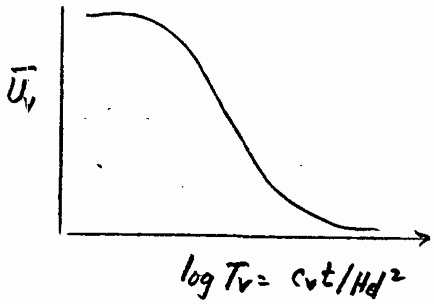
III RATE OF CONSOLIDATION AND COEF. OF PERMEABILITY (Hydraulic Conductivity)

Sheets A1, 2	Equations for Terzaghi and Vertical Drain Consolidation
Sheet B	DM-7 c_v vs w_L
Sheets C1, 2, 3	Permeability data from Tavenas et al. (1983)
Sheets D1, 2	" " " Mesri et al. (1994)
Sheet E	Mesri (1981) Illicon FD analysis of Gloucester Fill

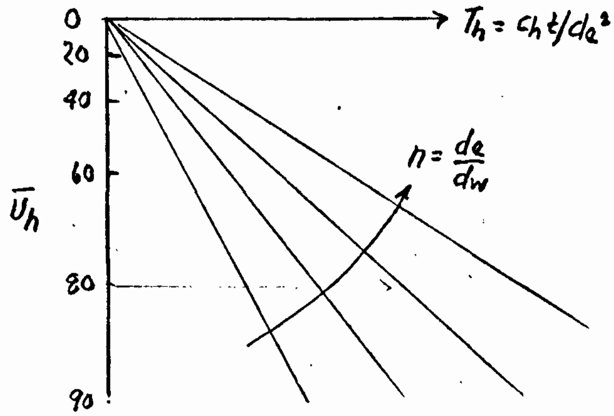
1. INTRODUCTION

1.1 Consolidation Theories

1) Terzaghi 1-D (Sheet A1)

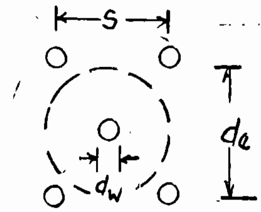


2) Vertical Drains (Sheet A2)



3) Combined Vertical & Horizontal Flow

$$(1-\bar{U}) = (1-\bar{U}_v)(1-\bar{U}_h)$$



For all three $\bar{U} = \rho_c / \rho_{cf}$: for constant m_v

1.2 Measurement of $c_v = k_v / m_v \cdot \gamma_w$

1) Incremental Oedometer

- $c_v = \dfrac{T H_d^2}{t}$ H_d = ave. for increment $\sqrt{t}$ · $T_{90} = 0.848$ (Taylor)

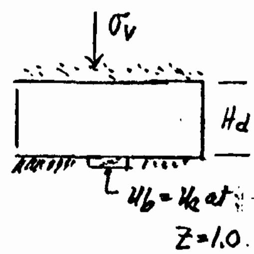
  Plot vs. ave. σ'_{vc} $\log t$ $T_{50} = 0.197$ (Casagrande)

- Typically for $t_c \approx 1$ day, $c_v(\sqrt{t}) \approx (2 \pm \frac{1}{2})\, c_v(\log t)$
  (See Section 3 possible explanation)

2) CRSC (Also see Section 8.3, Consol. Part II)

- $u_b / \sigma_v \approx$ 5-10% desirable*

- $c_v = \dfrac{k_v}{m_v \cdot \gamma_w}$ $k_v \leftarrow \dfrac{\dot{\varepsilon} H_d^2 \gamma_w}{2 u_b}$ $m_v \leftarrow \dot{\varepsilon} \dfrac{dt}{d\sigma_v}$ $\rightarrow \dfrac{H_d^2}{2 u_b}\left(\dfrac{d\sigma_v}{dt}\right)$



Linear theory assumes parabolic u_e distribution →
$\sigma'_v = \sigma_v - \frac{2}{3} u_b$

Mesri et al. recommends $\dot{\varepsilon} = 10 \times \dot{\varepsilon}_p$; $\dot{\varepsilon}_p = \dfrac{k_{v0}}{H_d^2\, 2^{C_c/C_k}} \cdot \dfrac{\sigma'_p}{\gamma_w} \cdot \dfrac{C_{\alpha e}}{C_c}$ (from Section 8.3, Consol. Part II)

* Discussion of effects with u_b/σ_v
- Much lower
- Much higher

3) DM-7 Correlation with Liquid Limit (Sheet 8)

$c_v(NC) \approx 10 - 50 \times 10^{-4}\ cm^2/sec$ for CL

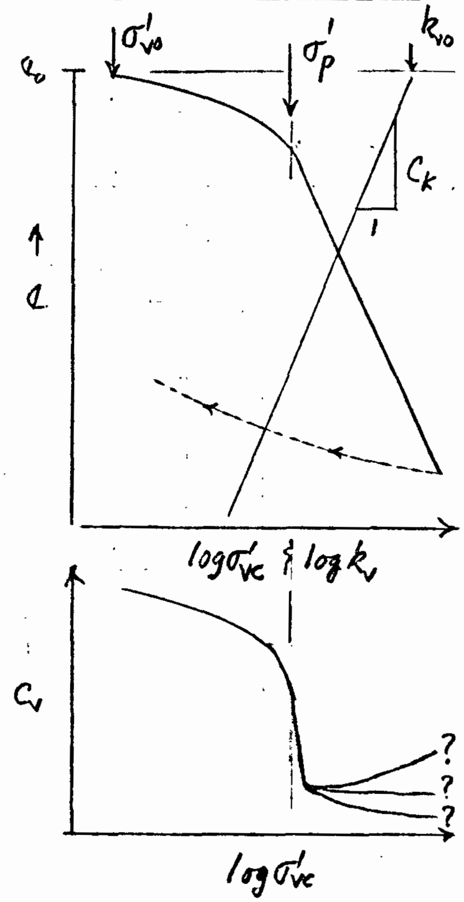
$\approx 1 - 10$ " " for CH

Note: CCL finds that measured $c_v(NC)$ data is typically scattered about the mean trend line

2. EFFECTS OF STRESS HISTORY AND DISTURBANCE

2.1 General Trends (Real data: p2a)

—— Data for no disturbance



1) Why is $c_v(OC) \gg c_v(NC)$?

2) What predict for c_v (unloading)?

3) Permeability Index, C_k (Also see Sect. 4.1)

$C_k = de/d\log k$

$\therefore\ k_v = k_{vo}\,(10)^{(e-e_0)/C_k}$

4) What predict for disturbed sample?
(+ why run tests w/ U/R cycle)

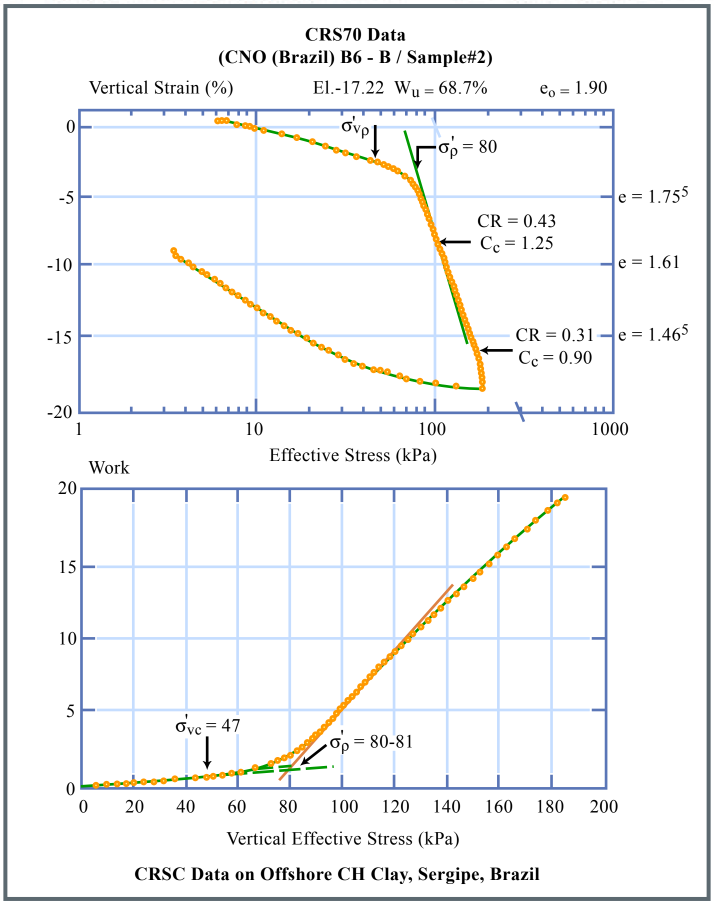


Figure by MIT OCW.

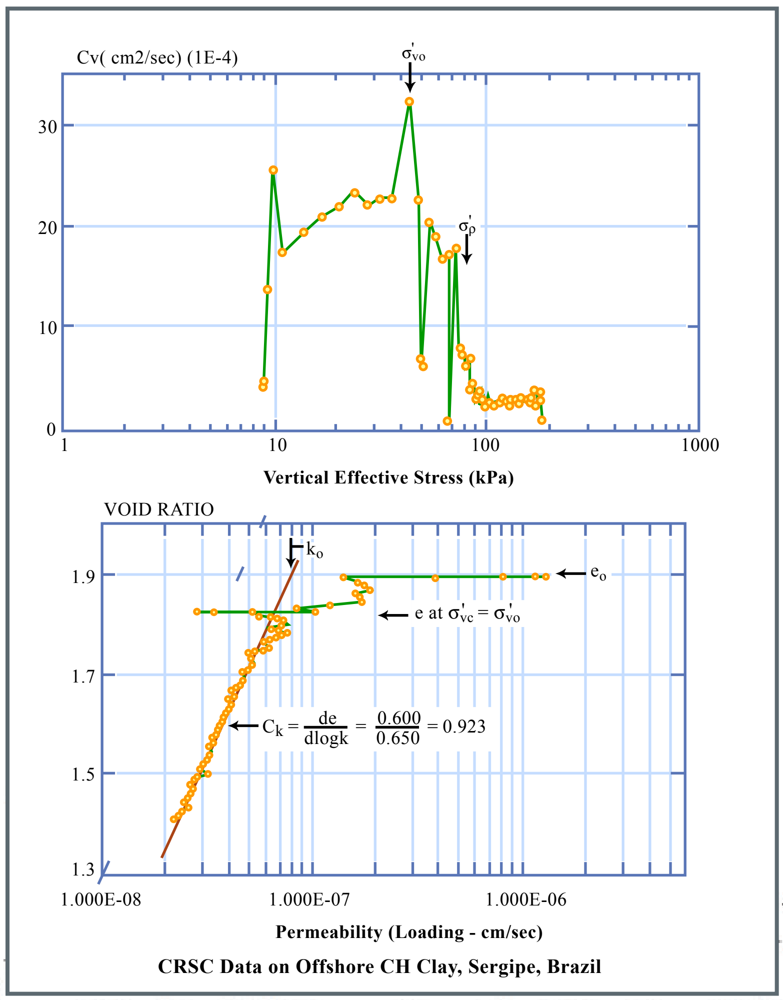


Figure by MIT OCW.

