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Department of Civil Engineering

CIV E 353 - Geotechnical Engineering I
Consolidation

Purpose

Determine the magnitude and time rate of settlement for a compressible cohesive soil.

Required reading Das 2006 Sections 10.4 to 10.16 (pages 312 to 358).

Theory

Bringing soil samples into the laboratory and subjecting them to a series of loads and measuring the corresponding settlement can determine the compressibility of undisturbed or remoulded samples of fine soils such as clays and clayey silts. The test is known as a one dimensional consolidation test (also known as an oedometer test). The compressibility of granular soil is usually estimated empirically from in situ (field) tests, such as the Standard Penetration Test.

The consolidation test generally consists of placing an undisturbed sample in a consolidometer, also known as an oedometer, where it is subjected to a constant vertical load. This vertical load causes an increase in pore water pressure within the sample that is greater than the static pore water pressure (u_s) due to the water bath. The component of pore water pressure above the static pore water pressure is known as excess pore water pressure (u_e). Thus, excess pore water pressure is the pressure due to the applied load.

Excess pore water pressure causes water to flow out of the sample towards the drainage boundaries (upper and lower porous stones). If the sample is considered to be 100 percent saturated and the soil grains are incompressible, settlement will occur only when water flows out of the sample voids and the soil particles rearrange to create a lower void ratio (tighter packing). The rate that a sample consolidates (decrease in volume due to the dissipation of excess pore water pressure) will depend on several factors: permeability, thickness, compressibility, pore fluid, initial void ratio, and degree of saturation.

Monitoring the compression of the sample due to an applied load increment is achieved by plotting log time vs vertical settlement curve, as shown in Fig. 1. This figure shows that sample compression can be divided into three parts

- Initial compression attributed to load seating, elastic expansion of the oedometer ring, compression of the porous stones, or the presence of air
- Primary compression due to consolidation resulting from the dissipation of excess pore pressures
- Secondary compression that is thought to be caused by a gradual readjustment of the soil particles

