Settlement of Shallow Foundations

CIVL 451 – Foundation Engineering – Classroom Notes

Allowable Bearing Pressure and Settlement

- It was previously discussed that the allowable bearing pressure is defined as a function of the; ultimate bearing capacity, allowable settlement and differential settlement between individual foundations.

- The allowable bearing pressure q_{all} will be the smaller bearing pressure obtained by considering the above, and it should be equal to or greater than the applied foundation pressure.

Foundation Settlement

- Settlement of foundations is assessed by considering the following;
  - **For cohesive soils;**

  Total settlement = undrained, elastic or immediate settlement +
  consolidation settlement +
  creep settlement

- Undrained, elastic or immediate settlement is considered to take place during construction or within a reasonably short time period after construction. It is considered to take place in undrained state and under constant volume due to distortional strains within the ground.

Foundation Settlement

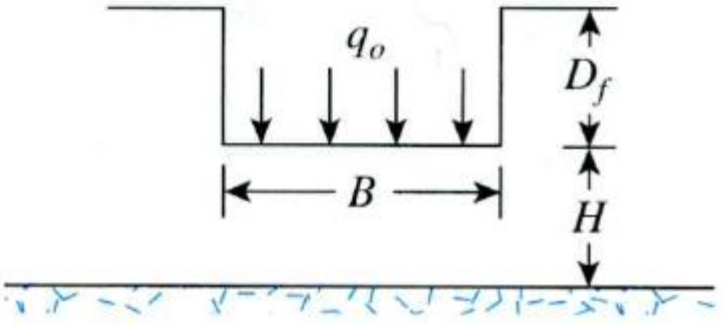
- Consolidation Settlement or Primary Consolidation is time dependent and occurs over a considerably long time period during the design life of the structure. The time rate of consolidation depends on the permeability of the ground and the drainage conditions.

- The Creep settlement is also time dependent and it is considered to commence after completion of the primary consolidation. Some references also define this component of the settlement as Secondary compression or Secondary consolidation.

Elastic Settlement

- Elastic settlement can be calculated using theory of elasticity as in the following equation, A1 and A2 coefficients of which are developed by Christian and Carrier (1978);

$$S_e = A_1 A_2 \frac{q_o B}{E_s}$$



where;

q_0: applied pressure at foundation base,

B: foundation width.

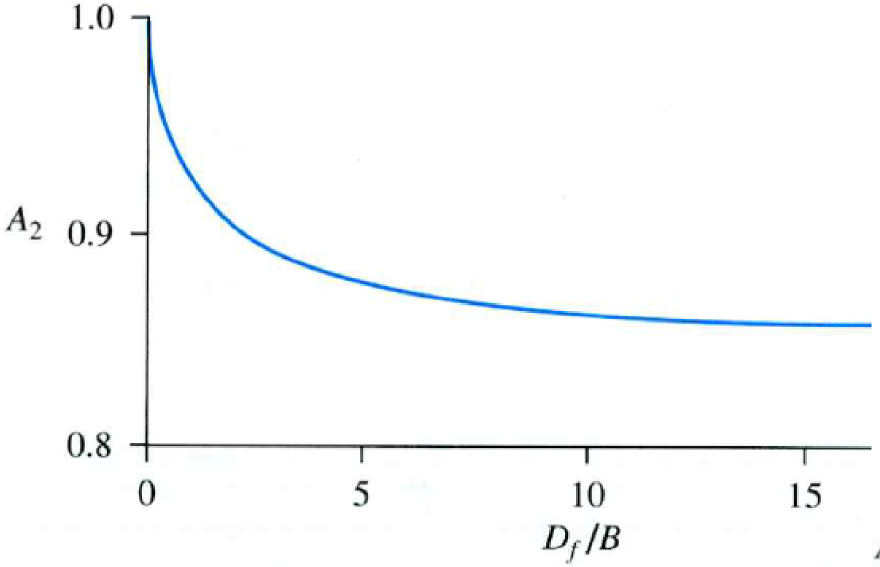
Df: foundation depth,

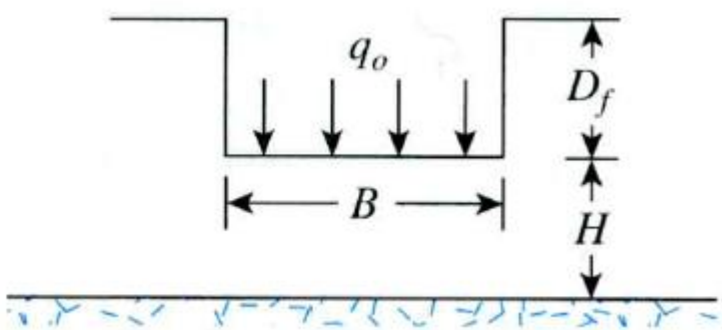
H: the vertical distance between hard stratum and the base of the foundation.

