Chapter 9

Settlement of Shallow Foundations

Omitted parts:

Section 9.7 & 9.8 & 9.9

CAUSES OF SETTLEMENT

Settlement of a structure resting on soil may be caused by two distinct kinds of action within the foundation soils:-

I. Settlement Due to Shear Stress (Distortion Settlement)

In the case the applied load caused shearing stresses to develop within the soil mass which are greater than the shear strength of the material, then the soil fails by sliding downward and laterally, and the structure settle and may tip of vertical alignment. This is what we referred to as BEARING CAPACITY.

II. Settlement Due to Compressive Stress (Volumetric Settlement)

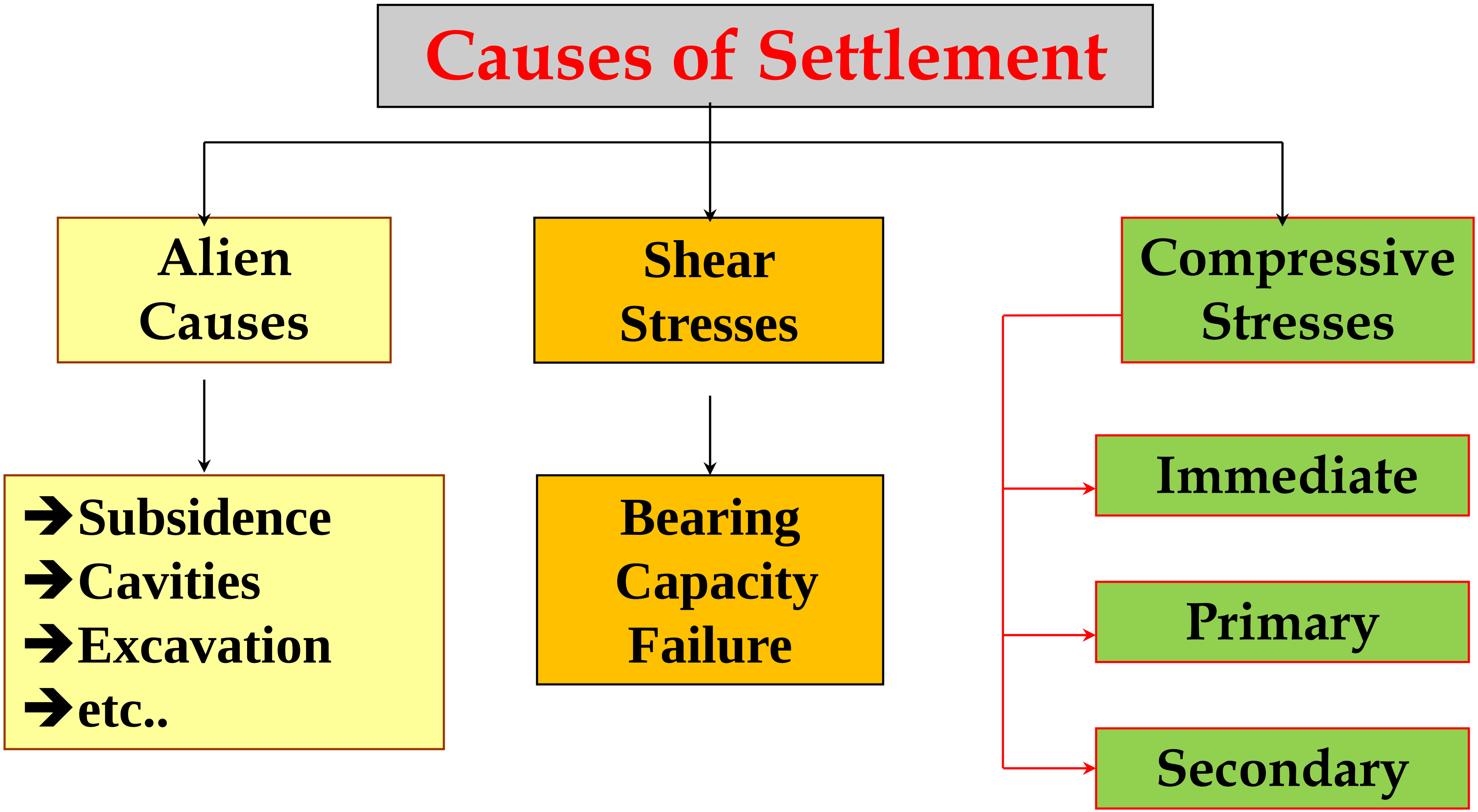
As a result of the applied load a compressive stress is transmitted to the soil leading to compressive strain. Due to the compressive strain the structure settles. This is important only if the settlement is excessive otherwise it is not dangerous.

ALLOWABLE BEARING CAPACITY

The allowable bearing capacity is the smaller of the following two conditions:

$$q_{all} = \text{smallest of} \begin{cases} \dfrac{q_u}{FS} \text{(to control shear failure)} \\ q_{all,settlement} \text{(to control settlement)} \end{cases}$$

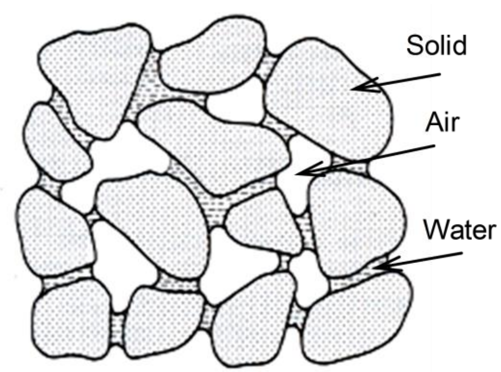
CAUSES OF SETTLEMENT



Mechanisms of Compression

Compression of soil is due to a number of mechanisms:

- **Deformation of soil particles or grains**
- **Relocations of soil particles**
- **Expulsion of water or air from the void spaces**



Components of Settlement

Settlement of a soil layer under applied load is the sum of two broad components or categories:

1. **Elastic settlement (or immediate) settlements**

2. **Consolidation settlement**

1. Elastic settlement (or immediate) settlements

Elastic or immediate settlement takes place instantly at the moment of the application of load due to the distortion (but no bearing failure) and bending of soil particles (mainly clay). It is not generally elastic although theory of elasticity is applied for its evaluation. It is predominant in coarse-grained soils.

Consolidation settlement

Consolidation settlement is the sum of two parts or types:

A. Primary consolidation settlement

In this the compression of clay is due to expulsion of water from pores. The process is referred to as primary consolidation and the associated settlement is termed primary consolidation settlement. Commonly they are referred to simply as consolidation and consolidation settlement (CE 481)

B. Secondary consolidation settlement

The compression of clay soil due to plastic readjustment of soil grains and progressive breaking of clayey particles and their inter-particles bonds is known as secondary consolidation or secondary compression, and the associated settlement is called secondary consolidation settlement or secondary compression.

Components of Settlement

The total settlement of a foundation can be expressed as:

$$S_T = S_e + S_c + S_s$$

S_T = Total settlement
S_e = Elastic or immediate settlement
S_c = Primary consolidation settlement
S_s = Secondary consolidation settlement

Total settlement S_T

- **Immediate settlement** S_e
- **Primary consolidation settlement** S_c
- **Secondary consolidation or creep** S_s

- **It should be mentioned that S_c and S_s overlap each other and impossible to detect which certainly when one type ends and the other begins. However, for simplicity they are treated separately and secondary consolidation is usually assumed to begin at the end of primary consolidation.**

Components of settlement

The total soil settlement S_T may contain one or more of these types:

Immediate settlement S_e

- Due to distortion or elastic deformation with no change in water content
- Occurs rapidly during the application of load
- Quite small quantity in dense sands, gravels and stiff clays

Primary consolidation settlement S_c

- Decrease in voids volume due to squeeze of pore-water out of the soil
- Occurs in saturated fine grained soils (low coefficient of permeability)
  Time dependent
- Only significant in clays and silts

Secondary consolidation or creep S_s

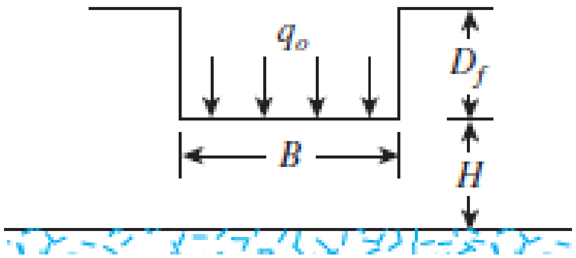
- Due to gradual changes in the particulate structure of the soil
- Occurs very slowly, long after the primary consolidation is completed
  Time dependent
- Most significant in saturated soft clayey and organic soils and peats

In granular soils, settlement occurs almost immediately upon applying the load.

In clay, most of the settlement occurs during the consolidation process.

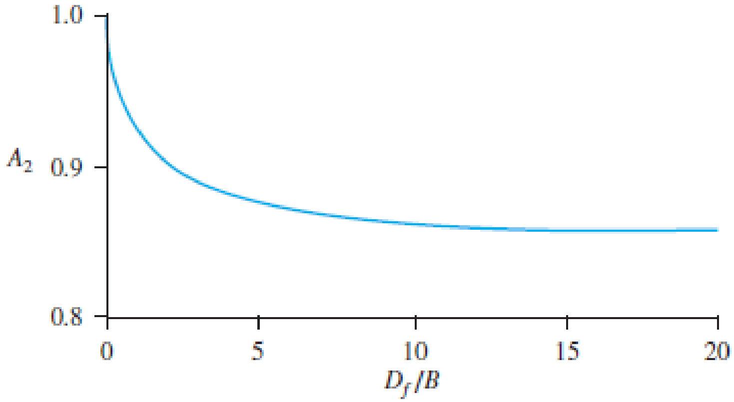
Secondary consolidation is assumed to occur on completion of primary consolidation. It is more significant than primary consolidation in organic soils.

Elastic Settlement of Shallow Foundation on Saturated Clay (μ_s = 0.5)



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

$A_1 = f(H/B, L/B)$
$A_2 = f(D_f/B)$
L = length of the foundation
B = width of the foundation
D_f = depth of the foundation
H = depth of the bottom of the foundation to a rigid layer
q_o = net load per unit area of the foundation



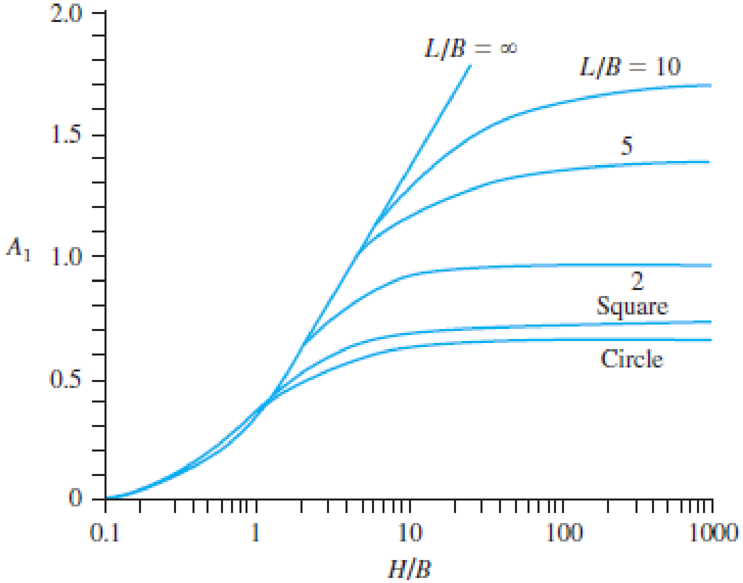


FIGURE 9.1

Elastic Settlement of Shallow Foundation on Saturated Clay (μ_s = 0.5)

$$E_s = \beta c_u$$

where c_u = undrained shear strength.

TABLE 9.1 Range of β for Saturated Clay [Eq. (9.2)][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]Based on Duncan and Buchignani (1976)

Elastic Settlement of Shallow Foundation

TABLE 9.2 Influence Factors to Compute *Average* Settlement of Flexible and Rigid Foundation

$m' = L/B$	Flexible	Rigid
Circle	0.85	0.79
1	0.95	0.82
1.5	1.20	1.07
2	1.30	1.21
3	1.52	1.42
5	1.82	1.60
10	2.24	2.00
100	2.96	3.40

Example 9.1

EXAMPLE 9.1

Consider a shallow foundation 2 m × 1 m in plan in a saturated clay layer. A rigid rock layer is located 8 m below the bottom of the foundation. Given:

Foundation: $D_f = 1$ m, $q_o = 120$ kN/m^2

Clay: $c_u = 150$ kN/m^2, OCR = 2, and plasticity index, PI = 35

Estimate the elastic settlement of the foundation.

SOLUTION

From Eq. (9.1),

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

Given:

$$\frac{L}{B} = \frac{2}{1} = 2$$

$$\frac{D_f}{B} = \frac{1}{1} = 1$$

$$\frac{H}{B} = \frac{8}{1} = 8$$

$$E_s = \beta c_u$$

For OCR = 2 and PI = 35, the value of $\beta \approx 480$ (Table 9.1). Hence,

$$E_s = (480)(150) = 72{,}000 \text{ kN/m}^2$$

Also, from Figure 9.1, $A_1 = 0.9$ and $A_2 = 0.92$. Hence,

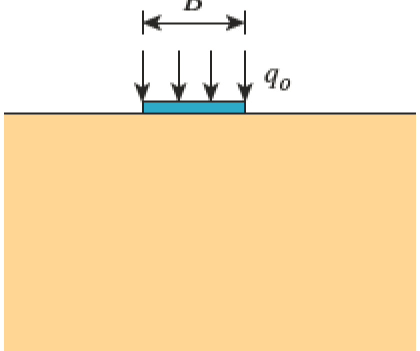
$$S_e = A_1 A_2 \frac{q_o B}{E_s} = (0.9)(0.92)\frac{(120)(1)}{72{,}000} = 0.00138 \text{ m} = \mathbf{1.38 \text{ mm}}$$

Settlement Based on the Theory of Elasticity

For a flexible rectangular foundation of dimensions B X L lying on an elastic half-space, the elastic settlement under a point on the foundation is

$$S_e = \frac{q_o B}{E_s}(1-\mu_s^2)I$$

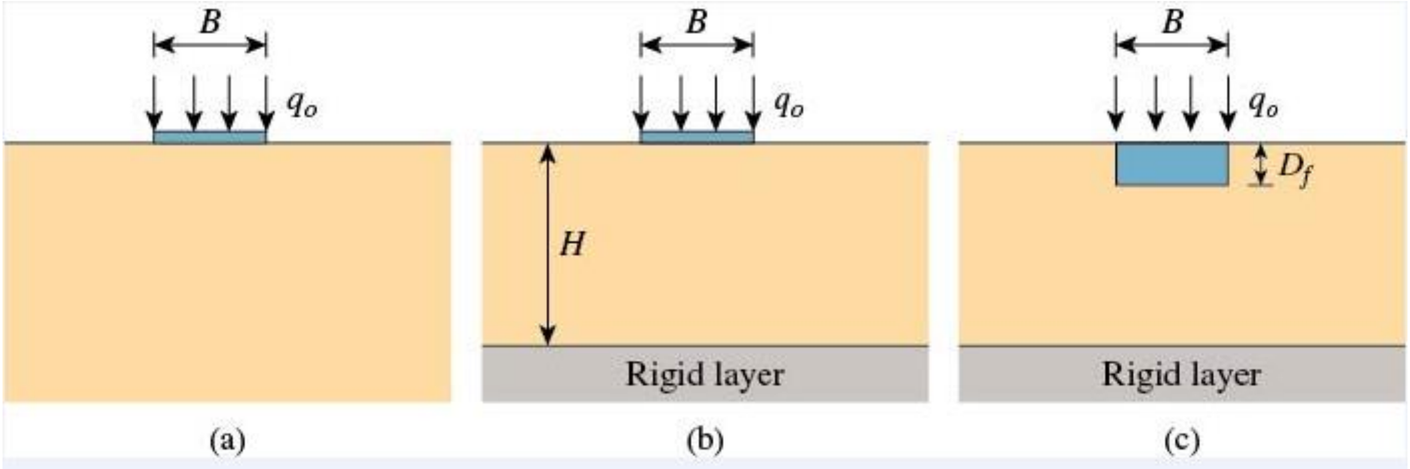
Where *I* is the influence factor that depends on the location of the point of interest on the foundation.



