5) Equations for Estimation of Pile Capacity

Ultimate bearing capacity of pile is given as,

$$Q_u = Q_p + Q_s$$

i) Point Bearing Capacity

For a shallow foundation with vertical loading,

$$q_u = cN_c F_{cs} F_{cd} + qN_q F_{qs} F_{qd} + \frac{1}{2}\gamma B N_\gamma F_{\gamma s} F_{\gamma d}$$

⇒ for pile

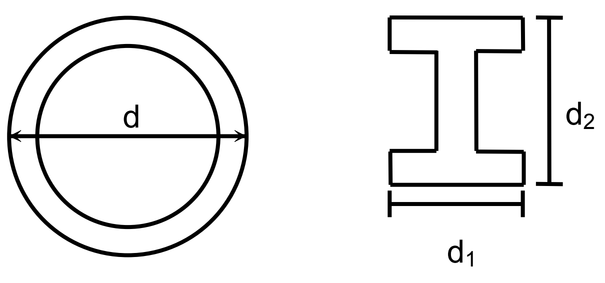
$$q_p = c' N^*{}_c + q' N^*{}_q + \gamma D N^*{}_\gamma$$

where N_c^*, N_q^* and N_γ^* include the necessary shape and depth factors, D is width of pile and q' is effective vertical stress at the level of pile tip.

⇒ Width of pile, D is relatively small

$$q_p = c' N^*{}_c + q' N^*{}_q$$

Therefore, $Q_p = A_p \cdot q_p = A_p (c' N_c^* + q' N_q^*)$



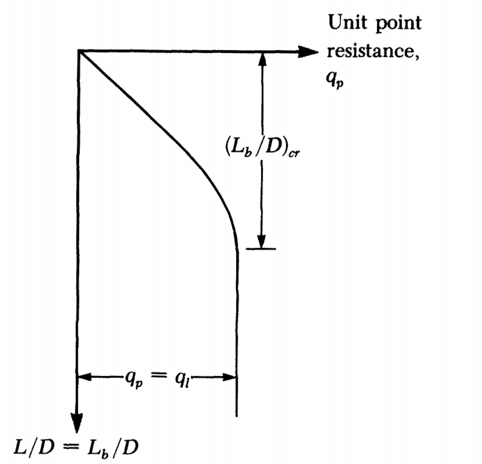
Pipe Pile H-Section pile

$$A_p = \frac{\pi d^2}{4} \qquad A_p = d_1 \cdot d_2$$

- *Determination of Bearing Capacity Factors* N_c^* *and* N_q^*

a) Meyerhof's Method

-



- $q_p \le q_l$
- $(L_b / D)_{cr}$ is a function of friction angle.

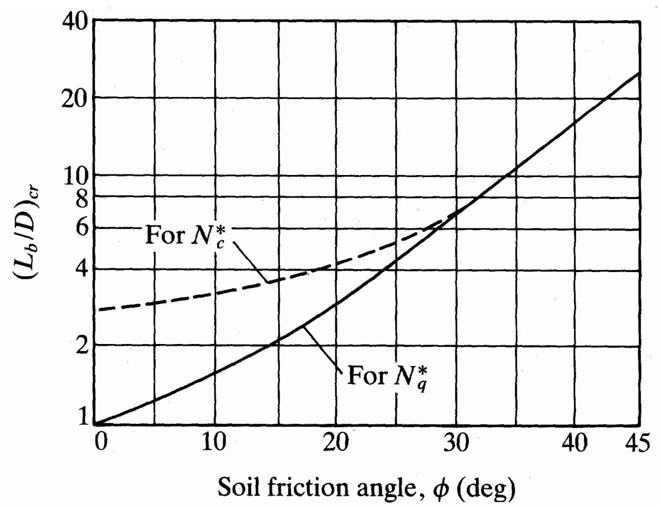


Figure. Variation of $(L_b/D)_{cr}$ with soil friction angle

- N_c^* and N_q^* reach the maximum values at $\frac{1}{2}(L_b/D)_{cr}$

  (in most cases, $L_b/D \geq \frac{1}{2}(L_b/D)_{cr}$)

