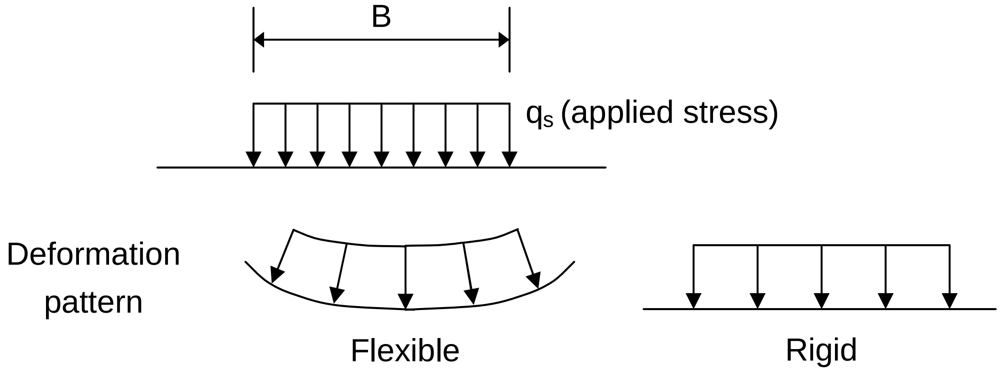
2.2 Rate-Independent Settlements

(1) <u>Elastic Theory</u>



- For D_f(=depth to the bottom of foundation level) = 0 and assuming soil as an elastic material,

$$S_i = \frac{\text{Immediate}}{\text{Settlement}} = q\,\frac{B}{E}\,I_p\,(1-\nu^2) \qquad \text{- (1)}$$

E, ν : "elastic" parameter for soil

ν = 0.5 for undrained loading

ν = 0.2~0.4 for drained loading

I_p : shape and rigidity factor

i) On an elastic half space of unlimited depth : Table 2-1 in p.2-18

ii) On an elastic half space of limited depth over a rigid base : Table 2-1 in p.2-19

- For D_f > 0 (<u>stiff to hard fine grained soil for rectangular footing</u>) → Fig. 2-10 in p.2-20

1. Get C_s. (→ I_p)
2. Calculate settlement for D_f = 0, $\delta_{v0} = \dfrac{0.75\, q_s\, B\, C_s \sqrt{L/B}}{E_s}$.
3. Obtain δ_{vd}/δ_{v0} ratio from chart, with $D/\sqrt{BL}$ and L/B.
4. then, get δ_{vd} = settlement at deep footing ($\delta_{vd} < \delta_{v0}$).

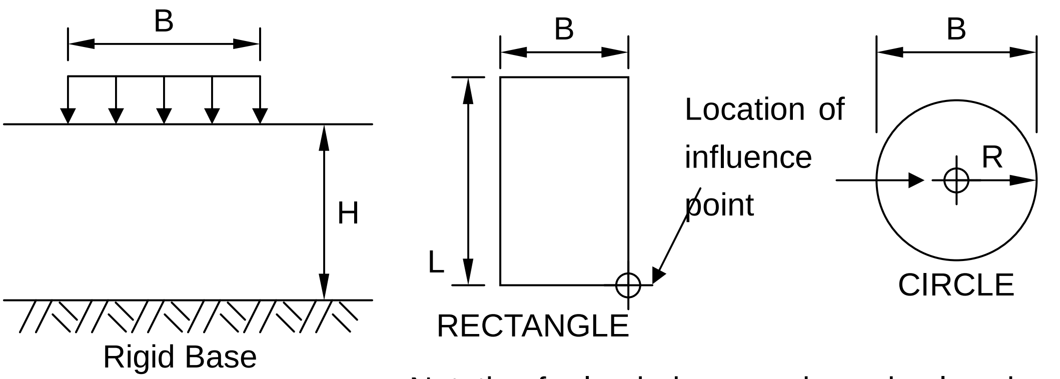
Table 2-1 Shape and rigidity factors I_p for calculating settlements of points on loaded area at the surface of an elastic half-space

