4/97 3/99
3/98 4/01

A MEASUREMENT OF UNDRAINED STRENGTH FOR UU CASE

$\bar{\sigma} \equiv \sigma'$

} For historical perspective since B&B (60) recommendations still dominate much of current practice

---

Sheets: FV-1, 2, 3
CP-1, 2 & 3
PM-1 to 6

4/9/90

IIA UNDRAINED STRESS-STRAIN-STRENGTH BEHAVIOR OF SATURATED COHESIVE SOILS

IIA MEASUREMENT OF UNDRAINED STRENGTH FOR UU CASE

1. INTRODUCTION

1.1 Background

- Objective - Since assume $\Delta w = 0$ for UU Case, want s_u of in situ soil to calculate $FS = s_u/\tau_m$
- Historically have used Total Stress Analysis (TSA), which for $S = 100\%$ → "$\phi = 0$", $c = s_u$, wherein s_u obtained by variety of both in situ & lab testing techniques that inherently assume:

  Either s_u = unique $f(w_f = w_N)$

  or s_u = " f(in situ $\bar{\sigma}_{cji}$)

1.2 Coverage of "Conventional" Testing Techniques

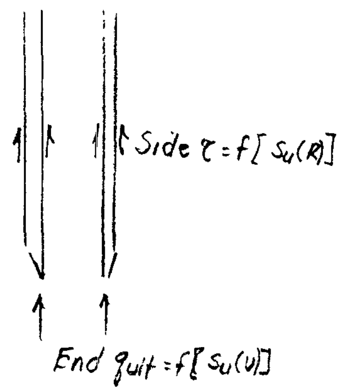
1) $s_u = f(w_f = w_N)$
   - In Situ: SPT FVT CPT SBPT DMT
   - Lab: "UU" type testing, e.g. UUC, LV, FC
2) $s_u = f(\bar{\sigma}_c)_{ij}$
   - Lab CU: CIUC $\bar{\sigma}_c \approx \bar{\sigma}_{v0}$, "CU" DS
   - New Techniques CK_0U: SHANSEP & Recompression (Cover under IIB: Sample Disturbance)

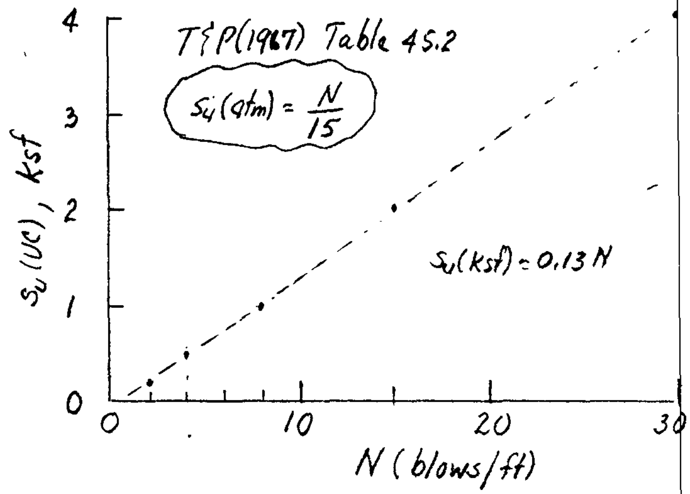
1.3 Discussion & Conclusions

1) Recommended practice à la Bishop & Bjerrum (1960)
2) Comparisons
3) Need for thorough evaluations of factors affecting in situ s_u
   - Sample Disturbance
   - Stress System = $b(\sigma_2)$ & δ(anisotropy)
   - Time = strain rate effects

2. IN SITU TESTING TECHNIQUES

2.1 SPT = Std. Penetration Test (ASTM D1586)





- Tokyo 4.2.2 JHS(1975) Insensitive clays, side $\tau \to 80\%$ of N

∴ Increasing $S_t \to$ reduced N for same $s_u(U)$

NG med-soft clays where often get "WOR" = wgt. of rod "WOH" - wgt of hammer

2.2 FVT = Field Vane Test (ASTM D2573)

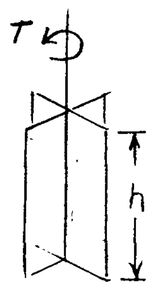
2.2.1 Test Procedures

Tokyo 77

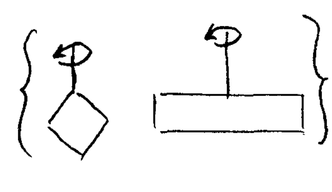
$$s_u = \frac{T}{\pi\left(\frac{d^2h}{2}+\frac{d^3}{6}\right)}$$

- Need gear system to obtain $\dot{\Theta} = 6°/min \to t_f$ few min. (Torque wrench → ∴ t_f = few seconds)
- Need correct/eliminate rod friction: Geonor (arm casing) vs Nilcon.
- Minimize blade t to reduce disturbance during insertion
- S_t after rotate 10 times
- Cal. s_u assuming equal τ everywhere (sides & ends)

2.2.2 Disadvantages



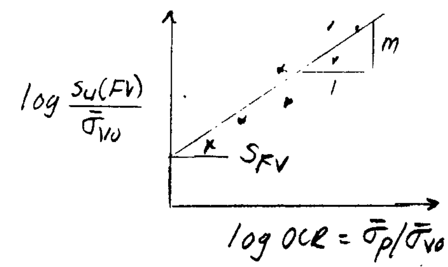
- No sample
- Limited to s_u < 0.5-1 TSF
- Not reliable if roots, shells, stones, etc. or if high $c_v \to$ partial drainage
- Very complex stress system with progressive failure
  - σ_{hc} probably very important
  - do NOT use to estimate s_u anisotropy



2.2.3 Advantages & Practical Application

1) Relatively simple and inexpensive (but much slower than CPT/DMT)
   Do get $S_t = s_u(U)/s_u(R)$

2) generally good-excellent for "s_u index" profiling if "homogeneous" clay → correlations with stress history



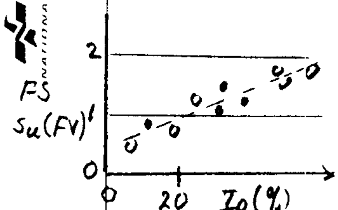
$$\frac{s_u(FV)}{\bar{\sigma}_{vo}} = S_{FV}(OCR)^m$$

(+FV-3)

Examples (FV-1) Fig. 8

{ Also Chandler (1988) w/ Consolidation II
$OCR = \left(\frac{s_u(FV)/\bar{\sigma}'_{vo}}{S_{FV}}\right)^{1.05}$ }

3) Correction Factor to obtain s_u for TSA à la Bjerrum (1972, 73)



- $s_u = \mu\, s_u(FV)$ (FV-1) Fig. 51 Case histories of failures
- COV ≈ 25% if no shells, fibers, sand, etc BUT NOT ALWAYS
  * Smith Bay Arctic Silt

2.2.4 Discussion

1) attempts to understand - separate components of μ vs I_p

   (FV-2) Fig. 9 & 10 Small t_f → too high s_u $+\mu_R$
   Mode shearing → too low s_u $-\mu_A$

2) Aas et al. (1986) "new" correction & effect of OCR
   - (FV-2) Fig. 9 - Not reliable James Bay

   } CCL doesn't like

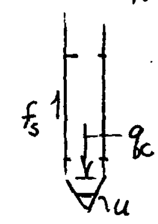
3) Incr. OCR - Why μ vs I_p maybe unsafe at higher OCR?

   - Values of m from $s_u(FV)/\bar{\sigma}'_{vo}$ vs OCR correlations
     SF('85) Table VI n = 9 → m ≈ 1.03 ± 0.26 >> m from lab CK_oUDSS

2.3 Cone Penetration Test (CPT) ASTM D 3441

Piezocone Penetration Test (PCPT = CPTU)

60° $A = 10 cm^2$
1-2 cm/s



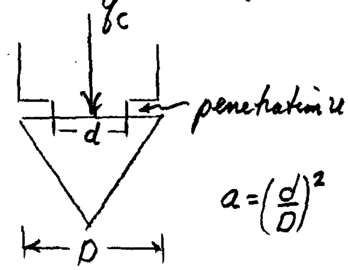
2.3.1 Testing Equipment / Correction

- Electrical essentially replaced mechanical
  More rapid + continuous data
- Some devices not reliable
  - f_s affects q_c and/or u — don't have saturated fine stone
- Pore pressure area correction

Fig. 27 SF 50A

$$q_t = q_c + u(1-a)$$

$(1-a)$: 0.15 - 0.6



$a = \left(\frac{d}{D}\right)^2$

(CP-1) Fig. 10 Example of large effect

2.3.2 Estimation s_u: Empirical Cone Factor N_k

1) Approach & Results

- $s_u = \dfrac{q_c - \sigma_{vo}}{N_k}$ Empirical correlations $N_k = \dfrac{q_c - \sigma_{vo}}{s_u \text{ Reference}}$
- ASCE "IN SITU" 75 $N_k = 5 \rightarrow 70$ Problems of Reference s_u eg UUC, FVT
- Aas et al (1986)
  (CP-1) Fig. 11 $N_k = \dfrac{q_c - \sigma_{vo}}{\mu\, s_u(FV)}$ ← Not corrected
  Medium-soft clays → $N_k = 15 \pm 5$

2) Discussion

- Need correlations → $s_u = \dfrac{q_t - \sigma_{vo}}{N_{kt}}$ • Corrected q_t • Ref. s_u CK₀U τ_{ave}
- Problems Arctic silts: high OCR & low temp. ($\approx 0°C$)
  (CP-2) Fig 6-3
  - Conv. s_u → $N_k = 15 \pm 5$
  - SHANSEP s_u(DSS) → N_k up 50 ± 10!
    & effects?