CRSC Data on Offshore CH Clay, Sergipe, Brazil

2.2 Variation in c_v(NC)

1) Mesri & Rokhsar (1974) ASCE, JGED 100(8)

$\cdot\ c_v = \dfrac{k_v}{m_v \cdot \gamma_w} = \dfrac{k_v(1+e_0)}{a_v \cdot \gamma_w}$

$a_v = de/d\sigma'_{vc} = \dfrac{0.434\, C_c}{\sigma'_v}$

$\dfrac{k_v}{k_{v0}} = (10)^{\left(\frac{e-e_0}{C_k}\right)}$; $e - e_0 = -C_c \log \sigma'/\sigma'_0$

$= (10)^{-\frac{C_c}{C_k}\log \sigma'/\sigma'_0} = (\sigma'/\sigma'_0)^{-C_c/C_k}$

$\rightarrow k_v = \dfrac{k_{v0}}{(\sigma'/\sigma'_0)^{C_c/C_k}}$

$\therefore\ c_v = \dfrac{k_0(1+e_0)\sigma'_v}{0.434\,\gamma_w \cdot C_c \left(\dfrac{\sigma'_v}{\sigma'_{v0}}\right)^{C_c/C_k}} \longrightarrow \dfrac{k_0(1+e_0)\sigma'_{v0}}{0.434\,\gamma_w\, C_c}$ for $C_c/C_k = 1$

$\cdot\ c_v(NC) \propto (\sigma'_v)^{1-C_c/C_k}$ $\therefore$ $C_c/C_k > 1 \rightarrow c_v(NC)$ dec. w/ inc. σ'_{vc}
" $< 1 \rightarrow$ " inc. " " "

2) Some labs (based on teaching at some schools, e.g. Duncan 1993 ASCE, JGE 119(9), p1347-1350) compute c_v using the initial H_d at start of test.

This produces large increase in c_v(NC) with increasing σ'_{vc}/σ'_p.

(Rationale for using initial Hd =)

3) CCL experience is that c_v(NC) remains ≈ constant, altho may get min. value just beyond σ'_p for S-shaped VCL
- See p3a for data on 2 clay deposits → $C_c \approx C_k$

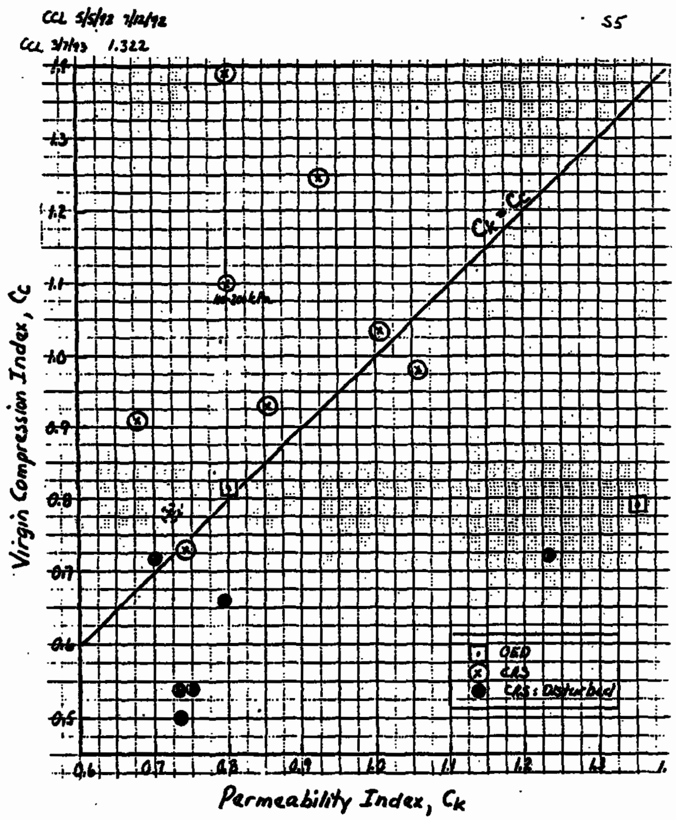


Fig. 6.5 Virgin Compression Index vs. Permeability Index
Sergipe Clay

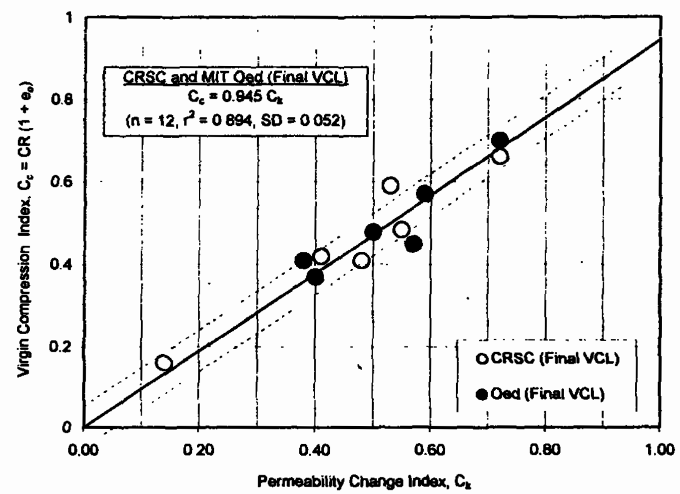


Figure 4.12: Final Virgin Compression Index versus Final Permeability Change Index from Continuous and Incremental Loading Tests

(S.Y. Ng 1998 SM thesis)

Data on Salt Lake City clays (CL/CH)
where $c_v(NC)$ = constant at high σ'_{vc}/σ'_p

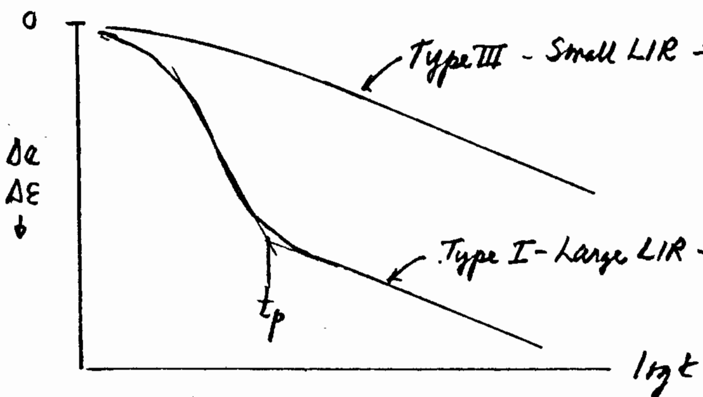
Virgin Compression Index vs. Permeability Index for Two Clay Deposits

3. EFFECTS OF LIR: NC OEDOMETER DATA

3.1 Some General Trends, t_c = 1 day Tests

1) Some Experimental Observations

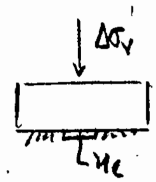
(a) Displacement vs log t

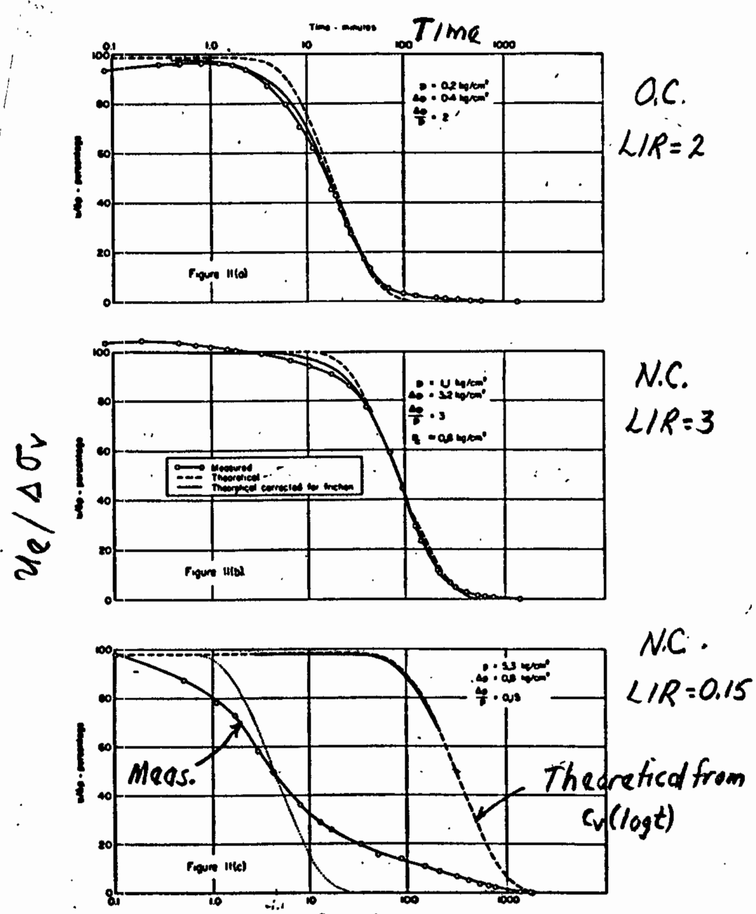


Question: Why get Type III curves?

Leonards & Girault (1961) 5th ICSMFE

(b) Excess u vs log t





O.C. LIR = 2

N.C. LIR = 3

Type I → good match

N.C. LIR = 0.15

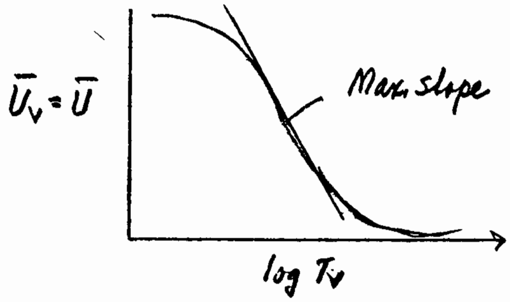
Type III → can't match (like c_v decr. w/ time)

Question: why $c_v(\sqrt{t}) > c_v(\log t)$?

Fig. 11 Influence of loading increment ratio on pore pressure dissipation rates. Undisturbed Mexico City clay.

3.2 Method to Predict Type III Curves (Mesri & Godlewski 1977 ASCE JGED GT5)

1) From Terzaghi Theory



Max. slope $d\bar{U}/d\log T_v = 0.66$ (See Sheet A1)

$\bar{U} = \varepsilon_c/\varepsilon_{cf}$

2) For constant m_v & c_v (means no prior secondary)

Max slope during primary $(d\varepsilon/\log t)_{max} = 0.66\,\varepsilon_{cf} = 0.66\,CR\log(\sigma'_{vf}/\sigma'_{vi})$

$= 0.66\,CR\log\left(1+\frac{\Delta\sigma_v}{\sigma'_{vi}}\right) = 0.66\,CR\log(1+LIR)$

3) Hence during primary

$R_p = \frac{(d\varepsilon/d\log t)_{max}}{CR} = 0.66\log(1+LIR)$ = 0.20 for $LIR = 1$
= 0.11^5 " = 0.5
= 0.05^2 " = 0.2
= 0.02^7 " = 0.1

4) What is typical rate of secondary compression (Consol Part IV)

$R_s = \frac{(d\varepsilon/d\log t)}{CR} = \frac{C_\alpha}{CR} = 0.045 \pm 0.015$ for CL-CH clays

5) Therefore low LIR → $R_p \le R_s$ & hence no break in curve!

6) What happens if $t_c > t_p$ as certainly occurs with $t_c = 24$hr?

