Settlement Analysis

- Settlement: Total vertical downward deformation at the surface resulting from the load is termed as settlement
- Type of settlement
- -**Elastic or temporary**
- Settlement du to elastic compression of soil solid and plastic flow of soil are usually reversible and recoverable on load release, immediate settlement fall in this category.
- **Permanent Settlement**:
- Settlement caused by distortion brought about sliding and rolling of soil particles under the action of applied stresses.
- Types of Settlement w.r.t Occurrence
- 1. **Primary consolidation settlement**
- **2. Secondary consolidation settlement**
- **3. Immediate or elastic settlement**
- Types of Settlement w.r.t uniformity
- **1. Uniform settlement**
- **2. Differential Settlement**

JANBU & BJERRUM METHOD
FOR ELASTIC SETTLEMENT UNDER UNDRAINED CONDITIONS

Based on elastic theory, the immediate/elastic settlement of flexible surface footing may be written as

$$\Delta i = qB\frac{(1-u^2)}{Es} I_f$$

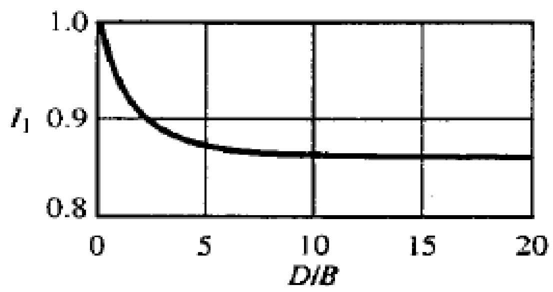
For u=0.5, Janbu & Bjerrum modify the above equation and adding I_1 & I_2 for I_f

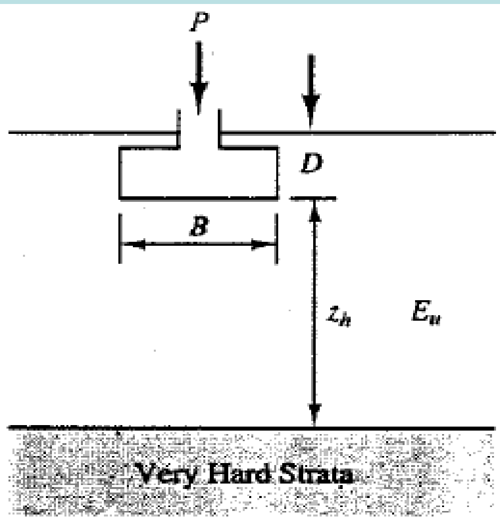
$$\Delta i = \frac{q_n B}{Es} I_1 I_2$$

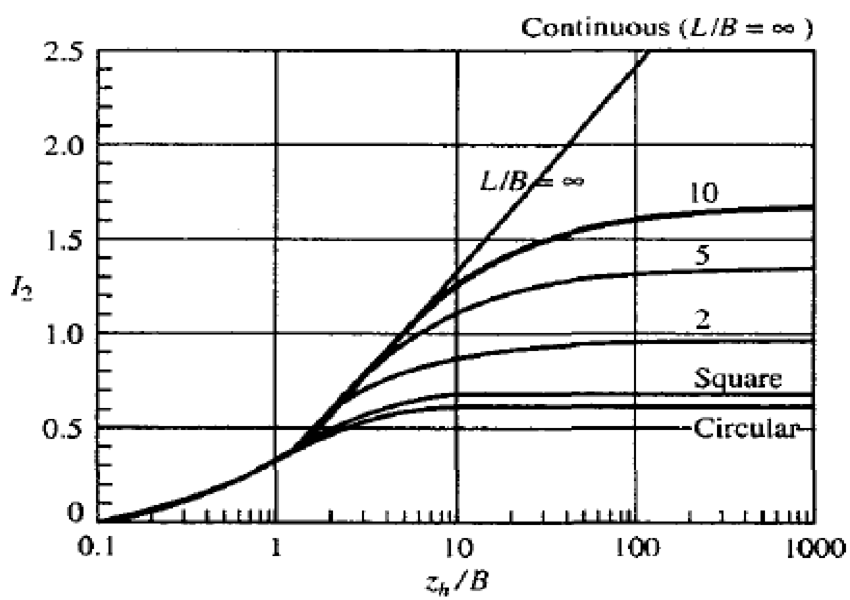
Δ_i = Elastic or immediate settlement
q_n= net footing pressure
B = width of footing
E = elastic modulus of soil
I_1, I_2 = Influence factors (from figures)

