CPTU Derived Soil Engineering Parameters for CLAY

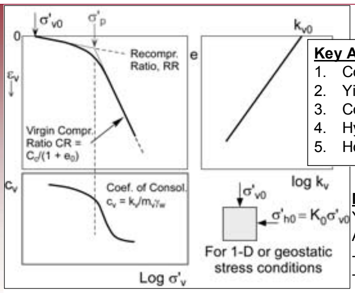
1. Key Aspects of Clay Soil Behavior

2. Important engineering design parameters

3. Background and application of CPTU correlations for estimation of design parameters

4. Applied to Case Studies in follow-on lecture.

Basic Soil Behavior - CLAY



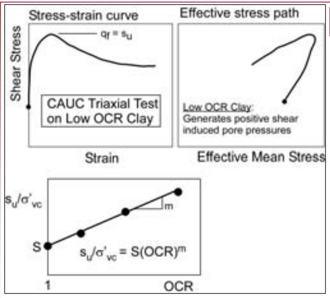
1-D Consolidation

Key Aspects:

1. Compressibility (RR and CR)
2. Yield stress (σ'_p)
3. Coefficient of consolidation (c_v)
4. Hydraulic conductivity (k_v)
5. Horizontal stress (σ'_{h0} or K_0)

Most Important Parameter:
Yield stress = $\sigma'_{vy} \equiv \sigma'_p \equiv p'_c$
Also known as:
- Preconsolidation stress
- Maximum past pressure

Basic Soil Behavior - CLAY



Undrained Shear Strength

Key Aspects:

1. Shear induced pore pressures
2. Effect of OCR
3. Anisotropy
4. Rate effects

Most Important Parameter:
Undrained shear strength = s_u

General Aspects of CPTU Testing in Clay

1. Penetration is generally undrained and therefore excess pore pressures will be generated.

2. Cone resistance and sleeve friction (if relevant) should be corrected using the measured pore pressures.

3. The measured pore pressures can also be used directly for interpretation in terms of soil design parameters.

Interpretation of CPTU data in clay

1. State Parameters = In situ state of stress and stress history

2. Strength parameters

3. Deformation characteristics

4. Flow and consolidation characteristics

5. In situ pore pressure

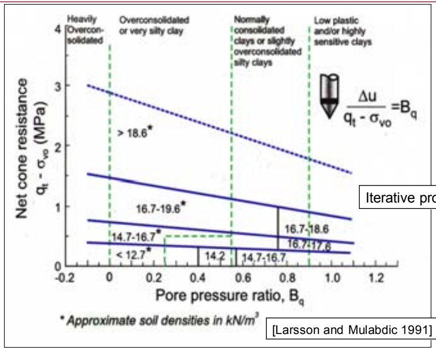
In Situ State Parameters

1. Soil Unit weight: γ_w for computation of in situ vertical effective stress (σ'_{v0})

2. Stress history
   σ'_p and OCR = σ'_p/σ'_{v0}

3. In situ horizontal effective stress
   $\sigma'_{h0} = K_0\sigma'_{v0}$

Estimation of Soil Unit Weight

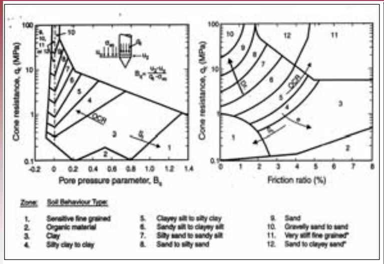


* Approximate soil densities in kN/m³

Iterative procedure

[Larsson and Mulabdic 1991]

Estimation of Soil Unit Weight



[Robertson et al. 1986]

Zone	Approximate Unit Weight (kN/m³)
1	17.5
2	12.5
3	17.5
4	18.0
5	18.0
6	18.0
7	18.5
8	19.0
9	19.5
10	20.0
11	20.5
12	19.0

Note: 1 kN/m³ ≈ 6.36 pcf

Stress History: OCR = σ'_p/σ'_{v0}

Estimation of Stress History (OCR or σ'_p) can be based on:

- Direct correlation with CPTU data
- Pore pressure differential via dual element piezocone
- Indirect correlation via undrained shear strength

CPTU Stress History Correlations

Wroth (1984), Mayne(1991) and others proposed theoretical basis (cavity expansion; critical state soil mechanics) for the following potential correlations between CPTU data and σ'_p or OCR:

σ'_p = = f(Δu_1 or Δu_2)
$\sigma'_p = f(q_t - \sigma_{v0})$
$\sigma'_p = f(q_t - u_2)$

OCR = $f(B_q = \Delta u_2/(q_t - \sigma_{vo}))$
OCR = $f(Q_t = (q_t - \sigma_{vo})/ \sigma'_{v0}))$
OCR = $f((q_t - u_2)/ \sigma'_{v0})$

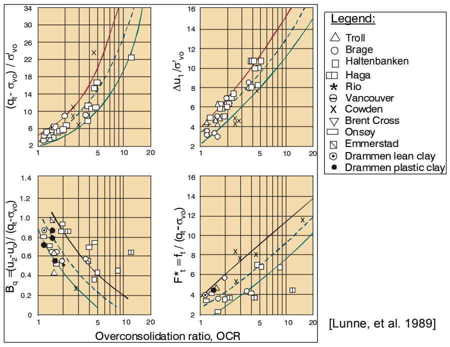
Most Common:

$\sigma'_p = k(q_t - \sigma_{v0})$

or

OCR = $k[(q_t - \sigma_{v0})/\sigma'_{v0}]$

CPTU Stress History Correlations



[Lunne, et al. 1989]

CPTU Stress History Correlations

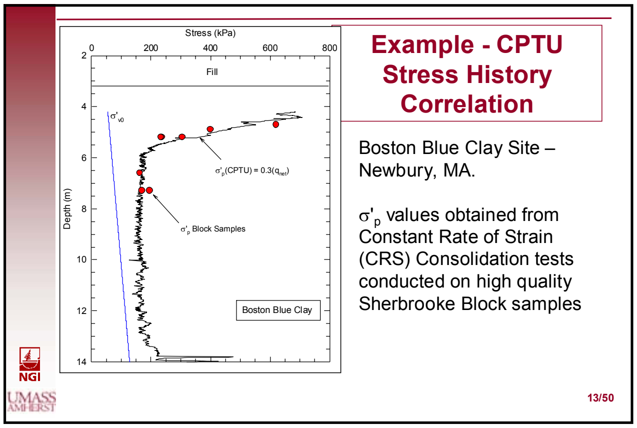
Comprehensive study initially by Chen and Mayne (1996) with later updates (e.g., Mayne 2005):

$\sigma'_p = 0.47(\Delta u_1) = 0.53(\Delta u_2)$

$\sigma'_p = 0.33(q_t - \sigma_{v0})$ ← Most common

$\sigma'_p = 0.60(q_t - u_2)$

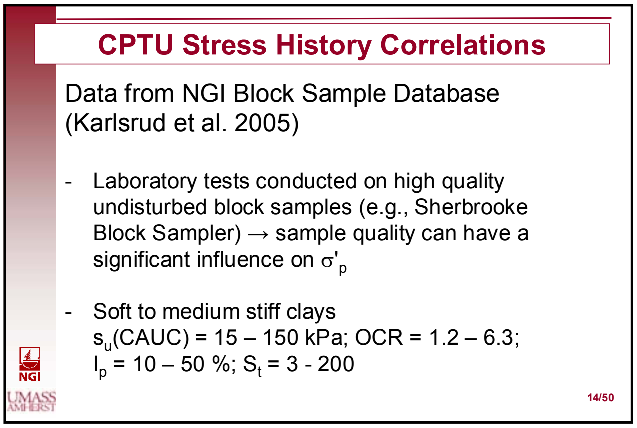
Note: values listed above are from best fit regressions; there is a sizable range in all values, e.g., k ranges from 0.2 to 0.5 for $\sigma'_p = k(q_t - \sigma_{v0})$



Example - CPTU Stress History Correlation

Boston Blue Clay Site – Newbury, MA.

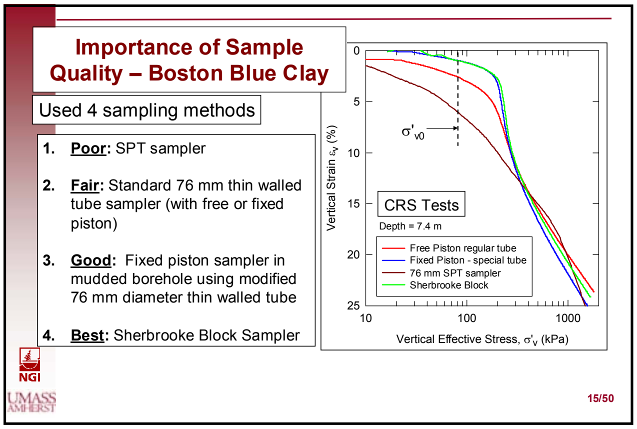
σ'_p values obtained from Constant Rate of Strain (CRS) Consolidation tests conducted on high quality Sherbrooke Block samples



CPTU Stress History Correlations

Data from NGI Block Sample Database (Karlsrud et al. 2005)

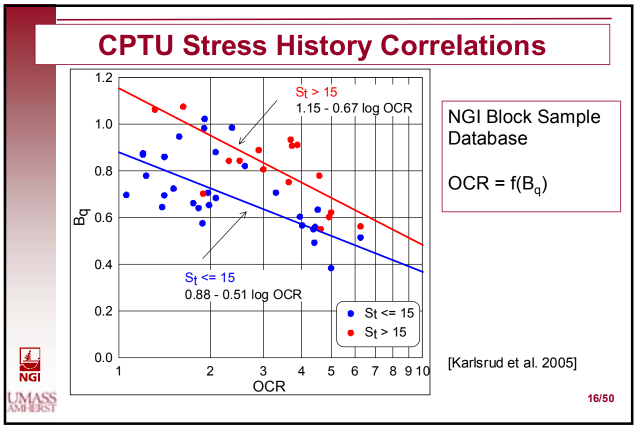
- Laboratory tests conducted on high quality undisturbed block samples (e.g., Sherbrooke Block Sampler) → sample quality can have a significant influence on σ'_p
- Soft to medium stiff clays s_u(CAUC) = 15 – 150 kPa; OCR = 1.2 – 6.3; I_p = 10 – 50 %; S_t = 3 - 200



