Consolidation principles in foundation design

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Abstract: The primary and secondary consolidation settlements, of saturated cohesive soils are generally estimated using consolidation theory. A consolidation test is performed to obtain a compression parameter for the amount of settlement and a consolidation parameter for the settlement rate estimate. The over consolidation ratio OCR can also be determined from this test. The test is performed on an "undisturbed" sample which is placed in a consolidation ring available in diameters ranging from 45 to 115 mm (1.8 to 4.5 in). The sample height is between Z(1 and 30 mm (0.75 and 1.5 in); 20 mm is the most commonly used thickness to reduce test time. The larger-diameter samples give better parameters, since about the same amount of disturbance is developed for any size sample, with the relative effects less for the larger samples. The most common test diameter is 64 mm (2.5 in), since this best balances the costs of sample recovery and disturbance effects. Tube diameters larger than 76 mm may result in a premium charge for the sample-particularly if a larger borehole must be made.


Key words: consolidation- soil pressure- premium change- undisturbed stress.

Introduction:

The consolidation test proceeds by applying a series of load increments to the sample and recording sample deformation at selected time intervals. Sufficient laboratory data should be obtained to allow computation of the water content w\textsubscript{s} and the specific gravity so that the void ratio at any time interval can be computed.

The load-deformation data are plotted on either a semi logarithmic plot or \sqrt{t} as illustrated in Fig. 2-10. The purpose of these plots is to obtain the time at some percent consolidation. The t\textsubscript{50} value (time at 50 percent) is most commonly used, and the procedure for obtaining it is to obtain the dial reading at 100 percent consolidation D\textsubscript{100} and the dial reading at the start of the test D\textsubscript{0}.

The procedure for finding D\textsubscript{0} is to either-use the actual initial dial reading at the start of the test or, if the initial curve is parabolic, find the apparent value. This may be necessary, since one cannot plot log time at t = 0. The corrected value of D\textsubscript{0} is found as follows:
1. Select a time t\textsubscript{1} in the parabolic portion.
2. Select a second time t\textsubscript{2} = 4t\textsubscript{1} in the parabolic part.
3. Obtain the offset between t\textsubscript{1} and t\textsubscript{2}.
4. Plot this offset distance above t\textsubscript{1} to obtain D\textsubscript{0}.

The D\textsubscript{100} value is obtained as the intersection of tangents drawn to the midcurve area and the end portion as shown on Fig. 2-10a. Considerable interpretation is necessary if the curve does not exhibit a pair of identifiable tangent zones. Sometimes an increase in vertical scale will improve the tangent locations.

The D\textsubscript{90} (or other percent consolidation value) is obtained from D\textsubscript{0} and D\textsubscript{100}. This value projected to the settlement curve allows one to obtain t\textsubscript{50} from the time axis.

The \sqrt{t} method is also used to obtain t\textsubscript{50}. This method involves plotting the dial reading versus \sqrt{time} with a straight line estimated for the first-several points. This line is extended to the abcissa, and a point 15 percent larger is located (see Fig. 2-10b). Through this point and the intercept of the ordinate axis a second straight line is drawn. When the dial reading versus time curve intersects this second line, the D\textsubscript{90} value is obtained. The apparent initial dial reading Do is obtained where the initial straight-line part of the settlement curve intersects the ordinate axis. With D\textsubscript{90} and D\textsubscript{0} values it is easy to obtain D\textsubscript{50} and t\textsubscript{50} which is most commonly used. Values of t\textsubscript{50} should compare by the two methods, but in real soils large differences are sometimes obtained. The \sqrt{time} method is more rapid, since the test for that load increment can be terminated when D9o is found; however,[1] if secondary compression is to be estimated, the semilog plot should be used).
The Coefficient of Consolidation \( c_v \)
The \( t_{50} \) data are used to compute the coefficient of consolidation \( c_v \) as

\[
c_v = \frac{T_i H^2}{t_{50}}
\]

where \( T_i \) = time factor

\( H \) = length of longest drainage path for a particle of water; in the laboratory it is the half sample thickness when drainage is from both faces

\( T_i \) = time for \( i \) percent consolidation to take place - \( t_{50} \) is usually used

Case I is usually assumed in the conventional laboratory test. For 50 percent consolidation Eq. becomes

\[
c_v = \frac{0.19 H^2}{t_{50}}
\]

The several load increments give separate values of \( c_v \) which can be plotted on the void ratio or strain versus log p curve shown in Fig. 2-ll. The plot is usually very erratic because of changes in void ratio, temperature, and \( S \).

The curve can be smoothed somewhat by using a small vertical scale-beyond this it is an exercise in engineering judgment to determine the value of \( c \), to use for estimating field settlements. The time for a given settlement to take place in the field is obtained as a rearrangement of Eq. to obtain

\[
T_i = \frac{T_i H^2}{c_v}
\]

Primary consolidation settlements occur during the time of an excess porepressure gradient caused by a stress change in the stratum of interest. At the end of primary consolidation the excess pore pressure is very nearly zero and the stress change has gone from a total to an effective state. Additional settlements termed secondary compression (or consolidation) continue for some additional time. These will be considered in a later section.

