# CONSOLIDATION BEHAVIOR OF SATURATED SOILS

## Part I INTRODUCTION

Page No.

1. Background 1
    - Compaction vs consolidation vs drained shear · Types of settlement
    - Coverage
2. Coefficient of Earth Pressure at Rest: Behavioral Trends 2
    - Relevance & stress path · Lab measurement techniques
    - NC $K_0$ · $K_0$ vs OCR · Effects of secondary compression
3. Estimation of In Situ $K_0$ from Lab Testing 10
    - Estimate from OCR · Recompression data (Mesri et al)
    - Others
4. Estimation of In Situ $K_0$ from In Situ Testing 12
    - EPC · HF · SBPT · DMT

NOTE: Will consider in situ testing during term in order to estimate following properties

| | EPC | SBPT | DMT | FVT | CPTU |
|---|---|---|---|---|---|
| $K_0$ | ✓ | ✓ | ✓ | | |
| Stress History | | | ✓ | ✓ | ✓ |
| $s_u$ | | ✓ | ✓ | ✓ | ✓ |
| $c_h$ | | | | | ✓ |

5. Concluding Remarks 16

Appendices

- E/H1 EPC & HF
- S1-S4 SBPT
- D1-D5 DMT
- Results from CAIT Special Test Program on Boston Blue Clay

# CONSOLIDATION BEHAVIOR OF SATURATED SOILS

## 1. BACKGROUND

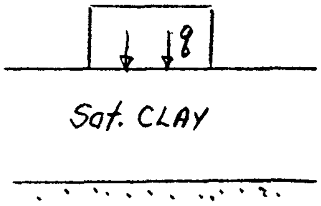
### 1.1 Difference Between:

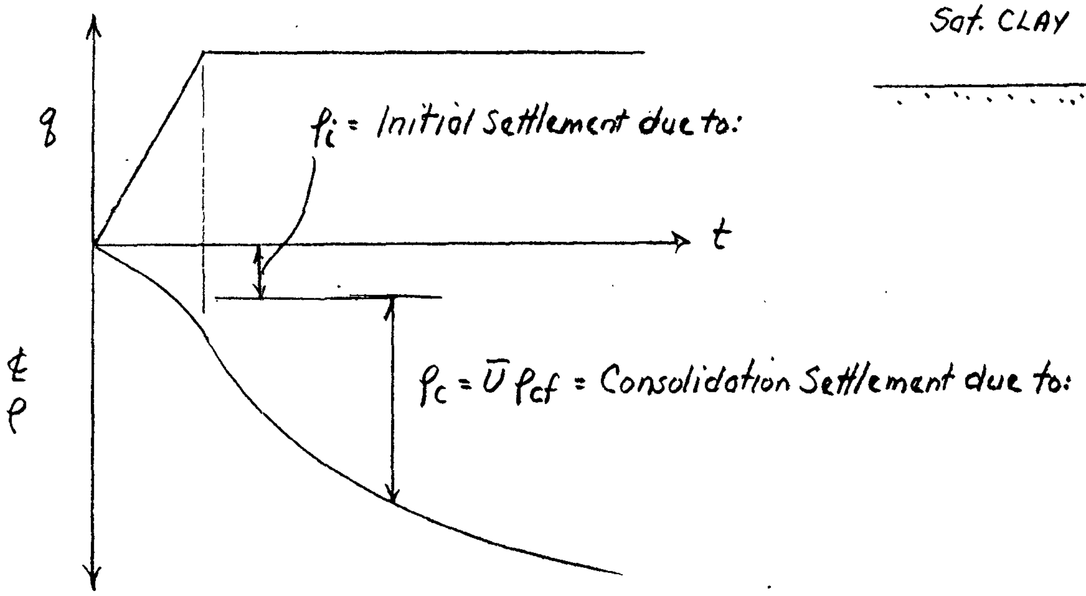
- Compaction

- Consolidation

- Drained Shear

### 1.2 Types of Settlement

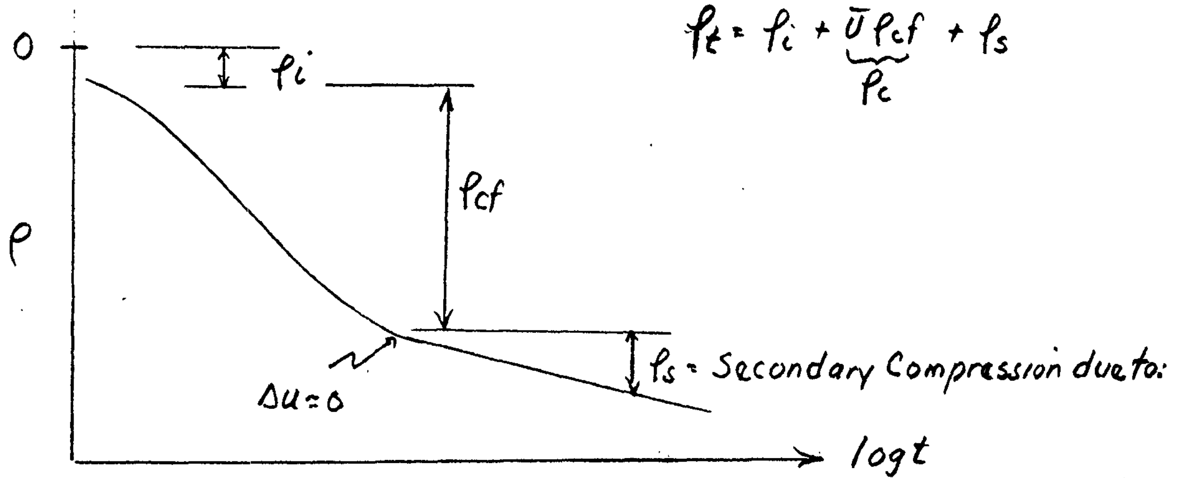




$\rho_i$ = Initial Settlement due to:

$\rho_c = \bar{U}\rho_{cf}$ = Consolidation Settlement due to:

$$\rho_t = \rho_i + \underbrace{\bar{U}\rho_{cf}}_{\rho_c} + \rho_s$$



$\rho_s$ = Secondary Compression due to:

5/95 2/97 2/21/99 2/01

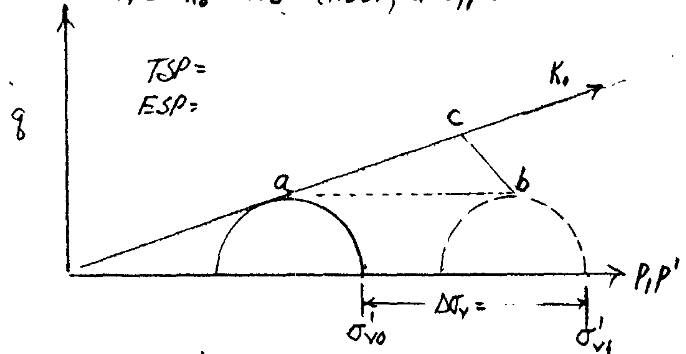
## 2. COEFFICIENT OF EARTH PRESSURE AT REST ($K_0$): BEHAVIORAL TRENDS

### 2.1 Relevance - Importance

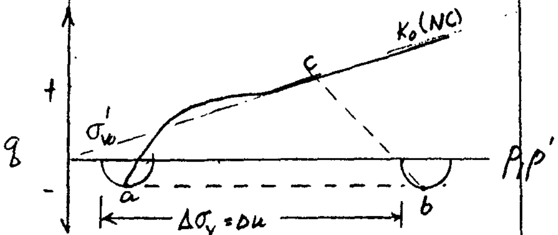
- Lab recompression $CK_0UD \rightarrow$ in situ $\sigma$-$\varepsilon$ properties
- Stresses on underground structures, e.g. retaining walls, tunnels, etc.
- Predictions of deformations due loading/unloading & especially "local yielding" $f = (1-K_0)/(2q_f/\sigma'_{v0})$

### 2.2. Stress Paths: 1-D Consolidation

NC $K_0 = 0.5$ (1.361, V5, p2)

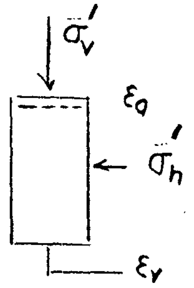


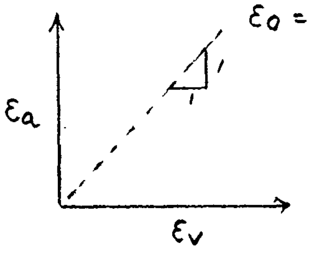
O.C. $K_0 = 2.0$



### 2.3 Lab Measurements of $K_0$

1) Triaxial: Stress Path Cell (p2a for data from MIT automated $CK_0$-TX)





$\varepsilon_a = \varepsilon_v \rightarrow \varepsilon_r = \varepsilon_h = 0$ for $K_0$

2) Instrumented Oedometer

- Square with pressure transducer (R.S. Ladd, 1965)
- Circular with fluid chamber

Brooker & Ireland, 1965 } U of I
Hendron, PhD? }
R.T. Martin – MIT
Mesri et al. 1993 U of I (p2b)

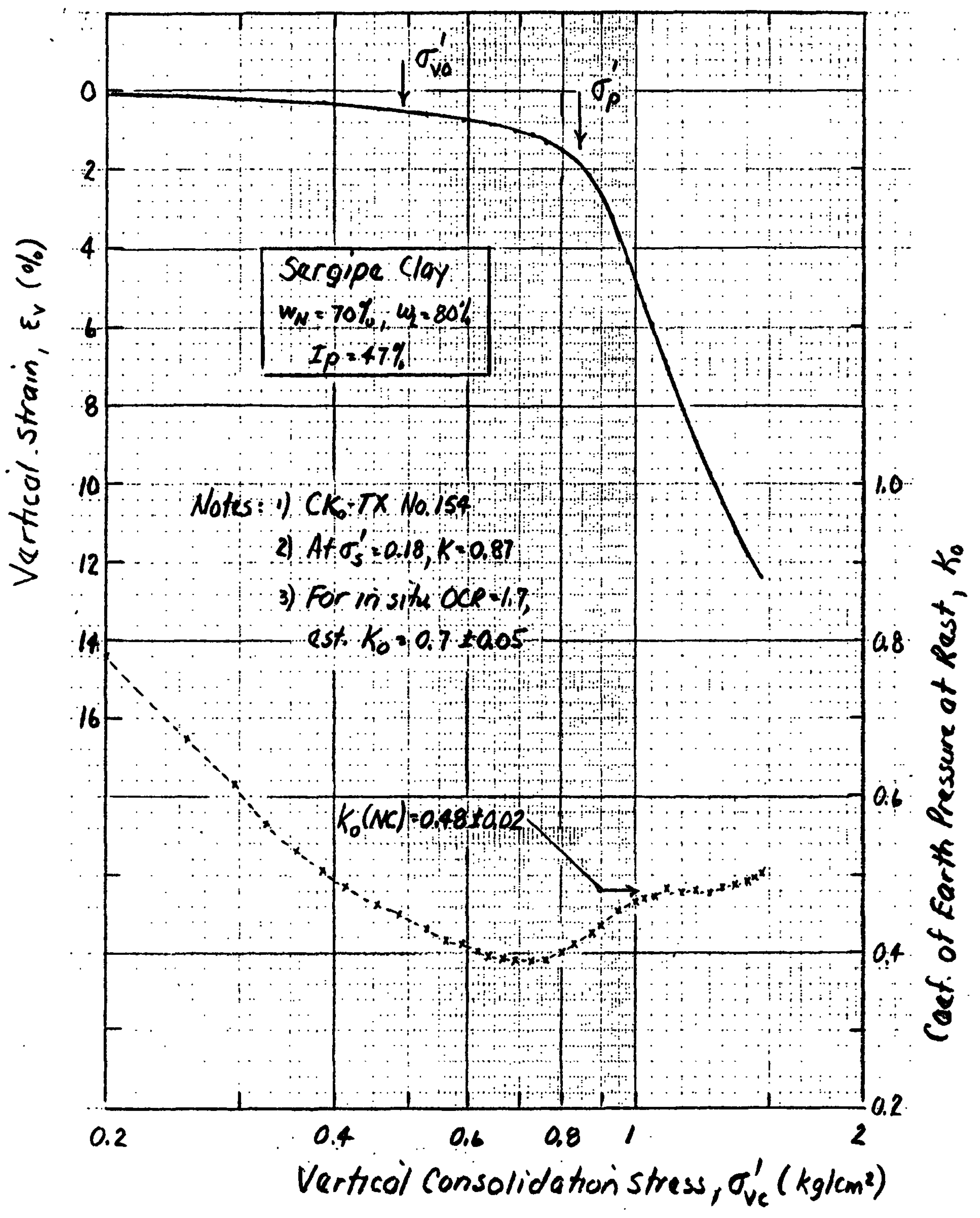
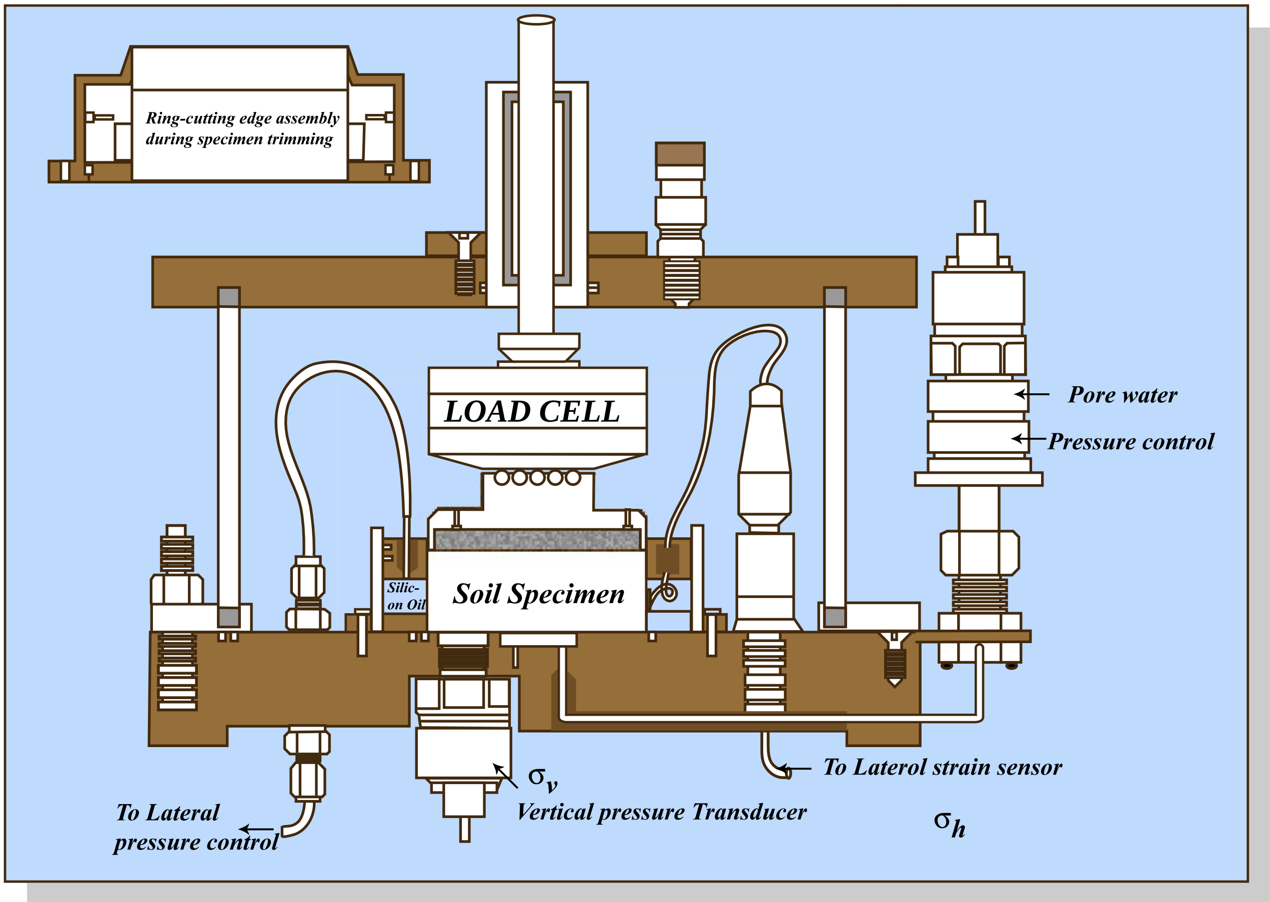
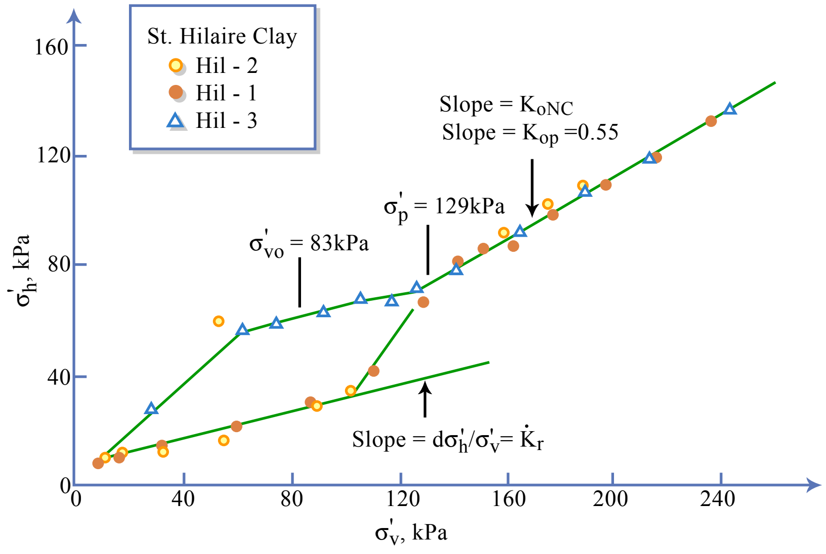


Fig.: Consolidation Data From MIT Automated Stress Path Triaxial Apparatus During 1-D Compression Of Undisturbed Soft Clay

Adapted from: Mesri, G. & Hayat, T.M. (1993). "The coefficient of earth pressure at rest", CGJ, 30(4), 647-666



*Special oedometer for measurement of horizontal pressure, together with measurement of vertical pressure at top and bottom and pore-water pressure at bottom*

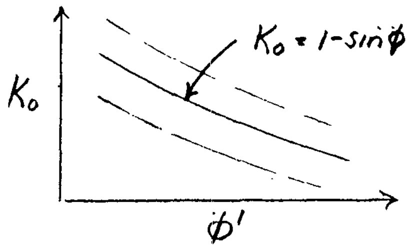


Specimens HIL-1 and HIL-2 subjected to laterally constrained (LC) compression from $\sigma'_s$, and specimen HIL-3 subjected to LC compression after consolidation under equal all around pressure to point a.

Figures by MIT OCW.