(a)

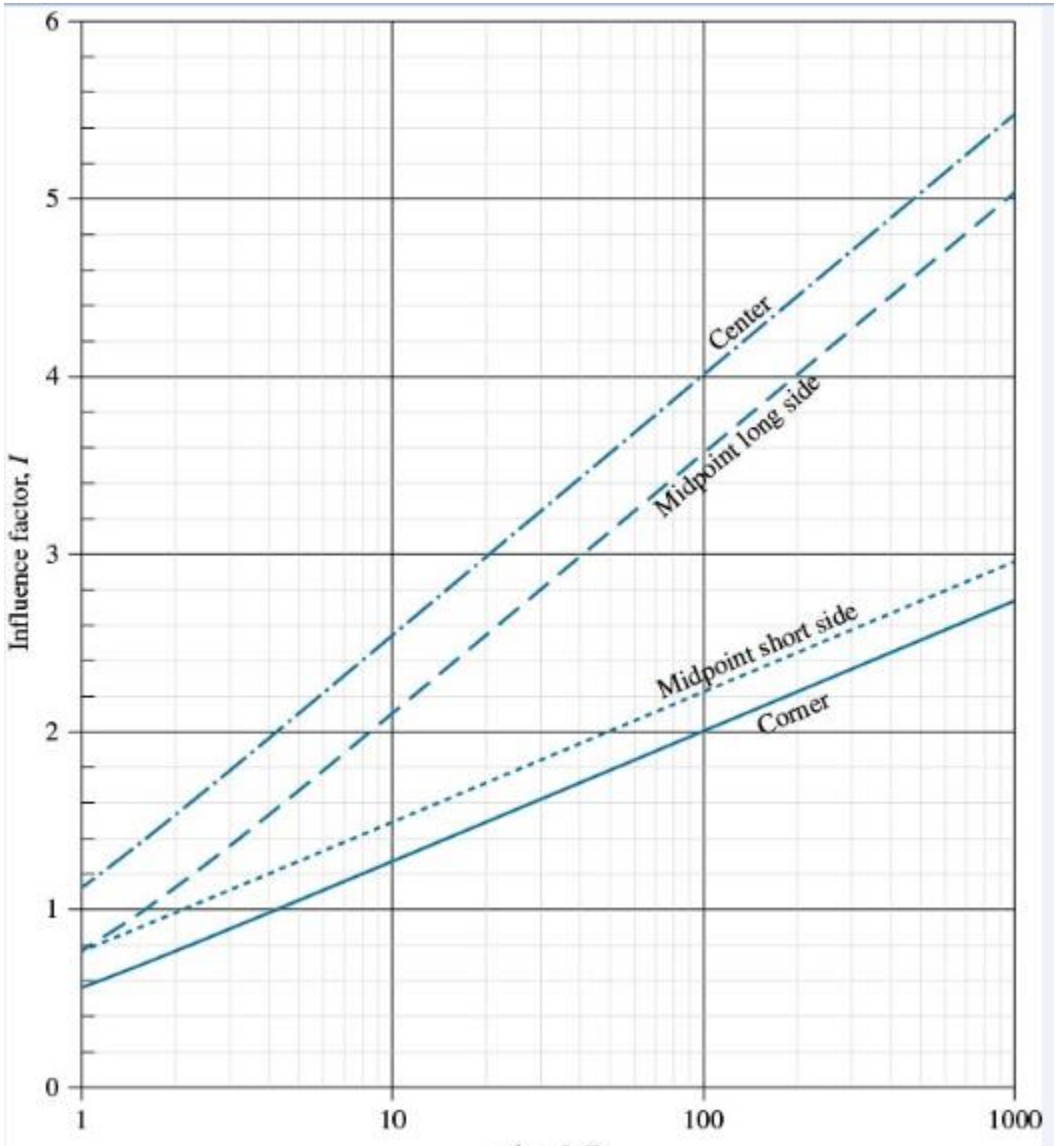
Settlement Based on the Theory of Elasticity

$$S_e = \frac{q_o B}{E_s}(1 - \mu_s^2) I$$



Settlement Based on the Theory of Elasticity

$$S_e = \frac{q_o B}{E_s}(1 - \mu_s^2) I$$



Elastic Settlement in Granular Soil

$$S_e = \frac{q_o B}{E_s}(1 - \mu_s^2) I_s I_f$$

Settlement Based on the Theory of Elasticity

$$I_s = \text{shape factor} = F_1 + \frac{1 - 2m_s}{1 - m_s} F_2$$

$$F_1 = \frac{1}{p}(A_0 + A_1)$$

$$F_2 = \frac{n'}{2p}\tan^{-1} A_2$$

$$A_o = m' \ln \frac{\left(1 + \sqrt{m'^2 + 1}\right)\sqrt{m'^2 + n'^2}}{m'\left(1 + \sqrt{m'^2 + n'^2 + 1}\right)}$$

$$A_1 = \ln \frac{\left(m' + \sqrt{m'^2 + 1}\right)\sqrt{1 + n'^2}}{m' + \sqrt{m'^2 + n'^2 + 1}}$$

$$A_2 = \frac{m'}{\left(n'\sqrt{m'^2 + n'^2 + 1}\right)}$$

Settlement Based on the Theory of Elasticity

TABLE 9.3 Variation of F_1 with m' and n'

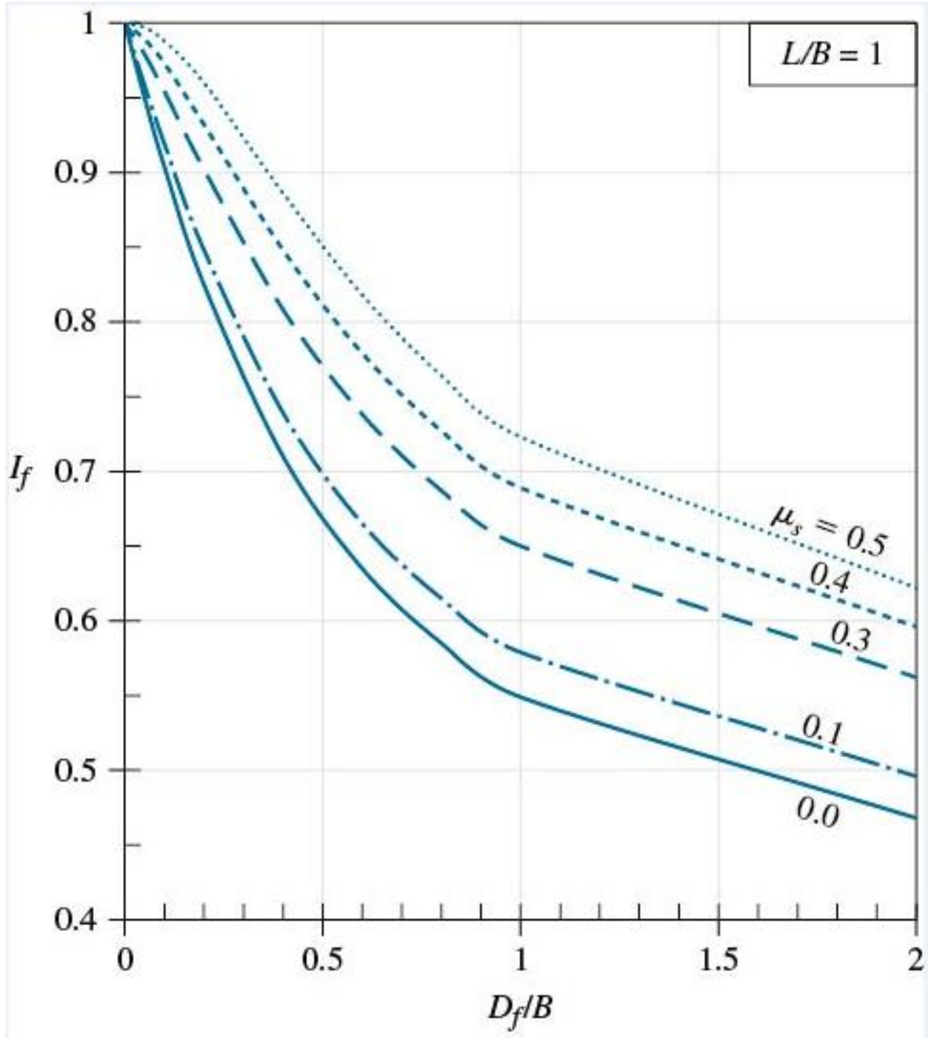
n'	m' = 1.0	1.2	1.4	1.6	1.8	2.0	2.5	3.0	3.5	4.0
0.25	0.014	0.013	0.012	0.011	0.011	0.011	0.010	0.010	0.010	0.010
0.50	0.049	0.046	0.044	0.042	0.041	0.040	0.038	0.038	0.037	0.037
0.75	0.095	0.090	0.087	0.084	0.082	0.080	0.077	0.076	0.074	0.074
1.00	0.142	0.138	0.134	0.130	0.127	0.125	0.121	0.118	0.116	0.115
1.25	0.186	0.183	0.179	0.176	0.173	0.170	0.165	0.161	0.158	0.157
1.50	0.224	0.224	0.222	0.219	0.216	0.213	0.207	0.203	0.199	0.197
1.75	0.257	0.259	0.259	0.258	0.255	0.253	0.247	0.242	0.238	0.235
2.00	0.285	0.290	0.292	0.292	0.291	0.289	0.284	0.279	0.275	0.271
2.25	0.309	0.317	0.321	0.323	0.323	0.322	0.317	0.313	0.308	0.305
2.50	0.330	0.341	0.347	0.350	0.351	0.351	0.348	0.344	0.340	0.336
2.75	0.348	0.361	0.369	0.374	0.377	0.378	0.377	0.373	0.369	0.365
3.00	0.363	0.379	0.389	0.396	0.400	0.402	0.402	0.400	0.396	0.392
3.25	0.376	0.394	0.406	0.415	0.420	0.423	0.426	0.424	0.421	0.418
3.50	0.388	0.408	0.422	0.431	0.438	0.442	0.447	0.447	0.444	0.441
3.75	0.399	0.420	0.436	0.447	0.454	0.460	0.467	0.458	0.466	0.464
4.00	0.408	0.431	0.448	0.460	0.469	0.476	0.484	0.487	0.486	0.484
4.25	0.417	0.440	0.458	0.472	0.481	0.484	0.495	0.514	0.515	0.515
4.50	0.424	0.450	0.469	0.484	0.495	0.503	0.516	0.521	0.522	0.522
4.75	0.431	0.458	0.478	0.494	0.506	0.515	0.530	0.536	0.539	0.539
5.00	0.437	0.465	0.487	0.503	0.516	0.526	0.543	0.551	0.554	0.554
5.25	0.443	0.472	0.494	0.512	0.526	0.537	0.555	0.564	0.568	0.569
5.50	0.448	0.478	0.501	0.520	0.534	0.546	0.566	0.576	0.581	0.584
5.75	0.453	0.483	0.508	0.527	0.542	0.555	0.576	0.588	0.594	0.597
6.00	0.457	0.489	0.514	0.534	0.550	0.563	0.585	0.598	0.606	0.609
6.25	0.461	0.493	0.519	0.540	0.557	0.570	0.594	0.609	0.617	0.621
6.50	0.465	0.498	0.524	0.546	0.563	0.577	0.603	0.618	0.627	0.632
6.75	0.468	0.502	0.529	0.551	0.569	0.584	0.610	0.627	0.637	0.643
7.00	0.471	0.506	0.533	0.556	0.575	0.590	0.618	0.635	0.646	0.653
7.25	0.474	0.509	0.538	0.561	0.580	0.596	0.625	0.643	0.655	0.662
7.50	0.477	0.513	0.541	0.565	0.585	0.601	0.631	0.650	0.663	0.671
7.75	0.480	0.516	0.545	0.569	0.589	0.606	0.637	0.658	0.671	0.680
8.00	0.482	0.519	0.549	0.573	0.594	0.611	0.643	0.664	0.678	0.688
8.25	0.485	0.522	0.552	0.577	0.598	0.615	0.648	0.670	0.685	0.695
8.50	0.487	0.524	0.555	0.580	0.601	0.619	0.653	0.676	0.692	0.703
8.75	0.489	0.527	0.558	0.583	0.605	0.623	0.658	0.682	0.698	0.710
9.00	0.491	0.529	0.560	0.587	0.609	0.627	0.663	0.687	0.705	0.716
9.25	0.493	0.531	0.563	0.589	0.612	0.631	0.667	0.693	0.710	0.723
9.50	0.495	0.533	0.565	0.592	0.615	0.634	0.671	0.697	0.716	0.719
9.75	0.496	0.536	0.568	0.595	0.618	0.638	0.675	0.702	0.721	0.735
10.00	0.498	0.537	0.570	0.597	0.621	0.641	0.679	0.707	0.726	0.740
20.00	0.529	0.575	0.614	0.647	0.677	0.702	0.756	0.797	0.830	0.858
50.00	0.548	0.598	0.640	0.678	0.711	0.740	0.803	0.853	0.895	0.931
100.00	0.555	0.605	0.649	0.688	0.722	0.753	0.819	0.872	0.918	0.956

Settlement Based on the Theory of Elasticity

TABLE 9.4 Variation of F_2 with m' and n'

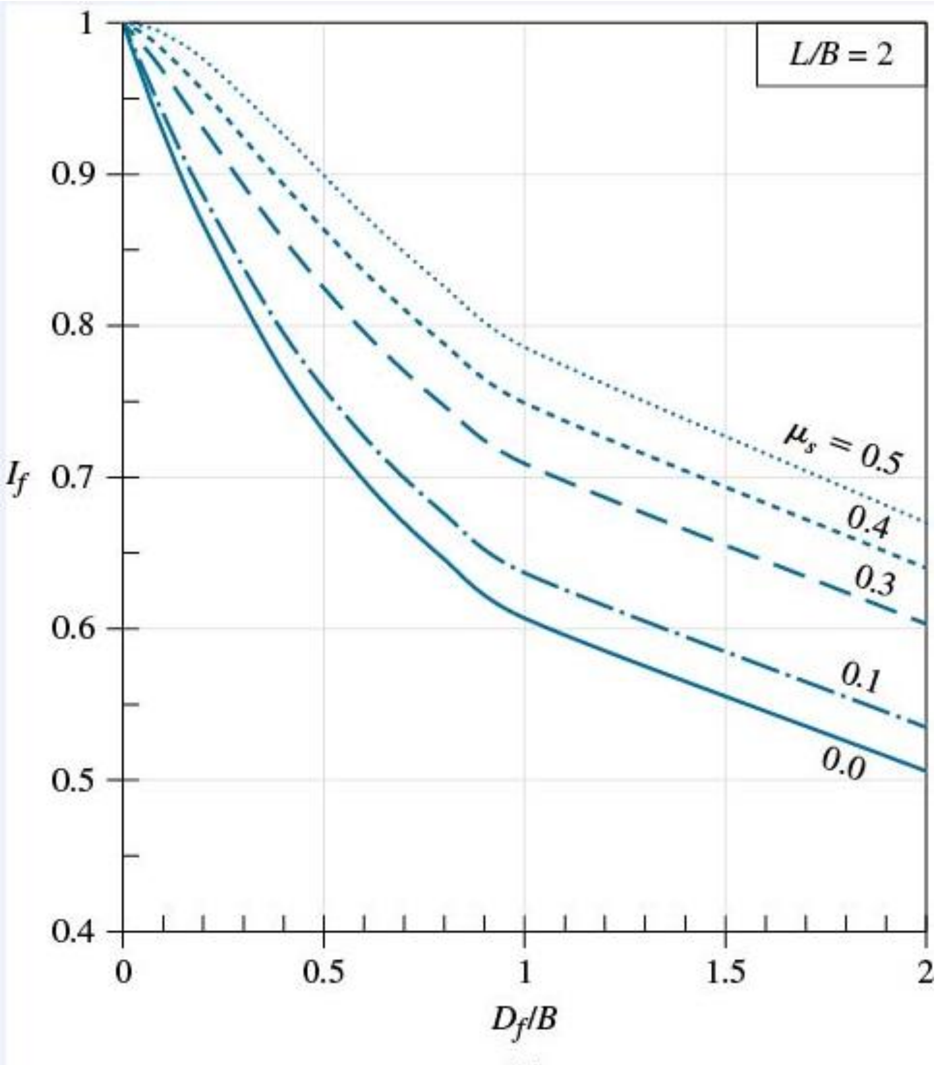
n'	m' = 1.0	1.2	1.4	1.6	1.8	2.0	2.5	3.0	3.5	4.0
0.25	0.049	0.050	0.051	0.051	0.051	0.052	0.052	0.052	0.052	0.052
0.50	0.074	0.077	0.080	0.081	0.083	0.084	0.086	0.086	0.0878	0.087
0.75	0.083	0.089	0.093	0.097	0.099	0.101	0.104	0.106	0.107	0.108
1.00	0.083	0.091	0.098	0.102	0.106	0.109	0.114	0.117	0.119	0.120
1.25	0.080	0.089	0.096	0.102	0.107	0.111	0.118	0.122	0.125	0.127
1.50	0.075	0.084	0.093	0.099	0.105	0.110	0.118	0.124	0.128	0.130
1.75	0.069	0.079	0.088	0.095	0.101	0.107	0.117	0.123	0.128	0.131
2.00	0.064	0.074	0.083	0.090	0.097	0.102	0.114	0.121	0.127	0.131
2.25	0.059	0.069	0.077	0.085	0.092	0.098	0.110	0.119	0.125	0.130
2.50	0.055	0.064	0.073	0.080	0.087	0.093	0.106	0.115	0.122	0.127
2.75	0.051	0.060	0.068	0.076	0.082	0.089	0.102	0.111	0.119	0.125
3.00	0.048	0.056	0.064	0.071	0.078	0.084	0.097	0.108	0.116	0.122
3.25	0.045	0.053	0.060	0.067	0.074	0.080	0.093	0.104	0.112	0.119
3.50	0.042	0.050	0.057	0.064	0.070	0.076	0.089	0.100	0.109	0.116
3.75	0.040	0.047	0.054	0.060	0.067	0.073	0.086	0.096	0.105	0.113
4.00	0.037	0.044	0.051	0.057	0.063	0.069	0.082	0.093	0.102	0.110
4.25	0.036	0.042	0.049	0.055	0.061	0.066	0.079	0.090	0.099	0.107
4.50	0.034	0.040	0.046	0.052	0.058	0.063	0.076	0.086	0.096	0.104
4.75	0.032	0.038	0.044	0.050	0.055	0.061	0.073	0.083	0.093	0.101
5.00	0.031	0.036	0.042	0.048	0.053	0.058	0.070	0.080	0.090	0.098
5.25	0.029	0.035	0.040	0.046	0.051	0.056	0.067	0.078	0.087	0.095
5.50	0.028	0.033	0.039	0.044	0.049	0.054	0.065	0.075	0.084	0.092
5.75	0.027	0.032	0.037	0.042	0.047	0.052	0.063	0.073	0.082	0.090
6.00	0.026	0.031	0.036	0.040	0.045	0.050	0.060	0.070	0.079	0.087
6.25	0.025	0.030	0.034	0.039	0.044	0.048	0.058	0.068	0.077	0.085
6.50	0.024	0.029	0.033	0.038	0.042	0.046	0.056	0.066	0.075	0.083
6.75	0.023	0.028	0.032	0.036	0.041	0.045	0.055	0.064	0.073	0.080
7.00	0.022	0.027	0.031	0.035	0.039	0.043	0.053	0.062	0.071	0.078
7.25	0.022	0.026	0.030	0.034	0.038	0.042	0.051	0.060	0.069	0.076
7.50	0.021	0.025	0.029	0.033	0.037	0.041	0.050	0.059	0.067	0.074
7.75	0.020	0.024	0.028	0.032	0.036	0.039	0.048	0.057	0.065	0.072
8.00	0.020	0.023	0.027	0.031	0.035	0.038	0.047	0.055	0.063	0.071
8.25	0.019	0.023	0.026	0.030	0.034	0.037	0.046	0.054	0.062	0.069
8.50	0.018	0.022	0.026	0.029	0.033	0.036	0.045	0.053	0.060	0.067
8.75	0.018	0.021	0.025	0.028	0.032	0.035	0.043	0.051	0.059	0.066
9.00	0.017	0.021	0.024	0.028	0.031	0.034	0.042	0.050	0.057	0.064
9.25	0.017	0.020	0.024	0.027	0.030	0.033	0.041	0.049	0.056	0.063
9.50	0.017	0.020	0.023	0.026	0.029	0.033	0.040	0.048	0.055	0.061
9.75	0.016	0.019	0.023	0.026	0.029	0.032	0.039	0.047	0.054	0.060
10.00	0.016	0.019	0.022	0.025	0.028	0.031	0.038	0.046	0.052	0.059
20.00	0.008	0.010	0.011	0.013	0.014	0.016	0.020	0.024	0.027	0.031
50.00	0.003	0.004	0.004	0.005	0.006	0.006	0.008	0.010	0.011	0.013
100.00	0.002	0.002	0.002	0.003	0.003	0.003	0.004	0.005	0.006	0.006