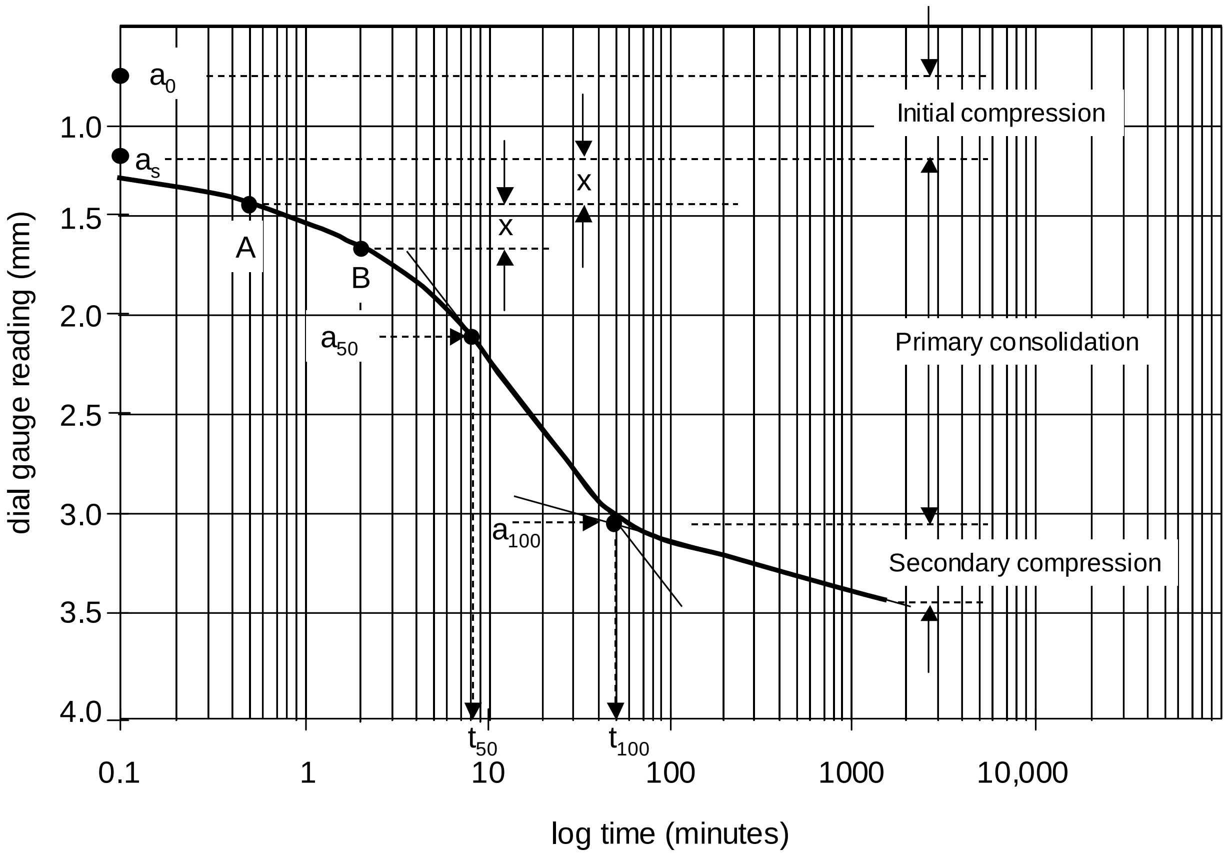

Fig. 1 Log time method

After a period of about 24 hours another increment of vertical load is applied. Data from several load increments is used to plot void ratio (e) vs. effective stress (σ') or e - log σ' curves (Das Fig. 10.13). The change in void ratio is computed using only the primary consolidation portion of the test data and phase relationships shown in Section 10.6 pages 317 to 318 and Das Fig. 10.12.

The e-log σ' plot is used to determine the Preconsolidation pressure (σ_c'), and the clay compressibility defined by Compression Index (C_c) and Swell (Recompression) Index (C_s), shown in Das Figures. 10.18 and 10.19. Example 10.3 shows how to calculate the Compression and Swell Index.

Unloading the sample can cause the soil to rebound elastically and to swell. Data obtained from unloading increments are treated in the same manner as loading increments.

<u>Procedure</u>

1 Determine the size and mass of the oedometer ring.

2. Trim the soil to fit and completely fill the ring. Determine the mass of the ring and the soil sample.

3. Assemble the apparatus using filter papers between the soil and the porous stones, balance the lever arm, and set the dial indicator to zero. The usual procedure is to start with a small stress and to **double** the stress for each load increment. Normal loadings will be 6.25, 12.5, 25, 50, 100, 200, and 400 kPa; then unload to 100, 25, and finally 6.25 kPa.

4. Add the first prescribed load to the hanger at the back of the machine. Record dial readings at the times shown on the data sheet.

   Note: Compression is likely to be minimal and rapid under this first load. When insignificant movement is occurring, fill the cell with distilled water that is at room temperature. If the sample starts to swell, stop the test and add another increment of load.

5. Continue taking readings at the suggested times given on the data sheet for the first hour. Allow the load to remain on the sample for 24 hours before applying the next load increment.

6. Following the load/unload sequence, allow the sample to swell for 24 hours at the final load of 6.25 kPa. Remove it from the cell, blot surplus water, and determine the mass of the ring plus sample.

7. Place both the ring and sample in an oven, dry, and obtain the mass of the dry soil plus ring.

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Results

1. Calculate the water content at the end of the test from:

$$w = \frac{M - M_s}{M_s} = \frac{Mass\ of\ soil - Mass\ of\ dry\ soil}{Mass\ of\ dry\ soil}$$

Express as a percent.

2. Calculate the following:

a) Height of solids (H_s) using:

$$H_s = \frac{M_s}{A G_s \rho_W}$$

where A is the sample cross sectional area
Warning: Use compatible units.

b) Void ratio at the start of the test (e_o) using:

$$e_o = \frac{H_o - H_s}{H_s} = \frac{H_o}{H_s} - 1$$

c) Height of voids (H_v) at the start of the test using:

$$H_v = H_o - H_s$$

3. Explain why changes in void ratio (during the consolidation test) can be expressed in terms of changes in sample height.

4. From the plots of compression vs. log time obtain the changes in height (ΔH) due to primary consolidation, and calculate the void ratio for each load increment using:

$$e_i = \frac{H_v - \sum_{i=0}^{i=n} \Delta H}{H_s}$$

5. Plot e-log σ' at the end of primary consolidation (Fig 1) and determine the Preconsolidation pressure (σ_c') using Casagrande method. Calculate the Swell Index (C_s) by taking the slope of the expansion line before the Preconsolidation pressure and the Compression Index (C_c) by taking the slope of the line after the Preconsolidation pressure.

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6. Using the empirical equations provided in Das Sections 10.11 and 10.12 and the clays Atterberg limits, insitu water content, and initial void ratio (e_0), estimate the clay Compression Index and Swell Index. Please note that symbol C'_c is used to represent the Compression Index of clay in the **remoulded** state. Compare these values with the Compression Index determined from the consolidation test and comment on applicability of the best-fit equations.

7. Calculate the Coefficient of Consolidation (c_v) for 50 percent consolidation for each increasing load increment only using

$$c_v = \frac{Tv\, d^2}{t_{50}}$$

Where: *d* is the length of longest drainage path computed by taking one - half the average sample thickness (double drainage) for each load increment and time factor (*Tv*) for 50 percent consolidation is 0.196.