## 2.4 Normally Consolidated $K_o$

1) Jaky (1944) Empirical correlation: $K_o = 1 - \sin\phi'$



| $\phi'$ | $K_o$ |
|---|---|
| 20 | 0.66 |
| 30 | 0.50 |
| 40 | 0.36 |

NOTE: Elastic Theory

$$K_o = \frac{\nu'}{1-\nu'} \qquad \nu' = 1/3 \rightarrow K_o = 0.5$$

2) Tokyo SOA (p4) + Mesri & Hayot, 1993 (p4a)

- Sands Fig 14 $K_o = 0.4 \pm 0.1$ $1-\sin\phi'$ not so good
  M & H, 93 $= 0.5 \pm 0.1$ $1-\sin\phi'_{cv}$ is good
- Clays Fig. 30 $K_o \approx 1-\sin\phi'$ with SD ± 0.05, quite good
  $\approx 0.45 - 0.7$

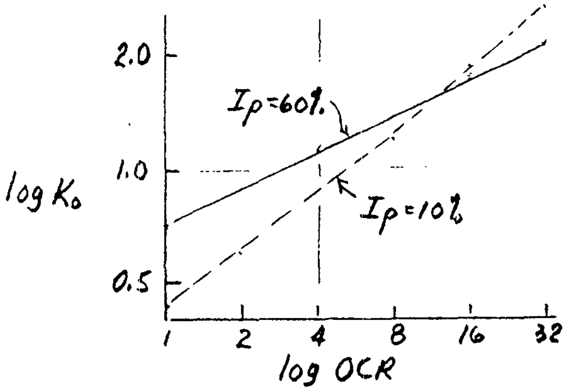
3) Mayne & Kulhawy (1982) JGED GT6

- Sands ($n = 90$) $K_o = 1 - 0.988 \sin\phi'$ ($r^2 = 0.39$)
- Clays ($n = 81$) $K_o = 1 - 0.987 \sin\phi'$ ($r^2 = 0.73$)

## 2.5 Overconsolidated $K_o$

1) General trends : Clays - UNLOADING

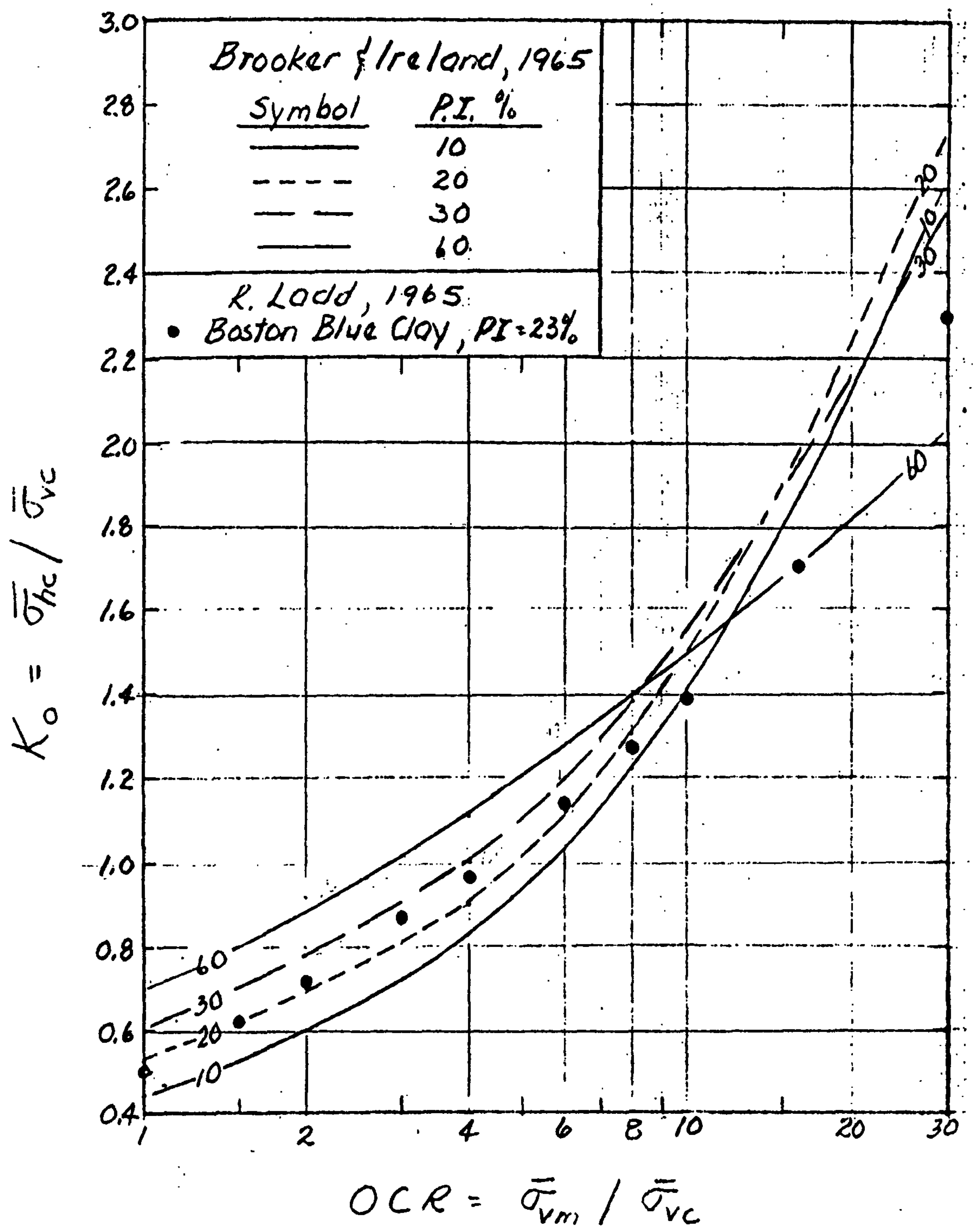
- Fig. 1-1, p3a $K_o$ vs log OCR Brooker & Ireland (1965)
  Remolded clays
- Convert to log $K_o$ vs log OCR



$$K_o = K_{o_{NC}} (OCR)^n$$

- $n$ decreases with incr. $I_p$
  à la Fig. 32 (p4) Tokyo SOA

$n \approx 0.4 \pm 0.05$

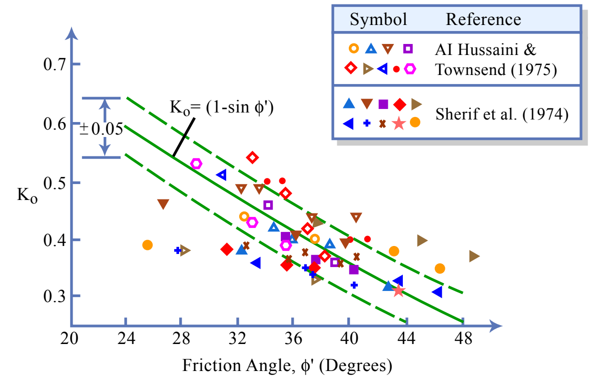


Note: Brooker & Ireland data redrawn from their Figure 11

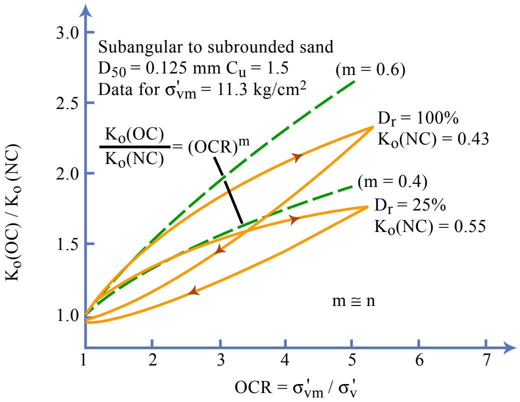
From Ladd (1973) "e Notes"

$K_o$ VERSUS OCR FOR SOILS OF VARYING PLASTICITY

Figure 1-1



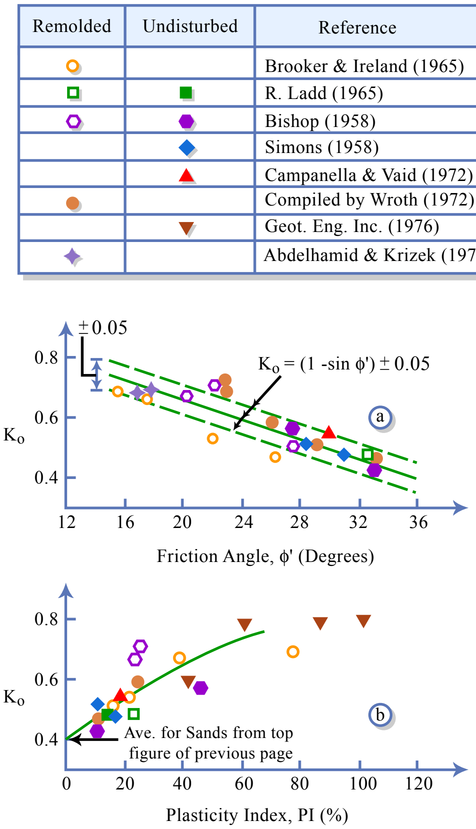
**Relationship between $K_o$ and Friction Angle for Normally Consolidated Sands.**



**Effect of Overconsolidation Ratio on $K_o$ of Reid-Bedford Sand.**

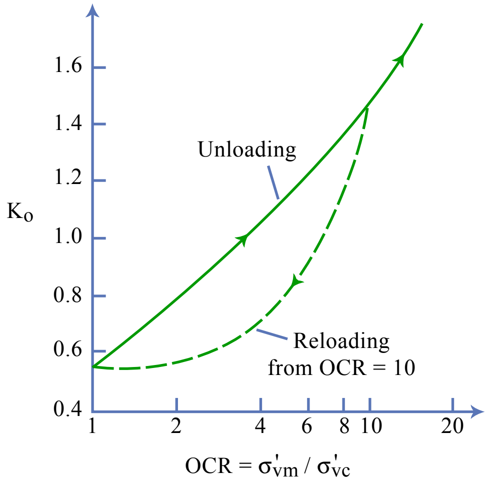
Figure by MIT OCW.

Adapted from: Al-Hussaini and Townsend, 1975.



**$K_o$ of Normally Consolidated Clays vs. Friction Angle (a) and Plasticity Index (b).**

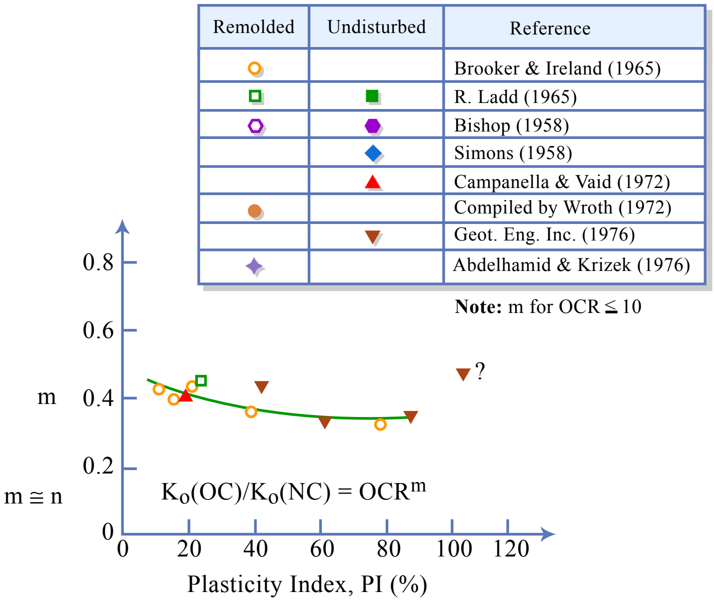
Figure by MIT OCW.



**$K_o$ vs. OCR for Haney Sensitive Clay During Unloading and Reloading.**

Figure by MIT OCW.

Adapted from: Campanella and Vaid, 1972.



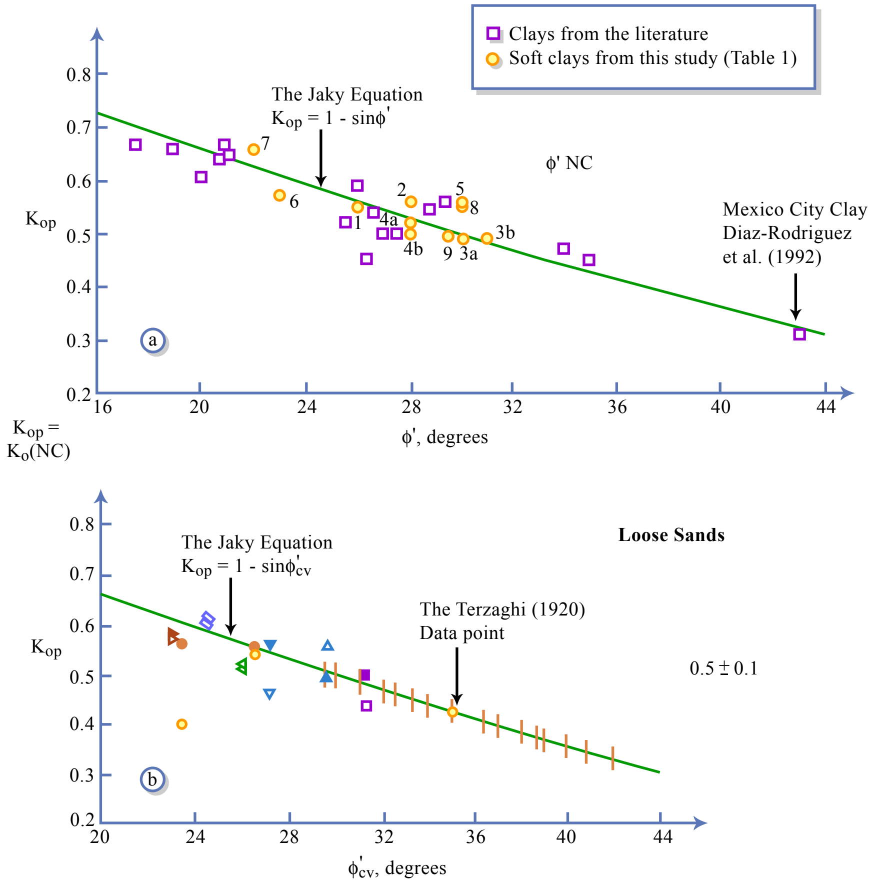
**Coefficient m Relating $K_o$ and OCR vs. Plasticity Index.**

Figure by MIT OCW.

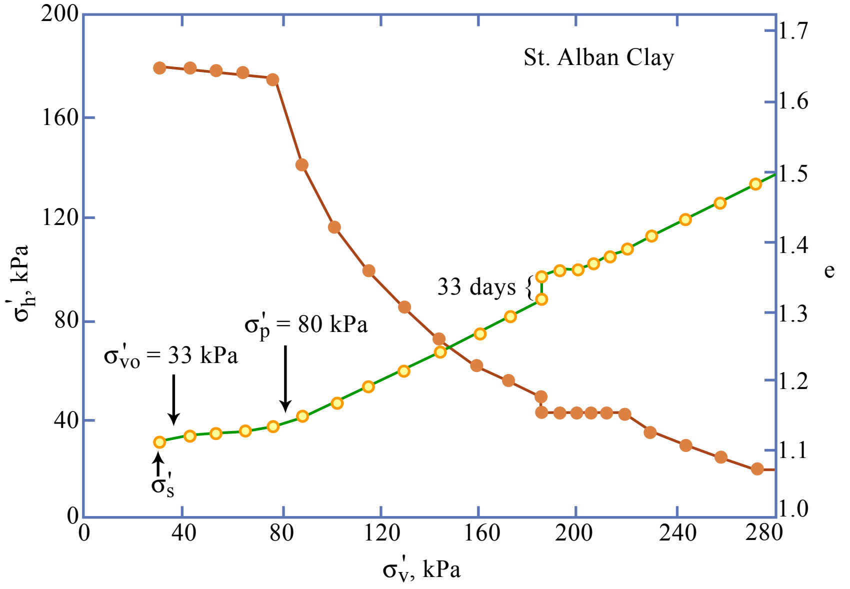
Adapted from: Ladd, et al. (1977) Tokyo SOA

CCL 3/5/95
1.322
654

p4a



(a) Data on $K_{op}$ of clays. (b) Data on $K_{op}$ of loose sands for which $\phi' = \phi'_{cv}$. Vertical lines indicate values of $\phi'_{cv}$ for granular soils assembled by Stroud (1988). Open symbols indicate $K_{op}$ determined during increase in $\sigma'_v$; closed symbols indicate $K_{op}$ determined during decrease in $\sigma'_v$ at $\sigma'_h/\sigma'_v = 1$.



**Laterally constrained secondary compression and associated increase in $\sigma'_h$ in triaxial cell.**

Figures by MIT OCW.

Adapted from: Mesri & Hayat CAN. GEOTECH. J. VOL. 30, 1993

2) Mayne & Kulhawy (1982) : Unloading

- Clays ($n = 82$): $n = 0.018 + 0.974 \sin\phi'$, ($r^2 = 0.45$)
- Sands ($n = 107$): $n = 0.929 - 0.852\, K_{o_{NC}}$, ($r^2 = 0.52$)

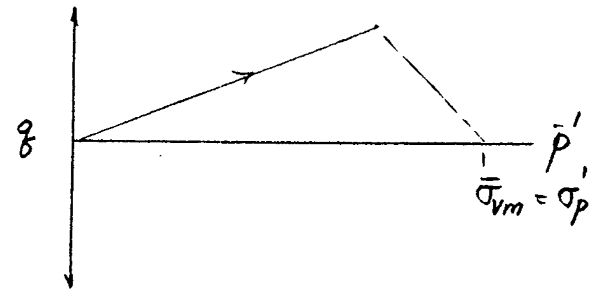
$$\approx 0.077 + 0.850 \sin\phi'$$

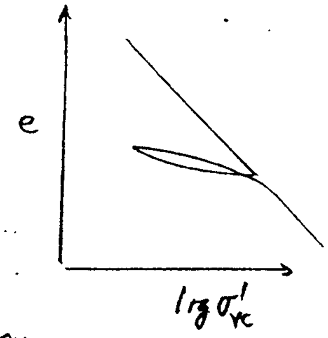
Mesri & Hayat (1993)

$n = 1 - K_{oNC}$

$\therefore\ n \approx \sin\phi' \longrightarrow$ $K_o \approx (1-\sin\phi)(OCR)^{\sin\phi'}$ Loading/Unloading

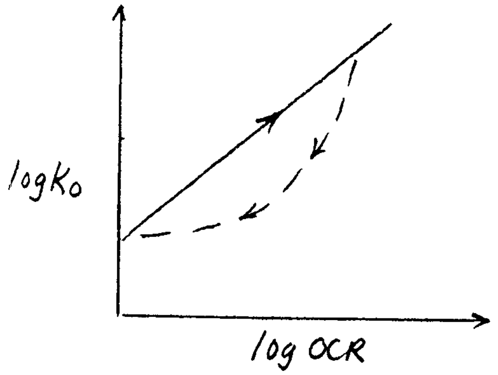
3) Limiting Value of $K_o = \dfrac{1 + (2c'/\bar{\sigma}'_{vc})\cos\phi' + \sin\phi'}{1-\sin\phi'}$ $\left\{ \begin{array}{l} K_o = N_\phi + \dfrac{2c'\sqrt{N_\phi}}{\sigma'_{vc}} \\ \sqrt{N_\phi} = \dfrac{\cos\phi'}{1-\sin\phi'} \end{array} \right.$





4) Reloading after Unloading → Hysteresis

- Tokyo SOA (p4) Fig. 15 Sand Fig. 31 Clay



Effect of Side Friction

Unloading → $K_o$ too high

Reloading → $k_o$ too low

- Mayne & Kulhawy (1982) : Reloading from max. OCR

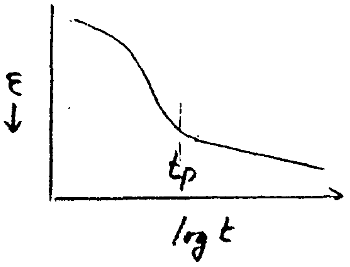
$$K_o = K_{oNC}\left[\frac{OCR}{(OCR_{max})^{1-n}} + 0.75\left(1 - \frac{OCR}{OCR_{max}}\right)\right]$$

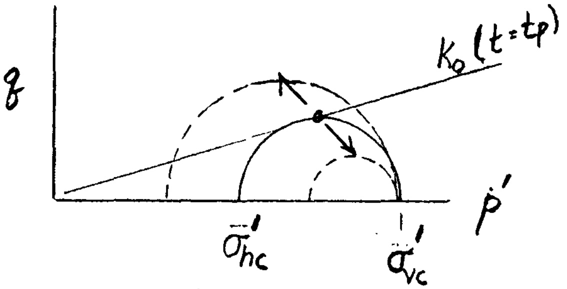
- Mesri & Hayat (1993) $K_o = \dot{K}_r + \dfrac{\sigma'_p}{\sigma'_v}(K_{oNC} - \dot{K}_r)$ (see p 26)
  Insitu recompression from $\sigma'_{vo}$

## 2.6 Effect of Secondary Compression on $K_o$

1) Schmertmann (1983) JGE, ASCE 109(1):

What happens to $K_o$ of NC clay during $t > t_p$?





ie: $\bar{\sigma}'_{hc}$ incr. → $K_o$ incr
" const → " const
" decr. → " decr.

