1.6 Consolidation Test

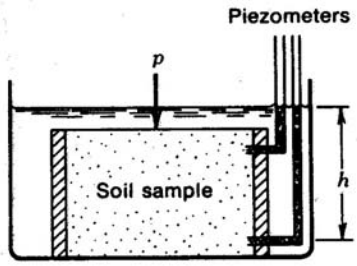
1.6.1 General

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

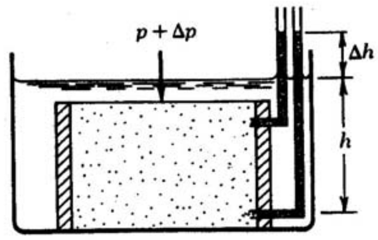
- It is a time dependent behavior of soil deformation.
  ⇒ Significant in **saturated clayey soils**.
  ⇒ Factors on consolidation time

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

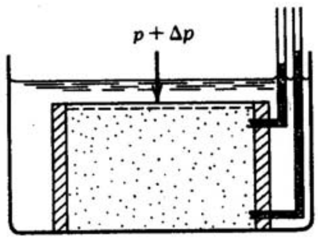
- Idealized stages in primary consolidation



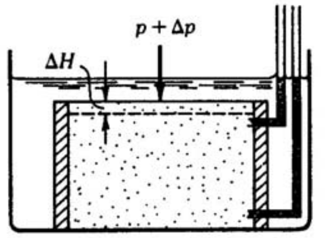
(*a*) Piezometers have reached static equilibrium under some compressive load p.



(*b*) On adding a load increment Δp the piezometers record a hydrostatic pressure increase of Δh as shown. There is often some finite time lag before Δh is fully developed but Δh is considered instantaneous in any idealization.



(*c*) Relative positions of piezometers some time after application of Δp. With shorter flow path the upper piezometer loses head faster than the bottom one.



(*d*) At end of primary consolidation under pressure increment Δp both piezometers have returned to the initial position of "*a*." Secondary compression will continue under Δp for some additional time so that the final total settlement will be larger than the ΔH at the end of primary consolidation.

Figure 13-2
Stages in primary consolidation (idealized).

- Consolidation theory follows Darcy's law.

  $v = ki = k(\Delta h/L) \quad \Rightarrow \quad \Delta t = L/v = L/\{ k(\Delta h/L)\} = \mathbf{L^2/(k\Delta h)}$

  $\Rightarrow$ Doubling L requires 4 times for consolidation.

  $\Rightarrow$ Consolidation rate is getting slower with decreasing Δh.

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.)

