Consolidation settlement

The total settlement of a foundation can then be given as

$$S_T = S_C + S_S + S_e$$

Where
S_T: *Total settlement*
S_C: *Primary consolidation settlement*
S_S: *Secondary consolidation settlement*
S_e: *Elastic settlement*

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

Fundamental of Consolidation settlement

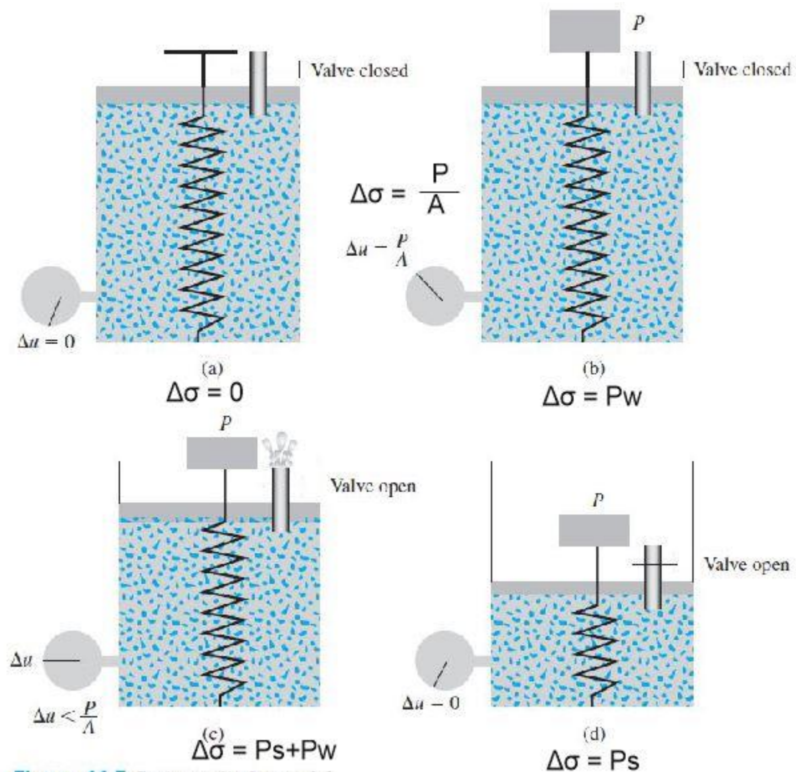


Figure 11.5 Spring-cylinder model

One-Dimensional Laboratory Consolidation Test

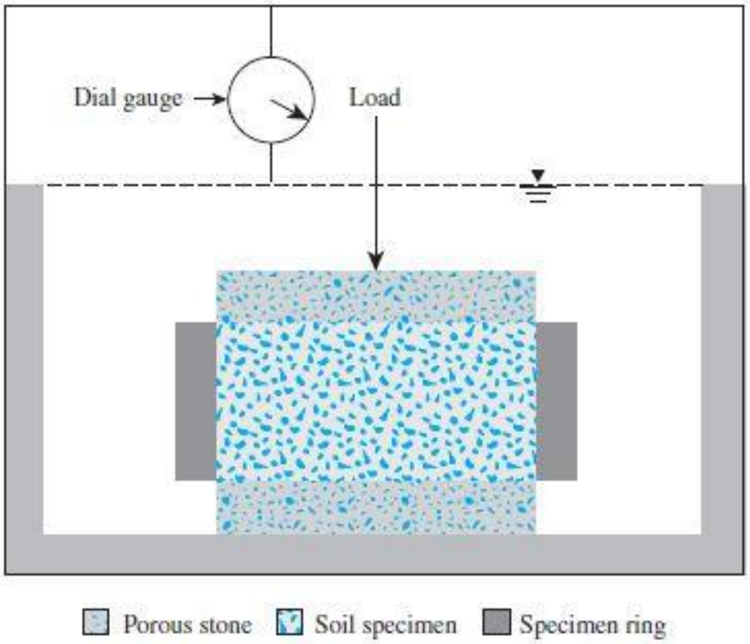
The one-dimensional consolidation testing procedure was first suggested by Terzaghi. This test is performed in a consolidometer (sometimes referred to as an *oedometer*). The schematic diagram of a consolidometer is shown in Figure 11.7a. Figure 11.7b. shows a photograph of a consolidometer. The soil specimen is placed inside a metal ring with two porous stones, one at the top of the specimen and another at the bottom. The specimens are usually 64 mm (≈ 2.5 in.) in diameter and 25 mm. (≈ 1 in.) thick. The load on the specimen is applied through a lever arm, and compression is measured by a micrometer dial gauge. The specimen is kept under water during the test. Each load usually is kept for 24 hours. After that, the load usually is doubled, which doubles the pressure on the specimen, and the compression measurement is continued. At the end of the test, the dry weight of the test specimen is determined. Figure 11.7c shows a consolidation test in progress (right-hand side).

The general shape of the plot of deformation of the specimen against time for a given load increment is shown in Figure 11.8. From the plot, we can observe three distinct stages, which may be described as follows:

Stage I: Initial compression, which is caused mostly by preloading.