→ See p9a

2) References & Test Results : TRIAXIAL CELL DATA

(a) Kavazanjian & Mitchell (1984) JGE, ASCE 110(4)

(b) Discussion to above + closure (1986) 111(10)

(c) Mesri & Costro (1987) JGE, ASCE 113(3)

→ (d) Mesri & Hayat (1993) CGJ, 30(4)

(a) & (b) NC SFBM See p8 Figs 6 & 7 $\Delta K_o / \Delta \log t = +0.02$

Hypothesize $K_o \to 1$ with geologic time

(c) 4 NC Clays see p8 Table 1, Fig. 8 $K_o$ increases w/ log t

Replaced by p9a

Hypothesize: $K_o$ incr. $\propto (OCR)^{n = \sin\phi}$

$$\& \ (OCR) = \left(\frac{t}{t_p}\right)^{\left[\frac{C_{\alpha e}/C_r}{1 - C_r/C_c}\right]} \approx \left(\frac{t}{t_p}\right)^{\frac{C_{\alpha e}}{C_r}}$$

3/5/95

3) References & Test Results : OEDOMETER CELL DATA

(e) Jamiolkowski, et al. (1985)

(f) Holtz et al., (1986) JGE, ASCE 112(8)

(e) Undisturbed Clay OCR=1 & 10 Sq. Oedometer · Transducer
p 9 Fig. 25
$\Delta K_0 \approx 0$

(f) Undisturbed Clay OCR=1
p 9 Fig. 3 & 4 $t/t_p \approx 10^4$

(e) 2 Undist/Remolded Clays OCR=1 MIT LSO
p 9 Fig. 25 $t/t_p \approx 10^2$
$\Delta K_0/\Delta \log t = 0.007 \pm 0.002$

4) Comparison

TX data → "large" increase with time
OED " → "no" " " "

5) Discussion · Possible Experimental Errors.

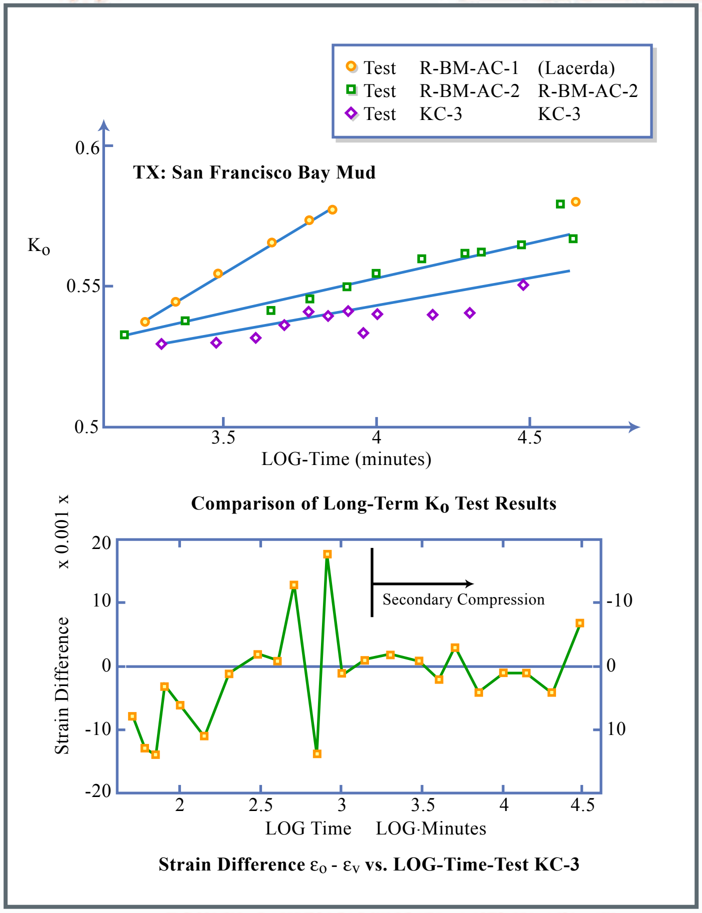
TX : Internal leakage (eg. membrane) → $K_0$
External " →
"Weekend" Effect (pertubations) →

MIT LSO : Cell leakage → $K_0$ too low

Sq. Oed :

U of I Oed (p 26) : M & H (93) say that secondary compr. → increase in side friction → reduced $\sigma_v'$ → don't measure increase in $K_0$

6) Conclusion



**Comparison of Long-Term $K_o$ Test Results**

**Strain Difference $\varepsilon_o$ - $\varepsilon_v$ vs. LOG-Time-Test KC-3**

Figure by MIT OCW. Adapted from:

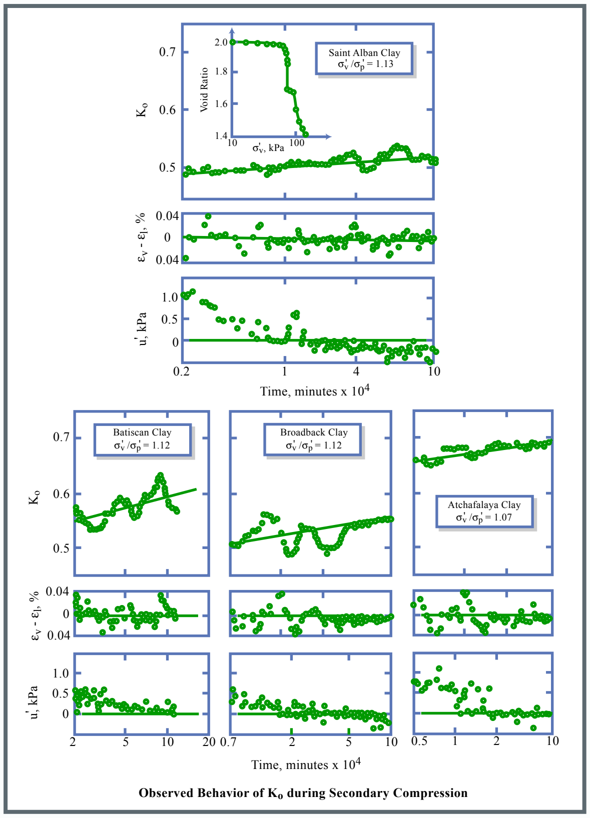
Kavazanjian & Mitchell (1985)

$K_o$ During Secondary:

TRIAXIAL CELL DATA

**TABLE 1.—Soft Clays Used in Investigation**

| Soft clay (1) | $w_o$ (%) (2) | $w_l$ (%) (3) | $w_p$ (%) (4) | $\sigma'_p/\sigma'_{vo}$ (5) |
|---|---|---|---|---|
| Saint Alban | 48–74 | 31–42 | 18–22 | 2.13–3.04 |
| Broadback | 42–48 | 28–36 | 19–25 | 2.40 |
| Atchafalaya | 52–78 | 82 | 33 | 1.14–1.22 |
| Batiscan | 82–88 | 49 | 22 | 1:62–1.72 |



**Observed Behavior of $K_o$ during Secondary Compression**

Figure by MIT OCW. Adapted from:

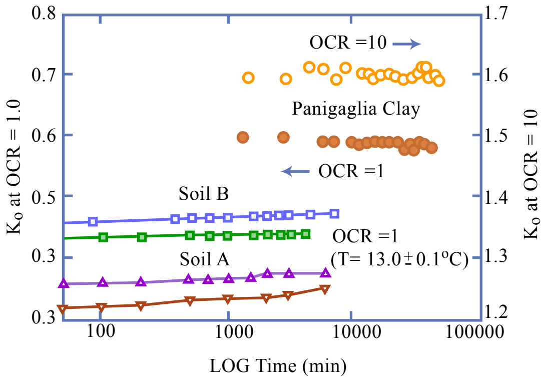
Mesri & Castro (1987)

# $K_0$ During Secondary:

## OEDOMETER CELL DATA

TUT : Square w/ transducer à la R.S. Ladd (65)

MIT : Circular w/ $H_2O$ cell à la R.T. Martin



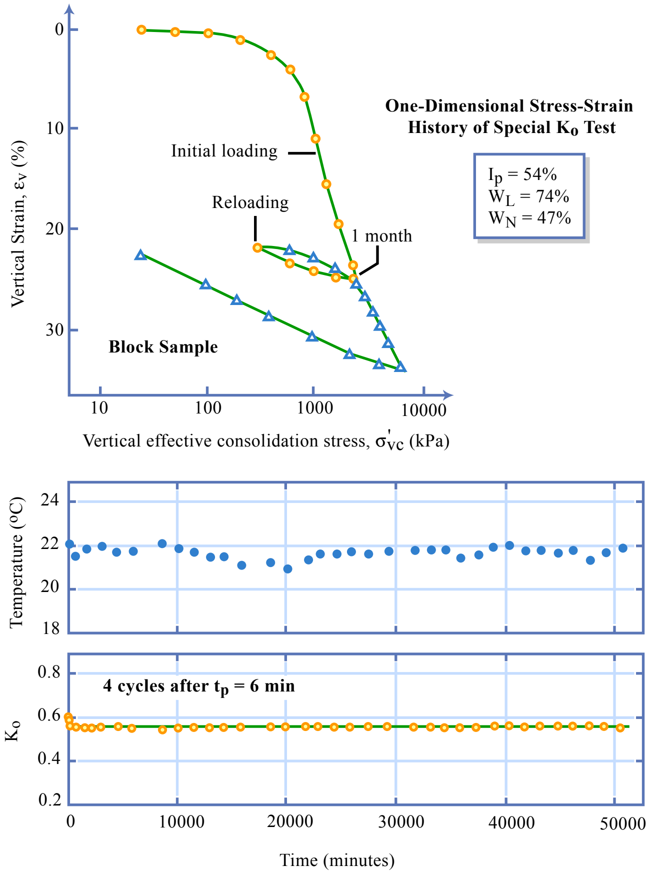
| Panigaglia Clay | | Soil A | Soil B |
|---|---|---|---|
| $W_L$ = 65%, $I_p$ = 40%, $C_{T1}/CR$ = 0.08 ± 0.01 | | △ Undisturbed<br>$W_L$ = 138%, $I_p$ = 78%<br>$\sigma'_{vc}$ = 50 kPa | □ Undisturbed<br>$W_L$ = 56%, $I_p$ = 32%<br>$\sigma'_{vc}$ = 390 kPa |
| ● At OCR = 1<br>$\sigma'_{vc}$ = 1000 kPa<br>T = 19.8 ± 0.5°C | ○ At OCR = 10<br>$\sigma'_{vc}$ = 475 kPa<br>T = 21.5 ± 0.5°C | ▽ Remodeled<br>$W_L$ = 84%, $I_p$ = 30%<br>$\sigma'_{vc}$ = 245 kPa | ▣ Remolded<br>$W_L$ = 56%, $I_p$ = 17%<br>$\sigma'_{vc}$ = 390 kPa |

**TUT** **MIT**

**Coefficient of Earth Pressure at Rest vs. Time for Undisturbed and Remoulded Clay**

Figure by MIT OCW.

Adapted from: Jamiolkowski, et al. (1985)



**$K_o$ and Temperature vs. Time for Undisturbed Montalto di Castro Clay**

Figure by MIT OCW.

Adapted from: Holtz et al. (1986)

Mesri & Hayat (1993) CGJ ;30(4), 647-666 Effect of Secondary Compression

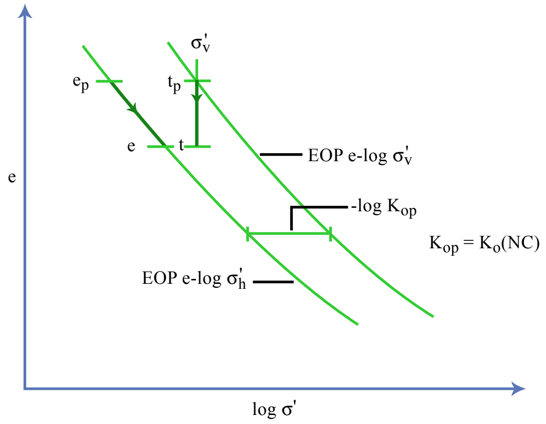
TABLE 1. Index properties of soft clays

| | Clay | $w_o$ (%) | $w_l$ (%) | $w_p$ (%) | CF (−2 μm%) | $\sigma'_{vo}$ (kPa) | $\sigma'_p/\sigma'_{vo}$ | $\phi'$ (deg.) | $C_\alpha/C_c$ |
|---|---|---|---|---|---|---|---|---|---|
| 1 | St. Hilaire | 61–68 | 55 | 23 | 77 | 83.4 | 1.40–1.57 | 26 | 0.031 |
| 2 | St. Esprit | 73–92 | 75 | 27 | 76 | 36.5 | 3.00–3.30 | 28 | 0.026 |
| 3*a* | St. Alban 1 | 58–64 | 43 | 21 | 40 | 32.7 | 2.10–3.37 | 30 | 0.025 |
| 3*b* | St. Alban 2 | 48–74 | 31–42 | 18–22 | 56 | 33.1 | 2.13–3.04 | 31 | 0.024 |
| 4*a* | La Grande 15*b* | 55–59 | 62 | 26 | 53 | 42.0 | 2.80–2.95 | 28 | 0.057 |
| 4*b* | La Grande 23*a* | 55–58 | 64 | 26 | 52 | 82.7 | 1.75–2.00 | 28 | 0.052 |
| 5 | Boston Blue | 27–30 | 32–36 | 17 | 36–44 | 154.9 | 3.29 | 30 | 0.026 |
| 6 | Vasby | 94–103 | 121 | 40 | 67 | 28.3 | 1.20–1.34 | 23 | 0.055 |
| 7 | Atchafalaya | 52–78 | 82 | 33 | 61 | 99.9 | 1.14–1.22 | 22 | 0.022 |
| 8 | Batiscan | 82–88 | 49 | 22 | 80 | 53.1 | 1.62–1.72 | 30 | 0.030 |
| 9 | Broadback | 42–48 | 28–36 | 19–25 | 46 | 55.0 | 2.16–2.40 | 30 | 0.040 |

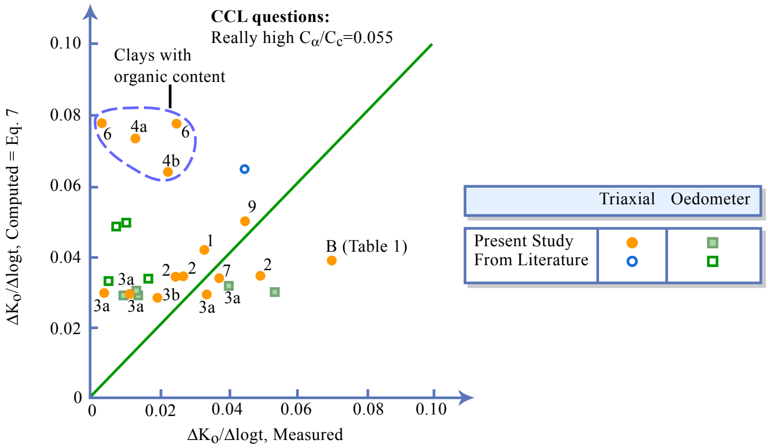
NOTE: $w_o$, initial water content; $w_l$, liquid limit; $w_p$, plastic limit; CF, clay fraction, less than 2 μm; $\sigma'_{vo}$, in situ effective vertical stress; $\sigma'_p$, preconsolidation pressure; $C_\alpha$, secondary compression index; $C_c$, compression index.

Fig.10 → $K_o = K_{op}\left(\frac{t}{t_p}\right)^{C_\alpha/C_c} = $ Eq 7

Note: $C_\alpha = C_{\alpha e}$



**Soil Behavior Assumed in Formulation of $e_p$, void ratio at the end of primary consolidation.**



**Measured and computed increase in $K_o$ during secondary compression in the NC compression range. Numbers refer to clays listed in Table 1.**

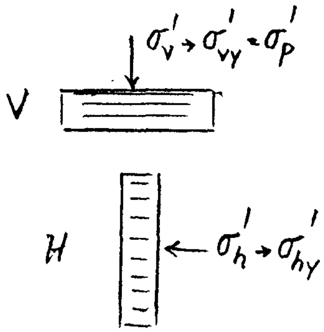
Figure by MIT OCW.

Authors comments on Fig. 11:

- Significant scatter related to experimental problems
- Ring friction in Oed. tests during secondary compression → unloading effect which may reduce or completely eliminate the increase in $K_o$

# 3. ESTIMATION OF IN SITU $K_o$ FROM LAB TESTING

## 3.1 Oedometer Tests on Vertical & Horizontal Specimens



1) Assumption that $K_0 = \sigma'_{hy} / \sigma'_{vy}$ *

- At best, would only work for OCR = 1

2) Becker et al. (1987) CGJ 24(4)

- See II p12 for details & example
- CCL tried → doesn't work (& Beeriaques)

3) Conclusion: Doesn't work.

## 3.2 Estimation from $K_o = f(OCR)$

1) Discussion of how get $K_o = f(OCR)$

- Empirical correlations
- Lab testing via $CK_o$-TX
  " " via Lateral Stress Oed.

2) Discussion of problem due to unloading vs reloading to in situ OCR

- Why unloading should → upper estimate

## 3.4 Conclusions

1) Always apply 3.2; [illegible]

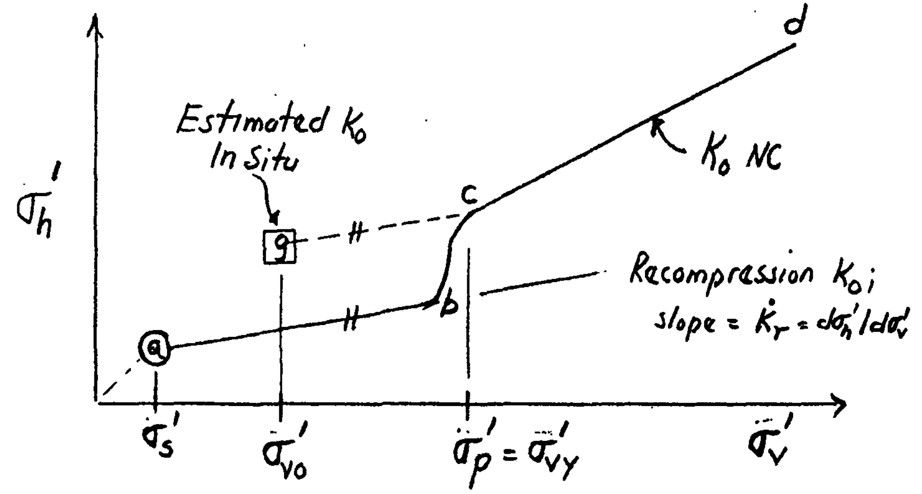
2) Also use 3.3 if have the data, e.g. from SHANSEP $CK_o$-TX testing

* Zeevaert (1953) 3rd ICSMFE V3, p 113
Tavenas et al (1975) ASCE "In Situ" Conf., V1, p 450-476

2/27/90 3/5/95 2/97 2/01

## 3.3 Measure $K_o$ During Recompression

1) Mesri & Castro (1987) JGE, ASCE 113(3) + Lefebvre (1979) + Mesri & Hayat (1993) CGJ



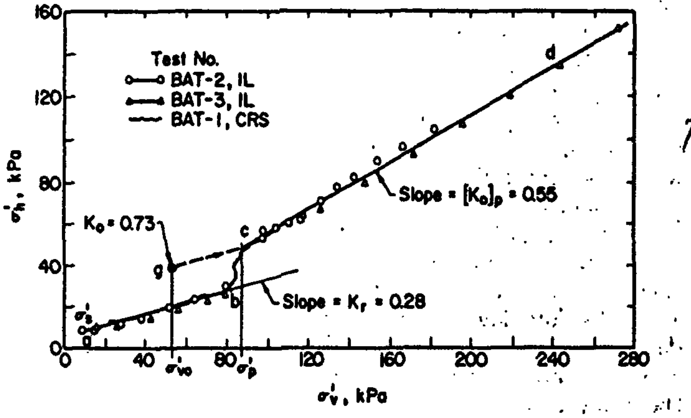


FIG. 9.—$\sigma_h'$ versus $\sigma_v'$ Path in One-Dimensional Compression and Construction for Estimating In-Situ $K_o$, Batiscan Clay

