16

Consolidation Test

INTRODUCTION

Consolidation is the process of time-dependent settlement of saturated clayey soil when subjected to an increased loading. In this chapter, the prodedure for one-dimensional laboratory consolidation test will be described, and methods of calculation of obtaining the void ratio-pressure curve (e vs. $\log p$), preconsolidation pressure (p), and the coefficient of consolidation (c_v) will be outlined.

EQUIPMENT

1. Consolidation unit
2. Specimen trimming device
3. Wire saw
4. Balance, sensitive to 0.01 g
5. Stop watch
6. Moisture can
7. Oven

The consolidation unit consists of a consolidometer and a loading unit. The consolidometer can either be (i) a floating ring consolidometer (Fig. 16-1*a*) or (ii) a fixed ring consolidometer (Fig. 16-1*b*). The floating ring condolidometer usually consists of a brass ring in which the soil specimen is placed. One porous stone is placed at the top of the specimen and another porous stone at the bottom. The soil specimen in the ring with the two porous stones are placed on a base plate. A plastic ring surrounding the specimen fits into a groove on the base plate. Load is applied through a loading head which is placed on the top porous stone. In the floating ring consolidometer, compression of the soil specimen occurs from the top and bottom towards the center.

The fixed ring consolidometer consists essentially of the same components, i.e., a hollow brass plate, two porous stones, a brass ring to hold the soil specimen and a metal ring which can be fixed tightly to the top of the base plate. The ring surrounds the soil specimen. A stand pipe is attached to the side of the base plate. This can be used for permeability determination of soil. In the fixed ring consolidometer, the compression of the specimen occurs from the top towards the bottom.

The specifications for the loading devices of the consolidation unit vary depending on the manufacturer. Figure 16-2 shows one type of loading device.

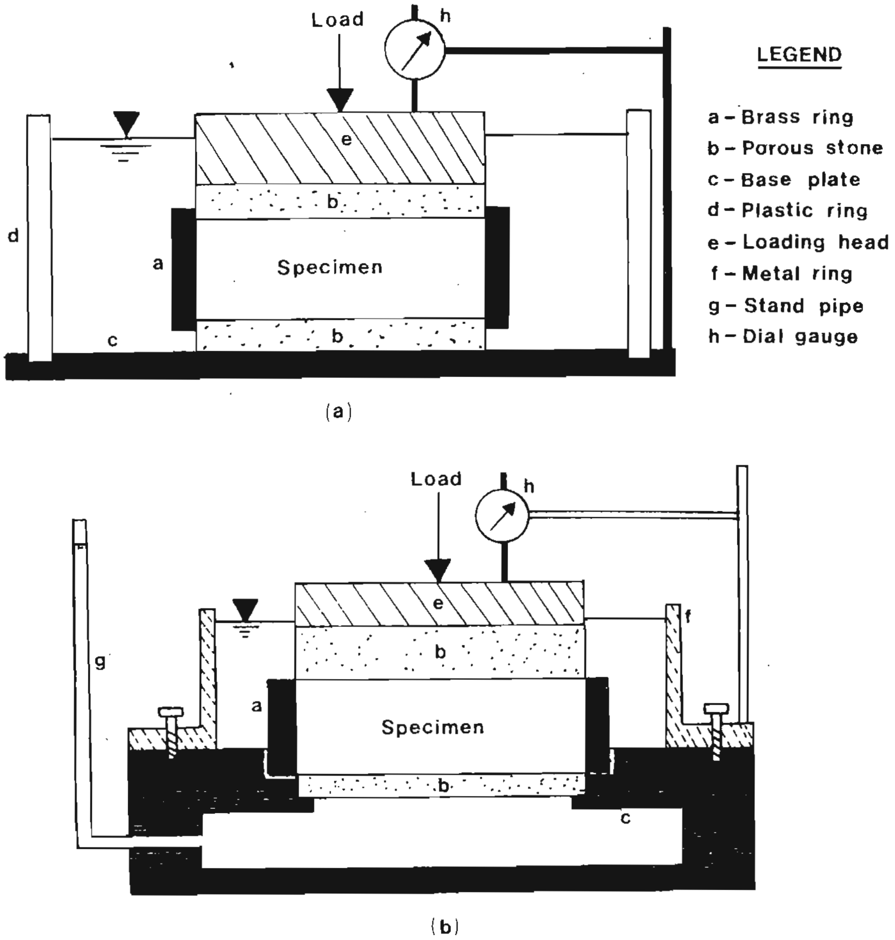

Figure 16-1. Schematic diagram of (a) floating ring consolidometer. (b) fixed ring consolidometer.