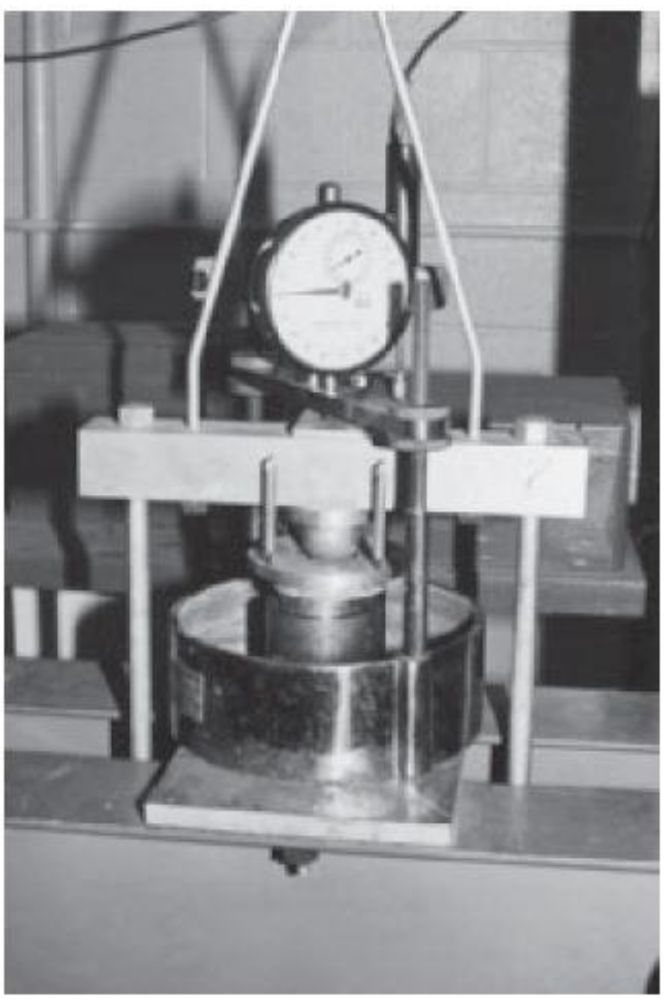
Stage II: Primary consolidation, during which excess pore water pressure gradually is transferred into effective stress because of the expulsion of pore water.

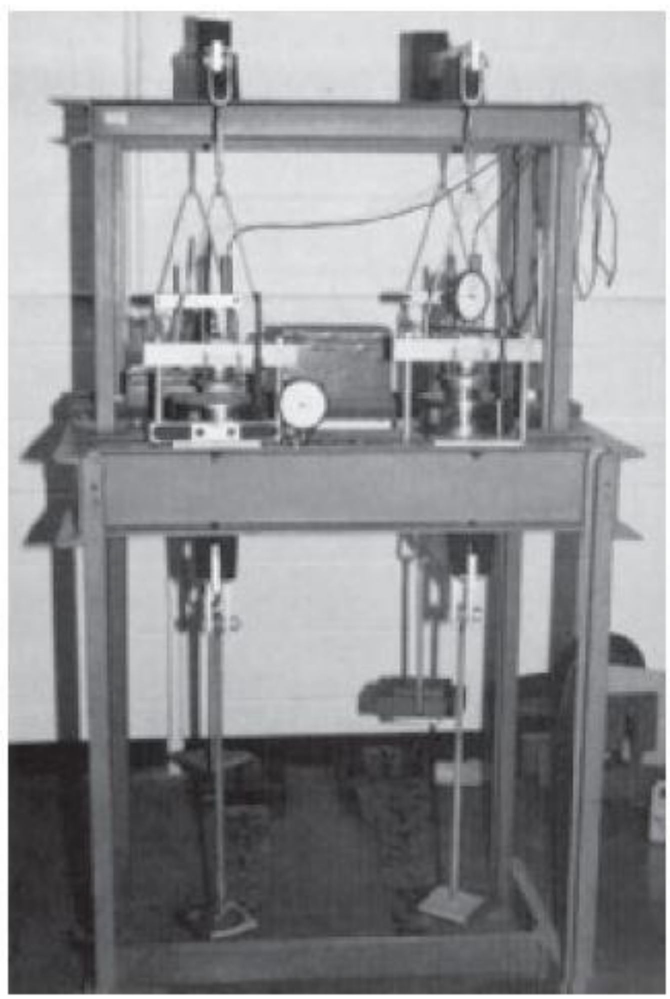
Stage III: Secondary consolidation, which occurs after complete dissipation of the excess pore water pressure, when some deformation of the specimen takes place because of the plastic readjustment of soil fabric.



(a)

Figure 11.7
(a) Schematic diagram of a consolidometer; (b) photograph of a consolidometer; (c) a consolidation test in progress (right-hand side) (*Courtesy of Braja M. Das, Henderson, Nevada*)