TX CELL Data

Also see p26 for M&H data & p11a,b&c for CHT data in BBC

TABLE 3.—Estimates of In-Situ $K_o$, and Measured Values of $K_r$ and $[K_o]_p$

| Soft clay (1) | $K_o$ (Eq. 14b) ($t/t_p$ = 10,000) (2) | $[\sigma_p']_h / [\sigma_p']_v$ (3) | $\sigma_{ho}'/\sigma_{vo}'$ (4) | $K_r$ (5) | $[K_o]_p$ (6) |
|---|---|---|---|---|---|
| Saint Alban | 0.55 | 0.72 | 0.79 | 0.26 | 0.49 |
| Broadback | 0.62 | 0.66 | 0.78 | 0.31 | 0.51 |
| Atchafalaya | 0.72 | 0.87 | 0.72 | 0.50 | 0.66 |
| Batiscan | 0.64 | 0.80 | 0.73 | 0.28 | 0.55 |

Delete 2/01

VSH Oed. → (3)

Above approach → (4)

NOTE: CCL doesn't understand reasoning of this approach, but agrees that measured $K_o$ at $\sigma_{vo}'$ will be MUCH TOO LOW

CCL 5/24/92 CCL 2/25/93 1.322 "Mesri" Techique → $K_o$

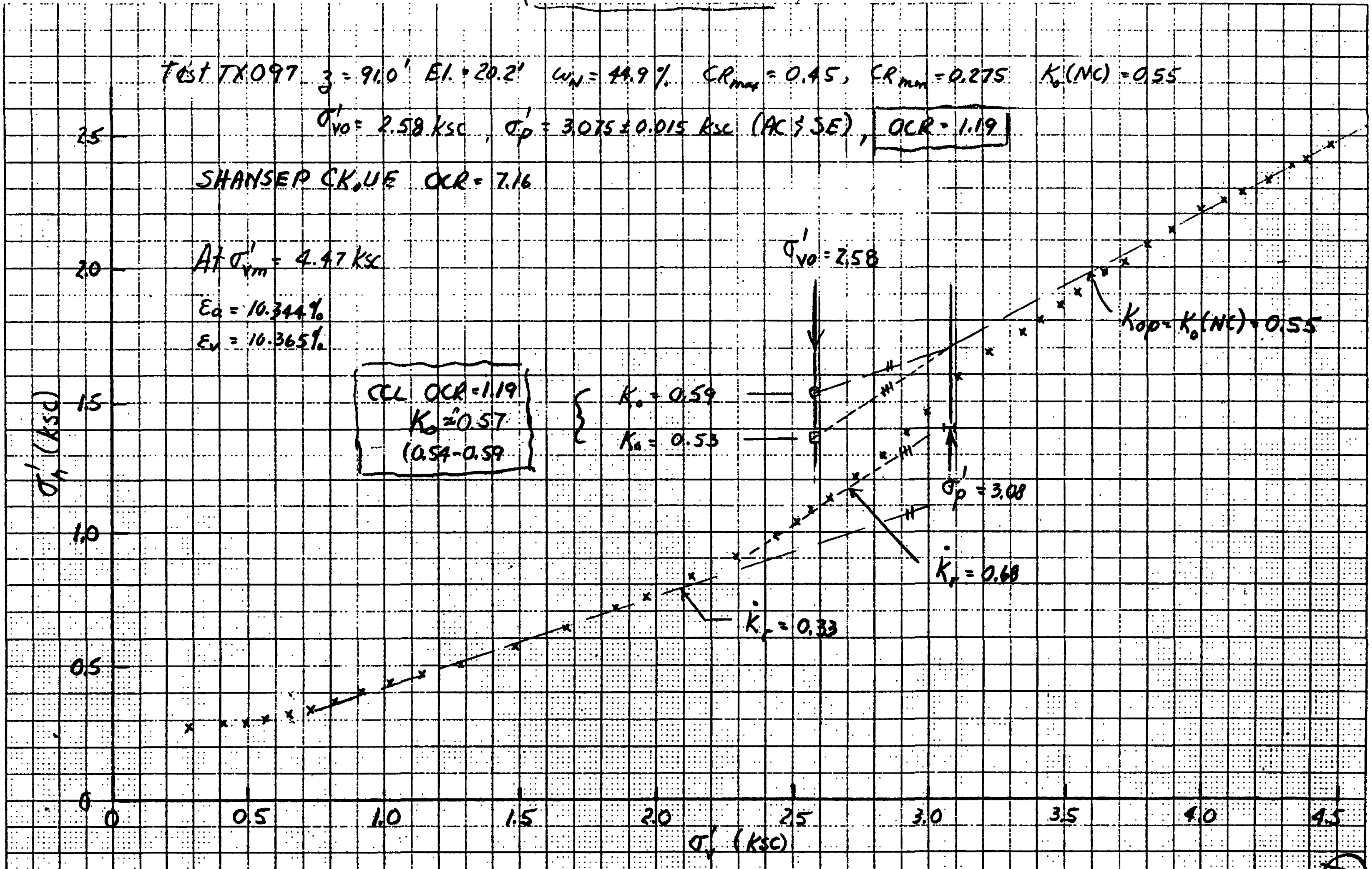


Fig. $CK_o$-TX97 : $\sigma'_h$ vs $\sigma'_v$ 1-D Compression : BBC Lower "Structured" Clay

p11b

CCL 5/25/92 CCL 2/25/93 1.322 "Mesri" → $K_o$

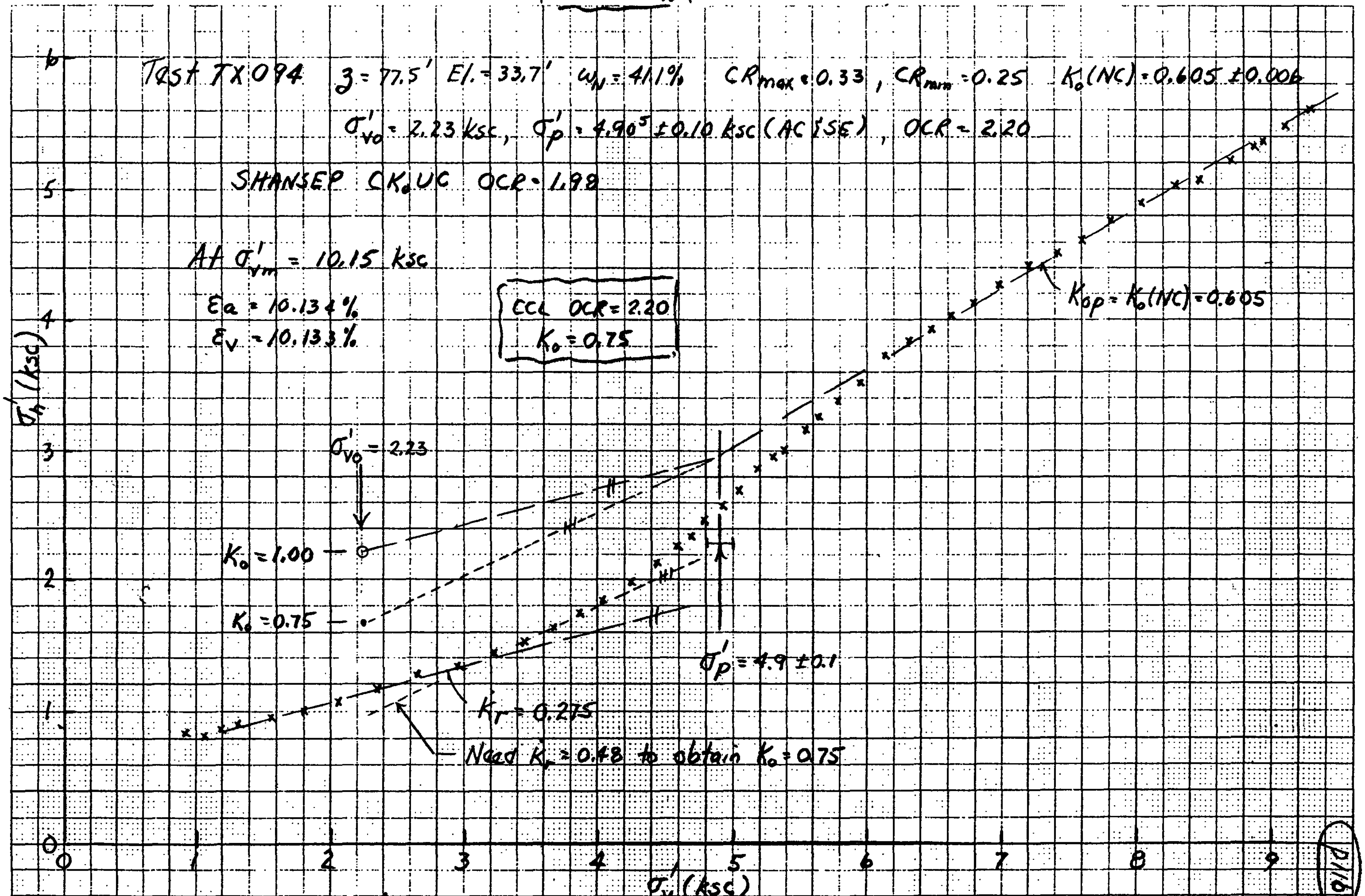
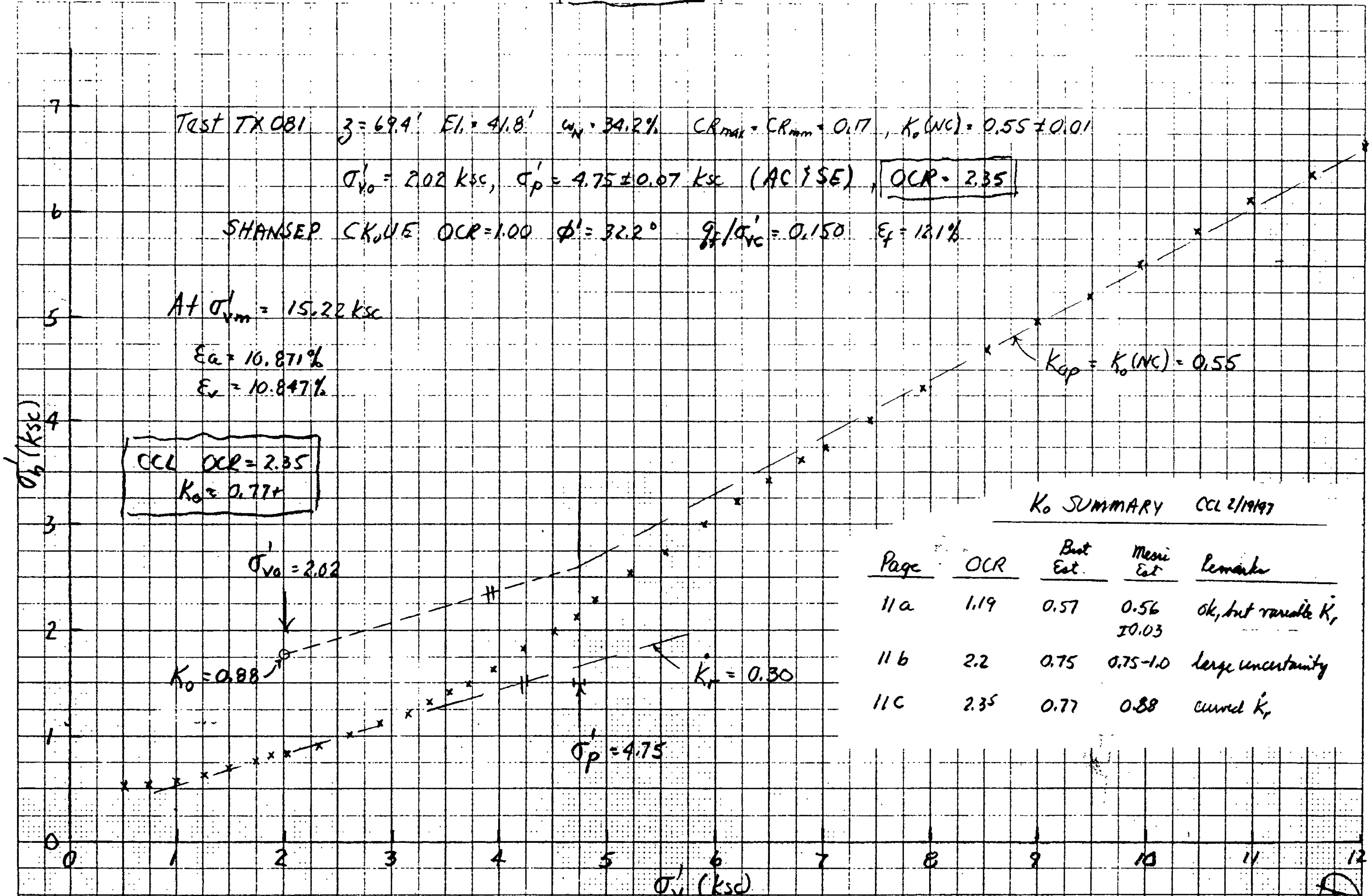


Fig. $CK_o$-TX 94: $\sigma'_h$ vs $\sigma'_v$ 1-D Compression: BBC Desiccated Crust with Some "Structure"

P116

CCL 5/26/92   CCL 2/25/93 1.322

"Mesri" → $K_o$



Test TX081   $z = 69.4'$  $El. = 41.8'$  $w_N = 34.2\%$  $CR_{max} = CR_{min} = 0.17$, $K_o(NC) = 0.55 \pm 0.01$

$\sigma_{vo}' = 2.02$ ksc, $\sigma_p' = 4.75 \pm 0.07$ ksc (AC & SE), $\boxed{OCR = 2.35}$

SHANSEP $CK_oUE$ OCR = 1.00  $\phi' = 32.2°$  $q_f/\sigma_{vc}' = 0.150$  $\varepsilon_f = 12.1\%$

At $\sigma_{vm}' = 15.22$ ksc

$\varepsilon_a = 10.871\%$

$\varepsilon_v = 10.847\%$

CCL OCR = 2.35
$K_o = 0.77+$

$K_o$ SUMMARY   CCL 2/19/97

| Page | OCR | Best Est | Mesri Est | Remarks |
|---|---|---|---|---|
| 11a | 1.19 | 0.57 | 0.56<br>±0.03 | ok, but variable $K_r$ |
| 11b | 2.2 | 0.75 | 0.75-1.0 | large uncertainty |
| 11c | 2.35 | 0.77 | 0.88 | curved $K_r$ |

Fig. $CK_o$-TX81: $\sigma_h'$ vs $\sigma_v'$ 1-D Compression: BBC Upper Desiccated Crust

p11c

# 4 ESTIMATION OF $K_0$ FROM IN SITU TESTING.

## 4.1 Tests Considered & Selected References

NOTE: ASCE Conference INSITU'86 "Use of In Situ Tests in Geotechnical Engineering", 1284p → many new papers

1) Total Stress Cell = Earth Pressure Cell (EPC)
   - Massarsch et al. (1975) ASCE IN SITU '75 Conf.
   - Jamiolkowski et al. (1985)

2) Hydraulic Fracturing Test (HFT)
   - See above

3) Self Boring Pressuremeter Test (SBPT)
   - Baguelin, et al. (1978) The Pressuremeter and Foundation Engineering, Trans Tech. Publ., Germany, 617p
   - Jamiolkowski, et al. (1985)

4) Marchetti Dilatometer Test (DMT)
   - Marchetti (1980), JGED, ASCE, 106(3)
   - Proc 1st Inter. Sym. on Penetration Testing, ISOPT-1, Orlando, March 1988, 2 Vol. Balkema
   - Jamiolkowski, et al. (1985)

---

NOTE 1), 2) & 3): "Measure" $\sigma_{ho} = \sigma'_{ho} + u$

∴ Therefore need independent estimates of $\sigma_{vo}$ & $u$ to obtain $K_o = \sigma'_{ho}/\sigma'_{vo}$

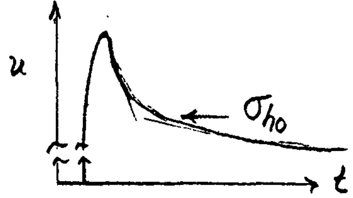
## 4.2 Total Stress = Earth Pressure Cell (EPC)

1) See Sheet E/H1 Fig.1

2) Inherent error → too high $K_o$ with increasing OCR

3) Probably best method for low OCR clays

## 4.3 Hydraulic Fracturing Test (HFT)



1) See Sheet E/H1 Fig.2

· Procedure

2) Bjerrum et al. (1972) - Limited $K_o < 1$ to get vertical cracks ($\perp$ to $\sigma_3$)

3) Lefebvre (1990-MIT) - Can still get vertical cracking for $K_o > 1$: treat as total stress cavity expansion (rather than increase in pore pressure → crack $\perp$ to $\sigma_3$). 4) Use if have hydraulic piezometers

## 4.4 Self-Boring Pressuremeter Test (SBPT)

1) Sheets S1-S4

2) Historical development: 1972

- English → Camkometer French → PAFSOR
- 3 independent papers → "derived" stress vs strain

$$\tau = \varepsilon_o \, dP/d\varepsilon_o = 0.434 \, dP/d\log(\Delta V/V)$$

- Resultant values of $c_u$ usually much too HIGH

PAFSOR Camkometer
- End effects Yes L/D=2-4 No L/D=8
- Disturbance Yes if $P_o$ too low
- Variable $\dot{\varepsilon}$ Yes
- Partial drainage ?
- Anisotropy. No (opposite)

2/97

4.4 Cont.

3) Use to estimate $\sigma_{ho}$ : Techniques

PAFSOR (S1)

CAMKOMETER (S2,3)

Which preferred?

4) Some results (S4)

CA/T STP data → too scattered to be of any use

5) CCL conclusion: expensive waste of $

## 4.5 Marchetti Dilatometer Test (DMT)

1) Sheets D1-D5

2) Testing technique (D1)

JHS (3/88) Civil Engr. Mag.
Total Cost/test ≈ $25±10

3) Overview of DMT "predictions" : ALL EMPIRICAL

2/97 2/01

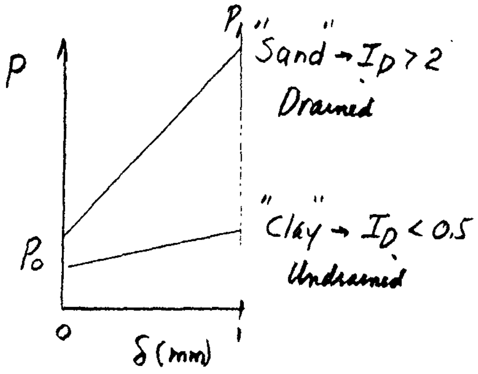
## 4.5 Cont.

4) Material Index, $I_D = \dfrac{\Delta P}{P_0 - u_0}$

Marchetti (1980)

- Reflects predominant "grain size"
- $\Delta P = f$ (soil stiffness - rapid loading)
- $P_0 - u_0 = f$ (soil strength - " " )

| $I_D$ | Soil Classification |
|---|---|
| < 0.1 | Peat & Sensitive Clay |
| 0.1 | CLAY |
| 0.35 | Silty CLAY |
| 0.6 | Clayey SILT |
| 0.9 | SILT |
| 1.2 | Sandy SILT |
| 1.8 | Silty SAND |
| 3.3 | SAND |



5) Horizontal Stress Index, $K_D = \dfrac{P_0 - u_0}{\sigma'_{vo}}$

- $K_0$ "uncemented & not aged" (D2 Fig. 11)

$$K_0 = \left(\frac{K_D}{1.5}\right)^{0.47} - 0.60$$

(D2 Fig. 4 - Other results)

- $OCR = \sigma'_p / \sigma'_{vo}$ "uncemented" $I_D < 1.2$ (D2 Fig. 11)

$$OCR = (0.5\, K_D)^{1.56}$$

- Undrained shear strength: uses SHANSEP Eqn

$$c_u / \sigma'_{vo} = 0.22\, (OCR)^{0.8}$$

(but you can select S & m)

6) Modulus: $E_D + I_D + K_D + R_M \rightarrow M = 1/m_v$ !

