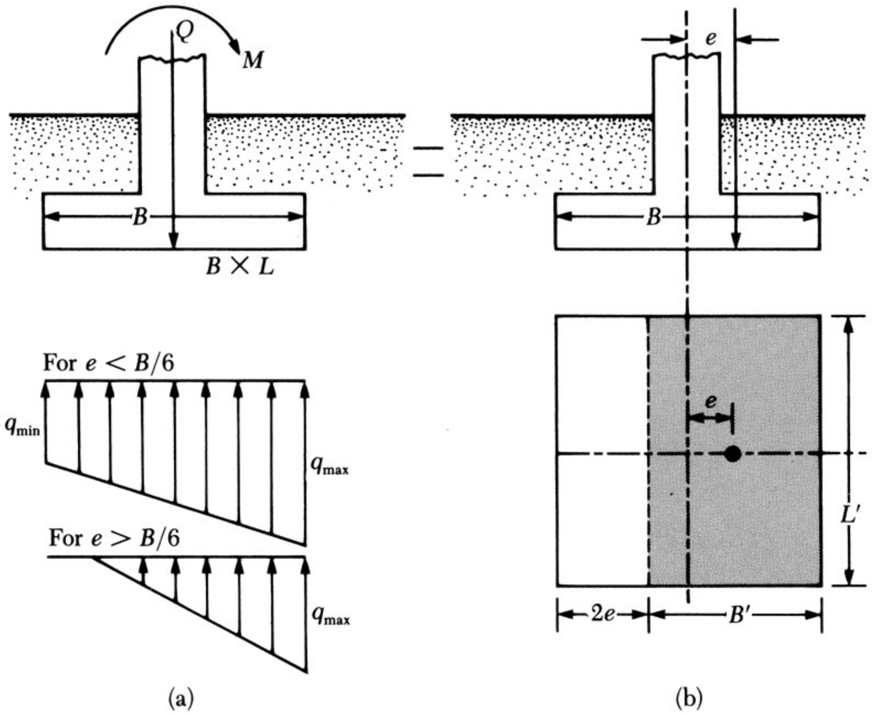
5) Eccentrically Loaded Foundations



For Q + M loading condition,

$$q_{\max,\,\min} = \frac{Q}{BL} \pm \frac{6M}{B^2 L} \qquad \text{for } e \le B/6$$

For Q with eccentricity e,

$$q_{\max,\min} = \frac{Q}{BL}\left(1 \pm \frac{6e}{B}\right) \qquad \text{for } e \le B/6$$

$$q_{\min} = 0, \quad q_{\max} = \frac{4Q}{3L(B-2e)} \qquad \text{for } e > B/6$$

Note :

*** Effective area method (Meyerhof(1953)**

B' = B –2e
(For Q+M loading condition, e= M/Q)

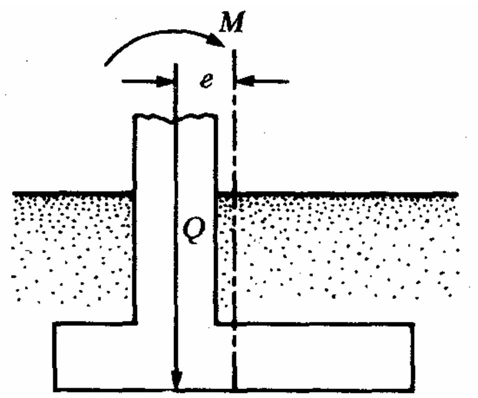
$$q_u = cN_c F_{cs} F_{cd} F_{ci} + qN_q F_{qs} F_{qd} F_{qi} + 1/2\gamma B' N_\gamma F_{\gamma s} F_{\gamma d} F_{\gamma i}$$

To get F_{cs}, F_{qs} and $F_{\gamma s}$, use B' instead of B. (Use B for F_{cd}, F_{qd} and $F_{\gamma d}$)

=> $Q_u = q_u(B')(L)$

=> F.S. = Q_u / Q

- To reduce the effects of eccentricity, use foundation of columns with off-center loading.