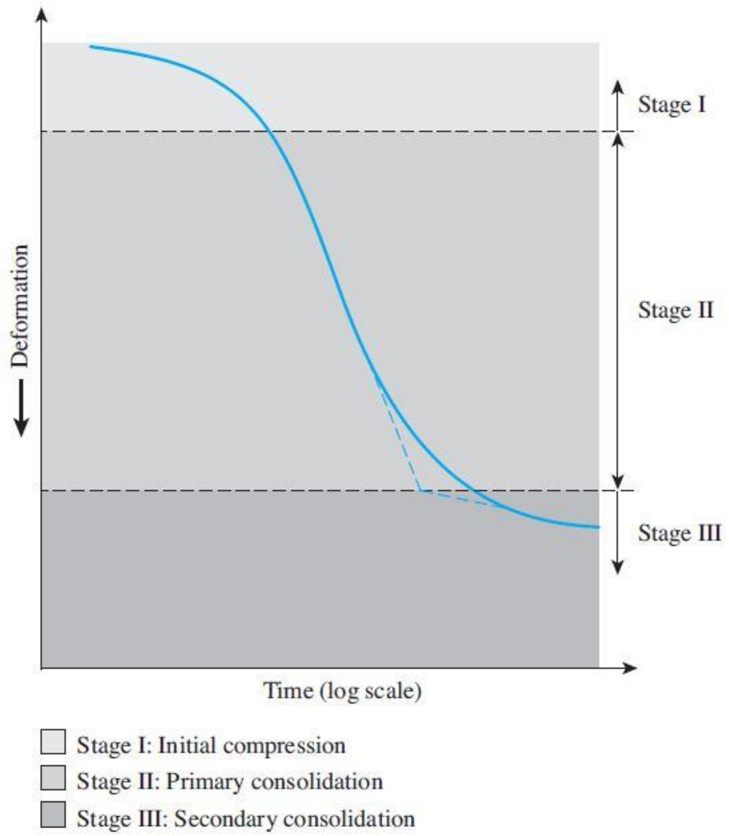


Figure 11.8 Time–deformation plot during consolidation for a given load increment

Calculation of Settlement from one dimensional consolidation

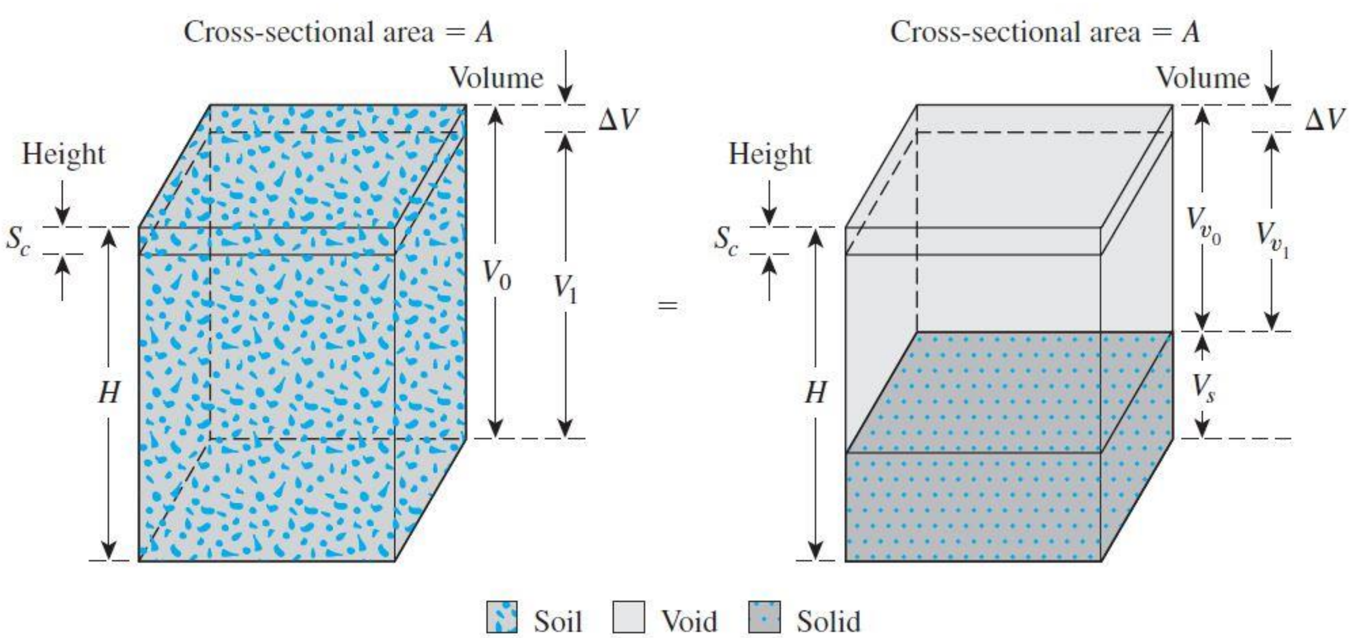


Figure 11.16 Settlement caused by one-dimensional consolidation

$$e_o = \frac{v_{vo}}{v_s} \ , \quad e_1 = \frac{v_{v1}}{v_s}, \Delta e = e_o - e_1 = \frac{v_{vo} - v_{v1}}{v_s} = \frac{\Delta v}{v_s}$$

$$\Delta v = \Delta e \, v_s \qquad (1)$$

But

$$v_o = v_s + v_{vo}$$

$$v_o = v_s + e_o v_s = v_s(1 + e_o)$$

$$v_s = \frac{v_o}{1+e_o} \qquad (2)$$

Sub 2 in 1

$$\Delta v = \Delta e \, \frac{v_o}{1+e_o} \qquad (3)$$

But from Fig.11.16

$$S_C A = \Delta v \qquad and \qquad v_o = AH \quad sub\ in\ Eq.3$$

$$S_C A = \Delta e \, \frac{AH}{1+e_o}$$

$$S_C = \Delta e \, \frac{H}{1+e_o}$$ **or**

$$S_C = \frac{\Delta e}{1+e_o} H \qquad (4)$$

Void ration – Pressure curve

After the time–deformation plots for various loadings are obtained in the laboratory, it is necessary to study the change in the void ratio of the specimen with pressure. Following is a step-by-step procedure for doing so:

Step 1: Calculate the height of solids, H_S in the soil specimen (Figure 11.9) using the equation