3) Conclusions CPTU (CPT not recommended as want q_t)
- Less reliable than FVT based on current data base
- But more efficient than FVT + excellent for soil type
- ∴ Should consider for major jobs → local correlations

NOTE: See ISOPT-1 (1988) - 2 Vol. Proceedings

See (CP-3) $\log (q_t - \sigma_{vo})/\sigma'_{vo}$ vs $\log$ OCR data for BBC
(i.e., problems with absolute value of q_t)

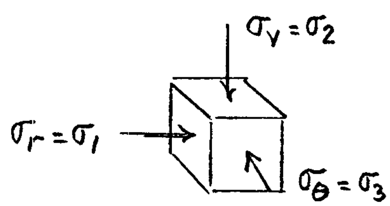
2.4 Self-Boring Pressuremeter Test (SBPT)

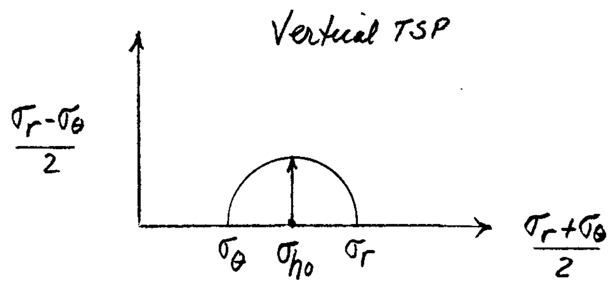
2.4.1 References

- Ladd et al. (1977) Tokyo SOA 4.2.6
- Jamiolkowski et al. (1985) SF SOA 3.2.4, 3.3.2
- Baguelin et al. (1978) The Pressuremeter & Fdn. Engr, Trans Tech Publ, Germany

2.4.2 Theoretical Interpretation: Undrained Cavity Expansion (CE)

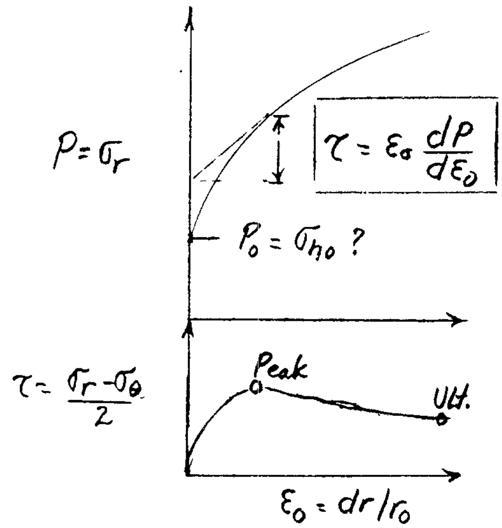
1) State of stress (CE) (Plane Strain)

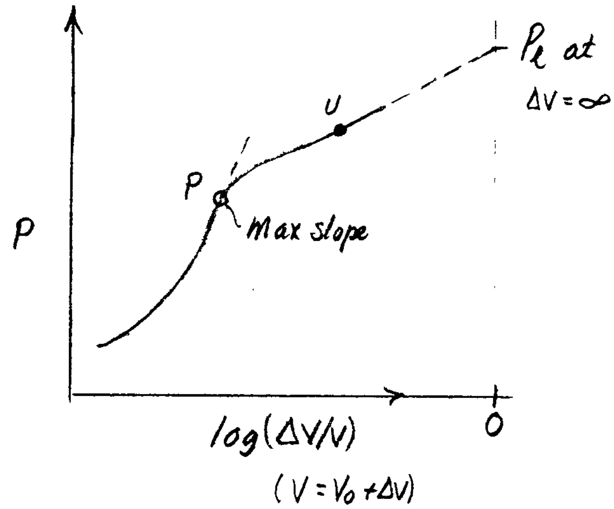




2) Derived stress vs strain : assumptions
- No disturbance $P_o = \sigma_{ho}$
- No end effects , $L/D \to \infty$
- Unique τ vs γ independent of varying $\dot{\varepsilon}$
- No drainage

3) Interpretation





$$\tau = 0.434 \frac{dP}{d\log(\Delta V/V)}$$

- Elasto-Plastic $s_u = \frac{P_\ell - P_0}{N_p}$ $N_p = [1 + \ln(G/s_u)]$

E_u/s_u	N_p
1000	9.0
100	5.6

2.4.3 Values of Derived s_u (e.g. Tokyo ('77) Table IV p473 9/11 soils → $s_u(P) = 1.2 - 2.5\, s_u(FV)$)

1) Peak s_u usually significantly > $s_u(C)$ - i.e. for $\delta = 0$
Ult. s_u " " > $s_u(Ave)$ for stability analyses

2) Possible explanations
- End effects : PAFSOR L/D = 2-4 Yes; CAMKOMETER L/D = 8 ok
- Disturbance :- yes if $P_0 < \sigma_{h0}$ Poorly understood
- $\tau = f(\dot{\varepsilon})$ yes
- Partial drainage - ?
- Anisotropy . Usually expect $s_u(E) < s_u(CE) < s_u(C)$ ($s_u(CE) \approx s_u(DSS)$)

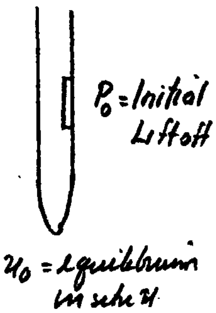
2.4.4 Conclusions
- SBPT not reliable for s_u or $\tau \sim \varepsilon_0$
- More → Menard or pushin - Totally empirical
(ASTM D 4719 (but no eqn for s_u)

Discussion of (PM-1) - (PM-6)

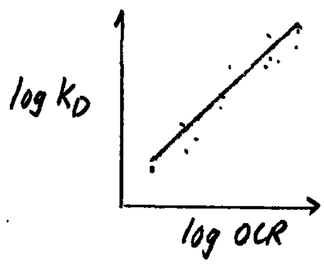
2.5 Marchetti Dilatometer Test (DMT)

(See Consolidation Notes on K_o & OCR for references & backup)

2.5.1 Procedure



- Measure P_o immediately after insertion
- Horizontal Stress Index $K_D = \dfrac{P_o - u_o}{\bar{\sigma}_{vo}}$
- Empirical correlation: Marchetti (1980) Fig 11(b)



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

Mechanically OC Cohesive soils

$$I_D = \frac{\Delta P}{P_o - u_o} < 0.6$$

- Uses SHANSEP eqn to compute s_u

$$s_u / \bar{\sigma}_{vo} = S (OCR)^m$$

Marchetti + most computerized DMT output use $S = 0.22$, $m = 0.8$

NOTE: if poor estimate of OCR, then obviously will have poor estimate of s_u

2.5.2 Discussion

- Limited empirical data base + don't understand "fundamentals"
- Less reliable than FVT
- Less reliable than CPTU
- Worth considering if don't have FVT or CPTU

2.6 MIT AFOSR Project

- Using Baligh Strain Path Method + Whittle MIT-E3 model to evaluate
  FVT CPTU SBPT + Pushin DMT Iowa Stepped Blade

3. LAB TESTING TECHNIQUES

3.1 Unconsolidated-Undrained Triaxial Compression (UUC)

1) Procedures ASTM D2850 UUC
D 2166 UC

UUC $\dot{\varepsilon}$ = 1%/min "plastic" materials
= 0.3%/min "brittle" " } → "t_f ≈ 15-20 min"

UC $\dot{\varepsilon}$ = 0.5 - 2%/min "$t_f \le$ 15 min" 1%/min. typical

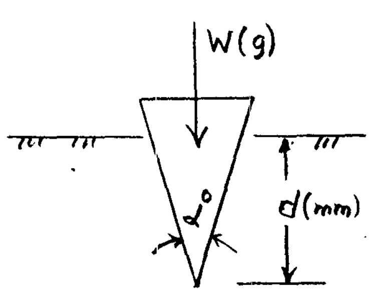
2) Comments
- Use $\sigma_c > 0$ if fissures, cohesionless zones (including shells) and/or if S<100%. $\sigma_c \approx \sigma_{v0}$ typical
- Advantages - see sample & get σ-ε curve
- Problems - reliability depends on compensating errors (covered 1.361 + later)

3.2 Other "UU" s_u Index Testing

- Lab vane h/d ≈ 2 d ≈ 4cm
- Torvane
- Fall cone
- Pocket penetrometer

Always use as part of test program on Undisturbed Samples

Fall Cone: Zreik, Ladd & Germaine [1995, GTJ, 18(4)] → new device to measure s_u → 0.1 kPa, (plus review of theory) using counterweight → W ≈ 1g



Typically α = 30° or 60°, W ≈ 10 or 100g, d = 10-20 mm

$$s_u(kPa) = 9.81\,K\left(\frac{W}{d^2}\right)$$

K from empirical correlations with lab vane

α° =	30°	45°	60°
K =	0.83	0.49	0.29

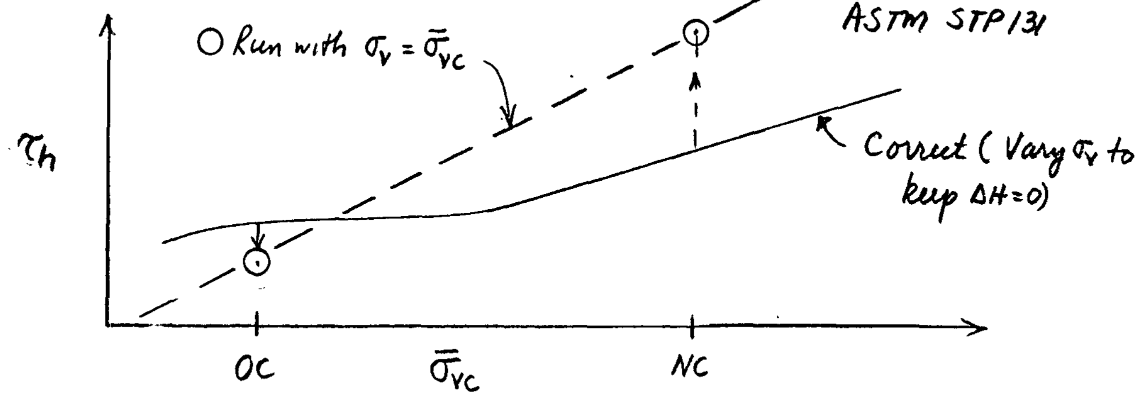
3.3 Consolidated-Undrained (CU)