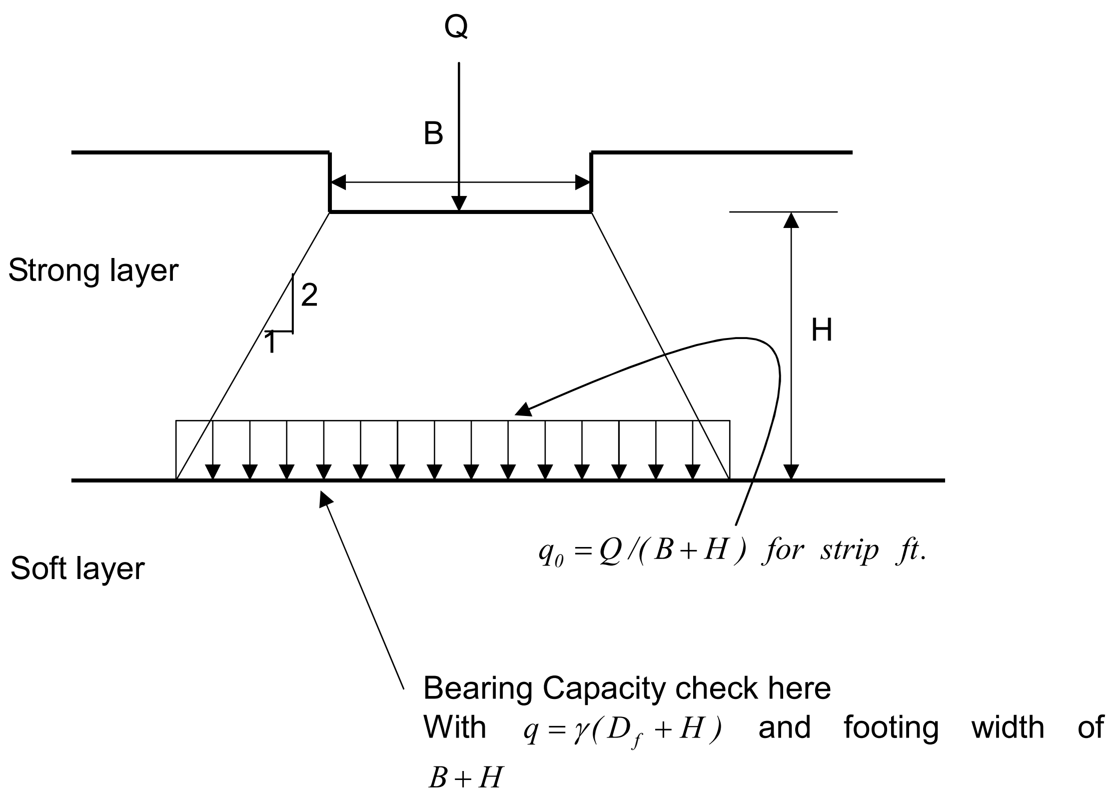


6) Effect of Layering

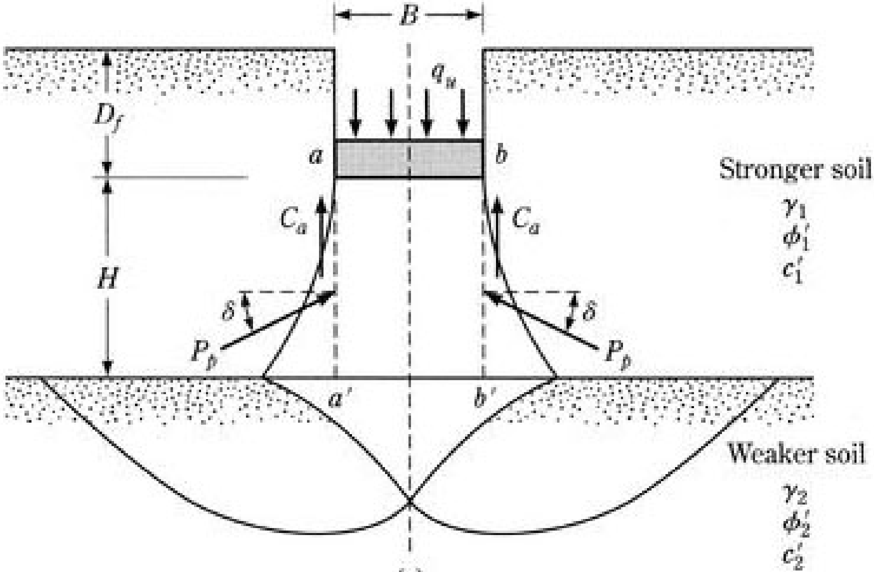
-

i) <u>Stronger soil underlain by weaker soil</u>

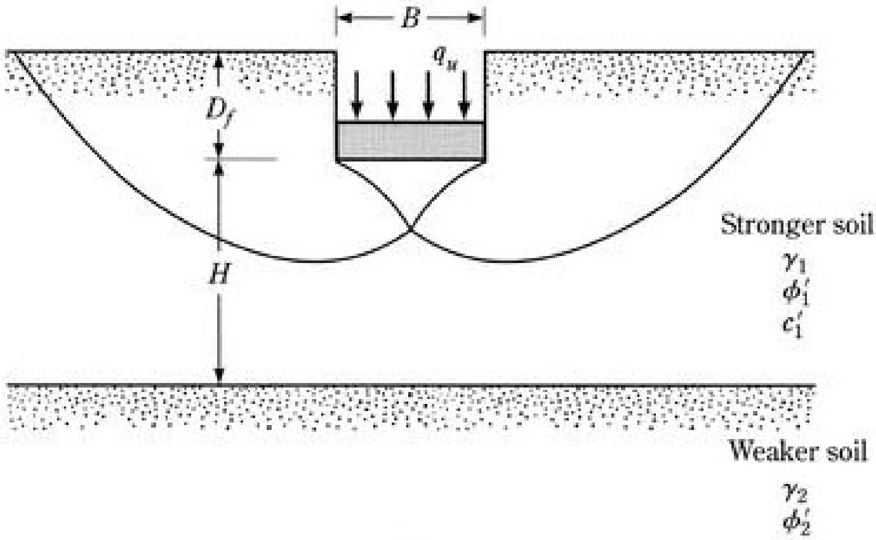
* Simplified approach



* General Approach



(a)



