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EARTHQUAKE RESISTANT DESIGN OF FOUNDATIONS: Lecture 3: Shallow Foundations – Bearing Capacity

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Module - 2

Shallow Foundations



Module -2: Chapters

1. General Requirements
2. Bearing Capacity and Settlement
3. Combined Footings
4. Raft Foundations
5. Dynamic Bearing Capacity



Chapter 2

Bearing Capacity and Settlement

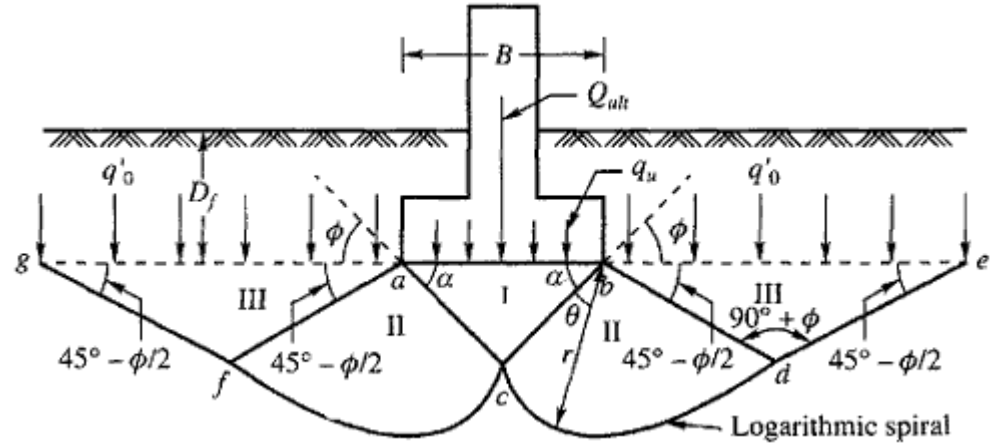


Terzaghi's Bearing Capacity Theory

Assumptions

- The footing is a long strip or a continuous footing
- 2D-plane strain condition.
- The soil fails under general shear failure.
- The load is vertical and concentrated.
- The ground surface is horizontal.

Failure Zone of a Footing



- **Zone-I: Elastic zone**
- **Zone-II: Zone of radial shear**
- **Zone-III: Rankine Passive Zone**

Terzaghi's Bearing Capacity Theory

Ultimate bearing capacity is given by

$$q_u = cN_c + qN_q + 0.5\gamma BN_\gamma \quad \text{(General shear failure and strip footing)}$$

cN_c = Effect of soil cohesion (Assuming the soil is weightless)

qN_q = Effect of the surcharge (with $c=0$ & $\gamma=0$)