3.3.1 CIUC

- Some use as "std" test w/ $\bar{\sigma}_c \leq \bar{\sigma}_{v0}$ (e.g., MRCE use $\sigma_c' = 0.8\,\sigma_{v0}'$)
- Usually → unsafe s_u, esp. at low OCR (1.361 + later)

3.3.2 "Rapid" Direct Shear

- Assume rapid shearing → CU test, but NOT VALID
  Taylor (1952)
  ASTM STP131



- Stories

3.3.3 Other CU (Later)

- DM-7 & USACE QRS (CCL'91, Section 6.2)
- CK_0U Recompression & SHANSEP

4 DISCUSSION

4.1 Bishop & Bjerrum (1960) Boulder ASCE "Strength" Conf.

1) Detailed evaluation of case histories of failures falling under UU Case ("no significant dissipation of excess u" + S = 100% so "$\phi = 0$"), but excluding natural slopes

2) s_u from either lab UUC or FVT

3) Results

No.	Type	FS (Mean ± SD)	Ip(%) / IL
22	Footings, loadtests & emb.	1.01 ± 0.06	47 ± 27% }n=14 0.75 ± 0.46
4	EOC excavation failures (intact clays)	1.02 ± 0.09	42 ± 19% 0.79 ± 0.34
7	Base failures of strutted excavations	0.96 ± 0.13	– –

4) Conclusions - How estimate s_u for "$\phi = 0$" analyses UU Case

- Obtain s_u from UUC (or UC) and FVT (uncorrected) ←
- CIUC $\bar{\sigma}_c = \bar{\sigma}_{v0}$ is unsafe, especially low OCR & Ip
- (Established std. practice worldwide for next ≥ 10-15 yr)

4.2 CCL Early Experience

- Circa 1957 as MIT graduate student à la Bjerrum $s_u(UUC) = 1.11\, s_u(FV)$ (q_f, τ_f)
- 1960-62 on HWL consulting job Kawasaki, Japan (Tanba, Tokyo Bay)

NC CL & CH, z = 20-35 m

$s_u(UUC)/\bar{\sigma}_{v0} \approx 0.28 \pm 0.03 \rightarrow F \approx 1.2$ Unsafe

$s_u(FV)/\bar{\sigma}_{v0} \approx 0.41 \pm 0.05 \rightarrow F > 1.5$ Safe

- Why difference?
  - Disturbance
  - Anisotropy
  - Strain rate

Deep BBC at I-95

Test	$s_u/\bar{\sigma}_{v0}$ (mean)
UC, UUC	0.13
FV	0.18
CK_0UC	0.33 (NC)

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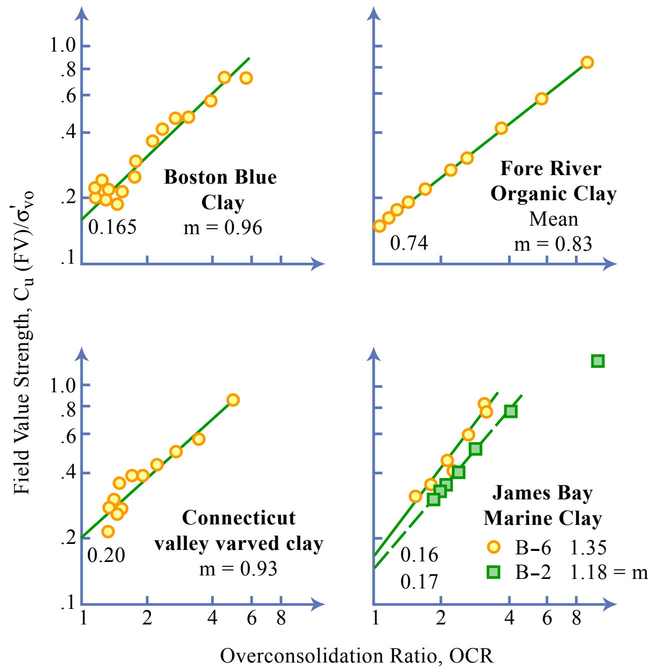
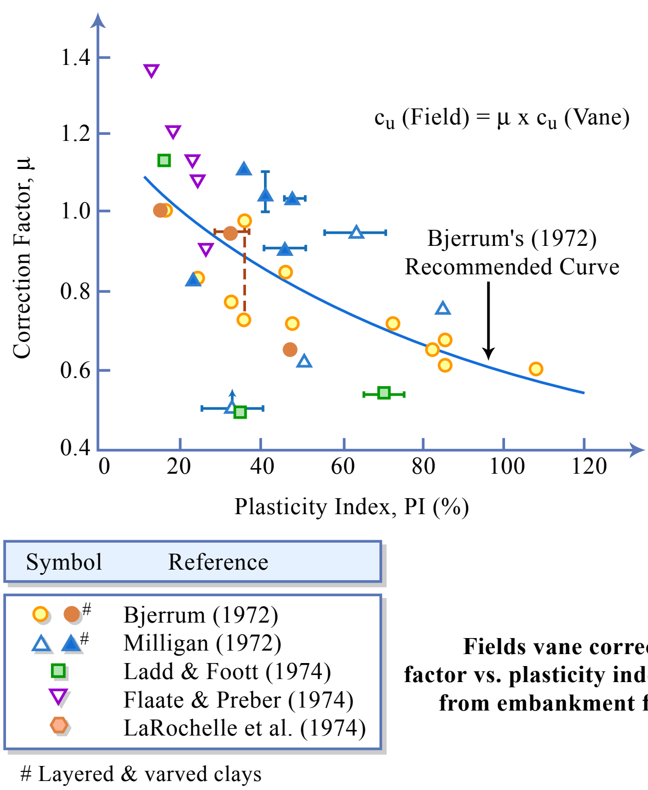
FV-1



Undrained strength ratio vs. OCR from Field Vane Tests
a) Boston Blue Clay, I-95 Saugus; MA
b) Connecticut Valley Varved Clay, Amherst, MA;
c) Organic Clay with Shells, Fore River, ME;
d) Jmaes Bay B-2 and B-6 marine Clays.

Figure by MIT OCW.

$$\frac{S_u(FV)}{\bar{\sigma}_{vo}} = S_{FV}(OCR)^m$$



Fields vane correction factor vs. plasticity index derived from embankment failures.

Figure by MIT OCW.

Adapted from:

Ladd et al. (1977) Tokyo SOA

Bjerrum (1972) $s_u = \mu\, s_u(FV)$

PTH (1974) $\mu \approx 1.0 - 0.5\log(I_p/20)$

1/97
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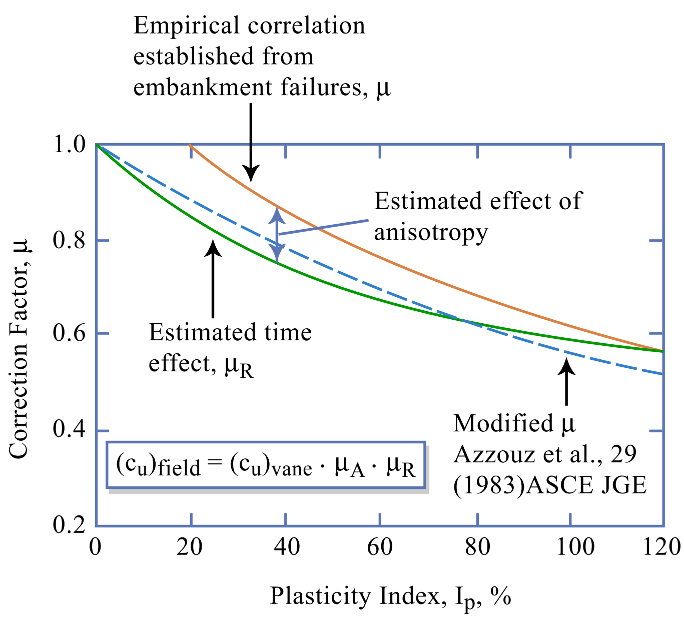
FV-2

CHANDLER ON UNDRAINED SHEAR STRENGTH OF CLAYS (1988)



Factors Relating Field Vane and Field Failure Strengths

Figure by MIT OCW.