Importance of Sample Quality – Boston Blue Clay

Used 4 sampling methods

1. **Poor**: SPT sampler
2. **Fair**: Standard 76 mm thin walled tube sampler (with free or fixed piston)
3. **Good**: Fixed piston sampler in mudded borehole using modified 76 mm diameter thin walled tube
4. **Best**: Sherbrooke Block Sampler

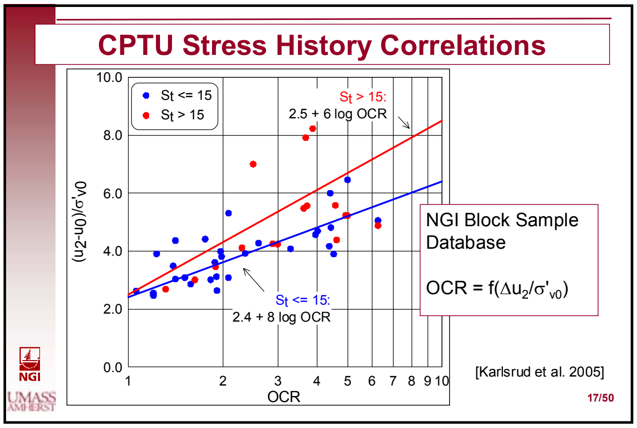


CPTU Stress History Correlations

NGI Block Sample Database

OCR = f(B_q)

[Karlsrud et al. 2005]

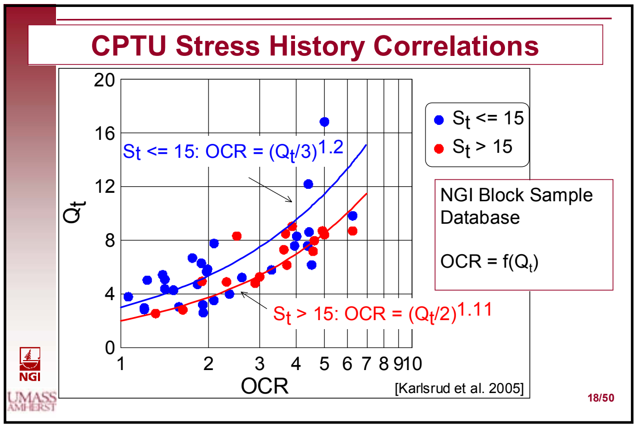


CPTU Stress History Correlations

NGI Block Sample Database

OCR = f($\Delta u_2/\sigma'_{v0}$)

[Karlsrud et al. 2005]



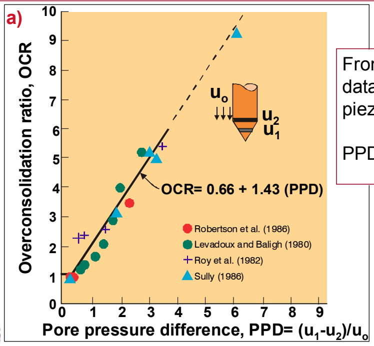
CPTU Stress History Correlations

NGI Block Sample Database

OCR = f(Q_t)

[Karlsrud et al. 2005]

CPTU Stress History Correlations

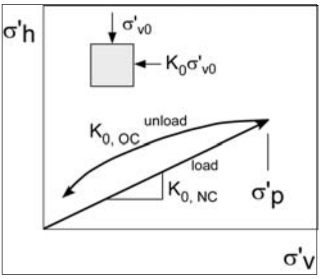


From pore pressure data using dual element piezocone

PPD = $(u_1 - u_2)/u_0$

[Sully et al.,1988]

K_0 – OCR Relationship for Clays



For simple case of loading followed by unloading, K_0 increases with increasing OCR such that:

$K_{0,OC} = K_{0,NC}(OCR)^n$

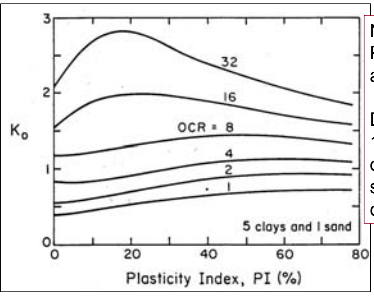
In Situ Horizontal Effective Stress

There are currently no reliable methods for determining the in situ horizontal effective stress, $\sigma'_{h0} = K_0(\sigma'_{v0})$ from CPTU data

For approximate (preliminary) estimates consider correlations based on:

- OCR via CPTU correlations for OCR or s_u
- Measured pore pressure difference

K_0-OCR-PI Relationship

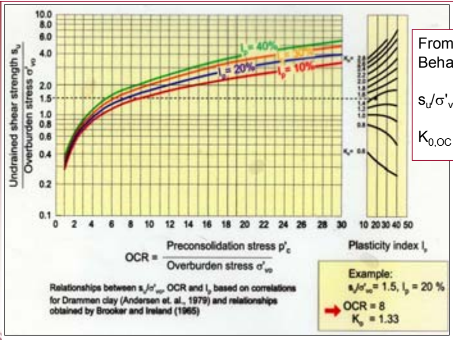


[Brooker and Ireland 1965]

Need values for Plasticity Index (PI) and OCR.