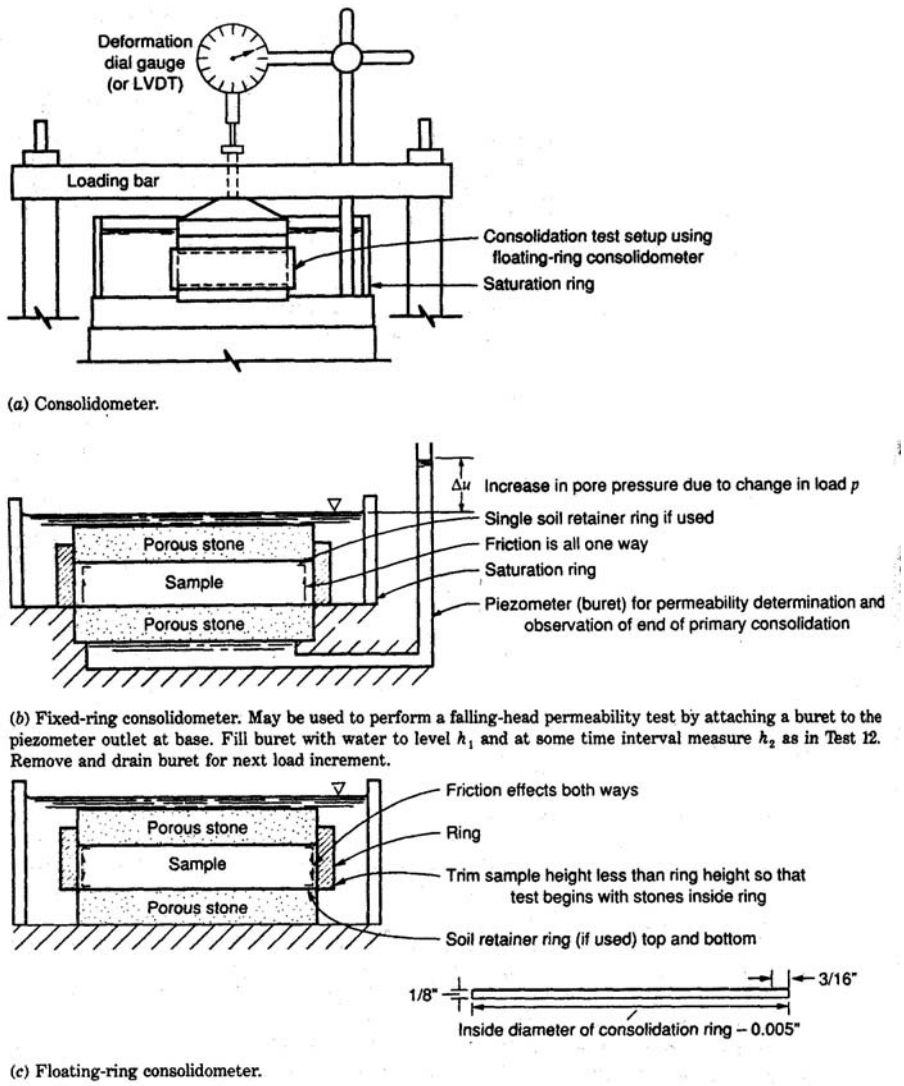


Figure 13-3
Select line details of a consolidation test.

- 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_{max})
  (unload → 2 steps $(\frac{1}{2}P_{max}, \frac{1}{8}P_{max})$)
  * 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)
  Dial gage reading × Calibration factor = Vertical deformation (ΔH)
  ⇒ Vertical strain $\varepsilon_{vertical}$ (= volumetric strain, ε_{volume}) = $\Delta H/H_o$
  ⇒ Change of void ratio, $\Delta e = (1+e_o)\ \varepsilon_{vertical}$
  * 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…

<u>1.6.3 Evaluating consolidation parameters from consolidation test</u>

Typical plot of the test results

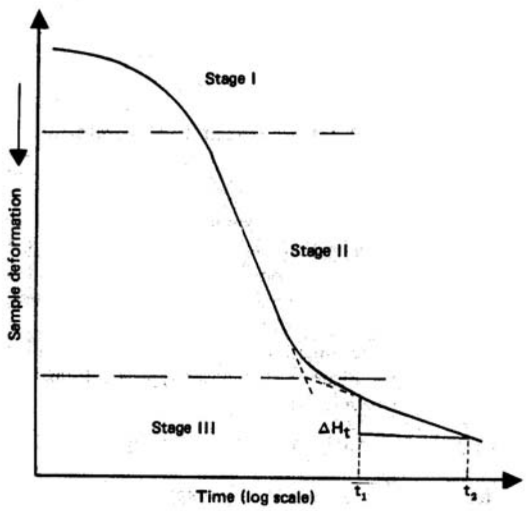


Fig. ΔH vs. t (log scale) for each load increment.

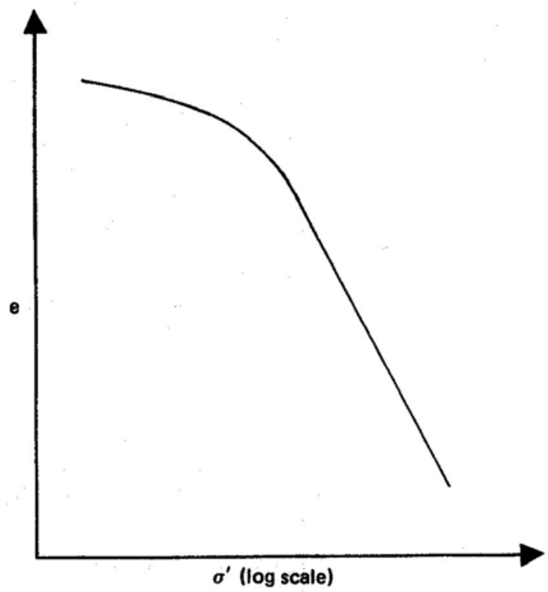


Fig. e vs. σ' (log scale)

1) Parameters for time dependent behavior.

