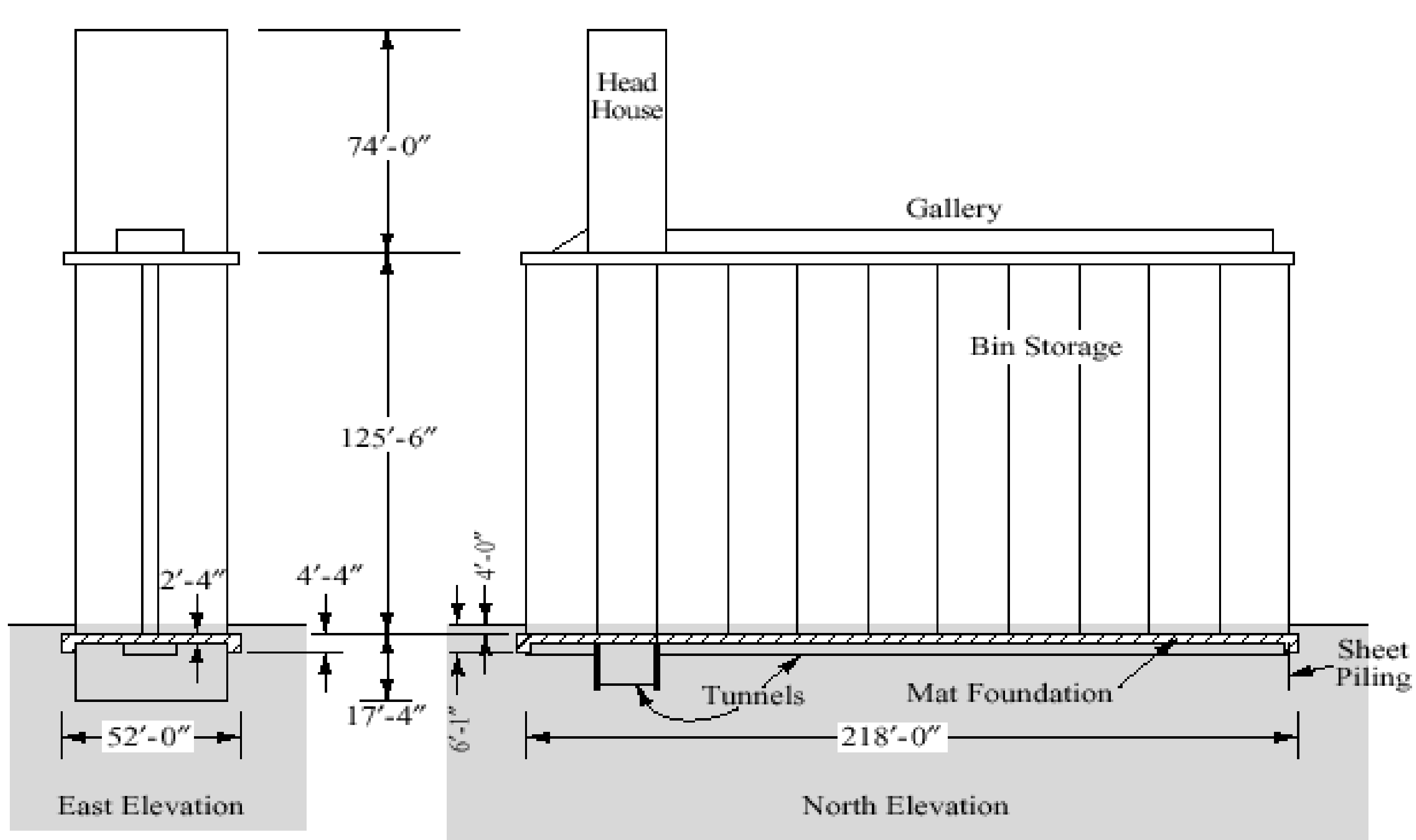


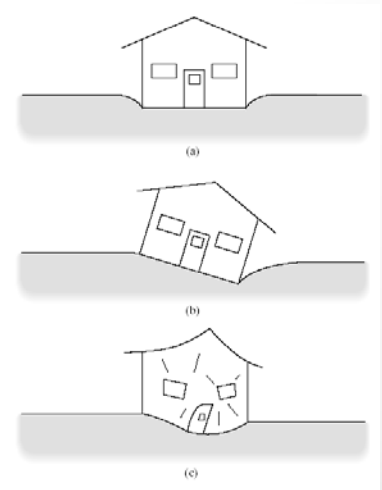
ENCE 4610 Foundation Analysis and Design

Lecture 5
Shallow Foundations
Total and Differential Settlement
Schmertmann's Method