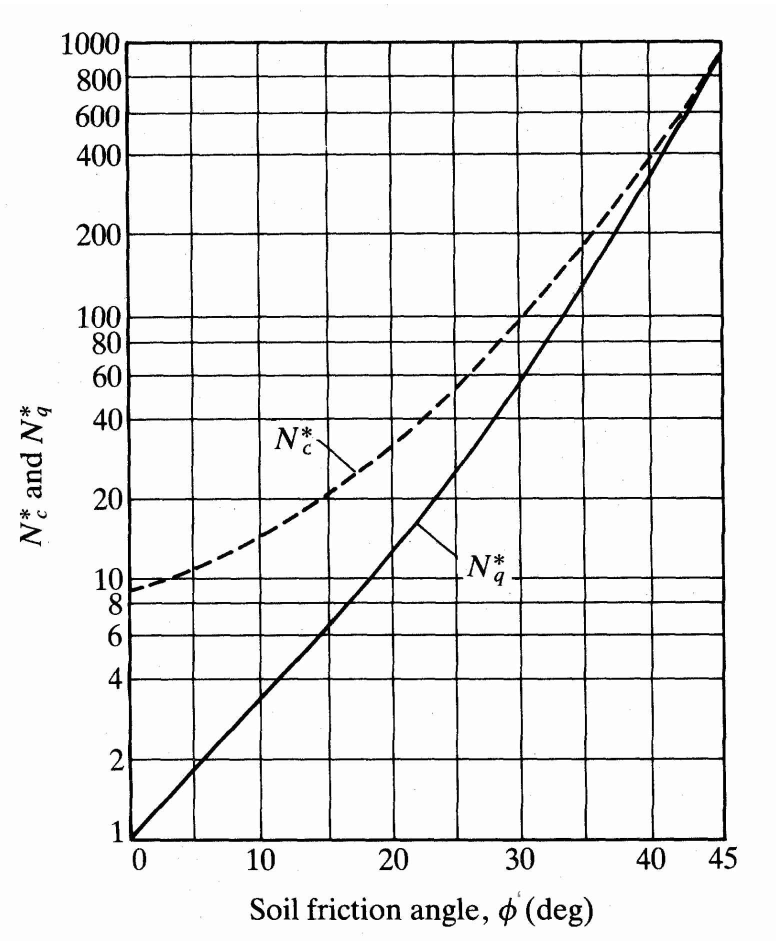


Figure. Variation of the maximum values of N_c^* and N_q^* with ϕ'

① Sand

$$Q_p = A_p q' N_q^* \leq A_p q_l \left(= 0.5 p_a N_q^* \tan\phi'\right)$$

where, p_a = atmospheric pressure ($=100 kN/m^2$)

- Based on field tests (SPT) for homogeneous granular soil

$$q_p(\mathrm{kN/m^2}) = 0.4\mathrm{p_a}(\mathrm{N_1})_{60}\mathrm{L_b/D} \leq 4\mathrm{p_a}(\mathrm{N_1})_{60}$$

($(N_1)_{60}$ = average corrected value of the SPT number about *10D* above and *4D* below the pile point)

② Saturated clays in undrained condition ($\phi = 0$)

$$Q_p = N_c^* c_u A_p = 9 c_u A_p$$

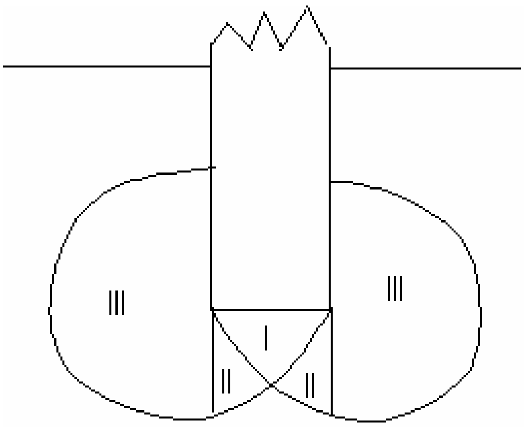
(c_u : undrained strength)