(b)

-

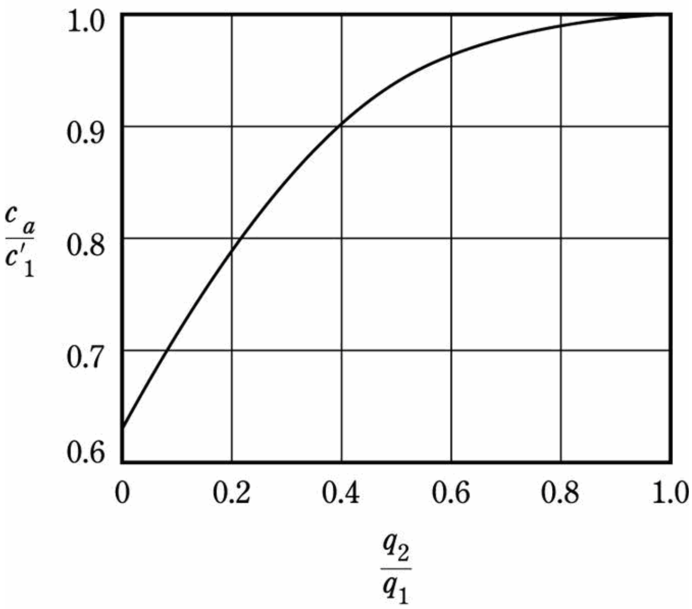
-

Layer 1 : Punching shear

For cohesion(c_a) effect, $q_{u1} = 2c_a H / B$.

$\leftarrow c_a$ given by relative cohesion based on c_1', with q_2 / q_1 .

where $q_1 = c_1' N_{c1} + 1/2 \gamma_1 B N_{\gamma 1}$, and $q_2 = c_2' N_{c2} + 1/2 \gamma_2 B N_{\gamma 2}$



For passive pressure effect,

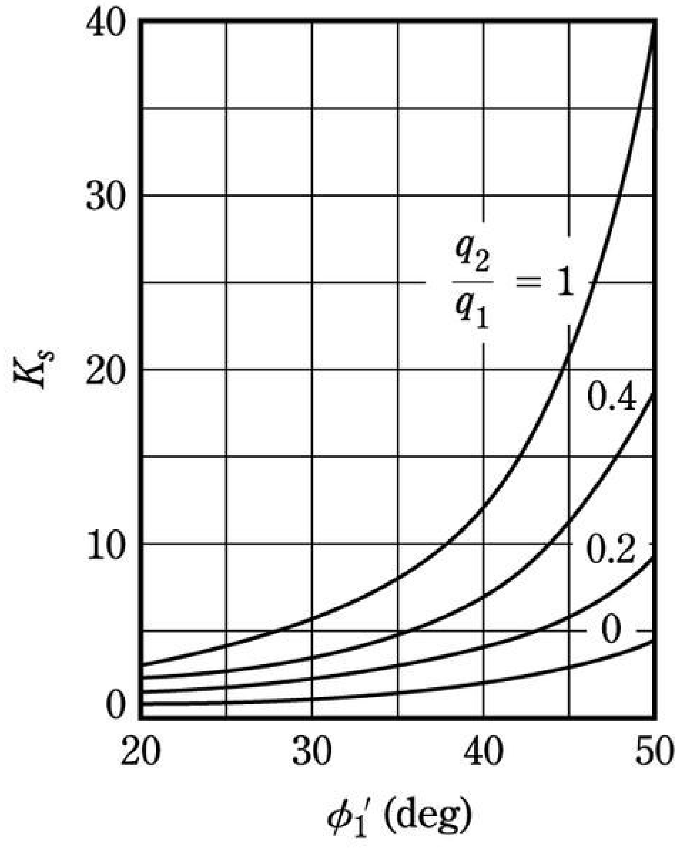
$$q_{u1} = 2P_P \sin\delta / B$$

$$\leftarrow \; P_P = 0.5\gamma_1 H^2 (1 + \frac{2D_f}{H}) \frac{K_{pH}}{\cos\delta},$$

where K_{PH} is the coefficient of passive earth pressure ($= (1+\sin\phi')/(1-\sin\phi')$).

Meyerhof recommends $K_s \tan\phi' = K_{PH} \tan\delta$, where K_s is punching shear resistance, and for sand layer over clay, K_s = *f(q₂/q₁, ϕ₁')* as shown below.

