1.6 Consolidation Test

1.6.1 General

- Consolidation can be defined as a dissipation process of excess pore pressure induced by applied load or change of boundary conditions.

- It is a time dependent behavior of soil deformation.
  \[ \Rightarrow \text{Significant in saturated clayey soils.} \]
  \[ \Rightarrow \text{Factors on consolidation time} \]

- Consolidation test determines parameters for the time dependent behavior of soils.
  1) The amount of deformation \( \Rightarrow \) (Primary) Consolidation settlement (+ Secondary compression settlement)
  2) Rate of consolidation (i.e. Consolidation time)
- Idealized stages in primary consolidation

- Consolidation theory follows Darcy's law.

\[ \nu = ki = k(\Delta h/L) \Rightarrow \Delta t = L/\nu = L/(k(\Delta h/L)) = L^2/(k\Delta h) \]

\[ \Rightarrow \text{Doubling } L \text{ requires 4 times for consolidation.} \]

\[ \Rightarrow \text{Consolidation rate is getting slower with decreasing } \Delta h. \]
1.6.2 Consolidation Test

- Simulates 1-dimensional state (flow and deformation)
  ⇒ Using a circular metal ring confining the sample.
  ⇒ (Possible to measure the pore pressure during consolidation and to perform the permeability tests in the oedometer.)
- Sample size: 20 – 40 mm thickness (H) and 45 – 113 mm diameter (D).
  D/H > 2.5 and D < {(Tube sample) - 6mm.}
  (Commonly used sample size: D = 63.5mm, H = 25.4mm)

- Ring-to-soil friction problems:
  ⇒ Should be reduced by limiting sample thickness, spraying the inner ring wall
  with tefron powder or using a tefron-lined ring.

- Equipment calibration
  ⇒ Check the compressibility’s of load block and porous stones, if necessary.

- A loading sequence and measurements
  1) A loading sequence
     * Applying loads with a load ratio $\Delta p/p = 1$ in general, such as
       (5, 10), 20, 40, 80, 160, 320, 640 … etc., kPa with at least 1 unload-reload
       cycle (after reaching maximum past pressure, $p_{\text{max}}$)
     * Each load is sustained for one day (24 hrs)
     * The specimen is kept under water throughout the test.
  2) Measurements
     * Measuring vertical deformation from dial gage or LVDT with time.
       (Vertical strain, volumetric strain, change of void ratio)
       \[
       \text{Dial gage reading} \times \text{Calibration factor} = \text{Vertical deformation} (\Delta H)
       \]
       ⇒ Vertical strain $\varepsilon_{\text{vertical}}$ (= volumetric strain, $\varepsilon_{\text{volume}}$) = $\Delta H/H_0$
       ⇒ Change of void ratio, $\Delta e = (1+e_0) \varepsilon_{\text{vertical}}$
     * Take a dial gage reading at time sequence for each load as below (example)
       8sec, 15sec, 30sec, 1min, 2min, 4min, 8min, 15min, 30min, 1hr, 2hr…
1.6.3 Evaluating consolidation parameters from consolidation test

Typical plot of the test results

Fig. $\Delta H$ vs. $t$ (log scale) for each load increment.

Fig. $e$ vs. $\sigma'$ (log scale)
1) Parameters for time dependent behavior.

- The coefficient of consolidation (\(c_v\)) and the secondary compression coefficient (\(c_\alpha\))

- From Terzaghi’s 1-dimensional consolidation theory

\[
T_i = \frac{c_v T_i}{H_d} \quad \text{and} \quad c_v = \frac{T_i H_d^2}{t_i}
\]

where \(T_i\) = time factor given in Table 13.1 → depend on boundary conditions of consolidation

\(t_i\) = corresponding time for \(T_i\)

\(H_d\) = the longest drainage path

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**Table 13-1** Time factors for indicated pressured distribution

<table>
<thead>
<tr>
<th>U, %</th>
<th>Case I</th>
<th>Case II</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>10</td>
<td>0.008</td>
<td>0.048</td>
</tr>
<tr>
<td>20</td>
<td>0.031</td>
<td>0.090</td>
</tr>
<tr>
<td>30</td>
<td>0.071</td>
<td>0.115</td>
</tr>
<tr>
<td>40</td>
<td>0.126</td>
<td>0.207</td>
</tr>
<tr>
<td>50</td>
<td>0.197</td>
<td>0.281</td>
</tr>
<tr>
<td>60</td>
<td>0.287</td>
<td>0.371</td>
</tr>
<tr>
<td>70</td>
<td>0.403</td>
<td>0.488</td>
</tr>
<tr>
<td>80</td>
<td>0.567</td>
<td>0.652</td>
</tr>
<tr>
<td>90</td>
<td>0.848</td>
<td>0.933</td>
</tr>
<tr>
<td>100</td>
<td>∞</td>
<td>∞</td>
</tr>
</tbody>
</table>