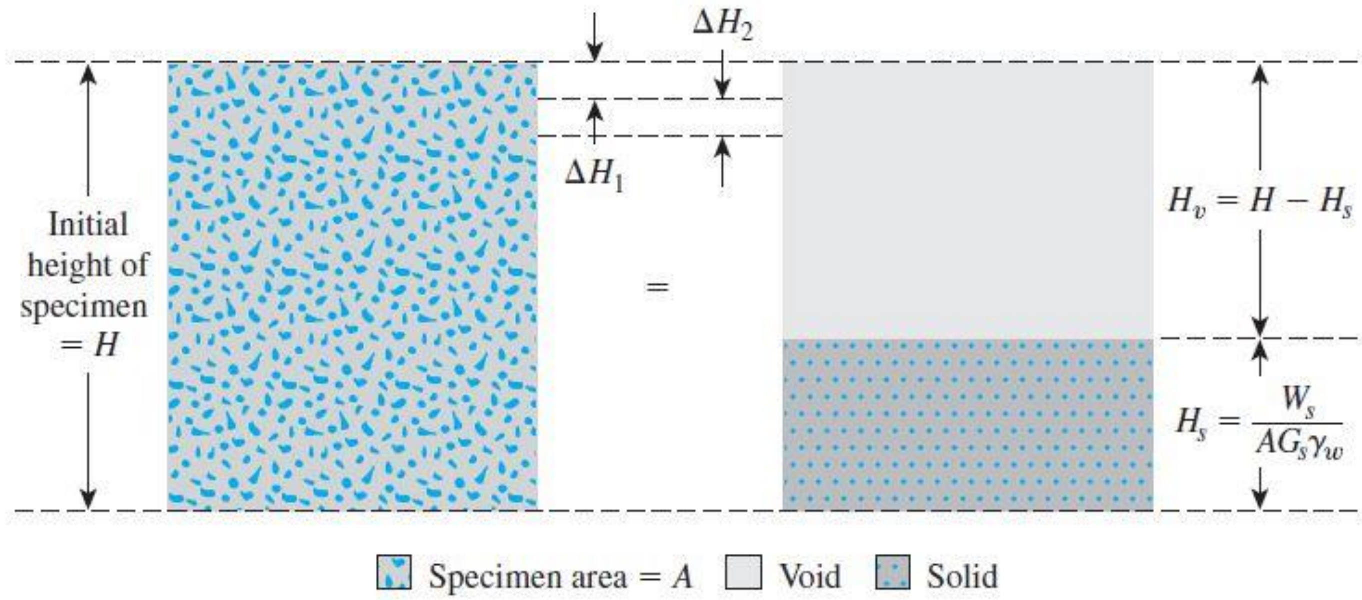


Figure 11.9 Change of height of specimen in one-dimensional consolidation test

$$H_S = \frac{W_S}{AG_S\gamma_w} = \frac{M_S}{AG_S\rho_w} \qquad (5)$$

Where W_S = the weight of soil

A= area of the specimen

γ = unit weight of soil

G_S = Specific gravity

Step 2: Calculate the initial height of voids as

$$H_v = H - H_S$$

where *H* is the initial height of the specimen.

Step 3: Calculate the initial void ratio, e_o, of the specimen, using Eq.1

$$e_O = \frac{H_v}{H_S}$$

Step 4: For the first incremental loading, σ_1 (total load/unit area of specimen), which causes a deformation _H_1, calculate the change in the void ratio as

$$\Delta v = \Delta e\, v_s \qquad (1)$$

$\Delta HA = \Delta e\, H_s A$ **from which**

$$\Delta e = \frac{\Delta H}{H_s}$$

Step 5: Calculate the new void ratio after consolidation caused by the pressure increment as

$$e_1 = e_0 - \Delta e$$

$$e_1 = e_0 - \frac{\Delta H_1}{H_s}$$

For the next loading, σ_2 (*note:* σ_2 equals the cumulative load per unit area of specimen), which causes additional deformation ΔH_2, the void ratio at the end of consolidation can be calculated as

$$e_2 = e_1 - \Delta e$$

$$e_2 = e_1 - \frac{\Delta H_2}{H_s}$$

The effective stress σ and the corresponding void ratios (e) at the end of consolidation are plotted on semi-logarithmic graph paper. The typical shape of such a plot is shown in Figure 11.10.

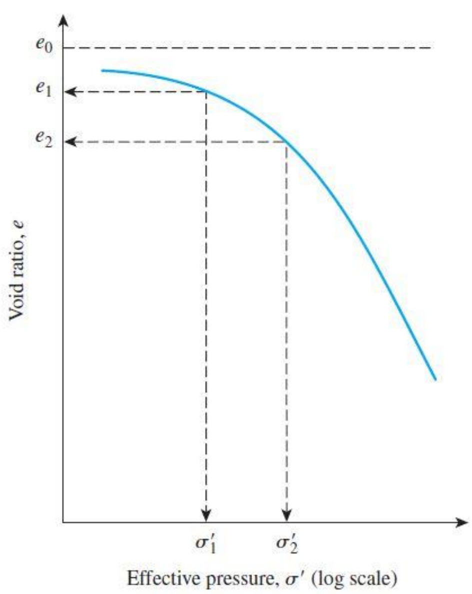


Figure 11.10 Typical plot of e against log σ'

Example 11.2

Following are the results of a laboratory consolidation test on a soil specimen obtained from the field: Dry mass of specimen = 128 g, height of specimen at the beginning of the test = 2.54 cm, $G_s = 2.75$, and area of the specimen = 30.68 cm^2.

Effective pressure, σ' (ton/ft^2)	Final height of specimen at the end of consolidation (cm)
0	2.540
0.5	2.488
1	2.465
2	2.431
4	2.389
8	2.324
16	2.225
32	2.115

Make necessary calculations and draw an e versus log σ' curve.