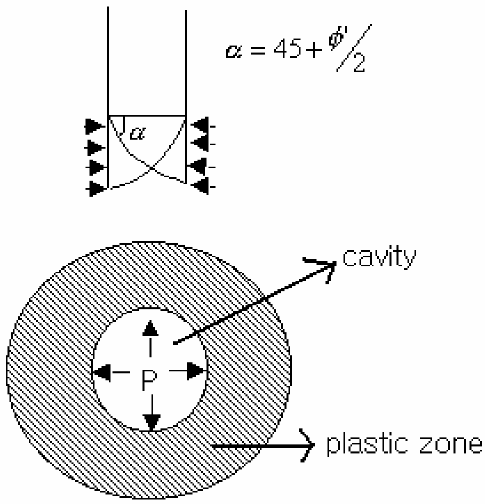
③ Soils with c' and ϕ',

$$Q_p = A_p \left(c' N_c^* + q' N_q^* \right)$$

b) Vesic's method

- Based on the theory of expansion of cavities





I : zone of compression
II : radial zone
III : plastic zone

- $Q_p = A_p q_p = A_p (c' N_c^* + \overline{\sigma'}_o N_\sigma^*)$

where, $\overline{\sigma'}_o$ = mean effective normal stress at pile tip

$= \dfrac{1 + 2K_o}{3} q'$

(q' = vertical effective stress at pile tip)

K_0 = earth pressure coefficient at rest ($= 1 - \sin\phi'$)

$$\overline{\sigma'}_o N_\sigma^* = q' N_q^*$$

$$N_\sigma^* = \frac{q'}{\sigma'_o} N_q^*$$

$$= \frac{3}{1 + 2K_o} N_q^*$$

$$N_\sigma^* = f(I_{rr}, \phi')$$

$$= \frac{3}{3-\sin\phi'} e^{(\pi/2-\phi')\tan\phi'} \tan^2(\pi/4+\phi'/2) I_{rr}^{\left(\frac{4\sin\phi'}{3+\sin\phi'}\right)}$$

$$N_c^* = (N_\sigma^* - 1)\cot\phi' \quad (For\ \phi' = 0,\ N_c^* = \frac{4}{3}(1+\ln I_{rr}) + \pi/2 + 1)$$

where, $I_{rr} = \frac{I_r}{1+I_r\Delta}$ =reduced rigidity index

$I_r = \frac{E_s}{2(1+\mu_s)(c'+q'\tan\phi)} = \frac{G_s}{c'+q'\tan\phi'}$ = rigidity index

(Refer to Table p.494)

$\Delta =$ Average volumetric strain in plastic zone

($\Delta = 0$ For dense sand or saturated clay, $\Rightarrow I_{rr} = I$)

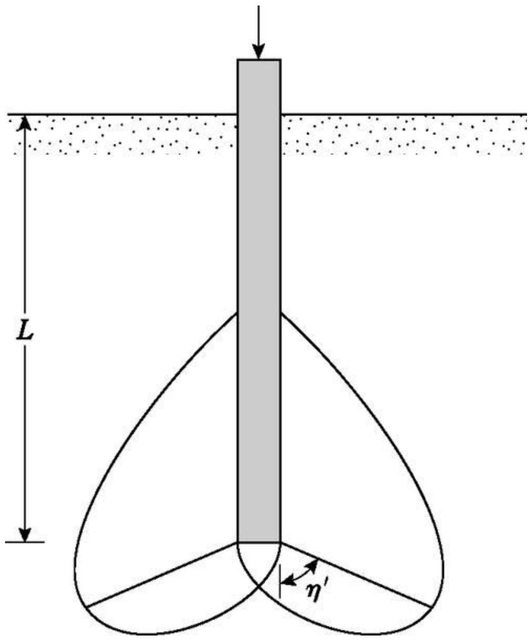
- N_σ^* *and* N_c^* can be obtained from Table 11.4 (p.495), with I_{rr} *and* ϕ'.

c) Janbu's method

$$Q_p = A_p(c' N_c^* + q' N_q^*)$$

$$N_q^* = (\tan\phi' + \sqrt{1+\tan^2\phi'})^2 e^{2\eta'\tan\phi'}$$

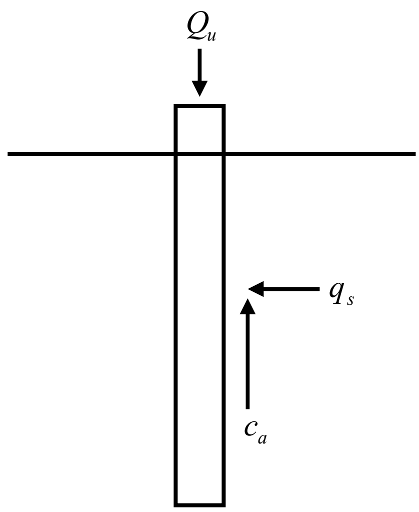
$$N_c^* = (N_q^* - 1)\cot\phi'$$



η' = 70° (soft clays) – 105° (dense sands)