Adapted from:

Chandler (1988)

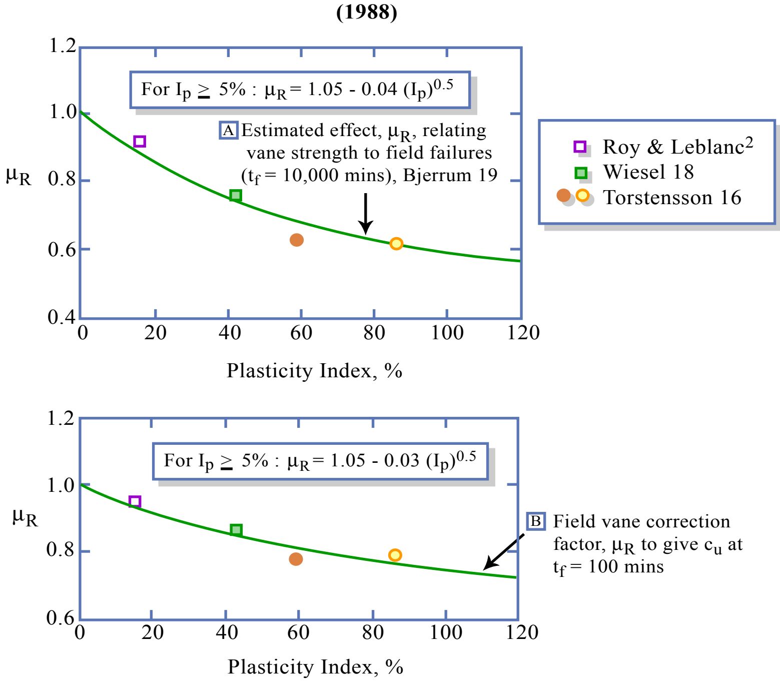
Attempts to understand FV μ factor

- μ_R = reduce $s_u(FV)$ due to rate effects
- μ_A = increase $s_u(FV)$ " " anisotropy

$\mu = \mu_A \cdot \mu_R$

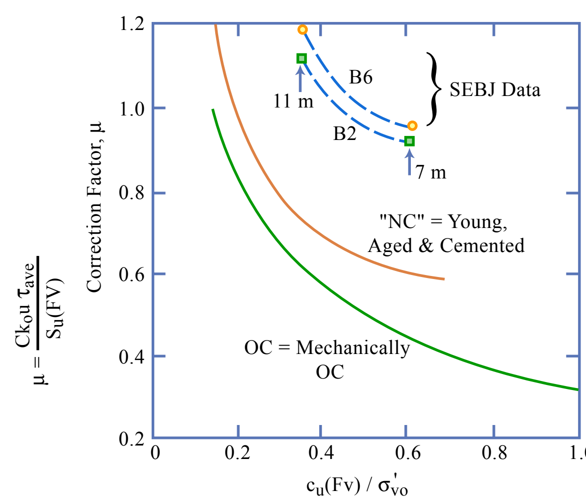
Adapted from: Bjerrum (1973)

CHANDLER ON UNDRAINED SHEAR STRENGTH OF CLAYS (1988)



Factor μ_R to Correct Field Value Strength for Strain-Rate Effects

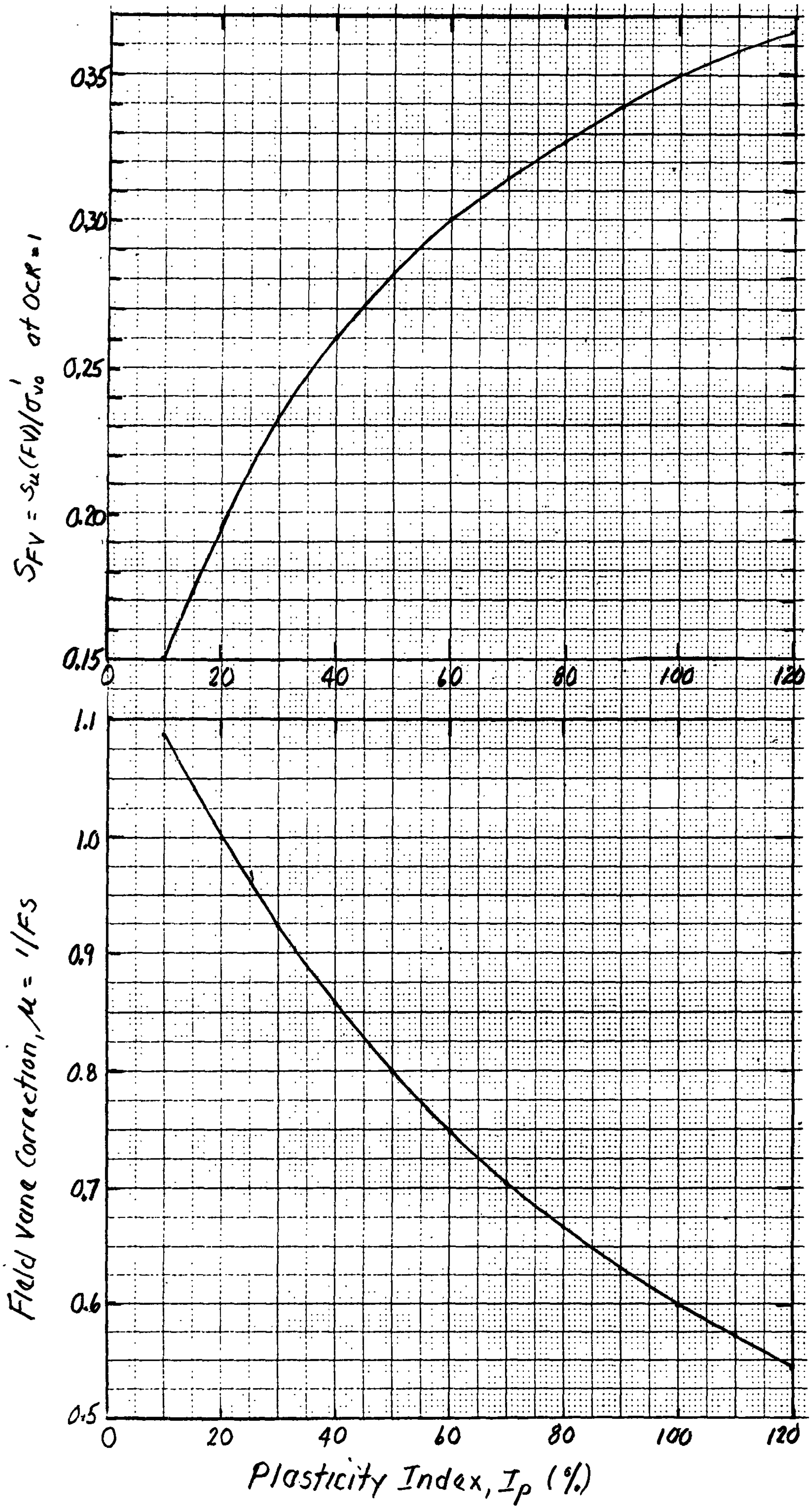
PROBLEMS WITH NEW NGI FV CORRECTION



Field Vane Correction Factor

Figures by MIT OCW.

$\mu = \frac{CK_0U \ \tau_{ave}}{S_u(FV)}$



Chandler (1988)
ASTM STP 1014

$$\frac{s_u(FV)}{\sigma'_{vo}} = S_{FV}(OCR)^m$$

↓

$$OCR = \left(\frac{s_u(FV)/\sigma'_{vo}}{S_{FV}}\right)^{1.05}$$

NOTE: $S_{FV} \approx$ Bjerrum (1972) for OCR = 1 "young" clays

Bjerrum (1972)
Field Vane
Correction Factor
from Case Histories
of Embankment
Failures

NOTE: Drawn by CCL from lmeer FS vs I_p

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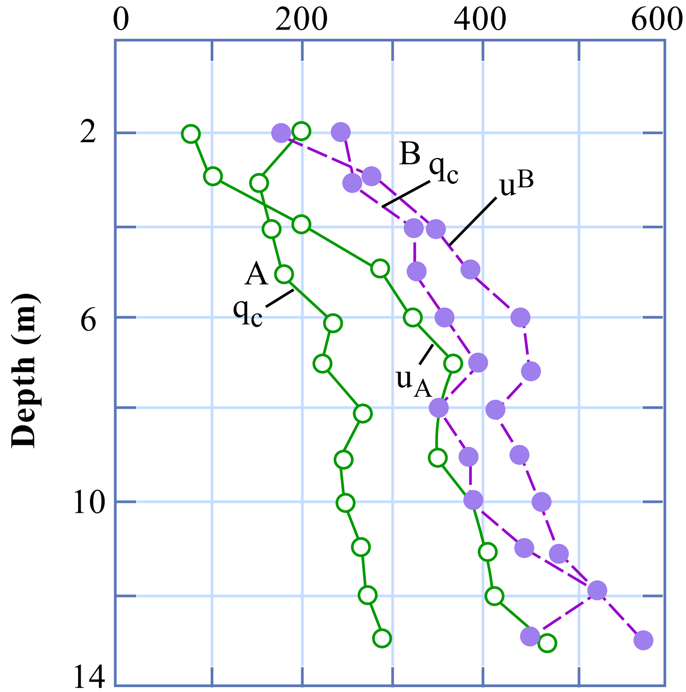
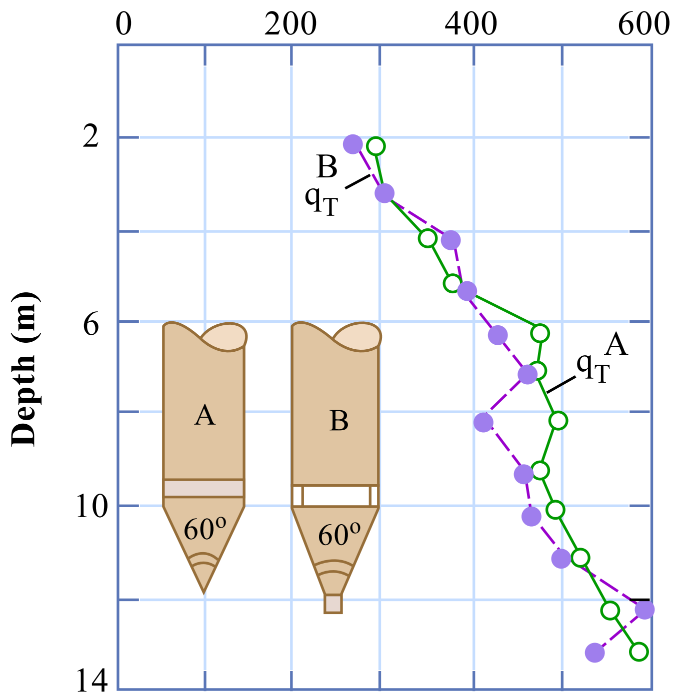
Aas et al. (1986) ASCE INSITU '86

CP-1

Measured Cone Resistance, (q_c) and Pore Pressure (u) (kPa)



Corrected Cone Resistance, q_T (kPa)



Piezocone A
Piezocone B

Effect of Pore Pressure on Cone Resistance in Emmerstad Quick Clay

Figures by MIT OCW.