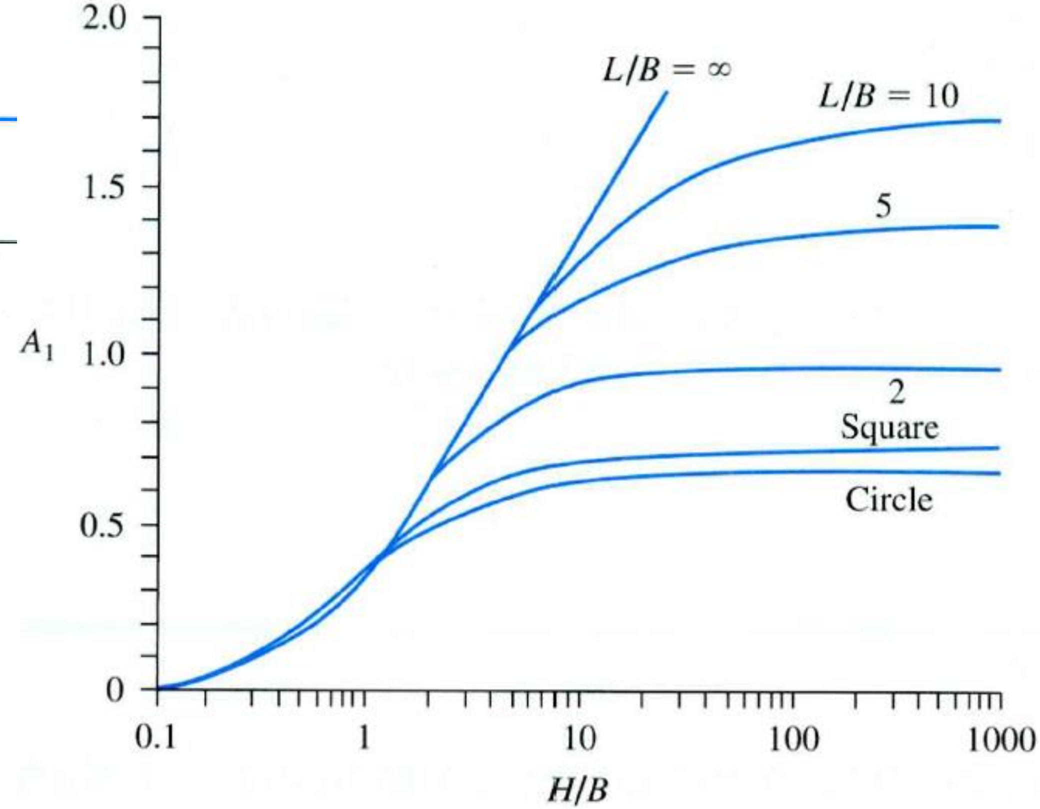
Es: Modulus of elasticity of the soil.

Elastic Settlement

- A1 and A2 can be determined from the following graphs;







Foundation Settlement

- The modulus of elasticity Es can be obtained using correlations;

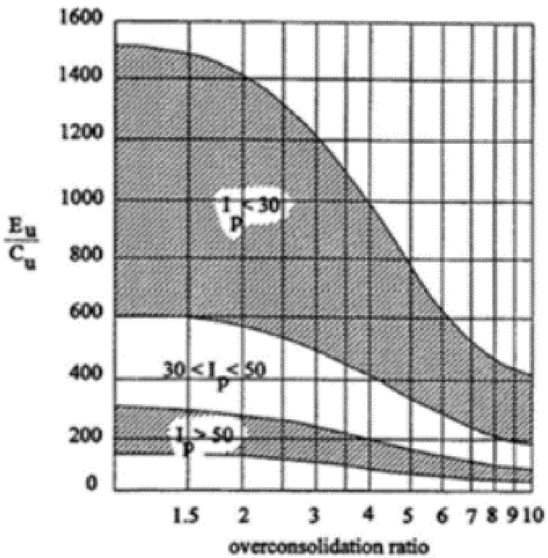


Table 5.7 Range of β for Clay [Eq. (5.31)][a]

Plasticity Index	β				
	OCR = 1	OCR = 2	OCR = 3	OCR = 4	OCR = 5
<30	1500–600	1380–500	1200–580	950–380	730–300
30 to 50	600–300	550–270	580–220	380–180	300–150
>50	300–150	270–120	220–100	180–90	150–75

[a]Interpolated from Duncan and Buchignani, (1976)

The modulus of elasticity (E_s) for clays can, in general, be given as

$$E_s = \beta c_u \tag{5.31}$$

where c_u = undrained shear strength.