During the consolidation test, when load is applied to a soil specimen, the nature of variation of side friction between the surrounding brass ring and the specimen are different for the fixed ring and the floating ring consolidometer, and this is shown in Fig. 16-3. In most cases, a side friction of 10% of the applied load is a reasonable estimate.

PROCEDURE

1. Prepare a soil specimen for the test. The specimen is prepared by trimming an undisturbed natural sample obtained in Shelby tubes. The Shelby tube sample should be about 1/4 in. to 1/2 in. (6.35 mm to 12.7 mm) larger in diameter than the specimen diameter to be prepared for the test.

   Note: For classroom instructional purposes, a specimen can be molded in the laboratory.
2. Collect some excess soil that has been trimmed in a moisture can for moisture content determination.
3. Collect some of the excess soil trimmed in Step 1 for determination of the specific gravity of soil solids, G_s.

4. Determine the weight of the consolidation ring (W_1).
5. Place the soil specimen in the consolidation ring. Use the wire saw to trim the specimen flush with the top and bottom of the consolidation ring. Record the size of the specimen.
6. Determine the weight of the consolidation ring and the specimen (W_2).
7. Saturate the lower porous stone on the base of the consolidometer.
8. Place the soil specimen in the ring over the lower porous stone.
9. Place the upper porous stone on the specimen in the ring.
10. Attach the top ring to the base of the consolidometer.
11. Add water to the consolidometer to submerge the soil and keep it saturated. In the case of the fixed ring consolidometer, the outside ring (attached to the top of the base) and the stand pipe connection attached to the base should be kept full with water. This needs to be done for the ***entire period of the test.***

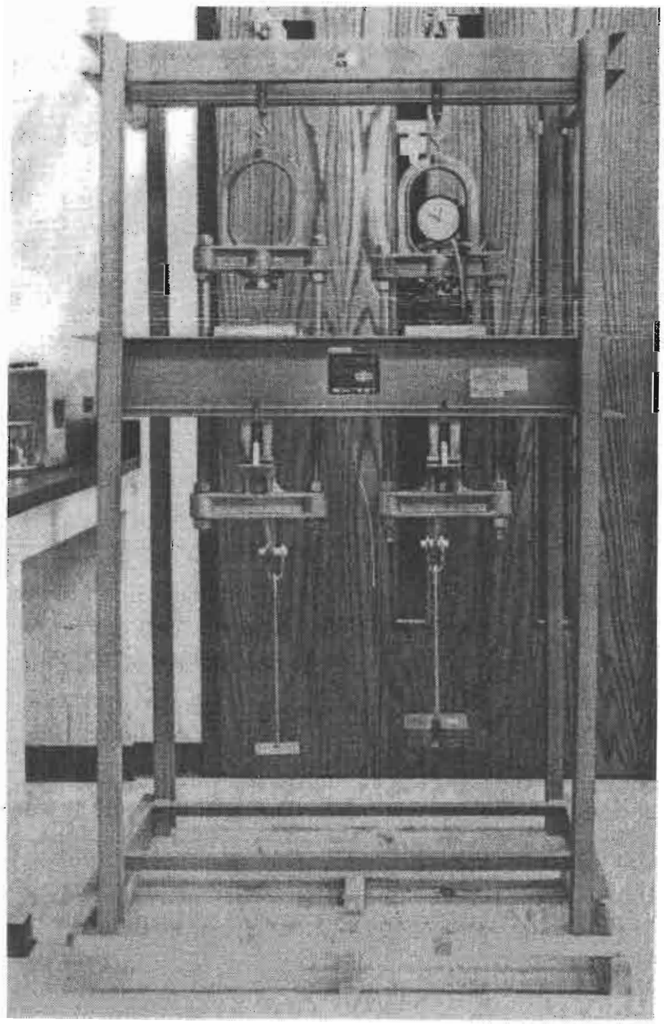

Figure 16-2. Consolidation loading assembly. In this assembly, two specimens can be simultaneously tested. Lever arm ratio for loading is 1:10.