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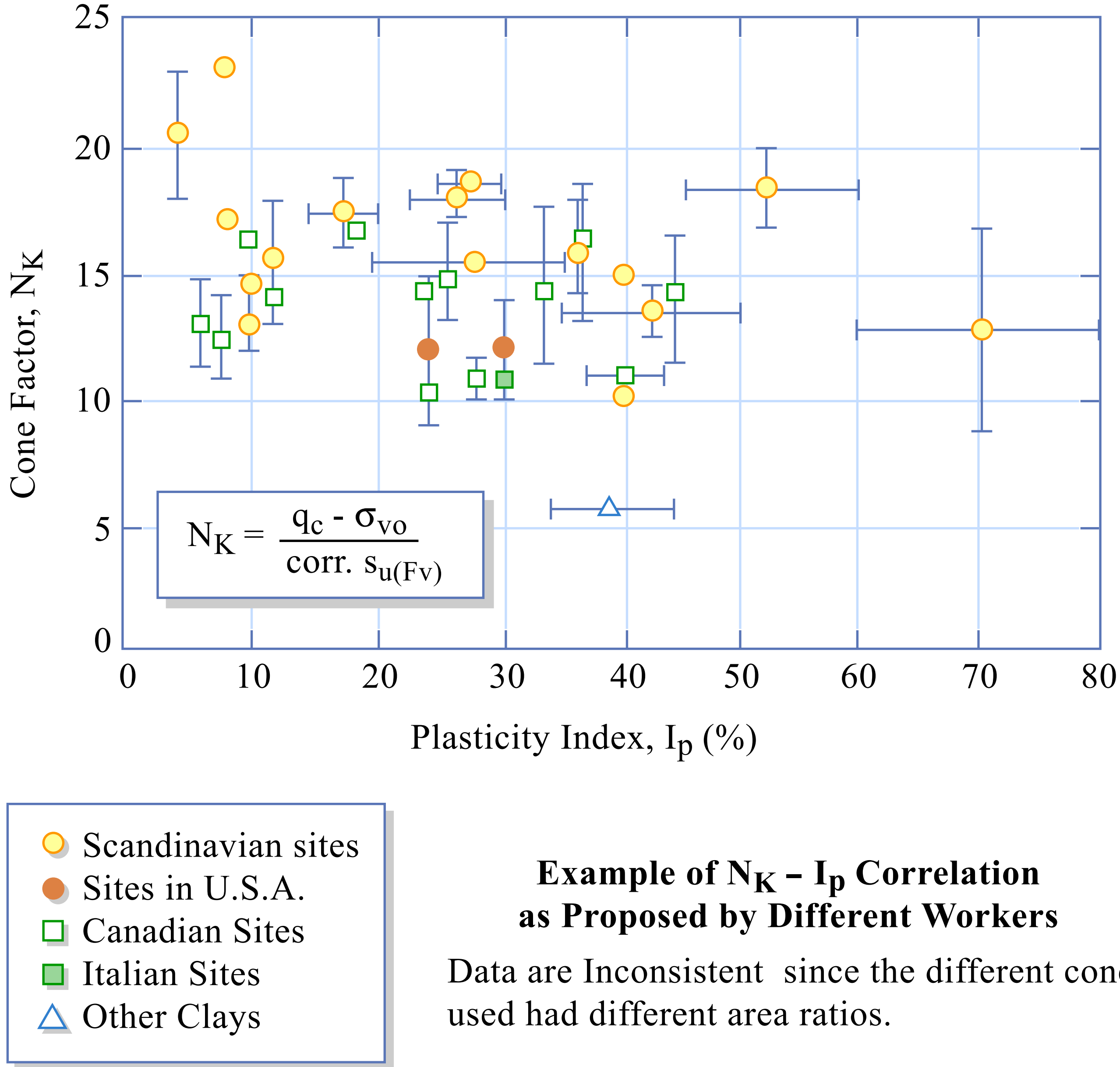
Aas et al. (1986) ASCE INSITU '86

CP-1



Example of N_K – I_p Correlation as Proposed by Different Workers

Data are Inconsistent since the different cones used had different area ratios.

Figure by MIT OCW.

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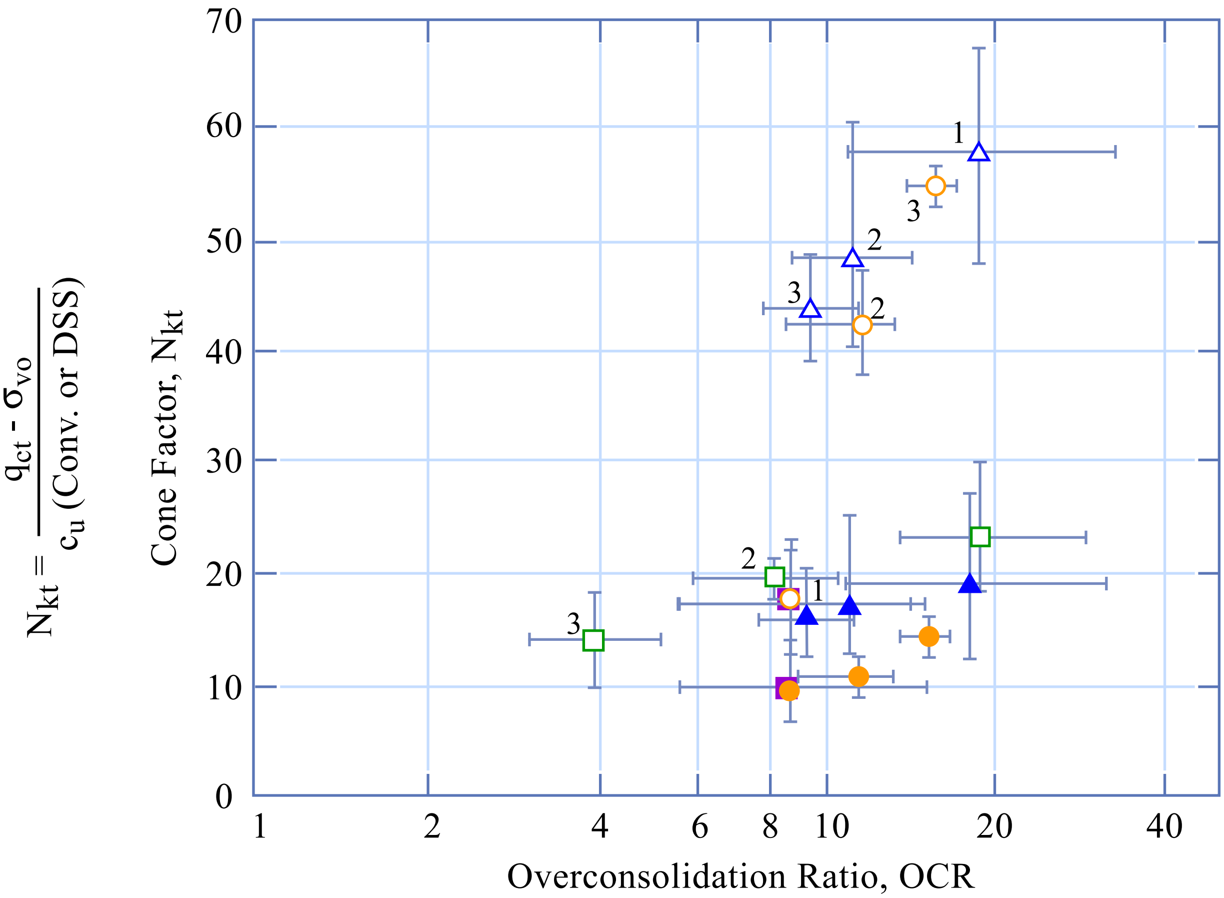
CP-2



□ Mukluk Proximal	} ML- MH $I_p \approx$ 10-30%
○ Smith Bay, Site T	} CL - $I_p \approx$ 25%
△ Smith Bay, Site W	CH
Solid : $C_u = C_u$(conv.)*	
Open : $C_u = C_u$(DSS)**	
■ Ice Gouged	

Note:
Numbers designate areas in table 6.1
* Mainly lab UUC & Mv
** Via SHANSEP with well defined OCR

Cone Factor vs. OCR. Collective Evaluation for Harrison Bay and Smith Bay Arctic Silts. (In situ temp $\approx$ -1°C)

Figure by MIT OCW.