For clays $\underline{E = 300 \text{ to } 500\ Su}$

Factors I_1 & I_2 for Janbu Method







Settlement by Schmertmann method

Schmertmaan (1970, 1978) developed settlement method for spread footings on granular soils
The method is very useful when
- **CPT data along the depth of subsoil is available for evaluation of Es of subsoil.**
- **Can be used with reasonable accuracy for other in-situ test data like SPT or others to give Es**

$$s = C1C_2q'\sum \frac{I_z}{Es}\Delta z$$

C_1 = embedment factor or depth factor = $1 - 0.5\frac{\sigma_o'}{q'}$

C_2 = time factor = 1 + 0.2 log (t/0.1)

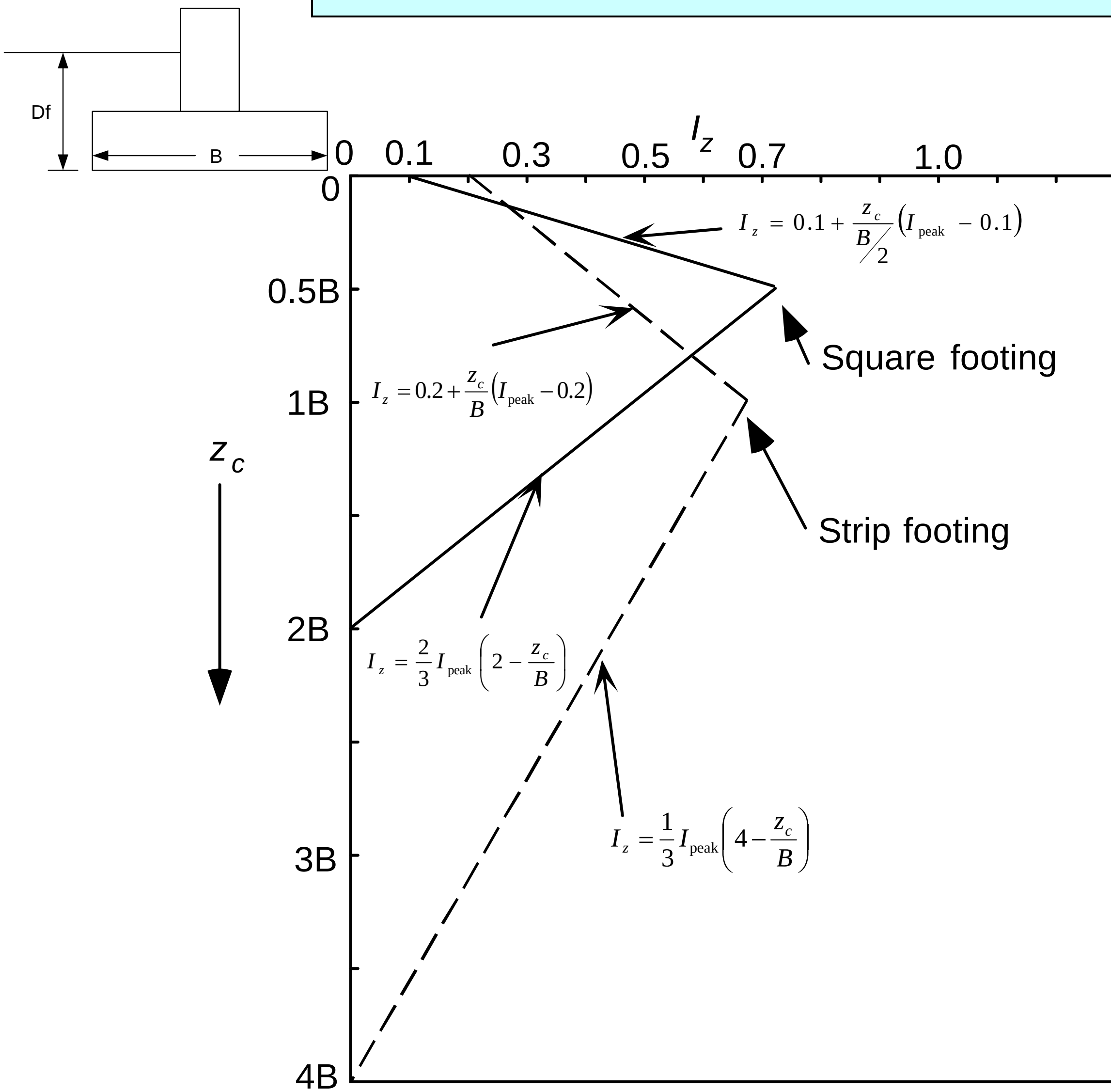
$q' =$ net contact pressure at footing base