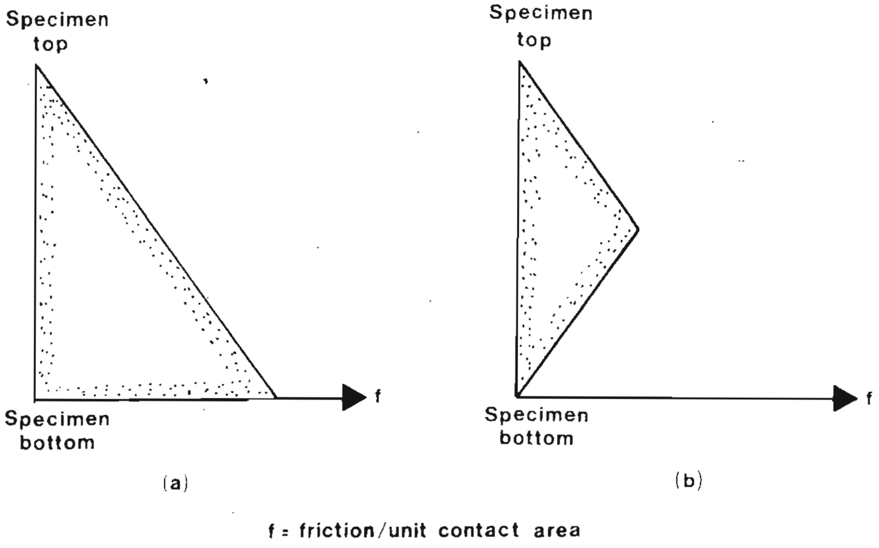

Figure 16-3. Nature of variation of soil-ring friction per unit contact areas in (a) fixed ring consolidometer. (b) floating ring consolidometer.

12. Place the consolidometer in the loading device.
13. Attach the vertical deflection dial guage to measure the compression of soil. It should be fixed in such a way that the dial is at the beginning of its release run. The dial gauge used should be calibrated to read as 1 small div = 0.0001 in. (0.00254 mm).
14. Apply load to the specimen such that the magnitude of pressure, p, on the specimen is 1/2 ton/ft^2 (47.88 kN/m^2). Take the vertical deflection dial guage reading at the following times, t, *counted from the time of the load application.* 0 min, 0.25 min, 1 min, 2.25 min, 4 min, 6.25 min, 9 min, 12.25 min, 20.25 min, 25 min, 36 min, 60 min, 120 min, 240 min, 480 min and 1440 min (24 hr).
15. The next day, add more load to the specimen such that the total magnitude of pressure on the specimen becomes 1 ton/ft^2 (95.76 kN/m^2). Take the vertical dial gauge readings at similar time intervals stated in Step 14. Note, here we have $\Delta p/p = 1$ (where Δp = increase of pressure and p = the existing pressure).
16. Repeat Step 15 for soil pressure magnitudes of 2 ton/ft^2 (191.52 kN/m^2), 4 ton/ft^2 (383.04 kN/m^2) and 8 ton/ft^2 (766.08 kN/m^2), etc. *Note:* In all cases $(\Delta p/p) = 1$.
17. At the end of the test, remove the soil specimen and determine its moisture content.

CALCULATION AND GRAPH

The calculation procedure for the test can be explained with reference to Tables 16-1 and 16-2 and Figs. 16-4, 16-5 and 16-6 which are the laboratory test results for a light brown clay.