- As the Es may vary with depth, Bowles (1987) recommends that a weighted average value can be used in the calculations such that;

$$E_s = \frac{\sum E_{s(i)} \Delta z}{\bar{z}}$$

where

$E_{s(i)}$ = soil modulus of elasticity within a depth Δz

$\bar{z}$ = H or $5B$, whichever is smaller

Consolidation Settlement

- The Primary Settlement can be determined considering one-dimensional consolidation theory;

$$S_{c(p)} = \frac{C_c H_c}{1+e_o} \log \frac{\sigma'_o + \Delta\sigma'_{av}}{\sigma'_o}$$ (for normally consolidated clays)

$$S_{c(p)} = \frac{C_s H_c}{1+e_o} \log \frac{\sigma'_o + \Delta\sigma'_{av}}{\sigma'_o}$$ (for overconsolidated clays with $\sigma'_o + \Delta\sigma'_{av} < \sigma'_c$)

$$S_{c(p)} = \frac{C_s H_c}{1+e_o} \log \frac{\sigma'_c}{\sigma'_o} + \frac{C_c H_c}{1+e_o} \log \frac{\sigma'_o + \Delta\sigma'_{av}}{\sigma'_c}$$ (for overconsolidated clays with $\sigma'_o < \sigma'_c < \sigma'_o + \Delta\sigma'_{av}$)

where

σ'_o = average effective pressure on the clay layer before the construction of the foundation

$\Delta\sigma'_{av}$ = average increase in effective pressure on the clay layer caused by the construction of the foundation

σ'_c = preconsolidation pressure

e_o = initial void ratio of the clay layer

C_c = compression index

C_s = swelling index

H_c = thickness of the clay layer

Consolidation Settlement

- The Primary Settlement can also be determined using coefficient of volume compressibility, Mv;

$$S_{c(p)-\mathrm{oed}} = \int \frac{\Delta e}{1+e_o} dz = \int m_v \Delta\sigma'_{(1)} dz$$

where

$S_{c(p)-\mathrm{oed}}$ = consolidation settlement calculated by using Eqs. (1.61), (1.63), and (1.65)
$\Delta\sigma'_{(1)}$ = effective vertical stress increase
m_v = volume coefficient of compressibility (see Chapter 1)

Creep Settlement

- Secondary compression or creep settlement can be calculated using the creep coefficient;

$$S_{c(s)} = C'_{\alpha} H_c \log(t_2/t_1)$$

where

$C'_{\alpha} = C_{\alpha}/(1 + e_p)$
e_p = void ratio at the end of primary consolidation
H_c = thickness of clay layer

Mesri (1973) correlated C'_{α} with the natural moisture content (w) of several soils, from which it appears that

$$C'_{\alpha} \approx 0.0001w \tag{5.94}$$

where w = natural moisture content, in percent. For most overconsolidated soils, C'_{α} varies between 0.0005 to 0.001.

Mesri and Godlewski (1977) compiled the magnitude of C_{α}/C_c (C_c = compression index) for a number of soils. Based on their compilation, it can be summarized that

- For inorganic clays and silts:

$$C_{\alpha}/C_c \approx 0.04 \pm 0.01$$

- For organic clays and silts:

$$C_{\alpha}/C_c \approx 0.05 \pm 0.01$$

- For peats:

$$C_{\alpha}/C_c \approx 0.075 \pm 0.01$$

Immediate Settlement

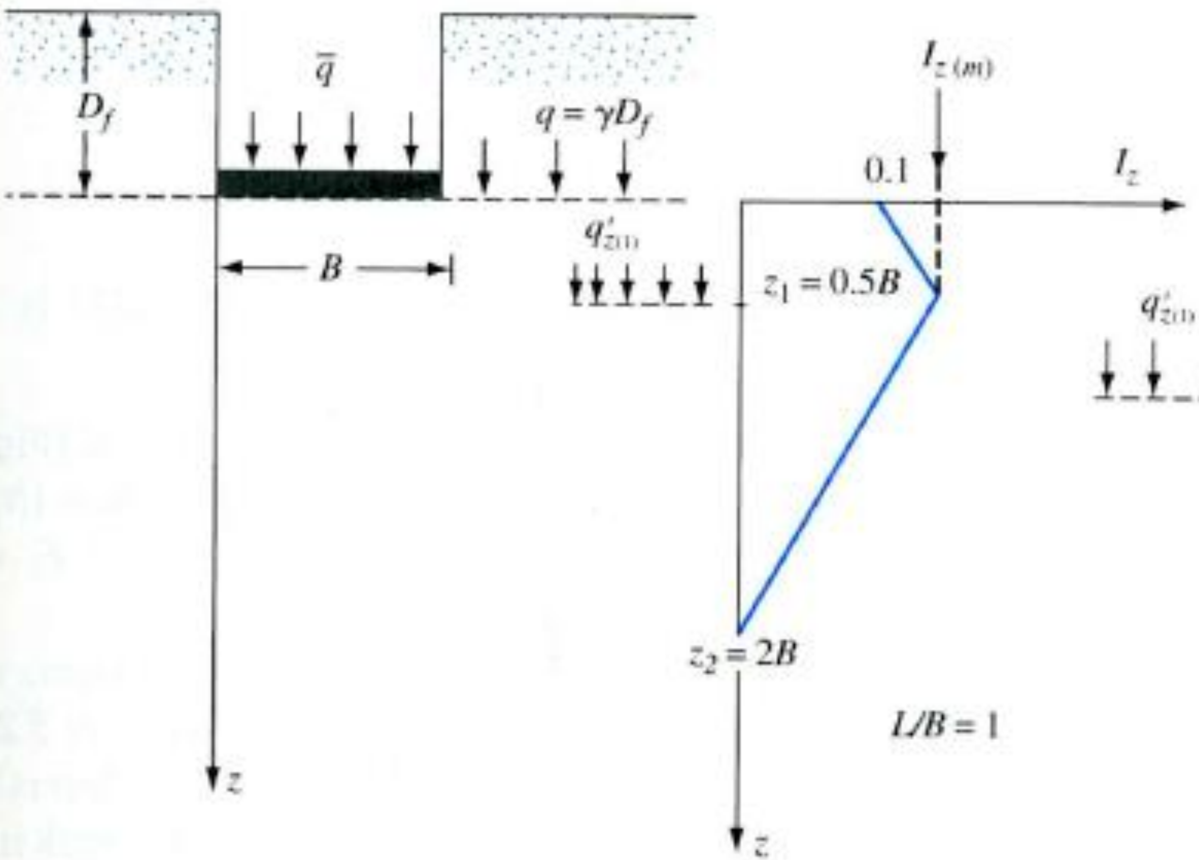
- For cohesionless soils;
Total settlement = immediate settlement + creep settlement