$\sigma_o' =$ **effective overburden pressure at footing depth**

I_z = strain influence factor at depth z below the footing base
Es = modulus of elasticity of soil

Es = 2.5~3.5 qc
Es = 2.5qc (for axisymtric case, i.e., for square or circular footing
Es = 3.5qc (for plane strain case, i.e., for strip footing, L/B>10)

Strain Influence Factor, I_z



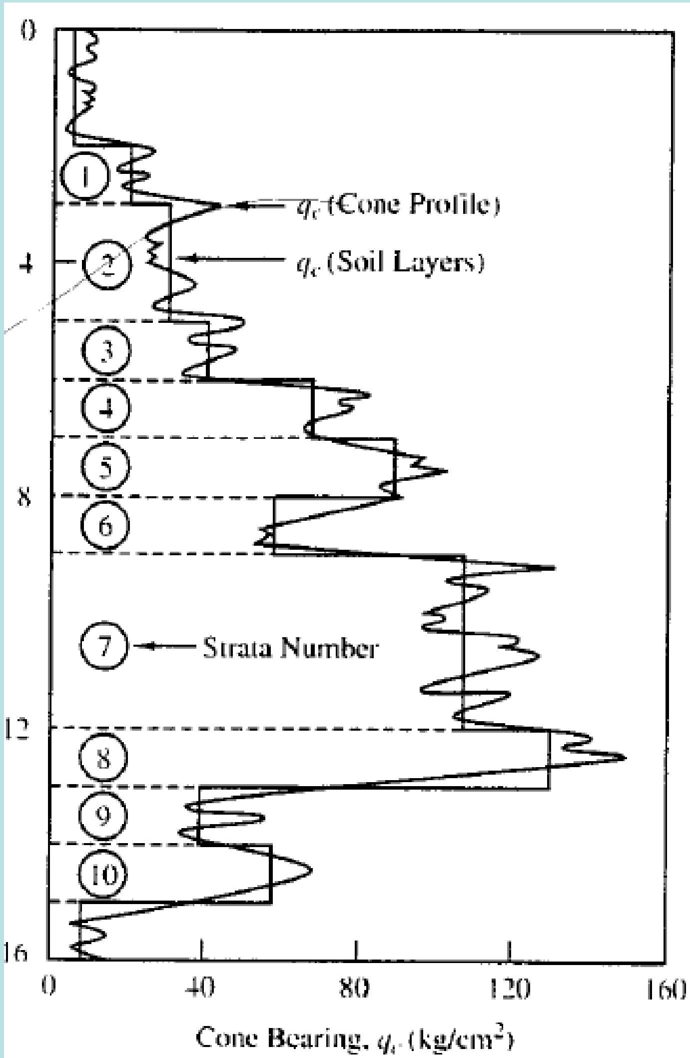
$$I_{z\ peak} = 0.5 + 0.1\left(\frac{q'}{\Delta\sigma'_{vp}}\right)^{1/2}$$

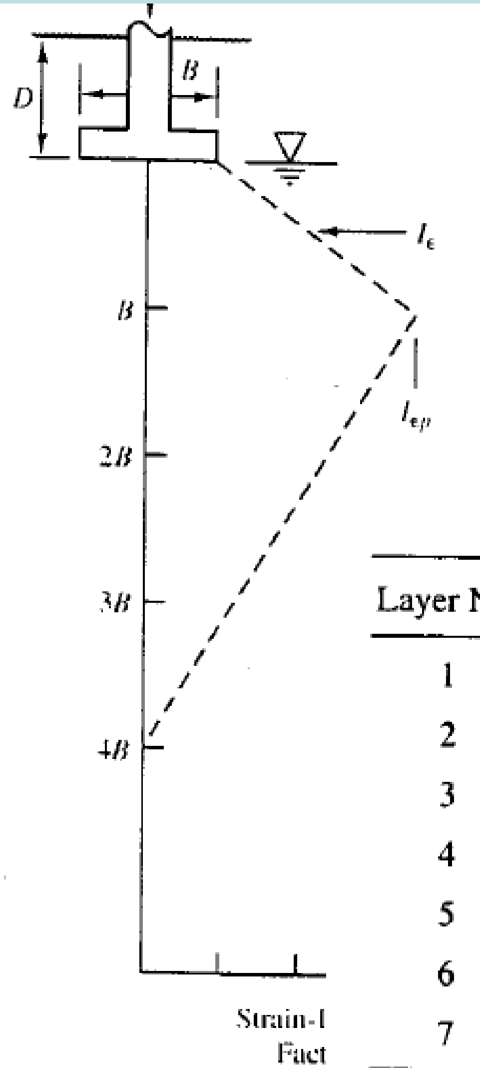
σ'_{vp} = effective overburden pressure at a depth of $0.5B$ (for square footing) and at depth B for strip footing