Settlement Based on the Theory of Elasticity



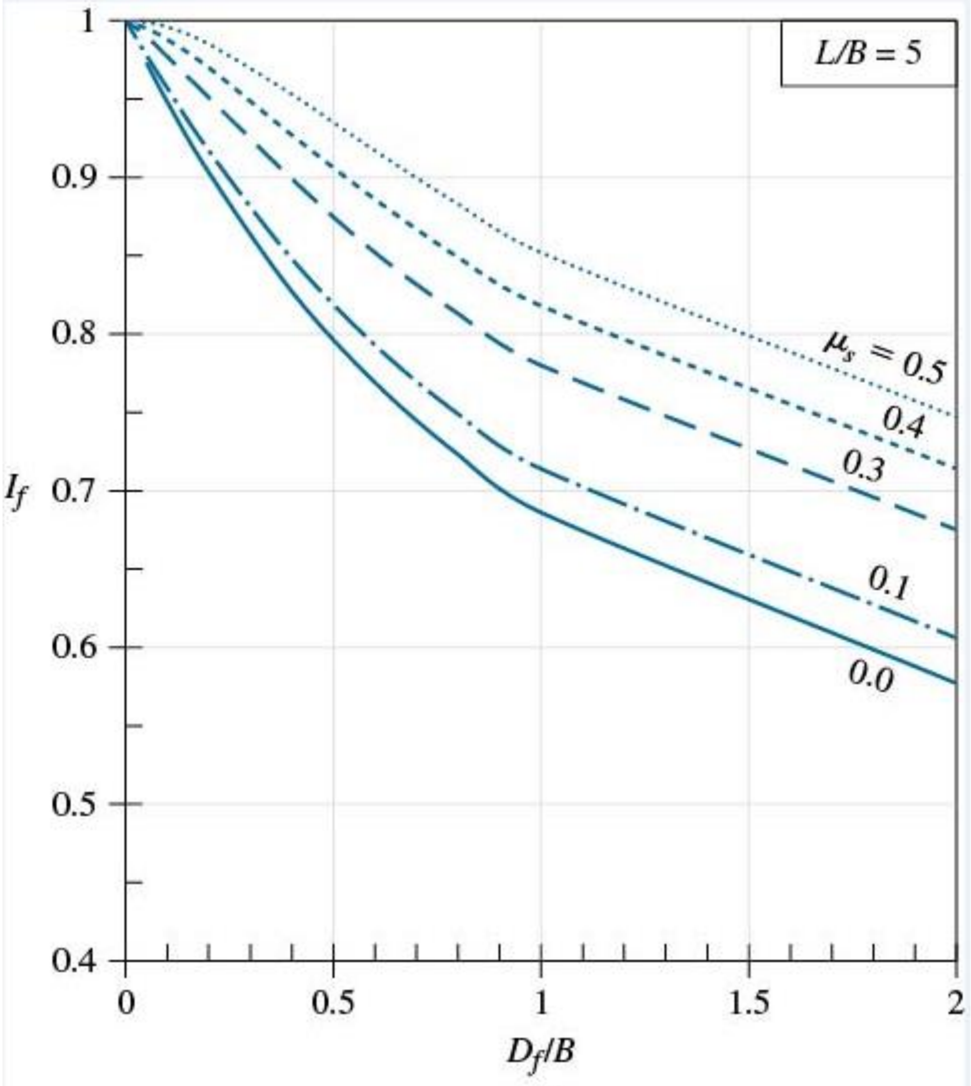
(a)

Settlement Based on the Theory of Elasticity



(b)

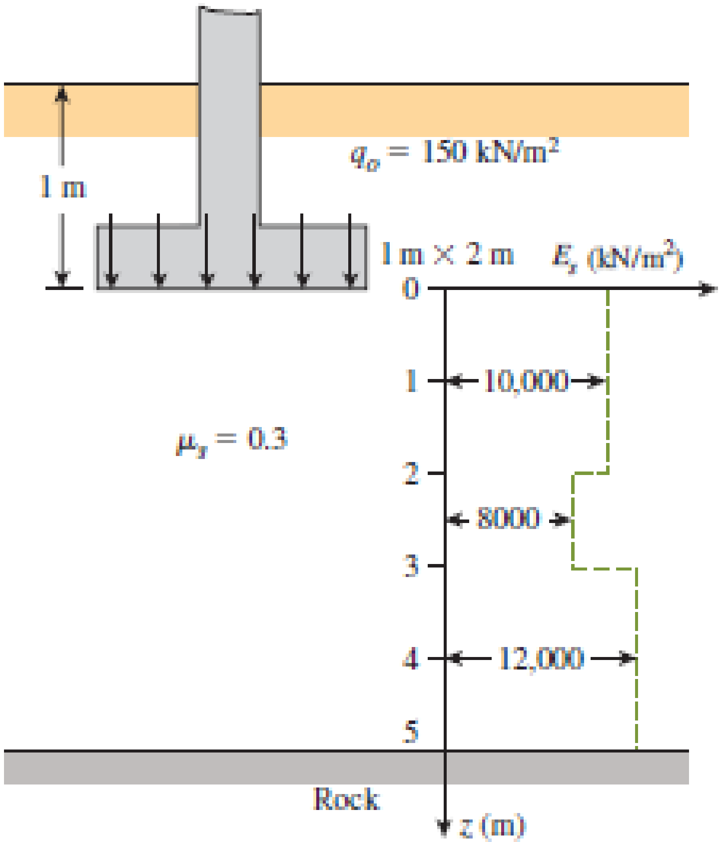
Settlement Based on the Theory of Elasticity



(c)

Example 9.2

A flexible shallow foundation 1 m × 2 m is shown in Figure 9.6. Calculate the elastic settlement at the center of the foundation.



Example 9.2

SOLUTION

We are given that $B = 1$ m and $L = 2$ m. Note that $\bar{z} = 5$ m $= 5B$. From Eq. (9.23),

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

$$= \frac{(10{,}000)(2) + (8000)(1) + (12{,}000)(2)}{5} = 10{,}400 \text{ kN/m}^2$$

For one of the four quarters of the foundation, $B = 0.5$ m and $L = 1.0$ m. Also, $H =$ 6.0 m (*Note:* The Steinbrenner factors in Tables 9.3 and 9.4 are for surface foundations with $D_f = 0$.)

$$m' = L/B = 2.0 \text{ and } n' = H/B = 12.0$$

From Table 9.3, $F_1 = 0.653$, and from Table 9.4, $F_2 = 0.028$.

From Eq. (9.11), with $\mu_s = 0.3$,

$$I_s = F_1 + \left(\frac{1 - 2\mu_s}{1 - \mu_s}\right) F_2 = 0.653 + \left(\frac{1 - 2 \times 0.3}{1 - 0.3}\right)(0.028) = 0.669$$

For $\mu_s = 0.3$, $L/B = 2$ and $D_f/B = 1$ (using $B = 1$ m for the entire foundation); from Figure 9.5b, $I_f = 0.71$.

From Eq. (9.22) and considering the four quarters,

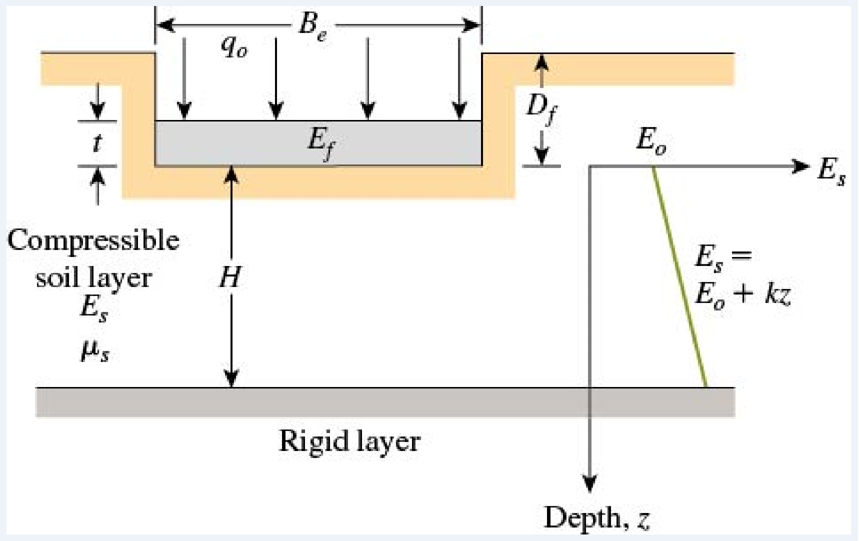
$$S_e = \frac{q_0 B}{E_s}(1 - \mu_s^2) I_s I_f$$

$$= \frac{(150)(0.5)}{(10{,}400)}(1 - 0.3^2)(0.669 \times 4)(0.71) = 0.0124 \text{ m} = \mathbf{12.4 \text{ mm}}$$

Improved Equation for Elastic Settlement

The improved formula takes into account

- the rigidity of the foundation,
- the depth of embedment of the foundation,
- the increase in the modulus of elasticity of the soil with depth, and
- the location of rigid layers at a limited depth



$$S_e = \frac{q_o B_e I_G I_F I_E}{E_o}\left(1 - \mu_s^2\right)$$

where

I_G = influence factor for the variation of E_s with depth

$$= f\left(\beta = \frac{E_o}{kB_e}, \frac{H}{B_e}\right)$$

I_F = foundation rigidity correction factor

I_E = foundation embedment correction factor

Equivalent diameter B_e of

Rectangular foundation $B_e = \sqrt{\frac{4BL}{\pi}}$

Circular foundation $B_e = B$

$$E_s = E_o + kz$$

Improved Equation for Elastic Settlement

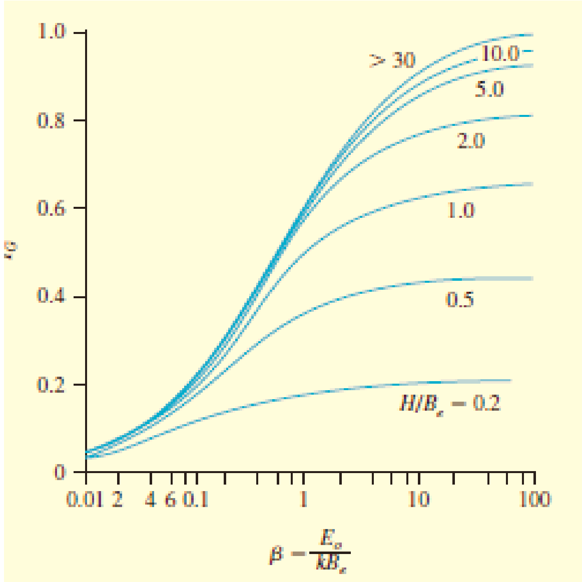
The foundation rigidity correction factor is

$$I_F = \frac{\pi}{4} + \frac{1}{4.6 + 10\left(\dfrac{E_f}{E_o + \dfrac{B_e}{2}k}\right)\left(\dfrac{2t}{B_e}\right)^3}$$

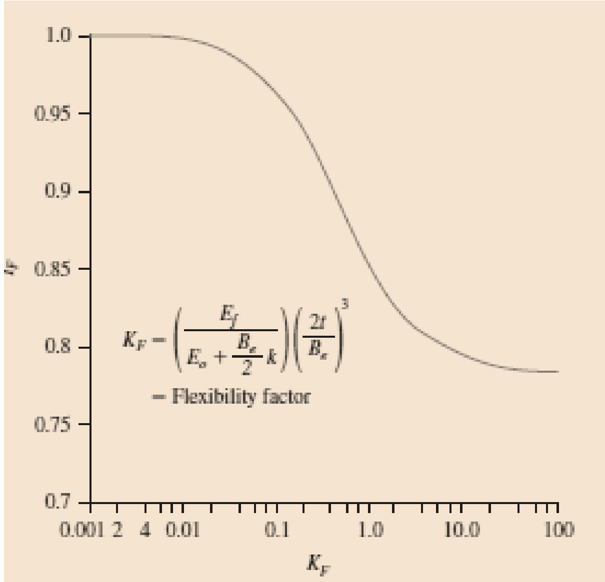
The embedment correction factor is

$$I_E = 1 - \frac{1}{3.5\exp(1.22\mu_s - 0.4)\left(\dfrac{B_e}{D_f} + 1.6\right)}$$

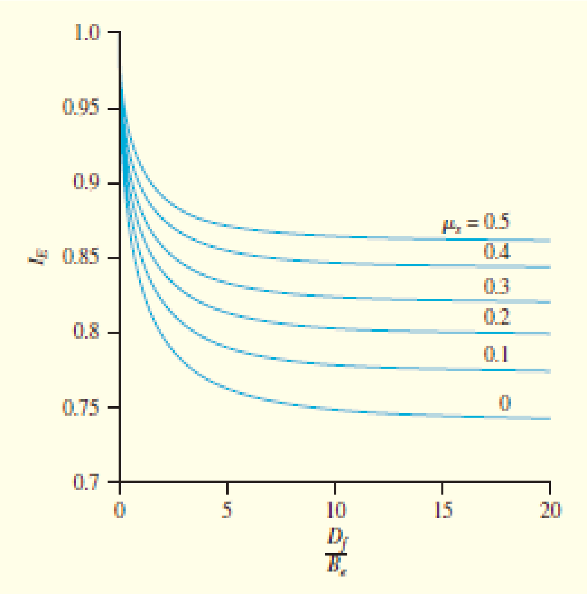
Improved Equation for Elastic Settlement



I_G



I_F



I_E

Example 9.3

EXAMPLE 9.3

For a shallow foundation supported by a silty sand, as shown in Figure 9.7,

Length $= L = 3$ m

Width $= B = 1.5$ m

Depth of foundation $= D_f = 1.5$ m

Thickness of foundation $= t = 0.3$ m

Load per unit area $= q_o = 240$ kN/m^2

$E_f = 16 \times 10^6$ kN/m^2

The silty sand soil has the following properties:

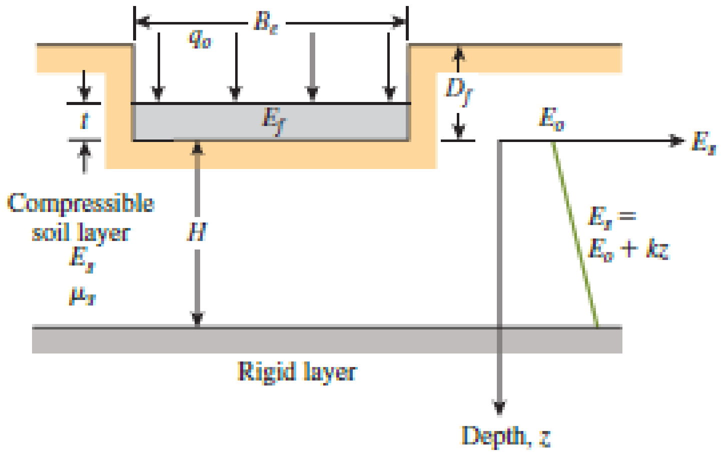
$H = 3.7$ m

$\mu_s = 0.3$

$E_o = 9700$ kN/m^2

$k = 575$ kN/m^2/m

Estimate the elastic settlement of the foundation.