Shape and Rigidity Factors I for Loaded Areas on an Elastic Half-Space of Infinite Depth				
Shape and Rigidity	Center	Corner	Edge/Middle Of Long Side	Average
Circle (flexible)	1.00		0.64	0.85
Circle (rigid)	0.79		0.79	0.79
Square (flexible)	1.12	0.56	0.76	0.95
Square (rigid)	0.82	0.82	0.82	0.82
Rectangle (flexible) Length/width				
2	1.53	0.76	1.12	1.30
5	2.10	1.05	1.68	1.82
10	2.56	1.28	2.10	2.24
Rectangle (rigid) Length/width				
2	1.12	1.12	1.12	1.12
5	1.60	1.60	1.60	1.60
10	2.00	2.00	2.00	2.00

Table 2-1 (continued) Shape and Rigidity Factors I_p for Calculating Settlements of Points on Loaded Areas at the Surface of an Elastic Half-Space

Shape and Rigidity Factor I for Loaded Areas on an Elastic Half-Space of Limited Depth Over a Rigid Base

H/B	Center of Rigid Circular Area Diameter = B	Corner of Flexible Rectangular Area				
		L/B = 1	L/B = 2	L/B = 5	L/B = 10	(strip) L/B=∞
For $\nu = 0.50$						
0.0	0.00	0.00	0.00	0.00	0.00	0.00
0.5	0.14	0.05	0.04	0.04	0.04	0.04
1.0	0.35	0.15	0.12	0.10	0.10	0.10
1.5	0.48	0.23	0.22	0.18	0.18	0.18
2.0	0.54	0.29	0.29	0.27	0.26	0.26
3.0	0.62	0.36	0.40	0.39	0.38	0.37
5.0	0.69	0.44	0.52	0.55	0.54	0.52
10.0	0.74	0.48	0.64	0.76	0.77	0.73
For $\nu = 0.33$						
0.0	0.00	0.00	0.00	0.00	0.00	0.00
0.5	0.20	0.09	0.08	0.08	0.08	0.08
1.0	0.40	0.19	0.18	0.16	0.16	0.16
1.5	0.51	0.27	0.28	0.25	0.25	0.25
2.0	0.57	0.32	0.34	0.34	0.34	0.34
3.0	0.64	0.38	0.44	0.46	0.45	0.45
5.0	0.70	0.46	0.56	0.60	0.61	0.61
10.0	0.74	0.49	0.66	0.80	0.82	0.81



