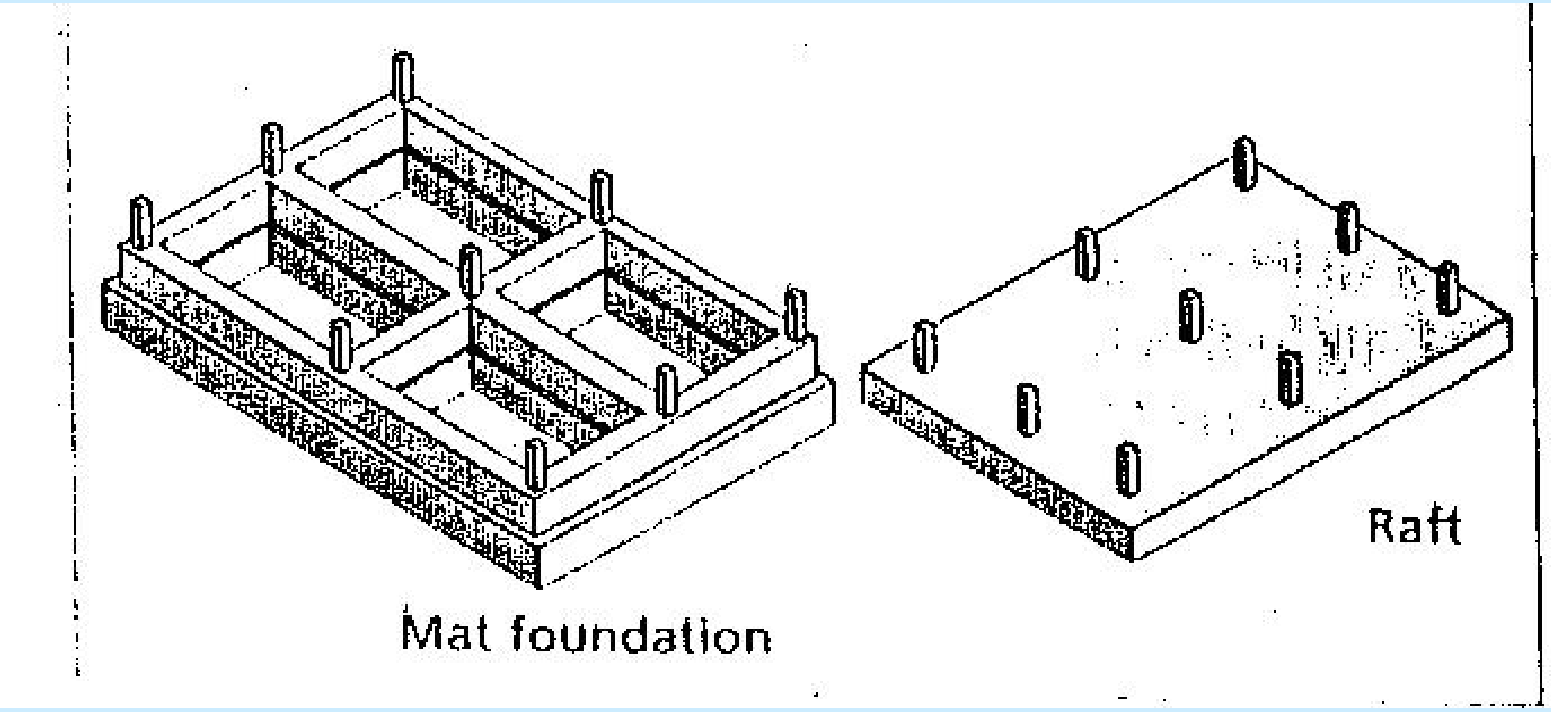


5) Mat or Raft Foundation

A large slab supporting a number of columns not all of which are in a straight line is called a mat or raft or mass foundation. These are usually considered where :

- the base soil has a low bearing capacity and differential settlements are likely.
- column loads are so large that the sum of areas of all individual or combined footings exceeds 1/2 to 2/3 of the total building area (to economize on framework costs).
- there is a large variation in the loads on individual columns.
- for basement at or below the GWT to act as a water barrier.

RAFT / MAT FOUNDATION



RAFT/MAT FOUNDATION

MODES OF BEARING CAPACITY FAILURE

A bearing capacity failure is defined as a foundation failure that occurs when the shear stresses in the soil exceed the shear strength of the soil.

Terzaghi (1943) classified shear failure of soil under a foundation base into following two modes 1 & 2 and then Vesic (1963) added the mode 3 depending on the type of soil & location of foundation.

1) General Shear Failure

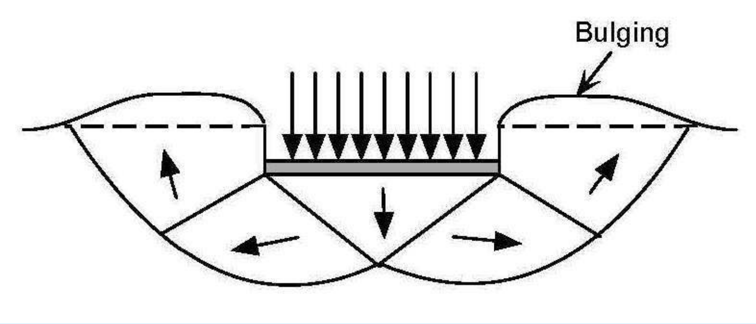
2) Local Shear Failure

3) Punching Shear Failure **{Vesic (1963) added}**

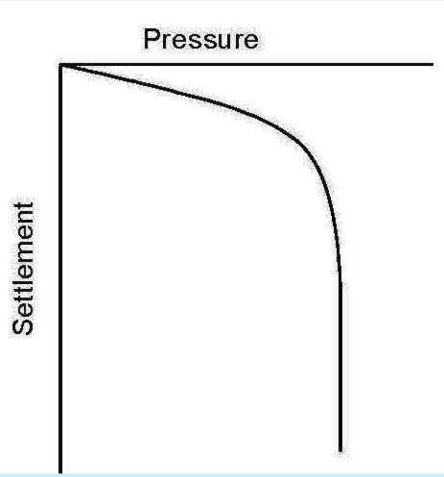
MODES OF BEARING CAPACITY FAILURE

1) General Shear Failure

- ☐ It involves total rupture of the underlying soil.
- ☐ Applicable to narrow footings placed at shallow depths on dense or overconsolidated cohesive soils of low compressibility.
- ☐ Soil around the footing bulges out.
- ☐ It is common under undrained conditions.