CONSOLIDATION TEST

(Time vs, vertical dial reading)

Description of soil Light brown clay

Pressure on specimen 4 ton/ft^2

Clock time of load application 8 : 35 am

Time after load application, t (min)	$\sqrt{t}$ (min$^{0.5}$)	Vertical dial reading (in)
0	0	0.0638
0.25	0.5	0.0654
1.0	1.0	0.0691
2.25	1.5	0.0739
4	2	0.0795
6.25	2.5	0.0833
9.0	3.0	0.0868
12.25	3.5	0.0898
16	4	0.0922
20.25	4.5	0.0941
25	5	0.0954
36	6	0.0979
60	7.75	0.1004
120	10.95	0.1019
240	15.49	0.1029
480	21.91	0.1048
1440	37.95	0.1059

Table 16-1

Table 16-2

CONSOLIDATION TEST

(Void ratio-pressure and coefficient of consolidation calculation)

Description of soil Light brown clay

Location El Paso

Specimen diameter 2·5 in.

Initial specimen height, $H_{t(i)}$ 1 in.

Moisture content: beginning of test 30.8 (%)

End of test 32·1 (%)

Weight of dry soil specimen 116·74

G_s 2·72

Height of solids, H_s 1·356 cm = 0·539 in

Pressure, p (T/ft²) (1)	Final dial reading (in) (2)	Change in specimen height (in) (3)	Final specimen height $Ht_{(f)}$ (in) (4)	Height of void, H_v (in) (5)	Final void ratio, e (6)	Average height during consolidation, $H_{t(av)}$ (in) (7)	Fitting time (sec) t_{90} (8)	Fitting time (sec) t_{50} (9)	c_v from x 10^3 (in²/sec) t_{90} (10)	c_v from x 10^3 (in²/sec) t_{50} (11)
0	0.0200		1·000	0·4610	0·855					
		0·0083				0·9959	302	68·7	0·696	0·711
$\frac{1}{2}$	0·0283		0·9917	0·4527	0·840					
		0·0073				0·9881	308	56·0	0·672	0·859
1	0·0356		0·9844	0·4454	0·826					
		0·0282				0·9703	492	144	0·406	0·322
2	0·0638		0·9562	0·4172	0·774					
		0·0421				0·9352	1102	294	0.131	0·147
4	0·1059		0.9144	0·3751	0·696					
		0·0455				0·8914	1354	240	0·124	0·163
8	0·1514		0.8686	0·3296	0·612					

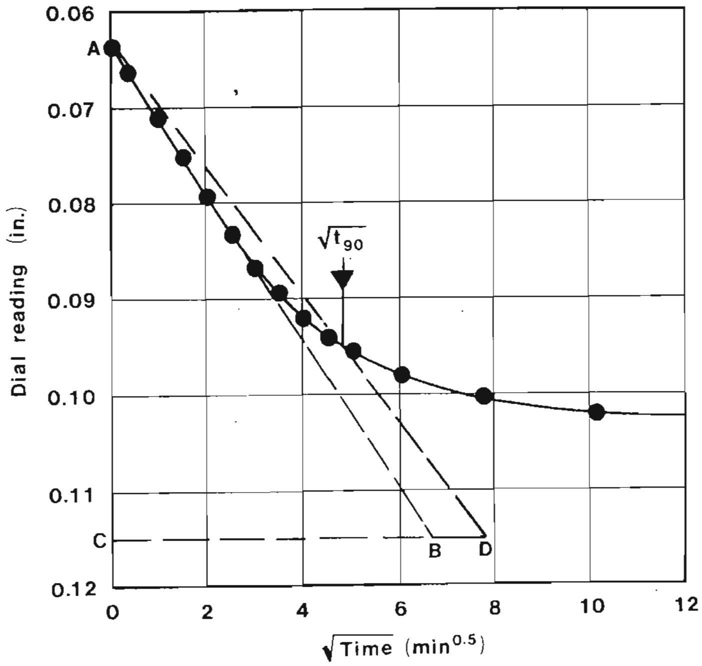

Figure 16-4. Plot of dial reading vs. $\sqrt{\text{time}}$ for the test results given in Table 16-1. Determination of t_{90} by square-root-of-time method.