Determine OCR from 1) CPTU correlations or via 2) undrained shear strength correlation (next slide)

NGI Relationship among OCR-s_u/σ'_{v0}-K_0-PI



$OCR = \frac{\text{Preconsolidation stress } p'_c}{\text{Overburden stress } \sigma'_{v0}}$

Relationships between s_u/σ'_{v0}, OCR and I_p based on correlations for Drammen clay (Andersen et. al., 1979) and relationships obtained by Brooker and Ireland (1965)

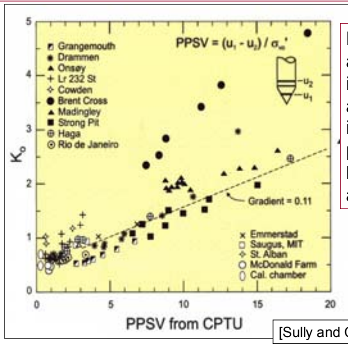
Example:
s_u/σ'_{v0} = 1.5, I_p = 20 %
OCR = 8
K_0 = 1.33

From Basic Soil Behavior

$s_u/\sigma'_{v0} = S(OCR)^m$

$K_{0,OC} = K_{0,NC}(OCR)^n$

Estimate K_0 from Dual Element Piezocone



[Sully and Campanella 1991]

Difference between u_1 and u_2 increases with increasing OCR → K_0 also increases with increasing OCR, hence positive correlation between $(u_1 – u_2)/\sigma'_{v0}$ and K_0.

Shear Strength of Clays

For most design problems in clays (especially loading) the critical failure condition is undrained.

1. Undrained Shear strength s_u (= c_u)

2. Remolded undrained shear strength (s_{ur}) or Sensitivity, $S_t = s_u/s_{ur}$

Note: 1kPa = 20.9 psf

Notes Regarding Undrained Shear Strength

1. The undrained shear strength is not unique.
2. The in situ undrained shear strength depends on many factors with the most important being: mode of shear failure, soil anisotropy, strain rate and stress history.
3. Therefore s_u required for analysis depends on the design problem.
4. Measured CPTU data are also influenced by such factors as anisotropy and rate effects.
5. The CPTU cannot directly measure s_u and therefore CPTU interpretation of s_u relies on a combination of theory and empirical correlations

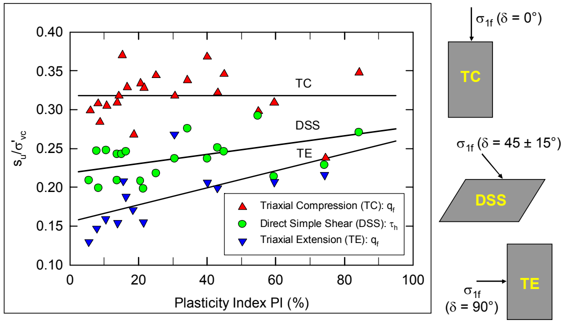
Theoretical Interpretation CPTU in Clay

1. Existing theories for interpretation of s_u from CPTU data involve several simplifications and assumptions. Therefore existing theories must be "calibrated" against measured data

2. Most important to use realistic and reliable soil data from high quality tests conducted on high quality samples

3. At NGI – key reference is to use s_u from Anisotropically consolidated triaxial compression (CAUC) tests conducted on high quality undisturbed samples. A secondary reference is to use the average s_u(ave) [or mobilized for stability problems] = 1/3[s_u(CAUC) = s_u(DSS) + s_u(CAUE)]

Undrained Shear Strength Anisotropy



[Ladd 1991, Ladd and DeGroot 2003]

Undrained Shear Strength from CPTU Data

Theories for interpretation:

1. Bearing capacity
2. Cavity expansion
3. Strain path methods

All result in a relationship of the form:
$q_t = N_c s_u + \sigma_0$, where σ_0 could = σ_{v0}, σ_{h0}, σ_{m0}

In practice most common to use:
$q_t = N_{kt} s_u + \sigma_{v0}$, for which theoretically N_{kt} = 9 to 18.

Undrained Shear Strength from CPTU Data

The empirical approaches available for interpretation of s_u from CPT/CPTU data can be grouped under 3 main categories:

1. s_u estimation using "total" cone resistance

2. s_u estimation using "effective" cone resistance

3. s_u estimation using excess pore pressure

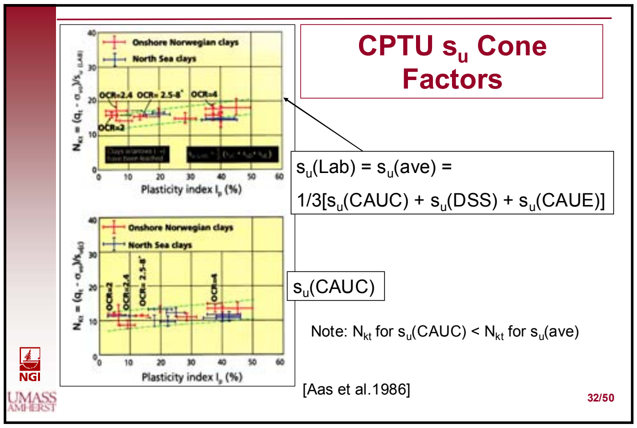
Undrained Shear Strength from CPTU Data

$s_u = q_{net}/N_{kt} = (q_t - \sigma_{v0})/N_{kt}$ Most Common

$s_u = \Delta u/N_{\Delta u} = (u_2 - u_0)/N_{\Delta u}$ Often used

$s_u = q_e/N_{ke} = (q_t - u_2)/N_{ke}$ Seldom used

Need empirical correlation factors N_{kt}, $N_{\Delta u}$, or N_{ke} factors as correlated to a specific measure of undrained shear strength, e.g., s_u(CAUC) or s_u(ave)