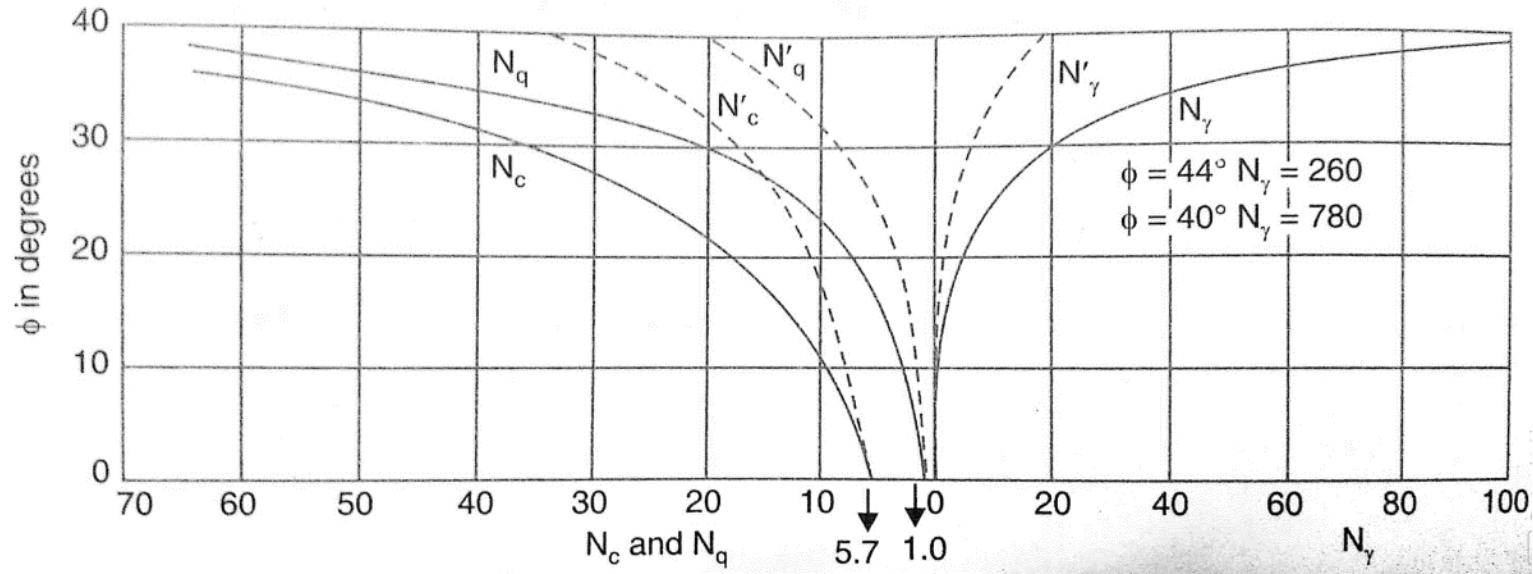
$0.5\gamma BN_\gamma$ = Weight of the soil in shear zone

N_c , N_q and N_γ are the dimensionless bearing capacity factors and are the functions of the ϕ (Angle of internal friction)

Terzaghi's bearing capacity factors

ϕ°	N_c	N_q	N_r	ϕ°	N_c	N_q	N_r
0	5.7	1.0	0.0	34	52.6	36.5	30.0
5	7.3	1.6	0.5	35	57.8	41.4	42.4
10	9.6	2.7	1.2	40	95.7	81.3	100.4
15	12.9	4.4	2.5	45	172.3	173.3	297.5
20	17.7	7.4	5.0	48	258.3	287.9	780.1
25	25.1	12.7	9.7	50	347.5	415.1	1153.2
30	37.2	22.5	19.7				

Terzaghi's bearing capacity factors



Terzaghi's (1943) proposed empirical adjustment to shear strength parameter c and ϕ to cover the local shear failure:

For Sand : $\phi = < 29^\circ$, $D_r < 20\%$, For c - ϕ soil, strain $> 10\%$

$$c_m = \frac{2}{3}c \qquad \tan \phi_m = \frac{2}{3} \tan \phi$$

$$q_u = \frac{2}{3}cN'_c + qN'_q + 0.5\gamma BN'_\gamma$$

Modification for square and circular footing , Terzaghi's (1943)