Example: **The figure shows the results of CPT sounding at a site. The subsoil at the site consists of young NC sand with some interbedded silts. The GWT is at 2 m below the surface. A strip footing (2.5x30 m) is to be funded at 2 m depth below the surface and will be loaded with gross bearing pressure of 200 kPa. Compute the settlement of the footing. (i) soon after construction (ii) after 5 years (iii) after 50 years of construction**

γ=17 kn/m3 above w/t

γ=20 kn/m3 below w/t





Layer No.	Depth (m)	q_c (kg/cm²)
1	2.0–3.0	20
2	3.0–5.0	30
3	5.0–6.0	41
4	6.0–7.0	68
5	7.0–8.0	90
6	8.0–9.0	58
7	9.0–12.0	108

Formulae to find stress for various footings

For circular foundations (adapted from Poulos and Davis, 1974):

$$\Delta\sigma_z = \left[1 - \left(\frac{1}{1 + \left(\frac{B}{2z_f}\right)^2}\right)^{1.50}\right](q - \sigma'_{zD}) \quad (7.6)$$

For square foundations:

$$\Delta\sigma_z = \left[1 - \left(\frac{1}{1 + \left(\frac{B}{2z_f}\right)^2}\right)^{1.76}\right](q - \sigma'_{zD}) \quad (7.7)$$

For continuous foundations of width B:

$$\Delta\sigma_z = \left[1 - \left(\frac{1}{1 + \left(\frac{B}{2z_f}\right)^2}\right)^{2.60}\right](q - \sigma'_{zD}) \quad (7.8)$$

For rectangular foundations of width B and length L:

$$\Delta\sigma_z = \left[1 - \left(\frac{1}{1 + \left(\frac{B}{2z_f}\right)^{1.38 + 0.62B/L}}\right)^{2.60 - 0.84B/L}\right](q - \sigma'_{zD}) \quad (7.9)$$

Timoshinko & Goodier Method

$$\Delta_H = q_o B' \frac{1-\mu^2}{E_s} I_i$$

(General Equation based on theory of elasticity)

Timoshinko & Goodier (1951) modify the above equation as below:

$$\boxed{\Delta_H = q_o B' \frac{1-\mu^2}{E_s} m I_s I_F}$$

q = contact pressure
B' = least lateral footing dimension of contributing base area
m = number of corners contributing to settlement, for corner
m = 1, for centre m=4
Es & u = elastic soil parameters