CPTU s_u Cone Factors

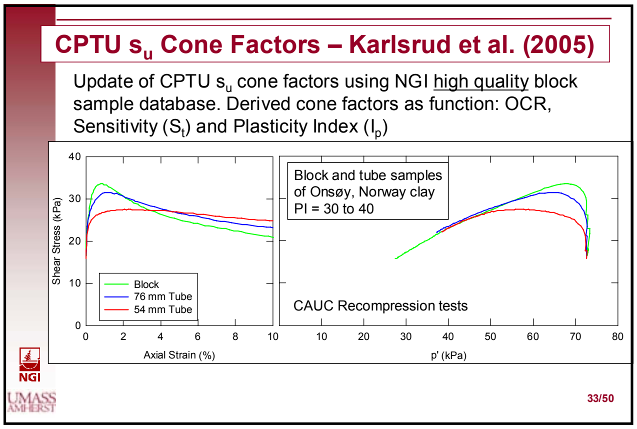
s_u(Lab) = s_u(ave) =

1/3[s_u(CAUC) + s_u(DSS) + s_u(CAUE)]

s_u(CAUC)

Note: N_{kt} for s_u(CAUC) < N_{kt} for s_u(ave)

[Aas et al.1986]

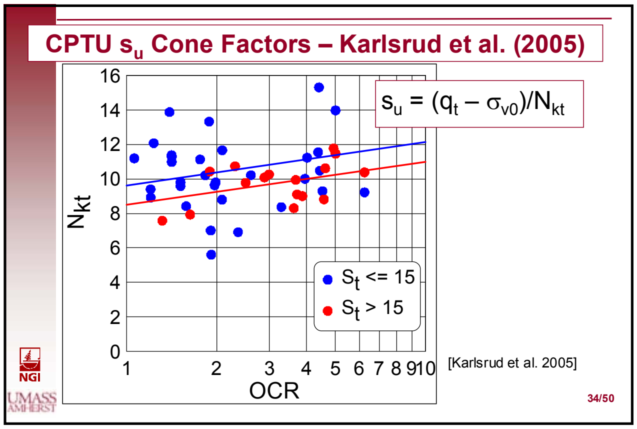


CPTU s_u Cone Factors – Karlsrud et al. (2005)

Update of CPTU s_u cone factors using NGI high quality block sample database. Derived cone factors as function: OCR, Sensitivity (S_t) and Plasticity Index (I_p)

Block and tube samples of Onsøy, Norway clay PI = 30 to 40

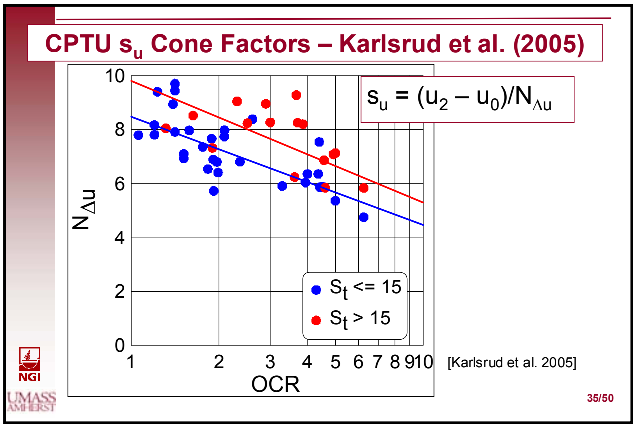
CAUC Recompression tests



CPTU s_u Cone Factors – Karlsrud et al. (2005)

$s_u = (q_t - \sigma_{v0})/N_{kt}$

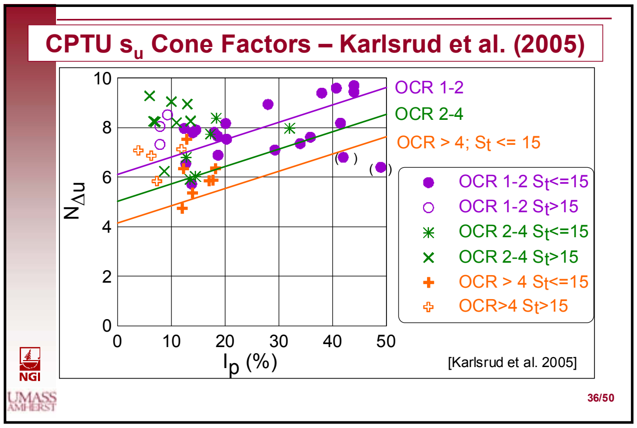
[Karlsrud et al. 2005]