Two Failure Modes: Strength and Serviceability

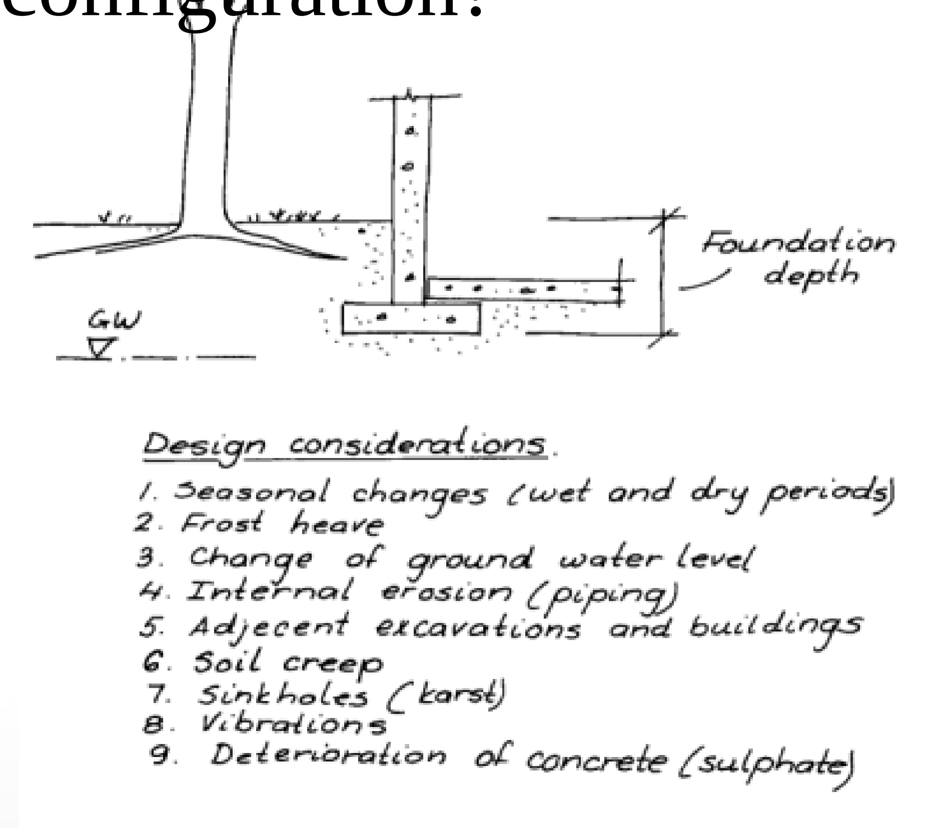
- Strength
  - Geotechnical Strength Requirements
    - Design to prevent failure by soil plastic shear failure
    - Failure is generally catastrophic
    - Can be done either using ASD or LRFD
  - Structural Strength Requirements
    - Design to avoid structural failure of foundation components
    - Similar to other structural analyses
  - Common examples: bearing capacity failure, retaining wall failure

- Serviceability
  - Generally refers to failure when gradual movement of the structure makes its use difficult or impossible
  - Failure is gradual
  - Can also be analyzed using ASD or LRFD
  - Most common example in geotechnical engineering is settlement failure