N_q^* and N_c^* are given in Table 11.5 (p.499)

ii) Frictional Resistance



$$Q_s = f_s A_s$$
$$= f_s (\sum pL)$$

where, p : perimeter of pile
L : pile length

$$f_s = c_a + q'_s \tan\delta$$

where, c_a = adhesion between soil and pile
q'_s = effective stress normal to side of pile
δ = interface friction angle

$$q_s = K\sigma_v'$$

where σ_v' = vertical effective stress prior to installation

K = earth pressure coefficient
= f(friction angle, method of installation, pile length, ….)

At top, $K \approx K_p$ and at tip, $K \approx K_o$ ⬅ For driven pile

● For sands

$$f_s = q'_s \tan\delta$$

$$= K\sigma_v' \tan\delta$$

Pile type	K
Bored or jetted	$\approx K_o = 1 - \sin\phi$
Low-displacement driven	$\approx K_o = 1 - \sin\phi$ to $1.4K_o = 1.4(1 - \sin\phi)$
High-displacement driven	$\approx K_o = 1 - \sin\phi$ to $1.8K_o = 1.8(1 - \sin\phi)$

$\delta \approx 2/3\phi'$ (sand with concrete)
$\delta \approx 1/2\phi'$ (sand with steel)

- Alternative way to get frictional resistance

Bhusen $\Rightarrow$ for high-displacement driven piles

$$K \tan\delta = 0.18 + 0.0065D_r$$
$$K = 0.5 + 0.008D_r$$

(D_r in %)

Meyerhof $\Rightarrow$ for high-displacement driven piles

$$f_{av} = 0.02 p_a (\overline{N}_1)_{60}$$

for low-displacement driven piles

$$f_{av} = 0.01 p_a (\overline{N}_1)_{60}$$

where, p_a = atmospheric pressure ($\approx 100 kN/m^2$)
$(\overline{N}_1)_{60}$ = average corrected value of 볐

Note :

● **For clays**

a) λ method

Based on the assumption that the displacement of soil caused by pile driving results in passive lateral pressure at any depth.

$$f_{av} = \lambda(\overline{\sigma_0'} + 2c_u)$$

$\overline{\sigma_0'}$ = mean effective vertical stress for the entire embedment depth

c_u : mean undrained shear strength ($\phi = 0$)

λ : decreases with embedment pile length (use average value).

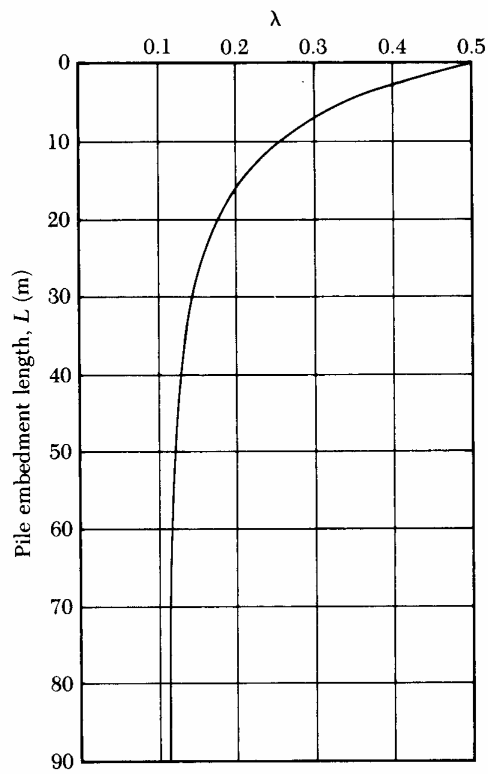


Figure. Variation of λ with pile embedment length
(redrawn after Mc Clelland, 1974)

$$Q_s = pLf_{av}$$

b) α method (undrained)