CPTU s_u Cone Factors – Karlsrud et al. (2005)

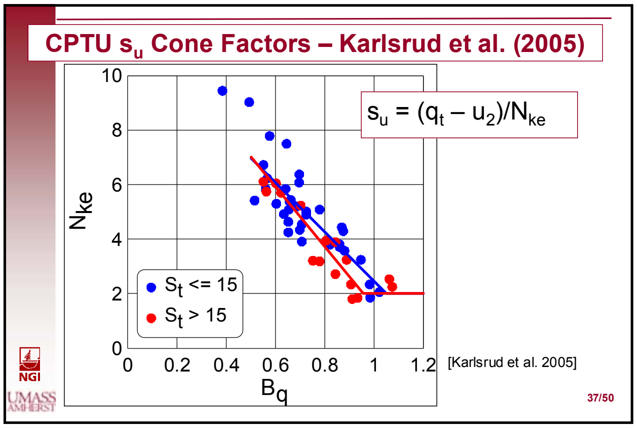
$s_u = (u_2 - u_0)/N_{\Delta u}$

[Karlsrud et al. 2005]



CPTU s_u Cone Factors – Karlsrud et al. (2005)

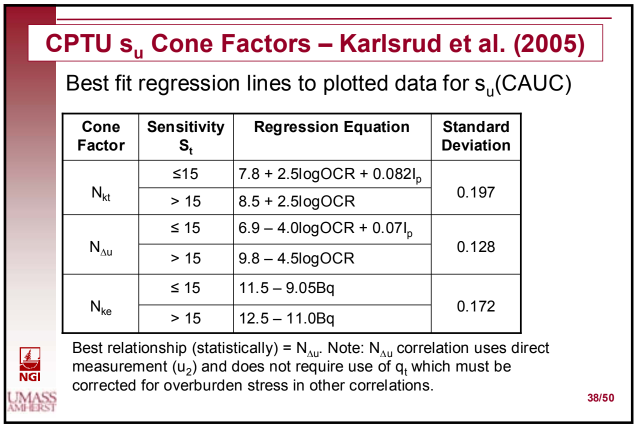
[Karlsrud et al. 2005]



CPTU s_u Cone Factors – Karlsrud et al. (2005)

$s_u = (q_t - u_2)/N_{ke}$

[Karlsrud et al. 2005]

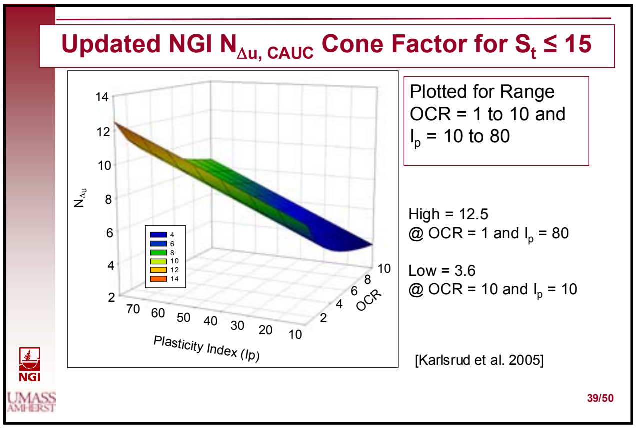


CPTU s_u Cone Factors – Karlsrud et al. (2005)

Best fit regression lines to plotted data for s_u(CAUC)

Cone Factor	Sensitivity S_t	Regression Equation	Standard Deviation
N_{kt}	≤15	$7.8 + 2.5\log OCR + 0.082I_p$	0.197
	> 15	$8.5 + 2.5\log OCR$	
$N_{\Delta u}$	≤ 15	$6.9 – 4.0\log OCR + 0.07I_p$	0.128
	> 15	$9.8 – 4.5\log OCR$	
N_{ke}	≤ 15	$11.5 – 9.05Bq$	0.172
	> 15	$12.5 – 11.0Bq$	

Best relationship (statistically) = $N_{\Delta u}$. Note: $N_{\Delta u}$ correlation uses direct measurement (u_2) and does not require use of q_t which must be corrected for overburden stress in other correlations.



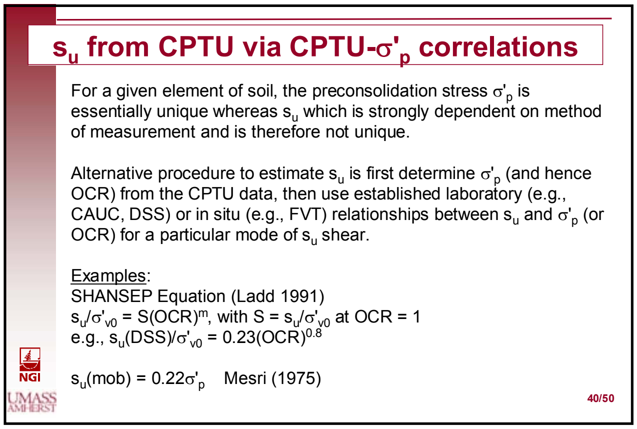
Updated NGI $N_{\Delta u, CAUC}$ Cone Factor for S_t ≤ 15