Solution

From Eq. (11.14),

$$H_s = \frac{W_s}{AG_s\gamma_w} = \frac{M_s}{AG_s\rho_w} = \frac{128\,\text{g}}{(30.68\,\text{cm}^2)(2.75)(1\,\text{g/cm}^3)} = 1.52\,\text{cm}$$

Now the following table can be prepared.

Effective pressure, σ' (ton/ft^2)	Height at the end of consolidation, H (cm)	$H_v = H - H_s$ (cm)	$e = H_v/H_s$
0	2.540	1.02	0.671
0.5	2.488	0.968	0.637
1	2.465	0.945	0.622
2	2.431	0.911	0.599
4	2.389	0.869	0.572
8	2.324	0.804	0.529
16	2.225	0.705	0.464
32	2.115	0.595	0.390

The e versus log σ' plot is shown in Figure 11.11

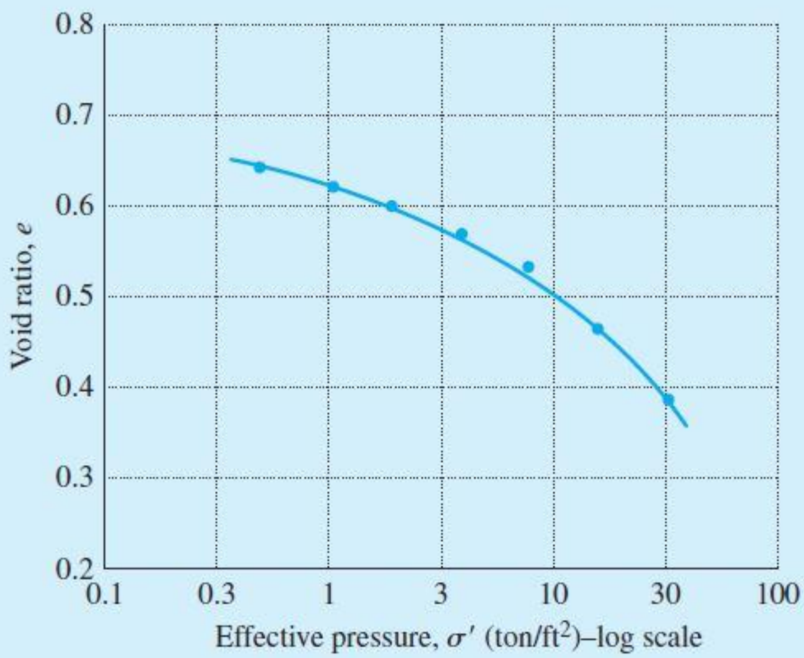


Figure 11.11 Variation of void ratio with effective pressure

For normally consolidated clay, the slope of e-p curve

$$C_C = \frac{\Delta e}{\log(\frac{\sigma+\Delta\sigma}{\sigma})} \qquad (6)$$

Combining Eq.6 and Eq.4

$$S_C = \frac{C_C H}{1+e_O} log(\frac{\sigma+\Delta\sigma}{\sigma}) \quad (7)$$

$$C_C = 0.009(\omega_L - 10)$$

ω_L: Liquid limit

Table 11.6 Correlations for Compression Index, C_c*

Equation	Reference	Region of applicability
$C_c = 0.007(LL - 7)$	Skempton (1944)	Remolded clays
$C_c = 0.01w_N$		Chicago clays
$C_c = 1.15(e_O - 0.27)$	Nishida (1956)	All clays
$C_c = 0.30(e_O - 0.27)$	Hough (1957)	Inorganic cohesive soil: silt, silty clay, clay
$C_c = 0.0115w_N$		Organic soils, peats, organic silt, and clay
$C_c = 0.0046(LL - 9)$		Brazilian clays
$C_c = 0.75(e_O - 0.5)$		Soils with low plasticity
$C_c = 0.208e_O + 0.0083$		Chicago clays
$C_c = 0.156e_O + 0.0107$		All clays

**After Rendon-Herrero, 1980. With permission from ASCE.*

Note: e_O = *in situ* void ratio; w_N = *in situ* water content.

Swell Index (C_s)

The swell index is appreciably smaller in magnitude than the compression index and generally can be determined from laboratory tests. In most cases,

$$C_s \simeq \frac{1}{5} \text{ to } \frac{1}{10} C_c$$

Example 11.3

The following are the results of a laboratory consolidation test:

Pressure, σ' (ton/ft^2)	Void ratio, e	Remarks	Pressure, σ' (ton/ft^2)	Void ratio, e	Remarks
0.25	1.03	Loading	8.0	0.71	Loading
0.5	1.02		16.0	0.62	
1.0	0.98		8	0.635	Unloading
2.0	0.91		4	0.655	
4.0	0.79		2	0.67	

a. Draw an e-log σ'_O graph and determine the preconsolidation pressure, σ'_c
b. Calculate the compression index and the ratio of C_s/C_c
c. On the basis of the average e-log σ' plot, calculate the void ratio at $\sigma'_O =$ 12 ton/ft^2