Notation for loaded areas, shown in plan view

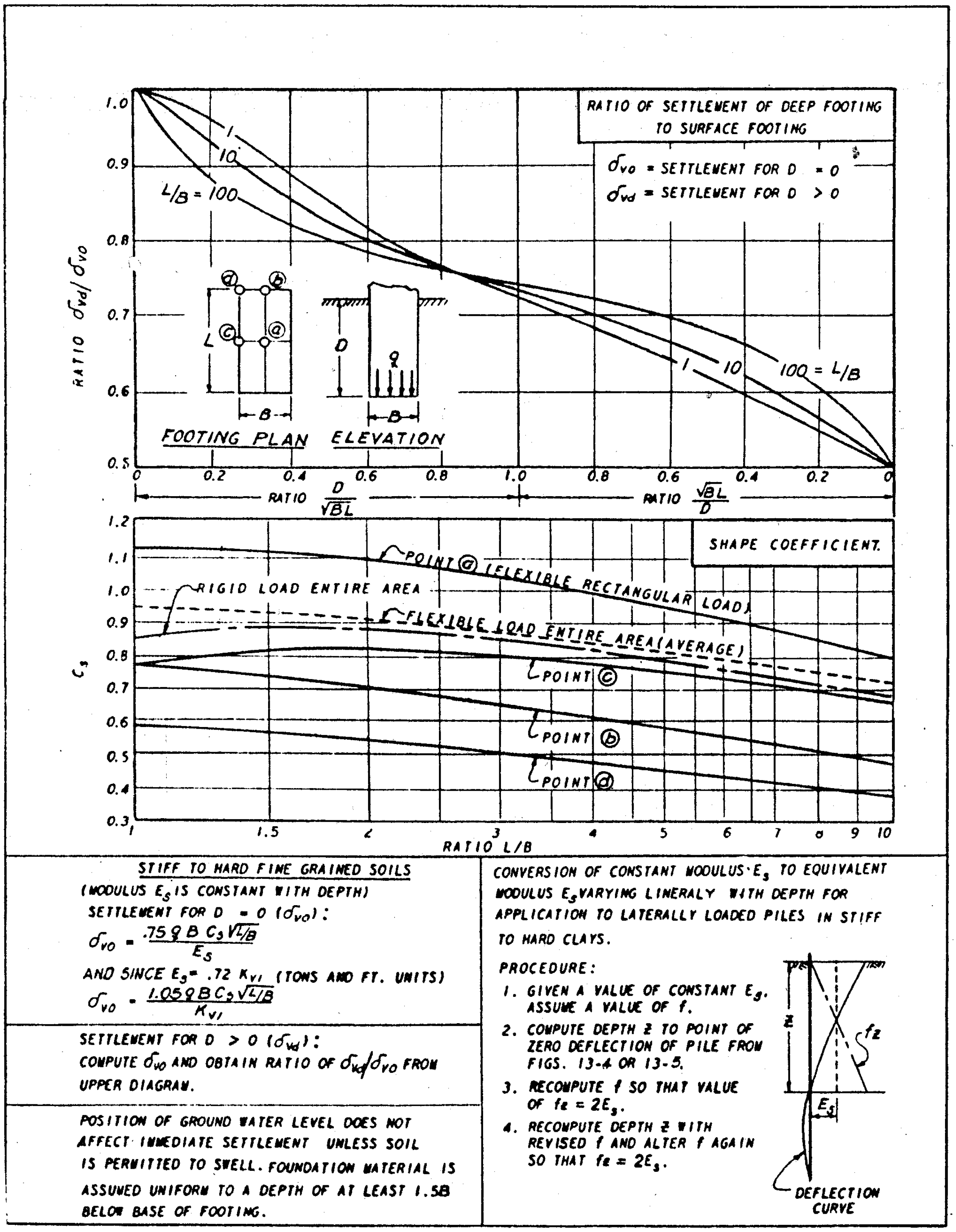


Fig. 2-10 Immediate Settlement of Isolated Footings on Stiff to Hard Fine Grained Soils (NAVFAC DM 7-11-11)

● Settlements on Soils

- Settlements
  - i) Immediate ⟶ Time independent settlements
  - ii) Primary consolidation, iii) Secondary compression ⟶ Time dependent settlements

- Sands → Immediate
  - → Settlement due to 2-D or 3-D deformations and volume compression ($\nu < 0.5$)

  Primary consolidation
  - → Settlement due to volume compression related to dissipation of pore pressure
  - → Not significant due to low compressibility of sands and implementation on existing immediate settlement computation method with ν value less than 0.5

  Secondary compression → creep

- Clays → Immediate (undrained)

  ↑

  2-D or 3-D conditions with $\nu = 0.5$

  Primary consolidation

  Secondary compression

(2) Immediate Settlements in Cohesive Soils

- 2-D or 3-D condition → very important
- 1-D condition → negligible (can be considered in unsaturated soils)
- Non-linearity is a key point to estimate settlements.