Example 9.3

SOLUTION

From Eq. (9.24), the equivalent diameter is

$$B_e = \sqrt{\frac{4BL}{\pi}} = \sqrt{\frac{(4)(1.5)(3)}{\pi}} = 2.39 \text{ m}$$

so

$$\beta = \frac{E_o}{kB_e} = \frac{9700}{(575)(2.39)} = 7.06$$

and

$$\frac{H}{B_e} = \frac{3.7}{2.39} = 1.55$$

From Figure 9.8, for $\beta = 7.06$ and $H/B_e = 1.55$, the value of $I_G \approx 0.7$. From Eq. (9.28),

$$I_F = \frac{\pi}{4} + \frac{1}{4.6 + 10\left(\dfrac{E_f}{E_o + \dfrac{B_e}{2}k}\right)\left(\dfrac{2t}{B_e}\right)^3}$$

$$= \frac{\pi}{4} + \frac{1}{4.6 + 10\left[\dfrac{16 \times 10^6}{9700 + \left(\dfrac{2.39}{2}\right)(575)}\right]\left[\dfrac{(2)(0.3)}{2.39}\right]^3} = 0.789$$

Example 9.3

From Eq. (9.29),

$$I_E = 1 - \frac{1}{3.5\exp(1.22\mu_s - 0.4)\left(\dfrac{B_e}{D_f} + 1.6\right)}$$

$$= 1 - \frac{1}{3.5\exp[(1.22)(0.3) - 0.4]\left(\dfrac{2.39}{1.5} + 1.6\right)} = 0.907$$

From Eq. (9.27),

$$S_e = \frac{q_o B_e I_G I_F I_E}{E_o}(1 - \mu_s^2)$$

so, with $q_o = 240\ \text{kN/m}^2$, it follows that

$$S_e = \frac{(240)(2.39)(0.7)(0.789)(0.907)}{9700}(1 - 0.3^2) \approx 0.02696\ \text{m} \approx \mathbf{27\ mm}$$

Settlement of Sandy Soil: Use of Strain Influence Factor

I. Solution of Schmertmann et al. (1978)

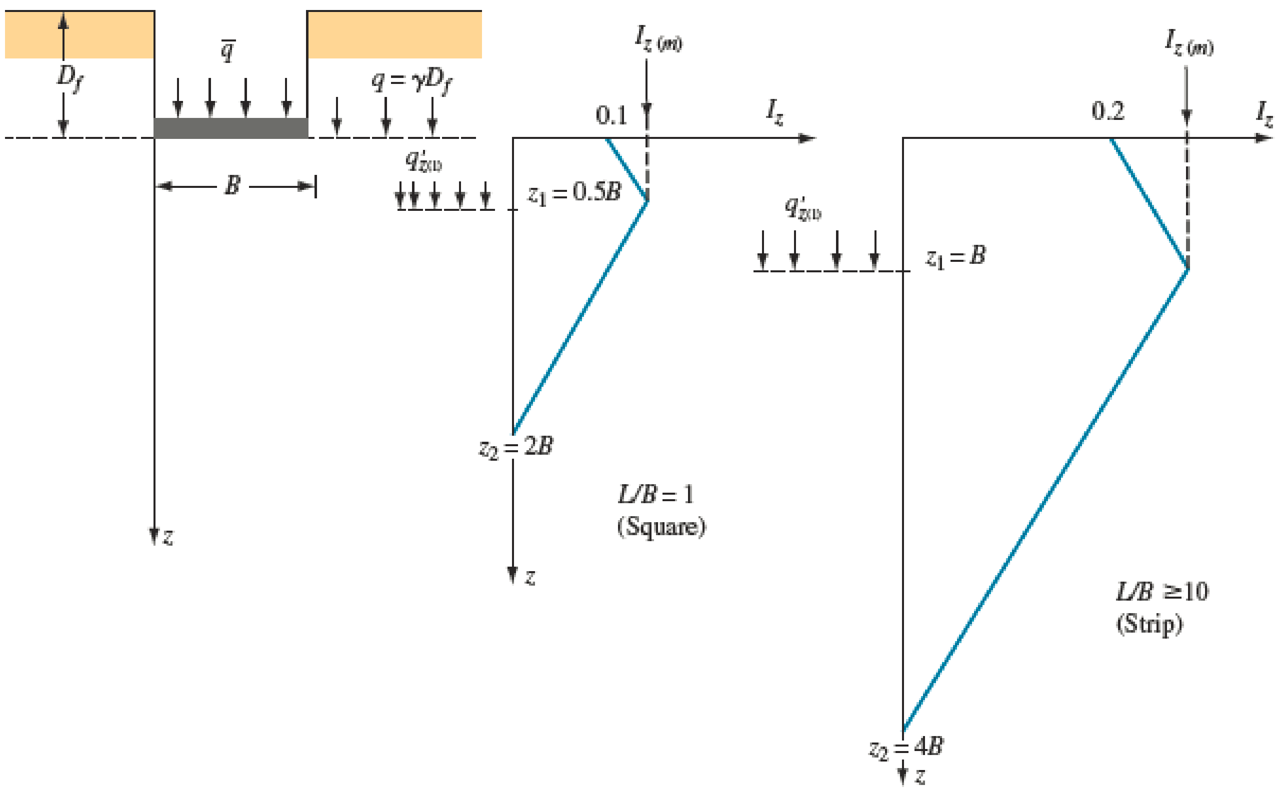
$$S_e = C_1 C_2 (\bar{q} - q) \sum_0^{z_2} \frac{I_z}{E_s} \Delta z$$

where

I_z = strain influence factor
C_1 = a correction factor for the depth of foundation embedment = $1 - 0.5\,[q/(\bar{q} - q)]$
C_2 = a correction factor to account for creep in soil
= $1 + 0.2 \log$ (time in years/0.1)
$\bar{q}$ = 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

Settlement of Sandy Soil: Use of Strain Influence Factor

The recommended variation of the strain influence factor I_z for square ($L/B = 1$) or circular foundations and for foundations with $L/B >= 10$ is shown in Figure
The I_z diagrams for $1 < L/B < 10$ can be interpolated.



Settlement of Sandy Soil: Use of Strain Influence Factor

Note that the maximum value of I_z [that is, $I_{z\,(m)}$] occurs at $z = z_1$ and then reduces to zero at $z = z_2$. 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

Settlement of Sandy Soil: Use of Strain Influence Factor

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 $z = 0$

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

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

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

- Variation of z_2/B

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

Schmertmann et al. (1978) suggested that

$$E_s = 2.5q_c \text{ (for square foundation)}$$

and

$$E_s = 3.5q_c \text{ (for } L/B \geq 10\text{)}$$

where q_c = cone penetration resistance.

It appears reasonable to write (Terzaghi et al., 1996)

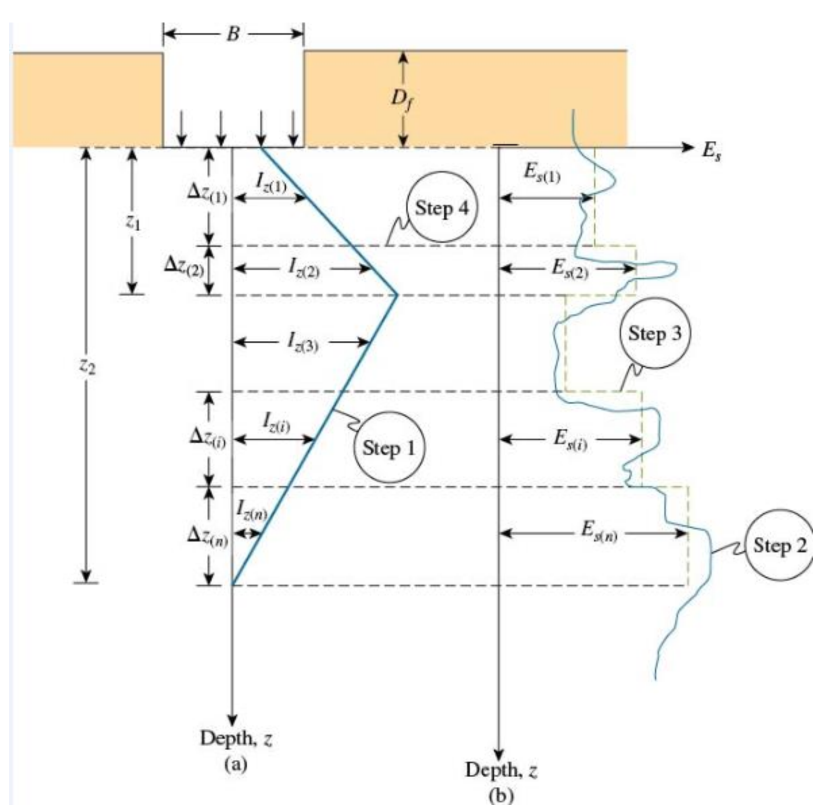
$$E_{s(\text{rectangle})} = \left(1 + 0.4 \log\frac{L}{B}\right)E_{s(\text{square})}$$

Procedure for calculation of S_e using the strain influence factor

Step 1. Plot the foundation and the variation of I_z with depth to scale (Figure 9.12a).
Step 2. Using the correlation from standard penetration resistance (N_{60}) or cone penetration resistance (q_c), plot the actual variation of E_s with depth (Figure 9.12b).
Step 3. Approximate the actual variation of E_s into a number of layers of soil having a constant E_s, such as $E_{s(1)}$, $E_{s(2)}$, . . . , $E_{s(i)}$, . . . $E_{s(n)}$ (Figure 9.12b).
Step 4. Divide the soil layer from $z = 0$ to $z = z_2$ into a number of layers by drawing horizontal lines. The number of layers will depend on the break in continuity in the I_z and E_s diagrams.
Step 5. Prepare a table (such as Table 9.5) to obtain $\Sigma \frac{I_z}{E_s} \Delta z$.
Step 6. Calculate C_1 and C_2.
Step 7. Calculate S_e from Eq. (9.30).

$\Sigma \frac{I_z}{E_s} \Delta z$.

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



Procedure for calculation of S_e using the strain influence factor

TABLE 9.5 Calculation of $\Sigma \frac{I_z}{E_s} \Delta z$

Layer no.	Δz	E_s	I_z at the middle of the layer	$\frac{I_z}{E_s} \Delta z$
1	$\Delta z_{(1)}$	$E_{s(1)}$	$I_{z(1)}$	$\frac{I_{z(1)}}{E_{s(1)}} \Delta z_1$
2	$\Delta z_{(2)}$	$E_{s(2)}$	$I_{z(2)}$	
⋮	⋮	⋮	⋮	
i	$\Delta z_{(i)}$	$E_{s(i)}$	$I_{z(i)}$	$\frac{I_{z(i)}}{E_{s(i)}} \Delta z_i$
⋮	⋮	⋮	⋮	⋮
n	$\Delta z_{(n)}$	$E_{s(n)}$	$I_{z(n)}$	$\frac{I_{z(n)}}{E_{s(n)}} \Delta z_n$
				$\Sigma \frac{I_z}{E_s} \Delta z$

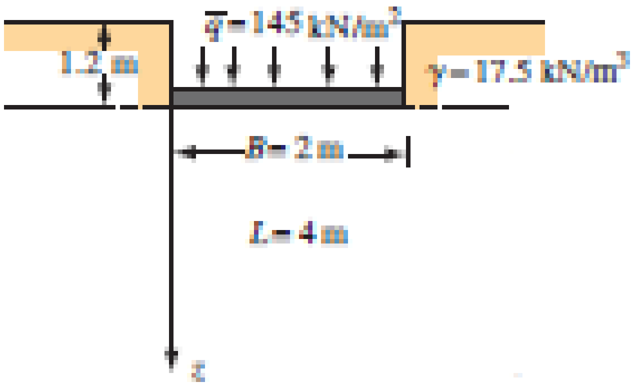
Example 9.4

EXAMPLE 9.4

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 9.13a. 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/m²)
0–0.5	2250
0.5–2.5	3430
2.5–6.0	2950

Estimate the elastic settlement of the foundation using the strain influence factor method.



Example 9.4

SOLUTION

From Eq. (9.33),

$$\frac{z_1}{B} = 0.5 + 0.0555\left(\frac{L}{B} - 1\right) = 0.5 + 0.0555\left(\frac{4}{2} - 1\right) \approx 0.56$$

$$z_1 = (0.56)(2) = 1.12 \text{ m}$$

From Eq. (9.34),

$$\frac{z_2}{B} = 2 + 0.222\left(\frac{L}{B} - 1\right) = 2 + 0.222(2 - 1) = 2.22$$

$$z_2 = (2.22)(2) = 4.44 \text{ m}$$

From Eq. (9.32), at $z = 0$,

$$I_z = 0.1 + 0.0111\left(\frac{L}{B} - 1\right) = 0.1 + 0.0111\left(\frac{4}{2} - 1\right) \approx 0.11$$

From Eq. (9.31),

$$I_{z(m)} = 0.5 + 0.1\sqrt{\frac{\bar{q} - q}{q'_{z(1)}}} = 0.5 + 0.1\left[\frac{145 - (1.2 \times 17.5)}{(1.2 + 1.12)(17.5)}\right]^{0.5} = 0.675$$

The plot of I_z versus z is shown in Figure 9.13c. Again, from Eq. (9.37),

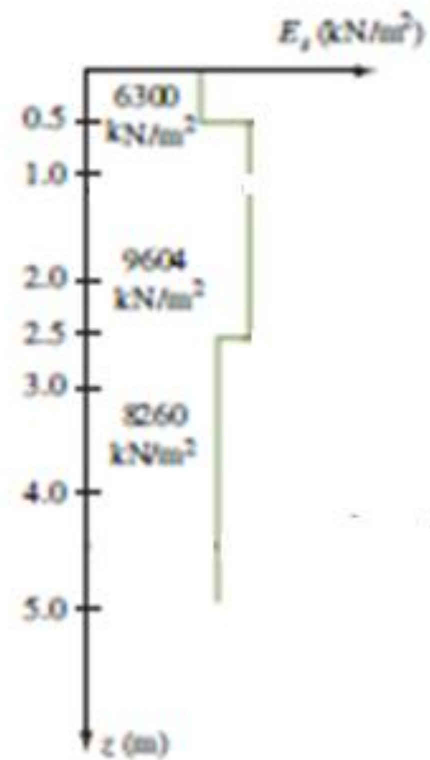
$$E_{s(\text{rectangle})} = \left(1 + 0.4\log\frac{L}{B}\right)E_{s(\text{square})} = \left[1 + 0.4\log\left(\frac{4}{2}\right)\right](2.5 \times q_c) = 2.8q_c$$

Example 9.4

$$E_{s(\text{rectangle})} = \left(1 + 0.4 \log\frac{L}{B}\right)E_{s(\text{square})} = \left[1 + 0.4 \log\left(\frac{4}{2}\right)\right](2.5 \times q_c) = 2.8q_c$$

Hence, the approximated variation of E_s with z is as follows:

z (m)	q_c (kN/m^2)	E_s (kN/m^2)
0–0.5	2250	6300
0.5–2.5	3430	9604
2.5–6.0	2950	8260



Example 9.4

The soil layer is divided into four layers as shown in Figures 9.13b and 9.13c. Now the following table can be prepared.

Layer no.	Δz (m)	E_s (kN/m^2)	I_z at middle of layer	$\frac{I_z}{E_s}\Delta z$ (m^3/kN)
1	0.50	6300	0.236	1.87×10^{-5}
2	0.62	9604	0.519	3.35×10^{-5}
3	1.38	9604	0.535	7.68×10^{-5}
4	1.94	8260	0.197	4.62×10^{-5}
				$\Sigma 17.52 \times 10^{-5}$

$$S_e = C_1 C_2(\bar{q} - q)\sum \frac{I_z}{E_s}\Delta z$$

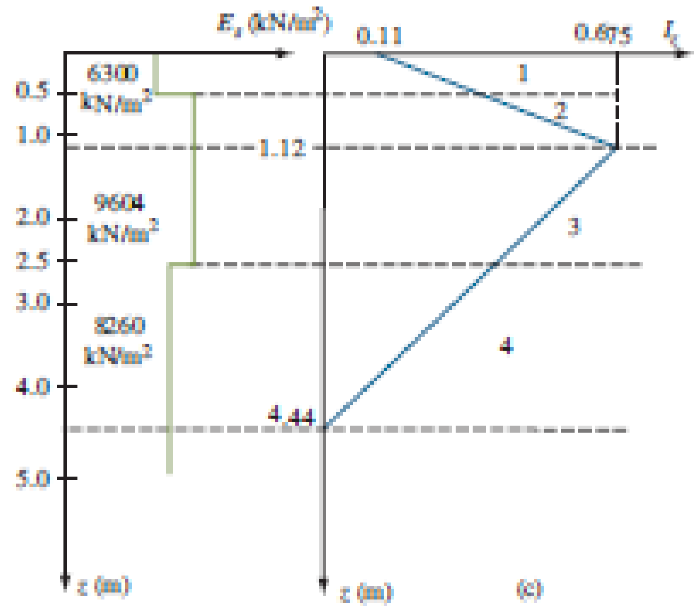
$$C_1 = 1 - 0.5\left(\frac{q}{\bar{q} - q}\right) = 1 - 0.5\left(\frac{21}{145 - 21}\right) = 0.915$$

Assume the time for creep is 10 years. So,

$$C_2 = 1 + 0.2\log\left(\frac{10}{0.1}\right) = 1.4$$

Hence,

$$S_e = (0.915)(1.4)(145 - 21)(17.52 \times 10^{-5}) = 2783 \times 10^{-5}\text{ m} = \mathbf{27.83\ mm}$$



Settlement of Sandy Soil: Use of Strain Influence Factor

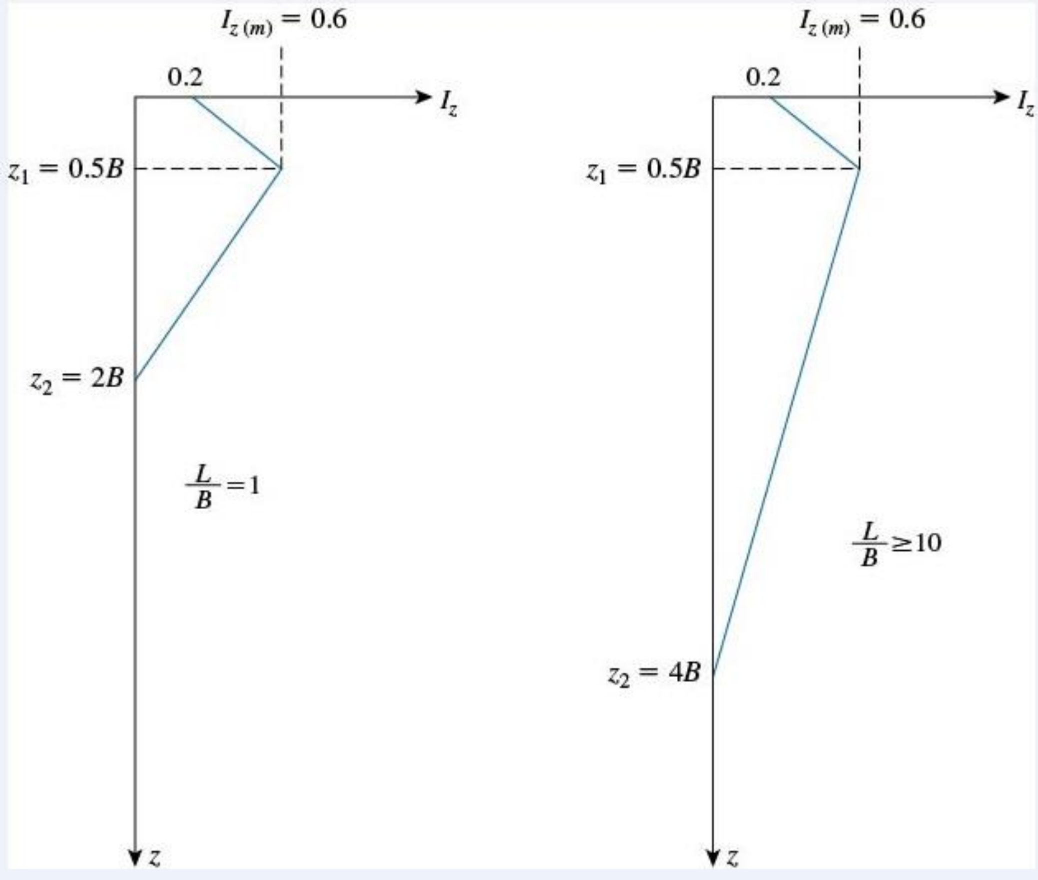
II. Solution of Terzaghi et al. (1996)

$$S_e = C_d(\bar{q} - q)\sum_{0}^{z_2}\frac{I_z}{E_s}\Delta z + \underbrace{0.02\left[\frac{0.1}{\frac{\sum(q_c\Delta z)}{z_2}}\right]z_2 \log\left(\frac{t \text{ days}}{1 \text{ day}}\right)}_{\text{Post-construction settlement}}$$

Settlement of Sandy Soil: Use of Strain Influence Factor

Terzaghi, Peck, and Mesri (1996) proposed a slightly different form of the strain influence factor diagram, as shown in Figure . According to Terzaghi et al. (1996),

At $z = 0$, $I_z = 0.2$ (for all L/B values)
At $z = z_1 = 0.5B$, $I_z = 0.6$ (for all L/B values)
At $z = z_2 = 2B$, $I_z = 0$ (for $L/B = 1$)
At $z = z_2 = 4B$, $I_z = 0$ (for $L/B \geq 10$)



Settlement of Sandy Soil: Use of Strain Influence Factor

For L/B between 1 and 10 (or > 10),

$$\frac{z_2}{B} = 2\left[1 + \log\left(\frac{L}{B}\right)\right]$$

In Eq. (7.29), q_c is in MN/m^2.