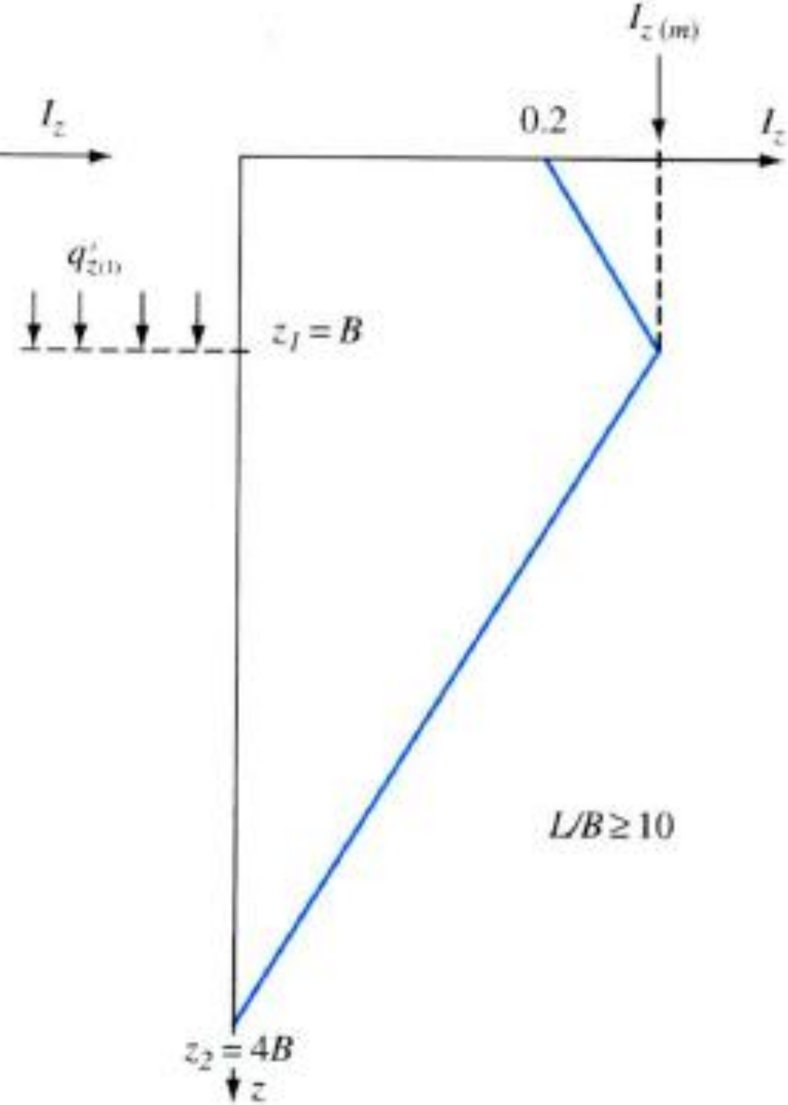
- There are several methods used for the calculation of settlement of shallow foundations on granular soil. Influence factor method by Schmertmann (1973) is used commonly;

$$S_e = C_1 C_2(\overline{q} - q)\sum_0^{z_2} \frac{I_z}{E_s}\Delta z$$

where

I_z = strain influence factor
C_1 = a correction factor for the depth of foundation embedment $= 1 - 0.5[q/(\overline{q} - q)]$
C_2 = a correction factor to account for creep in soil
$= 1 + 0.2 \log$ (time in years/0.1)
$\overline{q}$ = stress at the level of the foundation
$q = \gamma D_f$ = effective stress at the base of the foundation
E_s = modulus of elasticity of soil





The maximum value of I_z can be calculated as

$$I_{z(m)} = 0.5 + 0.1\sqrt{\frac{\bar{q} - q}{q'_{z(1)}}}$$

where

$q'_{z(1)}$ = effective stress at a depth of z_1 before construction of the foundation

The following relations are suggested by Salgado (2008) for interpolation of I_z at $z = 0$, z_1/B, and z_2/B for rectangular foundations.