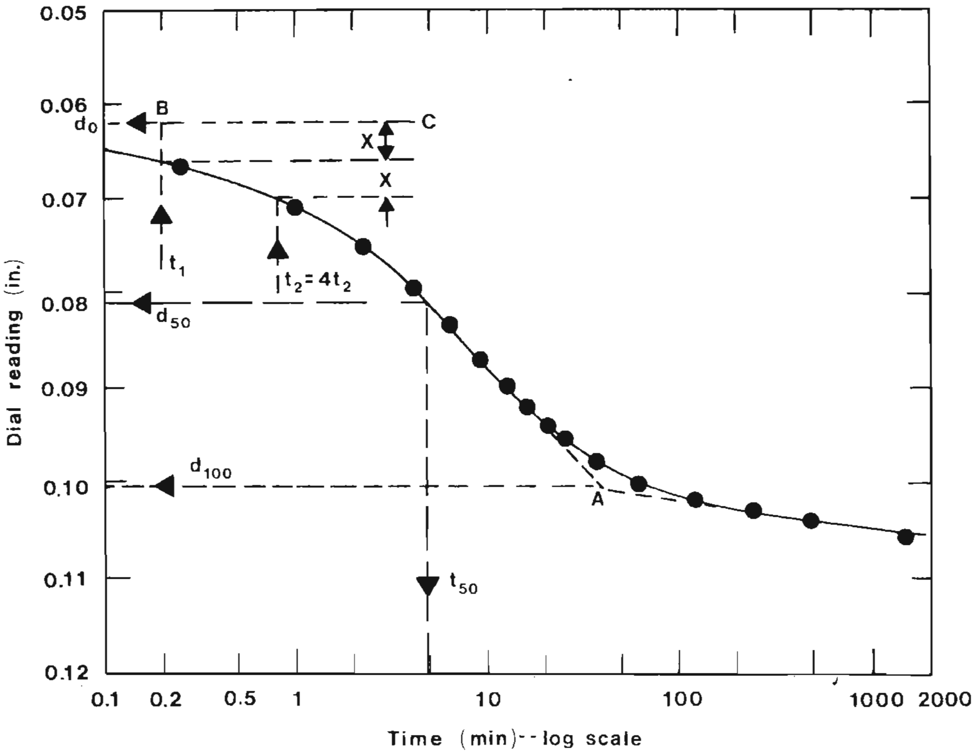

Figure 16-5. Logarithm-of-time curve fitting method for the laboratory results given in Table 16-1.

1. Collect all the time vs. vertical dial readings data. Table 16-1 shows the results of a pressure increase from $p = 2$ ton/ft^2 to $p + \Delta p = 4$ ton/ft^2.
2. Determine the time for 90% primary consolidation, t_{90}, from each set of time vs. vertical dial readings. An example of this is shown in Fig. 16-4 which is a plot of the results of vertical dial reading vs. $\sqrt{\text{time}}$ given in Table 16-1. Draw a tangent AB to the initial consolidation curve. Measure the length BC. Plot the point D such that the length of CD = 1.15 times the length BC. Join AD. The adscissa of the point of intersection of the line AD with consolidation curve will given $\sqrt{t_{90}}$. In Fig. 16-4, $\sqrt{t_{90}} = 4.75$ min$^{1/2}$, so $t_{90} = (4.75)^2 = 22.56$ min. This technique is referred to as the *square-root-of-time-fitting method* (Taylor, 1942).
3. Determine the time for 50% primary consolidation, t_{50}, from each set of time vs. vertical dial readings. The procedure for this is shown in Fig. 16-5, which is a semilogarithmic plot (vertical dial reading in natural scale and time in log scale) for the set of readings shown in Table 16-1. Project the straight line portion of the primary consolidation downwards and the straight line portion of the secondary consolidation backwards. The point of intersection of these two lines is *A*. The vertical dial reading corresponding to point *A* is d_{100} (dial reading at 100% primary consolidation). Select times t_1 and $t_2 = 4t_1$. (Note t_1 and t_2 should be within the top curved portion of the consolidation plot.) Determine the difference in dial readings, *X*, between times t_1 and t_2. Plot line *BC* which is vertically *X* distance above the point on the consolidation curve corresponding to time t_1. The vertical dial gauge reading corresponding to line *BC* is d_0, i.e., the reading for 0% consolidation. Determine the dial gauge reading corresponding to 50% primary consolidation as