- The coefficient of consolidation (c_v) and the secondary compression coefficient (c_α)
- From Terzaghi's 1-dimensional consolidation theory

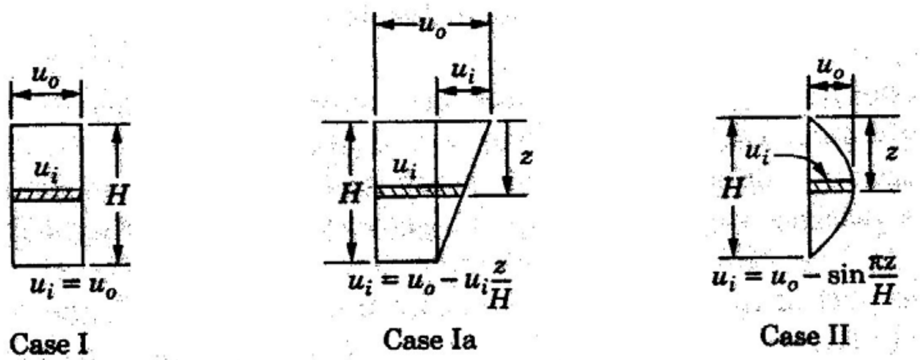
$$T_i = \frac{c_v t_i}{H_d^2} \quad \text{and} \quad c_v = \frac{T_i H_d^2}{t_i}$$

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

Table 13-1 Time factors for indicated pressured distribution



Pore-pressure distribution for case I usually assumed for case Ia.

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

i) Logarithm-of-time method

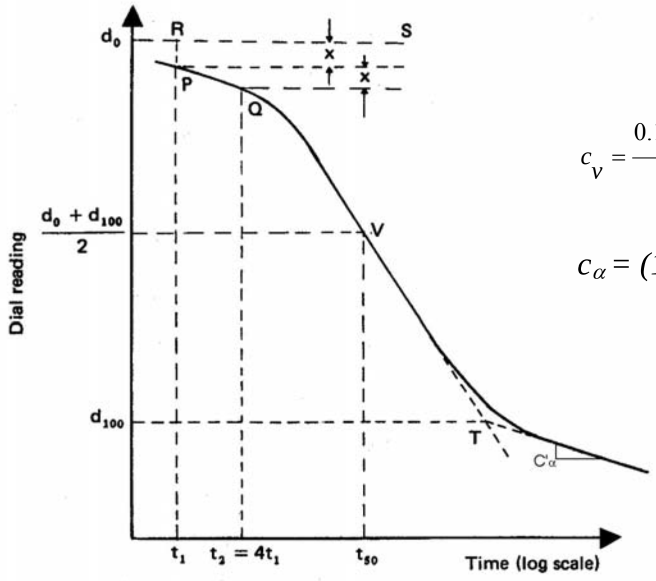
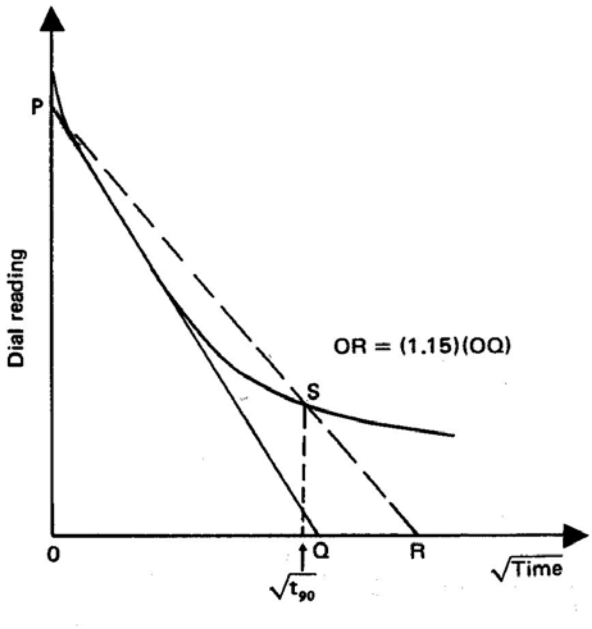