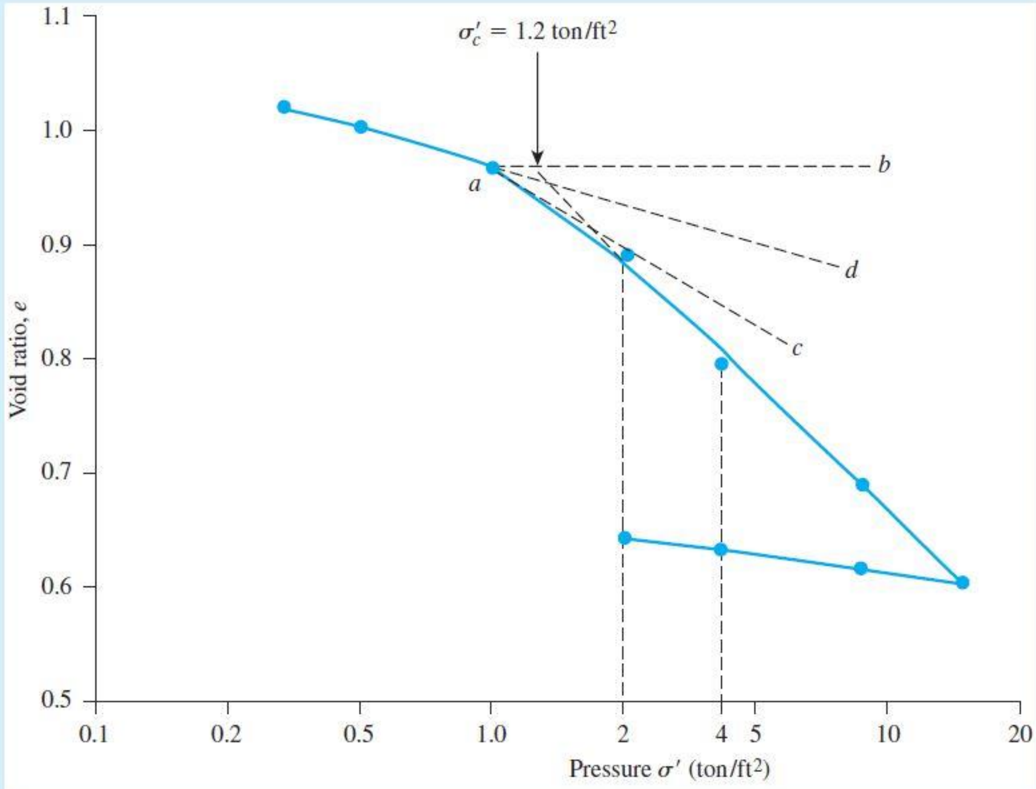


Figure 11.17 Plot of e versus log σ'

Solution

Part a

The e versus log σ' plot is shown in Figure 11.17. Casagrande's graphic procedure is used to determine the preconsolidation pressure:

$$\sigma'_O = \mathbf{1.2\ ton/ft^2}$$

Part b

From the average e-log σ' plot, for the loading and unloading branches, the following values can be determined:

Branch	e	σ'_O **(ton/ft²)**
Loading	0.9	2
	0.8	4
Unloading	0.67	2
	0.655	4

From the loading branch,

$$C_c = \frac{e_1 - e_2}{\log \dfrac{\sigma'_2}{\sigma'_1}} = \frac{0.9 - 0.8}{\log\left(\dfrac{4}{2}\right)} = \mathbf{0.33}$$

Example 11.4

A soil profile is shown in Figure 11.18. If a uniformly distributed load, $\Delta\sigma$, is applied at the ground surface, what is the settlement of the clay layer caused by primary consolidation if

a. The clay is normally consolidated

b. The preconsolidation pressure $(\sigma'_c) = 190 \text{ kN/m}^2$

c. $\sigma'_c = 170 \text{ kN/m}^2$

Use $C_s \approx \frac{1}{6}C_c$.

Solution

Part a

The average effective stress at the middle of the clay layer is

$$\sigma'_o = 2\gamma_{\text{dry}} + 4[\gamma_{\text{sat(sand)}} - \gamma_w] + \tfrac{4}{2}[\gamma_{\text{sat(clay)}} - \gamma_w]$$

$$\sigma'_o = (2)(14) + 4(18 - 9.81) + 2(19 - 9.81) = 79.14 \text{ kN/m}^2$$

From Eq. (11.31),

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

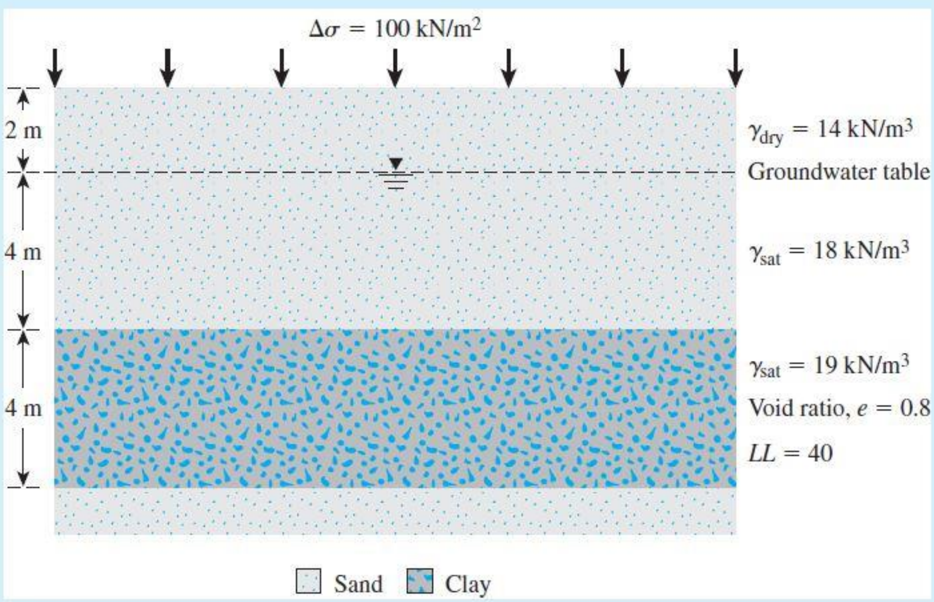


Figure 11.18

From Eq. (11.35),

$$C_c = 0.009(LL - 10) = 0.009(40 - 10) = 0.27$$

So,

$$S_c = \frac{(0.27)(4)}{1 + 0.8} \log\left(\frac{79.14 + 100}{79.14}\right) = 0.213 \text{ m} = \mathbf{213\ mm}$$