<D'Appolonia, et. al. (1971)>

- Immediate settlements that account for local yielding
  (Significant in $(FS)_{bc} < 3 \quad \Rightarrow$ increasing settlement.)
- Based on finite element analysis with an elasto-plastic soil model.

$$SR \text{ (Settlement Ratio)} = \frac{\delta_v}{\delta_c}$$

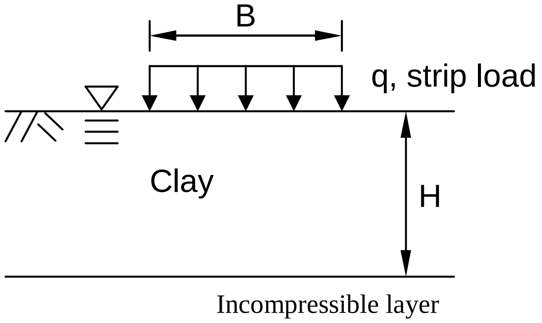
δ_v : elastic component of settlement (no yielding) $= qB\frac{(1-\nu)^2}{E_u} I_p$

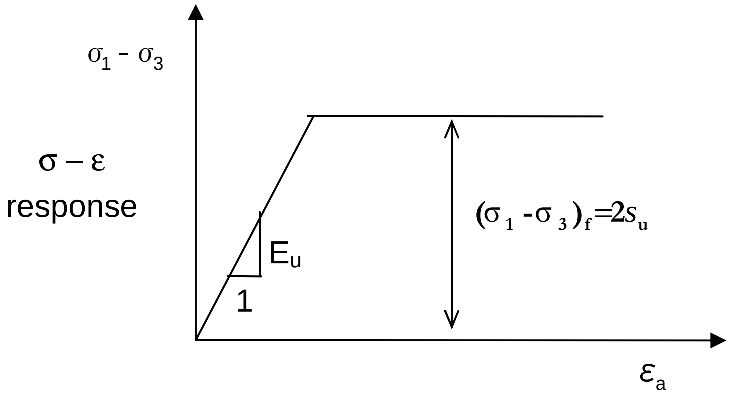
δ_c : immediate settlement corrected to allow for partial yield conditions.

- Method
  ∗ Strictly applicable to strip loads.
  (Conservative for loads of limited extent)
  ∗ Accounts for
  - initial shear stress ratio.
  - thickness of clay layer.
  - applied stress level.

- How was the method developed?

i) D'Appolonia (1971) performed numerical simulations of soil profile :





⇒ Computed $\delta_{FE.}$ (corresponds to δ_c) → settlement under center line of footing.

ii) Calculate $\delta_E (= \delta_v)$ based on elastic theory using same values of E_u that D'Appol. used in finite element simulations.

iii) Calculate SR(= δ_v / δ_c) using (1) and (2) for various conditions.

a) H/B

b) initial shear stress ratio ($f = \left(\dfrac{\sigma'_{v0} - \sigma'_{h0}}{2} \right) \Big/ s_u = \dfrac{(1-K_0)}{2 s_u / \sigma'_{v0}}$)

c) Applied stress $= q / q_u = 1/F.S.$

q_u : ultimate bearing capacity

→ Fig. 2-11 (NAVFAC DM 7.1 – 216) in p.2-25

(f ↑, H/B ↑, q/q_{ult} ↑. ⇒ SR ↓ (⇒ increase settlement))

- Approach to get δ_c

① Calculate f if we know K_o and s_u / σ'_{V0} .

or Estimate f from Fig. 2-12 (NAVFAC DM 7.1-217) in p.2-27.

② Obtain E_u

a) Using Table 2-2 (NAVFAC DM 7.1-215) in p.2-25.

b) Run high quality tests.

③ Perform undrained ultimate bearing capacity analysis.

$q_{ult} = 5.53c = 5.53s_u$

→ Ratio of q / q_{ult}

④ For given H/B, q / q_{ult} and f, obtain SR from Fig. 2-11 (NAVFAC DM 7.1-216) in p.2-25.