Fig. 5.37 Logarithm-of-time method for determination of C_v.

$$c_v = \frac{0.197 H_d^2}{t_{50}}$$

$$c_\alpha = (1+e_o)c_\alpha'$$

ii) Square-root-time method



$$c_v = \frac{0.848 H_d^2}{t_{90}}$$

Fig. 5.38 Square-root-of-time method for determination of C_v.

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})

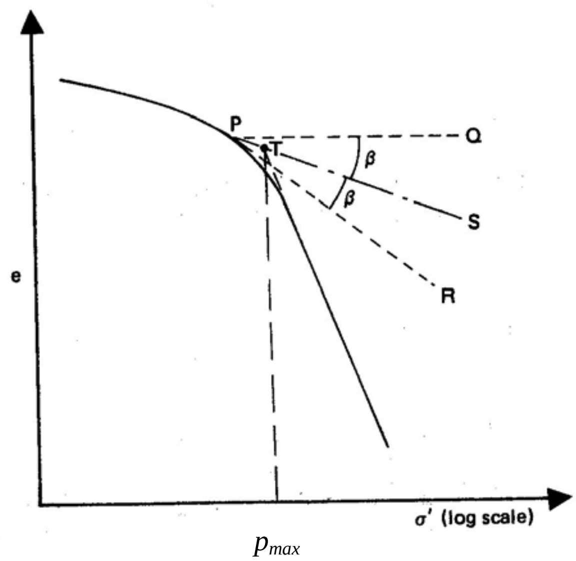


Fig. 5.32 Graphical procedure for determination of preconsolidation pressure.

ii) The compressive index (C_c), and the recompression (or swelling) index (C_r)

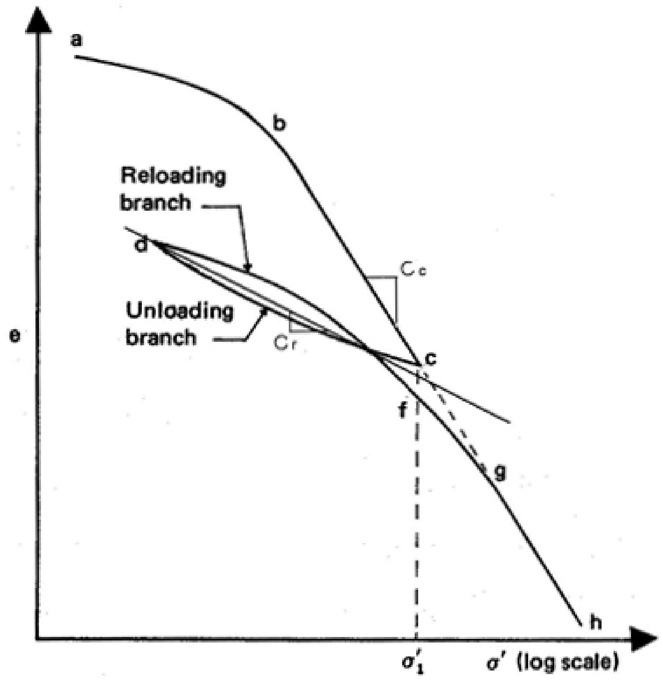


Fig. 5.31 Plot of void ratio vs. effective pressure showing unloading and reloading branches.

- $C_c = (1+e_o)C_c'$ and $C_r = (1+e_o)C_r'$
- Note : C_c', C_r' and c_α' is related to dial reading or volumetric(vertical) strain.

