

Lecture 11

Soil Compression: Elastic Settlement

Text: Das, 2010. Chapter 11

A stress increase caused by the construction of foundations or other loads compresses soil layers. Similarly stress decreases caused by excavation of soil layers causes decompression of the soil.

Compression is caused by:

1. Deformation of soil particles
2. Relocation of soil particles and
3. Expulsion of water or air from the void spaces

Compression is an effect on the volume and depth of a soil, causing settlement of constructed foundations and earthworks. This must be distinguished from *compaction*, which relates to the density and strength of a soil.

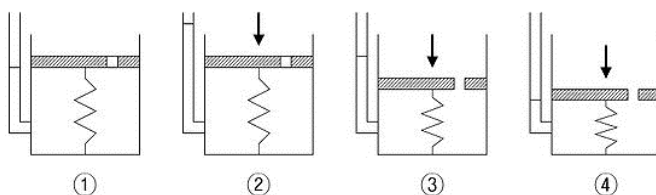
If settlement is not managed to tolerable limits there will be excessive deformation of structures or earthworks and structural functions will be impaired.

1/17

Soil Compressibility

In general soil settlement caused by loads may be divided into three time-phases:

- **Elastic (or immediate) settlement:** This is caused by elastic deformation of dry soil and of moist and saturated soils without any change in the moisture content. Gas, liquid and solid fractions of soil are all compressible.
- **Primary Consolidation Settlement:** This is the result of volume changes in saturated cohesive soils because of expulsion of air and water from voids
- **Secondary Consolidation Settlement:** This is observed in saturated cohesive soils and is the result of plastic adjustment (permanent deformation) of soil fabrics. It occurs at constant effective stress.



Initial loading causes an increase in pore pressure but no compression of the soil. As pore pressure dissipates, the soil is compressed.

http://en.wikipedia.org/wiki/Soil_mechanics

2/17

Soil Compressibility

The total settlement of the soil can then be given as:

$$S_T = S_e + S_c + S_s$$

S_T = total settlement

S_e = elastic settlement

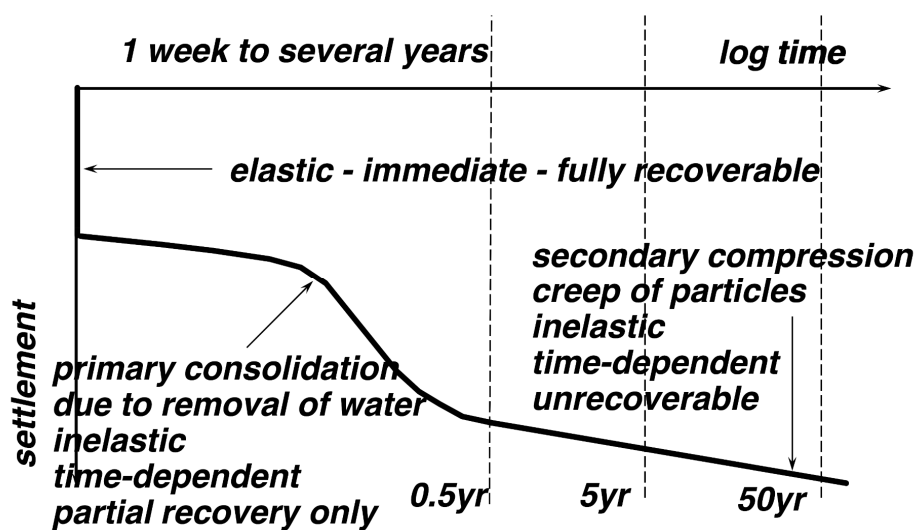
S_c = primary consolidation settlement

S_s = secondary consolidation settlement

When foundations are constructed on very compressible clays, the consolidation settlement can be several times greater than the elastic settlement.

3/17

Time-frame of Settlement



<http://en.wikipedia.org/wiki/Airport>

4/17

Elastic Settlement

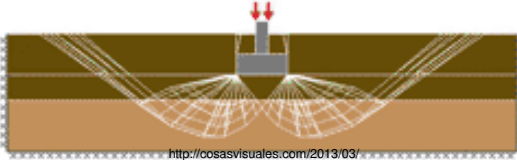
Elastic or immediate settlement of foundations occurs directly after the application of a load without a change in the moisture content of the soil.