$$I_s = I_1 + \frac{1-2\mu}{1-\mu} I_2$$

For I_1 & I_2 see table

I_F=Depth factor, see figure

Depth Factor, I_F

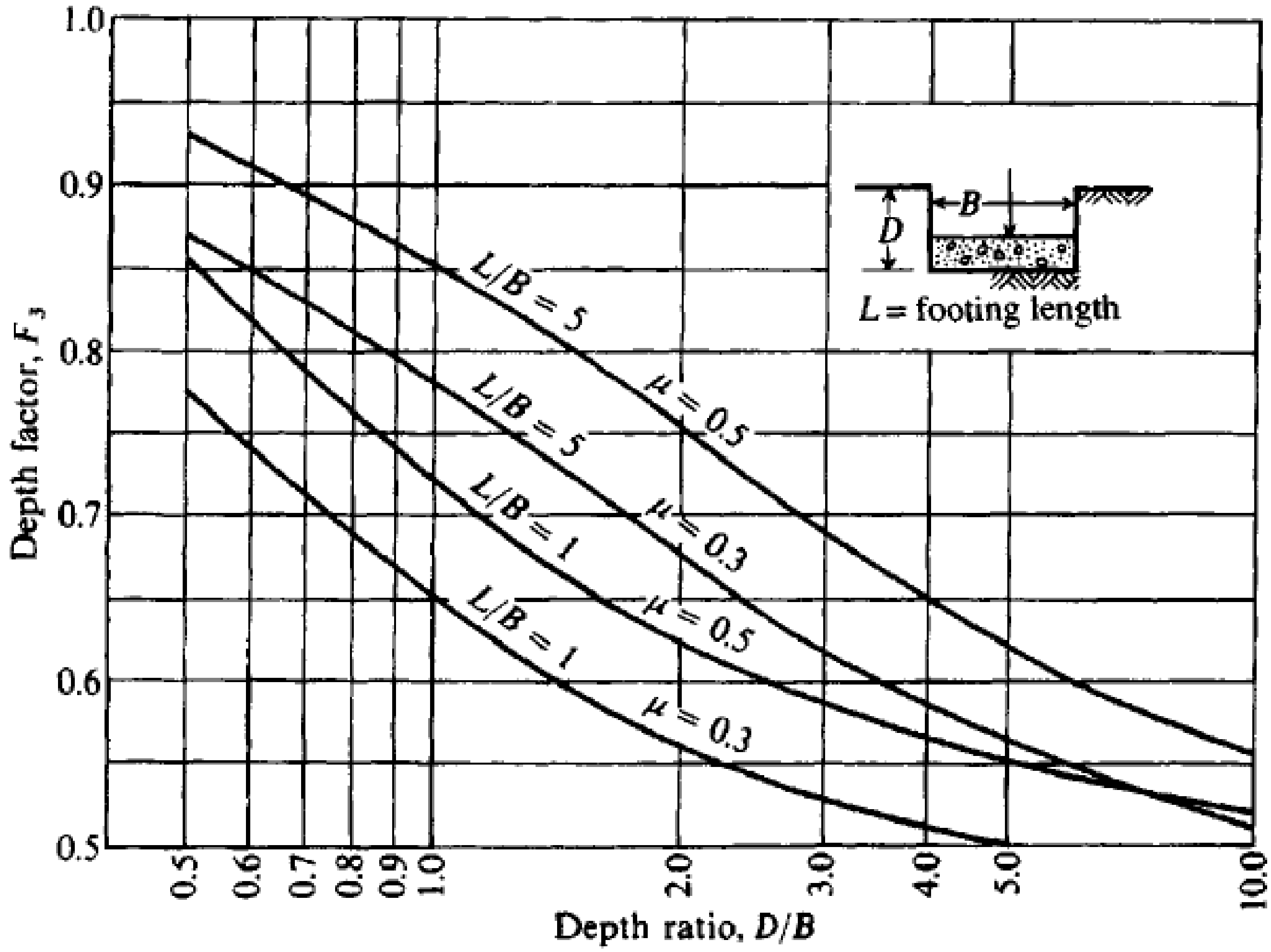


TABLE 5-2

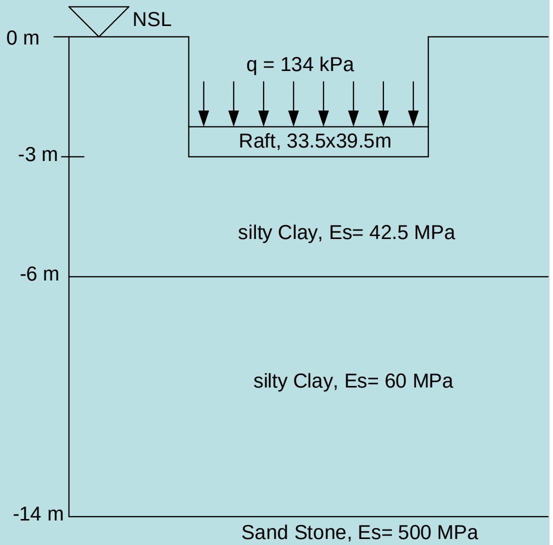
Values of I_1 and I_2 to compute the Steinbrenner influence factor I_s for use in Eq. (5-16*a*) for several $N = H/B'$ and $M = L/B$ ratios