Stress Distribution (by Meyerhof)

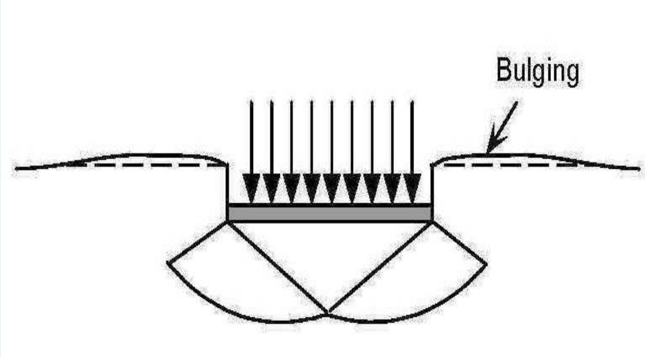


Load Settlement Curve

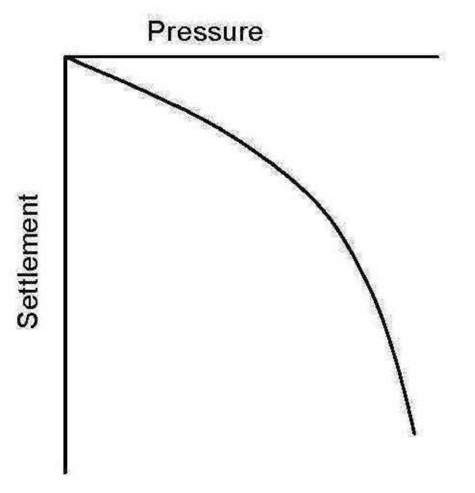
MODES OF BEARING CAPACITY FAILURE

2) Local Shear Failure

- ❑ Occurs in soils of high compressibility
- ❑ Slip surfaces/lines well defined below the footing only
- ❑ Slip lines extends only a short distance into the soil mass
- ❑ Slight heaving occurs
- ❑ Little or no tilting of the foundation
- ❑ UBC in not well defined from the settlement-pressure graph
- ❑ Usually settlement is the main design criterion.



Stress Distribution

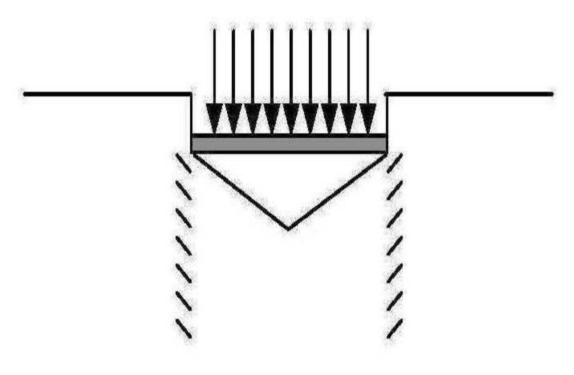


Load Settlement Curve

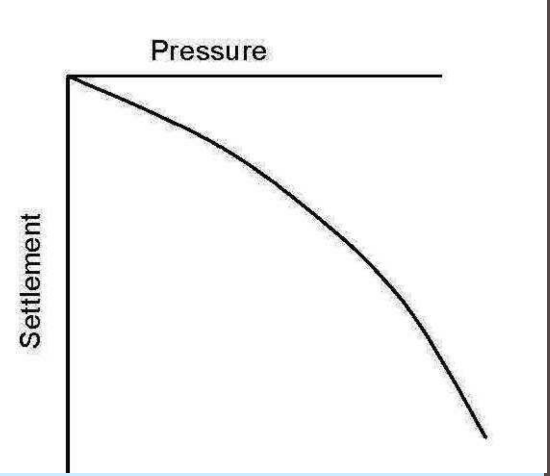
MODES OF BEARING CAPACITY FAILURE

3) Punching Shear Failure

- ❑ This failure occurs for soils in loose or soft state.
- ❑ Failure by considerable vertical downward movement i.e. shearing in the vertical direction around the edges of the footing.
- ❑ Slip surface restricted to vertical planes adjacent to the sides of the footing.
- ❑ No bulging usually, no tilting.
- ❑ Failure is usually slow and time consuming (conditions are drained)