⑤ Calculate $\delta_v = q \frac{B}{E_u} I_p (1 - \nu^2)$

where E_u is consistent with that found in step 2

⑥ $\delta_c = \frac{\delta_v}{SR}$

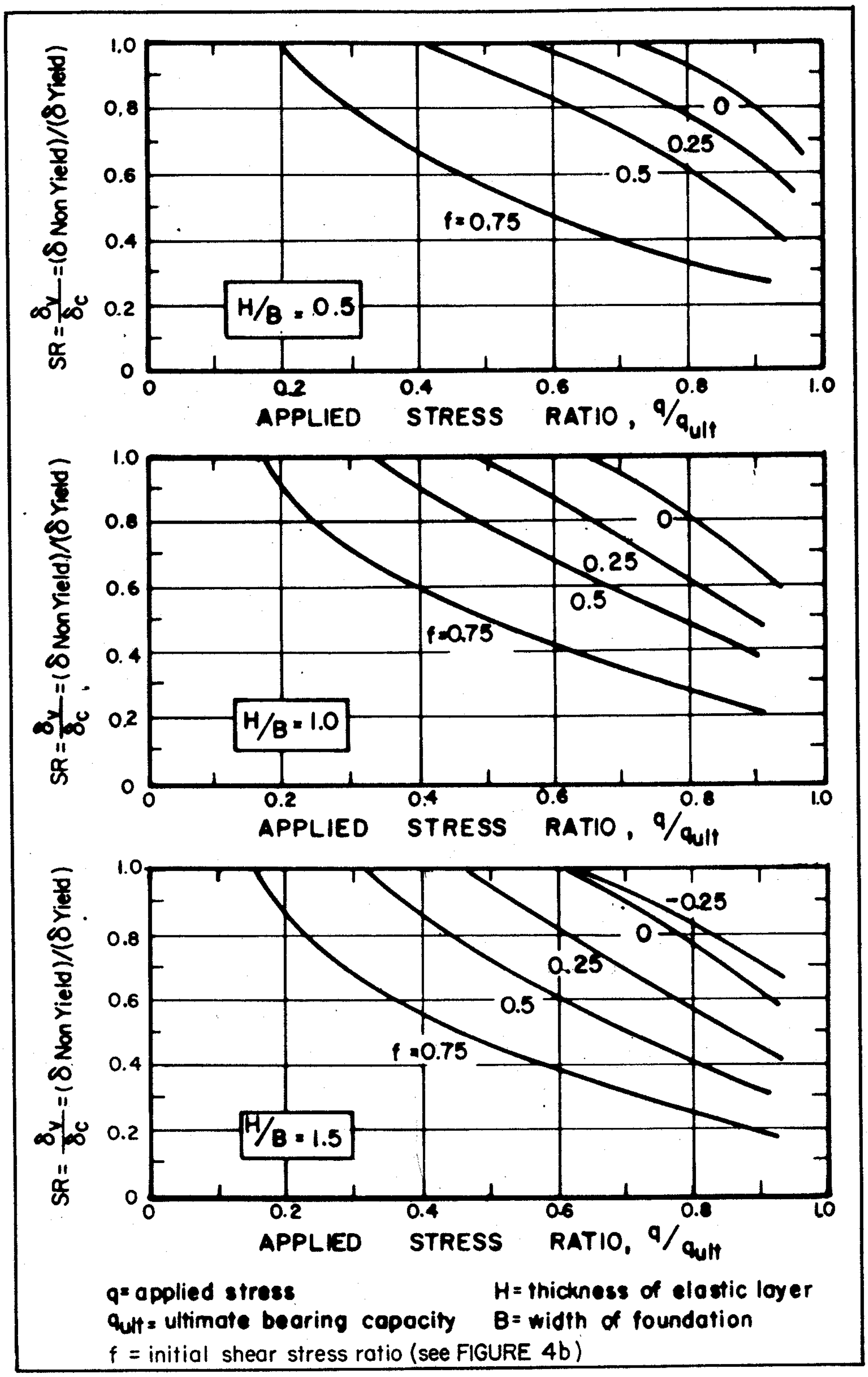


Fig. 2-11 Relationship Between Settlement Ratio and Applied Stress Ratio for Strip Foundation on Homogeneous Isotropic Layer (NAVFAC DM 7.1-216)

Table 2-2 Relationship Between Undrained Modulus and Overconsolidation Ratio (NAVFAC DM 7.1-215)

OCR	E_u/s_u		
	PI < 30	30 < PI < 50	PI > 50
< 3	600	300	125
3 ~ 5	400	200	75
> 5	150	75	50