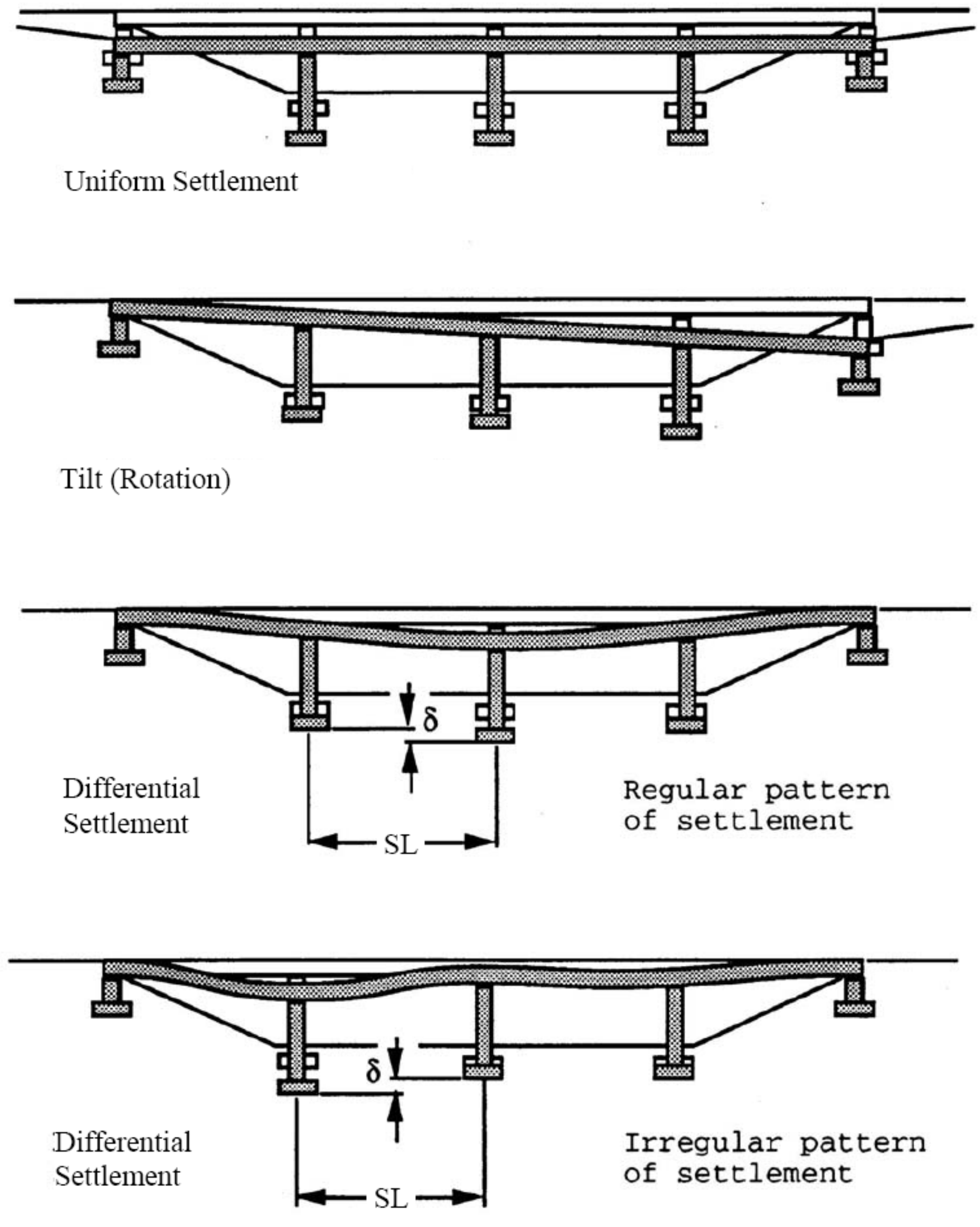
Goals in Settlement Analysis

- How much will the structure settle until it's either completely or partially inoperable?
- Analysis based on:
  - Type of Structure
  - Size of Structure
  - Use of Structure
- How much will the structure settle given the geotechnical configuration?



Types of Settlement

- Definitions of Settlement
  - o Absolute settlement, usually associated with uniform/total settlement
  - o Angular distortion settlement, usually associated with differential settlement
- Can be expensive and hinder the use of a structure
  - o “Bump in the bridge”
  - o Damage to walls and utilities (gas leaks and explosions)



A = Angular Distortion

$$A = \frac{\text{Difference in Settlement Between Foundations}}{\text{Distance Between Foundations}} = \frac{\delta}{SL}$$

Total vs. Differential Settlement

- Total Settlement
  - The uniform settlement of an entire structure
  - Assumes that the structure settles as a unit
  - Is expressed in units of length
  - Can be influenced by the following:
    - Neighboring structures (access, physical connection, utility connections)
    - Aesthetics
    - Drainage (a settled structure may be more vulnerable to ground water intrusion)

- Differential Settlement
  - The settlement of a structure from one column/pier/load bearing member to the next
  - Is expressed as a ratio of the distance between the relative settlement of two columns/piers and the distance between them
  - Can be influenced by the following:
    - Type of construction (steel, concrete, etc.)
    - Use of structure

“Typical” Values of Total Settlement

Table 8-14

Tolerable movement criteria for bridges (FHWA, 1985; AASHTO 2002, 2004)

Limiting Angular Distortion, δ/SL	Type of Bridge
0.004	Multiple-span (continuous span) bridges
0.005	Single-span bridges

Note: δ is differential settlement, SL is the span length. The quantity, δ/SL, is dimensionless and is applicable when the same units are used for δ and SL, i.e., if δ is expressed in inches then SL should also be expressed in inches.

Maximum Allowable Average Settlement of Some Structures
(Data from Item 53)

Type of Structure	Settlement, inches
Plain brick walls	
Length/Height ≥ 2.5	3
Length/Height ≤ 1.5	4
Framed structure	4
Reinforced brick walls and brick walls with reinforced concrete	6
Solid reinforced concrete foundations supporting smokestacks, silos, towers, etc	12

Example of Settlement Calculations

- Given
  - Steel framed office building, 20' column spacing, unreinforced load-bearing walls, δ /L < 1/1000
- Find
  - Allowable total settlement
  - Allowable differential settlement
- Solution
  - Typical total settlement specification = 4” (Frames structure)
  - Use δ /L = 1/1000 (Steel and concrete frame); δ_{du} = (1/1000)(20') = 0.02' = 0.25”