Pore-pressure distribution for case I usually assumed for case Ia.
i) Logarithm-of-time method

![Diagram](image1.png)

\[ c_v = \frac{0.197H^2}{d} \]

\[ c_a = (1 + e_a)c_a' \]

Fig. 5.37 Logarithm-of-time method for determination of \( C_u \).

ii) Square-root-time method

![Diagram](image2.png)

\[ c_v = \frac{0.848H^2}{d} \]

\[ OR = (1.15)(OQ) \]

Fig. 5.38 Square-root-of-time method for determination of \( C_u \).
2) Deformation parameters.

- The compressive index ($C_c$), the recompression (or swelling) index ($C_r$), and the preconsolidation pressure (or maximum past pressure) ($p_{max}$)

i) The preconsolidation pressure ($p_{max}$)

Fig. 5.32 Graphical procedure for determination of preconsolidation pressure.
ii) The compressive index \((C_c)\), and the recompression (or swelling) index \((C_r)\)

\[
C_c = (1+e_o)C_c' \quad \text{and} \quad C_r = (1+e_o)C_r'
\]

- Note: \(C_c', C_r'\) and \(c_\alpha'\) is related to dial reading or volumetric (vertical) strain.

\(C_c, C_r\) and \(c_\alpha\) is related to void ratio \(e\).
1.6.4 Rowe cell test

1) Rowe cell type test

- Specimen is loaded by 1) hydraulic pressure acting on a 2) flexible diaphragm (with/without rigid plate) 3) inside the cell.

- Overall features of the cell

Fig. Main features of 250mm diameter Rowe cell

- Consolidation is monitored by measurements of pore pressure and volume change (or vertical deformation) with time.

- Main advantages
- Limitations

- Analysis of the test results

① Deformation characteristics
   : Same as in the conventional oedometer test

② Coefficient of consolidation
   • Use curve fitting procedure
   • $T_v$ and $T_r$ values are summarized in the table
   • For vertical drainage, log $t$ method is generally adopted.
   • For radial drainage, $\sqrt{t}$ method is generally used.

Fig. Theoretical relationships between time factor and degree of consolidation for vertical drainage
Fig. Theoretical curve relating square-root time factor to degree of consolidation for drainage radially outwards to periphery with equal strain loading.
Table. Rowe cell consolidation tests - Data for curve fitting

<table>
<thead>
<tr>
<th>Test Ref.</th>
<th>Drainage direction</th>
<th>Boundary strain</th>
<th>Consolidation location</th>
<th>Theoretical time factor ( T_{50} )</th>
<th>Time function</th>
<th>Power curve slope factor</th>
<th>Measurement s used</th>
<th>Coefficient of consolidation</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) and (b)</td>
<td>Vertical, one way free and equal</td>
<td>Average Center of base</td>
<td>0.197 ((T_s)) 0.379 ((T_s))</td>
<td>(t^{0.5}) 1.15</td>
<td>(\Delta V) or (\Delta H^*)</td>
<td>(c_v = \frac{T_s}{t})</td>
<td>p.w.p</td>
<td></td>
</tr>
<tr>
<td>(c) and (d)</td>
<td>Vertical two way free and equal</td>
<td>Average</td>
<td>0.197 ((T_s)) 0.379 ((T_s))</td>
<td>(t^{0.5}) 1.15</td>
<td>(\Delta V) or (\Delta H^*)</td>
<td>(c_v = \frac{T_s}{t})</td>
<td>p.w.p</td>
<td></td>
</tr>
<tr>
<td>(e)</td>
<td>Radial outward free</td>
<td>Average Central</td>
<td>0.0632 ((Tv)) 0.200 ((Tv))</td>
<td>(t^{0.65}) 1.22</td>
<td>(\Delta V)</td>
<td>(c_m = \frac{T_v}{t})</td>
<td>p.w.p</td>
<td></td>
</tr>
<tr>
<td>(f)</td>
<td>Equal</td>
<td>Average Central</td>
<td>0.0866 ((Tv)) 0.173 ((Tv))</td>
<td>(t^{0.5}) 1.17</td>
<td>(\Delta V) or (\Delta H)</td>
<td>(c_m = \frac{T_v}{t})</td>
<td>p.w.p</td>
<td></td>
</tr>
<tr>
<td>(g)</td>
<td>Radial inward† free (r = 0.55R)</td>
<td>Average</td>
<td>0.193 ((Tr)) 0.191 ((Tr))</td>
<td>(t^{0.5}) 1.17</td>
<td>(\Delta V)</td>
<td>(c_n = \frac{T_r}{t})</td>
<td>p.w.p</td>
<td></td>
</tr>
<tr>
<td>(h)</td>
<td>Equal (r = 0.55R)</td>
<td>Average</td>
<td>0.195 ((Tr)) 0.195 ((Tr))</td>
<td>(t^{0.5}) 1.17</td>
<td>(\Delta V) or (\Delta H)</td>
<td>(c_n = \frac{T_r}{t})</td>
<td>p.w.p</td>
<td></td>
</tr>
</tbody>
</table>