2/19/97

4.5 Cont.

7) Output from actual test site (D3-5)

8) JHS (3/88) promotes for $\rho$ estimates (also sells equipment)

## 5. CONCLUDING REMARKS

1) Practical uses of $K_o$

a) Required for $CK_oU/D$ Recompression technique (since $K_c$ is much too low for 1-D reconsolidation to $\sigma'_{vo}$ à la pages 2a & 2b)

b) Required starting point for FE analyses

c) To estimate $\sigma_{ho}$ on underground structures (e.g, tunnels, retaining walls, etc)

2) Variation in $\sigma_{ho}/\sigma_{vo}$

- For simplicity, assume WT at GS and $\gamma_b = \gamma_w \rightarrow \gamma_t = 2\gamma_w$

$$\therefore \frac{\sigma_{ho}}{\sigma_{vo}} = \frac{K_o z\gamma_w + z\gamma_w}{2z\gamma_w} = \frac{K_o}{2} + 0.5$$

| $K_o$ | $\sigma_{ho}/\sigma_{vo}$ |
|---|---|
| 0.5 | 0.75 |
| 1.0 | 1.00 |
| 1.5 | 1.25 |

& $K_o = \pm 0.1 \rightarrow \Delta\sigma_{ho}/\sigma_{vo} = \pm 0.05$

CCL 2/20/99 2/25/01
21

# 1.322 Class Schedule, Reading Assignments, Etc. on CONSOLIDATION (Part C)

| Topics : From Handout Notes | Approx. No. Classes | Reading (Backup) Tokyo ('77) | SF ('85) | Other | Remarks |
|---|---|---|---|---|---|
| I Introduction<br>• Background<br>• $K_0$ : trends & measurement<br>• In situ testing | 2 | 4.2.7<br>(2.2.4<br>4.2.6) | (1.5)<br>&<br>(3.2) | – | Covers several in situ devices for estimating $K_0$ (Some also for OCR & strength) |
| II Amount of 1-D Consolidation ($\rho_{cf}$)<br>• Consolid. tests & $\rho_{cf}$ eqn.<br>• $\sigma'_p$ mechanisms & measurement<br>• Effects of disturbance, creep, etc<br>• In situ tests for SH profiling | 4 - 4½ | – | 2.2 | – | "Mini" problem : develop field & lab testing programs to determine best in situ test for stress history profiling |
| III Rate of Consolidation ($\rho_c$)<br>• Terzaghi theory & meas. of $c_v$<br>• Effects of SH, disturbance, etc.<br>• Permeability • Non-linear consolidation | 2 | – | (3.4) | – | – |
| IV Secondary Compression ($\rho_s$)<br>• $C_\alpha/C_c$ concept<br>• Hypothesis A vs B<br>• Surcharging | 1½ | (2.2.6) | 2.5 | – | Major Home Problem covering Parts I - IV |
| V 2 & 3-D Loading & Vertical Drains<br>• Initial settlement ($\rho_i$) and $\rho_{cf}$<br>• Rate of settlement<br>• Consolidation with vertical drains | 2 - 2½ | (2.2.5) | (3.3) | Foott &<br>Ladd (1981)<br>1.361<br>HP No. 12 | Self-graded home problem |
| VI Problem Soils<br>• High $S_t$ • Peats<br>• Collapsing & expansive<br>• Residual • Varved clay | 1½ - 2 | – | – | – | Emphasis on peats and collapsing/expansive soils |
|  | 13 - 14.5 |  |  |  |  |

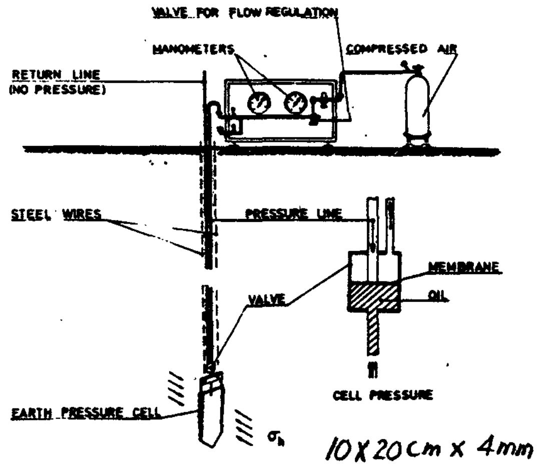
## Earth Pressure Cell (EPC)

- Penetrate with protective casing until 30 cm above depth
- Push in Cell & wait few days for equilibrium
- Measure $\sigma_h$ via "pressure balance" principle (deflection ≈ 5 μm)

## Hydraulic Fracturing Test (HFT)

- Install push-in or Casagrande type piezometer
- Increase $u$ in increments while monitoring dV/dt (flow rate). Large increase in dV/dt indicates formation of crack (hopefully radially-vertical)
- Reduce $u$ with measurements of dV/dt →

  $\sigma_{ho} = u$ when dV/dt = precracking value



10 X 20 cm x 4 mm

FIG. 1.—SCHEMATIC DIAGRAM OF THE EARTH PRESSURE CELL (GLÖTZL) METHOD

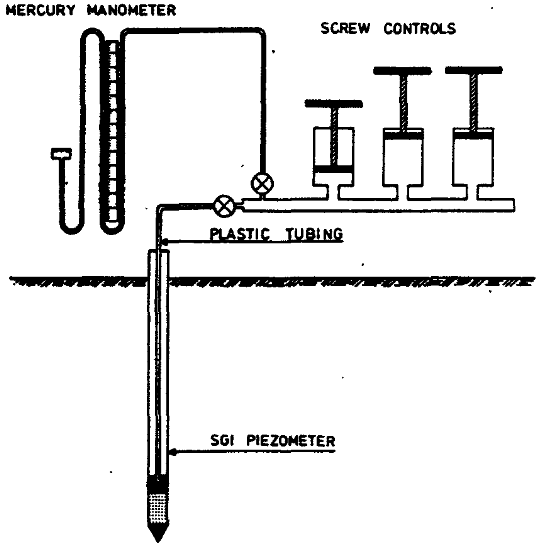
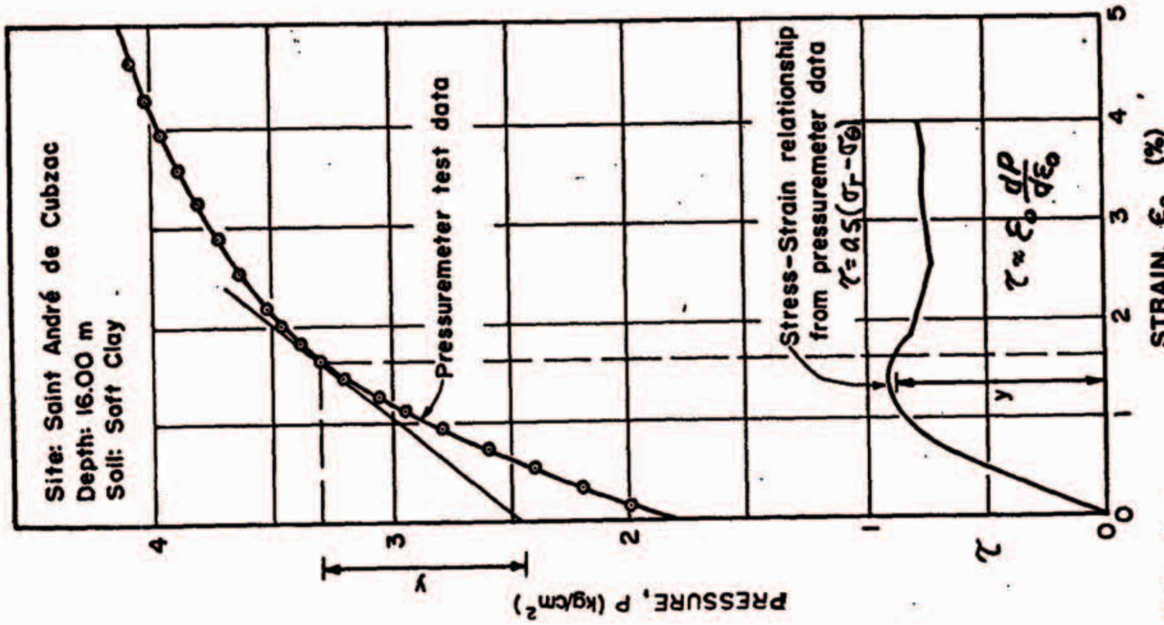


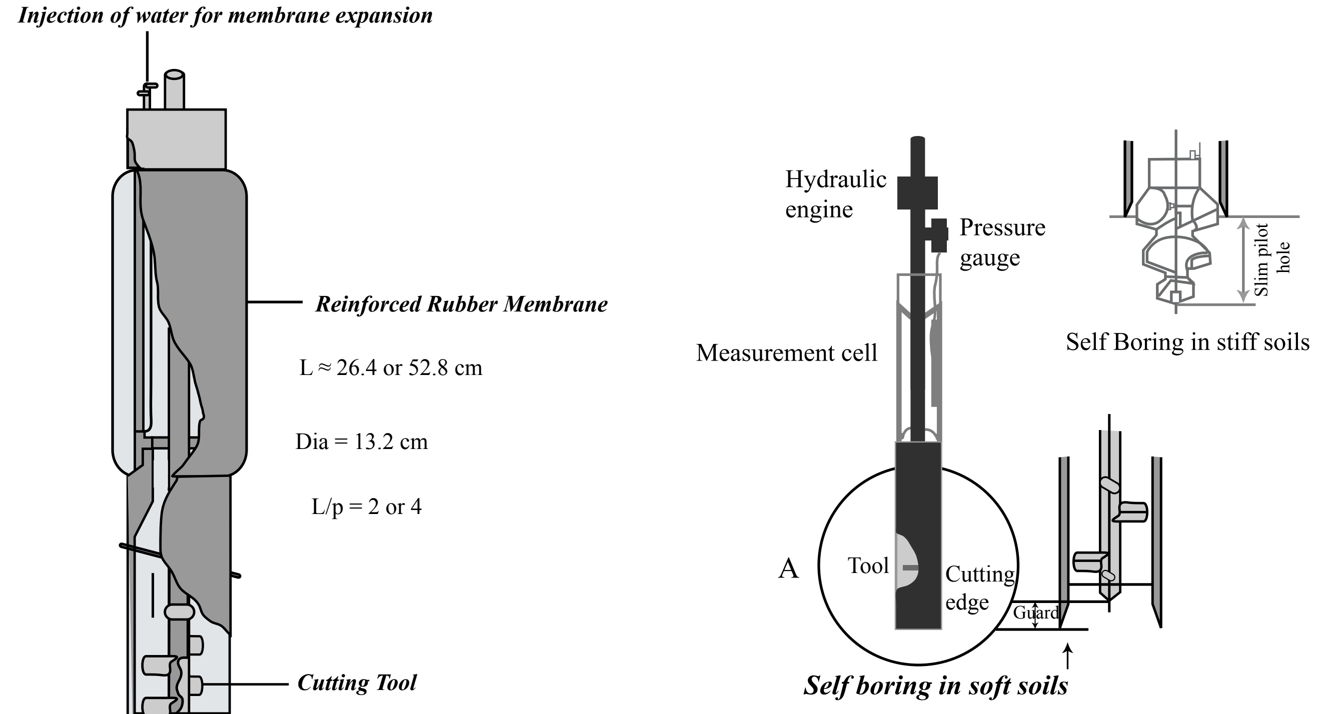
FIG. 2.—SCHEMATIC DIAGRAM OF THE HYDRAULIC FRACTURE METHOD

From Massarsch et al. (1975) ASCE Insitu Conf.



Tokyo(77)

Fig. 55 Data from an undrained Autoforeur pressuremeter test on clay (supplied by F. Schlosser).



*Drawing of the autoforeure presuremeter (supplied by F. Schlosser).*

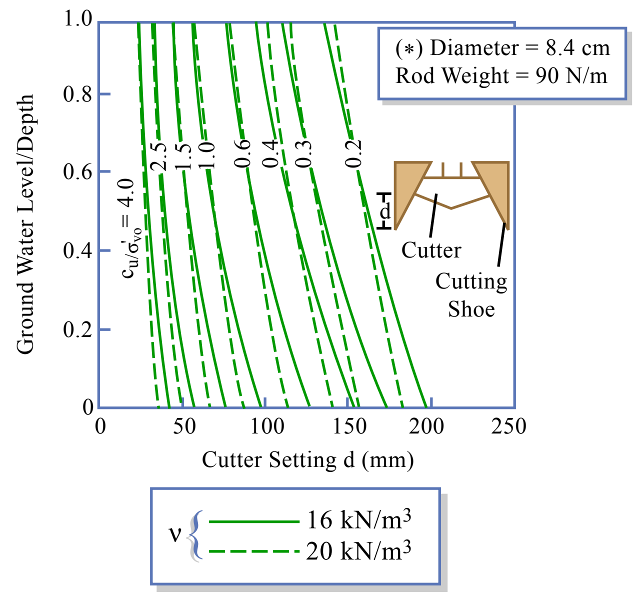
***SBP Type Pafsor***

Figure by MIT OCW.

Adapted from: Tokyo(77)

"French" PAFSOR

- Cutting drive mechanism above measurement (expansion) cell
- Inflated membrance during insertion (NOT RIGID)
- Expansion via water → AVERAGE P vs ΔV
- $\varepsilon_0 = \frac{\Delta r}{r_0} = \frac{1}{\sqrt{1-\Delta V/V}} - 1.00$



**Cutter Setting for Clays, Applicable to Camkometer Type MK III***

"English" CAMKOMETER

- Cutting drive mechanism of ground surface (vibrations)

Figure by MIT OCW.

Adapted from Clarke (1981).

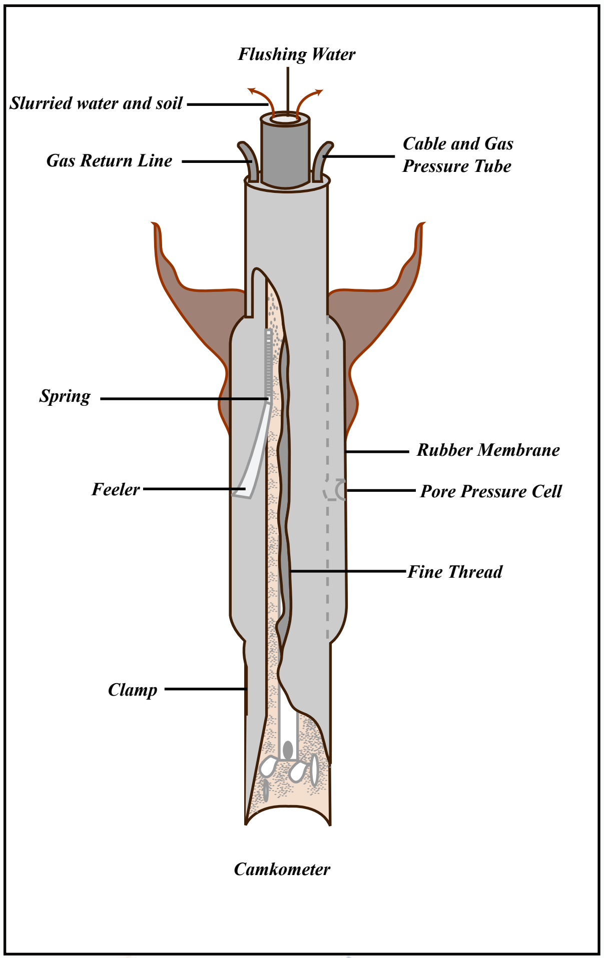


Figure by MIT OCW.

- Membrane against RIGID hollow cylinder during insertion
- Expansion via gas pressure with measurement of $\Delta r$ by 3 "feelers" (electric sensors)
  → 3 separate $P$ vs $\varepsilon_o = \Delta r/r_o$ (or use average $\varepsilon_o$)

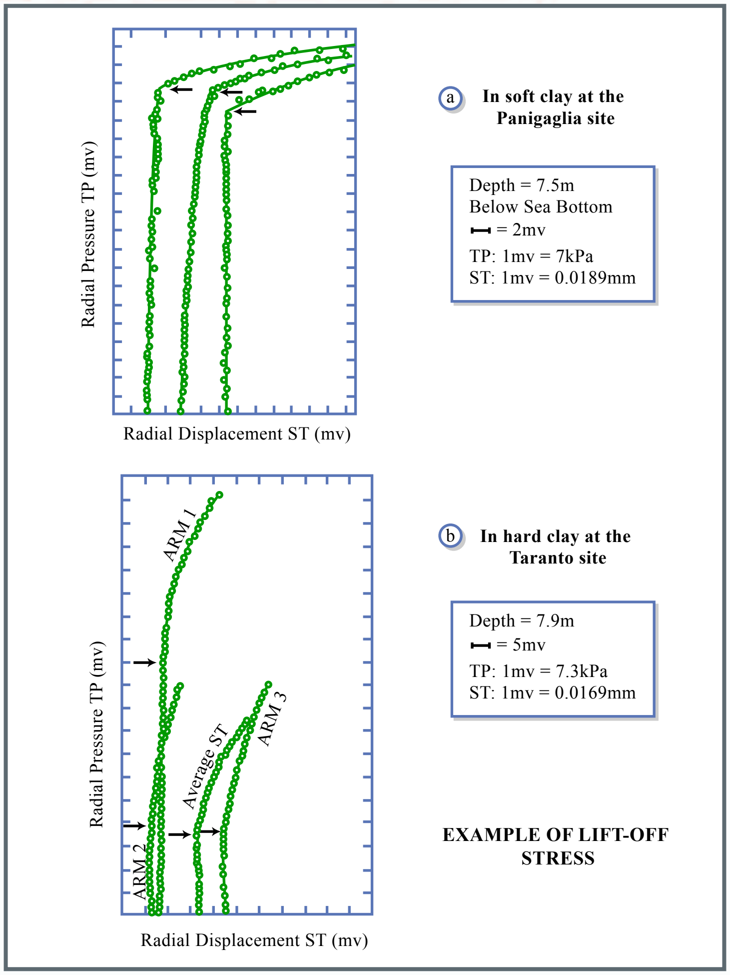
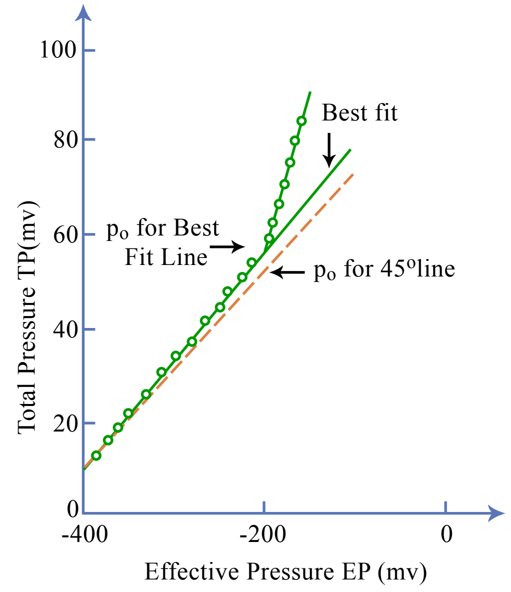


Figure by MIT OCW.

Use "lift off" $P = \sigma_{ho}$

(a) Soft Clay: 3 feelers → $\approx$ same $\sigma_{ho}$

(b) Stiff Clay: 3 feelers → different $\sigma_{ho}$

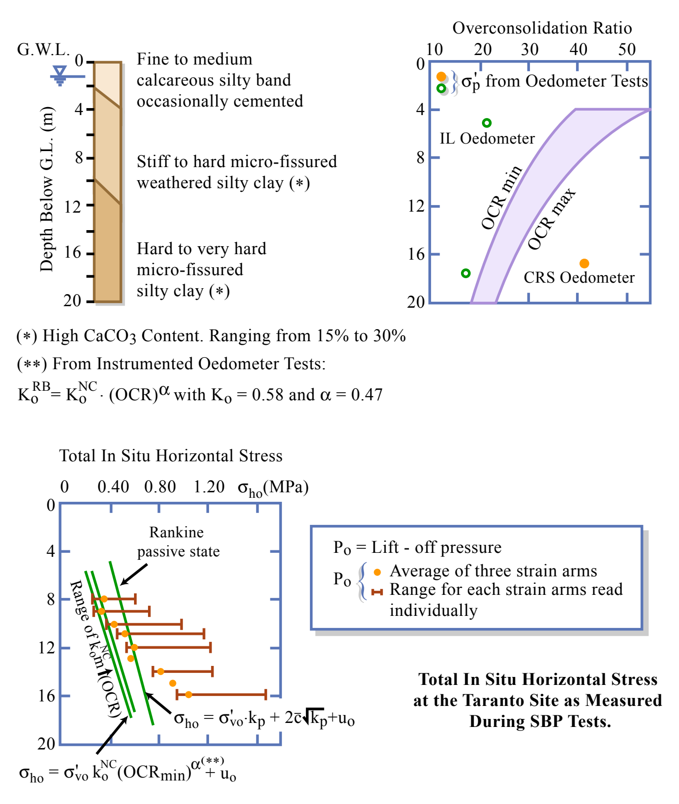


$p_o$ Determined from Total vs. Effective Pressure Plot

Figure by MIT OCW.