Estimation of Settlement

- As is typical in geotechnical engineering, there are many methods to estimate settlement
- Cohesive Soils
  - Classic primary one-dimensional consolidation settlement
  - Secondary Consolidation (secular effect)
  - Discussed in ENCE 3610
- Cohesionless Soils
  - Hough's Method (3610)
  - Schmertmann's Method (below)
- All Soils
  - Coefficient of Subgrade Reaction/Plate Load Tests (SL 6)
  - Elastic Methods (3610, used to estimate initial settlement for one-dimensional consolidation settlement

Schmertmann's Method

- Originally set forth by John Schmertmann, who did extensive research concerning settlement in sands (FL) and application of CPT methods to deep foundation capacity
- Several versions; modified version is presented
- Not necessary to use elastic settlement as initial settlement, as it incorporates theory of elasticity considerations
-

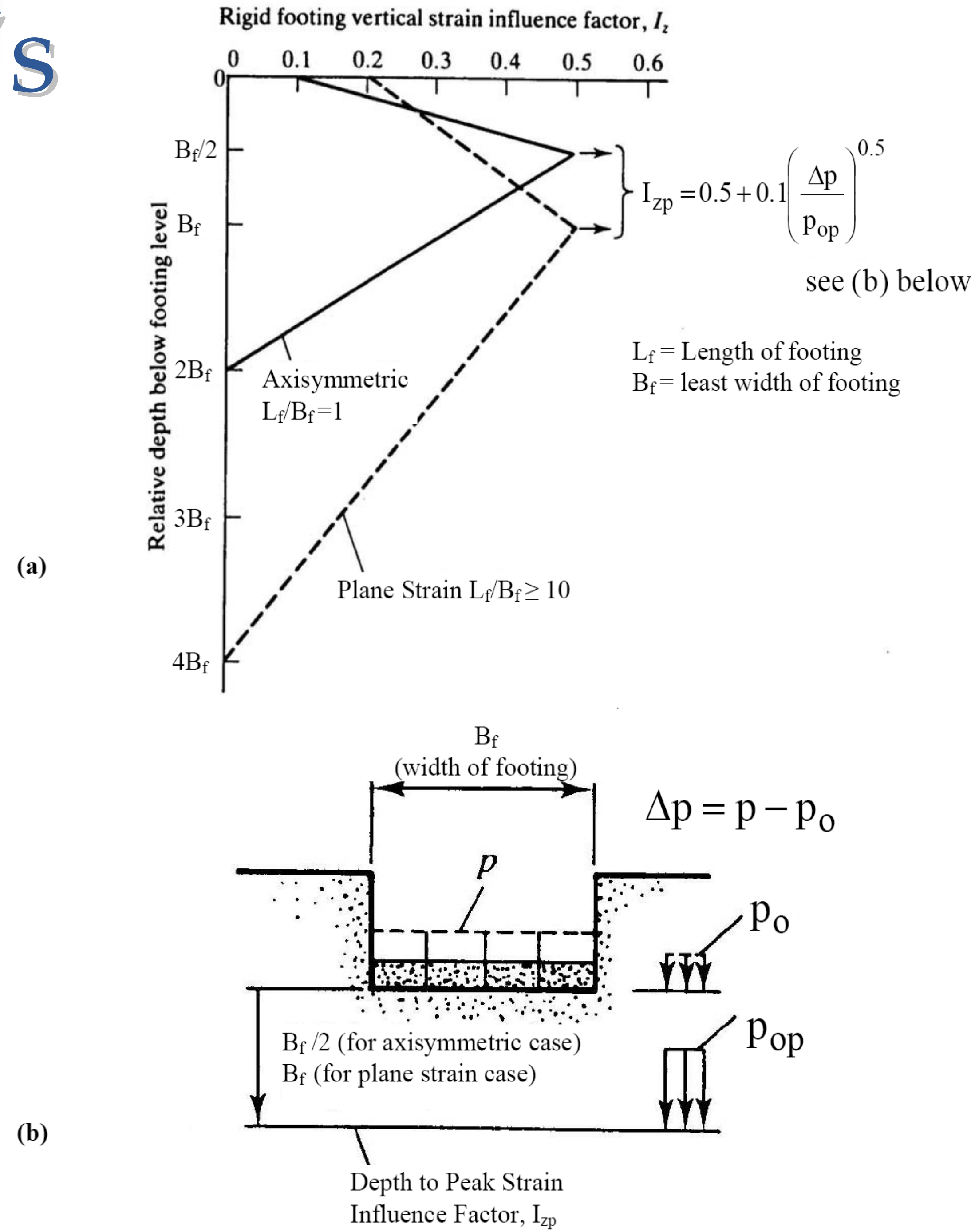


Figure 8-21. (a) Simplified vertical strain influence factor distributions, (b) Explanation of pressure terms in equation for I_{zp} (after Schmertmann, *et al.*, 1978).