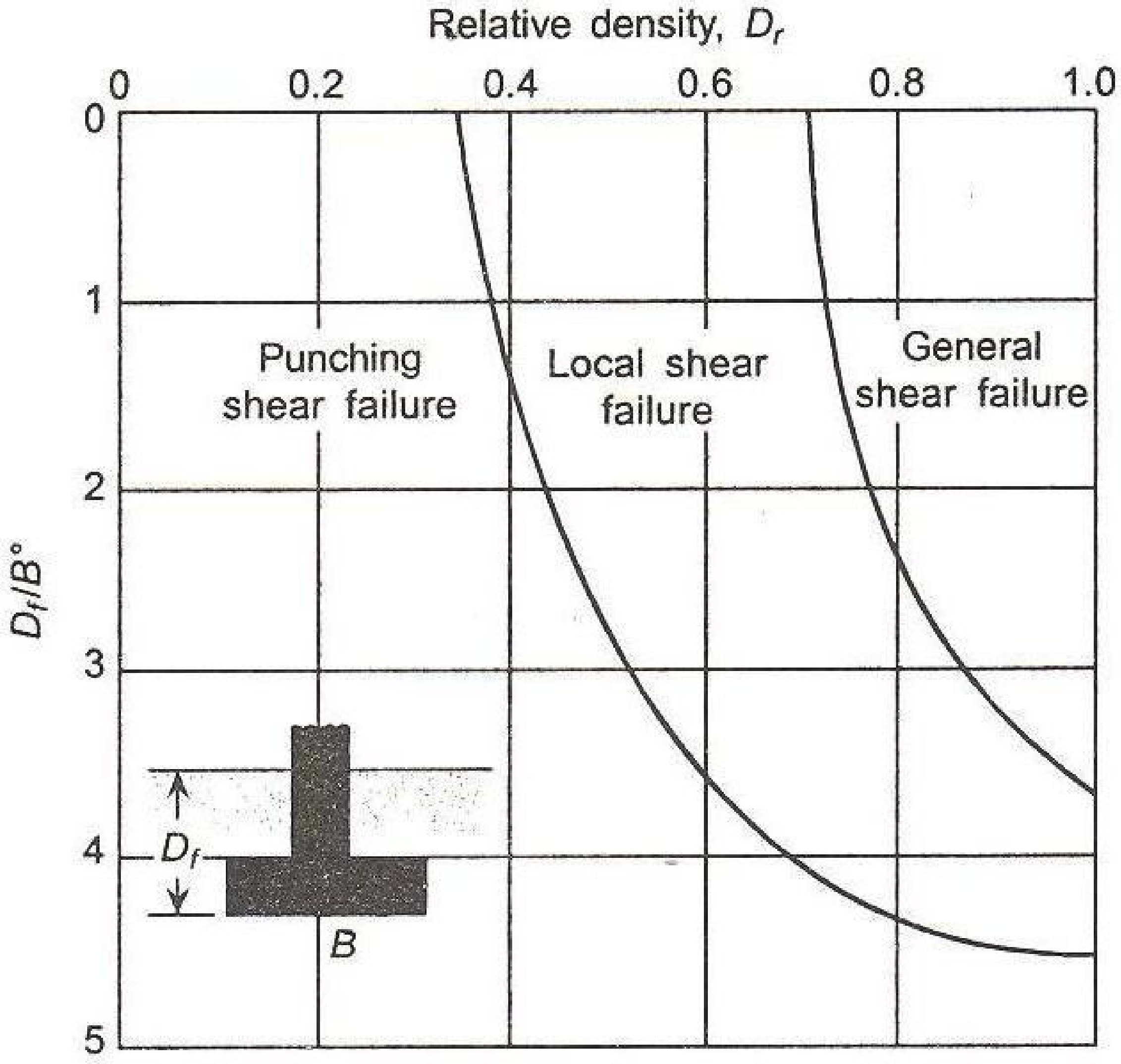


Stress Distribution



Load Settlement Curve

MODES OF BEARING CAPACITY FAILURE



Modes of bearing capacity failure in sand (Vesic, 1973).

Development of Bearing Capacity Theory

- **Application of limit equilibrium method was first employed by Prandtl on punching of thick masses of metal. He proposed the BC equation for shear failure of soil as given below:**

$$q_{ult} = \frac{c}{\tan\phi}\{\tan^2(45+\frac{\phi}{2})e^{\pi\tan\phi} - 1\}$$

- **Prandtl's equation shows that if the cohesion of the soil is zero, the bearing capacity would also be equal to zero. This is quite contrary to the actual conditions. For cohesion less soil, the equation is indeterminate**

- **The limitations of Prandtl approach were recognized and accounted to some extent by Terzaghi and others. Terzaghi proposed bearing capacity equation for shallow foundations.**

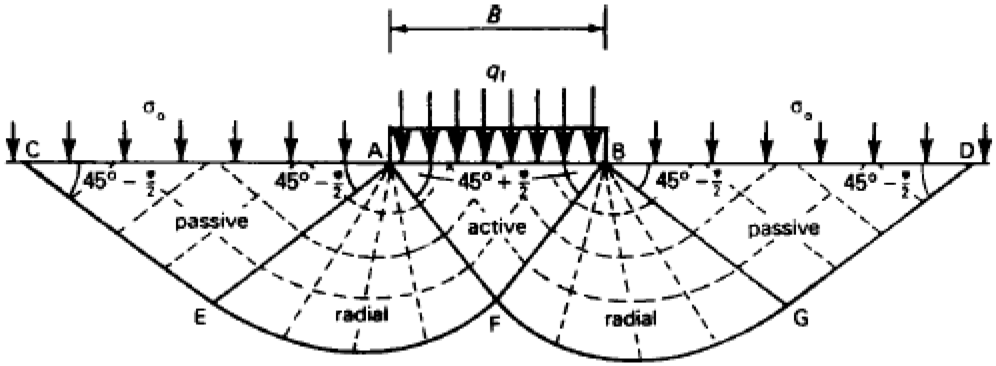
- **Meyerhof, Hanson, Vesic and others improved on Terzaghi's original theory and added other factors for a more complete analysis**

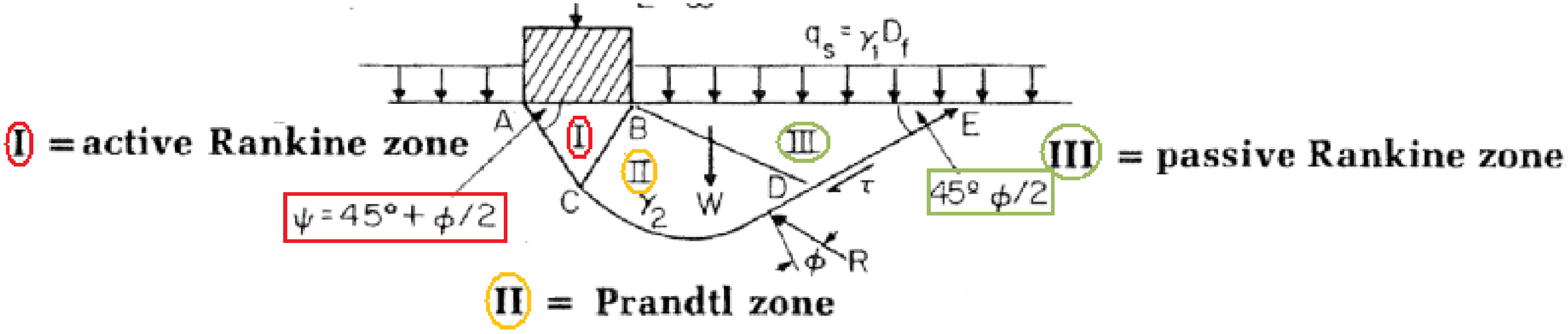
Terzaghi's Bearing Equation

Assumptions of Terzaghi's BC Equation:

- Depth of foundation is less than or equal to its width
- No sliding occurs between foundation and soil (rough foundation)
- Soil beneath foundation is homogeneous semi infinite mass
- Mohr-Coulomb model for soil shear strength applies
- General shear failure mode is the governing mode
- No soil consolidation occurs; undrained condition
- Soil above bottom of foundation has no shear strength; it provided only a surcharge load against the overturning load
- Applied load is compressive and applied vertically to the centroid of the foundation
- No applied moments present

Failure Geometry for Terzaghi's Method





$$q_u = q_c + q_q + q_\gamma$$

Terzaghi Bearing capacity equation

$$q_{ult} = cN_c Sc + \gamma D_f N_q + 0.5\gamma B N_\gamma S_\gamma$$

Shape Factors

	strip	**circular**	**square**	**rectangle**
Sc =	**1**	**1.3**	**1.3**	$1+0.3\frac{B}{L}$
S_γ **=**	**1**	**0.6**	**0.8**	$(1-0.2\frac{B}{L})$