Adapted from: MIT SM Thesis by C. De La Huerta (6/87)

Supplement to Section 2.4

Results from MIT AFOSR sponsored research on development on rational techniques for interpretation of in situ "penetration" tests in cohesive soils by Whittle et al., namely evaluation of disturbance affects with pressuremeter testing from C. Aubeny PhD thesis (6/92)

- PM-2 Schmetatic of SBPMT, FDPMT & PIPMT
- PM-3 Shear strains from installation PIPMT & ideal SBPMT
- PM-4 Predicted expansion curves as function of amount of disturbance for OCR=1 BBC
- PM-5 Predicted vs. measured expansion curves for OCR=4 BBC
- PM-6 Predicted s_u/σ'_{v0} as function of amount of disturbance for OCR=1 BBC.

NOTE: Predictions using Baligh's (1985) Strain Path Method and Whittle's (1987, 1992) MIT-E3 soil model

Paper: Whittle & Aubeny (1992) "The effects of installation disturbance on interpretation of in situ tests in clays" Wroth Symposium

• TYPES OF PRESSUREMETER

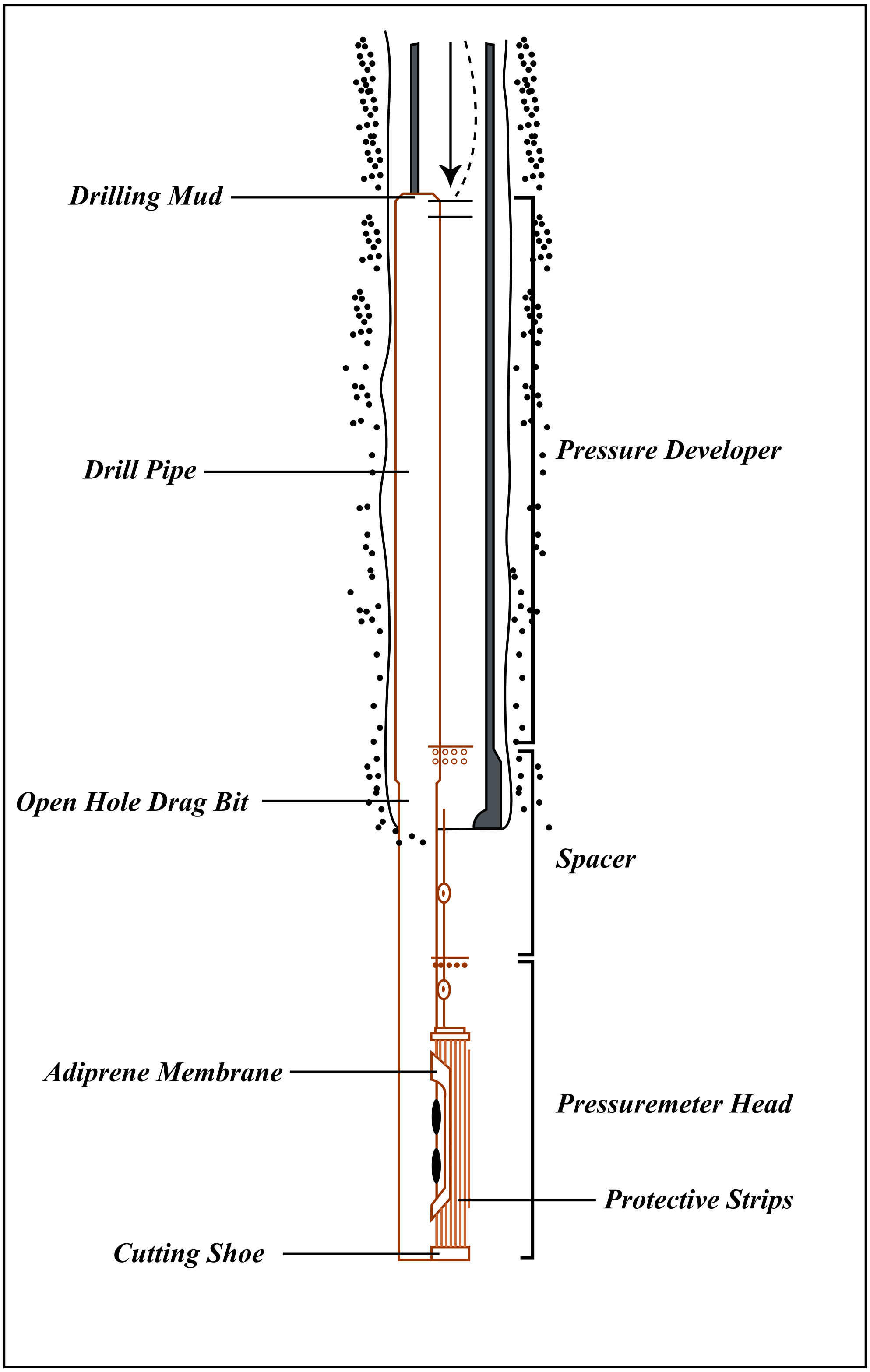
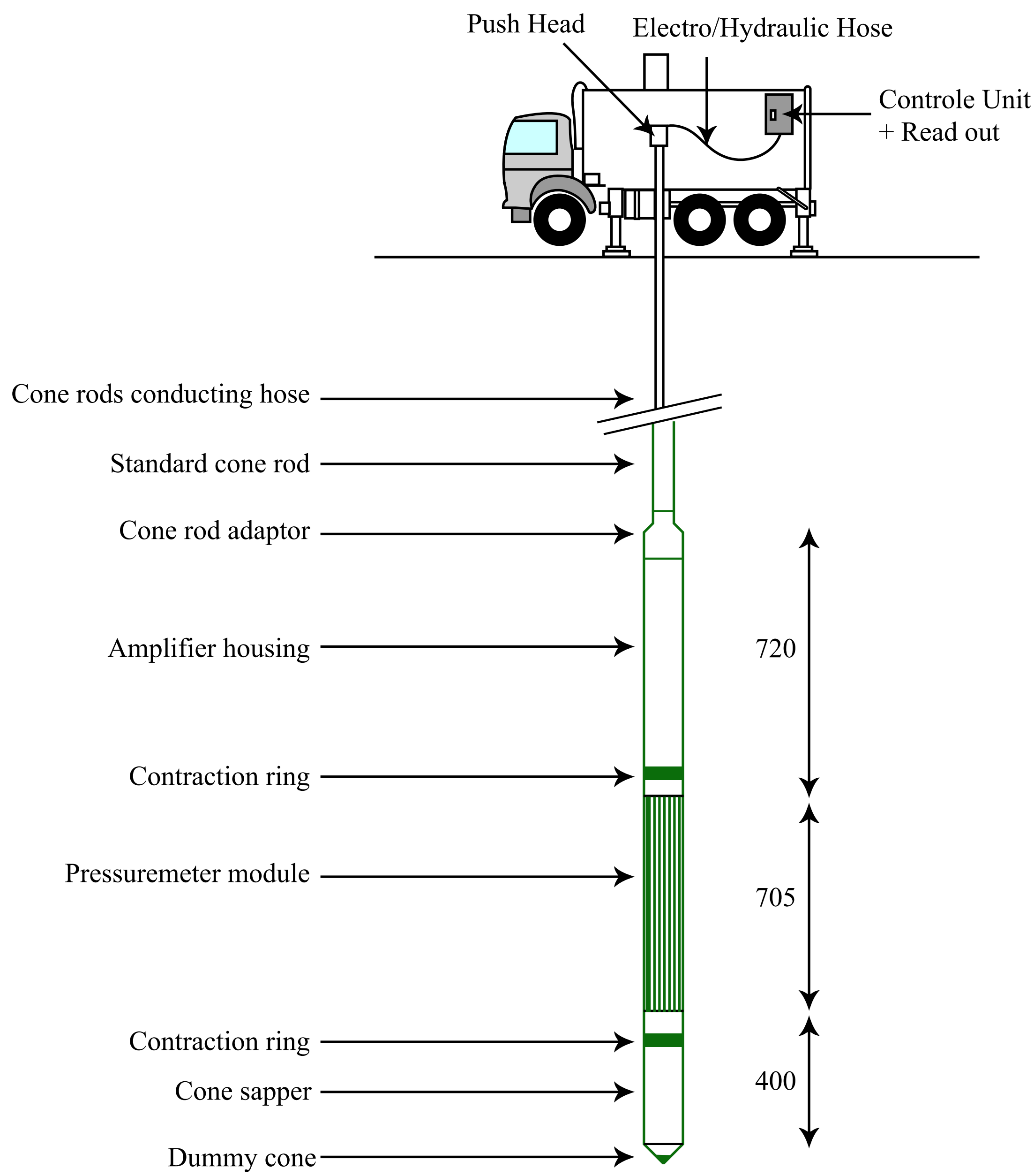


Figure by MIT OCW.