- Secondary compression → increase in σ'_p & reduction in ε_{cf}
- therefore should use redefined $LIR' = (\sigma'_{vf} - \sigma'_p)/\sigma'_p$

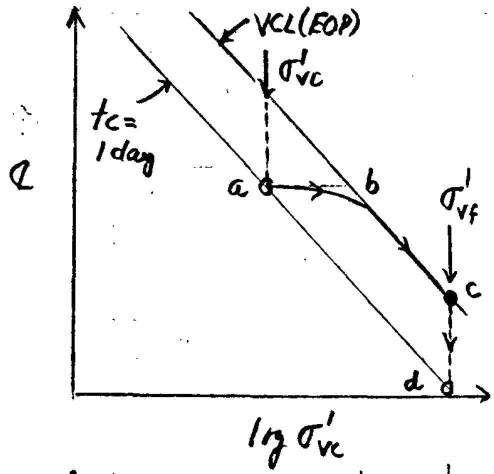
where $\sigma'_p = \sigma'_{vi}\,(t_c/t_p)^{C_\alpha/CR}$ since $\varepsilon_{cf} = CR\log\sigma'_{vf}/\sigma'_p$

Note: for $t_c/t_p = 100$ (t_c = 24hr, t_p = 15 min.) & $C_\alpha/CR = 0.045$, $\sigma'_p/\sigma'_{vi} = OCR = 1.23$

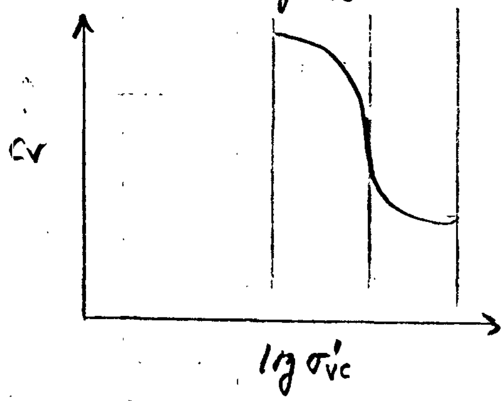
$LIR = 0.5 \rightarrow LIR' = 0.22 \rightarrow R_p = 0.057$
$= 0.35 \qquad = 0.057 \qquad = 0.016$

3.3 Effect of Prior Secondary Compression on Computed $c_v(NC)$: $L/R \approx 1$

1) Conceptual framework

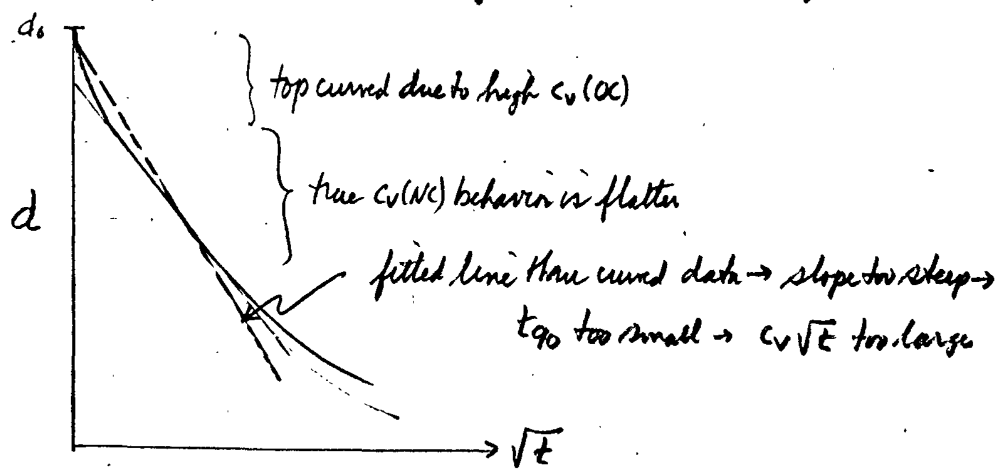


Loading path & behavior
- a-b reloading to VCL w/ high c_v(OC)
- bc virgin consolidation w/ low c_v(NC)
- cd secondary compression



4) Why do many engr. select $c_v(\sqrt{t})$ or ave. of $\sqrt{t}$ & log t methods?
- Because they believe that field rates of consolidation generally much faster than predicted from c_v(NC). However, most clays have initial OCR > 1

2) CCL predicted dial reading vs $\sqrt{t}$ (needs verification!)

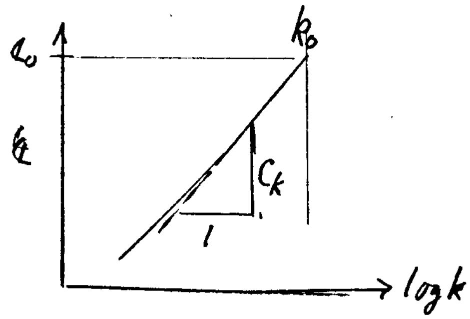


3) Compared to log t fitting method where definition of t_p (t_{100}) should be less affected by initial OC behavior and hence → lower and more realistic c_v(NC)

4. COEFFICIENT OF PERMEABILITY (HYR. CONDUCTIVITY)

4.1 Background (for soft, natural clays)

1) Objective is to Obtain e vs $\log k$ Relationship



$$C_k = de/d\log k = (e_0 - e)/\log k_0/k$$

$$\therefore k = k_0 (10)^{(e-e_0)/C_k}$$

2) Uses in Practice

- Compute c_v when small LIR → fitting methods not applicable.
- Consolidation analyses with Generalized Soil Model (e.g. MCC or MIT-E3)
- Seepage analyses

4.2 Experimental Procedures & Comparisons of $e - \log k$ Data

1) Experimental procedure

a) Backcal. from oed. → $k_v = c_v \cdot m_v \cdot \gamma_w = m_v \gamma_w \left(\frac{0.85\, H_d^2}{t_{90}} \text{ or } \frac{0.2\, H_d^2}{t_{50}} \right)$ ($\sqrt{t}$ or $\log t$)

b) CRSC → direct measurement, $k_v = \frac{\dot{\varepsilon} H_d^2 \gamma_w}{2 u_b}$

c) Falling head or constant head in

- Oedometer cell e.g. See Fig. 8 Sheet C1
- Triaxial cell

4.2 Cont.

2) Comparisons

Sheet C1 Fig. 16 $k_v(TX) = k_v(OED)$ as expected

Fig. 18 $k_v(OED) > k_v$ from c_v (log t) w/ small LIR

Sheet D1 Fig. 6 $k_v(OED) = k_v(CRSC)$

Fig. 7 $k_v(OED) > k_v$ from c_v(log t) by $\to$ X2

3) e - log k Data

Sheet C3 Fig. 2 & 3 (from CRSC): linear e - log k for $\varepsilon_v \lesssim 20\%$

Sheet D1 Fig. 8 (mostly CRSC?) : data on several clays over wide range of e

4.3 Some Observations

1) Values of k_{vo} Canadian Clays (mostly)

Sheet C2, Fig. 12 Generally $k_{vo} \approx 1 \times 10^{-7}$ cm/s (1×10^{-9} m/s)

Sheet D2, Fig 12 with range $0.5 - 50 \times 10^{-7}$ cm/s.

2) $\boxed{C_K \approx (1/3 - 1/2)\, e_0}$ Sheet D2, Fig. 11

3) Permeability anisotropy, $r_k = k_h / k_v$

- Marine clays $r_k \approx 1$-1.5
- Lacustrine clays $r_k < 5$ and usually < 3

} Sheets C2 & D2 $\to$ much less than many assume.

- Northeastern varved clays $r_k \approx 10 \pm 5$ (Consol. IV; MIT data)

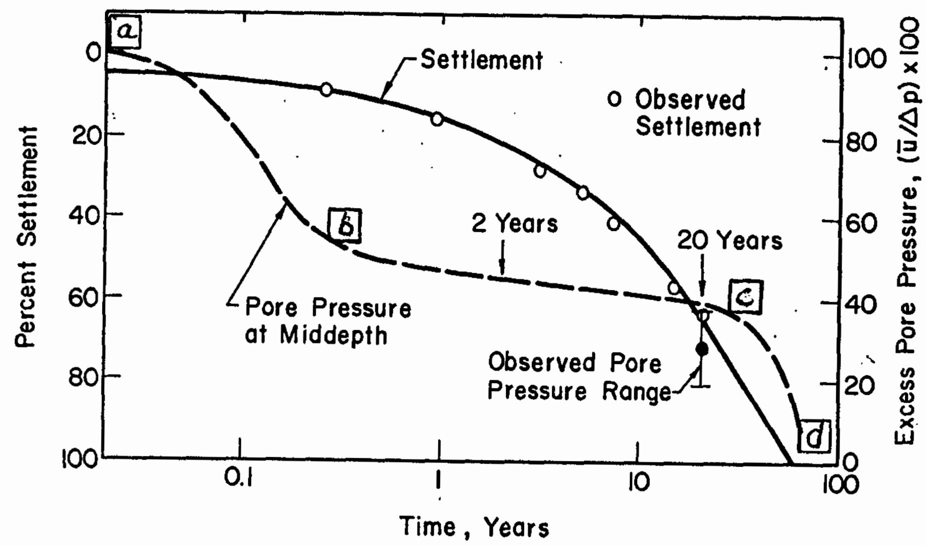
4) Empirical correlation to predict k_{vo}: Sheet D2, Fig. 10

k_{vo} vs e_0/CF as f(Activity = I_p/CF) ; CF = % -2μ

5. NON-LINEAR 1-D CONSOLIDATION ANALYSES

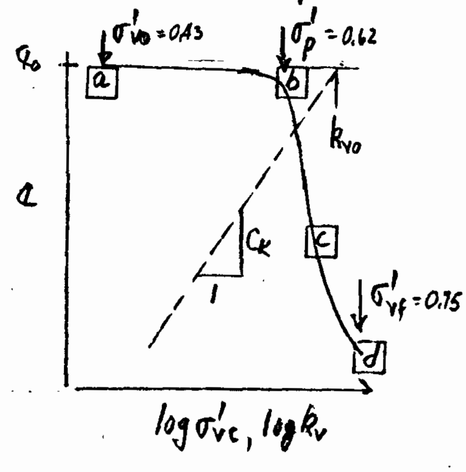
5.1 Settlement of Gloucester Fill on Canadian Quick Clay (Mesri 1981)

1) Background



- Test fill showed increasing slope of ρ vs log t with very little dissipation of u_e: attributed to "creep induced" $\uparrow u_e$ that offset decr. u_e due to consolidation
  Due to "structural viscosity"

2) Mesri analysis via non-linear Terzaghi model (See top Sheet E)



- Analysis where input e-log σ'_{vc} & e-log k.

3) Predicted-Measured Results (See bottom Sheet E for $u_e/\Delta\sigma_v$)

a-b: recompression $\sigma'_{v0} \to \sigma'_p$
- rapid decr. in u_e
- little ρ_c

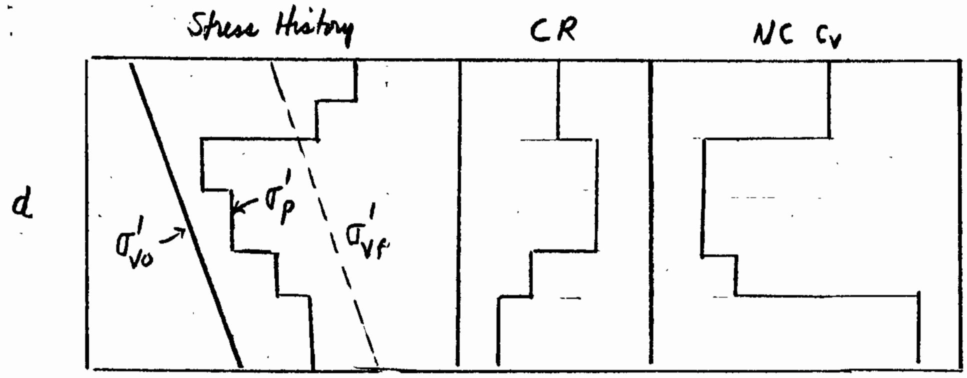
bc: virgin compression with $C_c \to \infty$
- small $-\Delta u_e = +\Delta\sigma'_{vc}$
- large ρ_c

cd: virgin compression with "small" C_c
- large $-\Delta u_e = +\Delta\sigma'_{vc}$
- moderate ρ_c