$$f_{av} = c_a = \alpha s_u$$

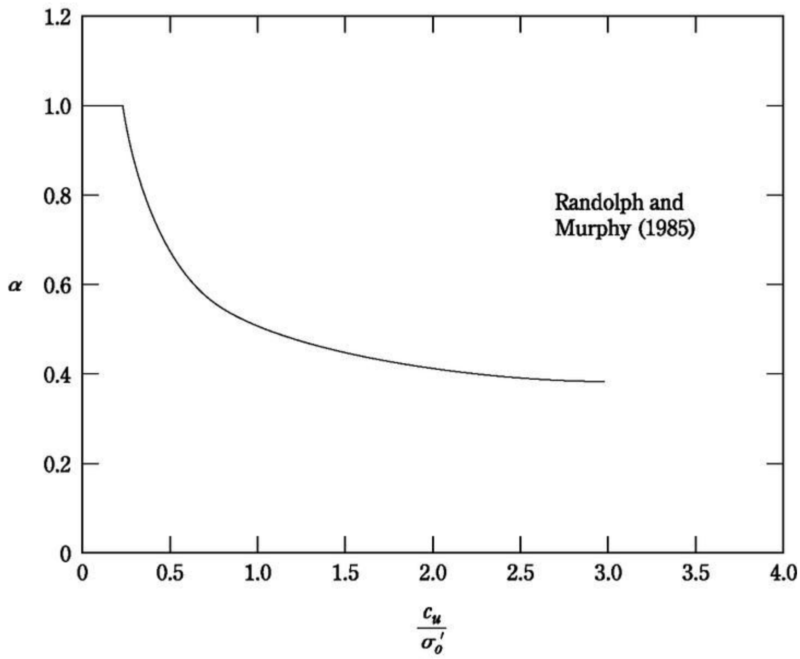


Figure. Variation of α with c_u / σ_0'

$$Q_s = \sum fp\Delta L = \sum \alpha c_u p\Delta L$$

c) β method

(Excess pore pressures developed during driving piles dissipate within a month or so. Frictional resistance can be determined on the basis of effective stress in a remolded state.)

$$f = \beta \sigma_0'$$

where, $\beta = K \tan \phi_R'$

ϕ_R' : (Drained) friction angle of remolded clay

σ_0' : vertical effective stress

$K = 1 - \sin \phi_R'$ $\Rightarrow$ For NC clay

$K = (1 - \sin \phi_R')\sqrt{OCR}$ $\Rightarrow$ For OC clay

$$f = (1 - \sin \phi_R')\sqrt{OCR}(\tan \phi_R')\sigma_0'$$

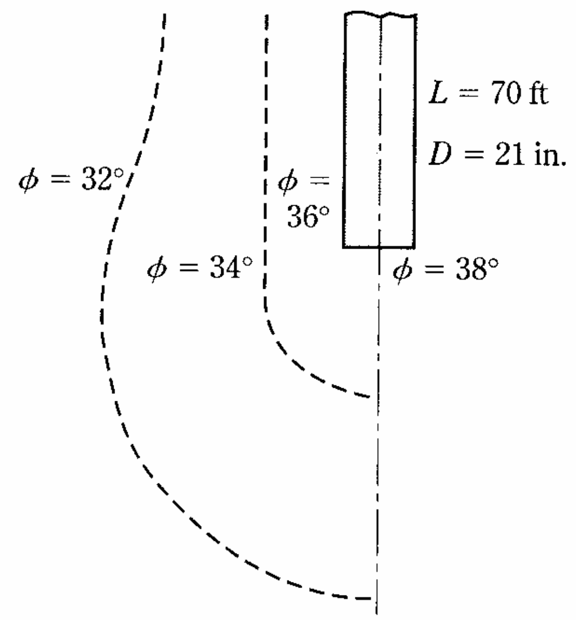
With the value of f, the total frictional resistance may be evaluated as

$$Q_s = \sum f p \Delta L$$

- **Allowable Pile Capacity**
  - F.S. ranges from 2.5-4.0 depending on uncertainties of ultimate load calculation.