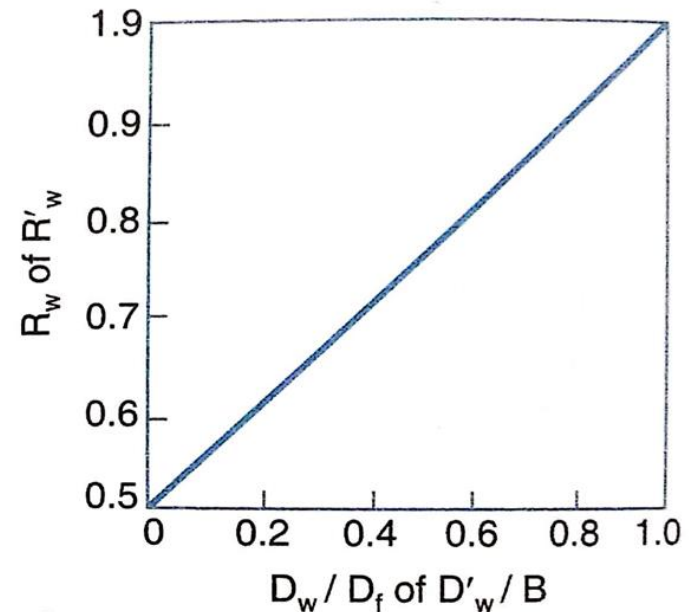
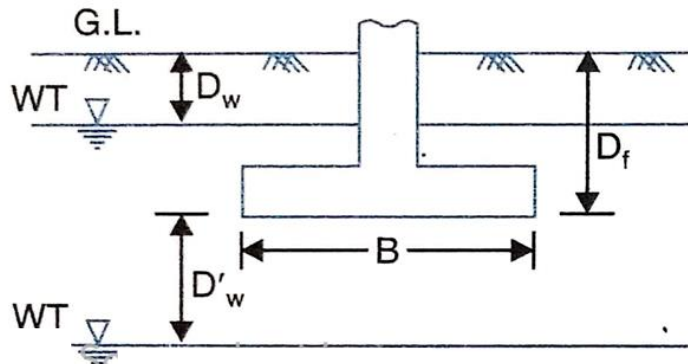
- **Square footing** $q_u = 1.2cN_c + qN_q + 0.4\gamma BN_\gamma$
- **Circular footing** $q_u = 1.2cN_c + qN_q + 0.3\gamma BN_\gamma$

Effect of Water Table

When, $\phi=0$, $q_{nu}=5.7c_u$

$C=0$, N_q & N_γ are influenced

$$q_u = cN_c + qN_q + 0.5\gamma BN_\gamma$$



$$q_u = cN_c + \gamma D_f N_q + 0.5\gamma B N_\gamma$$

a) When the water table is below the base of the footing

For the third term

$$\text{if } D'_w \geq B, \quad \gamma = \gamma_t$$

$$\text{if } 0 \leq D'_w \leq B, \quad \gamma = \gamma' + \left(\frac{D'_w}{B} \right) (\gamma_t - \gamma')$$

B) When the water table is above the base of the footing

For the second term

$$\text{if } D_w > D_f, \quad \gamma = \gamma_t$$

$$\text{if } 0 \leq D_w \leq D_f, \quad \gamma = \gamma' + \left(\frac{D_w}{D_f} \right) (\gamma_t - \gamma')$$

$$\text{Third term } \gamma = \gamma'$$

Skempton's Analysis (1951)

$$q_{nu} = c_u N_c$$

Bearing capacity analysis for saturated clay soil with $\phi_u = 0$,

- **For strip footing** $N_c = 5 \left(1 + 0.2 \frac{D_f}{B} \right)$ maximum 7.5
- **For square and circular footing** $N_c = 6 \left(1 + 0.2 \frac{D_f}{B} \right)$ limits value 9.0
- **For rectangular,** $N_c = 5 \left(1 + 0.2 \frac{D_f}{B} \right) \left(1 + 0.2 \frac{B}{L} \right)$ for $\frac{D_f}{B} \leq 2.5$
 $N_c = 7.5 \left(1 + 0.2 \frac{B}{L} \right)$ for $\frac{D_f}{B} > 2.5$

Unlike the Terzaghi theory, Skempton's analysis can be used any value of $\frac{D_f}{B}$

Other Researchers

- **Meyerhof's Analysis (1963)**

$$q_u = cN_c s_c d_c i_c + qN_q s_q d_q i_q + 0.5\gamma B N_\gamma s_\gamma d_\gamma i_\gamma$$

Symbols s, d and i stand for empirical correlation factors called the shape factor, depth factor and inclination factor, respectively. N_c & N_q are the same as Prandtl (1921) and N_γ was approximately established by Meyerhof.

- **Hansen's Recommendation (1957, 1970):** similar to the Meyerhof with difference in value of N_γ and correction factors.
- **Vesic's Bearing capacity Factors (1973):** Different table for N_γ .