8.5.1.1 Schmertmann's Modified Method for Calculation of Immediate Settlements

An estimate of the immediate settlement, S_i, of spread footings can be made by using Equation 8-16 as proposed by Schmertmann, *et al.* (1978).

$$S_i = C_1 C_2 \, \Delta p \sum_{i=1}^{n} \Delta H_i \quad \text{where} \quad \Delta H_i = H_c \left(\frac{I_z}{XE} \right) \qquad 8\text{-}16$$

where:

I_z = strain influence factor from Figure 8-21a. The dimension B_f represents the least lateral dimension of the footing after correction for eccentricities, i.e. use least lateral effective footing dimension. The strain influence factor is a function of depth and is obtained from the strain influence diagram. The strain influence diagram is easily constructed for the axisymmetric case ($L_f/B_f = 1$) and the plane strain case ($L_f/B_f \geq 10$) as shown in Figure 8-21a. The strain influence diagram for intermediate conditions can be determined by simple linear interpolation.

n = number of soil layers within the zone of strain influence (strain influence diagram).

Δp = ***net*** uniform applied stress (load intensity) at the foundation depth (see Figure 8-21b).

E = elastic modulus of layer i based on guidance provided in Table 5-16 in Chapter 5.

X = a factor used to determine the value of elastic modulus. If the value of elastic modulus is based on correlations with $N1_{60}$-values or q_c from Table 5-16 in Chapter 5, then use X as follows.

$X = 1.25$ for axisymmetric case ($L_f/B_f = 1$)
$X = 1.75$ for plane strain case ($L_f/B_f \geq 10$)

Use interpolation for footings with $1 < L_f/B_f \leq 10$

If the value of elastic modulus is estimated based on the range of elastic moduli in Table 5-16 or other sources use $X = 1.0$.

C_1 = a correction factor to incorporate the effect of strain relief due to embedment where:

$$C_1 = 1 - 0.5 \left(\frac{p_o}{\Delta p} \right) \geq 0.5 \qquad 8\text{-}17$$

where p_o is effective in-situ overburden stress at the foundation depth and Δp is the net foundation pressure as shown in Figure 8-21b

C_2 = a correction factor to incorporate time-dependent (creep) increase in settlement for t (years) after construction where:

$$C_2 = 1 + 0.2 \log_{10} \left(\frac{t(\text{years})}{0.1} \right) \qquad 8\text{-}18$$

8.5.1.2 Comments on Schmertmann's Method

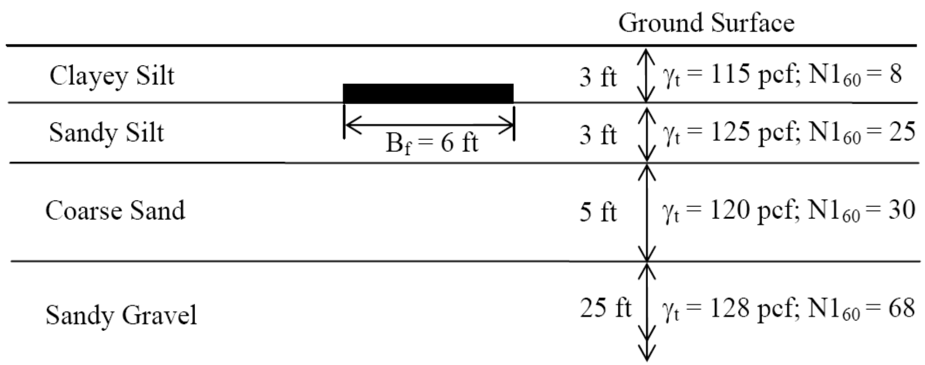
- **Effect of lateral strain**: Schmertmann and his co-workers based their method on the results of displacement measurements within sand masses loaded by model footings, as well as finite element analyses of deformations of materials with nonlinear stress-strain behavior that expressly incorporated Poisson's ratio. Therefore, the effect of the lateral strain on the vertical strain is included in the strain influence factor diagrams.

- **Effect of preloading:** The equations used in Schmertmann's method are applicable to normally loaded sands. If the sand was pre-strained by previous loading, then the actual settlements will be overpredicted. Schmertmann, *et al.* (1978) recommend a reduction in settlement after preloading or other means of compaction of half the predicted settlement. Alternatively, in case of preloaded soil deposits, the settlement can be computed by using the method proposed by D'Appolonia (1968, 1970), which includes explicit consideration of preloading.