Nc, Nq, Nγ are bearing capacity factor

Terzaghi’s BC Equations for different footings

$$q_{ult} = cN_c + \gamma D_f N_q + 0.5\gamma B N_\gamma$$

Strip footing

$$q_{ult} = 1.3cN_c + \gamma D_f N_q + 0.3\gamma B N_\gamma$$

Circular footing

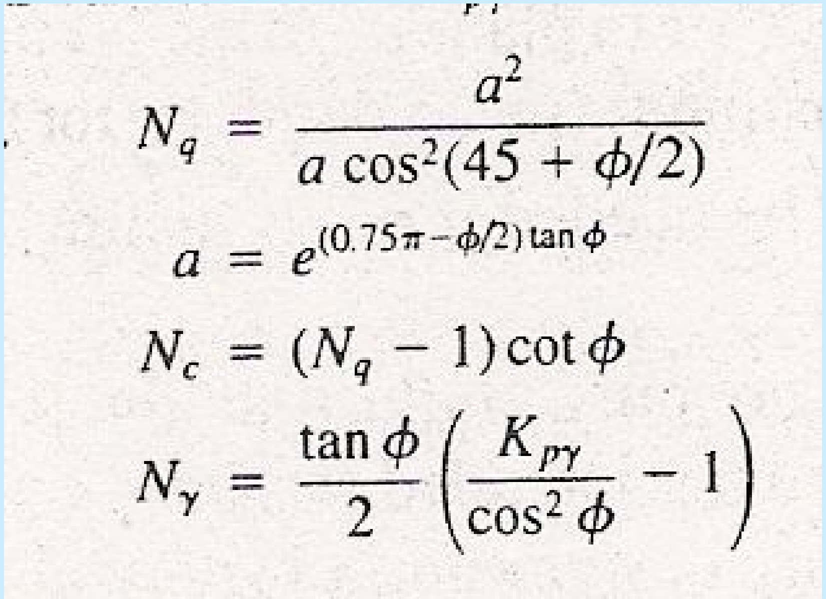
$$q_{ult} = 1.3cN_c + \gamma D_f N_q + 0.4\gamma B N_\gamma$$

Square footing

$$q_{ult} = cN_c(1 + 0.3\frac{B}{L}) + \gamma D_f N_q + 0.5\gamma B N_\gamma (1 - 0.2\frac{B}{L})$$

Rectangular footing

BC factors for use in Terzaghi's bearing capacity equation

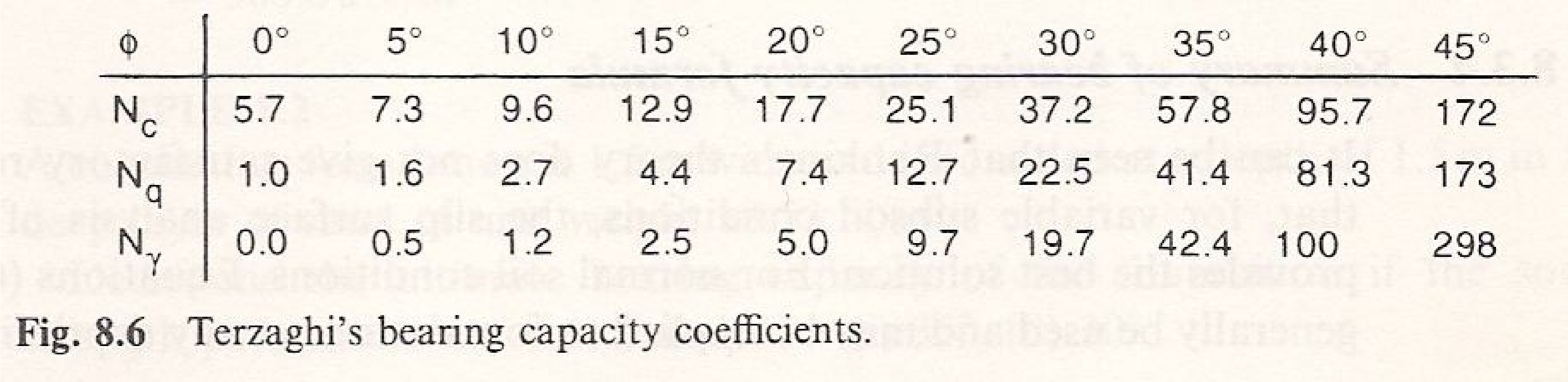


$$N_q = \frac{a^2}{a \cos^2(45 + \phi/2)}$$

$$a = e^{(0.75\pi - \phi/2)\tan\phi}$$

$$N_c = (N_q - 1)\cot\phi$$

$$N_\gamma = \frac{\tan\phi}{2}\left(\frac{K_{p\gamma}}{\cos^2\phi} - 1\right)$$



ϕ	0°	5°	10°	15°	20°	25°	30°	35°	40°	45°
N_c	5.7	7.3	9.6	12.9	17.7	25.1	37.2	57.8	95.7	172
N_q	1.0	1.6	2.7	4.4	7.4	12.7	22.5	41.4	81.3	173
N_γ	0.0	0.5	1.2	2.5	5.0	9.7	19.7	42.4	100	298

Fig. 8.6 Terzaghi's bearing capacity coefficients.

Effect of GWT on Bearing Capacity

W/T affect the value of BC as under:

$$q_{ult} = cN_c + \gamma D_f N_q R'_w + 0.5\gamma B N_\gamma R_w$$

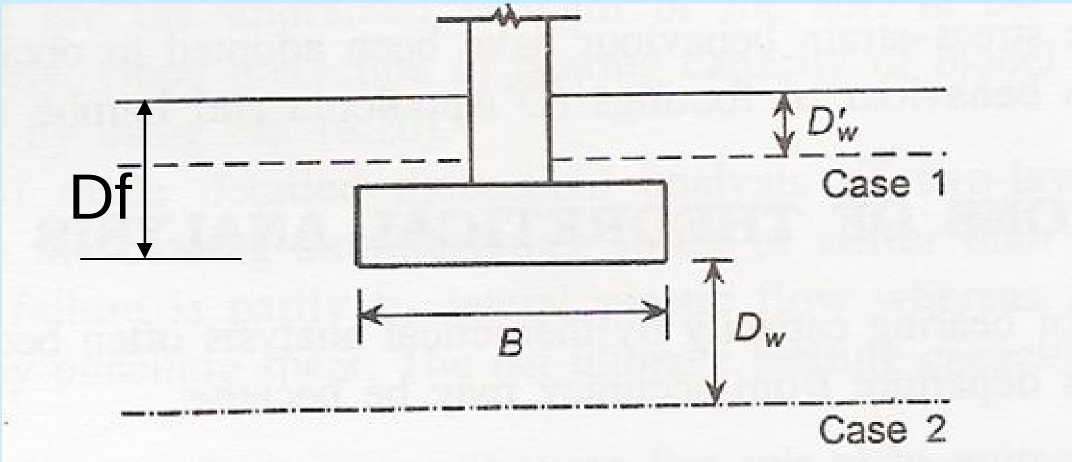


Fig. 6.12 Effect of ground water table.

$$R'_w = 0.5\left[1 + \frac{D'_w}{D_f}\right]$$

$$R_w = 0.5\left[1 + \frac{D_w}{B}\right]$$

Maximum value of Rw’ & Rw is 1

Terzaghi’s BC Equations

Few comments on Terzaghi equation:

1- The ultimate B.C increases with depth of footing.