- **General comments**

1)



2)

3)

6) Coyle and Castello Design Correlations

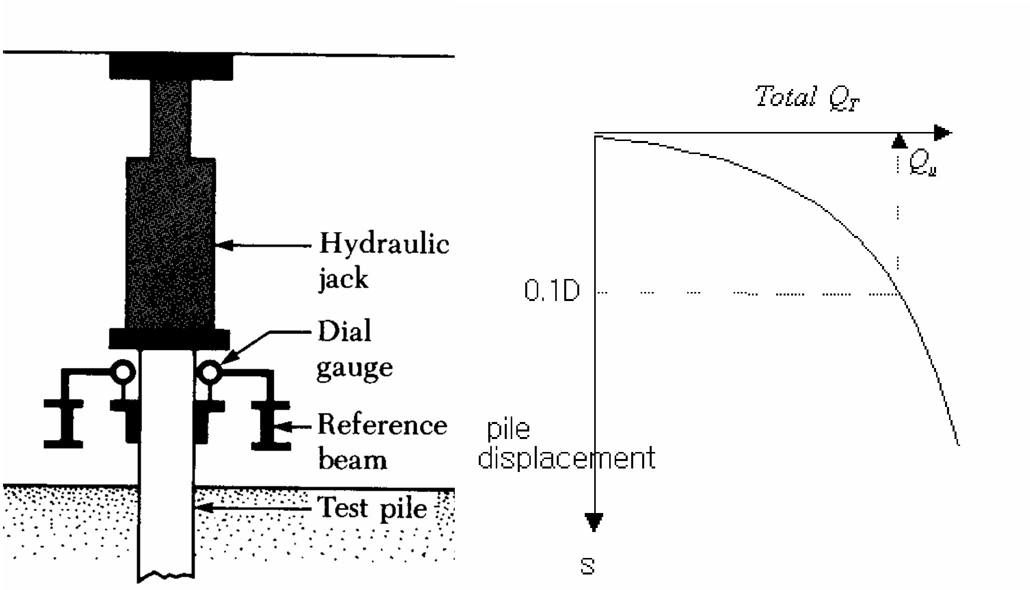
- Based on 24 large-scale field load tests of driven piles in sand.

$$Q_u = Q_p + Q_s = q' N_q^* A_p + f_{av} pL$$

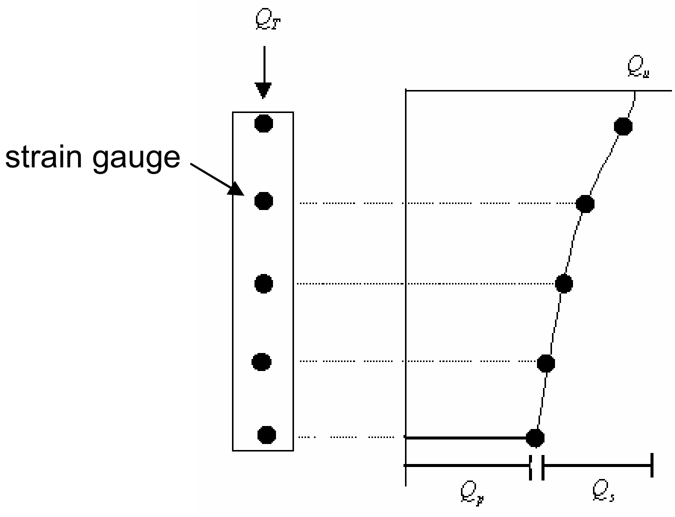
where, $f_{av} = K\sigma'_{v(ave)} \tan\delta$

↑
average effective stress along shaft

- Typical results of instrumented pile load tests



(a)



(b)

(a)

(b)