$$d_{50} = \frac{d_0 + d_{100}}{2} \qquad (16.1)$$

   The time corresponding to d_{50} on the consolidation is t_{50}. This is the logarithm-of-time curve fitting method (Casagrande and Fadum, 1940). In Fig. 16-5, $t_{50} =$ 4.9 min.
4. Complete the experimental data in Cols. 1, 2, 8 and 9 of Table 16-2. Columns 1 and 2 are obtained from time-dial reading tables (such as Table 16-1) and Cols. 8 and 9 are obtained from Steps 1 and 2, respectively.
5. Determine the height of solids of the specimen in the mold as (Table 16-2)

$$H_s = \frac{W_s}{(\frac{\pi}{4} D^2) G_s \gamma_w} \qquad (16.2)$$

H_S = height of solids
W_S = dry weight of soil specimen
D = diameter of the specimen
G_s = specific gravity soil solids
γ_w = specific gravity of soil solids

6. In Table 16-2, determine the change in heights, ΔH, of the specimen due to load increments from p to p + p (Col. 3). For example,

$$p = ½\ \text{ton/ft}^2,\ \text{final dial reading} = 0.0283\ \text{in.}$$

$$p + \Delta p = 1\ \text{ton/ft}^2,\ \text{final dial reading} = 0.0356\ \text{in.}$$

So

$$\Delta H = 0.0356 - 0.0283 = 0.0073\ \text{in.}$$

7. Determine the final specimen height, $H_{t(f)}$, at the end of consolidation due to a given loading (Col. 4 in Table 16-2). For example, in Table 16-2, $H_{t(f)}$ at $p = ½$ ton/ft² is 0.9917. ΔH between $p = ½$ ton/ft² and 1 ton/ft² is 0.0073 in. So, $H_{t(f)}$ at $p = 1$ ton/ft² is $0.9917 - 0.0073 = 0.9844$ in.
8. Determine the height of voids, H , in the specimen at the end of consolidation due to a given loading, *p*, as (Col. 5 of Table 16-2)

$$H_V = H_{t(f)} - H_s \tag{16.3}$$

9. Determine the final void ratio at the end of consolidation for each loading, *p*, (Col. 6, Table 16-2) as

$$e = \frac{H_V}{H_S} \tag{16.4}$$

10. Determine the average specimen height, $H_{t(av)}$, during consolidation for each incremental loading (Col. 7, Table 16-2). For example, in Table 16-2, the value of $H_{t(av)}$ between $p = ½$ ton/ft² to 1 ton/ft² is

$$\frac{H_{t(f)}\ \text{at}\ p = ½\ \text{ton/ft}^2 + H_{t(f)}\ \text{at}\ p = 1\ \text{ton/ft}^2}{2}$$

$$= \frac{0.9917 + 0.9844}{2} = 0.9811\ \text{in.}$$

11. Calculate the coefficient of consolidation, c_v (Col. 10, Table 16-2) from t_{90} (Col. 8) as

$$T_v = \frac{c_v t}{H^2} \tag{16.5}$$

where T_v = time factor, T_{90} = 0.848
H = maximum lenght of drainage path = $\frac{H_{t(av)}}{2}$
(since the specimen is drained at top and bottom)

So

$$c_v = \frac{0.848\ H^2_{t(av)}}{4\ t_{90}} \tag{16.6}$$

12. Calculate the coefficient of consolidation, c_v, (Col. 11, Table 16-2), from t_{50} (Col. 9) as

$$T_{v(50\%)} = 0.197 = \frac{c_v t_{50}}{H^2} = \frac{c_v t_{50}}{\left[\frac{H_{t(av)}}{2}\right]^2}$$