Plotted for Range
OCR = 1 to 10 and
I_p = 10 to 80

High = 12.5
@ OCR = 1 and I_p = 80

Low = 3.6
@ OCR = 10 and I_p = 10

[Karlsrud et al. 2005]



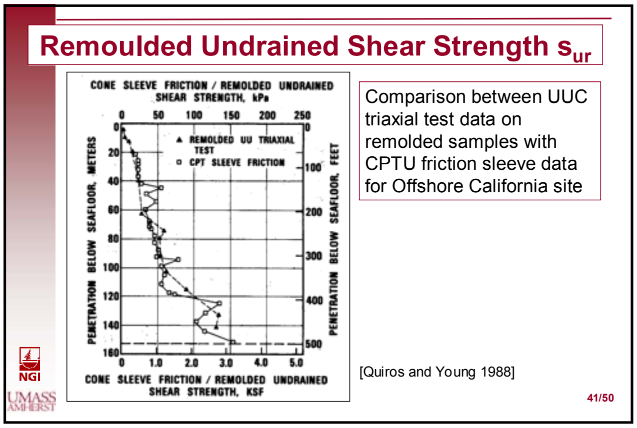
s_u from CPTU via CPTU-σ'_p correlations

For a given element of soil, the preconsolidation stress σ'_p is essentially unique whereas s_u which is strongly dependent on method of measurement and is therefore not unique.

Alternative procedure to estimate s_u is first determine σ'_p (and hence OCR) from the CPTU data, then use established laboratory (e.g., CAUC, DSS) or in situ (e.g., FVT) relationships between s_u and σ'_p (or OCR) for a particular mode of s_u shear.

Examples:
SHANSEP Equation (Ladd 1991)
$s_u/\sigma'_{v0} = S(OCR)^m$, with $S = s_u/\sigma'_{v0}$ at OCR = 1
e.g., $s_u(DSS)/\sigma'_{v0} = 0.23(OCR)^{0.8}$

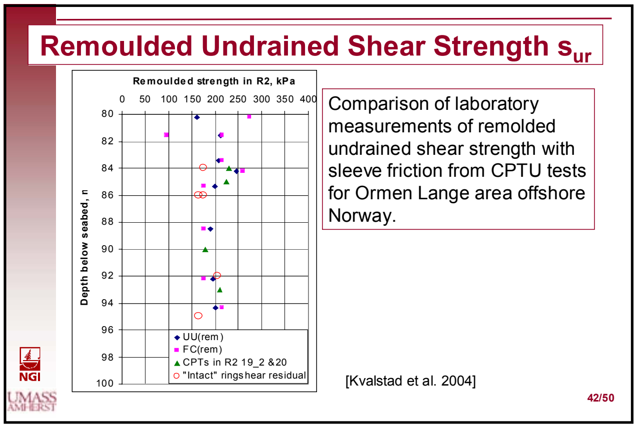
$s_u(mob) = 0.22\sigma'_p$ Mesri (1975)



Remoulded Undrained Shear Strength s_{ur}

Comparison between UUC triaxial test data on remolded samples with CPTU friction sleeve data for Offshore California site

[Quiros and Young 1988]

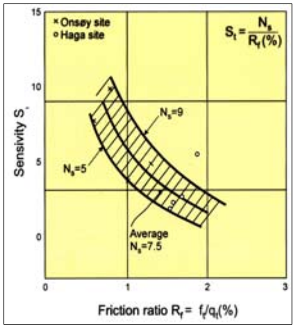


Remoulded Undrained Shear Strength s_{ur}

Comparison of laboratory measurements of remolded undrained shear strength with sleeve friction from CPTU tests for Ormen Lange area offshore Norway.

[Kvalstad et al. 2004]

Undrained Shear Strength Sensitivity, S_t



Relationship between Sensitivity and CPTU R_f for two sites in Norway

[Rad and Lunne 1986]

Deformation Parameters

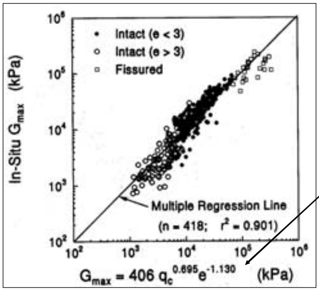
1. Constrained Modulus – for 1-D compression, M
2. Undrained Young's Modulus, E_u
3. Small strain shear modulus, G_{max}

Two approaches for use of CPT/CPTU data to estimate deformation parameters:

1. Indirect methods that require an estimate of another parameter such as undrained shear strength s_u.

2. Direct methods that relate cone resistance directly to modulus.

Example of Direct Correlation between CPTU and G_{max}



Mayne and Rix (1993)

Estimation of small strain shear modulus G_{max} for clays from CPT q_c data + estimate e.

Note: G_{max} is anisotropic + in the context of CPT/CPTU testing, better to measure directly down hole with seismic cone (= G_{vh})

Consolidation and Hydraulic Conductivity

Measurement: dissipation of penetration pore pressures during pause in penetration. Can be u_1 or u_2. Ideally measure until $\Delta u = 0$ but time depends on c_h and k_h.