- OCR = Overconsolidation ratio
- s_u = Undrained shear strength
- PI = Plastic index

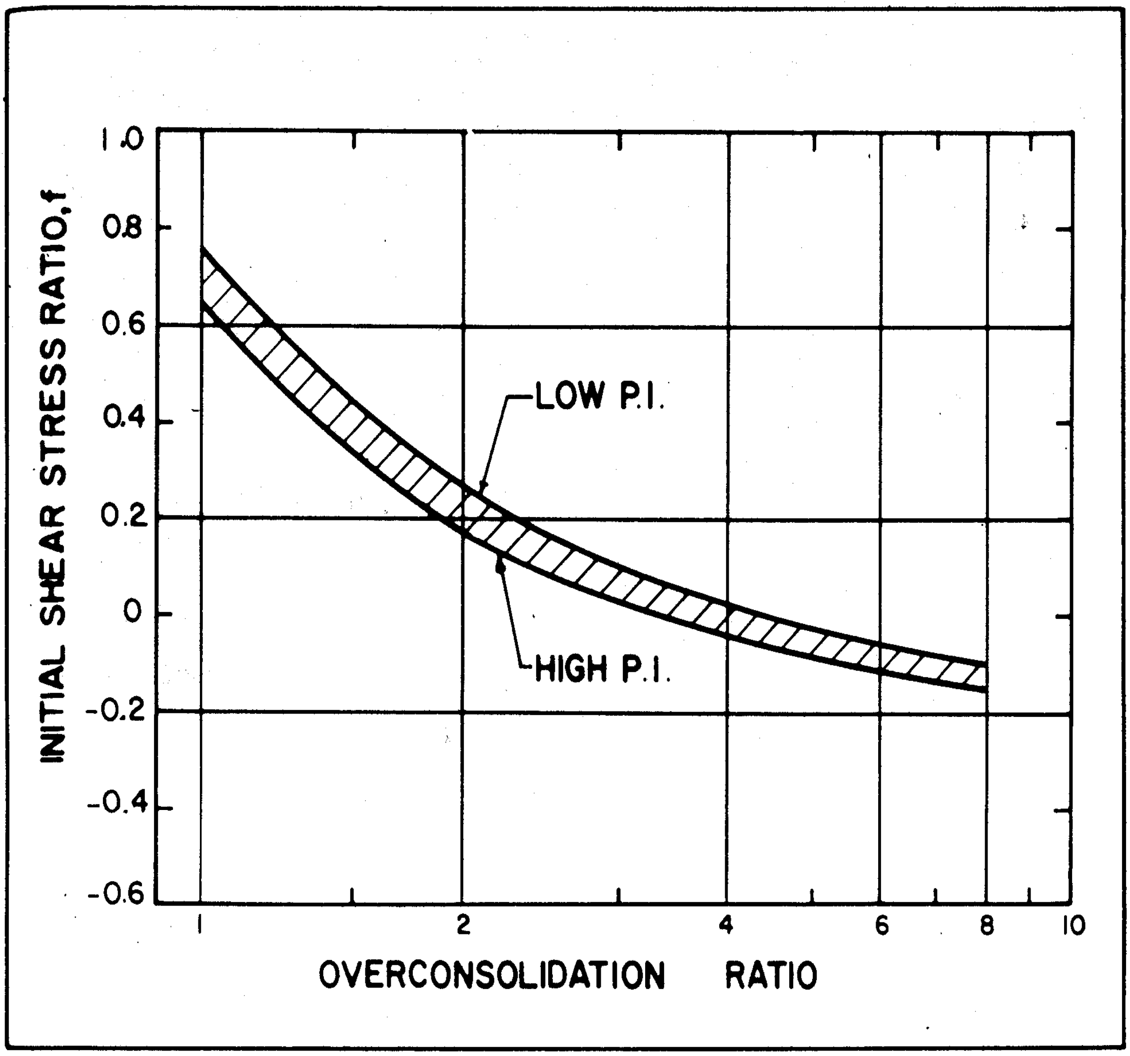


Fig. 2-12 Relationship Between Initial Shear Stress and Overconsolidation Ratio (NAVFAC DM 7.1-217)