- I_z at $z = 0$

$$I_z = 0.1 + 0.0111\left(\frac{L}{B} - 1\right) \leq 0.2 \tag{5.51}$$

- Variation of z_1/B for $I_{z(m)}$

$$\frac{z_1}{B} = 0.5 + 0.0555\left(\frac{L}{B} - 1\right) \leq 1 \tag{5.52}$$

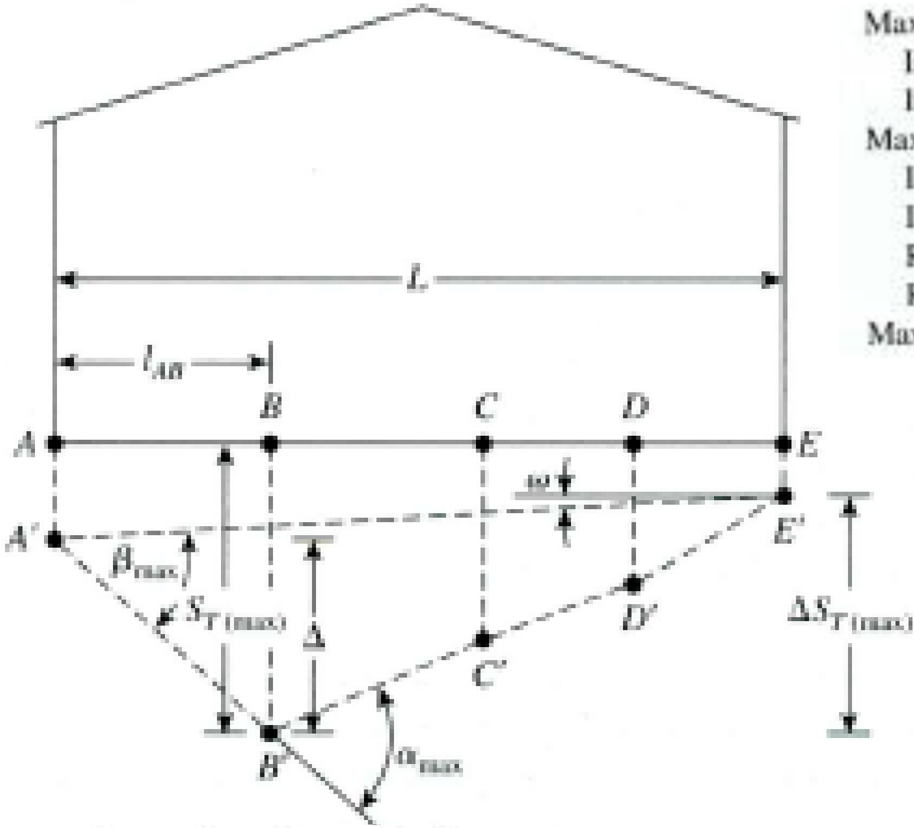
- Variation of z_2/B

$$\frac{z_2}{B} = 2 + 0.222\left(\frac{L}{B} - 1\right) \leq 4 \tag{5.53}$$

Exercises

- **Ex.** A foundation 4m x 2m carries a uniform pressure of 200kPa at a depth of 1m in a layer of saturated clay 11m deep and underlain by a hard stratum. If undrained elastic modulus, Es for the clay is 45MPa, determine the average value of immediate settlement under the foundation.
- **Ex.** A foundation 4m x 2m, carrying a uniform pressure of 150kPa, is located at a depth of 1m in a layer of clay 5m thick for which the value of Es is 40MPa. The layer is underlain by a second layer of clay 8m thick for which Es is 75MPa. A hard stratum lies below the second layer. Determine the average immediate settlement under the foundation.
- **Ex.** Consider a rectangular foundation 2 m × 4 m in plan at a depth of 1.2 m in a sand deposit, as shown in Figure 5.23a. Given: $\gamma = 17.5\ \text{kN/m}^3$; $\bar{q} = 145\ \text{kN/m}^2$, and the following approximated variation of q_c with z:

z (m)	q_c (kN/m^2)
0–0.5	2250
0.5–2.5	3430
2.5–5.0	2950



S_T = total settlement of a given point

ΔS_T = difference in total settlement between any two points

α = gradient between two successive points

β = angular distortion $= \dfrac{\Delta S_{T(ij)}}{l_{ij}}$

(*Note*: l_{ij} = distance between points i and j)

ω = tilt

Δ = relative deflection (i.e. movement from a straight line points)

$\dfrac{\Delta}{L}$ = deflection ratio

Maximum settlement, $S_{T(max)}$	
In sand	32 mm
In clay	45 mm
Maximum differential settlement, $\Delta S_{T(max)}$	
Isolated foundations in sand	51 mm
Isolated foundations in clay	76 mm
Raft in sand	51–76 mm
Raft in clay	76–127 mm
Maximum angular distortion, β_{max}	1/300

$$\Delta/L = 0.0003 \text{ for } L/H \le 2$$
$$\Delta/L = 0.001 \text{ for } L/H = 8$$

Category of potential damage	β_{max}
Safe limit for flexible brick wall ($L/H > 4$)	1/150
Danger of structural damage to most buildings	1/150
Cracking of panel and brick walls	1/150
Visible tilting of high rigid buildings	1/250
First cracking of panel walls	1/300
Safe limit for no cracking of building	1/500
Danger to frames with diagonals	1/600

Table 5.15 Recommendations of European Committee for Standardization on Differential Settlement Parameters

Item	Parameter	Magnitude	Comments
Limiting values for serviceability	S_T	25 mm	Isolated shallow foundation
		50 mm	Raft foundation
(European Committee for Standardization, 1994a)	ΔS_T	5 mm	Frames with rigid cladding
		10 mm	Frames with flexible cladding
		20 mm	Open frames
	β	1/500	—
Maximum acceptable foundation movement	S_T	50	Isolated shallow foundation
	ΔS_T	20	Isolated shallow foundation
(European Committee for Standardization, 1994b)	β	≈1/500	—

References

- B. M. Das, Principles of foundation engineering.
- R. F. Craig, Soil Mechanics.