2- The ultimate B.C of a cohesive soil (φ = 0) is independent of footing size, i.e. at the ground surface ($D_f = 0$) $q_u = 5.7c$.

3- The ultimate B.C of a cohesion less soil (c = 0) is directly dependent on footing size, but the depth of footing is more significant than size.

4- The above equations given by Terzaghi are for General Shear Failure case. For Local Shear Failure condition, following soil parameters were proposed by Terzaghi:

$$c' = 2/3\ c$$

$$\tan \varphi' = 2/3 \tan \varphi$$

General bearing capacity equation

Meherhof, Hansen & Vesic proposed the following general BC equation

$$q_{ult} = cN_c s_c d_c i_c g_c b_c + \bar{q} N_q s_q d_q i_q g_q b_q + 0.5\gamma B N_\gamma s_\gamma d_\gamma i_\gamma g_\gamma b_\gamma$$

s_c, s_q and s_γ are shape factors
d_c, d_q and d_γ are depth factors
i_c, i_q and i_γ are inclination factors
g_c, g_q and g_γ are ground factors (base on slope)
b_c, b_q and b_γ are base factors (inclination of base)

Example:

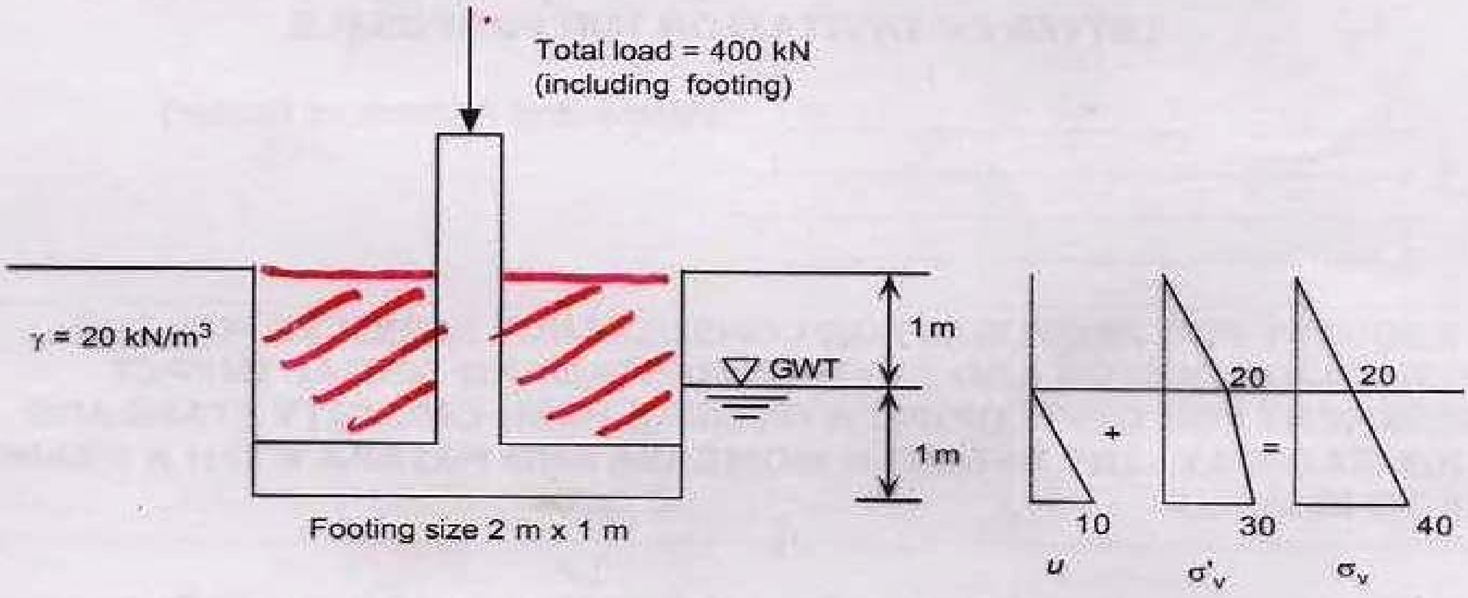
Determine the gross and net foundation pressure for the data shown in the figure.

Solution:

The initial total overburden pressure at foundation level, $\sigma_o = 2\times20 = 40$ kPa

The gross foundation pressure, $q = 400/\text{Area of footing} = 400/2 = 200$ kPa

The net foundation pressure, $q_n = 200 - 40 = 160$ kPa



The final effective stress at foundation level, $q' = 200 - u = 200 - 10 = 190$ kPa

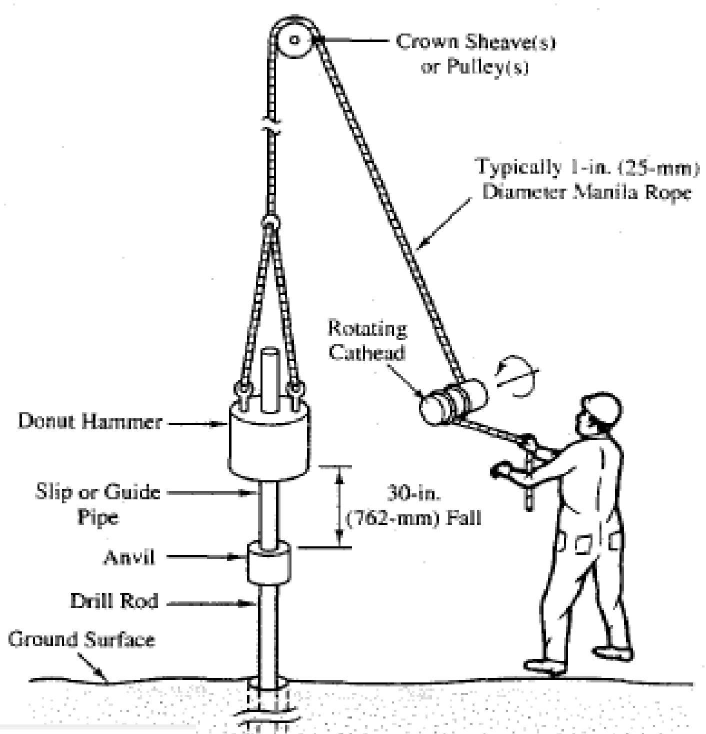
Effective stress due to overburden at foundation level, $\sigma'_v = 20 + 10 = 30$ kPa