As shown on the calculation sheet, the net height of the sample is computed by subtracting the initial compression from the total change in height. Plot c_v vs log σ' for the loading sequence only. Why does the Coefficient of Consolidation change with increases in stress?

Selected References

1. ASTM D698 - 78 and D1557 - 78.

2. Bowles, J.E., 1979, Physical and Geotechnical Properties of Soils, McGraw-Hill.

3. Craig, R.F., 1978, Soil Mechanics, Chapman and Hall.

4. Holtz, R.D., and Kovacs, W.D., 1981, An Introduction to Geotechnical Engineering, Prentice-Hall, Inc. New Jersey.

5. Koerner, R.M., 1984, Construction and Geotechnical Methods in Foundation Engineering, McGraw-Hill.

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Material Data Sheet

Soil Description_______________________________ Date ____________

Specific Gravity of Solids, G_s ________________

Natural Water Content (from trimmings) __________

Atterberg Limits LL _________ PL __________

Oedometer Ring No. ______ Height, mm ______ Diameter, mm _______

Area, mm^2 _______

	Before Loading	After Loading
Mass of Soil + Ring, g		
Mass of Dry Soil + Ring, g		
Mass of Ring, g		
Mass of Soil, M, g		
Mass of Dry Soil, M_s, g		
Mass of Water, M_w, g		
Water Content, w, %		
Height of Solids, H_s, mm $H_s = M_s/A\ G_s\ \rho_w$		
Height of Voids, H_v, mm $H_v = H - H_s$ Where H = sample height		
Degree of Saturation, S_r, % $S_r = (M - M_s)/H_v\ A\ \rho_w$		
Void Ratio, e $e = H_v/H_s$		

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Time-Compression Data Sheet

Project ______________________ Group Number ______________________

Load Applied ___________ kPa
Date Applied ___________
Applied by ___________

Load Applied ____________ kPa
Date Applied ____________
Applied by ____________

Time	Δ Time	Dial Rdg.	x.002 = mm	
	0			
	0.1			
	0.25			
	0.5			
	1			
	2			
	4			
	8			
	15			
	30			
	60			

Time	Δ Time	Dial Rdg.	x.002 = mm	
	0			
	0.1			
	0.25			
	0.5			
	1			
	2			
	4			
	8			
	15			
	30			
	60			

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Void Ratio (Primary Consolidation)

Sample ______________________________ Date ______________

Height of Solids, H_s, mm ________________

Initial Height of Voids, H_{vo}, mm __________

Applied Stress kPa (1)	Primary Consolidation mm (2)	Height of Voids $H_{vo} - \Sigma(2)$ mm (3)	Void Ratio (4)

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Coefficient of Consolidation

Soil Sample ____________________ Date ____________________

Initial Height of Sample, H_0, mm ____________________

Applied Stress kPa (1)	Total Change in Height mm (2)	Initial Compress mm (3)	Net Change in Height (2) – (3) mm (4)	Sample Height H_0 $-\Sigma(4)$ mm (5)	Drain Path *d* (6)	t_{50} minutes (7)	c_v m^2/yr (8)

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DETERMINATION OF CONSOLIDATION PARAMETERS USING THE LOG TIME METHOD

(refer to Fig. 1, page 2)

1. Mark the initial dial indicator reading at time 0 for the current load increment as a_o on the vertical axis.

2. Select two points on the curve (A, B) for which the values of time (*t*) are in a ratio of 4:1. (e.g. 0.25 and 1 min. or 0.5 and 2 min.)

3. Measure the vertical distance between A and B (X).

4. Measure out the vertical distance found in Step 3 above A and mark as a_s horizontally across to the vertical axis.

5. To check if completed correctly, steps 2 to 4 could be repeated using different pairs of points.

6. Label the distance between a_o and a_s as the region of initial compression. This difference between these two points is due mainly to the compression of small quantities of air in the soil and the degree of saturation being marginally below 100%.

7. Draw a best-fit linear line in the steep portion of the curve as shown in the Figure 1.

8. Look for where the experimental curve beings to curve at a slower rate on an almost horizontal plane.

9. Make another best-fit linear line running along this part of the curve to where it intersects with the line made in Step 7. Label this intersection as point a_{100}.

10. Label the region from a_s to a_{100} as the region of primary consolidation.

11. Beyond the point of intersection at a_{100}, the compression of the soil continues at a very slow rate for an indefinite period of time and can be labelled as the region of secondary compression.

12. Measure the vertical distance between a_s and a_{100} and divide this distance in half. Label this point as a_{50} where it intersects the curve.

13. Extend vertical lines down from a_{50} and a_{100}, labelling them t_{50} and t_{100}, respectively.