Assume $P = \sigma_{ho}$ when $\Delta P \rightarrow +\Delta u$

Adapted from: Wroth (1982), Lacasse and Lunne (1982).



(*) High $CaCO_3$ Content. Ranging from 15% to 30%

(**) From Instrumented Oedometer Tests:

$K_o^{RB} = K_o^{NC} \cdot (OCR)^{\alpha}$ with $K_o = 0.58$ and $\alpha = 0.47$

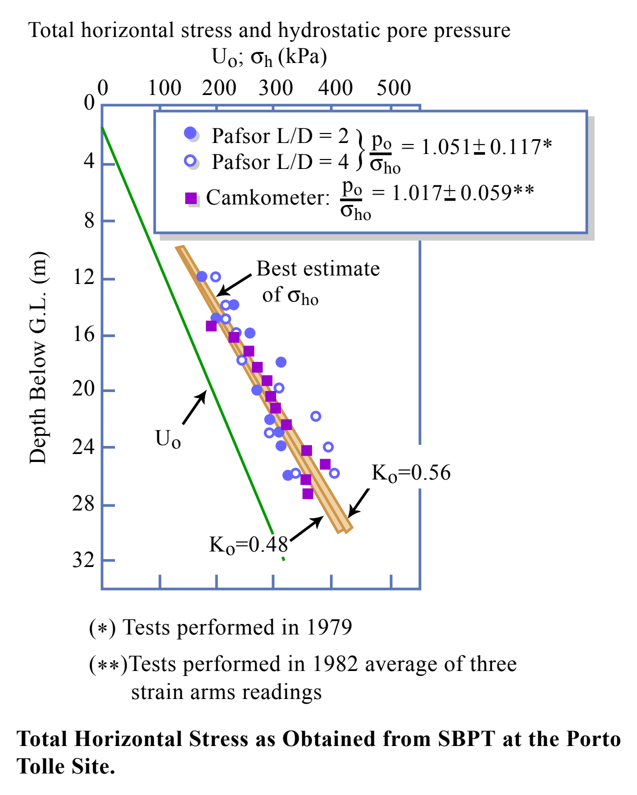
**Total In Situ Horizontal Stress at the Taranto Site as Measured During SBP Tests.**

Figure by MIT OCW.

Adapted from: Jamiolkowski, et al. (1985) ≡ SF (85)

Results CAMKOMETER - Stiff Clay Site

• Alot of $\sigma_{ho}$ data exceed Rankine passive $\sigma_{hp}$!



(*) Tests performed in 1979

(**)Tests performed in 1982 average of three strain arms readings

**Total Horizontal Stress as Obtained from SBPT at the Porto Tolle Site.**

Figure by MIT OCW.

Adapted from: Ghionna et al. (1981, 1983).

Results PAFSOR & CAMKOMETER - Soft Clay Site

Mean of scattered data → reasonable $K_o$

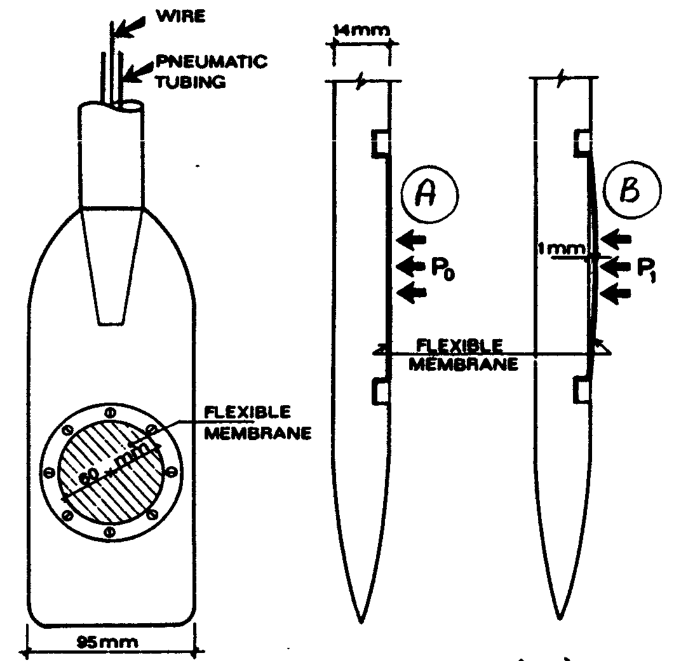


Fig.38: Marchetti Dilatometer. SF(85)

# Marchetti Dilatometer Test (DMT)

## Testing Procedure

1) Push (penetrate) at ≈ 2cm/s

2) Test at 20cm intervals <u>without</u> delay time ($t < 15s$)

(Have beeping sound with membrane in contact)

3) Increase $P$ via gas pressure + gage readings ($\pm 0.1$ bar)

- Beeping stops at liftoff = A reading → $P_0$
- Beeping starts again with $\delta = 1mm$ = B reading → $P_1$
- Do this within 15-30s

4) Decrease $P$, beeping stops & then starts when membrane again in contact = C reading → equilibrium $u$ in granular soils

## DMT Parameters ($u_0$ = equilibrium $u$)

1) Material Index, $I_D = \dfrac{\Delta P}{P_0 - u_0}$

2) Horizontal Stress Index, $K_D = \dfrac{P_0 - u_0}{\sigma'_{v0}}$

3) Dilatometer Modulus, $E_D = \dfrac{E}{1-\mu^2} = 38.2\,\Delta P$

## Calibration Information, $P_0$ & $P_1$

$Z_m$ = gage reading at zero pressure*

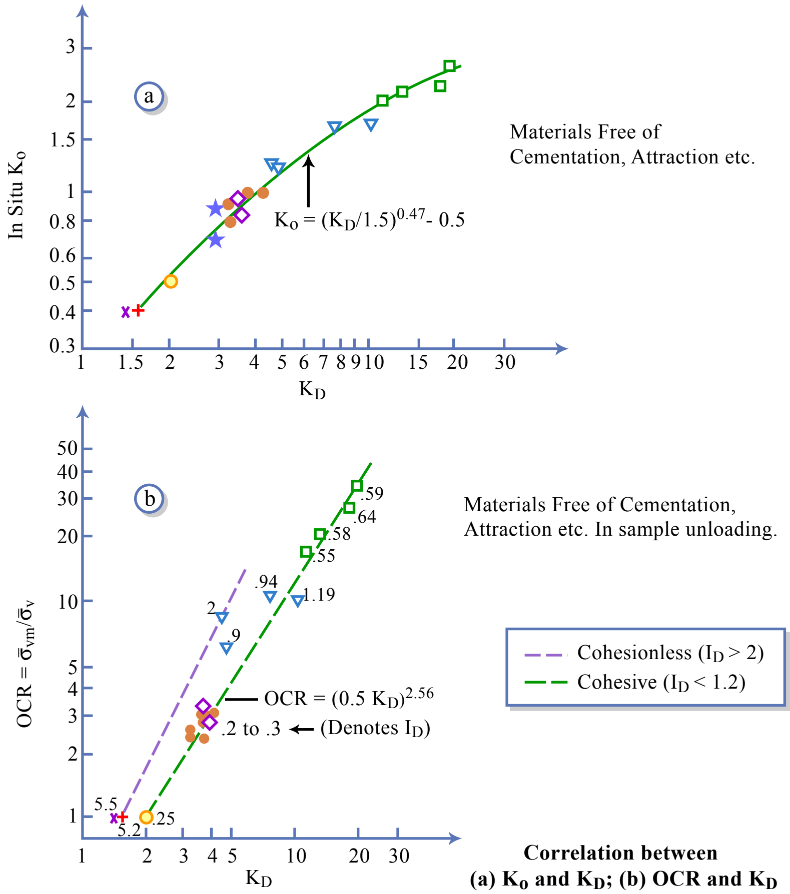
$\Delta A$ & $\Delta B$ = membrane stiffness corrections*

$P_0 = 1.05(A - Z_m + \Delta A) - 0.05(B - Z_m - \Delta B)$

$P_1 = B - Z_m - \Delta B$

$\Delta P = P_1 - P_0$

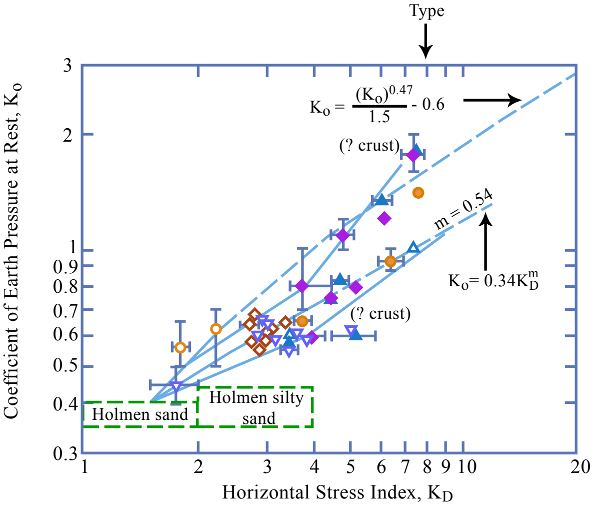
* Very important soft cohesive soils



**Correlation between (a) $K_o$ and $K_D$; (b) OCR and $K_D$**

Figure by MIT OCW.

Adapted from: Marchetti (1980)



| Symbol | Site | Reference $K_o$ |
|---|---|---|
| ▭ | Halmen | 1-sinφ' (φ' in CADC) |
| I | Drammen | Stress Cells |
| ○ | Drammen | $K_o$ - oedometer |
| ● | Haga | |
| ▲ | Haga | Field vane |
| △ | Onsay | |
| □ | Holmen | Self-boring pressuremeter |
| ◆ | Haga | |
| ◇ | Onsay | |
| ▽ | Onsay | Hydraulic Fracturing |

**Relationship between horizontal stress index, $K_D$, and coefficient of earth pressure at rest at NGI sites.**

Figure by MIT OCW.

Adapted from: Lacasse & Lunne (1988) ISOPT-1

1.322

CCL 3/1/87

2/88

-3/89

LOCATION: D-9 - BLADE ORIENTATED EAST-WEST MEMBRANE FACING NORTH    UMT
PERFORMED - DATE: 24 FEBRUARY 1987
BY: DR. CHARLES LADD, MARVIN OOSTERBAAN, ALFRED MYERS, JEFF GOODWIN, GARY CLIFFORD

D3

CALIBRATION INFORMATION:
DELTA A = .20 BARS   DELTA B = .45 BARS   GAGE 0 = .20 BARS   $z_m$   GWT DEPTH= 1.00 M
$\Delta A$   $\Delta B$

1 BAR = 1.019 KG/CM2 = 1.044 TSF = 14.51 PSI    ANALYSIS USES H2O UNIT WEIGHT = 1.000 T/M3

| Z (M) | THRUST (KG) | A (BAR) | B (BAR) | ED (BAR) | ID | KD | UO (BAR) | GAMMA (T/M3) | $\sigma'_{vo}$<br>SV (BAR) | $\sigma'_p$<br>PC (BAR) | OCR | KO | $c_u$<br>CU (BAR) | PHI (DEG) | M (BAR) | SOIL TYPE |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 8.31 | | 5.70 | 14.00 | 279. | 1.75 | 9.20 | .717 | 1.800 | .500 | 11.33 | 22.67 | 1.47 | | 30.6 | 674.7 | SANDY SILT |
| 8.92 | | 4.20 | 8.60 | 137. | 1.22 | 5.90 | .777 | 1.800 | .548 | 3.02 | 5.52 | 1.15 | | 27.7 | 270.7 | SANDY SILT |
| 9.53 | | 5.10 | 7.80 | 75. | .52 | 6.98 | .837 | 1.800 | .596 | 4.19 | 7.03 | 1.46 | .626 | | 159.2 | SILTY CLAY |
| 10.14 | | 5.00 | 10.80 | 188. | 1.41 | 5.97 | .897 | 1.800 | .644 | 4.50 | 6.99 | 1.14 | | 28.3 | 375.1 | SANDY SILT |
| 10.75 | | 3.70 | 7.00 | 97. | 1.07 | 3.79 | .957 | 1.700 | .689 | 1.87 | 2.71 | .95 | | | 148.2 | SILT |
| 11.36 | | 4.80 | 11.80 | 231. | 1.92 | 4.71 | 1.017 | 1.900 | .736 | 6.07 | 8.24 | .96 | | 29.3 | 414.7 | SILTY SAND |
| 11.97 | | 6.80 | 15.80 | 304. | 1.65 | 6.70 | 1.077 | 1.950 | .792 | 9.04 | 11.41 | 1.20 | | 29.4 | 644.1 | SANDY SILT |
| 12.58 | | 8.60 | 20.00 | 392. | 1.63 | 8.16 | 1.136 | 1.950 | .849 | 13.29 | 15.66 | 1.36 | | 29.9 | 902.9 | SANDY SILT |
| 13.19 | | 5.50 | 7.80 | 60. | .41 | 4.68 | 1.196 | 1.800 | .901 | 3.40 | 3.77 | 1.11 | .574 | | 103.6 | SILTY CLAY |
| 13.80 | | 5.40 | 7.20 | 42. | .30 | 4.32 | 1.256 | 1.700 | .946 | 3.14 | 3.32 | 1.04 | .545 | | 68.7 | CLAY |
| 14.41 | | 5.80 | 7.80 | 49. | .32 | 4.47 | 1.316 | 1.700 | .988 | 3.46 | 3.51 | 1.07 | .594 | | 82.4 | CLAY |
| 15.02 | | 5.80 | 7.50 | 38. | .25 | 4.25 | 1.376 | 1.700 | 1.030 | 3.33 | 3.24 | 1.03 | .580 | | 62.0 | CLAY |
| 15.63 | | 5.80 | 7.50 | 38. | .26 | 4.02 | 1.436 | 1.700 | 1.072 | 3.19 | 2.98 | .99 | .565 | | 59.9 | CLAY |
| 16.24 | | 6.00 | 7.60 | 35. | .22 | 4.00 | 1.496 | 1.700 | 1.114 | 3.29 | 2.95 | .99 | .583 | | 54.0 | CLAY |

$$P_0 = 1.05\,(A - z_m + \Delta A) - 0.05\,(B - z_m - \Delta B)$$

$$P_1 = (B - z_m - \Delta B)$$

$$I_D = (P_1 - P_0)/(P_0 - u_0) \rightarrow \text{Soil Type } \& \ \gamma_t$$

$$\left.\begin{array}{l} K_D = (P_0 - u_0)/\sigma'_{vo} \rightarrow K_0 = \left(\frac{2}{3} K_D\right)^{0.47} - 0.60 \\ \rightarrow OCR = \left(\frac{1}{2} K_D\right)^{1.56} \\ \rightarrow c_u = \sigma'_{vo}\, 0.22\,(OCR)^{0.8} \end{array}\right\} \text{Cohesive Soils}$$

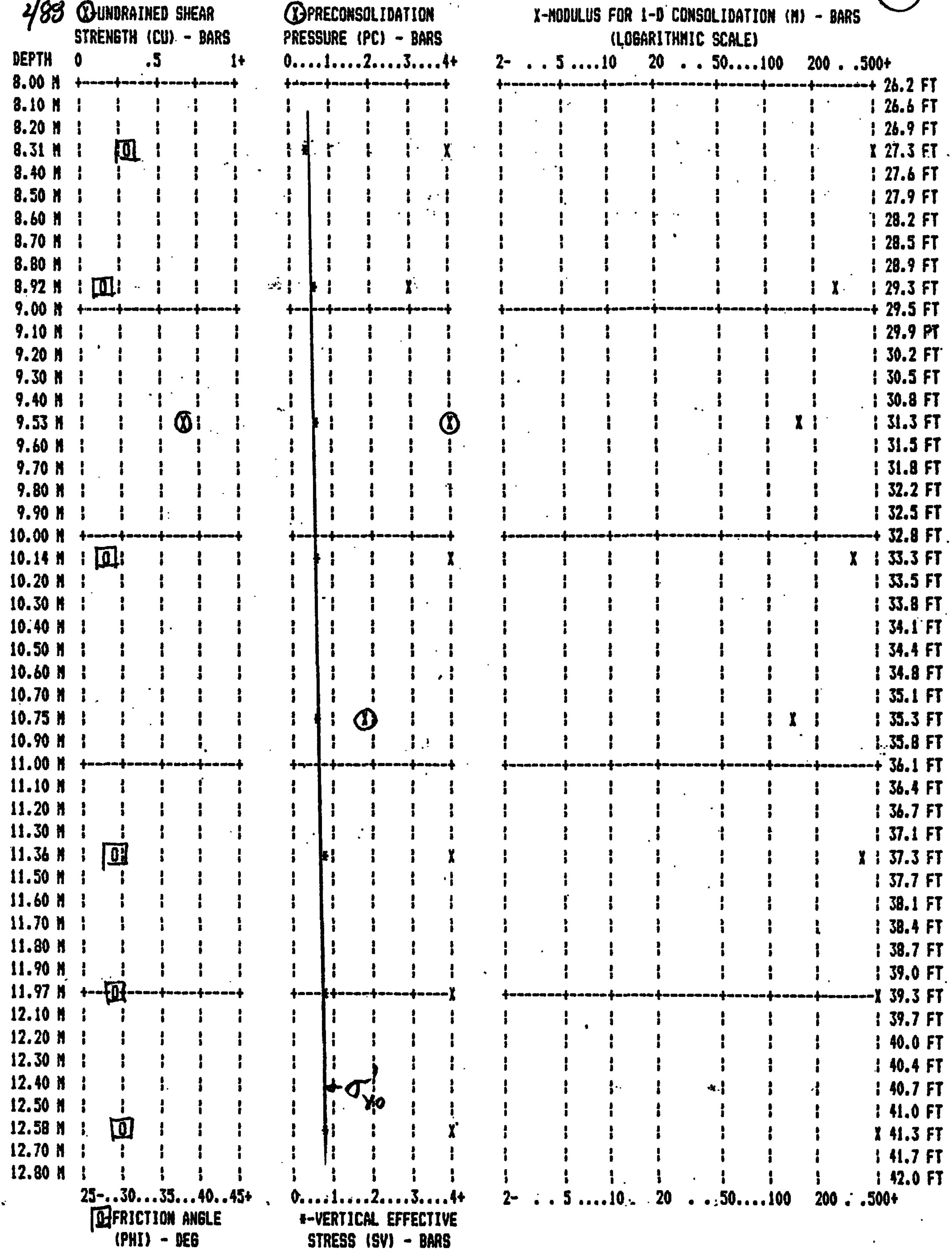
1.322

CCL 3/87

3/89 2/88

Cohesive

(D4)