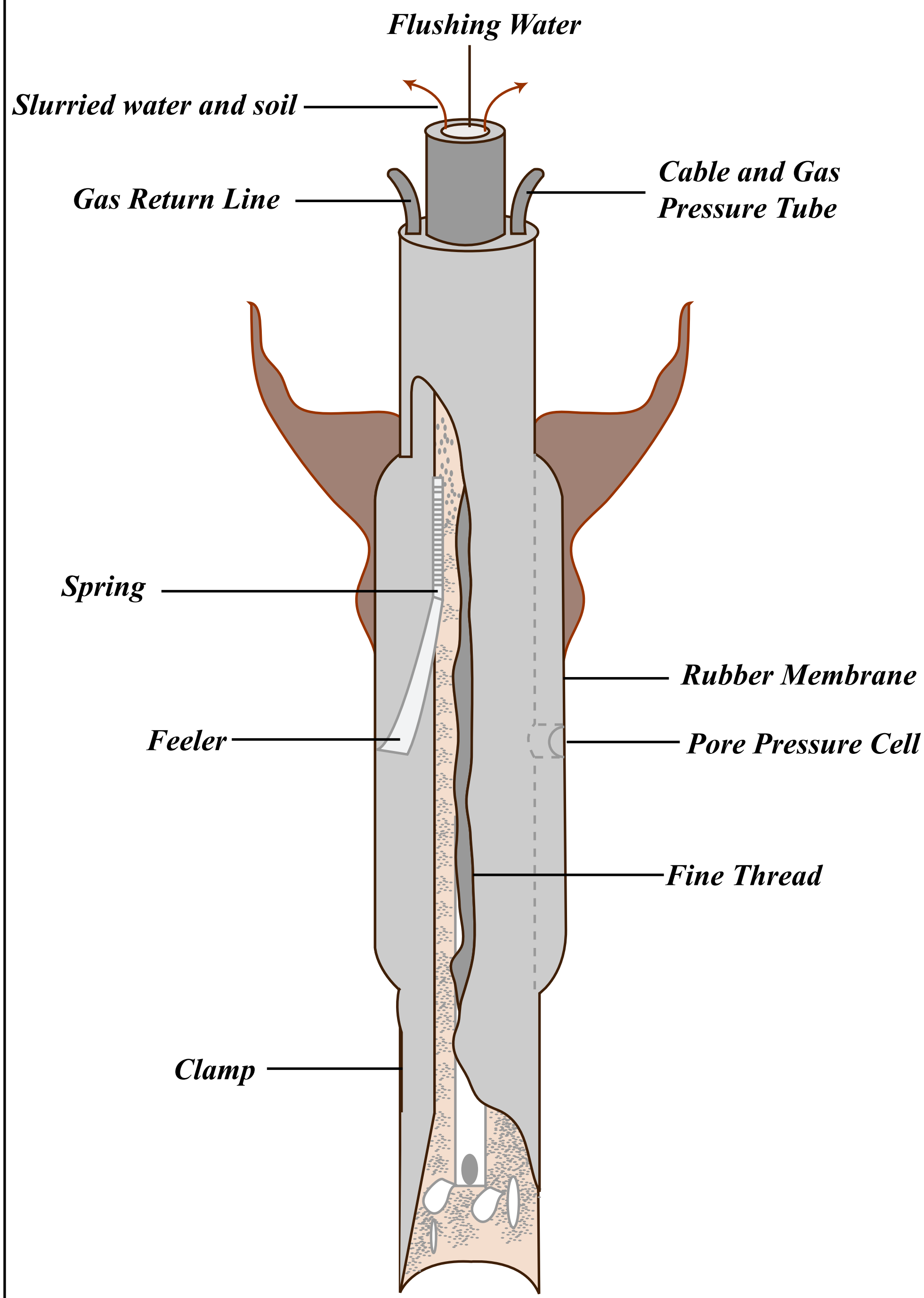
• PUSH-IN
(DIPMT)



Full Displacement or Cone Pressuremeter

Figure by MIT OCW.

- FULL DISPLACEMENT
  OR
  CONE PRESSUREMETER



Camkometer

Figure by MIT OCW.

• SELF BORING
(SB PMT)

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PM-3

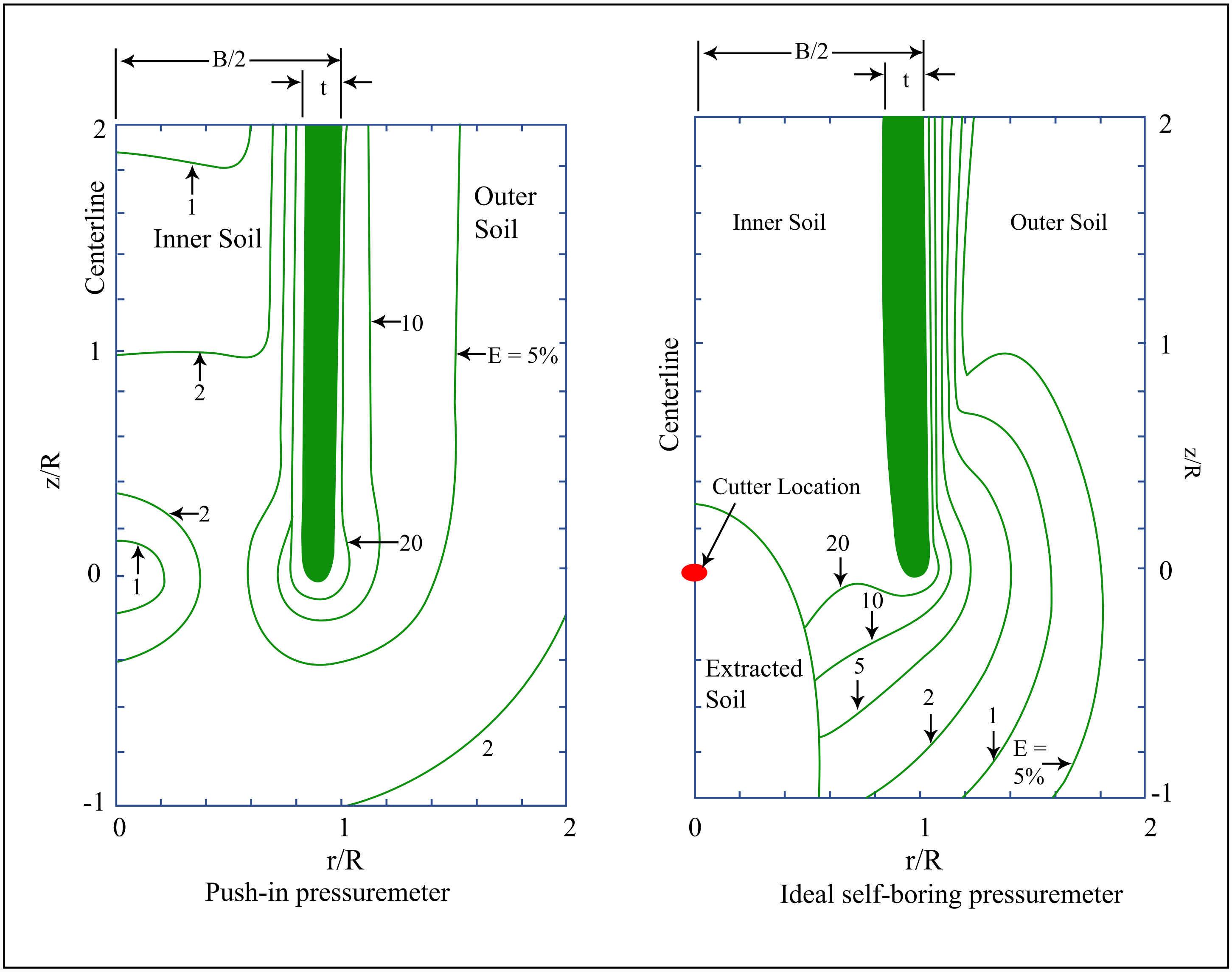

Figure by MIT OCW.

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PM-4

ASSUMPTIONS

- LONG CAVITY (PLANE STRAIN)
- FAR ABOVE TIP
- UNDRAINED BEHAVIOR

$$f = \frac{\text{Volume Soil Extracted}}{\text{Volume Device Inserted}}$$

DISPLACEMENT TYPE

SELF BORING TYPE

∞

$$s_u/\sigma'_{v0} = \left\{ \frac{d\left(\frac{p-u_0}{\sigma'_{v0}}\right)}{d\log(\Delta V/V)} \right\}_{max} \times 0.434$$