Thus, $$q_{u1} (= 2P_p \sin\delta / B) = \gamma_1 H^2 (1 + \frac{2D_f}{H}) K_s \frac{\tan\phi'}{B}$$



Layer 2 : General shear failure

$$q_{u2} = c_2' N_{c2} + 1/2\gamma_2 B N_{\gamma 2} + \gamma_1 (H + D_f) N_{q2}$$

- Ultimate bearing capacity

$$q_u = q_{u1} + (q_{u2} - \gamma_1 H)$$

$$= \underbrace{\frac{2c_a H}{B} + \gamma_1 H^2 (1 + \frac{2D_f}{H}) K_s \frac{\tan\phi_1}{B}}_{\text{punching shear for layer 1}} + \underbrace{c_2' N_{c2} + 1/2\gamma_2 B N_{\gamma 2} + \gamma_1 (H + D_f) N_{q2}}_{\text{general shear for layer 2}} - \underbrace{\gamma_1 H}_{\text{additional weight}}$$

For strong clay over soft clay,

$$q_u = \frac{2c_a H}{B} + c_2' N_{c2} + \gamma_1 D_f \leq \text{ general shear failure of top soil}$$

$$= c_1' N_{c1} + \gamma_1 D_f$$

For dense sand over soft clay,

$$q_u = \gamma_1 H^2 (1 + \frac{2D_f}{H}) K_s \frac{\tan\phi'}{B} + c_2' N_{c2} + \gamma_1 D_f$$

$$\leq \text{ general shear failure of top soil } = \frac{1}{2}\gamma_1 B N_{\gamma 1} + \gamma_1 D_f N_{q1}$$

To consider shape effect for layered soil, Meyerhof recommends use of factor (1+B/L) for punching shear terms and values as below for remained terms.

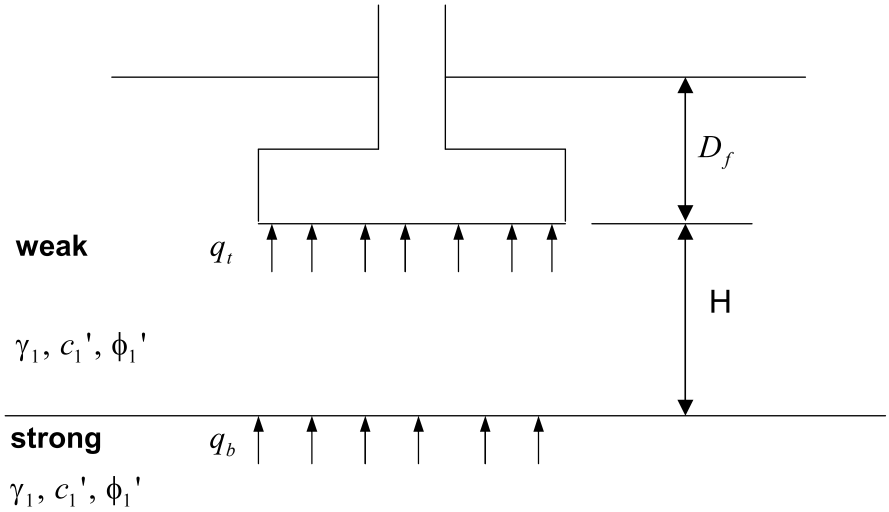
For $\phi = 0$:

$$F_{cs} = 1 + 0.2B/L,\ F_{qs} = 1,\ F_{\gamma s} = 1$$

For $\phi \geq 0$:

$$F_{cs} = 1 + 0.2(B/L)\tan^2(45 + \phi'/2),\ F_{qs} = F_{\gamma s} = 1 + 0.1(B/L)\tan^2(45° + \phi'/2)$$

ii) Weak soil over strong soil.



$$q_u = q_t + (q_b - q_t)\,(1 - \frac{H}{H_f})^2 \geq q_t$$

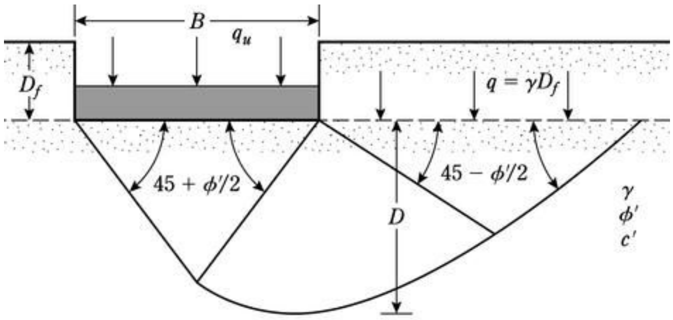
where, q_t : Bearing capacity of top soil.
q_b : Bearing capacity of bottom soil.
H_f : Failure depth (from bottom of footing) (=B).