  C_c, C_r and c_α 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

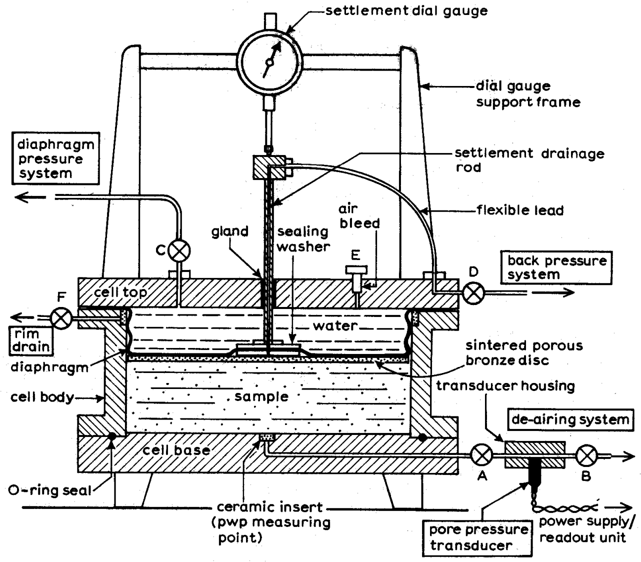


Fig. Main features of 250mm diameter Rowe cell

- 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.

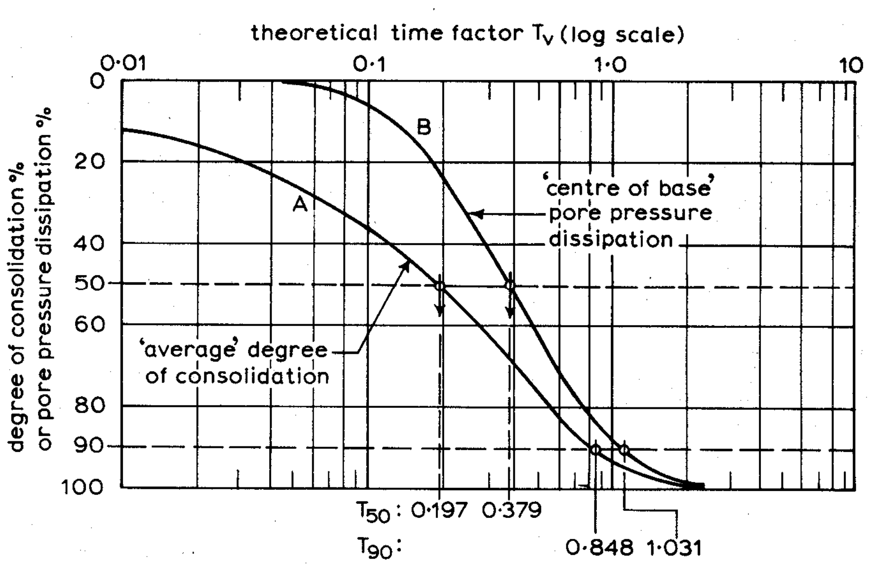


Fig. Theoretical relationships between time factor and degree of consolidation for vertical drainage