The relationships for E_s are

$$E_s = 3.5q_c \text{ (for square and circular foundations)}$$

and

$$E_{s(\text{rectangular})} = \left[1 + 0.4\left(\frac{L}{B}\right)\right]E_{s(\text{square})} \quad (\text{for } L/B \geq 10)$$

TABLE 9.6 Variation of C_d with D_f/B*

D_f/B	C_d
0.1	1
0.2	0.96
0.3	0.92
0.5	0.86
0.7	0.82
1.0	0.77
2.0	0.68
3.0	0.65

*Based on data from Terzaghi et al. (1996)

Example 9.5

EXAMPLE 9.5

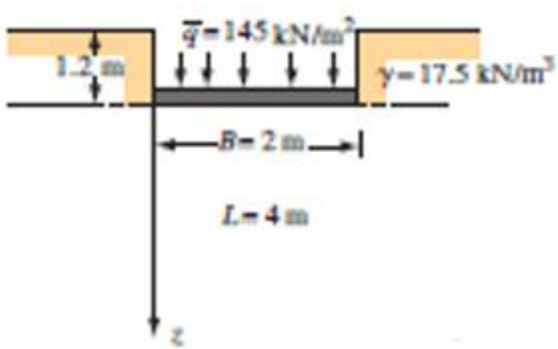
Solve Example 9.4 using the method of Terzaghi et al. (1996).

EXAMPLE 9.4

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 9.13a. Given: $\gamma = 17.5$ kN/m³, $\bar{q} = 145$ kN/m², and the following approximated variation of q_c with z:

z (m)	q_c (kN/m²)
0–0.5	2250
0.5–2.5	3430
2.5–6.0	2950

Estimate the elastic settlement of the foundation using the strain influence factor method.



Example 9.5

SOLUTION

Given: $L/B = 4/2 = 2$.

Figure 9.15a shows the plot of I_z with depth below the foundation. Note that

$$\frac{z_2}{B} = 2\left[1 + \log\left(\frac{L}{B}\right)\right] = 2[1 + \log(2)] = 2.6$$

or

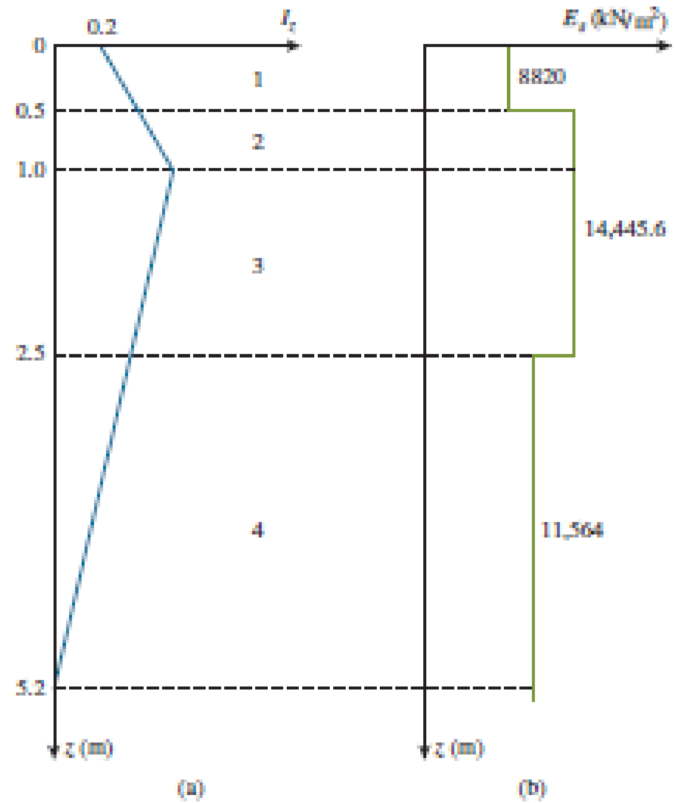
$$z_2 = (2.6)(B) = (2.6)(2) = 5.2 \text{ m}$$

Also, from Eqs. (9.40) and (9.41),

$$E_s = \left[1 + 0.4\log\left(\frac{L}{B}\right)\right](3.5q_c) = \left[1 + 0.4\log\left(\frac{4}{2}\right)\right](3.5q_c) = 3.92q_c$$

The following table can be prepared and shows the variation of E_s with depth, which is shown in Figure 9.15b.

z (m)	q_c (kN/m^2)	E_s (kN/m^2)
0–0.5	2250	8820
0.5–2.5	3430	14,445.6
2.5–6	2950	11,564



Example 9.5

Again, $D_f/B = 1.2/2 = 0.6$. From Table 9.6, $C_d \simeq 0.85$.

The following table is used to calculate $\sum_0^{z_2} \frac{I_z}{E_s}\Delta z$.

Layer no.	Δz (m)	E_s (kN/m²)	I_z at the middle of the layer	$\frac{I_z}{E_s}\Delta z$ (m³/kN)
1	0.5	8820	0.3	1.7×10^{-5}
2	0.5	14,445.6	0.5	1.73×10^{-5}
3	1.5	14,445.6	0.493	5.12×10^{-5}
4	2.7	11,564	0.193	4.5×10^{-5}
				$\Sigma\ 13.06 \times 10^{-5}$ m²/kN

Thus,

$$C_d(\bar{q} - q)\sum_0^{z_2} \frac{I_z}{E_s}\Delta_z = (0.85)(145 - 21)(13.06 \times 10^{-5}) = 1376.5 \times 10^{-5} \text{ m}$$

Postconstruction creep is

$$0.02\left[\frac{0.1}{\frac{\sum(q_c\Delta z)}{z_2}}\right] z_2 \log\left(\frac{t \text{ days}}{1 \text{ day}}\right)$$

$$\frac{\sum(q_c\Delta z)}{z_2} = \frac{(2250 \times 0.5) + (3430 \times 2) + (2950 \times 2.7)}{5.2}$$

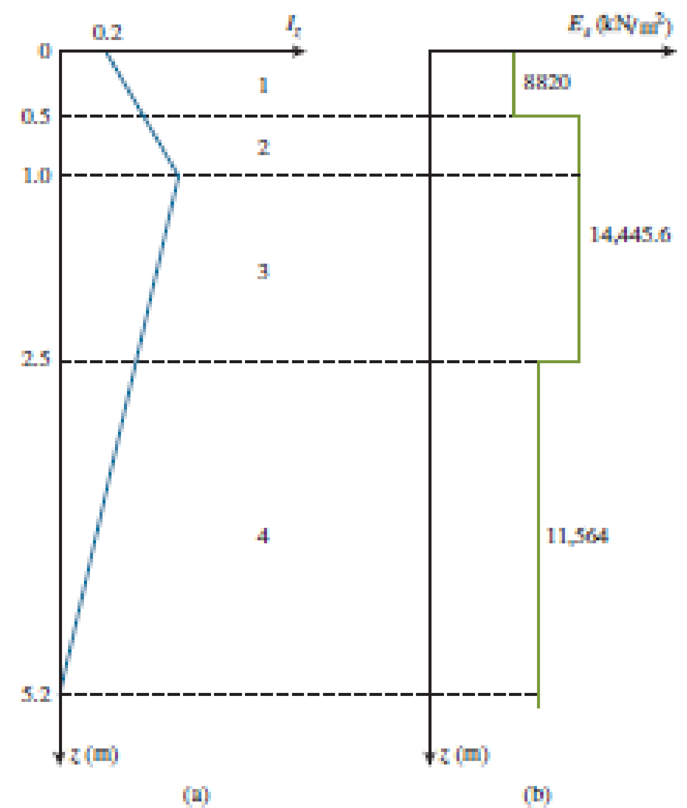
$$= 3067.3 \text{ kN/m}^2 \simeq 3.07 \text{ MN/m}^2$$

Hence, the elastic settlement is

$$S_e = 1376.5 \times 10^{-5} + 0.02\left[\frac{0.1}{3.07}\right](5.2)\log\left(\frac{10 \times 365 \text{ days}}{1 \text{ day}}\right)$$

$$= 2583.3 \times 10^{-5} \text{ m}$$

$$\simeq \mathbf{25.83\ mm}$$



Example 9.5

Note: The magnitude of S_e is about 93% of that found in Example 9.4. In Example 9.4, the elastic settlement was about 19.88 mm, and settlement due to creep was about 7.95 mm. However, in Example 9.5, elastic settlement is about 13.77 mm, and the settlement due to creep is about 12.07 mm. Thus the magnitude of creep settlement is about 50% more in Example 9.5. However, the magnitude of elastic settlement in Example 9.4 is about 30% more compared to that in Example 9.5. This is because of the assumption of the $E_s - q_c$ relationship.

Settlement of Foundation on Sand Based on Standard Penetration Resistance

Terzaghi and Peck's Method

$$S_{e,\,\text{foundation}} = S_{e,\,\text{plate}}\left(\frac{2B}{B+0.3}\right)^2\left(1-\frac{1}{4}\frac{D_f}{B}\right)$$

where *B* is in meters

The last term takes into account the reduction in settlement with the increase in foundation depth. Leonards (1986) suggested replacing ¼ by 1/3, based on additional load test data. The values of *Se*, plate can be obtained from Figure 9.16,which summarizes the plate loading test data given by Terzaghi and Peck (1967). These load tests were carried out on thick deposits of normally consolidated drained sand. This method was originally proposed for square foundations but can be applied to rectangular and strip foundations with caution. The deeper influence zone and increase in the stresses within the underlying soil mass in the case of rectangular or strip foundations are compensated by the increase in the soil stiffness.

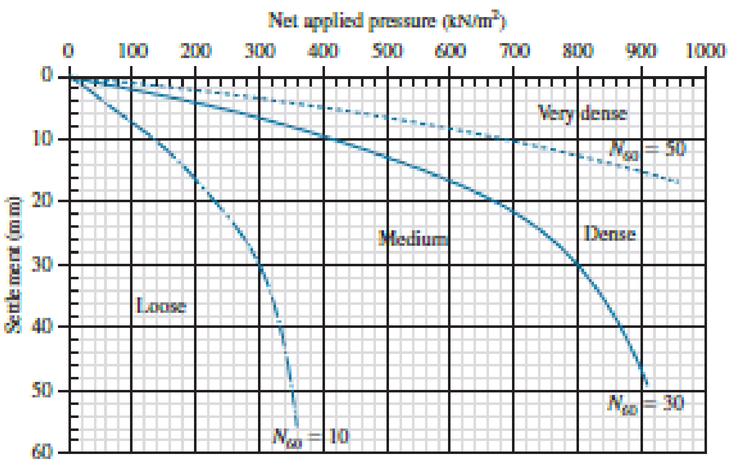


FIGURE 9.16 Settlement of 300 mm × 300 mm plate (Load test data from Late Professor G.A. Leonards, Purdue University)

Example 9.6

EXAMPLE 9.6

A 2.5 m square foundation placed at a depth of 1.5 m within a sandy soil applies a net pressure of 120 kN/m^2 to the underlying ground. The sand has $\gamma = 18.5$ kN/m^3 and $N_{60} = 25$. What would be the settlement?

SOLUTION

For net applied pressure = 120 kN/m^2 and $N_{60} = 25$; from Figure 9.16, $S_{e,\,plate} = 4$ mm.

From Eq. (9.43),

$$S_{e,\,foundation} = S_{e,\,plate}\left(\frac{2B}{B+0.3}\right)^2\left(1-\frac{1}{3}\frac{D_f}{B}\right)$$

$$= (4)\left(\frac{2\times 2.5}{2.5+0.3}\right)^2\left(1-\frac{1}{3}\times\frac{1.5}{2.5}\right) = \mathbf{10.2\ mm}$$

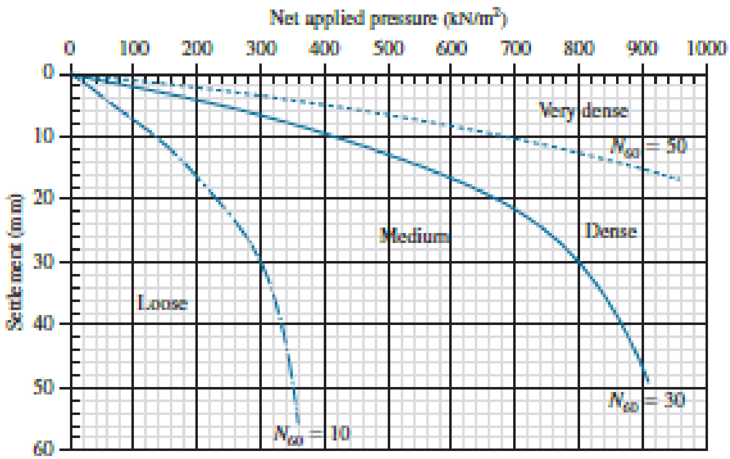


FIGURE 9.16 Settlement of 300 mm × 300 mm plate (Load test data from Late Professor G.A. Leonards, Purdue University)

Settlement of Foundation on Sand Based on Standard Penetration Resistance

Meyerhof's Method

$$S_e(\text{mm}) = \frac{1.25 q_{\text{net}}(\text{kN/m}^2)}{N_{60} F_d} \quad (\text{for } B \leq 1.22 \text{ m})$$

$$S_e(\text{mm}) = \frac{2 q_{\text{net}}(\text{kN/m}^2)}{N_{60} F_d} \left(\frac{B}{B + 0.3} \right)^2 \quad (\text{for } B > 1.22 \text{ m})$$

$$q_{\text{net}}(\text{kN/m}^2) = \frac{N_{60}}{0.05} F_d \left(\frac{S_e}{25} \right) \quad (\text{for } B \leq 1.22 \text{ m})$$

$$q_{\text{net}}(\text{kN/m}^2) = \frac{N_{60}}{0.08} \left(\frac{B + 0.3}{B} \right)^2 F_d \left(\frac{S_e}{25} \right) \quad (\text{for } B > 1.22 \text{ m})$$

The N_{60} is the standard penetration resistance between the bottom of the foundation and 2*B* below the bottom.

Settlement of Foundation on Sand Based on Standard Penetration Resistance

Burland and Burbidge's Method

1. Variation of Standard Penetration Number with Depth:

Obtain the field penetration numbers N_{60} with depth at the location of the foundation The following adjustments of N_{60} may be necessary:

For gravel or sandy gravel

$$N_{60(a)} = 1.25\, N_{60}$$

For fine sand or silty sand below the groundwater table and N_{60} >15,

$N_{60(a)} = 15+0.5(N_{60} -15)$

where $N_{60(a)}$ = adjusted N_{60} value.

2. Determination of Depth of Stress Influence (z'):

In determining the depth of stress influence, the following three cases may arise:

Case I. If N_{60} [or $N_{60(a)}$] is approximately constant with depth, calculate z' from

$$\frac{z'}{B_R} = 1.4\left(\frac{B}{B_R}\right)^{0.75}$$

where

$$B_R = \text{reference width}\begin{cases} = 1 \text{ ft (if } B \text{ is in ft)} \\ = 0.3 \text{ m (if } B \text{ is in m)} \end{cases}$$

B = width of the actual foundation

Case II. If N_{60} [or $N_{60(a)}$] is increasing with depth, use the above Equation.

Case III. If N_{60} [or $N_{60(a)}$] is decreasing with depth, $z' = 2B$ or to the bottom of soft soil layer measured from the bottom of the foundation (whichever is smaller).