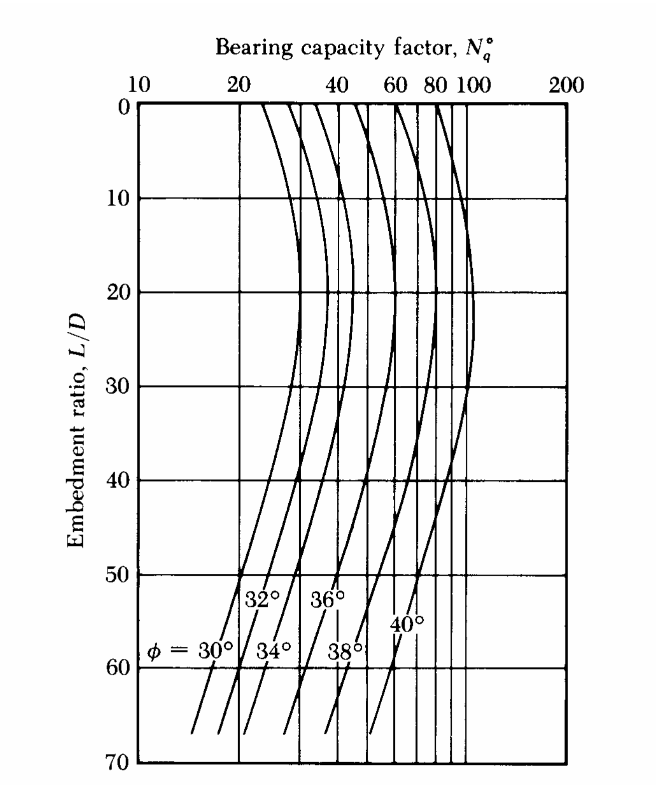
(c)

i) Point resistance, Q_p

$$Q_p = q' N_q^* A_p$$

Q_p, q', A_p : known $\Rightarrow$ N_q^* can be computed.

$\Rightarrow$ Fig 11.14 shows N_q^* with varying L/D and ϕ'.



N_q^* increases, reaches maximum and decreases thereafter with L/D.

ii) Frictional resistance, Q_s

$$Q_s = f_{av} pL$$

Q_s, p, L : known $\Rightarrow f_{av}$ can be computed.

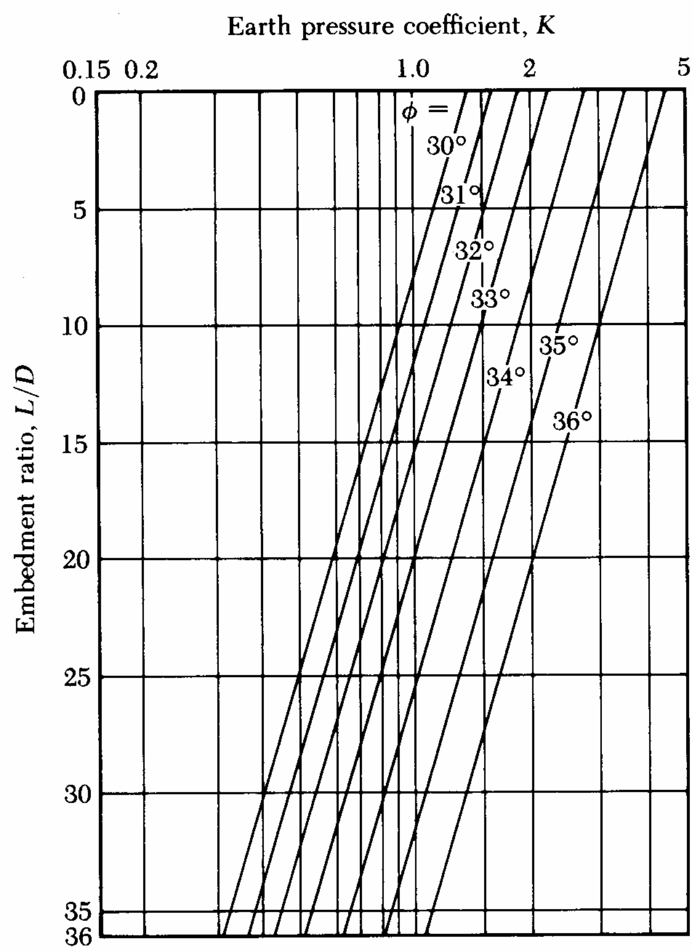
$$f_{av} = K\sigma'_{v(ave)} \tan\delta$$

δ : assumed as $0.8\phi'$

$f_{av}, \sigma'_{v(ave)}$: known

➡ K can be computed

Fig 11.19 shows K with varying L/D and ϕ'.



Finally, we can get

$$Q_u = q^{'} N_q^{*} A_p + pLK\overline{\sigma_v^{'}}\tan(0.8\phi)$$

↑ ↑

(obtained from Fig 11.14 and 11.19, according to given $\phi^{'}$ and L/D.)