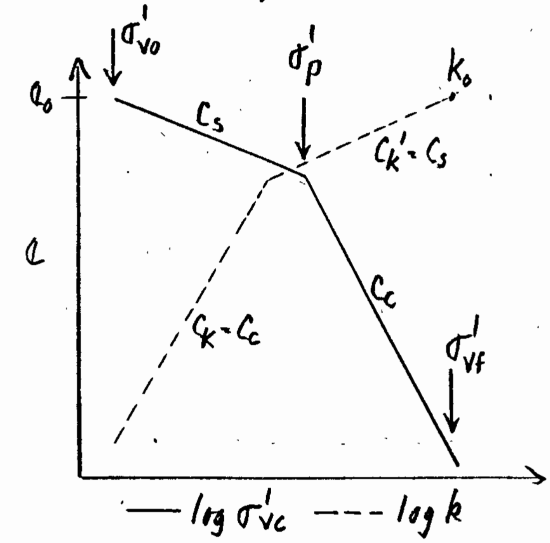
4) CCL Comment: Altho excellent prediction (& non-linear e-log σ'_{vc} very important), Part III will conclude that clay probably has significant viscous behavior

5.2 Finite Element Analyses of 1-D Consolidation Using MCC Model

1) Objective: Predictions of ρ_c and u_e vs t for compressible foundation layer having complex consolidation parameters, e.g. for staged construction (TPS breakwater)



2) Desired use of MCC model (for each uniform layer).



a) 1st pick values of σ'_{vo}, σ'_p, e_o, C_c & C_s to define compressibility in conventional terms

b) Also need to define e vs $\log k$ to model desired c_v values

- Using $C_k = C_c \rightarrow \approx$ constant c_v (NC)
- Using $C'_k = C_s \rightarrow c_v(\mathrm{OC}) = \frac{C_c}{C_s} c_v(\mathrm{NC})$

3) Must convert above data into MCC model parameters (other than $\lambda = C_c/2.3$ & $\kappa = C_s/2.3$ which are easy)

a) Location of VCL in terms of e vs $\bar{p}_e$ ($K_c = 1$)*

b) Definition of $\bar{p}_m$ at end of yield surface that is consistent with yielding at desired $\sigma'_{vy} = \sigma'_p$

c) Definition of initial stress state: $\bar{q}_0 = \sigma'_{vo}(1 - K_{oOC})$

$$\bar{p}_0 = \frac{\sigma'_{vo}}{3}(1 + 2K_{oOC})$$

* Therefore need to convert 1-D VCL on SBS ($\bar{p}_c$ for K_{oNC}) to end point at $\bar{p}_e$!

4) Problem further complicated by fact that MCC uses:

For $M=1.2$, $m=0.8$ & $\nu'=0.3$

- For OC (elastic) clay, $K_{0OC} = \nu'/(1-\nu')$ — $K_{0}OC = 0.43$
- For NC (yielded) clay, $K_{0NC} = f(M, m \,\&\, \nu')$ — $K_{0NC} = 0.65$

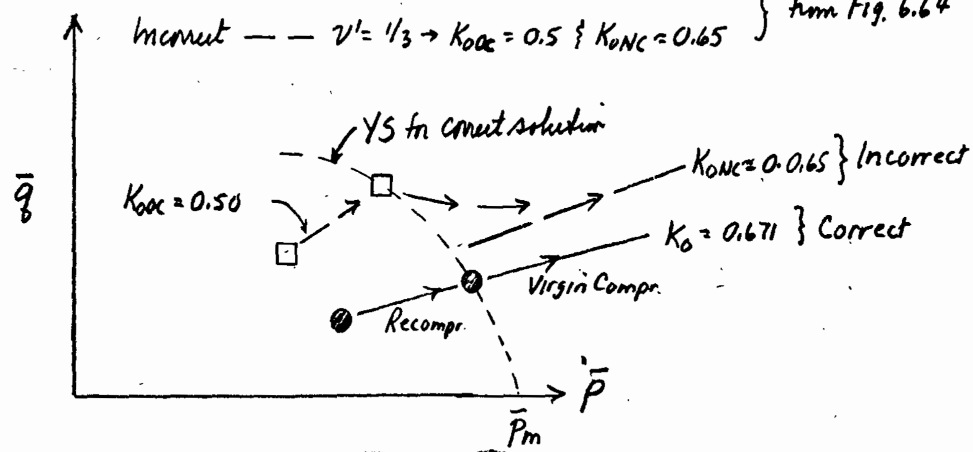
From Wood (1990) p 238

$$\frac{R_{K_0}(1+\nu')(1-m)}{3(1-2\nu')} + \frac{3R_{K_0}\,m}{M^2 - R_{K_0}^2} = 1, \text{ where } R_{K_0} = (\bar{q}/\bar{p}) \text{ for NC } K_0 = \frac{3(1-K_{0NC})}{(1+2K_{0NC})}$$

* Therefore MUST select (for chosen values of M & m) the single value of ν' that will $\rightarrow$ $K_{0OC} = K_{0NC}$ (see attached Fig. 6.64, p11a)

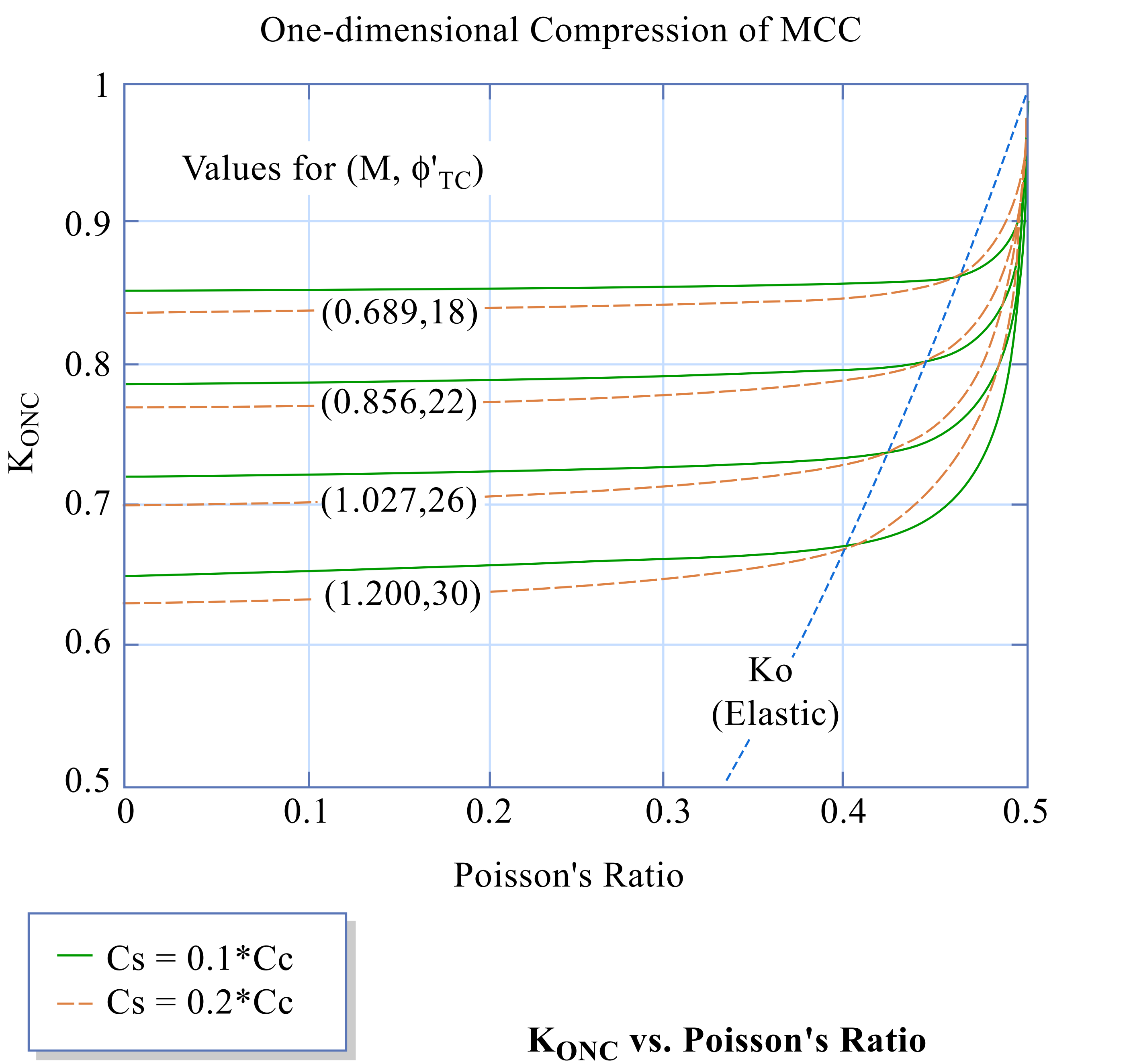
$M=1.2$ & $m=0.8$

Correct —— $\nu' = 0.4015 \rightarrow K_{0OC} = K_{0NC} = 0.671$ } from Fig. 6.64
Incorrect – – $\nu' = 1/3 \rightarrow K_{0OC} = 0.5$ & $K_{0NC} = 0.65$



i.e. Incompatible K_0 values $\rightarrow$ yielding at wrong σ'_p and incorrect C_c (since K_0 is changing).

CCL 3/14/96 1.322 Consolidation III p11a
3/3/99



K_{ONC} vs. Poisson's Ratio for 1-D Compression (Using MCC Model)

Figure by MIT OCW.

Adapted from S-M Lee doctoral thesis, 1995.

6. BACKANALYSIS OF FIELD CONSOLIDATION DATA

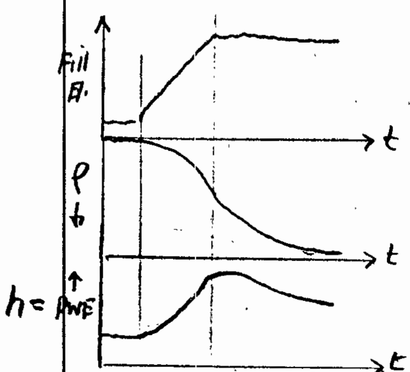
6.1 Background (See Section 6.4 for analysis of data with Vertical Drains)

1) Objective is to back calculate values of $c_v(\rho)$ from field ρ data and/or values of $c_v(u)$ from piezometer data using Terzaghi theory

2) However, field conditions never exactly meet Terzaghi's assumption, e.g.
   - Load not exactly 1-D → finite ρ_i and $u_o \neq \Delta\sigma_v$
   - $m_v \neq$ constant
   - $c_v \neq$ constant

3) Hence backanalyses are not that easy

4) Definitions:



ρ_t = measured total settlement
ρ_i = estimated initial "
$\rho_c = \rho_t - \rho_i$ = consolidation settlement
ρ_{cf} = estimated final consolidation settlement
u = measured pore pressure = $(h - h_e)/\gamma_w$
u_s = equilibrium " "
u_e = excess " " $= u - u_s$
u_o = initial excess " "

6.2 Conventional Method

1) Basic eqn $c_v = \dfrac{T_v}{t} H_d^2 = \dfrac{\Delta T_v}{\Delta t} H_d^2$ use "incremental" time to avoid problem of defining $t = 0$

2) For ρ data, get $T_v = f(t)$ from $\bar{U} = \dfrac{\rho_c}{\rho_{cf}} = \dfrac{\rho_t - \rho_i}{\rho_{cf}}$ → problems in estimating both ρ_i and ρ_{cf}

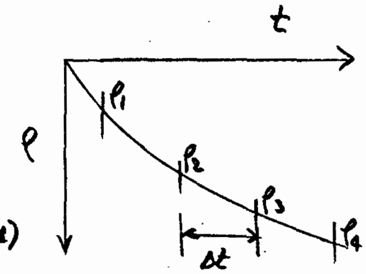
3) For u data, get $T_v = f(t)$ from $U_z = 1 - \dfrac{u_e}{u_o}$ at corresponding $Z = z/H_d$ → problems in estimating u_o and maybe u_s and Z

t	ρ	$\rho_c = \rho - \rho_i$	$\bar{U}_v = \rho_c/\rho_{cf}$	T_v	$\Delta T_v/\Delta t$
80	✓	✓	0.25	0.05	$0.10/120 \times H_d^2 \to c_v(\rho)$
200	✓	✓	0.44	0.15	