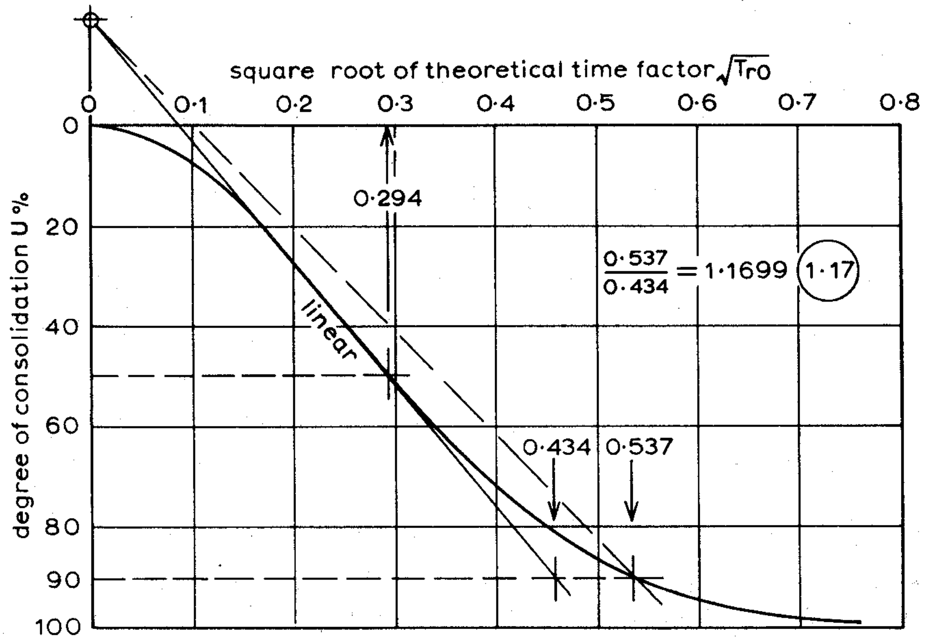


Fig. Theoretical curve relating square-root time factor to degree of consolidation for drainage radially outwards to periphery with equal strain loading

Table. Rowe cell consolidation tests - Data for curve fitting

Test Ref.	*Drainage direction*	*Boundary strain*	*Consolidation location*	*Theoretical time factor* T_{50}	T_{90}	*Time function*	*Power curve slope factor*	*Measurements used*	*Coefficient of consolidation*
(a) and (b)	Vertical, one way	Free and equal	Average	0.197	0.848	$t^{0.5}$	1.15	ΔV or ΔH*	$c_v = \frac{T_v H^2}{t}$
				(T_v)					
			Center of base	0.379	1.031			p.w.p	
(c) and (d)	Vertical two way	Free and equal	Average	0.197 (T_v)	0.848	$t^{0.5}$	1.15	ΔV or ΔH*	$c_v = \frac{T_v (H/2)^2}{t}$
(e)	Radial outward	Free	Average	0.0632	0.335	$t^{0.465}$	1.22	ΔV	$c_{ro} = \frac{T_{ro} R^2}{t}$
				(T_{ro})					
			Central	0.200	0.479			p.w.p	
(f)		Equal	Average	0.0866	0.288	$t^{0.5}$	1.17	ΔV or ΔH	$c_{ro} = \frac{T_{ro} R^2}{t}$
				(T_{ro})					
			Central	0.173	0.374			p.w.p	
(g)	Radial inward†	Free	Average	0.193	0.658	$t^{0.5}$	1.17	ΔV	$c_{ri} = \frac{T_{ri} D^2}{t}$
				(T_{ri})					
			r = 0.55R	0.191	0.656			p.w.p	
(h)		Equal	Average	0.195	0.649	$t^{0.5}$	1.17	ΔV or ΔH	$c_{ri} = \frac{T_{ri} D^2}{t}$
				(T_{ri})					
			r = 0.55R	0.195	0.648			p.w.p	