### Table 2-4 Time factors for indicated pressure distribution

<table>
<thead>
<tr>
<th>( U )</th>
<th>( t_{50} )</th>
<th>Case I</th>
<th>Case II</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.000</td>
<td>0.000</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>0.008</td>
<td>0.048</td>
<td>0.006</td>
</tr>
<tr>
<td>20</td>
<td>0.031</td>
<td>0.060</td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>0.071</td>
<td>0.115</td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>0.126</td>
<td>0.207</td>
<td>0.281</td>
</tr>
<tr>
<td>50</td>
<td>0.197</td>
<td>0.281</td>
<td>0.371</td>
</tr>
<tr>
<td>60</td>
<td>0.287</td>
<td>0.371</td>
<td>0.488</td>
</tr>
<tr>
<td>80</td>
<td>0.567</td>
<td>0.652</td>
<td>0.933</td>
</tr>
<tr>
<td>90</td>
<td>0.848</td>
<td></td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>( \infty )</td>
<td>0.933</td>
<td>0.933</td>
</tr>
</tbody>
</table>

Primary consolidation settlements occur during the time of an excess porepressure gradient caused by a stress change in the stratum of interest. At the end of primary consolidation the excess pore pressure is very nearly zero and the stress change has gone from a total to an effective state. Additional settlements termed secondary compression (or consolidation) continue for some additional time. These will be considered in a later section.

The sharp break in the e versus log p or \( \varepsilon \) versus log p curve is used to estimate whether the soil is preconsolidated. Casagrande (1936) proposed the method shown in Fig. 2-11 a to determine a value of \( p_c \). Steps in the method are:
1. Determine by eye the sharpest curvature and draw a tangent.
2. Draw a horizontal line through the tangent point and bisect the angle a thus produced [2].

Method of correcting normally consolidated clay [after Schmertmann (1975)] is shown on (a). Data used to plot both curves are shown on (6). Slight discrepancy between $C'_c$, values due to plotting.

Substituting $\Delta e$ from Eq. (a), we obtain

$$\Delta n = \frac{a_v \Delta P}{1 + \epsilon_o}$$

where $m_v = \text{coefficient of volume compressibility}$:

$$m_v = \frac{a_v}{1 + \epsilon_o} = \frac{\epsilon}{\Delta P} = \frac{1}{E}$$

From Fig. 2-12 the settlement $\Delta H$ is by proportion

$$\frac{\Delta H}{H} = \frac{\Delta e}{\epsilon_o} \quad (f)$$

or

$$\Delta H = m_v \Delta P = \epsilon H \quad (g)$$

where $H = \text{total thickness of stratum}$ and $\epsilon = \text{average unit strain in H}$.

From inspection of Fig. 2-13

$$\Delta H = \frac{C_c H \log P_o + \Delta P}{1 + \epsilon_o} \quad (h)$$

For a normally consolidated soil with increase in effective pressure of $\Delta P$ we have

$$P_2 = P_o + \Delta P \quad \text{and} \quad P_1 = P_o$$

$$\Delta H = \frac{C_c P_2 \log P_o + \Delta P}{1 + \epsilon_o} \quad (i)$$

From the definition of $C_s$ and Eq. (f),

$$\Delta H = \frac{C_c H \log P_2}{1 + \epsilon_o} \quad (j)$$

and $p_1 = P_o$ and

$$\Delta H = \frac{C_c \log P_2}{1 + \epsilon_o} \quad (k)$$
Void ratio versus log p curves. (a) General plot for a reconsolidated soil with method shown to correct for sample disturbance using $C_c$. (b) $C_c$ is not clearly identified when the soil structure collapses to produce a sharp break in curve. Also

$$
\varepsilon = \frac{\Delta H}{H_t} = \frac{\Delta H}{1 + e_o} = C'_c \log \frac{p_2}{p_1}
$$

Equating $\Delta H$,

$$
C'_c (1 + e_o) \log \frac{p_2}{p_1} = C_c \log \frac{p_2}{p_1}
$$

$$
C'_c = \frac{C_c}{1 + e_o}
$$

The settlement using $C'_c$ is

$$
\Delta H = C'_c H \log \frac{p_2}{p_1}
$$

Soil relationships for settlement equations. Left side is laboratory, right side field relationships. And for normally consolidated clay[3].

$$
\Delta H = C'_c H \log \frac{p_o + \Delta p}{p_o}
$$

**Conclusion**

1- Settlement computations for preconsolidated soils are similar except that the slope of the $\varepsilon$ versus log $p$ or $\varepsilon$ versus log $p$ curve between $p_o$ and $p_c$.

2- The total $JH$ is the sum of the computed settlements along the two branches and should be significantly less than for a normally consolidated soil.

**Reference**


2- Blaine, E. S. (1967), Practical Lessons in Caisson Sinking from the Baton Rouge Bridge, ENR, Feb. 6, pp. 213-21 S.