6.3 Asaoka (1978), Orleach (1983) Methods

↑ Sola { Fdns 18(4), 87-101 ↑ MIT SM thesis

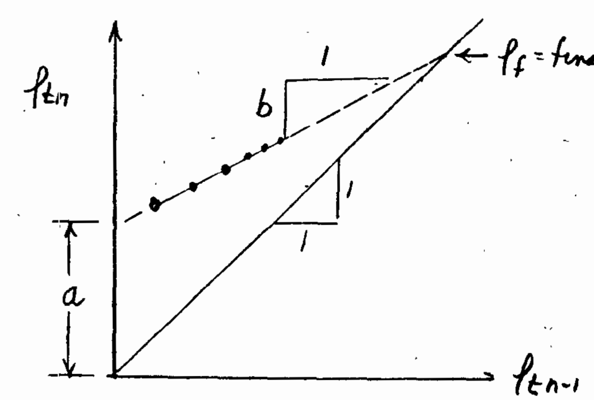
1) For $T_v > 0.15 - 0.2$, Terzaghi full solution simplies to: $(\bar{U}_v > 45\% - 50\%)$



Eq. A $\bar{U}_v = \frac{\rho_c}{\rho_{ct}} = 1 - \frac{8}{\pi^2} e^{-\frac{\pi^2 c_v t}{4 H_d^2}} \rightarrow c_v(\rho)$

Eq. B $U_z = 1 - \frac{u_e}{u_0} = 1 - \frac{4}{\pi} \sin \frac{\pi Z}{2} e^{-\frac{\pi^2 c_v t}{4 H_d^2}} \rightarrow c_v(u)$

2) To apply Eq. A, obtain values of ρ_t at equal Δt intervals and plot ρ_{tn} vs ρ_{tn-1}, where ρ_{tn} = value at time t
& ρ_{tn-1} = " " " $t = t - \Delta t$



• $\rho_{tn} = a + b\rho_{tn-1}$

$* \; c_v(\rho) = -\frac{4 H_d^2}{\pi^2} \frac{\ln b}{\Delta t}$

$* \; \rho_f = \rho_{ct} + \rho_i = \frac{a}{(1-b)}$

Note: Use LR → intercept a and slope b

Comments (For constant load, m_v and H_d)

1) approach is very attractive since it eliminates problems of having to estimate ρ_i and ρ_{ct} and also predicts final settlement at EOP

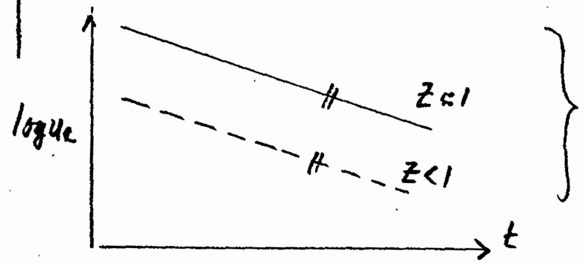
2) However, if applied to ρ data that includes $T_v < 0.15$, (i.e., $\bar{U} < 45\%$), this approach:

From MIT research on TPS project (+ HP#4)
{ • greatly overestimates $c_v(\rho)$
• " underestimates ρ_f } Not appreciated in practice!
even though the LR $r^2 \approx 1.0$ }

3) To apply Eq. B, plot $\log u_e$ vs t for each piezometer

$$* \; c_v(u) = \frac{4 H_d^2}{\pi^2} \frac{\ln(u_{e1}/u_{e2})}{(t_2 - t_1)}$$ independent of $Z = z/H_d$!

NOTE! At $T_v < 0.15$, get obvious curvature in plot of $\log u_e$ vs t



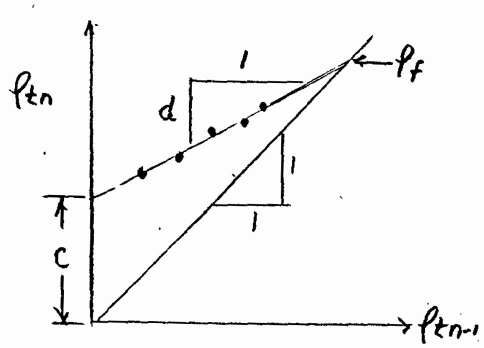
For constant load, u_s & c_v

6.4 Analysis of Settlement & Piezometer Data for Vertical Drains

(Note: For no vertical drainage, constant σ_v, u_s, c_h, etc)

From Sheet A2 equations, Asaoka & Orleach methods reduce to:

1) Settlement data (again from ρ_1, ρ_2, ρ_3 etc. at equal Δt)

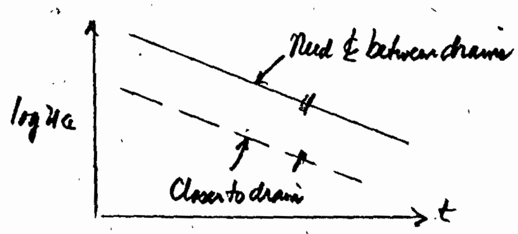


$\cdot \; \rho_{tn} = c + d \cdot \rho_{tn-1}$

$$* \; c_h(\rho) = -\frac{d_e^2 F_n}{8} \frac{\ln d}{\Delta t}$$

$$* \; \rho_f = \rho_i + \rho_{cf} = \frac{c}{(1-d)}$$

2) Piezometer data (Independent of r/r_w)



$$* \; c_h(u) = \frac{d_e^2 F_n}{8} \frac{\ln(u_{e1}/u_{e2})}{\Delta t}$$

7. MISCELLANEOUS

7.1 Effect of Temperature

- From 1.361 Part IV-3, $k = \left(\frac{\gamma}{\mu}\right)(K$ = physical permeability

  $\uparrow$ permeant γ = unit weight
  μ = viscosity
  poise = dyne sec/cm²

- From Lambe (1951)

T (°C)	μ (millipoise)	μ_{20}/μ_T
0	17.97	0.56²
5	15.2	0.66⁴
10	13.1	0.77
15	11.45	0.88
20	10.09	1.00
25	8.95	1.13
30	8.00	1.26

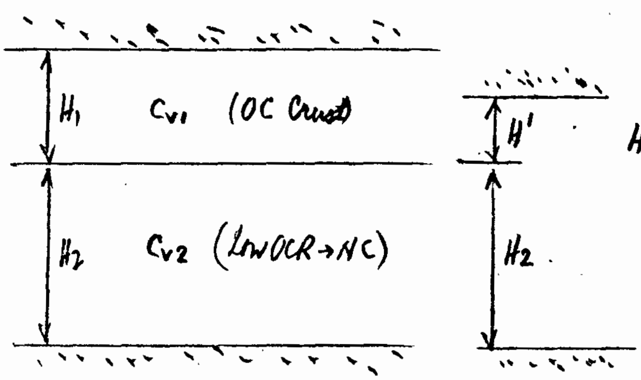
$$k_T = k_{20°C} \frac{\mu_{20}}{\mu_T}$$

≈ 22% decr. / 10°C below R.T (20°C)

- In situ $T \approx 10$°C NE down to ≈ 5°C in deep water gulf Mex ≈ 0°C Arctic

- Since $c_v \propto k$, then c_v also decreases with decreasing temp.

7.2 Consolidation of Layered System (Sowers 1962 in Fdn. Engn. (p578) edited by G A Leonards)



Approximation

$$H' = H_1 \sqrt{\frac{c_{v2}}{c_{v1}}}$$

Use c_{v2} with $2H_d = H_2 + H'$

Note: Can extend to more than two layers using same concept

CCL 3/24/96 3/1/98

Note: Plotted from Table 1 of Scott (1961), JSMFD, ASCE, 87(SM1)

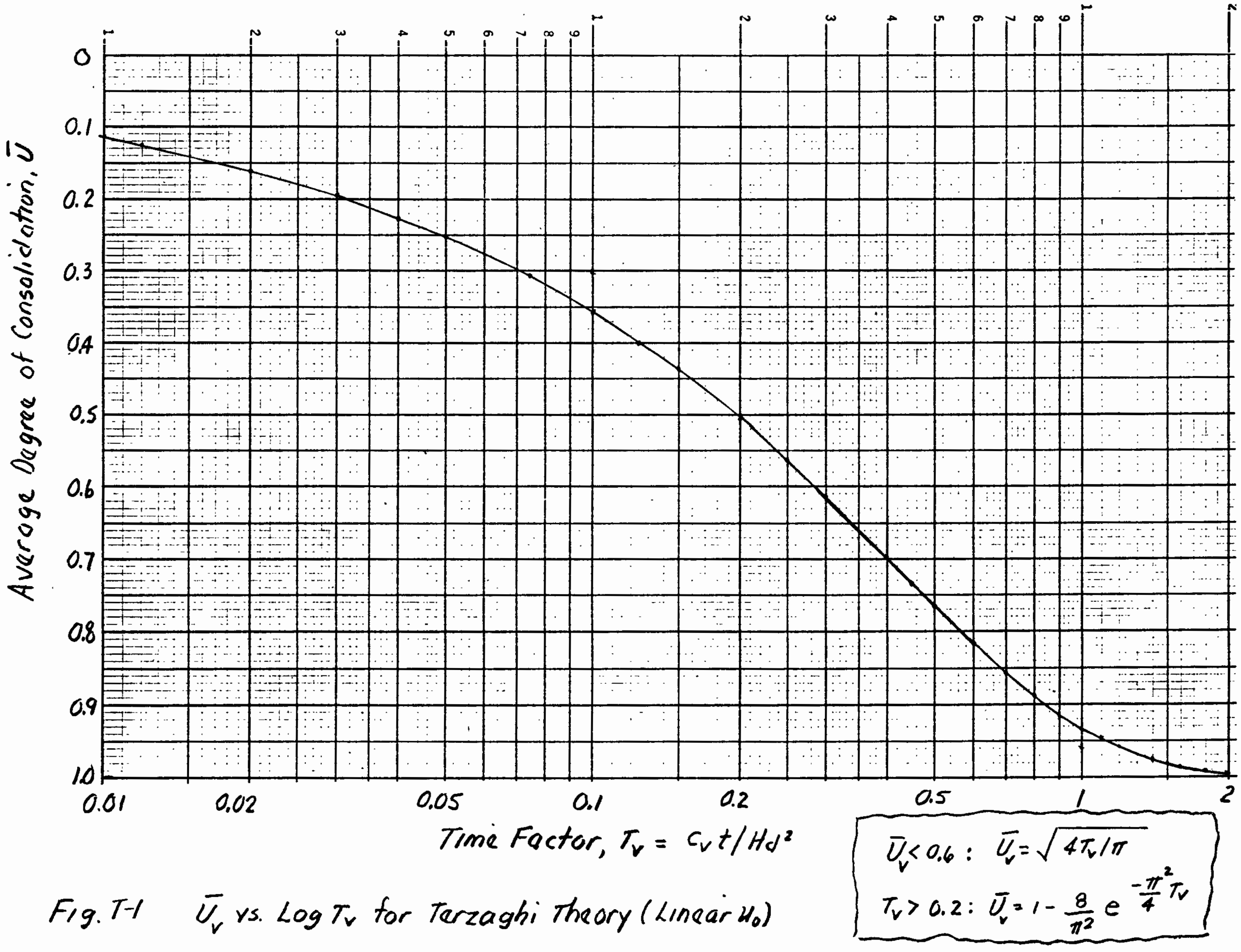
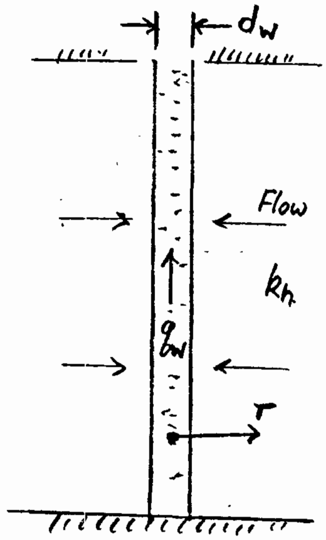