For soft clay over stiff clay,

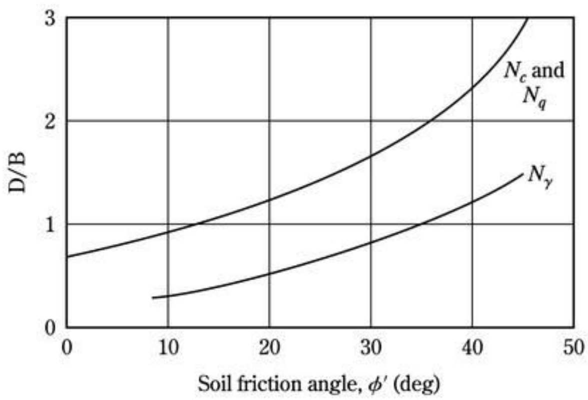
$$q_t = c_1' N_{c1} + \gamma_1 D_f = q_{u\min} \quad (for \;\; H \geq B)$$
$$q_b = c_2' N_{c2} + \gamma_1 D_f = q_{u\max} \quad (for \;\; H = 0)$$

iii) Foundation Supported by a Soil with a Rigid Base at Shallow Depth
(Mandel & Salencon (1972))

* The extent of the failure zone below the bottom of foundation, D

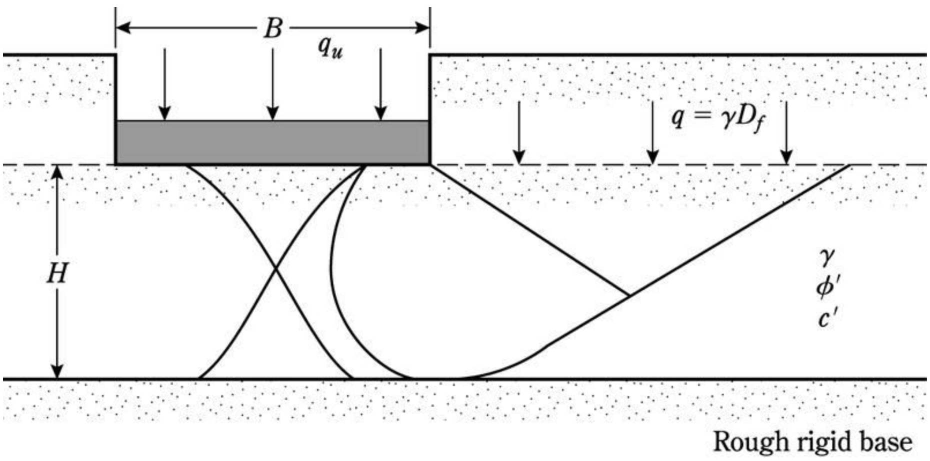


(a)



(b)

- The failure surface in case that depth to a rigid, rough base H is smaller than D,