Granular

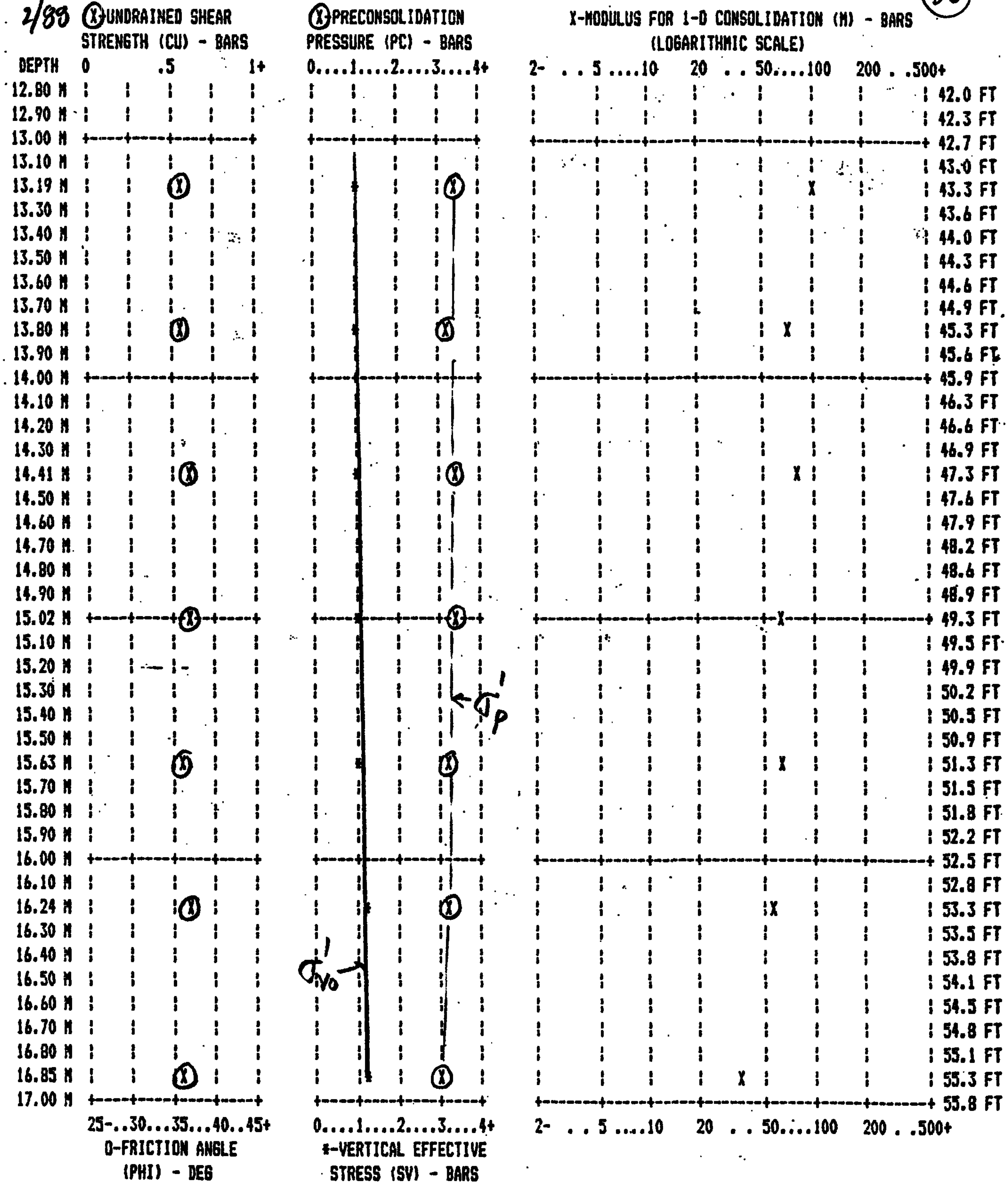
1.322

CCL 3/87 3/89

2/88

D5

Varved CLAY



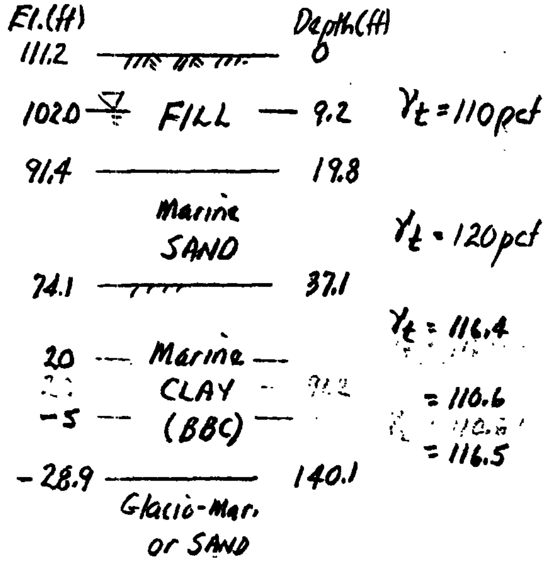
END OF SOUNDING

Note: After inputting $u_o$ & $\sigma'_{vo}$ for 1st test, data plus correlations with $\gamma_t$ → computed $u_o$ & $\sigma'_{vo}$ vs depth

2/19/97

## $K_o$ INFORMATION from SOUTH BOSTON CAIT STP

### A. General Soil Profile (Not to scale)



Project El. = NGVD + 100.0' = BCB + 94.35'

See Fig. 2 for $w_N$ & AL

### B. Stress History

- Fig. SH-1 El. vs. Linear Regression $\sigma'_p$
  Note: Crust $\sigma'_p$ thought to be due to desiccation
- Fig. SH-2 El. vs. $u$, $\sigma'_{vo}$ & $\sigma_v$

### C. $K_o$ Data from Lab Testing

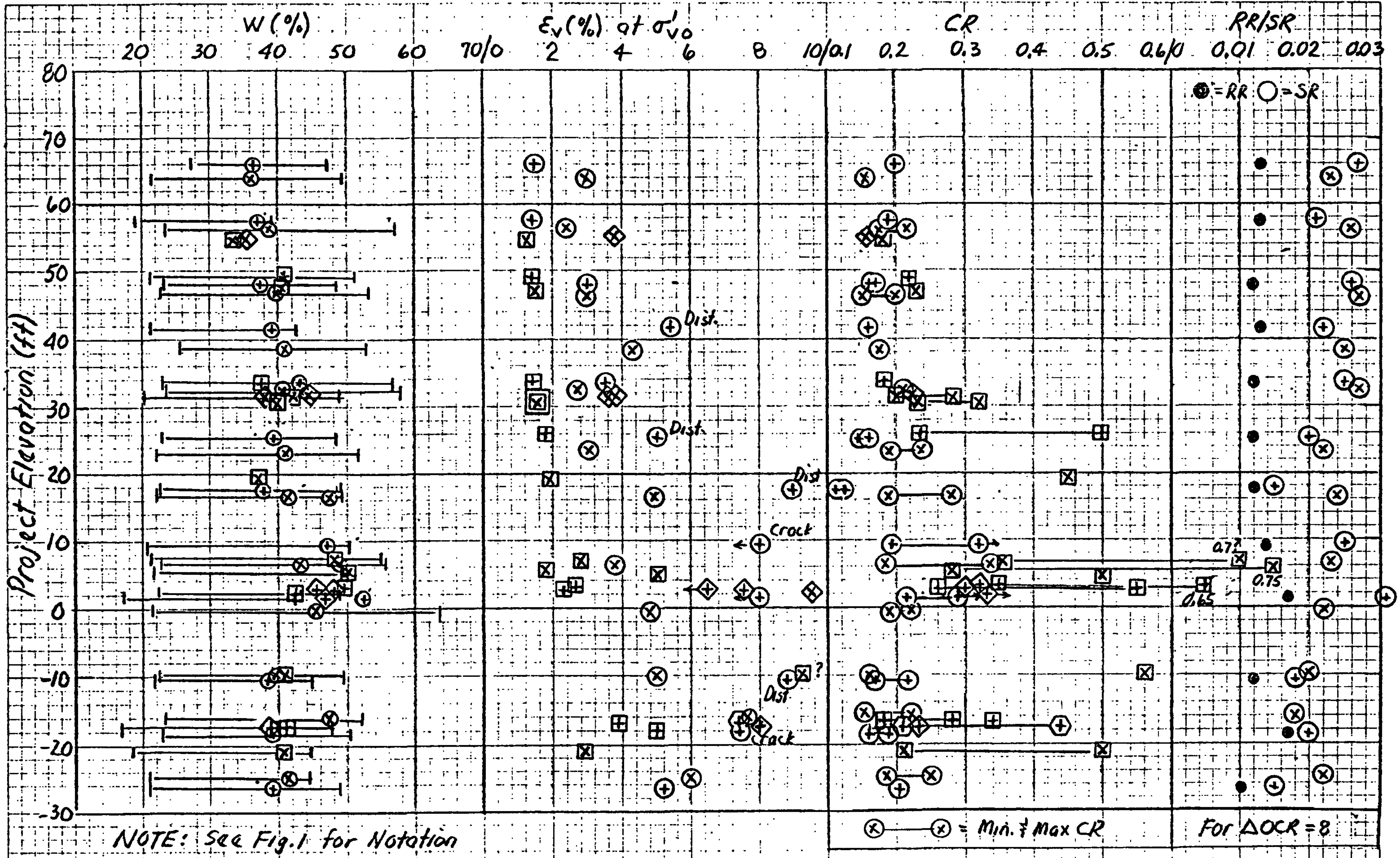
- Fig. $K_o$-1 El. vs $K_o$(NC) from $CK_o$-TX
- " $K_o$-2 $K_o$ vs $(1-\sin\phi')$
- $K_o = K_{oNC}(OCR)^n$ LSO & $CK_o$-TX suggest $n = 1.11 - 1.30^5 K_oNC$

### D. $K_o$ Data from Field Testing

- Fig STP-1 Sketch of SBPT using jetting to install
- " -2 El. vs $u_o$, $\sigma'_{vo}$, $\sigma_{vo}$, est $\sigma_{ho}$ & $\sigma_{ho}$ data from SBPT
- " -3 El vs $K_o$ from EPC, SBPT & DMT

CCL 2/25/93

CCL CA/T 7/12/90 7/22/90 8/7/90 9/19/90



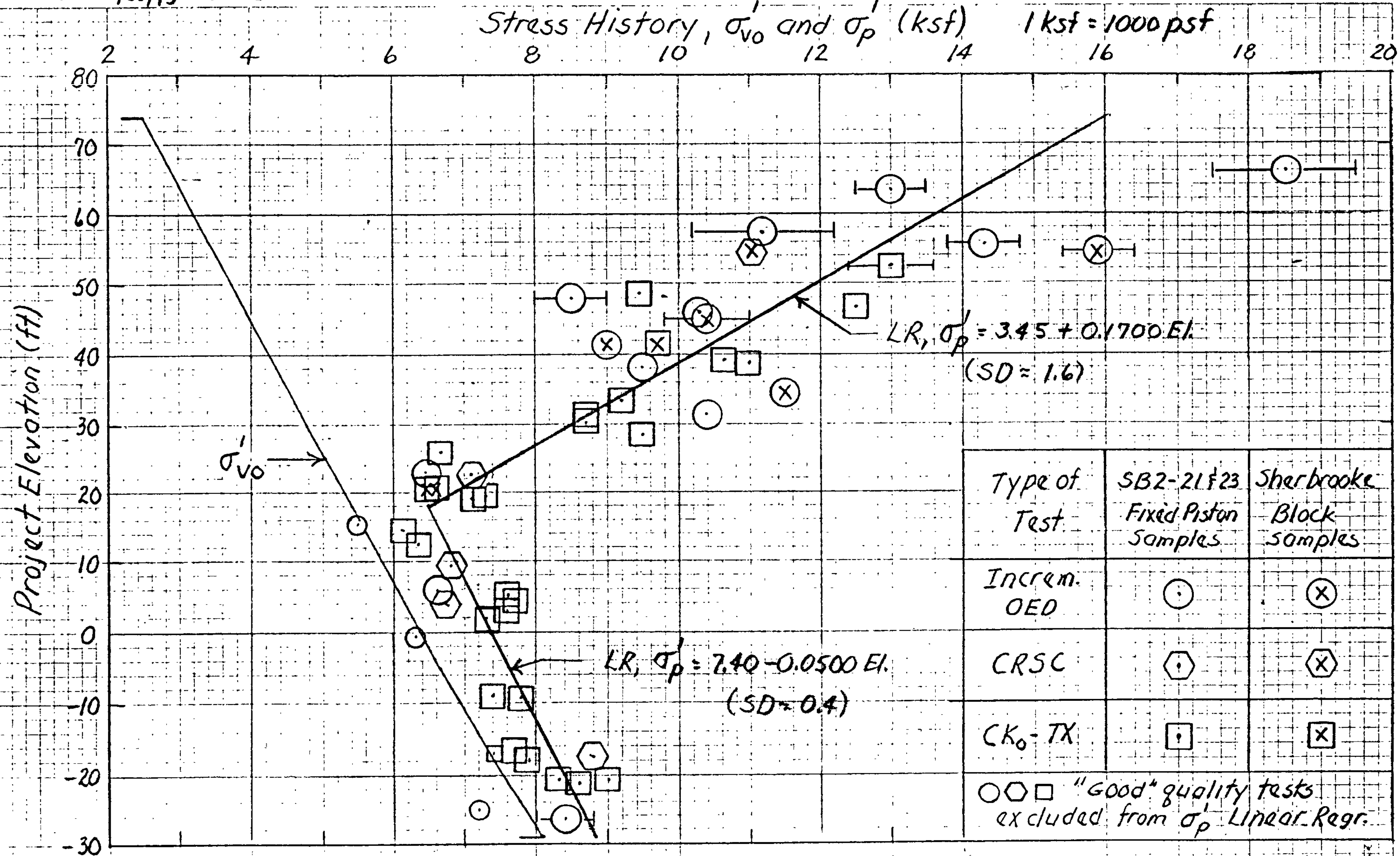
NOTE: See Fig.1 for Notation

Fig. 2 CA/T South Boston STP: Index Properties and Compressibility from Lab. Consolidation Testing

SB5

CCL 2/25/93 1.322

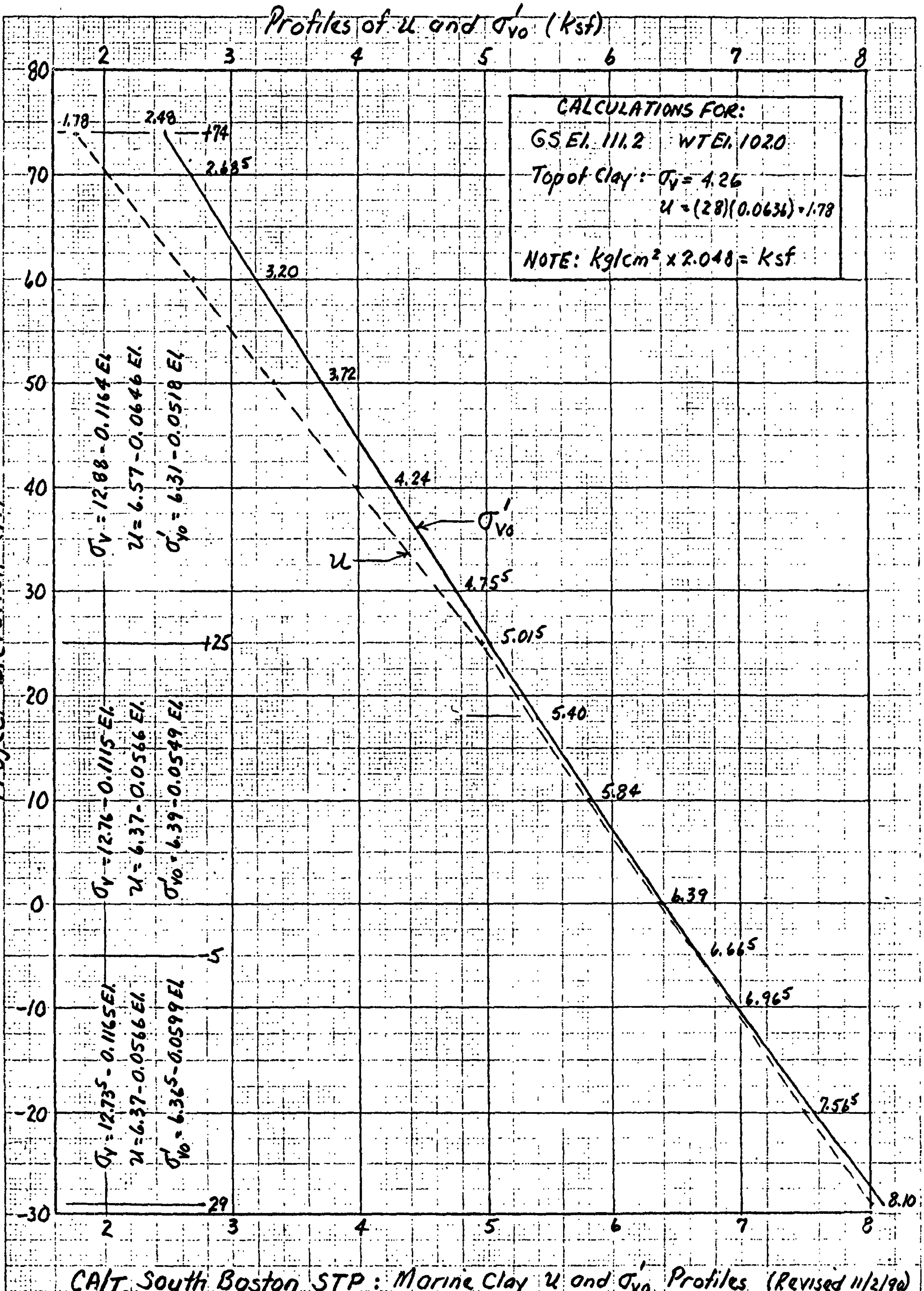
CCL CAIT 12/30/90
3/28/91



NOTES: GS El. = 111.2 ; WT El. = 102.0 with $\gamma_w$ = 63.6 pcf ; u in Marine Clay from piezometers at El. 50, 25, -1 and -32

Fig. SH-1. CA/T South Boston STP: Stress History from Laboratory Consolidation Tests

CMI CCL 11/10/90



CA/T South Boston STP: Marine Clay $u$ and $\sigma'_{vo}$ Profiles (Revised 11/2/90)