Fig. T-1 $\bar{U}_v$ vs. Log T_v for Terzaghi Theory (Linear u_0)

A. Geometric Factors



Equivalent spacing $= d_e$

Square $d_e = 1.128 \times S$

Triangular $d_e = 1.050 \times S$

$S =$ actual spacing

Drain diameter $= d_w$

spacing ratio $n = d_e/d_w$

Spacing Factor $F_n = \dfrac{n^2}{n^2-1} \ln n - \dfrac{3n^2-1}{4n^2}$

$\approx \ln n - 0.75$ for large n

Note: Alidrain, $d_w = 0.22 ft = 6.7 cm$

B. Consolidation vs Time Factor (Equal Strain Theory)

- $T_h = \dfrac{t\, c_h}{(d_e)^2}$; $c_h = \dfrac{k_h}{m_v \cdot \gamma_w} = \dfrac{k_h}{k_v} c_v = r_k c_v$

- $\bar{U}_h = 1 - e^{-\frac{8T_h}{F_n}}$ or $t = \dfrac{d_e^2}{8 c_h} F_n \ln \dfrac{1}{(1-\bar{U}_h)}$

$$1 - U_h = \frac{u}{u_0} = \frac{1}{F_n}\left[\ln\left(\frac{r}{r_w}\right) - \frac{(r/r_e)^2 - 1/n^2}{2}\right] e^{-\frac{8T_h}{F_n}}$$

where $r_e = d_e/2$; $r_w = d_w/2$

Fig. 1 Barron (1948) Theory for Consolidation with Vertical Drains (ASCE Transactions Vol 113, Paper No. 2346)

CCL 12/88 1.322 Consol. III

Adapted from NAVFAC DM-7.1 (May 1982)
Figure 4 Page 7.1-144

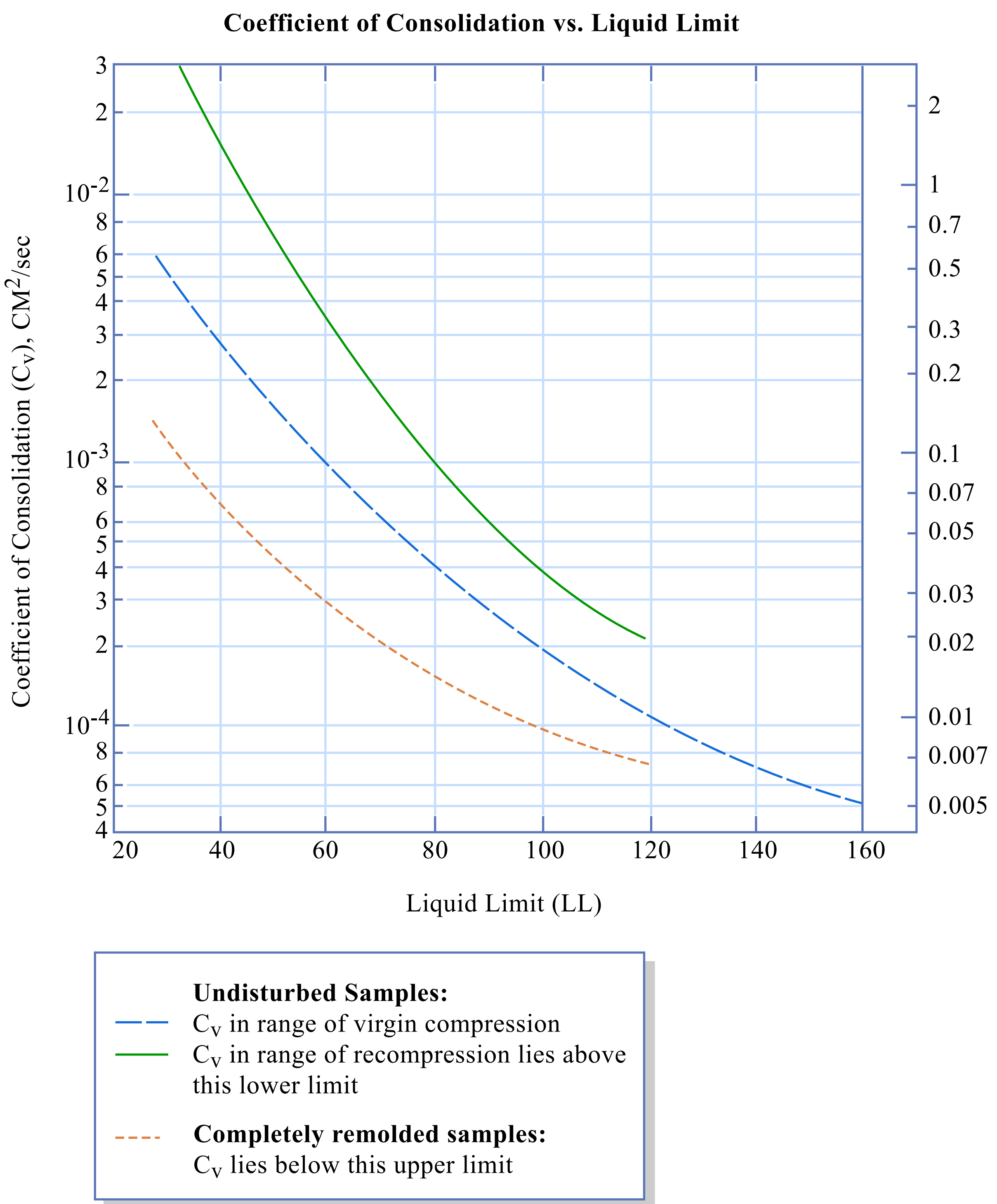


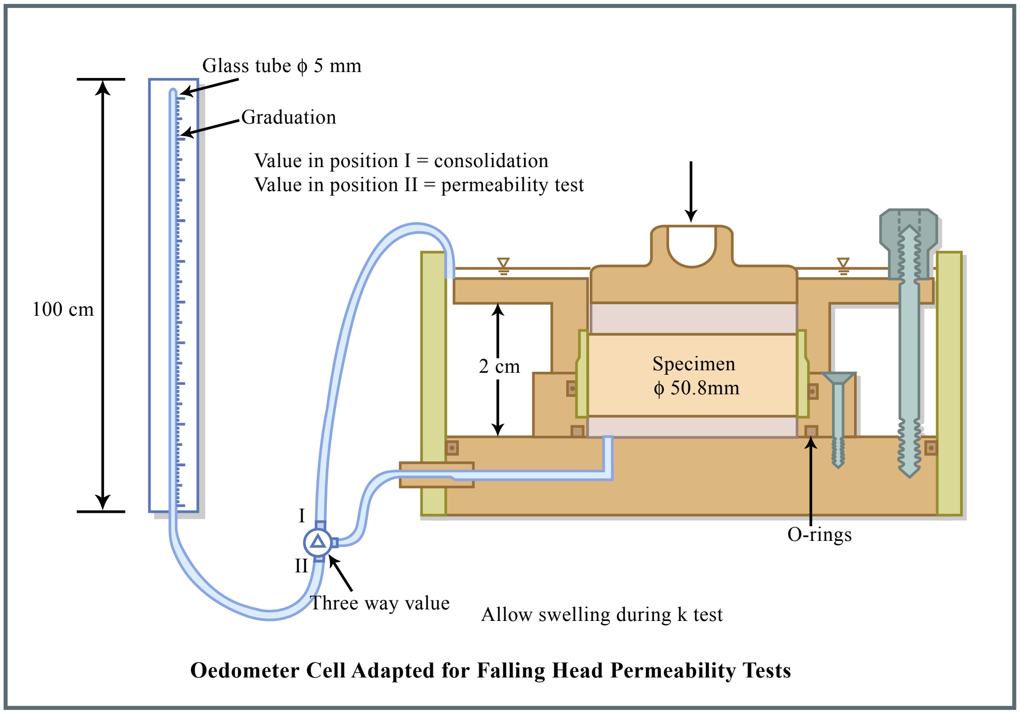
Figure by MIT OCW.

B

3/3/98 8/97

Supplement on Permeability of Cohesive Soils

Data from Tavenas et al (1983) Parts I & II CGJ No.4 pp 629-660



Oedometer Cell Adapted for Falling Head Permeability Tests

Figure by MIT OCW.

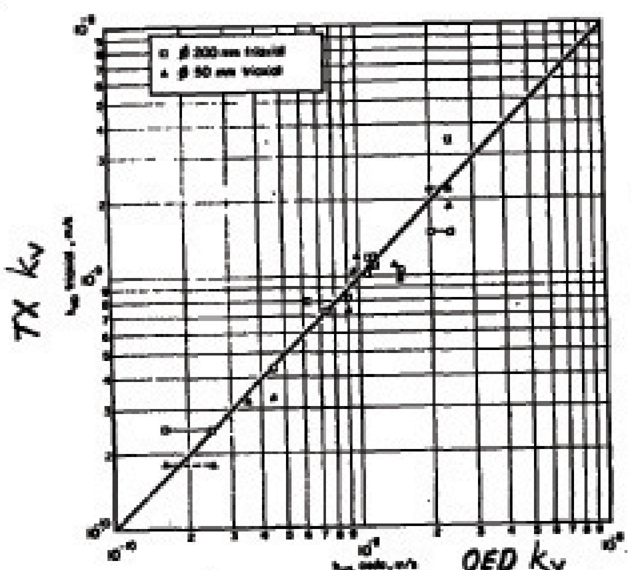


FIG. 16. Comparison of permeabilities measured in large triaxial and small oedometer tests.

Good agreement (as expected)

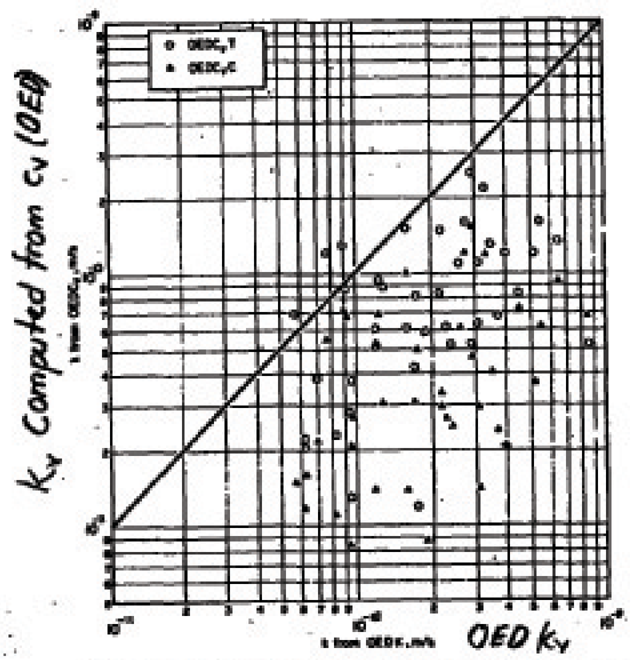


FIG. 18. Comparison of permeabilities measured in OEDK and computed from OEDc, on Champlain clay specimens.

c_v (log t) from tests with low LIR + values generally much too low for these sensitive clays

3/90 3/3/98

TABLE 1. Properties of the investigated clays

Site	Depths (m)	w (%)	w_L (%)	w_p (%)	I_p (%)	I_L	CF % < 2μ	σ_p' (kPa)	C_c
Champlain sea clays									
St-Zotique	2.00	91	61	25	36	1.8	80	50	6.0
	to	to	to	to	to	to	to	to	to
	17.00	63	43	23	20	2.2	60	240	2.0
Fort Lennox	6.10	79	70	22	48	1.2	81	180	3.0
St-Hilaire	9.50	69	55	23	32	1.4	71	125	4.0
Mascouche	3.80	61	55	24	31	1.2	76	290	2.8
Louiseville	2.90	79	71	27	44	1.2	77	80	3.7
	to	to	to	to	to	to	to	to	to
	26.00	60	59	25	34	0.8	85	300	2.2
Batiscan	5.50	80	35	22	17	2.6	77	80	2.2
	to	to	to	to	to	to	to	to	to
	20.50	71	54	24	31	1.5	91	190	4.5
St-Thuribe	6.90	52	44	22	22	1.3	44	195	1.2
St-Alban	1.90	90	53	25	28	2.7	78	40	2.5
	to	to	to	to	to	to	to	to	to
	7.80	40	28	18	10	2.0	31	100	1.2
Other Canadian clays									
B2	4.90	31	30	15	15	1.4	36	150	0.3
	to	to	to	to	to	to	to	to	to
	13.10	38	20	14	06	2.9	43	105	0.5
B6	2.80	53	24	14	21	2.1	76	130	0.7
	to	to	to	to	to	to	to	to	to
	13.40	29	44	25	09	0.9	51	180	0.3
Matagami*	1.90	108	74	25	49	2.3	91	55	5.6
	to	to	to	to	to	to	to	to	to
	10.30	48	48	28	20	1.4	65	90	1.2
Other clays									
Atchafalaya	20.80	65	99	37	62	0.5	76	160	1.1
Bäckebol	5.40	81	74	28	46	1.1	59	55	2.2
Lilla Mellösa	4.30	104	111	38	73	0.9	63	40	3.1

*Properties measured on bulk specimen.