- **C_2 correction factor**: The time duration, t, in Equation 8-18 is set to 0.1 years to evaluate the settlement immediately after construction, i.e., $C_2 = 1$. If long-term creep deformation of the soil is suspected then an appropriate time duration, t, can be used in the computation of C_2. **As explained in Sections 5.4.1 and 7.6, creep deformation is not the same as consolidation settlement.** This factor can have an important influence on the reported settlement since it is included in Equation 8-16 as a multiplier. For example, the C_2 factor for time durations of 0.1 yrs, 1 yr, 10 yrs and 50 yrs are 1.0, 1.2, 1.4 and 1.54, respectively. In cohesionless soils and unsaturated fine-grained cohesive soils with low plasticity, time durations of 0.1 yr and 1 yr, respectively, are generally appropriate and sufficient for cases of static loads. Where consolidation settlement is estimated in addition to immediate settlement, $C_2 = 1$ should be used.

The use of Schmertmann's modified method to calculate immediate settlement is illustrated numerically in Example 8-2.

Example 8-2: A 6 ft x 24 ft footing is founded at a depth of 3 ft below ground elevation with the soil profile and average $N1_{60}$ values shown. Determine the settlement in inches (a) at the end of construction and (b) 1 year after construction. There is no groundwater. The footing is subjected to an applied stress of 2,000 psf.



Solution:

Step 1: Begin by drawing the strain influence diagram. The L_f/B_f ratio for the footing is $24'/6' = 4$. From Figure 8-21(a), determine the value of the strain influence factor at the base of the footing, I_{ZB}, as follows:

$I_{ZB} = 0.1$ for axisymmetric case $(L_f/B_f = 1)$
$I_{ZB} = 0.2$ for plane strain case $(L_f/B_f \geq 10)$

Difference between axisymmetric L_f/B_f and plane strain $L_f/B_f = 9$
Difference between axisymmetric I_{ZB} and plane strain $I_{ZB} = 0.1$
Use linear interpolation for $L_f/B_f = 4$:

$\Delta(L_f/B_f)$ with respect to axisymmetric $L_f/B_f = 4\text{-}1 = 3$. Therefore

$$I_{ZB} = 0.1 + \frac{(0.2 - 0.1)}{9}(3) = 0.1 + \frac{0.1}{3} = 0.133$$

Step 2: Determine the maximum depth of influence, D_I, as follows:

$D_I = 2B_f$ for $L_f/B_f = 1$
$D_I = 4B_f$ for $L_f/B_f > 10$

By using linear interpolation $L_f/B_f = 4$ as before:

$\Delta(L_f/B_f)$ with respect to axisymmetric $L_f/B_f = 4\text{-}1 = 3$. Therefore

$$D_I = 2B_f + \frac{(4B_f - 2B_f)}{9}(3) = 2B_f + \frac{2B_f}{3} = \frac{6B_f + 2B_f}{3} = \frac{8B_f}{3}$$

$$D_I = \frac{8}{3}(6\,\text{ft}) = 16\,\text{ft}$$

Step 3: Determine the depth to the peak strain influence factor, D_{IP}, as follows:

From Figure 8-21(a) $D_{IP} = B_f/2$ for $L_f/B_f = 1$
$D_{IP} = B_f$ for $L_f/B_f > 10$

Use linear interpolation for $L_f/B_f = 4$:

$\Delta(L_f/B_f)$ with respect to axisymmetric $L_f/B_f = 4\text{-}1 = 3$. Therefore

$$D_{IP} = \frac{B_f}{2} + \frac{\left(B_f - \frac{B_f}{2}\right)}{9}(3) = \frac{B_f}{2} + \frac{B_f}{6} = \frac{3B_f + B_f}{6} = \frac{4B_f}{6}$$

$$D_{IP} = \frac{4}{6}(6\,\text{ft}) = 4\,\text{ft}$$

Step 4: Determine the value of the maximum strain influence factor, I_{ZP}, as follows:

$$I_{ZP} = 0.5 + 0.1\left(\frac{\Delta p}{p_{op}}\right)^{0.5}$$

$$\Delta p = 2{,}000\,\text{psf} - 3\,\text{ft}(115\,\text{pcf}) = 1{,}655\,\text{psf}$$

$$p_{op} = 3\,\text{ft}(115\,\text{pcf}) + 3\,\text{ft}(125\,\text{pcf}) + 1\,\text{ft}(120\,\text{pcf})$$

$$p_{op} = 345\,\text{psf} + 375\,\text{psf} + 120\,\text{psf} = 840\,\text{psf}$$

$$I_{ZP} = 0.5 + 0.1\sqrt{\frac{1{,}655\text{psf}}{840\text{psf}}} = 0.64$$

Step 5: Draw the I_Z vs. depth diagram as follows and divide it into convenient layers by using the following guidelines:

- The depth of the peak value of the strain influence is fixed. To aid in the computation, develop the layering such that one of the layer boundaries occurs at this depth even though it requires that an actual soil layer be sub-divided.
- Limit the top layer as well as the layer immediately below the peak value of influence factor, I_{zp}, to $2/3B_f$ or less to adequately represent the variation of the influence factor within D_{IP}.
- Limit maximum layer thickness to 10 ft (3 m) or less.
- Match the layer boundary with the subsurface profile layering.