The magnitude of the elastic settlement will depend on the flexibility of the foundation and the type of material on which it is resting.

Previously, calculations of stress increase (which cause elastic settlement) were based on the following assumptions:

- The load is applied at the ground surface
- The loaded foundation is flexible
- The soil medium is homogenous, elastic, isotropic and extends to a great depth.

In the following development we will relax some or all of these restrictions and be more specific about which assumptions are most critical.

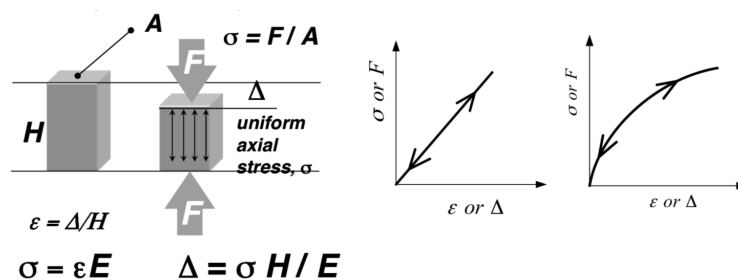


Note that we are not yet considering deformations due to soil failure (we'll get to that soon enough)

Elastic Settlement

Elastic settlement is:

- Fully recoverable or reversible
- Not time-dependent
- Based on calculations derived from the theory of elasticity



http://www.scielo.br/scielo.php?pid=S0006-87052001000200002&script=sci_arttext

Flexible and Inflexible Foundations

In general, foundations are not perfectly flexible and are embedded a certain distance below the ground surface

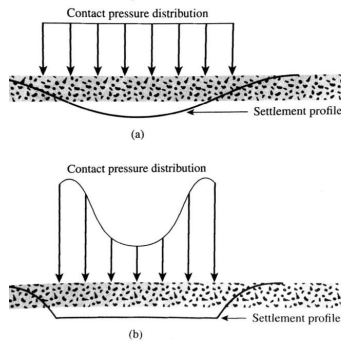


Figure 11.1: Elastic settlement profile and contact pressure in CLAY: (a) flexible foundation; (b) rigid foundation (Das, 2010, p. 295)

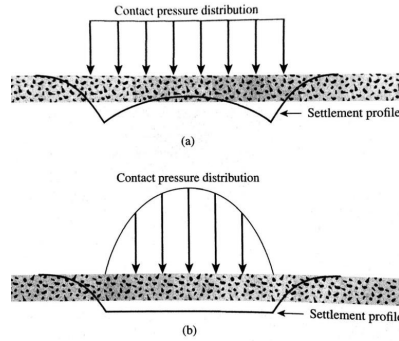


Figure 11.2: Elastic settlement profile and contact pressure in SAND: (a) flexible foundation; (b) rigid foundation (Das, 2010, p. 296)

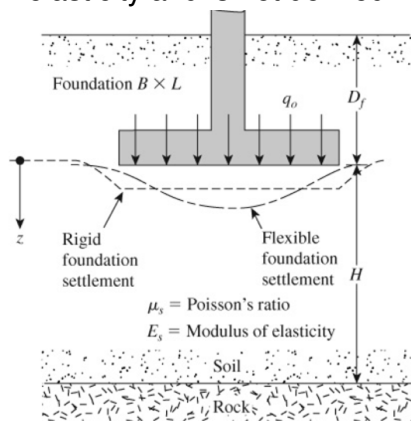
Figure 11.1 compares a perfectly flexible and a perfectly rigid foundation resting on an elastic cohesive material such as saturated clay. Flexure or non-flexure of the foundation results in redistribution either of the stress or the deformation of the soil.

Figure 11.2 shows a similar comparison for an elastic, non-cohesive soil such as loose sand. The sand at the edge of a flexible foundation is pushed outward and the foundation sags at the edges.