· All are medium-soft sedimentary clays
· Mostly marine of moderate-high I_L

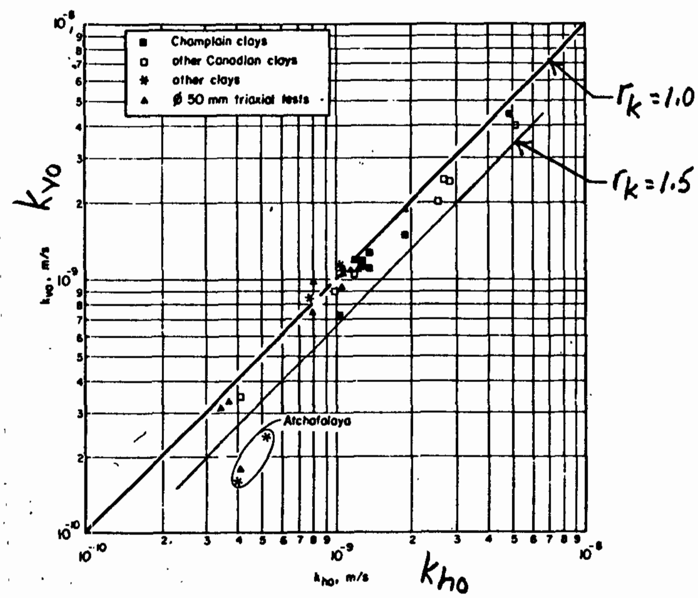


FIG. 12. Comparison of vertical and horizontal permeabilities in intact natural clays.

Olson & Daniel (1981)
ASTM STP 746

Marine clays:
$r_k = k_h/k_v \approx 1 - 1.5$ typically

Larsson (1981) SGR No.12
$r_k = k_h/k_v \approx 1$ Swedish clays

Also see Fig. 12 Sheet D2

General observation: linear e vs $\log k$ for $\frac{\Delta e}{(1+e_0)} < 20\%$

$\therefore C_k = \frac{\Delta e}{\Delta \log k} \approx \text{constant} \rightarrow \boxed{k = k_0 (10)^{\frac{e - e_0}{C_k}}}$

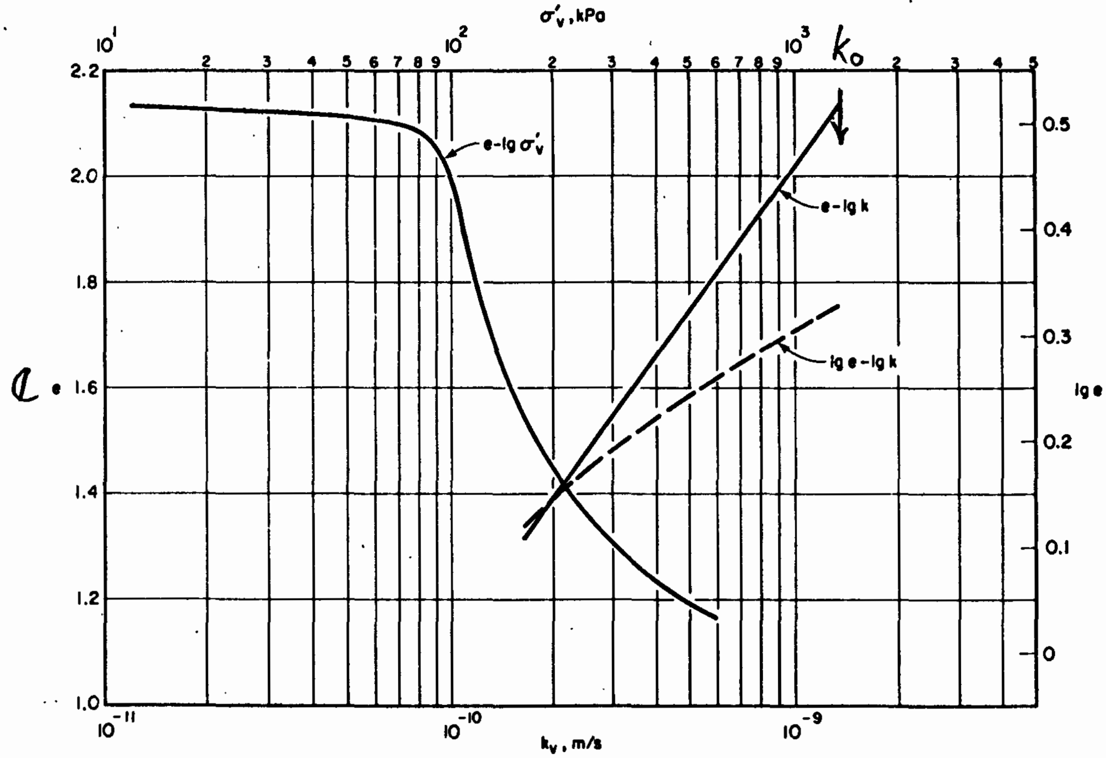


FIG. 2. Variation of permeability with void ratio. Batiscan clay.

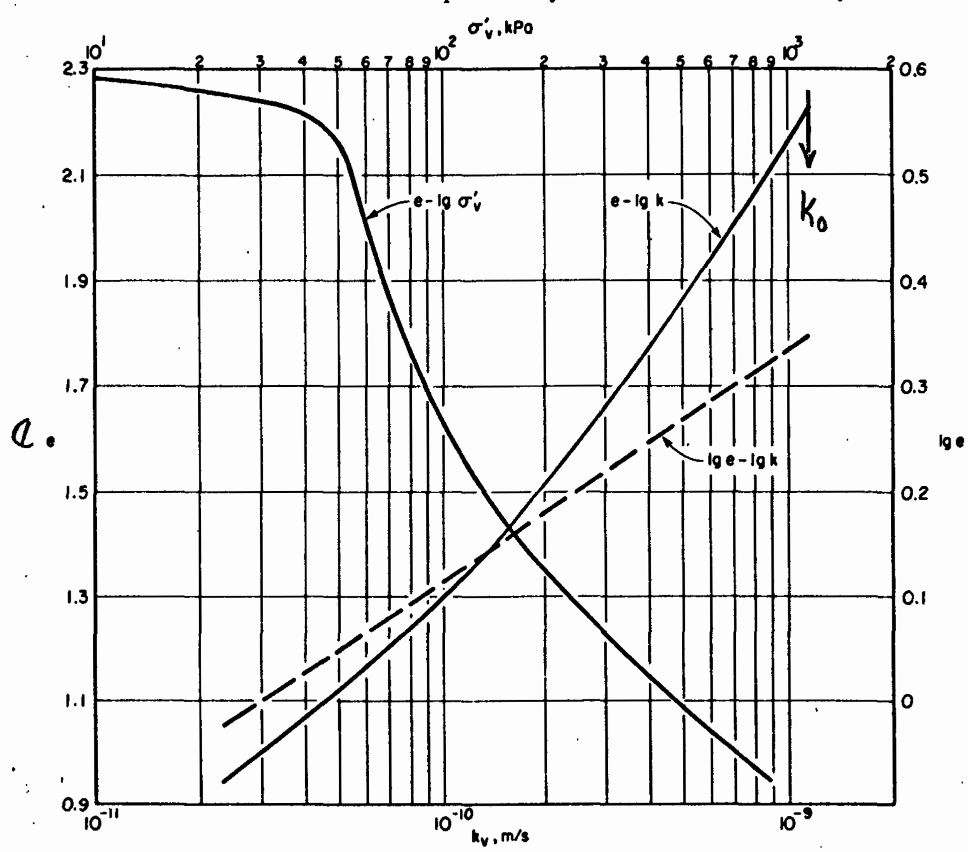


FIG. 3. Variation of permeability with void ratio. Bäckebol clay.

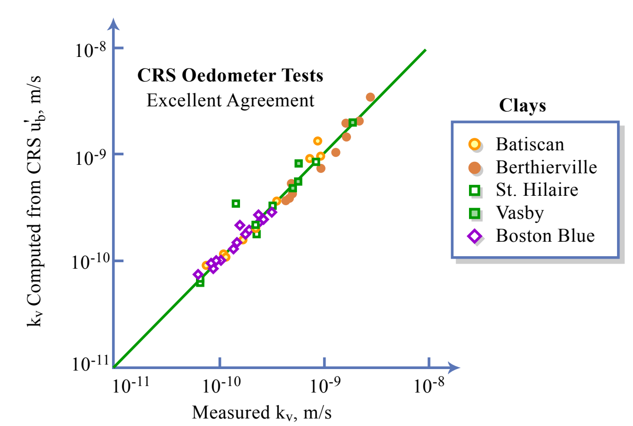
C3

Table 1. Index Properties of Soft Clays

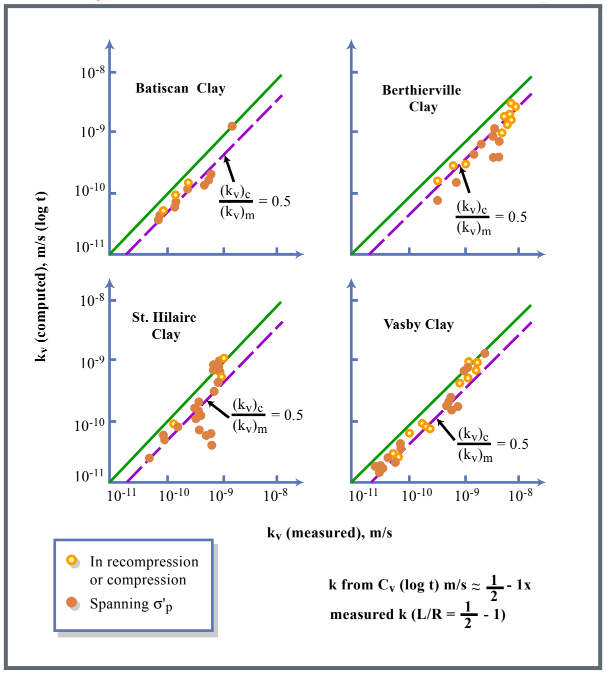
Clay	w_o %	w_L %	w_P %	CF %	σ'_{vo} kPa	σ'_p/σ'_{vo}
St. Hilaire	61-84	55	23	77	83	1.4-1.6
St. Esprit	73-92	75	27	76	37	3.0-3.3
St. Alban 1	58-64	43	21	40	33	2.1-3.4
La Grande 15b	55-59	62	26	53	42	2.8-3.0
La Grande 23a	55-58	64	26	52	83	1.8-2.0
Boston Blue	27-30	32-36	17	36-44	155	3.3
Vasby 1	94-122	121	40	67	28	1.2-1.3
Vasby 2	91-102	108	36	67	36	1.2-1.3
Atchafalaya	52-78	82	33	61	100	1.1-1.2
Batiscan	71-88	49	22	80	45-53	1.6-1.7
Broadback 2	42	28	19	46	55	2.2-2.4
Broadback 6	48	36	25	67		2.6-3.2
Berthierville	57-70	46	24	36	39	1.4-1.5