Settlement of Foundation on Sand Based on Standard Penetration Resistance

Burland and Burbidge's Method

3. Calculation of Elastic Settlement S_e

The elastic settlement of the foundation, S_e, can be calculated from

$$\frac{S_e}{B_R} = \alpha_1 \alpha_2 \alpha_3 \left[\frac{1.25\left(\frac{L}{B}\right)}{0.25 + \left(\frac{L}{B}\right)} \right]^2 \left(\frac{B}{B_R}\right)^{0.7} \left(\frac{q'}{p_a}\right)$$

where

α_1 = a constant
α_2 = compressibility index
α_3 = correction for the depth of influence
p_a = atmospheric pressure = 100 kN/m^2
L = length of the foundation

TABLE 9.7 Summary of q', α_1, α_2, and α_3

Soil type	q'	α_1	α_2	α_3
Normally consolidated sand	q_{net}	0.14	$\frac{1.71}{[\overline{N}_{60} \text{ or } \overline{N}_{60(a)}]^{1.4}}$	$\alpha_3 = \frac{H}{z'}\left(2 - \frac{H}{z'}\right)$ (if $H \le z'$) or $\alpha_3 = 1$ (if $H > z'$) where H = depth of compressible layer
Overconsolidated sand ($q_{net} \le \sigma'_c$) where σ'_c = preconsolidation pressure	q_{net}	0.047	$\frac{0.57}{[\overline{N}_{60} \text{ or } \overline{N}_{60(a)}]^{1.4}}$	
Overconsolidated sand ($q_{net} > \sigma'_c$)	$q_{net} - 0.67\sigma'_c$	0.14	$\frac{0.57}{[\overline{N}_{60} \text{ or } \overline{N}_{60(a)}]^{1.4}}$	

Table 9.7 summarizes the values of q', α_1, α_2, and α_3 to be used in Equation for various types of soils. Note that, in this table, $\overline{N}_{60}$ or $\overline{N}_{60(a)}$ = average value of N_{60} [or $N_{60(a)}$ in the depth of stress influence.

Example 9.7

EXAMPLE 9.7

A shallow foundation measuring 1.75 m × 1.75 m is to be constructed over a layer of sand. Given $D_f = 1$ m; N_{60} is generally increasing with depth; $\overline{N}_{60}$ in the depth of stress influence = 10, $q_{net} = 120$ kN/m². The sand is normally consolidated. Estimate the elastic settlement of the foundation. Use the Burland and Burbidge method.

SOLUTION

From Eq. (9.52),

$$\frac{z'}{B_R} = 1.4\left(\frac{B}{B_R}\right)^{0.75}$$

Depth of stress influence,

$$z' = 1.4\left(\frac{B}{B_R}\right)^{0.75} B_R = (1.4)(0.3)\left(\frac{1.75}{0.3}\right)^{0.75} \approx 1.58 \text{ m}$$

From Eq. (9.53),

$$\frac{S_e}{B_R} = \alpha_1\alpha_2\alpha_3\left[\frac{1.25\left(\frac{L}{B}\right)}{0.25 + \left(\frac{L}{B}\right)}\right]^2\left(\frac{B}{B_R}\right)^{0.7}\left(\frac{q'}{p_a}\right)$$

For normally consolidated sand (Table 9.7),

$$\alpha_1 = 0.14$$

$$\alpha_2 = \frac{1.71}{(\overline{N}_{60})^{1.4}} = \frac{1.71}{(10)^{1.4}} = 0.068$$

$$\alpha_3 = 1$$

$$q' = q_{net} = 120 \text{ kN/m}^2$$

So,

$$\frac{S_e}{0.3} = (0.14)(0.068)(1)\left[\frac{(1.25)\left(\frac{1.75}{1.75}\right)}{0.25 + \left(\frac{1.75}{1.75}\right)}\right]^2\left(\frac{1.75}{0.3}\right)^{0.7}\left(\frac{120}{100}\right)$$

$S_e \approx 0.0118$ m = **11.8 mm**

Effect of the Rise of Water Table on Elastic Settlement

Terzaghi (1943) suggested that the submergence of soil mass reduces the soil stiffness by about half, which in turn doubles the settlement. In most cases of foundation design, it is considered that, if the ground water table is located 1.5*B* to 2*B* below the bottom of the foundation, it will not have any effect on the settlement. The total elastic settlement (S'_e) due to the rise of the ground water table can be given as:

$$S'_e = S_e C_w$$

where

S_e = elastic settlement before the rise of ground water table

C_w = water correction factor

- Peck, Hansen, and Thornburn (1974):

$$C_w = \frac{1}{0.5 + 0.5\left(\frac{D_w}{D_f + B}\right)} \geq 1$$

- Teng (1982):

$$C_w = \frac{1}{0.5 + 0.5\left(\frac{D_w - D_f}{B}\right)} \leq 2 \qquad \left(\begin{array}{l}\text{for water table below the}\\ \text{base of the foundation}\end{array}\right)$$

- Bowles (1977):

$$C_w = 2 - \left(\frac{D_w}{D_f + B}\right)$$

Example 9.12

EXAMPLE 9.12

Consider the shallow foundation given in Example 9.7. Due to flooding, the groundwater table rose from $D_w = 4$ m to 2 m (Figure 9.28). Estimate the total elastic settlement S'_e after the rise of the water table. Use Eq. (9.80).

SOLUTION

From Eq. (9.79),

$$S'_e = S_e C_w$$

From Eq. (9.80),

$$C_w = \frac{1}{0.5 + 0.5\left(\dfrac{D_w}{D_f + B}\right)} = \frac{1}{0.5 + 0.5\left(\dfrac{2}{1 + 1.75}\right)} = 1.158$$

Hence,

$$S'_e = (11.8 \text{ mm})(1.158) = \mathbf{13.66\ mm}$$

EXAMPLE 9.7

A shallow foundation measuring 1.75 m × 1.75 m is to be constructed over a layer of sand. Given $D_f = 1$ m; N_{60} is generally increasing with depth; $\overline{N}_{60}$ in the depth of stress influence = 10, $q_{net} = 120$ kN/m². The sand is normally consolidated. Estimate the elastic settlement of the foundation. Use the Burland and Burbidge method.

$$S_e \approx 0.0118 \text{ m} = \mathbf{11.8\ mm}$$

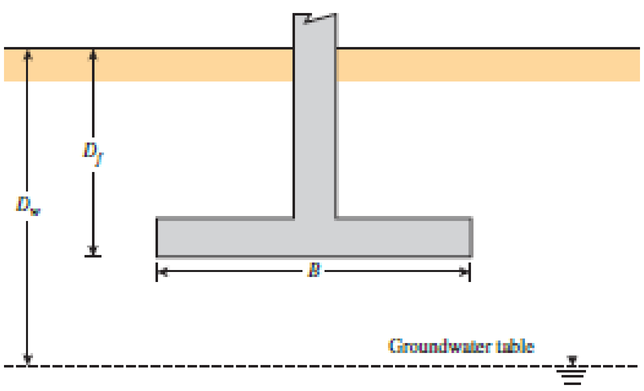


FIGURE 9.28 Effect of rise of groundwater table on elastic settlement in granular soil

Effect of the Rise of Water Table on Elastic Settlement

Method of Shahriar et al. (2014)

When the water table is present in the vicinity of the foundation, the unit weight of the soil has to be reduced for calculation of bearing capacity. Any future rise in the water table can reduce the ultimate bearing capacity. A future water table rise in the
vicinity of the foundation in granular soil can reduce the soil stiffness and, hence, produce additional settlement. Terzaghi (1943) concluded that when the water table rises from very deep to the foundation level, the settlement will be doubled in granular soil. Provided that the settlement is doubled when the entire sand layer beneath the foundation is submerged, laboratory model test results and numerical modeling work by Shahriar et al. (2014) show that the additional settlement produced by the rise of water table to any height can be expressed as:

$$S_{e,\,\text{additional}} = \frac{A_w}{A_t} S_e$$

where S_e is the elastic settlement computed in dry soil, A_w is the area of the strain influence diagram submerged due to water table rise, and A_t is the total area of the strain influence diagram under the foundation

Example 9.13

EXAMPLE 9.13

A pad foundation 2.5 m × 2.5 m in plan, when placed at a depth of 1.5 m in sand, applies 175 kN/m^2 pressure to the underlying ground. Given: $\gamma = 18.0$ kN/m^3. Currently the water table is at 6.5 m below the foundation, and the expected settlement is 15.0 mm. In the future, as the worst-case scenario, it is expected that the water table could rise by 4.0 m, as shown in Figure 9.29a. What would be the total settlement of the foundation if this occurs? Use Eq. (9.37).

SOLUTION

The influence factor diagram needs to be drawn first. From Eq. (9.31) and Figure 9.11,

$$I_{z(m)} = 0.5 + 0.1\sqrt{\frac{\bar{q} - q}{q'_{z(1)}}} = 0.5 + 0.1\sqrt{\frac{175 - (18.0)(1.5)}{(18.0)\left[1.5 + \left(\frac{2.5}{2}\right)\right]}} = 0.67$$

Example 9.13

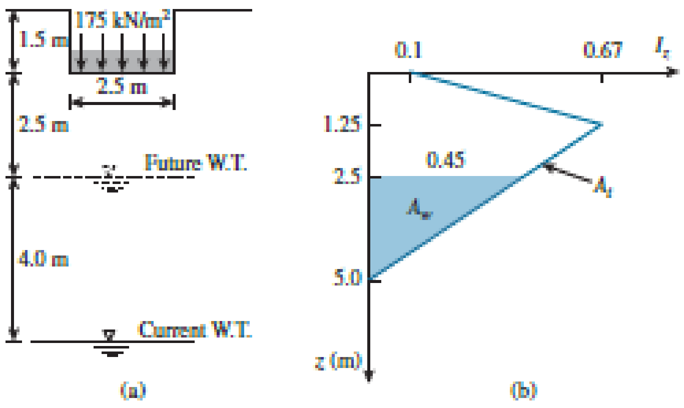


FIGURE 9.29

The I_z versus z diagram is shown in Figure 9.29b. Currently, the water table is below the influence zone. $S_e = 15.0$ mm. The total area of the influence diagram A_t is given by

$$A_t = \left(\frac{0.10 + 0.67}{2}\right) \times 1.25 + \frac{1}{2} \times 0.67 \times 3.75 = 1.738 \text{ m}$$

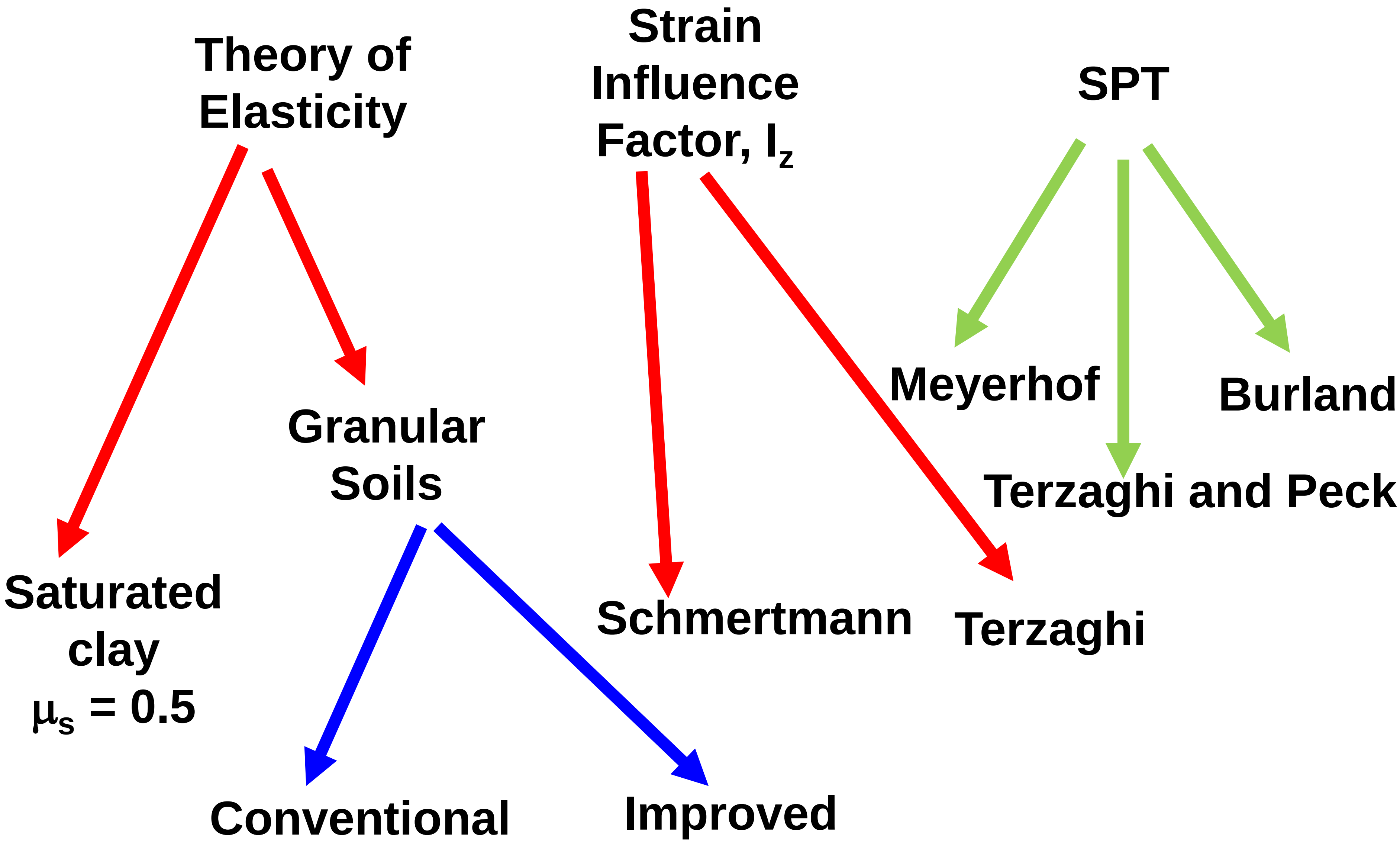
$$A_w = \frac{1}{2} \times 2.5 \times 0.45 = 0.563 \text{ m}$$

From Eq. (9.83),

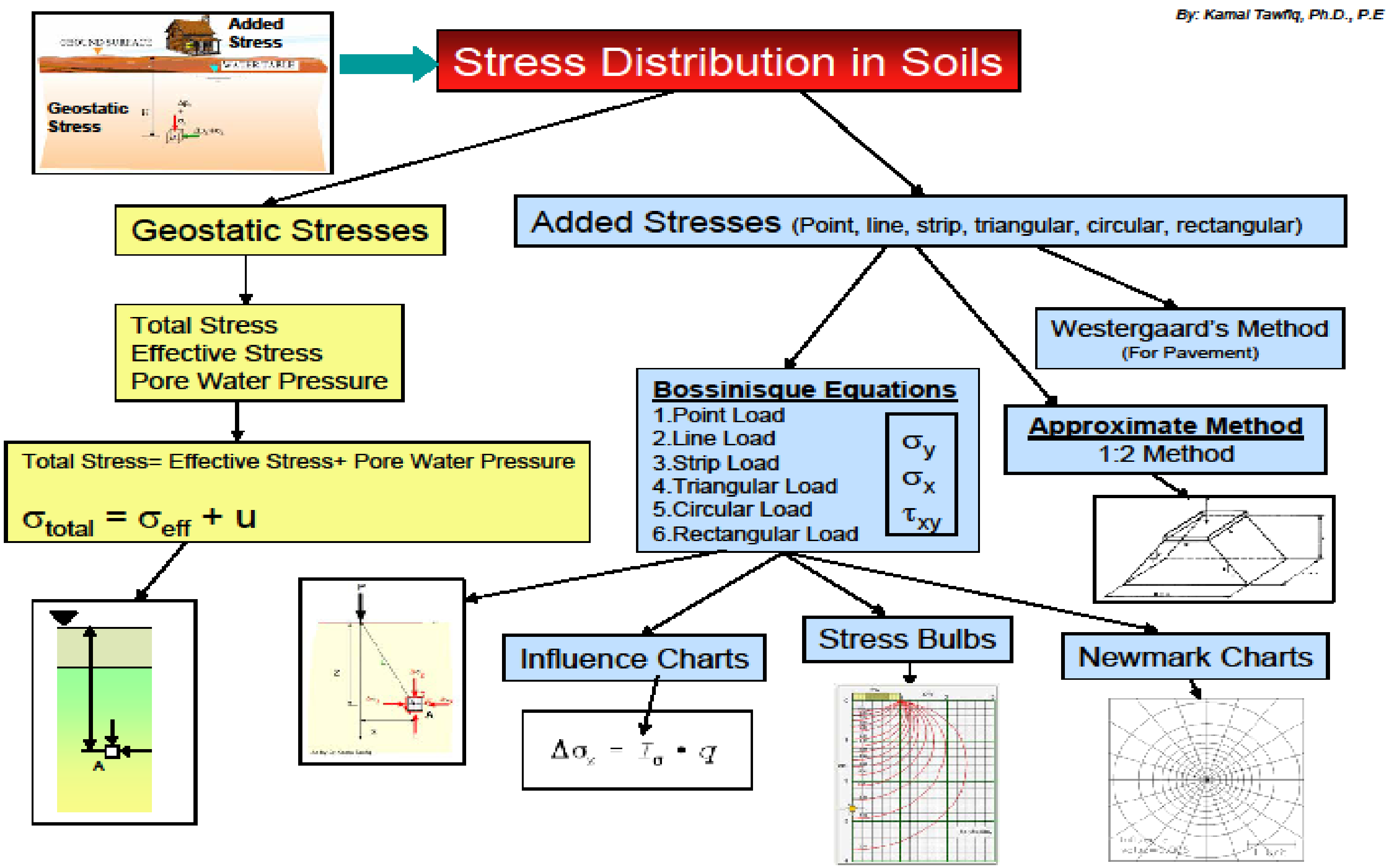
$$S_{e,\text{ additional}} = \frac{A_w}{A_t} S_e = \frac{0.563}{1.738} \times 15.0 = 4.9 \text{ mm}$$

The total settlement would be 15.0 + 4.9 = **19.9 mm.**

SUMMARY


Theory of Elasticity
Saturated clay
$\mu_s = 0.5$
Granular Soils
Conventional
Improved
Strain Influence Factor, I_z
Schmertmann
Terzaghi
SPT
Meyerhof
Terzaghi and Peck
Burland