† Drain ratio ((Diameter of drains)/(Diameter of specimen)) = 1/20

* ΔH with equal strain only

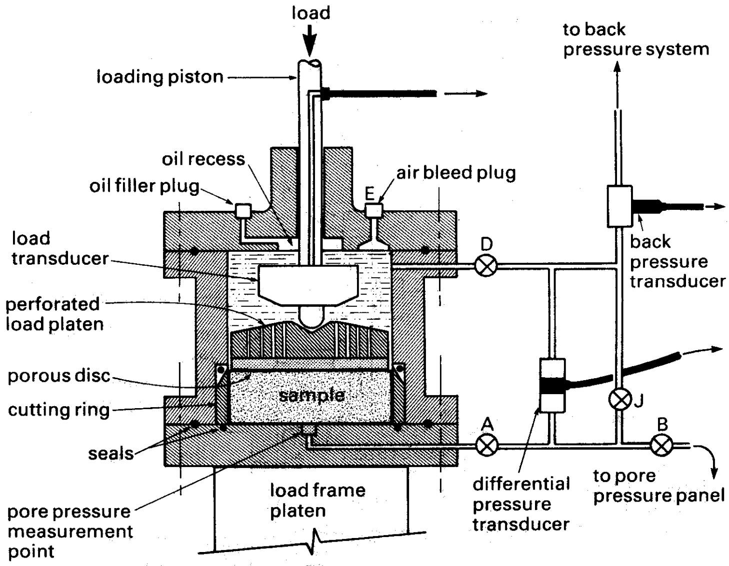
R : radius of specimen

D : diameter of specimen

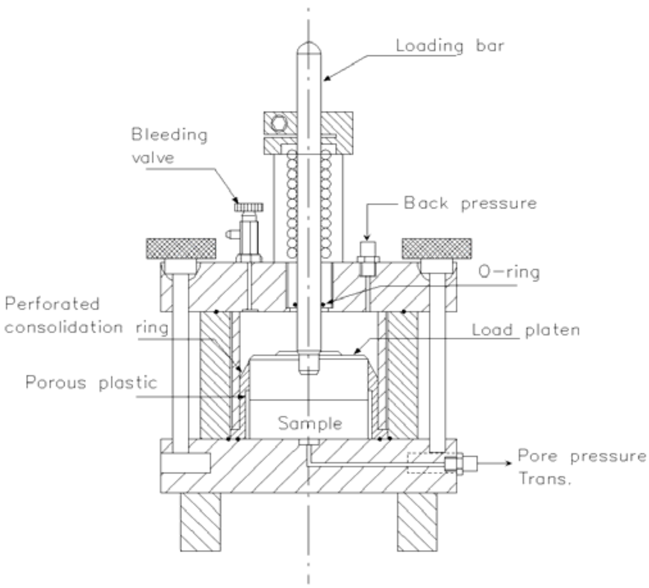
2) CRS Test (Constant Rate of Strain Test)

- 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

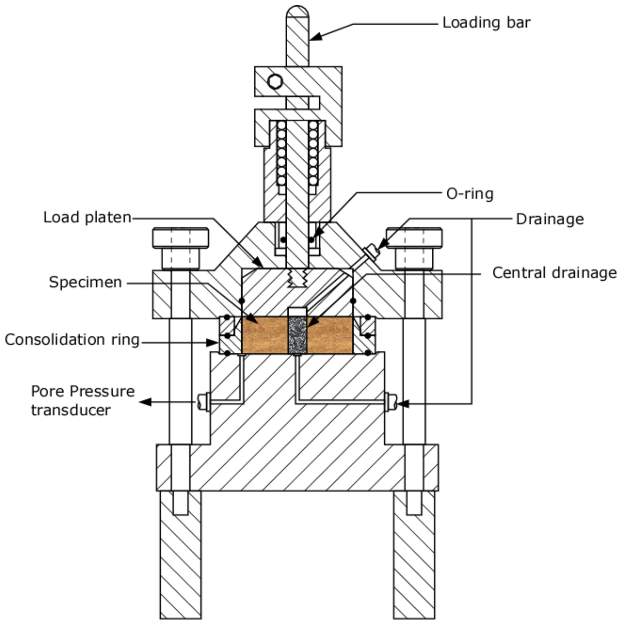
①For vertical drainage



②For radially outward drainage



③For 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

$$\overline{\sigma}'_v = (\sigma_v^3 - 2\sigma_v^2 u_b + \sigma_v u_b^2)^{1/3}$$

- Coefficient of consolidation for vertical flow

$$c_v = -\frac{H^2 \log\left(\frac{\sigma_{v2}}{\sigma_{v1}}\right)}{2\Delta t \log\left(1 - \frac{u_b}{\sigma_v}\right)}$$

where, σ_v is the total vertical stress, H is the current specimen height, u_b is the excess pore pressure at the bottom and σ_{v1}, σ_{v2} is the total stresses at times t_1, t_2, respectively

② Radially outward drainage CRS test

- Average effective vertical stress

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

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

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

- Coefficient of consolidation for radially outward flow

$$c_{ro} = \frac{R^2 \sigma'_v \log(\sigma'_{v2} / \sigma'_{v1})}{1.736 u_c \Delta t}$$

where, R is the radius of the sample.

③ Radially inward drainage CRS test

- Effective vertical stress

$$\bar{\sigma}_v' = \sigma_v - \alpha_{ri} u_o$$

$$\alpha_{ri} = \frac{N^4 - 4N^2 + 3 + 4\ln N}{(1-N^2)(2-2N^2+4\ln N)}$$

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

- Coefficient of consolidation for radially inward flow

$$c_{ri} = \frac{R^2 \sigma_v' \log(\sigma_{v2}' / \sigma_{v1}')}{1.736 u_o \Delta t} (N^2 - 1 - 2\ln N)$$