- EFFECT OF DISTURBANCE ON EXPANSION CURVE

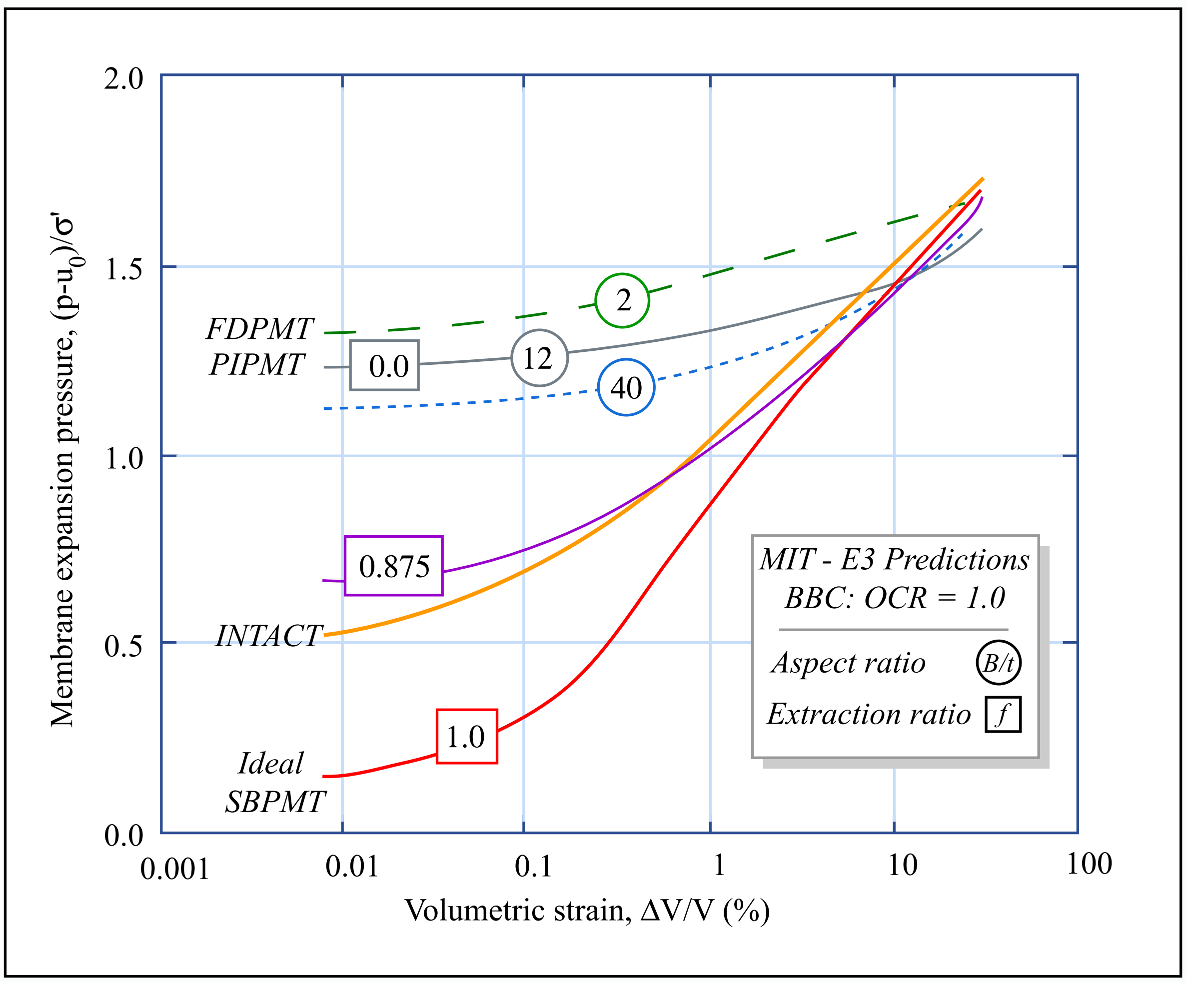

Figure by MIT OCW.

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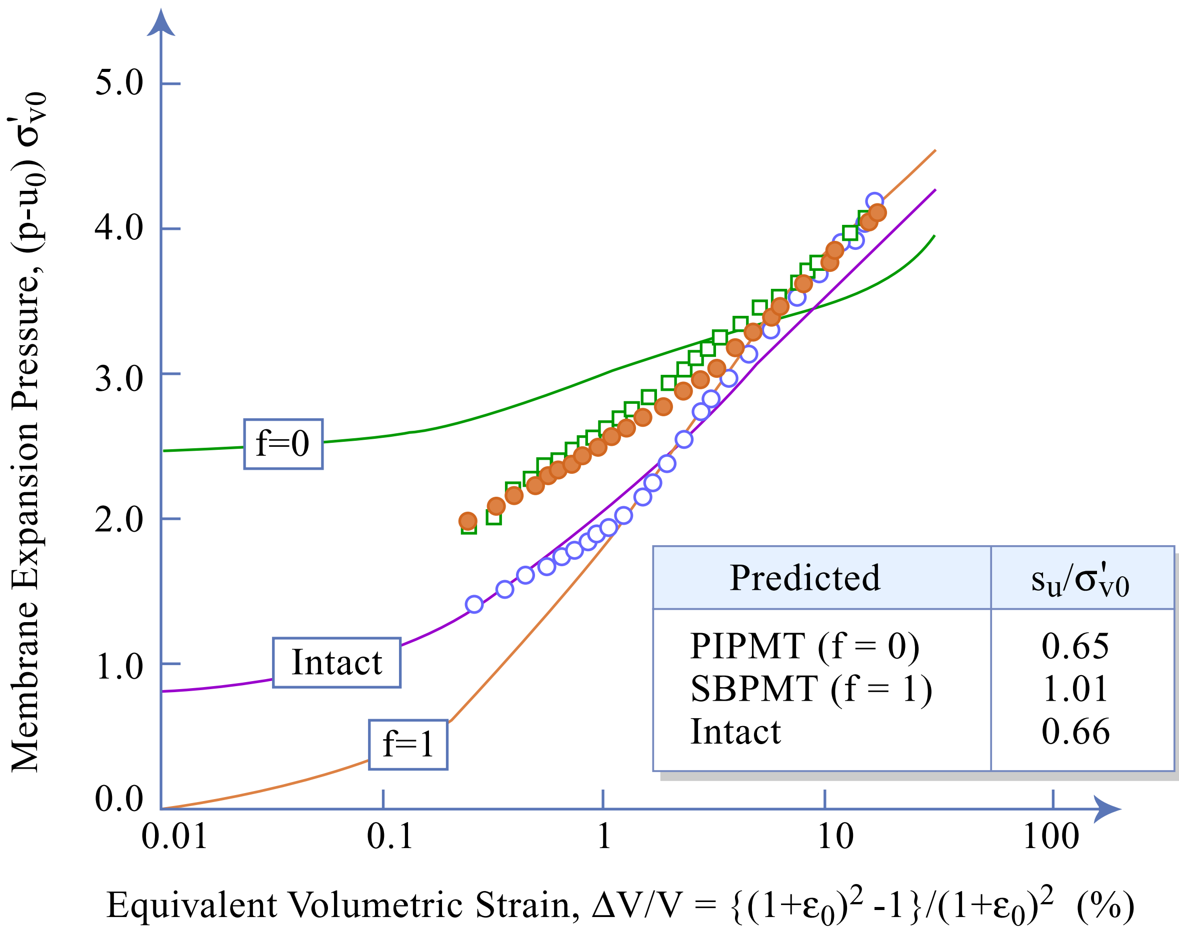
(PM-5)

Intact = ideal cavity expansion



Predicted	s_u/σ'_{v0}
PIPMT (f = 0)	0.65
SBPMT (f = 1)	1.01
Intact	0.66

Measured	s_u/σ'_{v0}
Arm 1 ○	1.35
Arm 2 □	0.68
Arm 3 ●	0.68

Measured Data South Boston Test Site
(Ladd, 1991)

• EVALUATION OF PREDICTIONS (OCR≈4)
SBPMT IN BOSTON BLUE CLAY

Figure by MIT OCW.

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PM-6

- DISPLACEMENT PRESSUREMETERS
- SELF BORING PRESSUREMETERS

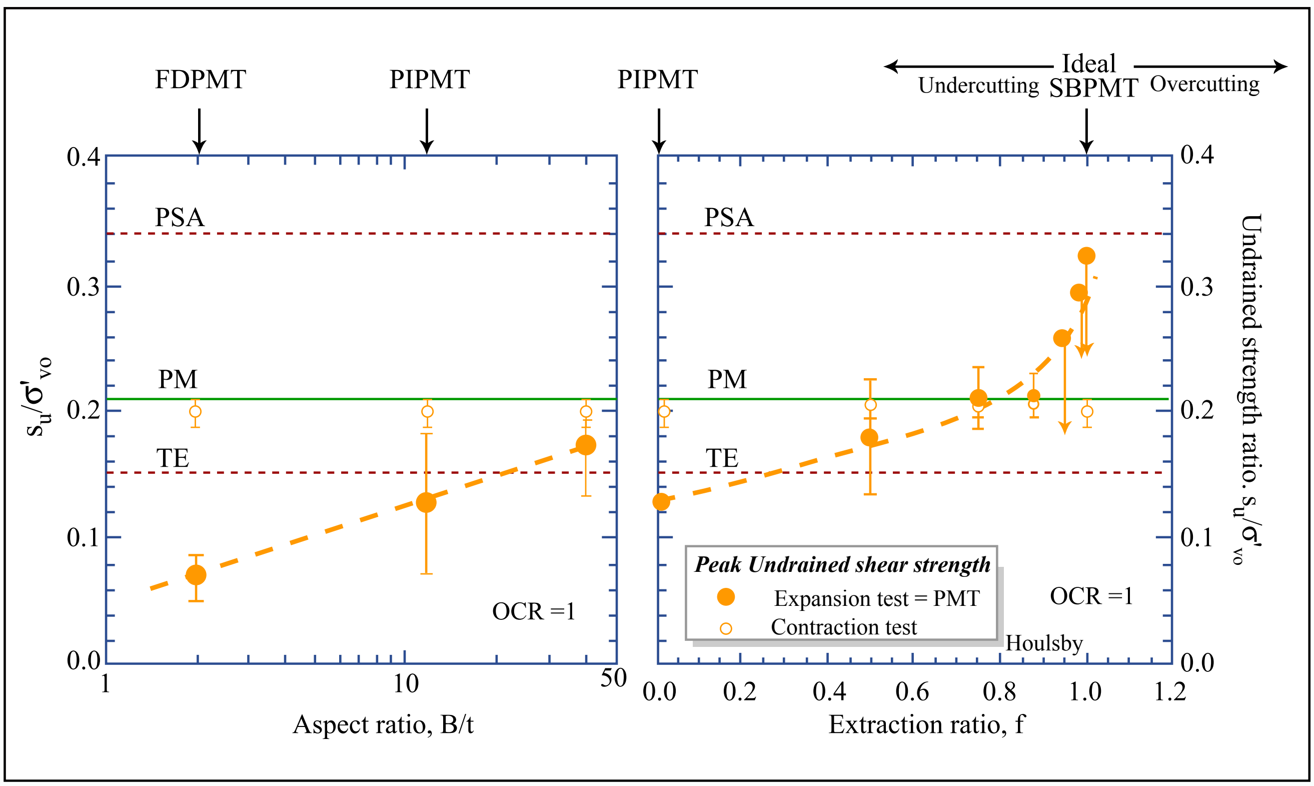

Figure by MIT OCW.

- SUMMARY OF s_u/σ'_{vc} PREDICTIONS
  - BBC · OCR = 1