Fig. SH-2

CCL 2/25/93 1.322

CCL 2/25/93 1.322

CCL 9/16/90 9/24/90 10/10/90
10/20/90

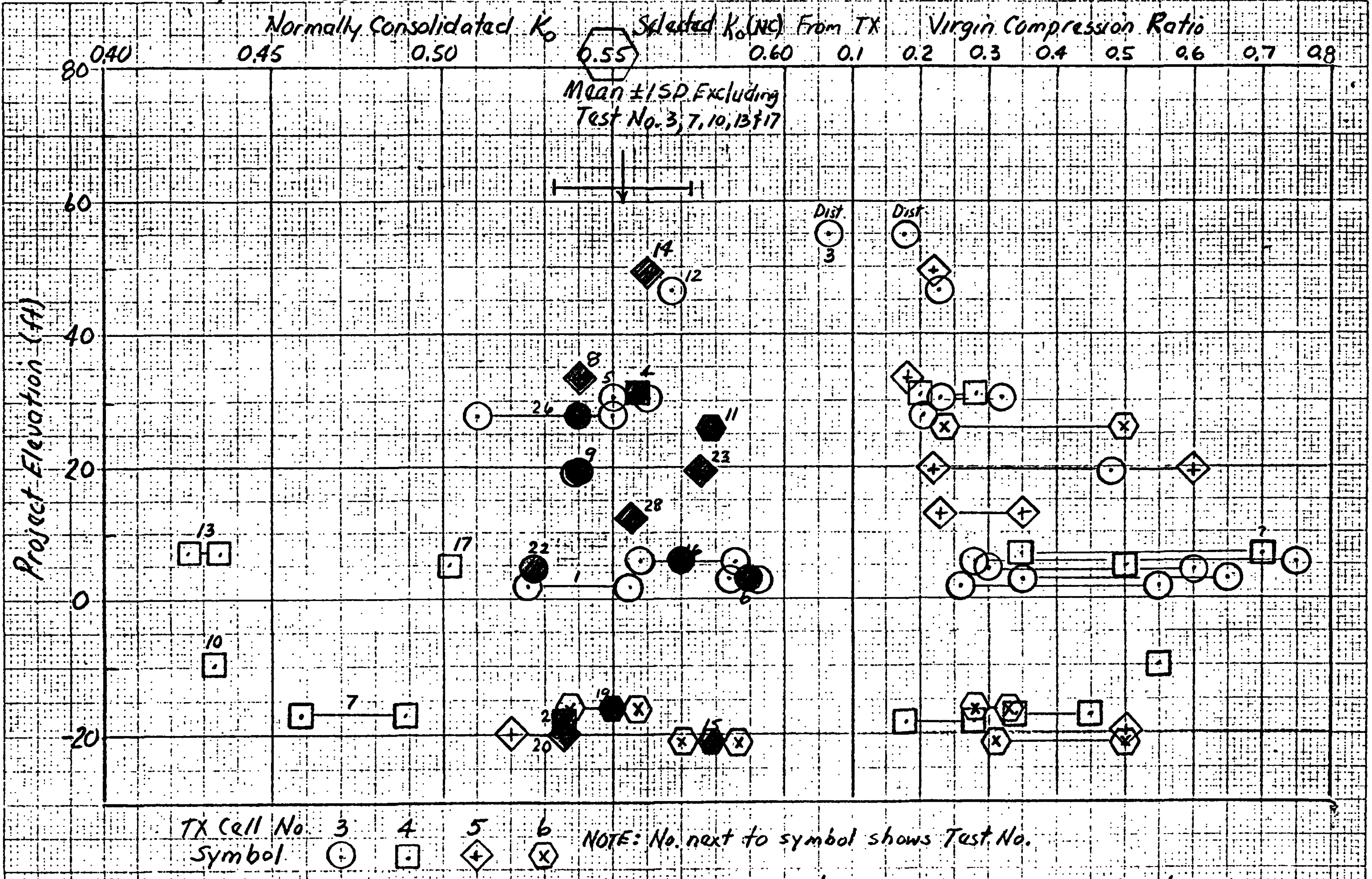
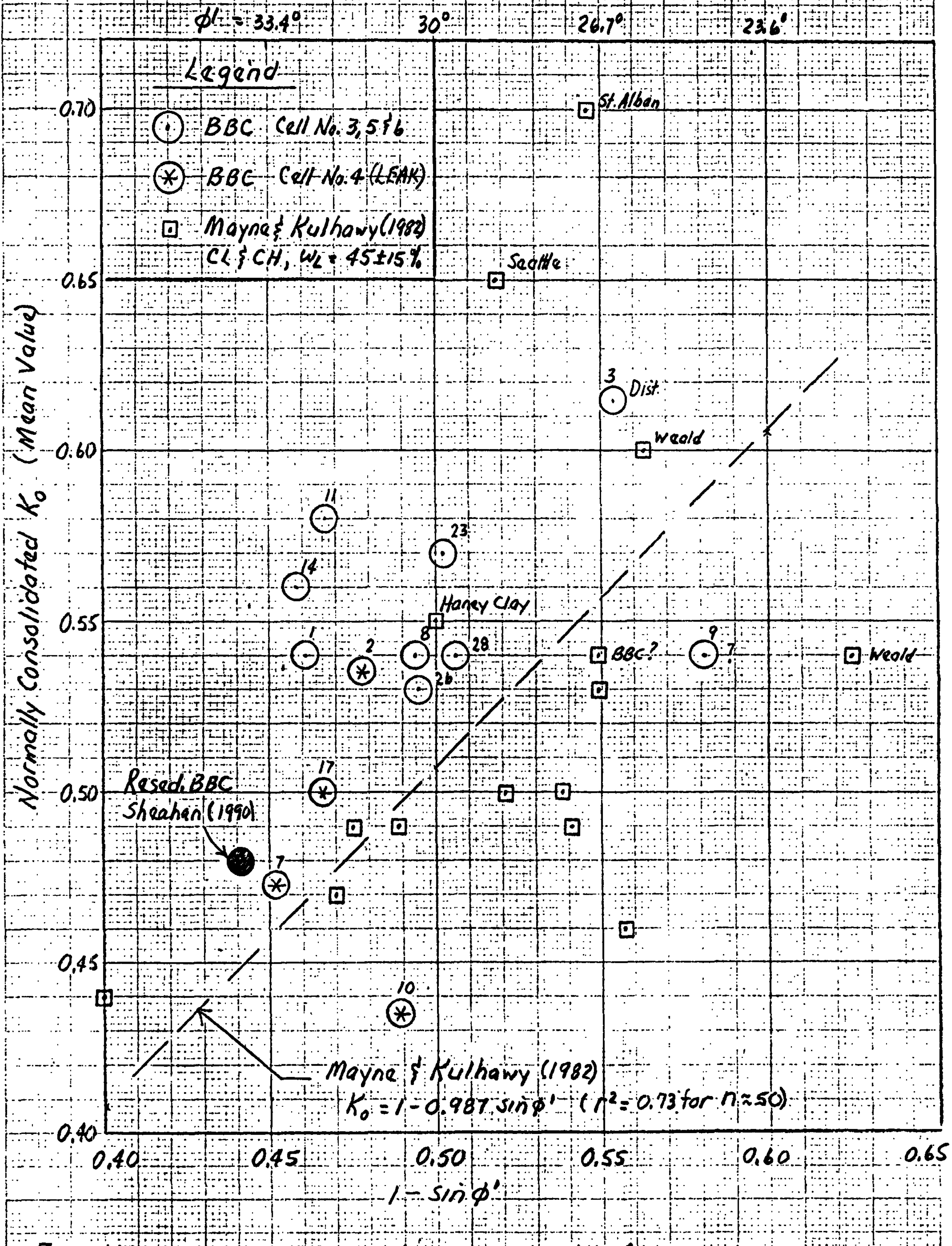


Fig. $K_o$-1 CA/T SB STP : Triaxial $K_o$ and CR vs. Elevation for Normally Consolidated Clay

CA/T CCL 9/24/90
10/20/90



CCL 2/25/93 1.322

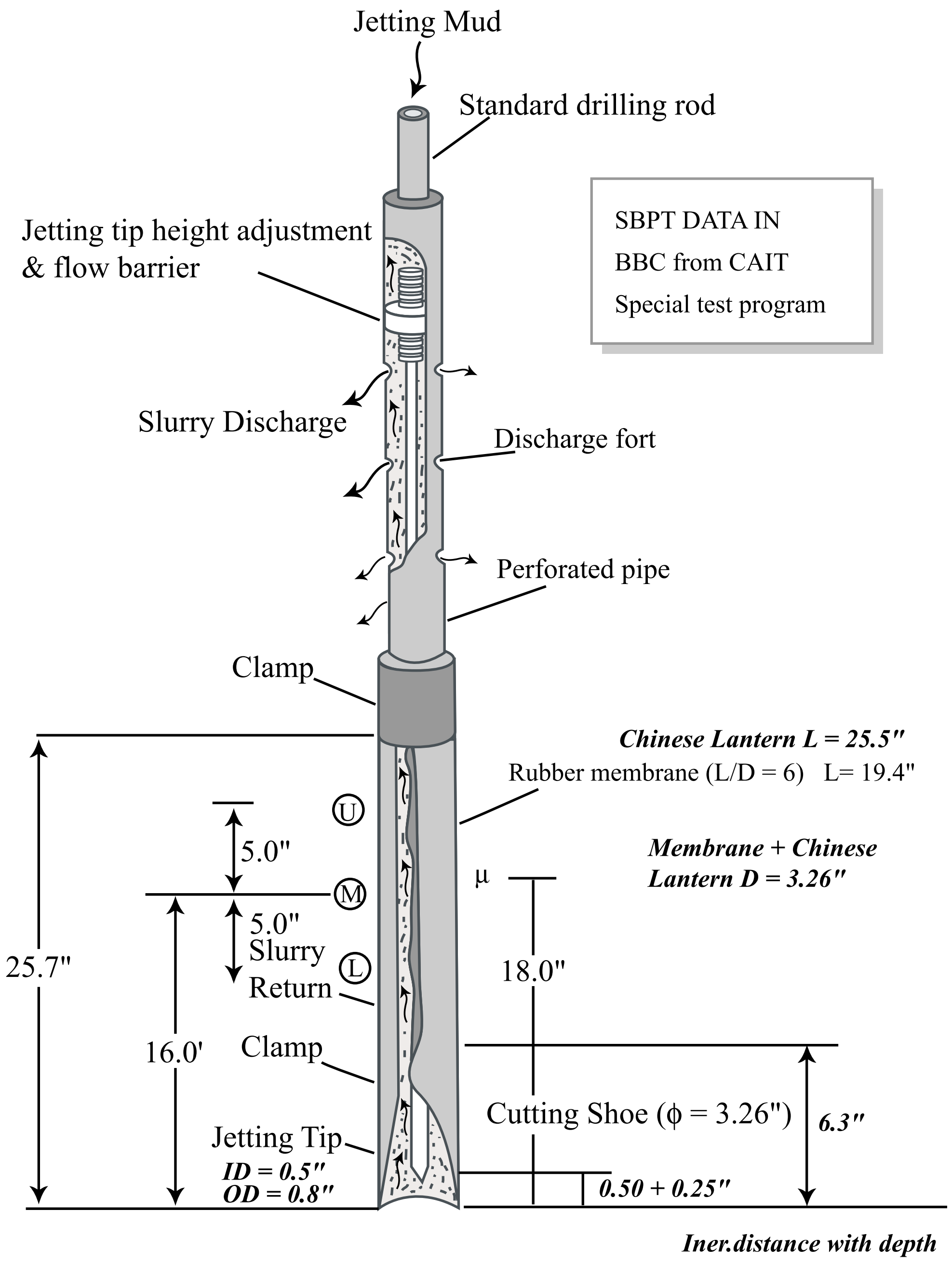
Fig. $K_o$-2 CA/T SB STP: $K_o$ vs. $(1-\sin\phi')$ for OCR=1

1.322 Consolidation Part I

Supplement for Section 4

2/23/93
CCL 3/2/92 1.322

CCL 8/9/91



***Sketch of the Jetting pressure meter (Adapted from Hughes, Jefferies and Morris, 1984)***

Figure by MIT OCW.

**(Adapted from Hughes, Jefferies and Morris, 1984)**

( UNH Final Report to H&A, 6/91)

Fig STP-1

CCL
8/9/91

2/28/93 1.322 CA/T STP Boston Blue Clay

# CENTRAL ARTERY (I-93)/THIRD HARBOR TUNNEL (I-90)
# SELF-BORING PRESSUREMETER TESTING
# TOTAL HORIZONTAL STRESS

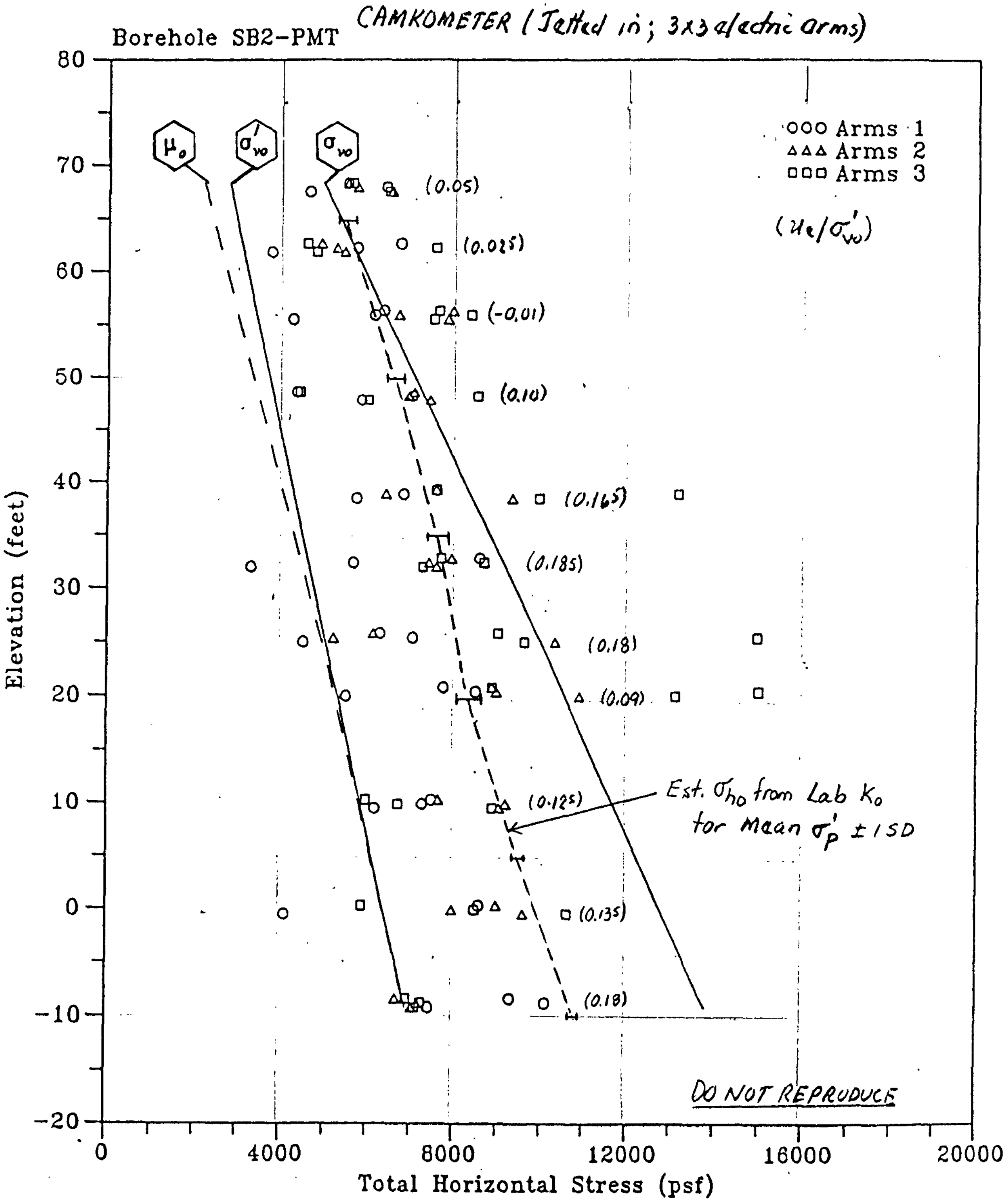


Figure 6: "Corrected" Total Horizontal Stresses from Self-Boring Pressuremeter Tests
(From UNH Final Report to HSA, 6/91)

Fig STP-2

CCL 8/91 3/2/92 1.322 CA/T STP Boston Blue Clay
2/28/93

# CENTRAL ARTERY (I-93)/THIRD HARBOR TUNNEL (I-90)
# SELF-BORING PRESSUREMETER TESTING
# COEFFICIENT OF EARTH PRESSURE AT-REST

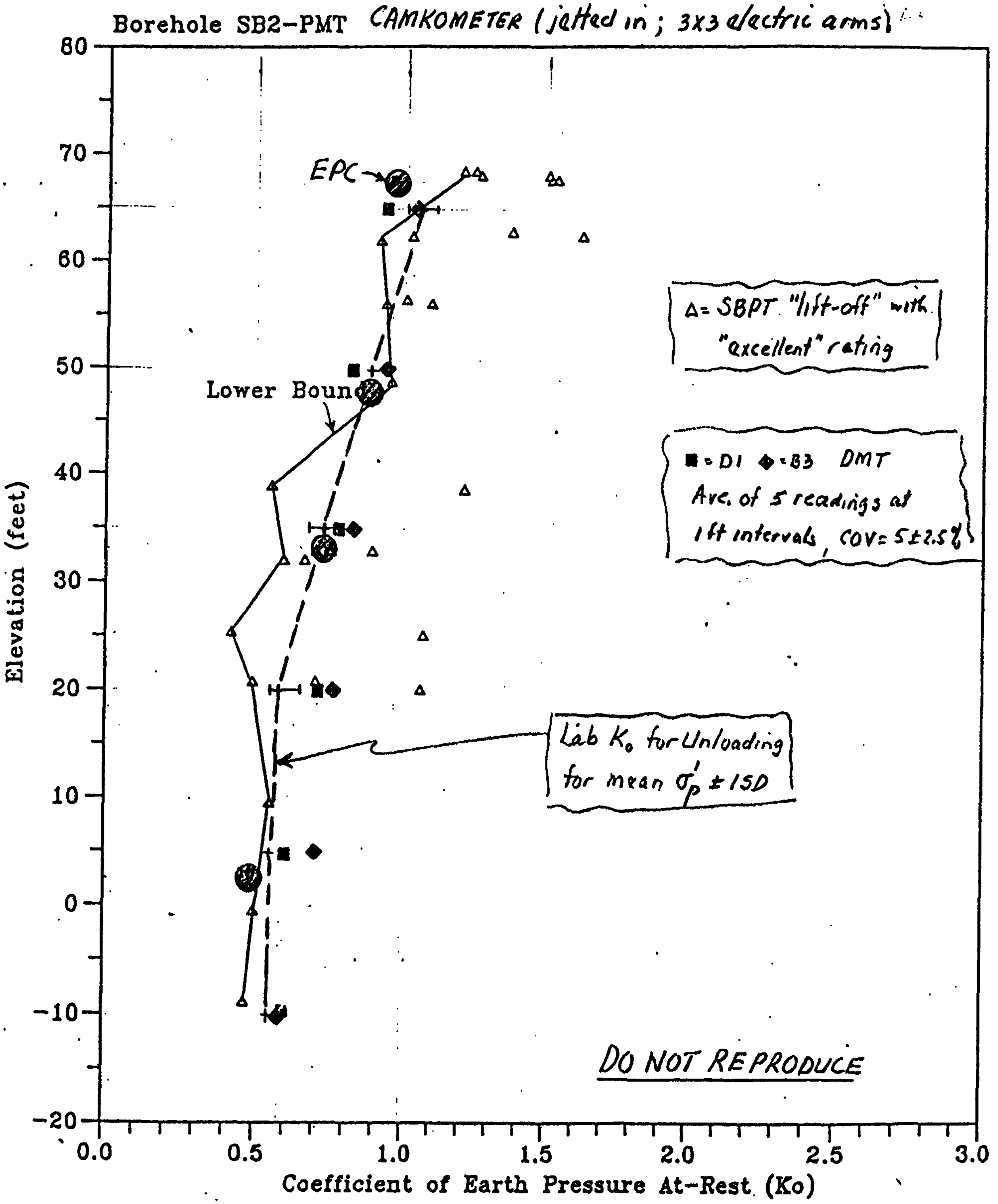


Figure 7: Coefficients of Earth Pressure At-Rest

EPC
SBPT
DMT

Fig STP-3

CCL 2/20/99
21

# 1.322 Class Schedule, Reading Assignments, Etc. on CONSOLIDATION (Part C)

| Topics : From Handout Notes | Approx. No. Classes | Reading (Backup) | | | Remarks |
|---|---|---|---|---|---|
| | | Tokyo ('77) | SF ('85) | Other | |
| I Introduction<br>• Background<br>• $K_o$ : trends & measurement<br>• In situ testing | 2 | 4.2.7<br>(2.2.4<br>4.2.6) | (1.5)<br>&<br>(3.2) | – | Covers several in situ devices for estimating $K_o$ (Some also for OCR & strength) |
| II Amount of 1-D Consolidation ($\rho_{cf}$)<br>• Consolid. tests & $\rho_{cf}$ eqn.<br>• $\sigma'_p$ mechanisms & measurement<br>• Effects of disturbance, creep, etc<br>• In situ tests for SH profiling | 4 - 4½ | – | 2.2 | – | "Mini" problem : develop field & lab testing programs to determine best in situ test for stress history profiling |
| III Rate of Consolidation ($\rho_c$)<br>• Terzaghi theory & meas. of $c_v$<br>• Effects of SH, disturbance, etc<br>• Permeability • Non-linear consolidation | 2 | – | (3.4) | – | – |
| IV Secondary Compression ($\rho_s$)<br>• $C_\alpha/C_c$ concept<br>• Hypothesis A vs B<br>• Surcharging | 1½ | (2.2.6) | 2.5 | – | Major Home Problem covering Parts I - IV |
| V 2 & 3-D Loading & Vertical Drains<br>• Initial settlement ($\rho_i$) and $\rho_{cf}$<br>• Rate of settlement<br>• Consolidation with vertical drains | 2 - 2½ | (2.2.5) | (3.3) | Foott &<br>Ladd (1981)<br>1.361<br>HP No. 12 | Self-graded home problem |
| VI Problem Soils<br>• High $S_t$ • Peats<br>• Collapsing & expansive<br>• Residual • Varved clay | 1½ - 2 | – | – | – | Emphasis on peats and collapsing/expansive soils |
| | 13 - 14.5 | | | | |