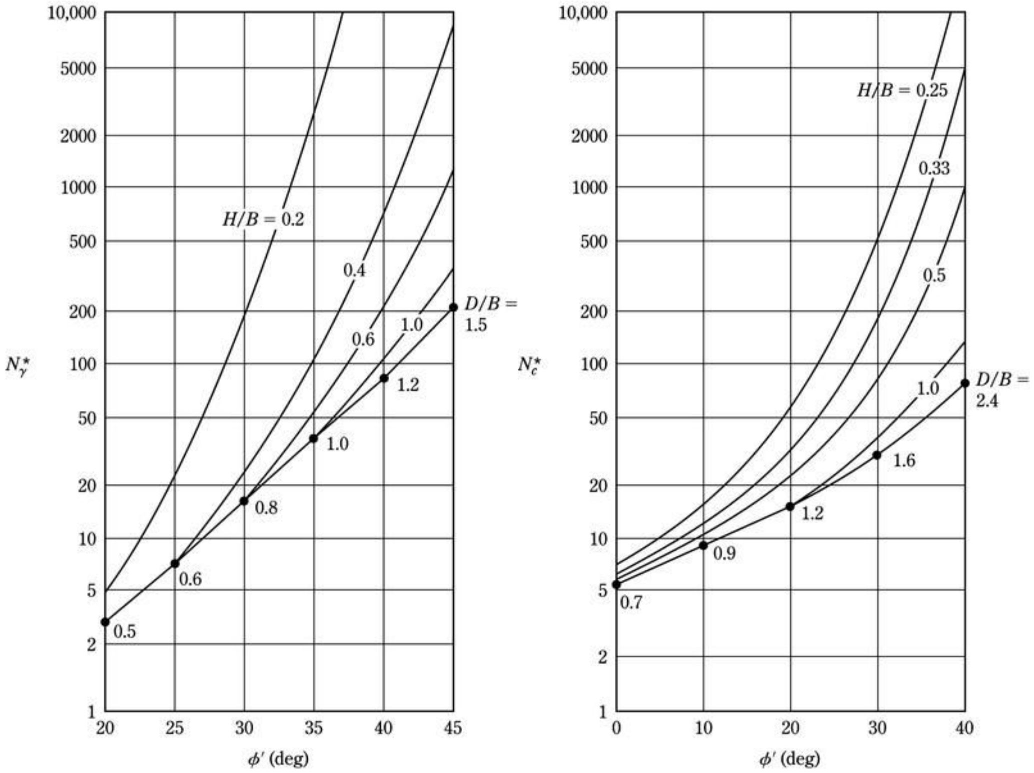


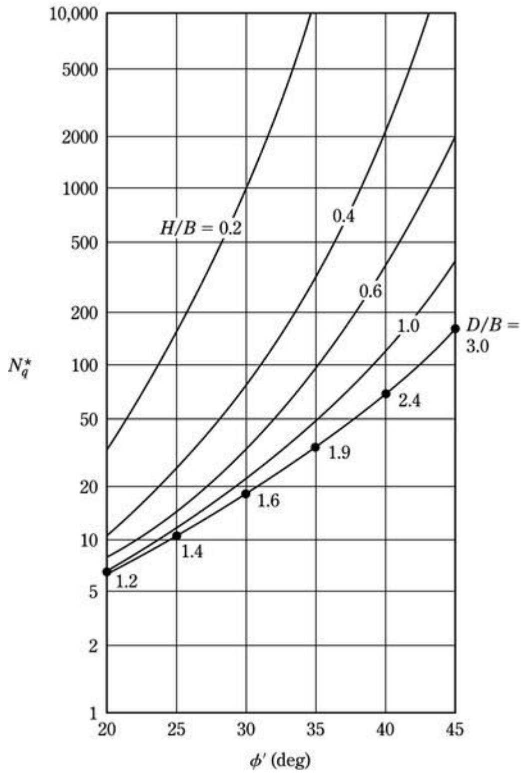
- The ultimate bearing capacity of a rough continuous foundation with a rigid, rough base at a shallow depth

$$q_u = c' N_c^{\ *} + qN_q^{\ *} + \frac{1}{2}\gamma B N_\gamma^{\ *}$$

where, $N_c^{\ *}$, $N_q^{\ *}$, $N_\gamma^{\ *}$ = modified bearing capacity factors

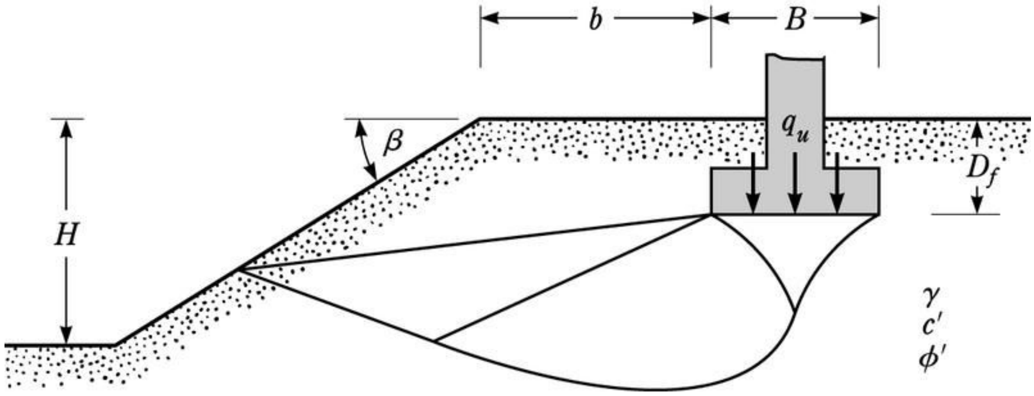
(Mandel and Sclencon (1972))





For $H \geq D$, $N_c^* = N_c$, $N_q^* = N_q$ and $N_\gamma^* = N_\gamma$

7) Bearing Capacity of Foundations on Top of Slope



*

* Meyerhof recommends :

$$q_u = c' N_{cq} + \frac{1}{2}\gamma B N_{\gamma q}$$

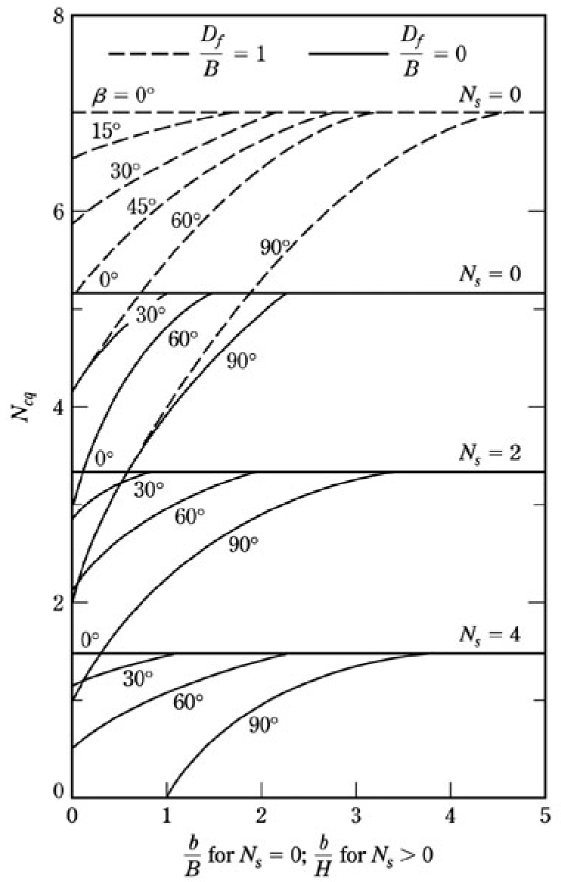
where N_{cq} *and* $N_{\gamma q}$ are given in Figures on next page.