† Drain ratio \(((\text{Diameter of drains})/(\text{Diameter of specimen}))\) = 1/20

* \(\Delta H\) with equal strain only

\[ R \]: radius of specimen
\[ D \]: diameter of specimen
2) CRS Test (Constant Rate of Strain Test)

- Consolidation pressure is applied by strain control loading.
- Test is performed with monitoring the axial load, vertical displacement and pore pressure with/without volume change during loading.
- Testing apparatus

① For vertical drainage

② For radially outward drainage
For radially inward drainage

- Advantages
  ① Usually completed in much shorter time than the incremental loading test.
  ② Provide continuous measurements.
  ③ Allow easier conversion to automation.
  ④ Generally more efficient, and less labor to perform.
  ⑤ Can be saturated using back pressure

- Limitations
  ① Rate of strain must be slow enough to prevent development of excessive pore pressure (i.e. hydraulic gradient). (\(\Delta u / \Delta \sigma_v \leq 30\%\) for vertical drainage by ASTM)
  ② Special attention is given to exclude or minimize the friction between loading bar and the guide wall of top cap of the cell and top cap and consolidation cell.
  ③ Must saturate the sample
  ④ Need a little more complicated device with pore pressure measurement.
  ⑤ Have difficulty in unload-reload cycle test
- Analysis of test results

① Vertical drainage CRS test (Wissa et al., 1971)
- Nonlinear steady state theory accepted in ASTM
- Average effective vertical stress

$$\bar{\sigma}'_v = (\sigma'_v - 2\sigma'_{v_b} + \sigma'_{v_e})^{1/3}$$

- Coefficient of consolidation for vertical flow

$$c_v = \frac{H^2 \log\left(\frac{\sigma_{v_2}}{\sigma_{v_1}}\right)}{2\Delta t \log\left(1 - \frac{u_b}{\sigma_v}\right)}$$

where, \(\sigma_v\) is the total vertical stress, \(H\) is the current specimen height, \(u_b\) is the excess pore pressure at the bottom and \(\sigma_{v_1}, \sigma_{v_2}\) is the total stresses at times \(t_1, t_2\), respectively

② Radially outward drainage CRS test
- Average effective vertical stress

$$\bar{\sigma}'_v = \sigma_v - \alpha_{ro} u_c$$

$$\alpha_{ro} = \frac{\bar{u}}{u_c} = \frac{1}{2}$$

where, \(u_c\) is the excess pore pressure at the center of the sample, and \(\alpha_{ro}\) is the ratio of average pore water pressure (\(\bar{u}\)) to the pore pressure at center.

- Coefficient of consolidation for radially outward flow

$$c_{ro} = \frac{R^2 \sigma'_{v_c} \log(\sigma'_{v_2} / \sigma'_{v_1})}{1.736 u_c \Delta t}$$

where, \(R\) is the radius of the sample.
Radially inward drainage CRS test

- Effective vertical stress

\[
\sigma' = \sigma_v - \alpha_{rI} u_o
\]

\[
\alpha_{rI} = \frac{N^4 - 4N^2 + 3 + 4 \ln N}{(1 - N^2)(2 - 2N^2 + 4 \ln N)}
\]

where \( u_o \) is the excess pore pressure at the outer boundary of the sample, \( \alpha_{rI} \) is the ratio of average pore water pressure (\( \bar{u} \)) to the pore pressure at the outer boundary, \( N \) is the drainage ratio (\( \frac{r_w}{R} \)), and \( r_w \) and \( R \) is the drainage radius, and radius of sample, respectively.

- Coefficient of consolidation for radially inward flow

\[
c_{ri} = \frac{R^2 \sigma'_v \log(\sigma'_{v2} / \sigma'_{v1})}{1.736u_o\Delta t}(N^2 - 1 - 2 \ln N)
\]