Part b

$$\sigma'_O + \Delta\sigma' = 79.14 + 100 = 179.14 \text{ kN/m}^2$$

$$\sigma'_c = 190 \text{ kN/m}^2$$

Because $\sigma'_O + \Delta\sigma' < \sigma'_c$, use Eq. (11.33):

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

$$C_s = \frac{C_c}{6} = \frac{0.27}{6} = 0.045$$

$$S_c = \frac{(0.045)(4)}{1 + 0.8} \log\left(\frac{79.14 + 100}{79.14}\right) = 0.036 \text{ m} = \mathbf{36\ mm}$$

Part c

$$\sigma'_o = 79.14 \text{ kN/m}^2$$

$$\sigma'_o + \Delta\sigma' = 179.14 \text{ kN/m}^2$$

$$\sigma'_c = 170 \text{ kN/m}^2$$

Because $\sigma'_o < \sigma'_c < \sigma'_o + \Delta\sigma'$, use Eq. (11.34)

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

$$= \frac{(0.045)(4)}{1.8} \log\left(\frac{170}{79.14}\right) + \frac{(0.27)(4)}{1.8} \log\left(\frac{179.14}{170}\right)$$

$$\approx 0.0468 \text{ m} = \mathbf{46.8\ mm}$$

Secondary consolidation settlement

At the end of primary consolidation (that is, after complete dissipation of excess pore water pressure) some settlement is observed because of the plastic behavior of soil. This stage of consolidation is called *secondary consolidation*. During secondary consolidation the plot of deformation against the log of time is practically linear. The variation of the void ratio, e, with time t for a given load increment will be similar to that shown in Figure 11.20. From Figure 11.20, the secondary compression index can be defined as

$$C_\alpha = \frac{e_2 - e_1}{Log t_2 - log t_1} = \frac{\Delta e}{log \frac{t_2}{t_1}}$$

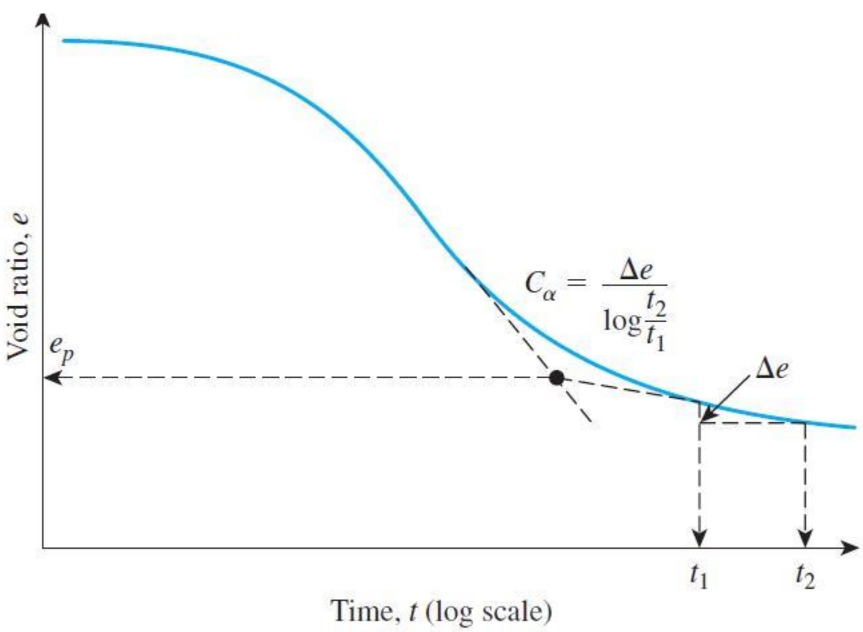


Figure 11.20 Variation of e with log t under a given load increment and definition of secondary consolidation index

where C_α = secondary compression index

Δe = change of void ratio

t_1, t_2 = time

$$C'_\alpha = \frac{C_\alpha}{e_P + 1}$$

$S_S = C'_\alpha H * log\frac{t_2}{t_1}$

where e_P void ratio at the end of primary consolidation

Example

The primary consolidation was ended after 1.5 years; the secondary consolidation of normally consolidated soil is after 5 years. The following properties were measured.

$$C_C = 0.28, \quad C_\alpha = 0.02, \quad \sigma = \frac{130kM}{m2}, \quad \Delta\sigma = 47\frac{kN}{m2}, \quad e_O = 0.8, \quad H = 3m$$

What is the total settlement?