Stresses Distribution in Soils



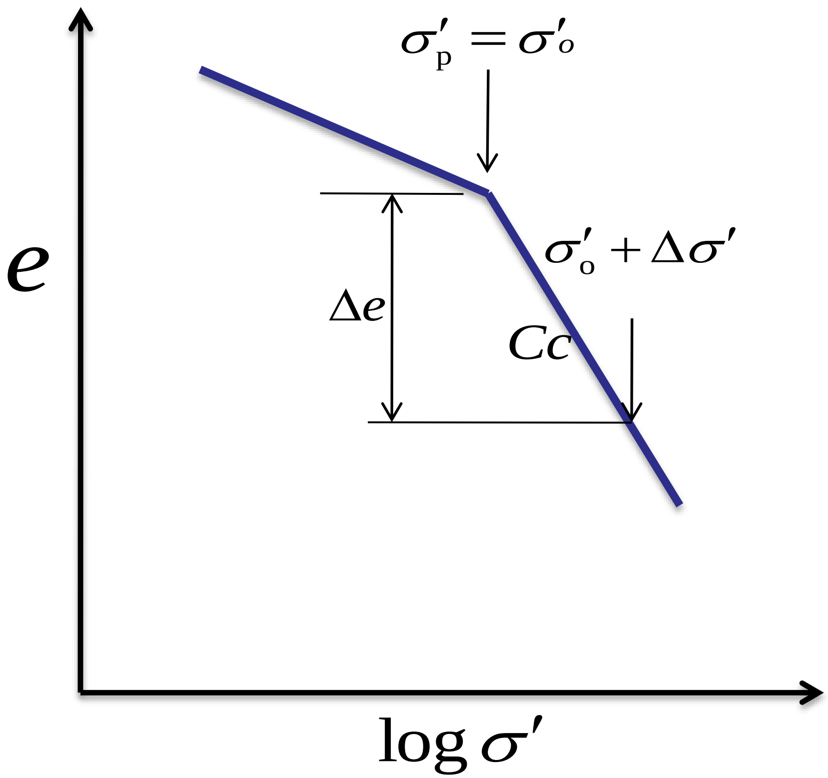
Calculation of Primary Consolidation Settlement

a) Normally Consolidated Clay ($\sigma'_0 = \sigma_c'$)

$$S_c = \frac{\Delta e}{1+e_o} H$$

$$\Delta e = C_c \log\left(\frac{\sigma'_o + \Delta\sigma}{\sigma'_o}\right)$$

$$S_c = \frac{C_c H}{1+e_o} \log\left(\frac{\sigma'_o + \Delta\sigma'}{\sigma'_o}\right)$$



Calculation of Primary Consolidation Settlement

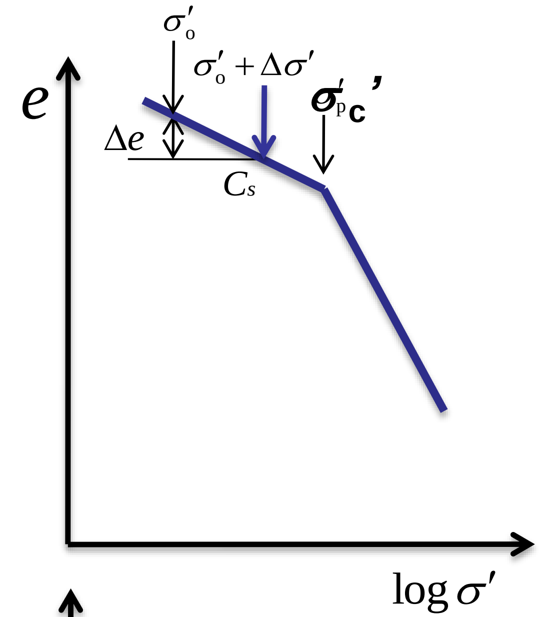
b) Overconsolidated Clays

$$S_c = \frac{\Delta e}{1+e_o} H$$

Case I: $\sigma'_0 + \Delta\sigma' \leq \sigma_c'$

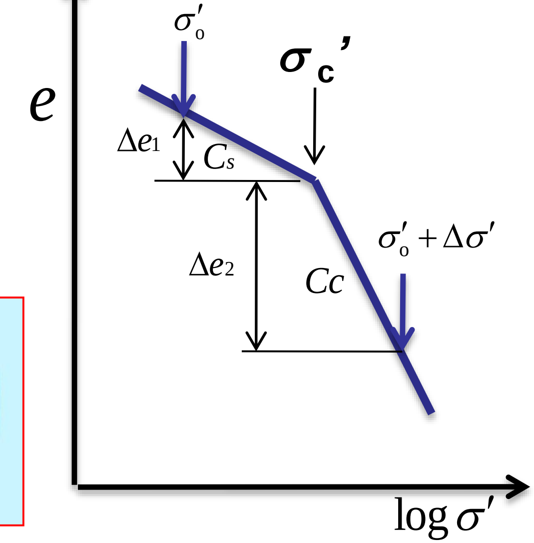
$$\Delta e = C_s[\log(\sigma'_o + \Delta\sigma') - \log \sigma'_o]$$

$$S_c = \frac{C_s H}{1+e_o} \log\left(\frac{\sigma'_o + \Delta\sigma'}{\sigma'_o}\right)$$



Case II: $\sigma'_0 + \Delta\sigma' > \sigma_c'$

$$S_c = \frac{C_s H}{1+e_o} \log\frac{\sigma'_c}{\sigma'_o} + \frac{C_c H}{1+e_o} \log\left(\frac{\sigma'_o + \Delta\sigma'}{\sigma'_c}\right)$$



Summary of calculation procedure

1. Calculate σ'_o at the middle of the clay layer
2. Determine σ'_c from the e-log σ' plot (if not given)
3. Determine whether the clay is N.C. or O.C.
4. Calculate $\Delta\sigma$
5. Use the appropriate equation

- If N.C. $$S_c = \frac{C_c H}{1+e_o} \log\left(\frac{\sigma'_o + \Delta\sigma'}{\sigma'_o}\right)$$
- If O.C. $$S_c = \frac{C_s H}{1+e_o} \log\left(\frac{\sigma'_o + \Delta\sigma'}{\sigma'_o}\right)$$ *If* $\sigma'_o + \Delta\sigma \le \sigma'_c$

$$S_c = \frac{C_s H}{1+e_o} \log\frac{\sigma'_c}{\sigma'_o} + \frac{C_c H}{1+e_o} \log\left(\frac{\sigma'_o + \Delta\sigma'}{\sigma'_c}\right)$$ *If* $\sigma'_o + \Delta\sigma > \sigma'_c$

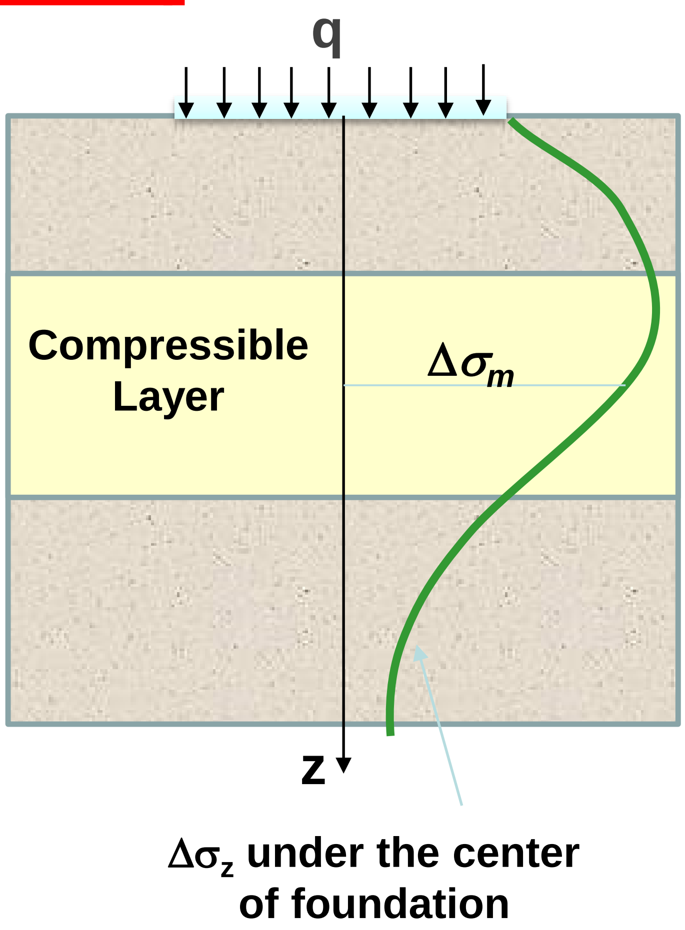
Nonlinear pressure increase

Approach 1: Middle of layer (midpoint rule)

- For settlement calculation, the pressure increase $\Delta\sigma_z$ can be approximated as :

$$\Delta\sigma_z = \Delta\sigma_m$$

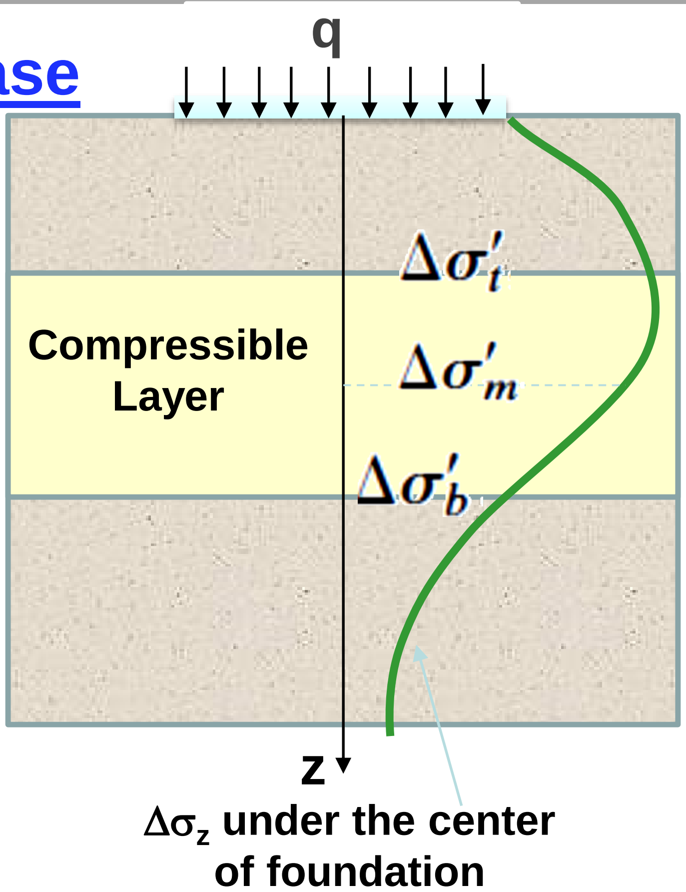
where $\Delta\sigma_m$ represent the increase in the effective pressure in the middle of the layer.



Nonlinear pressure increase

Approach 2: Average pressure increase

- **For settlement calculation we will use the average pressure increase $\Delta\sigma_{av}$, using weighted average method (Simpson's rule):**



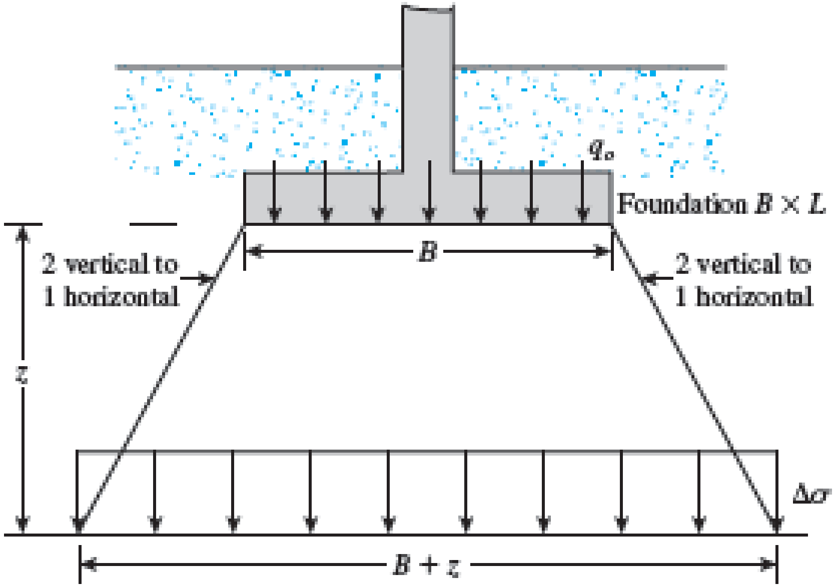
$$\Delta\sigma'_{av} = \frac{\Delta\sigma'_t + 4\Delta\sigma'_m + \Delta\sigma'_b}{6}$$

where $\Delta\sigma_t$, $\Delta\sigma_m$ and $\Delta\sigma_b$ represent the increase in the pressure at the top, middle, and bottom of the clay, respectively, under the center of the footing.

Stress from Approximate Method

2:1 Method

$$\Delta\sigma = \frac{q_o \times B \times L}{(B + z)(L + z)}$$



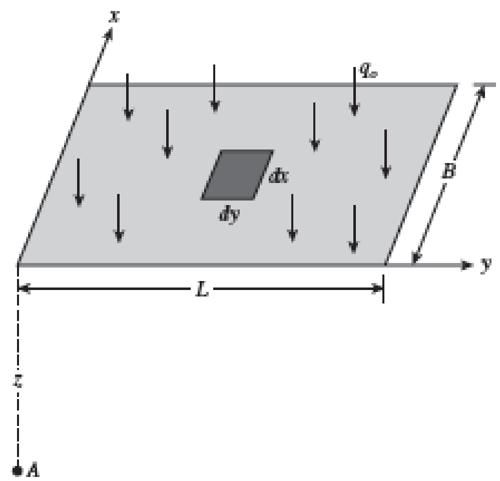
Stress below a Rectangular Area

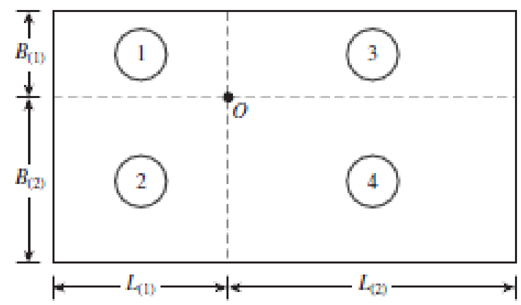
$$\Delta\sigma = \int_{y=0}^{L}\int_{x=0}^{B} \frac{3q_o\,(dx\,dy)z^3}{2\pi(x^2+y^2+z^2)^{5/2}} = q_o I$$

$$I = \text{influence factor} = \frac{1}{4\pi}\left(\frac{2mn\sqrt{m^2+n^2+1}}{m^2+n^2+m^2n^2+1}\cdot\frac{m^2+n^2+2}{m^2+n^2+1} + \tan^{-1}\frac{2mn\sqrt{m^2+n^2+1}}{m^2+n^2+1-m^2n^2}\right)$$

$$m = \frac{B}{z}$$

$$n = \frac{L}{z}$$





Stress below a Rectangular Area

Table 6.4 Variation of Influence Value I [Eq. (6.10)][a]

m	*n*											
	0.1	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**	**0.9**	**1.0**	**1.2**	**1.4**
0.1	0.00470	0.00917	0.01323	0.01678	0.01978	0.02223	0.02420	0.02576	0.02698	0.02794	0.02926	0.03007
0.2	0.00917	0.01790	0.02585	0.03280	0.03866	0.04348	0.04735	0.05042	0.05283	0.05471	0.05733	0.05894
0.3	0.01323	0.02585	0.03735	0.04742	0.05593	0.06294	0.06858	0.07308	0.07661	0.07938	0.08323	0.08561
0.4	0.01678	0.03280	0.04742	0.06024	0.07111	0.08009	0.08734	0.09314	0.09770	0.10129	0.10631	0.10941
0.5	0.01978	0.03866	0.05593	0.07111	0.08403	0.09473	0.10340	0.11035	0.11584	0.12018	0.12626	0.13003
0.6	0.02223	0.04348	0.06294	0.08009	0.09473	0.10688	0.11679	0.12474	0.13105	0.13605	0.14309	0.14749
0.7	0.02420	0.04735	0.06858	0.08734	0.10340	0.11679	0.12772	0.13653	0.14356	0.14914	0.15703	0.16199
0.8	0.02576	0.05042	0.07308	0.09314	0.11035	0.12474	0.13653	0.14607	0.15371	0.15978	0.16843	0.17389
0.9	0.02698	0.05283	0.07661	0.09770	0.11584	0.13105	0.14356	0.15371	0.16185	0.16835	0.17766	0.18357
1.0	0.02794	0.05471	0.07938	0.10129	0.12018	0.13605	0.14914	0.15978	0.16835	0.17522	0.18508	0.19139
1.2	0.02926	0.05733	0.08323	0.10631	0.12626	0.14309	0.15703	0.16843	0.17766	0.18508	0.19584	0.20278
1.4	0.03007	0.05894	0.08561	0.10941	0.13003	0.14749	0.16199	0.17389	0.18357	0.19139	0.20278	0.21020
1.6	0.03058	0.05994	0.08709	0.11135	0.13241	0.15028	0.16515	0.17739	0.18737	0.19546	0.20731	0.21510
1.8	0.03090	0.06058	0.08804	0.11260	0.13395	0.15207	0.16720	0.17967	0.18986	0.19814	0.21032	0.21836
2.0	0.03111	0.06100	0.08867	0.11342	0.13496	0.15326	0.16856	0.18119	0.19152	0.19994	0.21235	0.22058
2.5	0.03138	0.06155	0.08948	0.11450	0.13628	0.15483	0.17036	0.18321	0.19375	0.20236	0.21512	0.22364
3.0	0.03150	0.06178	0.08982	0.11495	0.13684	0.15550	0.17113	0.18407	0.19470	0.20341	0.21633	0.22499
4.0	0.03158	0.06194	0.09007	0.11527	0.13724	0.15598	0.17168	0.18469	0.19540	0.20417	0.21722	0.22600
5.0	0.03160	0.06199	0.09014	0.11537	0.13737	0.15612	0.17185	0.18488	0.19561	0.20440	0.21749	0.22632
6.0	0.03161	0.06201	0.09017	0.11541	0.13741	0.15617	0.17191	0.18496	0.19569	0.20449	0.21760	0.22644
8.0	0.03162	0.06202	0.09018	0.11543	0.13744	0.15621	0.17195	0.18500	0.19574	0.20455	0.21767	0.22652
10.0	0.03162	0.06202	0.09019	0.11544	0.13745	0.15622	0.17196	0.18502	0.19576	0.20457	0.21769	0.22654
∞	0.03162	0.06202	0.09019	0.11544	0.13745	0.15623	0.17197	0.18502	0.19577	0.20458	0.21770	0.22656