N		M = 1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.0
0.2	I_1 =	0.009	0.008	0.008	0.008	0.008	0.008	0.007	0.007	0.007	0.007	0.007
	I_2 =	0.041	0.042	0.042	0.042	0.042	0.042	0.043	0.043	0.043	0.043	0.043
0.4		0.033	0.032	0.031	0.030	0.029	0.028	0.028	0.027	0.027	0.027	0.027
		0.066	0.068	0.069	0.070	0.070	0.071	0.071	0.072	0.072	0.073	0.073
0.6		0.066	0.064	0.063	0.061	0.060	0.059	0.058	0.057	0.056	0.056	0.055
		0.079	0.081	0.083	0.085	0.087	0.088	0.089	0.090	0.091	0.091	0.092
0.8		0.104	0.102	0.100	0.098	0.096	0.095	0.093	0.092	0.091	0.090	0.089
		0.083	0.087	0.090	0.093	0.095	0.097	0.098	0.100	0.101	0.102	0.103
1.0		0.142	0.140	0.138	0.136	0.134	0.132	0.130	0.129	0.127	0.126	0.125
		0.083	0.088	0.091	0.095	0.098	0.100	0.102	0.104	0.106	0.108	0.109
1.5		0.224	0.224	0.224	0.223	0.222	0.220	0.219	0.217	0.216	0.214	0.213
		0.075	0.080	0.084	0.089	0.093	0.096	0.099	0.102	0.105	0.108	0.110
2.0		0.285	0.288	0.290	0.292	0.292	0.292	0.292	0.292	0.291	0.290	0.289
		0.064	0.069	0.074	0.078	0.083	0.086	0.090	0.094	0.097	0.100	0.102
3.0		0.363	0.372	0.379	0.384	0.389	0.393	0.396	0.398	0.400	0.401	0.402
		0.048	0.052	0.056	0.060	0.064	0.068	0.071	0.075	0.078	0.081	0.084

TABLE 5-2
Values of I_1 and I_2 to compute the Steinbrenner influence factor I_s for use in Eq. (5-16*a*) for several $N = H/B'$ and $M = L/B$ ratios

N	M = 1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.0
4.0	0.408	0.421	0.431	0.440	0.448	0.455	0.460	0.465	0.469	0.473	0.476
	0.037	0.041	0.044	0.048	0.051	0.054	0.057	0.060	0.063	0.066	0.069
5.0	0.437	0.452	0.465	0.477	0.487	0.496	0.503	0.510	0.516	0.522	0.526
	0.031	0.034	0.036	0.039	0.042	0.045	0.048	0.050	0.053	0.055	0.058
6.0	0.457	0.474	0.489	0.502	0.514	0.524	0.534	0.542	0.550	0.557	0.563
	0.026	0.028	0.031	0.033	0.036	0.038	0.040	0.043	0.045	0.047	0.050
7.0	0.471	0.490	0.506	0.520	0.533	0.545	0.556	0.566	0.575	0.583	0.590
	0.022	0.024	0.027	0.029	0.031	0.033	0.035	0.037	0.039	0.041	0.043
8.0	0.482	0.502	0.519	0.534	0.549	0.561	0.573	0.584	0.594	0.602	0.611
	0.020	0.022	0.023	0.025	0.027	0.029	0.031	0.033	0.035	0.036	0.038
9.0	0.491	0.511	0.529	0.545	0.560	0.574	0.587	0.598	0.609	0.618	0.627
	0.017	0.019	0.021	0.023	0.024	0.026	0.028	0.029	0.031	0.033	0.034
10.0	0.498	0.519	0.537	0.554	0.570	0.584	0.597	0.610	0.621	0.631	0.641
	0.016	0.017	0.019	0.020	0.022	0.023	0.025	0.027	0.028	0.030	0.031
20.0	0.529	0.553	0.575	0.595	0.614	0.631	0.647	0.662	0.677	0.690	0.702
	0.008	0.009	0.010	0.010	0.011	0.012	0.013	0.013	0.014	0.015	0.016
500.0	**0.560**	0.587	0.612	0.635	0.656	0.677	0.696	0.714	0.731	0.748	0.763
	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.001	0.001	0.001	0.001

Example: A raft 33.5x39.5 m in plan is founded at 3 m depth, the contact pressure on the mat and the soil profile is shown in the figure below. Estimate elastic settlement by Timoshinko and Goodier method.