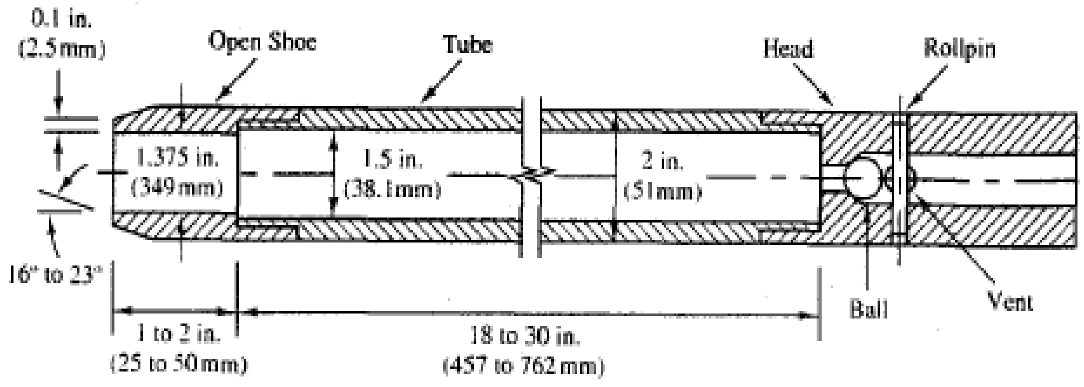
Net increase in effective stress at foundation level, $q'_n = 190 - 30 = 160$ kPa

BEARING CAPACITY FROM SPT

SPT-N Value:

Number of blows required for 12 inch penetration of split spoon sampler under the impact of a standard wt. of 140 lbs dropped from a height of 30 inch





BEARING CAPACITY FROM SPT

Consistency of Cohesive Soil Based on SPT-N value

Description	**Very Soft**	**Soft**	**Medium**	**Stiff**	**Very Stiff**	**Hard**
Unconfined compressive strength, q_u (tsf)	0 – 0.25	0.25 – 0.5	0.5 – 1.0	1.0 – 2.0	2.0 – 4.0	4.0 – UP
Standard Penetration Test value, *N*	**0 – 2**	**3 – 4**	**5 – 8**	**9 – 16**	**17 – 32**	**33 – UP**
Approx. range of saturated unit weight, γ_{sat} (pcf)	100 – 120		100 – 130	120 – 140		130^+

BEARING CAPACITY FROM SPT

Consistency of Cohesionless Soil Based on SPT-N value

Description	**Very Loose**	**Loose**	**Medium**	**Dense**	**Very Dense**
Relative density, D_r	0 – 0.15	0.15 – 0.35	0.35 – 0.65	0.65 – 0.85	0.85 – 1.00
Standard Penetration Test value, *N*	**0 – 4**	**5 – 10**	**11 – 30**	**31 – 50**	**51 – UP**
Approximate angle of internal friction, ϕ (degree)	25 – 28	28 – 30	30 – 35	35 – 40	38 – 43
Approximate range of moist unit weight, γ (pcf)	70 – 100	90 – 115	110 – 130	110 – 140	130 – 150
Submerged unit weight, γ_{sub}	60	55 – 65	60 – 70	65 – 85	75

BEARING CAPACITY FROM SPT

- **Bowles (1988)---w.r.t settlement**

$Q_a = 20\, N\, K_d (S/25)$ (for $B \leq 1.25$ m)

$Q_a = 12.5 N (1+0.3/B)^2\, K_d\, (S/25)$ (for $B > 1.25$ m)

Q_a = Allowable bearing pressure (kPa) for a settlement of ‘S’ in mm

N = SPT resistance in blows/300 mm (statistical average value for the footing influence zone of about 0.5 B above footing base to at least 2B below.

B = Width of footing in meters.

K_d = Depth factor = $(1+0.33D_f/B) \leq 1.33$

BEARING CAPACITY FROM SPT

- **Teng (1962) –w.r.t shear failure**

For Square Footing:

$$Qs = 0.105BN^2R'_w + 0.314\,(100 + N^2)\,D_fR_w$$

For Strip Footing:

$$Qs = 0.157BN^2R'_w + 0.362(100 + N^2)\,D_fR_w$$

Where,

Q*s* = net safe bearing capacity w.r.t. shear failure alone for FOS of 3 in psf or kPa

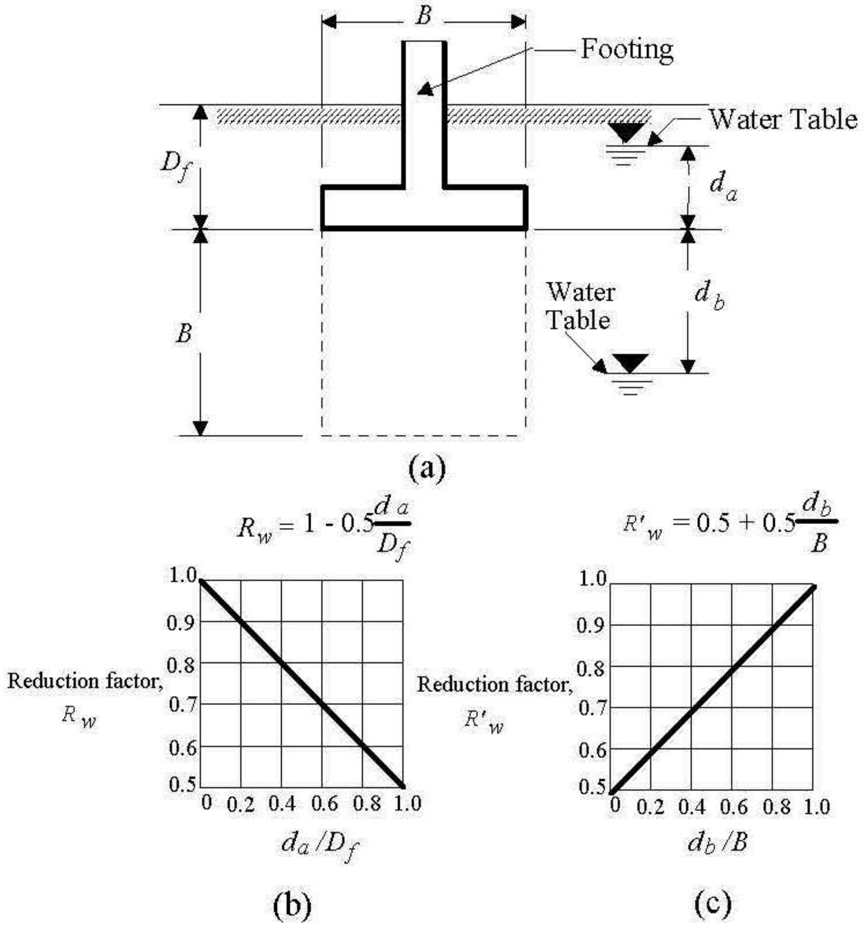
B = footing width in meters or ft

N = SPT resistance in blows/300 mm or blows/ft

D = footing depth in meters or ft

Rw & *R'w* = water table reduction factor

Calculation of Rw & R'w, water table reduction factor



Correction factors for position of water level: (a) depth of water level with respect to dimension of footing; (b) water level above base of footing; (c) water level below base of footing.