For N_{cq} in Figure 4.12,

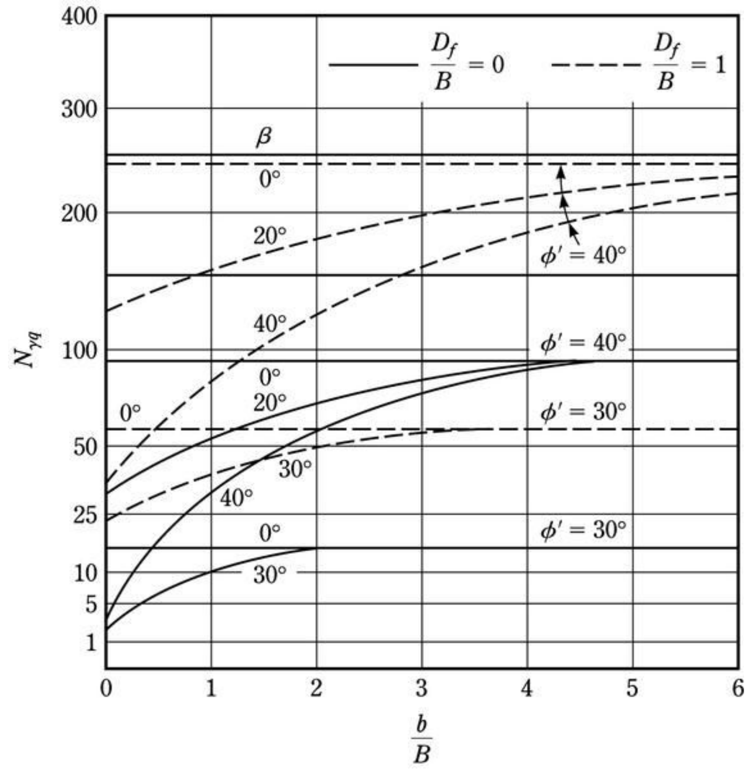
i) N_s (= stability number) = $\gamma H / c'$

ii) If $B < H$, use the curves for $N_s = 0$

If $B \geq H$, use the curves for the calculated N_s



$\frac{D_f}{B} = 1$
$\frac{D_f}{B} = 0$
$\beta = 0°$
$N_s = 0$
15°
30°
45°
60°
90°
0°
$N_s = 0$
30°
60°
90°
N_{cq}
0°
$N_s = 2$
30°
60°
90°
0°
$N_s = 4$
30°
60°
90°
0
2
4
6
8
0
1
2
3
4
5
$\frac{b}{B}$ for $N_s = 0$; $\frac{b}{H}$ for $N_s > 0$



$\frac{D_f}{B} = 0$
$\frac{D_f}{B} = 1$
β
0°
20°
$\phi' = 40°$
40°
$\phi' = 40°$
0°
20°
0°
$\phi' = 30°$
30°
40°
0°
$\phi' = 30°$
30°
$N_{\gamma q}$
400
300
200
100
50
25
10
5
1
0
1
2
3
4
5
6
$\frac{b}{B}$

8) Selection of Soil Strength Parameters

i) Saturation

Generally

Saturated strength < Unsaturated strength

To design for the worst-case conditions, the saturated strength is nearly always used.

ii) The fundamental bearing capacity formulas are based on continuous footings (Plane strain conditions)

⇨ Formulas for other shapes are derived from the continuous footing using empirical adjustments.

⇨ Plane strain strength should be used for bearing capacity analysis regardless of footing shape.

⇨ However, engineers rarely consider the differences between plane strain and axisymmetric strengths from tests, and plane strain testing device is more complicated and need experienced skill to handle.

⇨ So, axisymmetric strength is generally used.

iii) Drained vs. Undrained Strength (Saturated soils)

- Sands : Drained strength
- Clays → Normally consolidated or lightly overconsolidated conditions (positive pore water pressure)
  Undrained strength < Drained strength
  → Heavily overconsolidated conditions (negative pore pressure)
  Undrained strength > Drained strength
- Intermediate soils : More conservative approach ⇒ undrained strength.