- Comments

i) When H/B > 1.5, influence of the greater depth of clay is small.
→ Use chart for H/B=1.5 for all values.

ii) Settlements are at the centerline of strip footing.

iii) Unless the soil is highly anisotropic($E_{u(horizontal)} > E_{u(vertical)}$), the results of isotropic analysis are good enough to estimate δ_c .

iv) Influence of strength nonhomogeneity on settlment is relatively small, compared to f.

v) Immediate settlements in clays are important when clay is highly plastic or organic. $\frac{E_u}{s_u}$ decreases with increasing plasticity.

vi) When immediate settlements are significant, then creep movements are likely to occur.

vii) Surface footing only.→ Need modification for embedded footing.

(3) Immediate Settlements in cohesionless soils.

- Elastic theory
- SPT
- Plate Load Test
- CPT

i) Elastic Theory

- Same procedure as before

→ Problem : E value?

↓

Typical, $E = K(\sigma'_3)^n$

n ≈ 1/2, K=constant

→ To obtain E in lab. testing,

we need to know : Insitu D_r (relative density) + (water content)

(Evaluate D_r from empirical correlation with SPT and CPT results.)

→Find $\gamma_{d\max}$ and $\gamma_{d\min}$.

→Reconstitute sample to appropriate γ_d (corresponding to D_r) and water content.

→Run shear test.

ii) SPT

- Meyerhof

For B ≤ 4’ , $S_e\ (\text{in.}) = \dfrac{4q_s}{N}$ (q_s in klb/ft^2)

For B> 4’ , $S_e\ (\text{in.}) = \dfrac{KC_d q_s}{N\left(\dfrac{B+1}{B}\right)^2}$ (B in feet, q_s in klb/ft^2)

K ≡ constant

= 12 (original value) → very conservative

= 8 (max. settlement)

= 4 (average settlement)

C_d ≡ correction factor for embedment depth,

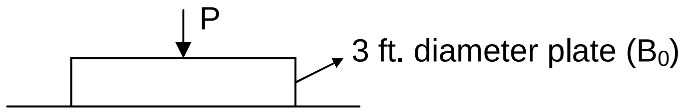
D_f =0 → C_d =1

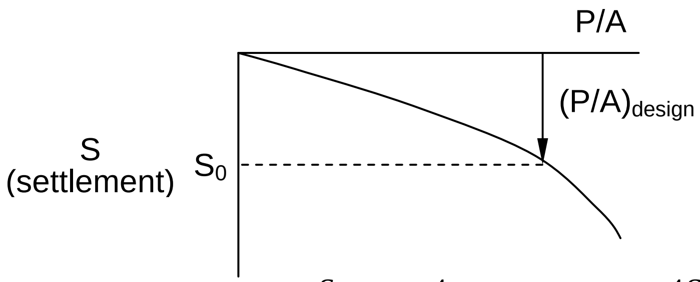
D_f =B → C_d =0.75

q_s ≡ average pressure

N ≡ average N value in the stressed zone (≈ 0~2B)

iii) Plate Load Test





$$\frac{S}{S_o} = \frac{4}{\left(1+\dfrac{B_0}{B}\right)^2} \Rightarrow S = \frac{4S_o}{\left(1+\dfrac{B_0}{B}\right)^2}$$

B/B_0 > 4~5 → not a good results,

sometimes actual settlements ≈ 3 x estimated settlements.

- Bonds recommends,

$$\frac{(S/B)}{(S_0/B_0)} = \left(\frac{B}{B_0}\right)^n$$

n = 0.03 to 0.05 for clay
0.08 to 0.10 for sandy clay
0.40 to 0.50 for dense sand
0.25 to 0.35 for medium dense sand
0.20 to 0.25 for loose sand

- Problem