BEARING CAPACITY FROM CPT

- **Meyerhof (1956)**

For a maximum settlement of 25 mm, Meyerhof proposed the following equation:

$$q_a = 3.6\, q_c \quad \text{(kPa)} \qquad \text{for } B \leq 1.2 \text{ m}$$

$$q_a = 2.1\, q_c\, (1 + 1/B)^2 \quad \text{(kPa)} \qquad \text{for } B > 1.2 \text{ m}$$

Where,

B = footing width in meters.

qc = CPT cone resistance

Notes:

above equations are based on the approximate rule that $N = q_c/4$ (in kg/cm^2).

q_a is halved if the sand within the stresses zone is submerged.

For rafts and pier foundations, double the q_a values determined above.

BEARING CAPACITY FROM CPT

- **Schmertmann (1978)**

The bearing capacity factors for use in Terzaghi's bearing capacity equation can be estimated as:

$$0.8\,N_q \cong 0.8\,N_\gamma \cong q_c \qquad D/B \leq 1.5.$$

Where q_c is average cone resistance over depth interval from $B/2$ above to $1.1B$ below footing base.

For Cohesionless Soils

Strip: $Q_{ult} = 28 - 0.0052(300 - q_c)^{1.5}$ (Kg/cm^2)

Square: $Q_{ult} = 48 - 0.009(300 - q_c)^{1.5}$ (Kg/cm^2)

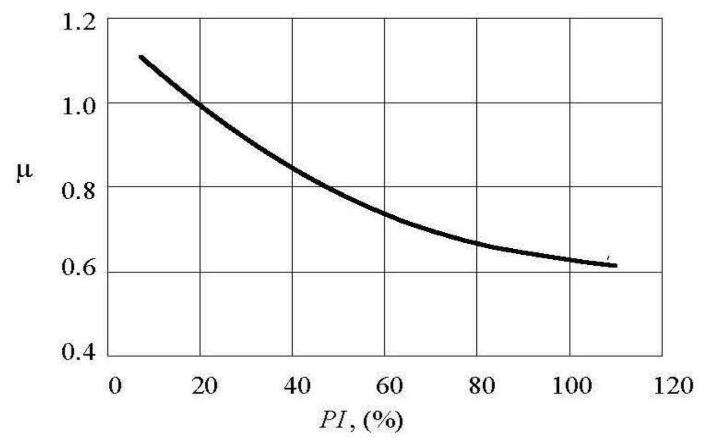
For Cohesive Soils

Strip: $Q_{ult} = 2 + 0.28q_c$ (Kg/cm^2)

Square: $Q_{ult} = 5 + 0.34q_c$ (Kg/cm^2)

3) BEARING CAPACITY FROM VANE SHEAR TEST

$$Q_{ult} = 5\mu\tau_u(1+0.2D_f/B)(1+0.2B/L)+q$$



Correction factor for the field vane test as a function of PI, (after Bjerrum, 1972, and Ladd, et al., 1977).

Where,

μ= strength reduction factor

τ_u = undrained shear strength

$= T/3.6D^3$

T = measured torque

D = blade diameter of vane

q= total overburden pressure at foundation level.

FACTORS AFFECTING B.C.

1) **Soil Type**

General B.C equation for *c*- ϕ soil

$$Q_{ult} = cN_c + \bar{q}N_q + 0.5\gamma BN_\gamma$$

For cohesive soil ($\phi = 0$)

$$Q_{ult} = cN_c + \bar{q}N_q$$

$$Q_{un} = cNc + q(Nq - 1), \quad \bar{\phi} = 0, \quad Nq=1, Nc=5.7$$

$$Q_{un} = cNc = 5.7c \sim qu$$

Q_{un} depends on cohesion only

For non-cohesive soil ($c \overline{=} 0$)

$$Q_{un} = q(Nq - 1) + 0.5\gamma BN_\gamma$$

Q_{un} depends on both B and Depth

FACTORS AFFECTING B.C.

2) **Conditions of the soil Deposits**

- ❑ Condition of a soil mass is dependent on its unit weight.
- ❑ For cohesive soil, it is expressed as very soft, soft, firm, stiff, very stiff and hard.
- ❑ For non-cohesive soil, it is expressed as very loose, loose, medium dense, dense and very dense.
- ❑ The unit weight of soil affects the overburden and friction component of B.C. equation.

So effect of unit weight on BC is self evident from BC equation

3) **Width (B) and Depth (D_f) of Footing**

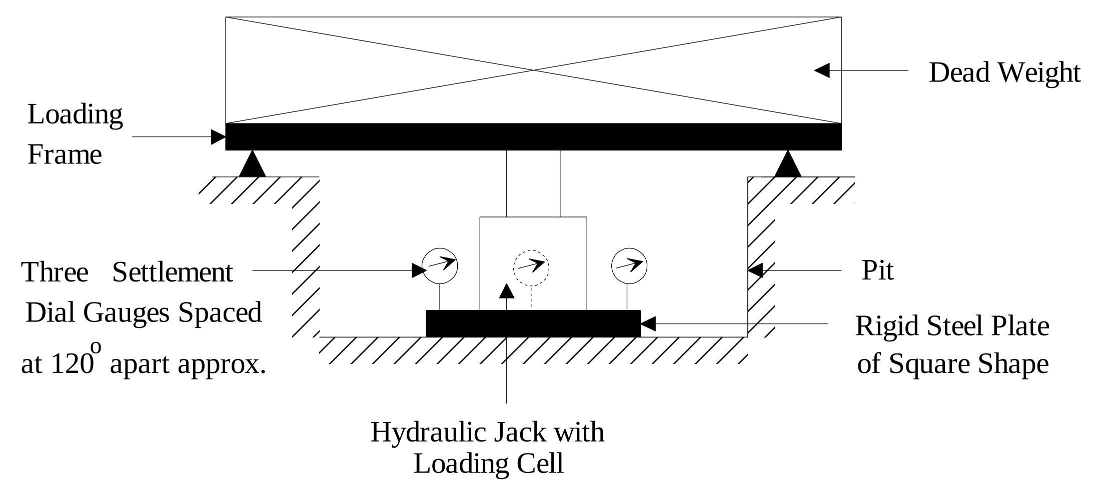
For non-cohesive & c-ϕ soil:

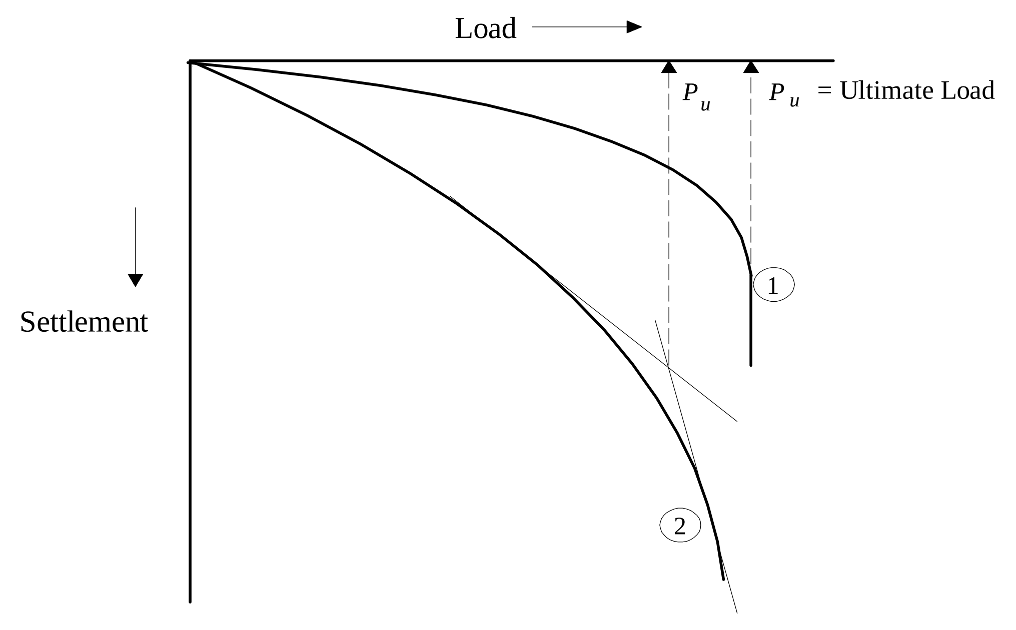
Q_{ult} increases by increasing B & D_f.

For cohesive soil:

Q_{ult} increases by increasing D_f only.

BEARING CAPACITY FROM PLATE LOAD TEST





Data Reduction and Analysis of PLT

The ultimate load can be obtained:

- directly from the curve (1) or
- using two tangents method, curve (2).

then

q_{ult}, foundation = q_{ult}, load test for clay

$$q_{\text{ult}} = q_{\text{plate}} \left(\frac{B_{\text{foundation}}}{B_{\text{plate}}} \right)$$

for sand

Settlement of prototype footing (Terzaghi and Peck, 1948):

$$s_f = s_p \left(\frac{B_f}{B_p} \right)$$

for clays, and

$$S_f = Sp \left(\frac{\mathrm{B_f}}{\mathrm{B_p}} \right)^2 \left(\frac{\mathrm{B_p} + 1}{\mathrm{B_f} + 1} \right)^2$$

for sands

BY LABORATORY UNCONFINED COMPRESSION TEST

The B.C of a cohesive soil can also be evaluated from the unconfined compressive test on cohesive soils. The unconfined compression test is termed as unconfined compressive stress which is equal to:

qu = 2C

and C = qu/2 and f =0 (for undrained condition)

By Terzaghi’s equation, the BC of cohesive soils for f =0 case is

qun = CNc Nc = 5.7 or approximately 6

qun = 6C

for FS=3

qns = 2C = qu

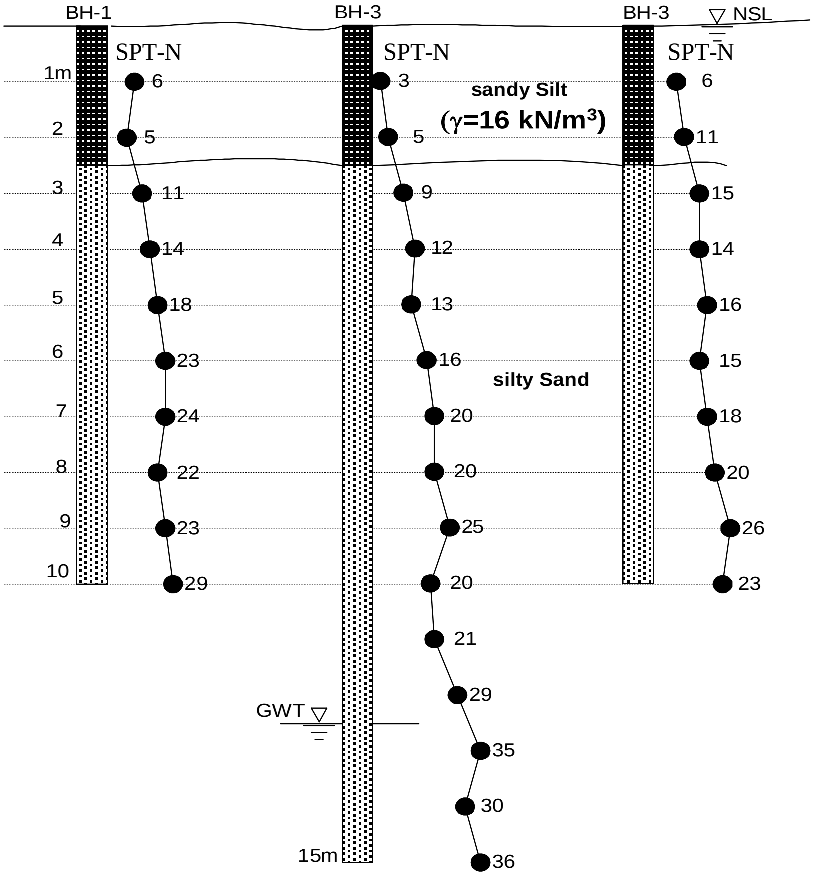
Therefore, the net safe bearing capacity (qns) of cohesive soil can be taken approximately equal to unconfined compression strength of cohesive soil.

Presumptive Bearing Pressures from the International Building Code (IBC, 1997)

Soil or Rock Classification	**Allowable Bearing Pressure, q_a**	
	(kPa)	**(lbs/ft^2)**
Crystalline Bedrock	600	12,000
Sedimentary or Foliated Rocks	300	6,000
Sandy gravel, or gravel (GW, GP)	250	5,000
Sand, silty Sand, clayey sand, silty gravel, clayey gravel, (SW, SP, SM, SC, GM and GC)	150	3,000
Clay, sandy clay, silty clay, or clayey silt, (CL, ML, MH, CH)	100	2,000
Mud, organic silt, organic clay, peat or unprepared fill	0	0

Assignment

Q-1: Figure below shows SPT-N profile at a certain site on which a three storied commercial plaza is to be constructed. The foundation system for this facility will comprise isolated footings connected with tie beams. The building will also have one basement with clear height of 3 m. The footings will be founded at 1 m below the finished floor level of the basement. Estimate allowable bearing capacity for square footings with width between 1.0 m to 3m.



The subsoil profile at the proposed site.