$$C_C = \frac{\Delta e}{log\frac{\sigma+\Delta\sigma}{\sigma}}, \quad 0.28 = \frac{\Delta e}{log\frac{130+47}{130}}, \quad \Delta e = 0.134$$

$$e_0 - e_p = 0.578, \quad 0.8 - e_p = 0.134, e_p = 0.666$$

$$S_c = \frac{0.28*3m}{1+0.8} = 466mm$$

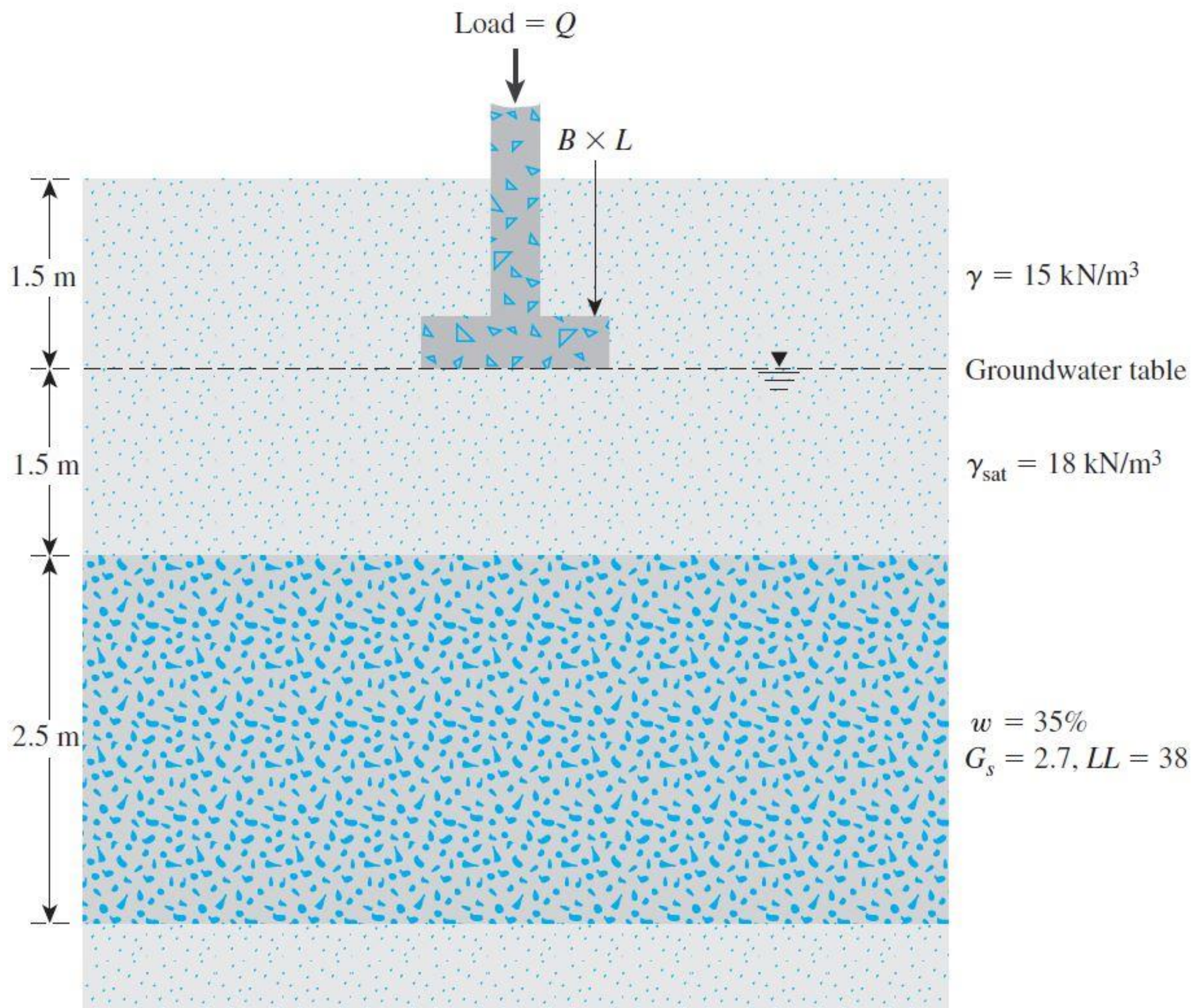
$$C'_\alpha = \frac{C_\alpha}{e_P+1} = \frac{0.02}{0.666+1} = 0.012$$

$$S_S = C'_\alpha H * log\frac{t_2}{t_1} = 0.012 * 3m * \log\left(\frac{5}{1.5}\right) = 0.0188m = 18.8mm$$

$$S_T = S_C + S_S = 466 + 18.8 = 484.8mm$$

Problem1

Given that $B = 1m$, $L = 3m$ and $Q = 110\ kN$ calculate the primary consolidation settlement of the foundation.



Answer: $S_C = 27.4mm$

Problem2

The following are the results of a consolidation test.

- Plot the $e - log\sigma\ curve$ curve
- Using Casagrande's method, determine the preconsolidation pressure
- Calculate the compression index, Cc, from the laboratory $e - log\sigma$ curve

e	σ, kN/m2
1.1	26.896
1.085	53.792
1.055	107.584
1.01	215.168
0.94	430.336
0.79	860.672
0.63	1721.344

Problem3

The results of a laboratory consolidation test on a clay specimen are the following.

σ, kN/m2	Total height of specimen at the end of consolidation, cm
24.45	1.764538
48.9	1.7399
97.8	1.70307
195.6	1.65608
391.2	1.614932
782.4	1.588008

Given the initial height of specimen 2cm., *Gs* = 2.68, mass of dry specimen $w_s = 95.2\ gm$_ and area of specimen A=31.6 cm^2.

a. Plot the *e*-log s_ curve

b. Determine the preconsolidation pressure

c. Calculate the compression index, *Cc*