IS Code Recommendation (IS 6403: 1981)

General shear $q_{nu} = cN_c s_c d_c i_c + q(N_q - 1)s_q d_q i_q + 0.5\gamma B N_\gamma s_\gamma d_\gamma i_\gamma w'$

- N_c , N_γ and N_q recommended by Vesic (1973). w' is a factor which takes into account the effect of water table. $w'=1$ if the WT is at the depth $D_f + B$ below the ground level or for $D'_w \geq B$ where D'_w depth of water table measured from the base of the foundation. All factors are shown in next slide.
- For $D'_w = 0$, $w' = 0.5$. if $0 < D'_w < B$, $w' = 0.5 - 1$

Local shear $q_{nu} = \frac{2}{3}cN'_c s_c d_c i_c + q(N'_q - 1)s_q d_q i_q + 0.5\gamma B N'_\gamma s_\gamma d_\gamma i_\gamma w'$

Bearing Capacity factors (IS 6403: 1981)

TABLE 1 BEARING CAPACITY FACTORS
(Clause 5.1.1)

BEARING CAPACITY FACTORS			
ϕ (Degrees)	N_c	N_q	N_γ
0	5.14	1.00	0.00
5	6.49	1.57	0.45
10	8.35	2.47	1.22
15	10.98	3.94	2.65
20	14.83	6.40	5.39
25	20.72	10.66	10.88
30	30.14	18.40	22.40
35	46.12	33.30	48.03
40	75.31	64.20	109.41
45	138.88	134.88	271.76
50	266.89	319.07	762.89

NOTE — For obtaining values of N'_c , N'_q and N'_γ , calculate $\phi' = \tan^{-1}$ (0.67 $\tan \phi$). Read N_c , N_q , and N_γ from the Table corresponding to the value of ϕ' instead of ϕ which are values of N'_c , N'_q , N'_γ respectively.

Shape Factors (s_c , s_q and s_γ) (IS 6403: 1981)

5.1.2.1 The shape factors shall be as given in Table 2.

TABLE 2 SHAPE FACTORS

SL No.	SHAPE OF BASE	SHAPE FACTOR		
		s_c	s_q	s_γ
i)	Continuous strip	1.00	1.00	1.00
ii)	Rectangle	$1 + 0.2 B/L$	$1 + 0.2 B/L$	$1 - 0.4 B/L$
iii)	Square	1.3	1.2	0.8
iv)	Circle	1.3	1.2	0.6

Use B as the diameter in the bearing capacity formula.

Depth Factors (d_c , d_q and d_γ) (IS 6403: 1981)

The depth factors shall be as follows:

$$d_c = 1 + 0.2 \frac{D_f}{B} \sqrt{N_\phi}$$

$$d_q = d_\gamma = 1 \quad \text{for } \phi < 10^\circ$$

$$d_q = d_\gamma = 1 + 0.1 \frac{D_f}{B} \sqrt{N_\phi} \quad \text{for } \phi > 10^\circ$$

Where ,

$$N_\phi = \tan^2 \left(\frac{\pi}{4} + \frac{\phi}{2} \right)$$

Inclination Factors (i_c , i_q and i_γ) (IS 6403: 1981)

- The inclination factors shall be as under:

$$i_c = i_q = \left(1 - \frac{\alpha}{90}\right)^2$$

$$i_\gamma = \left(1 - \frac{\alpha}{\phi}\right)^2$$

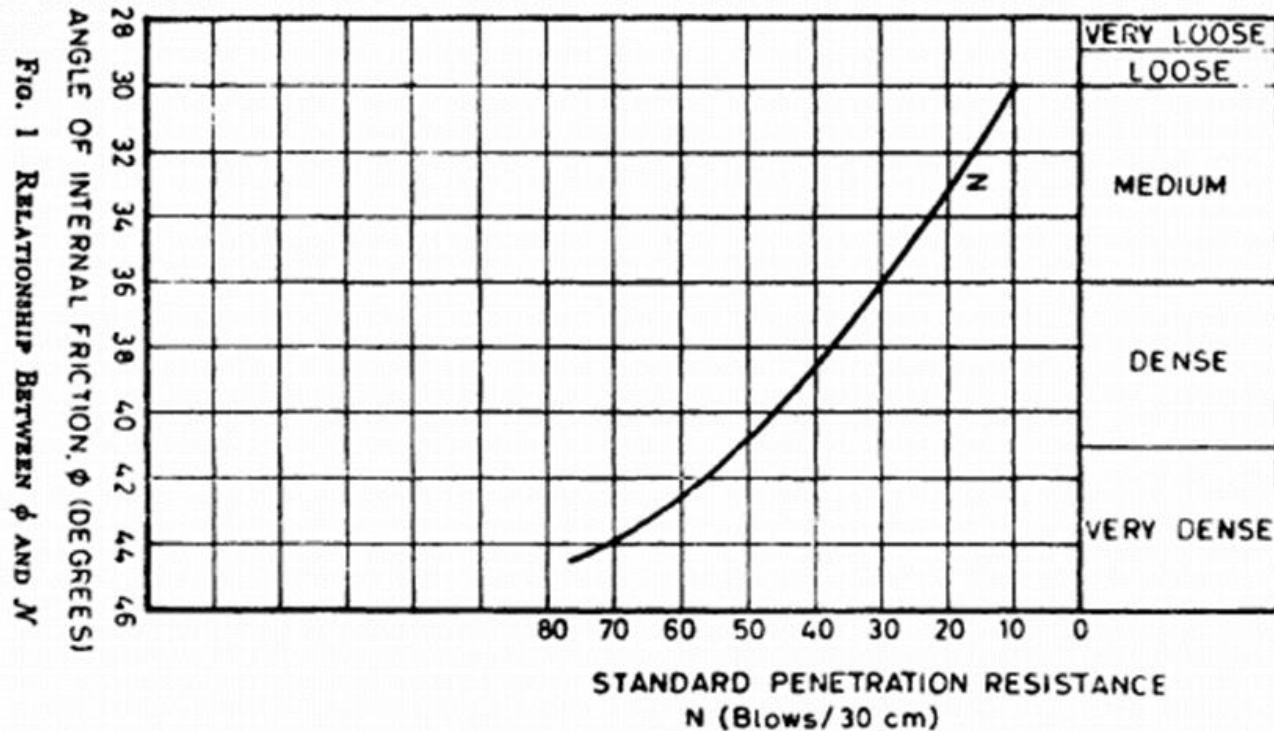
- α - Inclination of the load to the vertical in degrees

Cohesionless Soils: Failure Mode Based on Relative Density

TABLE 3 METHOD OF ANALYSIS BASED ON RELATIVE DENSITY

SL No.	RELATIVE DENSITY (DENSITY INDEX)	VOID RATIO	CONDITION	METHOD OF ANALYSIS
i)	Greater than 70 percent	Less than 0.55	Dense	General shear
ii)	Less than 20 percent	Greater than 0.75	Loose	Local shear (as well as punching shear)
iii)	20 to 70 percent	0.55 to 0.75	Medium	Interpolate between i) and ii)

Cohesionless Soils: Relationship between ϕ and N



Bearing capacity of granular soils based on SPT

- Corrected N is used. Empirical correlations between N and relative density or ϕ values are available. The N_q and N_γ to be used in equation based on ϕ values.

SPT-N	ϕ (Degree)	D_r (%)	Description
<4	25-30	0	Very Loose
4-10	27-32	15	Loose
10-30	30-35	65	Medium
30-50	35-40	85	Dense
>50	38-43	100	Very Dense

Bearing Capacity of layered soil

$$C_{av} = \frac{c_1 H_1 + c_2 H_2 + \dots c_n H_n}{\sum H_i}$$

$$\tan \phi_{av} = \frac{\tan \phi_1 H_1 + \tan \phi_2 H_2 + \dots \tan \phi_n H_n}{\sum H_i}$$

Factors influences bearing capacity

☐ Cohesionless soils

$$q_u = qN_q + 0.5\gamma BN_\gamma$$

1. D_r and ϕ
2. Width B and Depth D_f
3. Unit weight γ
4. Position of the WT

☐ Cohesive soils $q_{nu} = cN_c$

Thank You