$$m = \frac{B}{z}$$

$$n = \frac{L}{z}$$

Three-Dimensional Effect on Primary Consolidation Settlement

$$S_{c(p)} = K_{cr(} \quad S_{c(p)-oed}$$

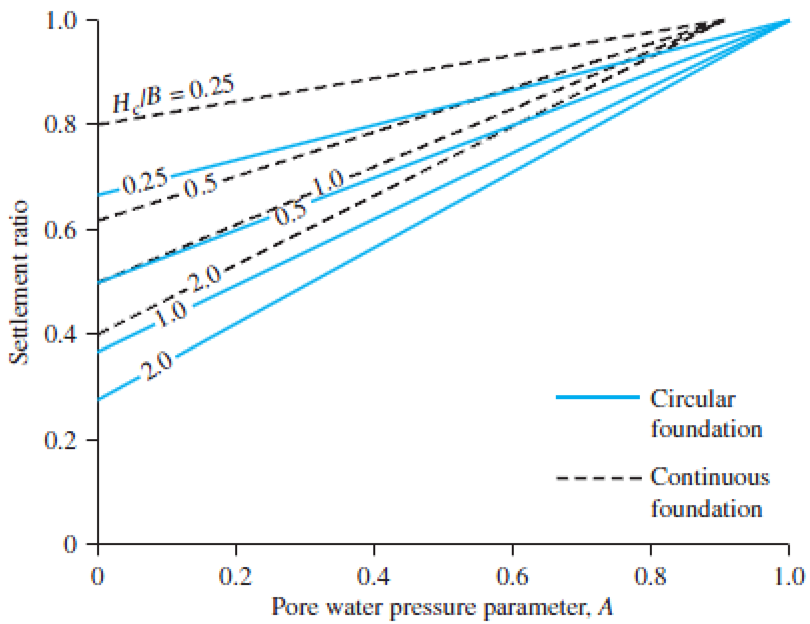


Figure 7.22 Settlement ratios for circular (K_{cir}) and continuous (K_{str}) foundations

$$S_{c(p)} = K_{cr(OC)} \, S_{c(p)-oed}$$

TABLE 9.9 Variation of $K_{cir(OC)}$ with OCR and B/H_c

OCR	$K_{cir(OC)}$		
	$B/H_c = 4.0$	$B/H_c = 1.0$	$B/H_c = 0.2$
1	1	1	1
2	0.986	0.957	0.929
3	0.972	0.914	0.842
4	0.964	0.871	0.771
5	0.950	0.829	0.707
6	0.943	0.800	0.643
7	0.929	0.757	0.586
8	0.914	0.729	0.529
9	0.900	0.700	0.493
10	0.886	0.671	0.457
11	0.871	0.643	0.429
12	0.864	0.629	0.414
13	0.857	0.614	0.400
14	0.850	0.607	0.386
15	0.843	0.600	0.371
16	0.843	0.600	0.357

Example 9.14

EXAMPLE 9.14

A plan of a foundation 1 m × 2 m is shown in Figure 9.33. Estimate the consolidation settlement of the foundation, taking into account the three-dimensional effect. Given: $A = 0.6$.

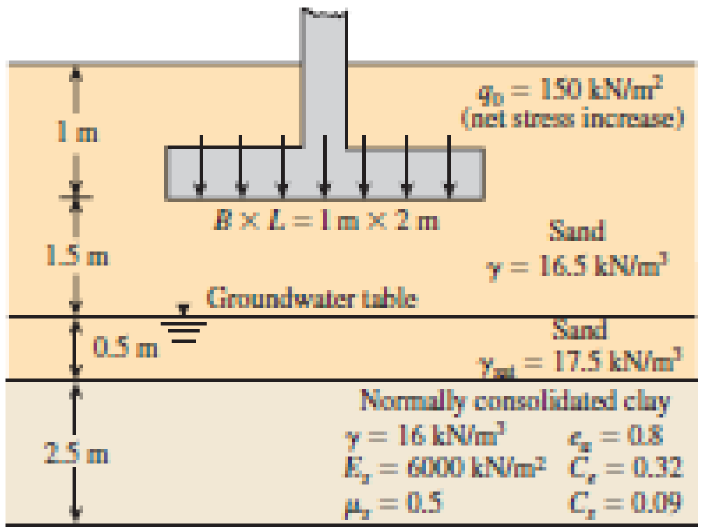


FIGURE 9.33 Calculation of primary consolidation settlement for a foundation

Example 9.14

SOLUTION

The clay is normally consolidated. Thus,

$$S_{c(p)-net} = \frac{C_c H_c}{1 + e_o} \log \frac{\sigma'_o + \Delta\sigma'_{av}}{\sigma'_o}$$

so

$$\sigma'_o = (2.5)(16.5) + (0.5)(17.5 - 9.81) + (1.25)(16 - 9.81)$$
$$= 41.25 + 3.85 + 7.74 = 52.84 \text{ kN/m}^2$$

From Eq. (8.26),

$$\Delta\sigma'_{av} = \tfrac{1}{6}(\Delta\sigma'_t + 4\Delta\sigma'_m + \Delta\sigma'_b)$$

We divide the foundation into four quarters, compute the stress increase under a corner of each quarter using Eq. (8.10), and multiply by four. For each quarter, $B = 0.5$ m and $L = 1.0$ m.

Location	z (m)	$m = B/z$	$n = L/z$	I	$\Delta\sigma' = 4q_o I$
Top	2.0	0.25	0.50	0.0475	$28.5 = \Delta\sigma'_t$
Middle	3.25	0.154	0.308	≈ 0.0213	$12.75 = \Delta\sigma'_m$
Bottom	4.5	0.111	0.222	≈ 0.0113	$6.75 = \Delta\sigma'_b$

Now,

$$\Delta\sigma'_{av} = \tfrac{1}{6}(28.5 + 4 \times 12.75 + 6.75) = 14.38 \text{ kN/m}^2$$

so

$$S_{c(p)-net} = \frac{(0.32)(2.5)}{1 + 0.8} \log\left(\frac{52.84 + 14.38}{52.84}\right) = 0.0465 \text{ m}$$
$$= \mathbf{46.5\ mm}$$

Example 9.14

Now assuming that the 2:1 method of stress increase (see Figure 8.9) holds, the area of distribution of stress at the top of the clay layer will have dimensions

$$B' = \text{width} = B + z = 1 + (1.5 + 0.5) = 3 \text{ m}$$

and

$$L' = \text{width} = L + z = 2 + (1.5 + 0.5) = 4 \text{ m}$$

The diameter of an equivalent circular area, B_{eq}, can be given as

$$\frac{\pi}{4}B_{eq}^2 = B'L'$$

so that

$$B_{eq} = \sqrt{\frac{4B'L'}{\pi}} = \sqrt{\frac{(4)(3)(4)}{\pi}} = 3.91 \text{ m}$$

Also,

$$\frac{H_c}{B_{eq}} = \frac{2.5}{3.91} = 0.64$$

From Figure 9.32, for $A = 0.6$ and $H_c/B_{eq} = 0.64$, the magnitude of $K_{cr} \approx 0.78$. Hence,

$$S_{c(p)} = K_{cir}S_{c(p)-oed} = (0.78)(46.5) \approx 36.3 \text{ mm}$$

Secondary Consolidation Settlement

The magnitude of the secondary consolidation can be calculated as:

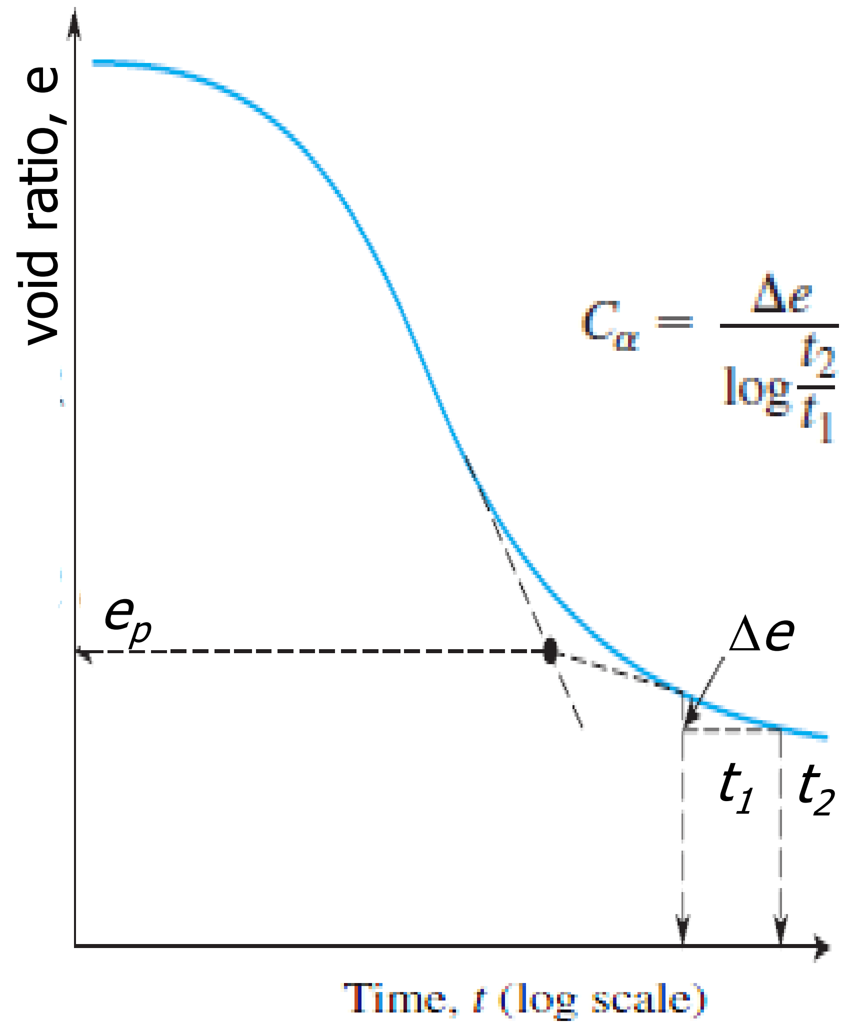
$$S_s = \frac{H}{1 + e_p} \Delta e$$

e_p void ratio at the end of primary consolidation,
H thickness of clay layer.

$$\Delta e = C_\propto log\,(t_2/t_1)$$

C_α = coefficient of secondary compression

$$S_s = \frac{C_\alpha H}{1 + e_p} log\left(\frac{t_2}{t_1}\right)$$



Secondary Consolidation Settlement

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

$C'_\alpha = C_\alpha/(1 + e_p)$
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

$$C'_\alpha \approx 0.0001w$$

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:

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

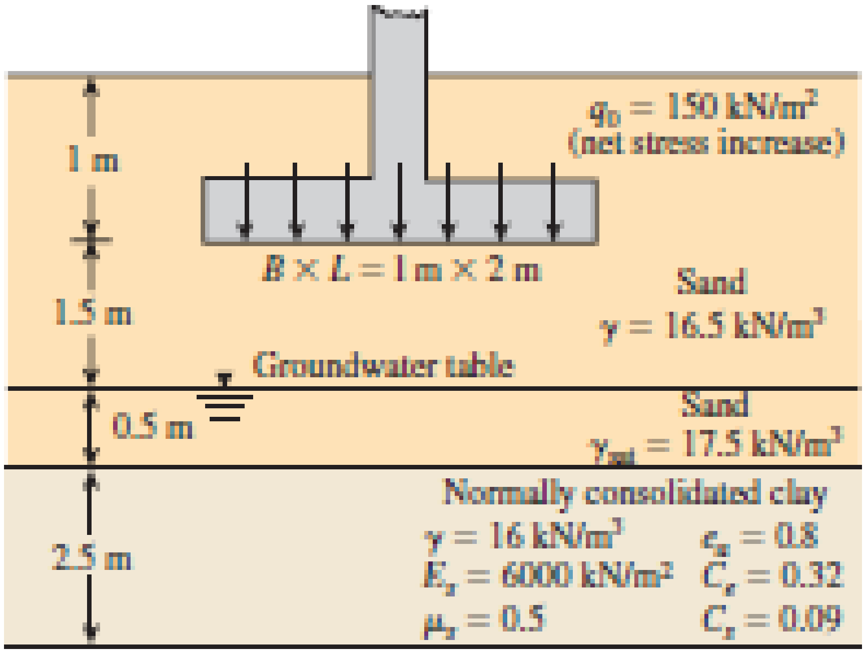
- For peats:

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

Example 9.15

EXAMPLE 9.15

Refer to Example 9.14. Given for the clay layer: $C_\alpha = 0.02$. Estimate the total consolidation settlement five years after the completion of the primary consolidation settlement. (*Note:* Time for completion of primary consolidation settlement is 1.3 years.)



Example 9.15

SOLUTION

From Eq. (2.53),

$$C_c = \frac{e_1 - e_2}{\log\left(\frac{\sigma_2'}{\sigma_1'}\right)}$$

For this problem, $e_1 - e_2 = \Delta e$. Referring to Example 9.14, we have

$$\sigma_2' = \sigma_o' + \Delta\sigma' = 52.84 + 14.38 = 67.22 \text{ kN/m}^2$$
$$\sigma_1' = \sigma_o' = 52.84 \text{ kN/m}^2$$
$$C_c = 0.32$$

Hence,

$$\Delta e = C_c \log\left(\frac{\sigma_o' + \Delta\sigma}{\sigma_o'}\right) = 0.32 \log\left(\frac{67.22}{52.84}\right) = 0.0335$$

Given: $e_o = 0.8$. Hence,

$$e_p = e_o - e = 0.8 - 0.0335 = 0.7665$$

From Eq. (9.92),

$$C_\alpha' = \frac{C_\alpha}{1 + e_p} = \frac{0.02}{1 + 0.7665} = 0.0113$$

From Eq. (9.91),

$$S_{c(s)} = C_\alpha' H_c \log\left(\frac{t_2}{t_1}\right)$$

Note: $t_1 = 1.3$ years; $t_2 = 1.3 + 5 = 6.3$ years.

Thus,

$$S_{c(s)} = (0.0113)(2.5 \text{ m}) \log\left(\frac{6.3}{1.3}\right) = 0.0194 \text{ m} = 19.4 \text{ mm}$$

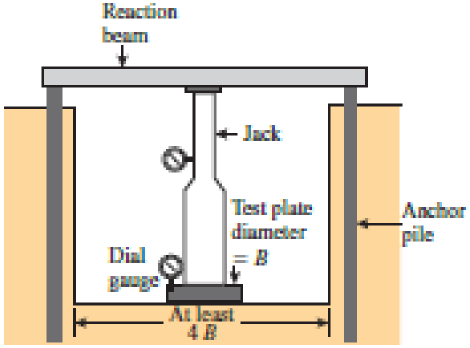
Total consolidation settlement is

$$\underbrace{36.3 \text{ mm}}_{\substack{\uparrow \\ \text{Example 9.14} \\ \text{(primary} \\ \text{consolidation} \\ \text{settlement)}}} + 19.4 = \mathbf{55.7\ m}$$

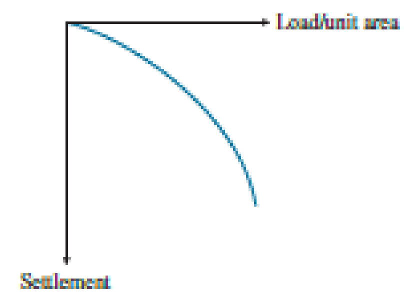
Field Load Test

The Plate Load Test (PLT)

The ultimate load-bearing capacity of a foundation, as well as the allowable bearing capacity based on tolerable settlement considerations, can be effectively determined from the field load test, generally referred to as the *plate load test*. The plates that are used for tests in the field are usually made of steel and are 25 mm thick and 150 mm to 762 mm in diameter. Occasionally, square plates that are 305 mm 3 305 mm are also used.



To conduct a plate load test, a hole is excavated with a minimum diameter of $4B$ (B is the diameter of the test plate) to a depth of D_f , the depth of the proposed foundation.



The plate is placed at the center of the hole, and a load that is about one-fourth to one-fifth of the estimated ultimate load is applied to the plate in steps by means of a jack. During each step of the application of the load, the settlement of the plate is observed on dial gauges. At least one hour is allowed to elapse between each application.

The test should be conducted until failure, or at least until the plate has gone through 25 mm of settlement.

Field Load Test

The Plate Load Test (PLT)

For tests in clay,

$$q_{u(F)} = q_{u(P)}$$

where

$q_{u(F)}$ = ultimate bearing capacity of the proposed foundation
$q_{u(P)}$ = ultimate bearing capacity of the test plate

For tests in sandy soils,

$$q_{u(F)} = q_{u(P)} \frac{B_F}{B_P}$$

where

B_F = width of the foundation
B_P = width of the test plate

FIGURE 9.36 Plate load test in the field (Courtesy of Braja M. Das, Henderson, Nevada)

The allowable bearing capacity of a foundation, based on settlement considerations and for a given intensity of load, q_o, is

$$S_F = S_P \frac{B_F}{B_P} \quad \text{(for clayey soil)}$$

and

$$S_F = S_P \left(\frac{2B_F}{B_F + B_P} \right)^2 \quad \text{(for sandy soil)}$$

The end