Solution. For clay, estimate $\mu = 0.35$ (reference used 0.2). Compute

$$E_{s(\text{average})} = \frac{3 \times 42.5 + 8 \times 60}{11} = 55 \text{ MPa}$$

From base to sandstone $H = 14 - 3 = 11$ m.

$$B' = \frac{33.5}{2} = 16.75 \text{ m (for center of mat)} \rightarrow \frac{H}{B'} = \frac{11}{16.75} = 0.66 \text{ (use 0.7)}$$

Interpolating in Table 5-2, we obtain $I_1 = 0.0815$; $I_2 = 0.086$:

$$I_s = 0.0815 + \frac{1 - 2(0.35)}{1 - 0.35}(0.0865) = 0.121$$

$$\frac{D}{B} = \frac{3}{33.5} = 0.09; \text{ use } I_F = 0.95$$

With four contributing corners $m = 4$ and Eq. (5-16*a*) gives

$$\Delta H = q_o B' \frac{1 - \mu^2}{E_s} 4 I_s I_F$$

$$\Delta H = 134(16.75)\frac{1 - 0.35^2}{55 \times 1000}(4 \times 0.121)(0.95)(1000) = \mathbf{16.5} \text{ mm}$$

TABLE 5-6

Equations for stress-strain modulus E_s by several test methods

E_s in kPa for SPT and units of q_c for CPT; divide kPa by 50 to obtain ksf. The N values should be estimated as N_{55} and not N_{70}. Refer also to Tables 2-7 and 2-8.

Soil	SPT	CPT
Sand (normally consolidated)	$E_s = 500(N + 15)$ $= 7000\sqrt{N}$ $= 6000N$ — — — ‡$E_s = (15\,000 \text{ to } 22\,000) \cdot \ln N$	$E_s = (2 \text{ to } 4)q_u$ $= 8000\sqrt{q_c}$ — — — $E_s = 1.2(3D_r^2 + 2)q_c$ *$E_s = (1 + D_r^2)q_c$
Sand (saturated)	$E_s = 250(N + 15)$	$E_s = Fq_c$ $e = 1.0 \quad F = 3.5$ $e = 0.6 \quad F = 7.0$
Sands, all (norm. consol.)	¶$E_s = (2600 \text{ to } 2900)N$	
Sand (overconsolidated)	†$E_s = 40\,000 + 1050N$ $E_{s(\mathrm{OCR})} \approx E_{s,\mathrm{nc}}\sqrt{\mathrm{OCR}}$	$E_s = (6 \text{ to } 30)q_c$
Gravelly sand	$E_s = 1200(N + 6)$ $= 600(N + 6) \quad N \le 15$ $= 600(N + 6) + 2000 \quad N > 15$	
Clayey sand	$E_s = 320(N + 15)$	$E_s = (3 \text{ to } 6)q_c$
Silts, sandy silt, or clayey silt	$E_s = 300(N + 6)$ If $q_c < 2500$ kPa use $\quad$ §$E_s' = 2.5q_c$ $2500 < q_c < 5000$ use $\quad E_s' = 4q_c + 5000$ where $E_s' = \text{constrained modulus} = \dfrac{E_s(1-\mu)}{(1+\mu)(1-2\mu)} = \dfrac{1}{m_v}$	$E_s = (1 \text{ to } 2)q_c$
Soft clay or clayey silt		$E_s = (3 \text{ to } 8)q_c$

General Range of Es

Soil	E_s, MPa
Clay	
Very soft	2–15
Soft	5–25
Medium	15–50
Hard	50–100
Sandy	25–250
Glacial till	
Loose	10–150
Dense	150–720
Very dense	500–1440
Loess	15–60
Sand	
Silty	5–20
Loose	10–25
Dense	50–81
Sand and gravel	
Loose	50–150
Dense	100–200
Shale	150–5000
Silt	2–20

Poisson's Ratio

Values or value ranges for Poisson's ratio μ

Type of soil	μ
Clay, saturated	0.4–0.5
Clay, unsaturated	0.1–0.3
Sandy clay	0.2–0.3
Silt	0.3–0.35
Sand, gravelly sand	−0.1–1.00
commonly used	0.3–0.4
Rock	0.1–0.4 (depends somewhat on type of rock)
Loess	0.1–0.3
Ice	0.36
Concrete	0.15
Steel	0.33