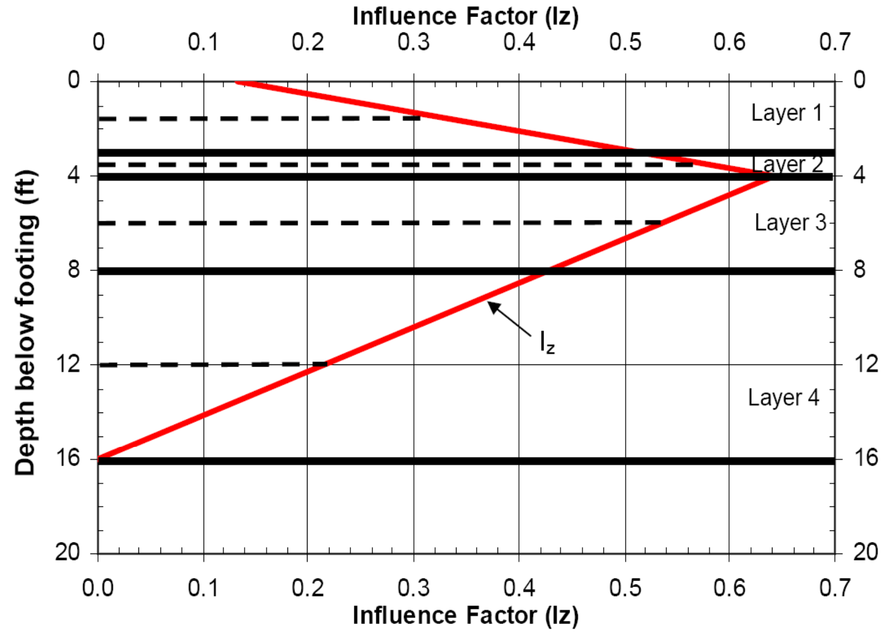
In accordance with the above guidelines, the influence depth of 16 ft is divided into 4 layers as shown below. Since the strain influence diagram starts at the base of the footing, the thickness of Layer 1 corresponds to the thickness of the sandy silt layer shown in the soil profile. Likewise, Layer 4 corresponds to the thickness of the sandy gravel layer that has been impacted by the strain influence diagram. The sum of the thicknesses of Layers 2 and 3 correspond to the thickness of the coarse sand layer shown in the soil profile. The sub-division is made to account for the strain influence diagram going though its peak value within the coarse sand layer. The minimum and maximum layer thicknesses are 1 ft (Layer 2) and 8 ft (Layer 4), respectively. The layer boundaries are shown by solid lines while the layer centers are shown by dashed lines.

Step 6: Determine value of elastic modulus E_s from Table 5-16 from Chapter 5.

Layer 1: Sandy Silt: $E = 4N1_{60}$ tsf
Layer 2: Coarse Sand: $E = 10N1_{60}$ tsf
Layer 3: Coarse Sand: $E = 10N1_{60}$ tsf
Layer 4: Sandy Gravel: $E = 12N1_{60}$ tsf

Since the elastic modulus E_s is based on correlations with $N1_{60}$-values obtained from Table 5-16, calculate the X multiplication factor as follows:

$X = 1.25$ for $L_f/B_f = 1$
$X = 1.75$ for $L_f/B_f \geq 10$



Use linear interpolation for $L_f/B_f = 4$

Δ (L_f/B_f) with respect to axisymmetric $L_f/B_f = 4\text{-}1 = 3$

$$X = 1.25 + \frac{(1.75 - 1.25)}{9}(3) = 1.42$$

Step 7: Using the thickness of each layer, H_c, and the relevant values for that particular layer, determine the settlement by setting up a table as follows:

Layer	H_c (inches)	$N1_{60}$	E (tsf)	XE (tsf)	Z_i (ft)	I_Z at Z_i	$\Delta H_i = \frac{I_Z}{XE} H_c$ (in/tsf)
1	36	25	100	142	1.5	0.323	0.0819
2	12	30	300	426	3.5	0.577	0.0163
3	48	30	300	426	6	0.533	0.0601
4	96	68	816	1,159	12	0.213	0.0177
						ΣH_i=	**0.1760**