7/17

Elastic Settlement Calculation

Settlement under a flexible foundation is based on the theory of elasticity and is not derived here:



B = Width of the foundation
 L = Length of the foundation
 D_f = Depth of the foundation
 H = Depth to the rock from foundation level

Figure 11.3: Elastic settlement of flexible and rigid foundations (Das, 2010, p. 296)

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

Bowels (1987)

q_0 = net applied pressure on the foundation

μ_s = Poisson's ratio of soil

E_s = Average modulus of elasticity from
 $z = 0$ to about $z = 4B$

$B' = B/2$ for the centre of foundation
 $= B$ for corner of foundation

I_s = shape factor (Steinbrenner, 1934)

I_f = depth factor (Fox, 1948)

8/17

Elastic Settlement Calculation

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

I_s = shape factor

$\alpha = 4$ at the centre of a foundation

$\alpha = 1$ at the corner of a foundation

$$I_s = F_1 + \frac{1 - 2\mu_s}{1 - \mu_s} F_2$$

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

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

$$A_0 = m' \ln \frac{(1 + \sqrt{m'^2 + 1}) \sqrt{m'^2 + n'^2}}{m' (1 + \sqrt{m'^2 + n'^2 + 1})}$$

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

$$A_2 = \frac{m'}{n' \sqrt{m'^2 + n'^2 + 1}}$$

To calculate the settlement
at the centre of the foundation

$$m' = \frac{L}{B} \quad n' = \frac{H}{(B/2)}$$

To calculate the settlement
at a corner of the foundation

$$m' = \frac{L}{B} \quad n' = \frac{H}{B}$$

9/17

Elastic Settlement Calculation

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

I_f = depth factor

$$I_f = f \left(\frac{D_f}{B}, \mu_s, \frac{L}{B} \right)$$

As a first estimate, I_f averages around 0.7. See Table 11.3 (Das).

10/17

Table 11.3 Variation of I_f with L/B and D_f/B

L/B	D_f/B	I_f		
		$\mu_s = 0.3$	$\mu_s = 0.4$	$\mu_s = 0.5$
1	0.5	0.77	0.82	0.85
	0.75	0.69	0.74	0.77
	1	0.65	0.69	0.72
2	0.5	0.82	0.86	0.89
	0.75	0.75	0.79	0.83
	1	0.71	0.75	0.79
5	0.5	0.87	0.91	0.93
	0.75	0.81	0.86	0.89
	1	0.78	0.82	0.85

(Source: Das, 2010, p. 302)

11/17

Elastic Settlement Calculation

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

Representative values of the modulus of elasticity E_s and Poisson's ratio μ_s are given in tables 11.4 and 11.5

Table 11.4 Representative Values of the Modulus of Elasticity of Soil

Soil type	E_s (kN/m ²)
Soft clay	1,800–3,500
Hard clay	6,000–14,000
Loose sand	10,000–28,000
Dense sand	35,000–70,000

Table 11.5 Representative Values of Poisson's Ratio

Type of soil	Poisson's ratio, μ_s
Loose sand	0.2–0.4
Medium sand	0.25–0.4
Dense sand	0.3–0.45
Silty sand	0.2–0.4
Soft clay	0.15–0.25
Medium clay	0.2–0.5

(Source: Das, 2010, p. 302-3)

12/17

Due to the heterogeneous nature of soil deposits, the magnitude of E_s may vary with depth. For that reason, Bowles (1987) recommended using average of E_s

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

$E_{s(i)}$ = soil modulus of elasticity within a depth Δz
 $\bar{z} = H$ or $5B$, whichever is smaller

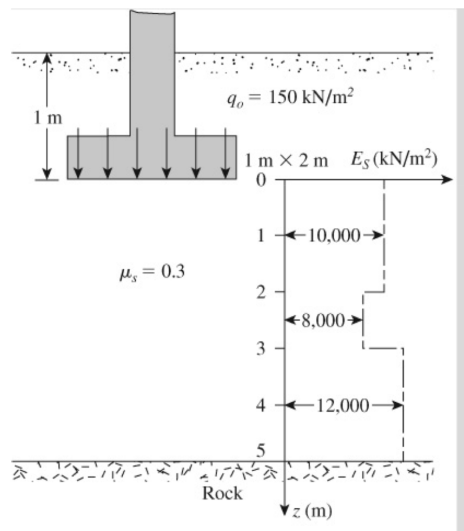
Lastly a correction for rigid foundation settlement is estimated as:

$$S_{e(\text{rigid})} = 0.93 S_{e(\text{flexible, centre})}$$

1317

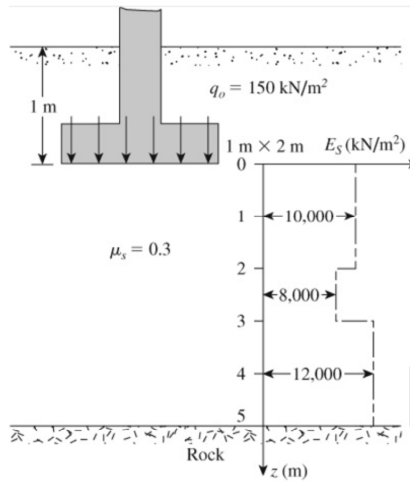
Example 11.1

A flexible shallow foundation 1 m X 2 m is shown below. Calculate the elastic settlement at the centre of the foundation.



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

1417



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

$$B = 1 \text{ m}, L = 2 \text{ m} \quad \bar{z} = 5 \text{ m} = 5B$$

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

$$E_s = \frac{(10,000 \times 2) + (8,000 \times 1) + (12,000 \times 2)}{5} = 10,400 \text{ kPa}$$

For centre of foundation

$$\alpha = 4, \quad m' = \frac{L}{B} = \frac{2}{1} = 2, \quad n' = \frac{H}{(B/2)} = \frac{5}{0.5} = 10$$

$$B' = \frac{B}{2} = \frac{1}{2} = 0.5$$

1517

$$m' = 2, \quad n' = 10$$

From tables, $F_1 = 0.641$ $F_2 = 0.031$

$$I_s = F_1 + \frac{1 - 2\mu_s}{1 - \mu_s} F_2 = 0.641 + \frac{1 - 2 \times 0.3}{1 - 0.3} \times 0.031 = 0.659$$

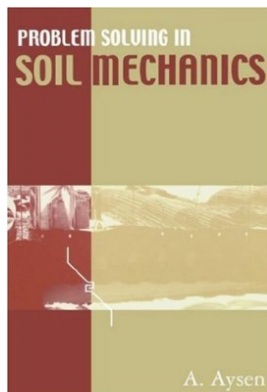
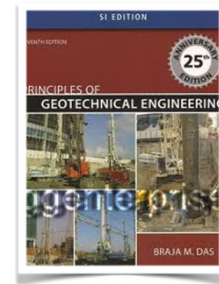
$$\frac{D_f}{B} = \frac{1}{1} = 1, \quad \frac{L}{B} = \frac{2}{1} = 2, \quad \mu_s = 0.3 \text{ from figures, } I_f = 0.709$$

$$S_e = q_0 (\alpha B') \frac{1 - \mu_s^2}{E_s} I_s I_f = 150 \times 4 \times 0.5 \times \frac{(1 - 0.3^2)}{10,400} \times 0.659 \times 0.709 = 0.01227 = 12.27 \text{ mm}$$

1617

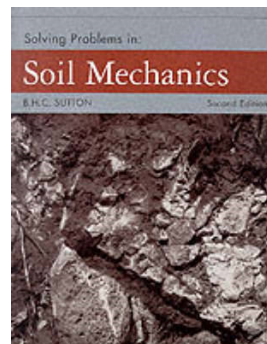
Readings

Chapter 11.1-11.2 Das

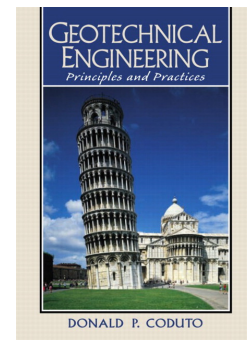


<http://www.ebay.com/ctg/Problem-Solving-Soil-Mechanics-A-Aysen-2004-Paperback-/52853454>

<http://www.bookdepository.com/Solving-Problems-Soil-Mechanics-BHC-Sutton/9780582089716>



17/17



<http://www.tower.com/foundation-design-principles-practices-donald-p-coduto-hardcover/wapi/100501083>