Mesri et al. (1994) 13th ICSMFE
New Delhi, Vol 1, p 187-192

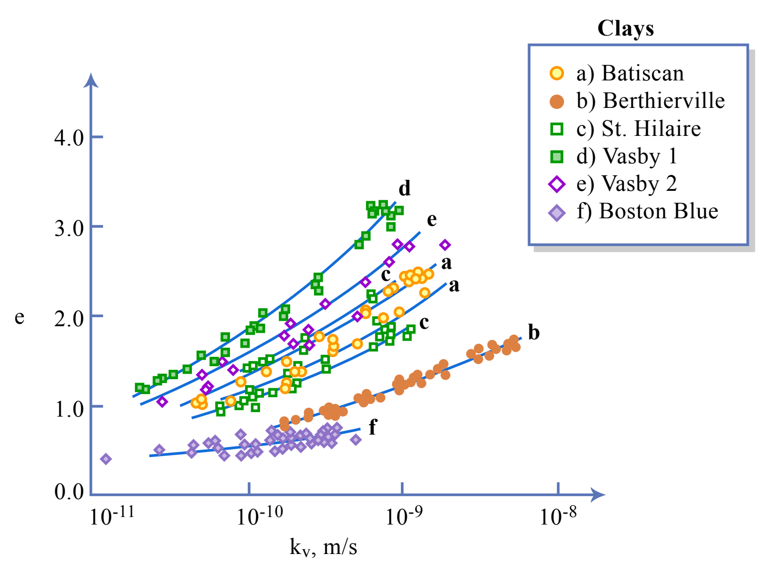
- Ran constant / falling head tests in oedometer (IL) & CRSC cells
- 3 PhD Students T.W. Feng, S. Ali, T.M. Hayat



k_v from CRS u'_b compared to direct measurements



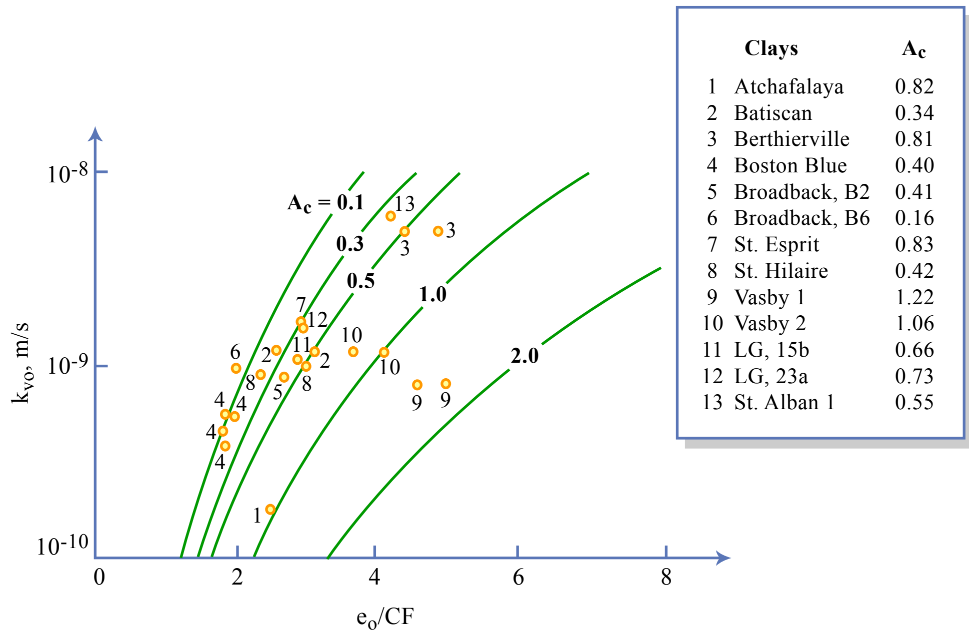
Figures by MIT OCW.



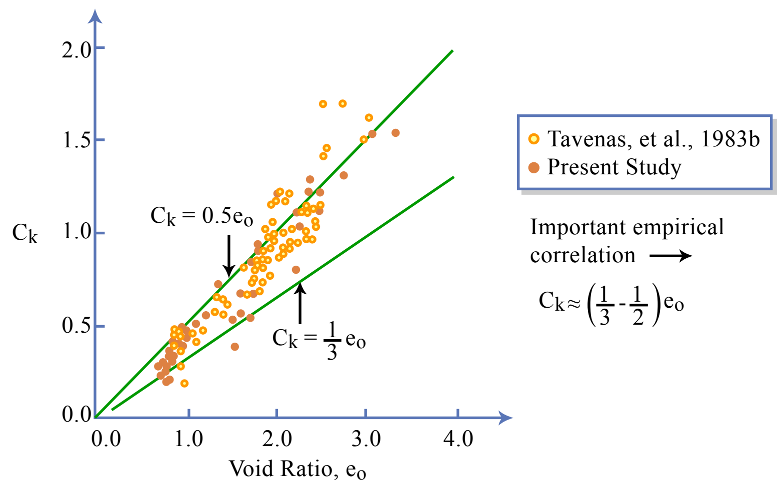
e - log k_v of soft clays

e vs. log k (mostly from CRSC)

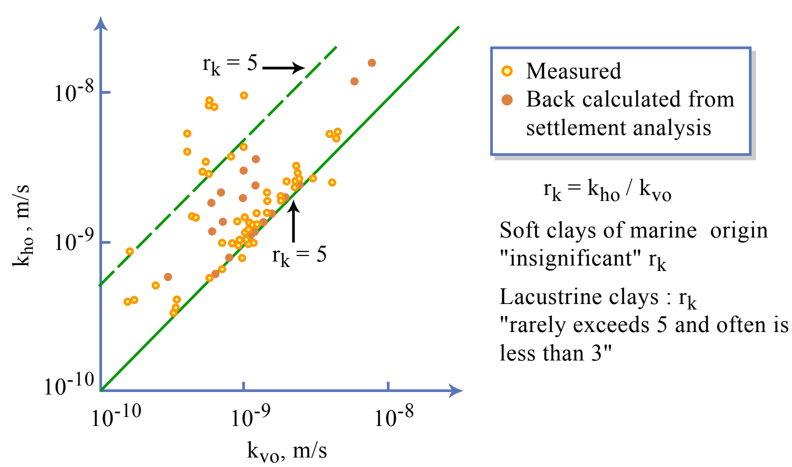
D1



k_{vo} - e_o/CF relationships for different A_c



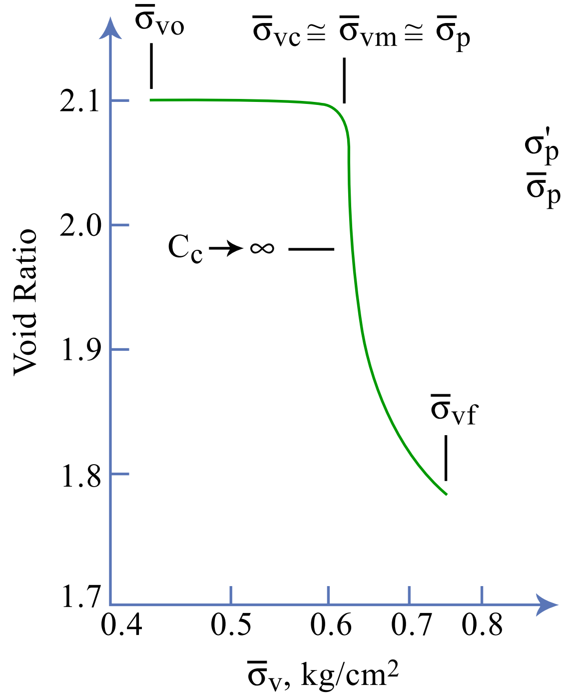
C_k - e_o of soft clays



k_{ho} of soft clays as compared to k_{vo}

Figures by MIT OCW.

Gloucester, Canada (Mesri, 1981)



$e_o = 2.10$

$\sigma'_p = \bar{\sigma}_{vo} = 0.43$ kg/cm^2

$\bar{\sigma}_p = \bar{\sigma}_{vm} = \bar{\sigma}_{vc} = 0.62$ kg/cm^2

$\bar{\sigma}_{vf} = 0.75$ kg/cm^2

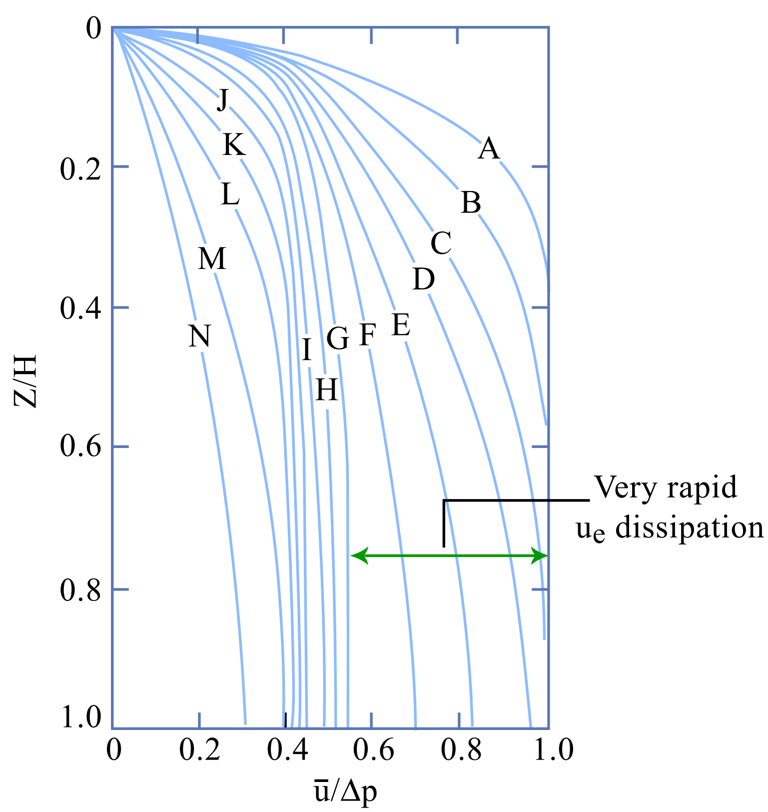
$k_o = 0.5 \times 10^{-7}$ cm/sec

$C_k = 1.0 = \Delta e / \Delta \log k$

$C_\alpha / C_c = 0.04$

$H = 3.6$ m

$$C_v = \frac{k}{m_v \cdot \gamma_w} \left\{ \begin{array}{l} e_o - e = C_k \log(k_o/k) \\ m_v = \dfrac{0.434\, C_c}{(1+e_o)\, \bar{\sigma}_v} \end{array} \right.$$



A	1 day
B	3 days
C	1 week
D	2 weeks
E	1 month
F	2.5 months
G	3 months
H	6 months
I	1 year
J	2 years
K	4 years
L	8 years
M	16 years
N	40 years

Figure by MIT OCW.

Adapted from:

Mesri (1981) ILLICON (Finite Difference) Consolidation Analyses

E