Step 8: Determine embedment factor (C_1) and creep factor (C_2) as follows:

a) Embedment factor

$$C_1 = 1 - 0.5\left(\frac{p_o}{\Delta p}\right) = 1 - 0.5\left(\frac{3\,\text{ft} \times 115\,\text{pcf}}{1655\,\text{psf}}\right) = 0.896$$

b) Creep Factor

$$C_2 = 1 + 0.2\log_{10}\left(\frac{t(\text{years})}{0.1}\right)$$

- For end of construction t(yrs) = 0.1 yr (1.2 months)

$$C_2 = 1 + 0.2\log_{10}\left(\frac{0.1}{0.1}\right) = 1.0$$

- For end of 1 year:

$$C_2 = 1 + 0.2\log_{10}\left(\frac{1}{0.1}\right) = 1.2$$

Step 9: Determine the settlement at end of construction as follows:

$$S_i = C_1 C_2 \Delta p \sum H_i$$

$$S_i = (0.896)(1.0)\left(\frac{1{,}655\,\text{psf}}{2{,}000\,\text{psf}/\text{tsf}}\right)\left(0.1760\,\frac{\text{in}}{\text{tsf}}\right)$$

$$S_i = 0.130\,\text{inches}$$

Step 10: Determine the settlement after 1 year as follows:

$$S_i = 0.130\,\text{inches}\left(\frac{1.2}{1.0}\right) = 0.156\,\text{inches}$$

8.5.1.3 Tabulation of Parameters in Schmertmann's Method

To facilitate computations, Table 8-11 presents a tabulation of the various parameters involved in computation of settlement by Schmertmann's method. This table was generated by using the linear interpolation scheme demonstrated in Example 8-2. Linear interpolation may be used for L_f/B_f values between those presented in Table 8-11.

Table 8-11

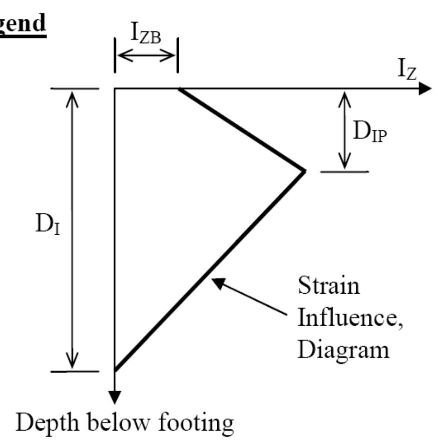
Values of parameters used in settlement analysis by Schmertmann's method

L_f/B_f	I_z at footing base, I_{ZB}	Depth to I_{zp}, D_{IP}	Depth of I_Z diagram, D_I	X factor	L_f/B_f	I_z at footing base, I_{ZB}	Depth to I_{zp}, D_{IP}	Depth of I_Z diagram, D_I	X factor
		Note 1	Note 1	Note 2			Note 1	Note 1	Note 2
1.00	**0.100**	**0.500**	**2.000**	**1.250**	**6.00**	**0.156**	**0.778**	**3.111**	**1.528**
1.25	0.103	0.514	2.056	1.264	6.25	0.158	0.792	3.167	1.542
1.50	0.106	0.528	2.111	1.278	6.50	0.161	0.806	3.222	1.556
1.75	0.108	0.542	2.167	1.292	6.75	0.164	0.819	3.278	1.569
2.00	**0.111**	**0.556**	**2.222**	**1.306**	**7.00**	**0.167**	**0.833**	**3.333**	**1.583**
2.25	0.114	0.569	2.278	1.319	7.25	0.169	0.847	3.389	1.597
2.50	0.117	0.583	2.333	1.333	7.50	0.172	0.861	3.444	1.611
2.75	0.119	0.597	2.389	1.347	7.75	0.175	0.875	3.500	1.625
3.00	**0.122**	**0.611**	**2.444**	**1.361**	**8.00**	**0.178**	**0.889**	**3.556**	**1.639**
3.25	0.125	0.625	2.500	1.375	8.25	0.181	0.903	3.611	1.653
3.50	0.128	0.639	2.556	1.389	8.50	0.183	0.917	3.667	1.667
3.75	0.131	0.653	2.611	1.403	8.75	0.186	0.931	3.722	1.681
4.00	**0.133**	**0.667**	**2.667**	**1.417**	**9.00**	**0.189**	**0.944**	**3.778**	**1.694**
4.25	0.136	0.681	2.722	1.431	9.25	0.192	0.958	3.833	1.708
4.50	0.139	0.694	2.778	1.444	9.50	0.194	0.972	3.889	1.722
4.75	0.142	0.708	2.833	1.458	9.75	0.197	0.986	3.944	1.736
5.00	**0.144**	**0.722**	**2.889**	**1.472**	**10.00**	**0.200**	**1.000**	**4.000**	**1.750**
5.25	0.147	0.736	2.944	1.486	**> 10**	**0.200**	**1.000**	**4.000**	**1.750**
5.50	0.150	0.750	3.000	1.500					
5.75	0.153	0.764	3.056	1.514					

Notes:

1. The depths are obtained by multiplying the value in this column by the footing width, B_f.
2. If elastic modulus is not based on SPT or CPT, then X=1.0. See Section 8.5.1.1 for a discussion on values of X factor.

Legend



Questions?