$$c_v = \frac{0.197 H^2_{t(av)}}{4 t_{50}} \tag{16.7}$$

For example, between p = ½ ton/ft^2 to 1 ton/ft^2,

$$H_{t(av)} = 0.9881 \text{ in.}; \ t_{50} \ 56.0 \text{ sec};$$

$$c_v = \frac{0.197(0.9881)^2}{4(56)} = 0.859 \times 10^{-3} \ in^2/sec$$

13. Plot a semilogarithmic graph of pressure vs. final void ratio (Col. 1 vs. Col. 6, Table 16-2). Pressure *p* is plotted on the log scale, and the final void ratio on the linear scale. As an example, the results of Table 16-2 are plotted in Fig. 16-6. Note that the plot has a curved upper portion and, after that, *e* vs. *log p* has a linear relationship.
14. Calculate the compression index, C_c. This is the slope of the linear portion of the *e* vs. *log p* plot (Step 13). In Fig. 16-6

$$C_c = \frac{e_1 - e_2}{\log \frac{p_2}{p_1}} = \frac{0.696 - 0.612}{\log \frac{8}{4}} = 0.279$$

15. On the semilogarithmic graph (Step 13), using the same horizontal scale (i.e. the scale for *p*), plot the values of c_v (Cols. 10 and 11, Table 16-2). As an example, the values determined in Table 16-2 are plotted in Fig. 16-6. Note, c_v is plotted on the linear scale corresponding to the average value of *p*

(i.e., $\frac{p_1 + p_2}{2}$)

16. Determine the *preconsolidation pressure*, p_c. The procedure can be explained with the aid of the *e-log p* graph drawn in Fig. 16-6 (Casagrande, 1936). First, determine the point *A* which has the smallest radius of curvature in the *e-log p* plot. Draw a horizontal line *AB*. Draw a line *AD* which is the *bisector* of the angle *BAC*. Project the straight line portion of the *e-log p* plot backwards to meet line *AD* at *E*. The pressure corresponding to point *E* is the preconsolidation pressure. In Fig. 16-6, p_c = 1.6 ton/ft^2.

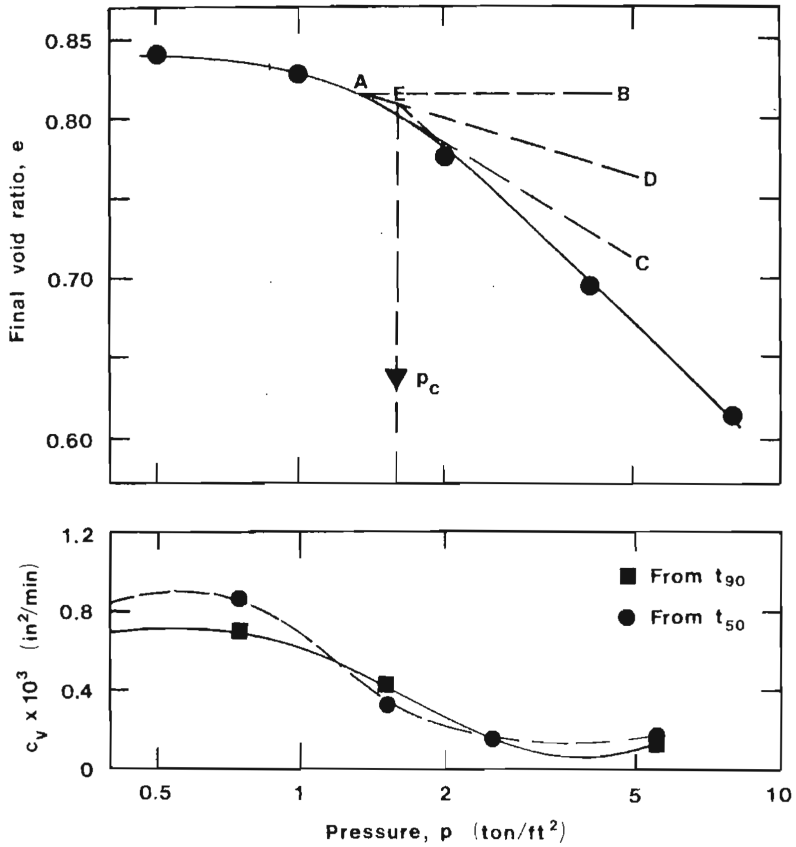

Figure 16-6. Plot of void ratio and the coefficient of consolidation against pressure for the soil reported in Table 16-2.