9) Bearing Capacity on Rocks

* Problems :

* The allowable bearing pressure may be determined in at least four ways (Kulhawy and Goodman, 1980) :

- Presumptive values found in building codes (Table 6.5)
- Empirical rules
- Rational methods based on bearing capacity and settlement analyses
- Full scale load tests

*

* Semi-empirical approach for bearing capacity (Carter and Kulhawy, 1988)

$$q_u = JcN_{cr}$$

where :

q_u = net ultimate bearing capacity

J = correction factor *(Figure 6.17)*

c = cohesive strength of the rock mass

ϕ = friction angle of the rock mass

N_{cr} = bearing capacity factor *(Figure 6.18)*

H = vertical spacing of discontinuities

S = horizontal spacing of discontinuities

B = width of footing

* Modification of c' and ϕ' from lab test results.

$\phi' = (0.5 - 0.75)\phi'_{lab}$, $c = a_E c'_{lab}$

a_E = 0.1 for RQD < 70% Linearly increasing

a_E = 0.6 for RQD = 100%

<RQD : Rock Qualitly Designation>

* If rock mass is very strong, the strength of the footing concrete may governs the bearing capacity.

<Typical allowable bearing pressures for foundation on bedrock>

Rock Type	Rock Consistency	Allowable Bearing Pressure	
		(lb/ft^2)	(kPa)
Massive crystalline igneous and metamorphic rock : Granite, diorite, basalt, gneiss, thoroughly cemented conglomerate	Hard and sound (minor cracks OK)	120,000 ~ 200,000	6,000 ~ 10,000
Foliated metamorphic rock : Slate, schist	Medium hard, sound (minor cracks OK)	60,000 ~ 80,000	3,000 ~ 4,000
Sedimentary rock : Hard cemented shales, siltstone, sandstone, limestone without cavities	Medium hard, sound	30,000 ~ 50,000	1,500 ~ 2,500
Weathered or broken bedrock of any kind : compaction shale or other argillaceous rock in sound condition	soft	16,000 ~ 24,000	800 ~ 1,200

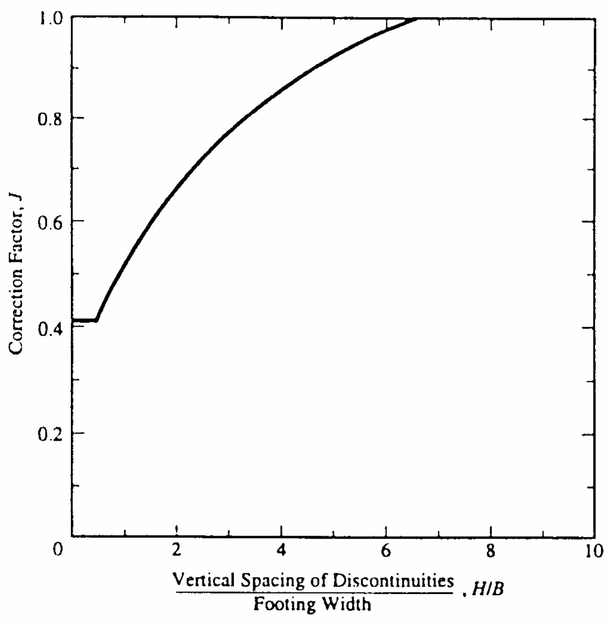


Figure 6.17 Correction factor, J, for Equation 6.54 (Adapted from Carter and Kulhawy, 1988. Copyright ©1988 Electric Power Research Institute, reprinted with permission).

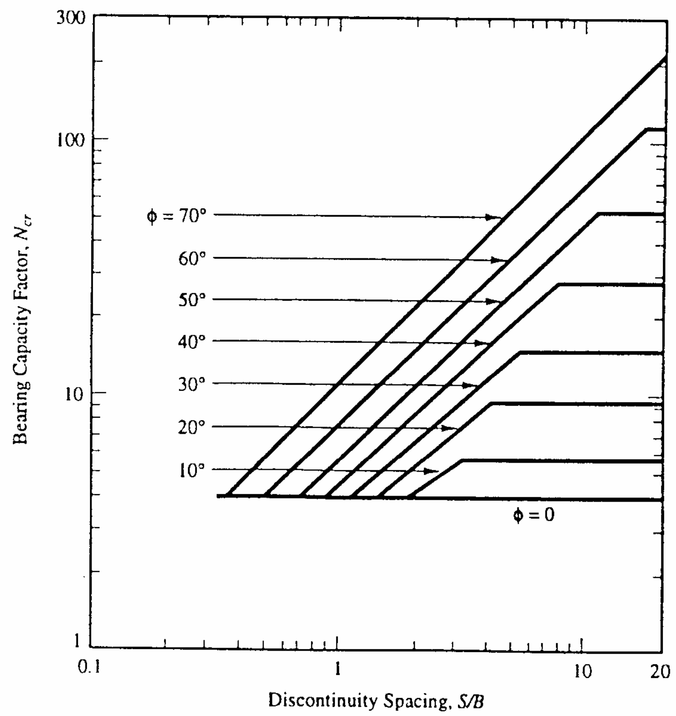


Figure 6.18 Bearing capacity factor, N_{cr}, for Equation 6.54 (Adapted from Carter and Kulhawy, 1988. Copyright ©1988 Electric Power Research Institute, reprinted with permission).