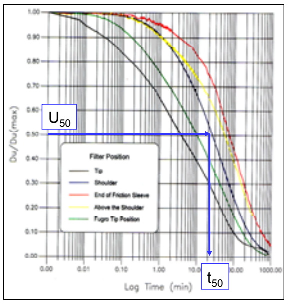
Derived Soil Properties:

1. Coefficient of Consolidation, c_h

2. Hydraulic Conductivity (= permeability), k_h

Since the dissipation is radial, c_h and k_h are derived. Some clays can have highly anisotropic consolidation and flow parameters (e.g., varved clays) – need to use published anisotropy ratios to estimate k_v and c_v.

CPTU Normalized Dissipation Curves



Bothkennar, UK (= soft clay) Dissipation Tests at 15 m depth

Typically plot:
$U = \Delta u/\Delta u_i$ as function t which for the u_2 position = $(u_2 - u_0)/(u_i - u_0)$
where
u_0 = in situ pore pressure before penetration, and
$u_i = u_2$ at t = 0

Theory for CPTU derived c_h and k_h

c_h Terzaghi Theory: $c_v = (TH^2)/t$

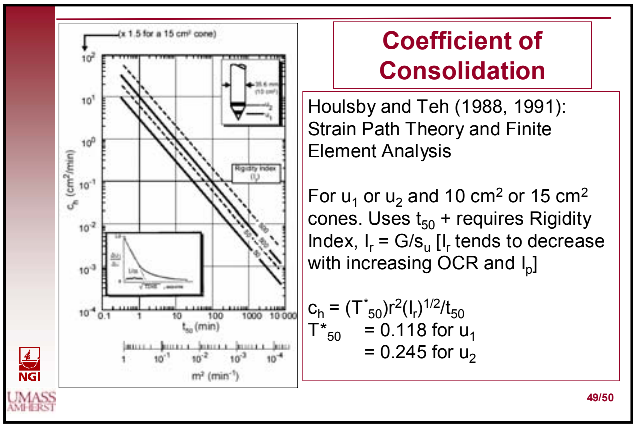
Torstensson (1975, 1977) suggested use time at 50% dissipation and for CPTU geometry thus,

$c_h = (T_{50}/t_{50})r^2$

Hence for 10 cm^2 cone, $c_h = 0.00153/t_{50}$ [m^2/s]

k_h Terzaghi Theory: $k_h = c_h \gamma_w m_h$

Determine c_h from dissipation test + need estimate m_h = coefficient of volume change, which can be correlated to q_c or q_t



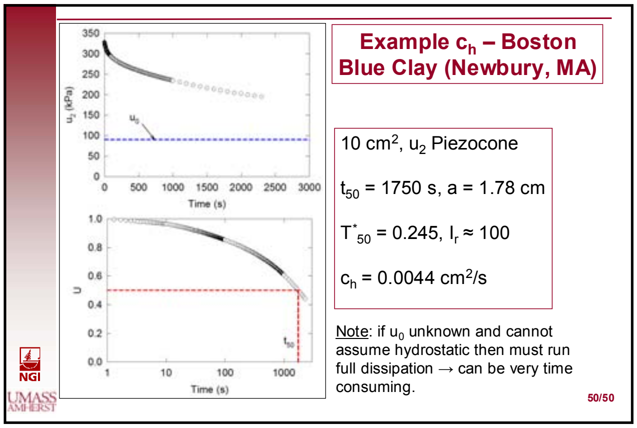
Coefficient of Consolidation

Houlsby and Teh (1988, 1991): Strain Path Theory and Finite Element Analysis

For u_1 or u_2 and 10 cm^2 or 15 cm^2 cones. Uses t_{50} + requires Rigidity Index, $I_r = G/s_u$ [I_r tends to decrease with increasing OCR and I_p]

$c_h = (T^*_{50})r^2(I_r)^{1/2}/t_{50}$

T^*_{50} = 0.118 for u_1
= 0.245 for u_2



Example c_h – Boston Blue Clay (Newbury, MA)

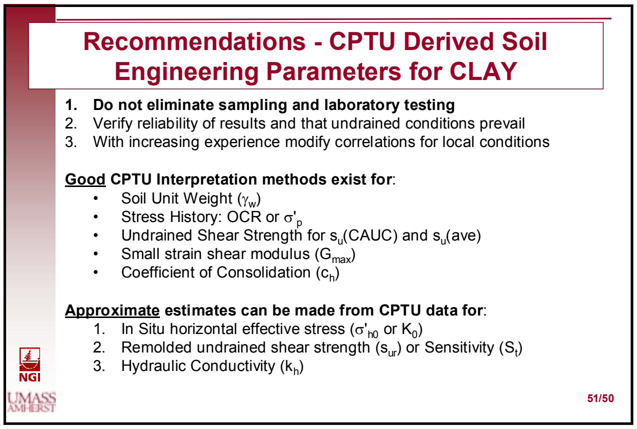
10 cm^2, u_2 Piezocone

t_{50} = 1750 s, a = 1.78 cm

T^*_{50} = 0.245, $I_r \approx 100$

c_h = 0.0044 cm^2/s

Note: if u_0 unknown and cannot assume hydrostatic then must run full dissipation → can be very time consuming.



Recommendations - CPTU Derived Soil Engineering Parameters for CLAY

1. **Do not eliminate sampling and laboratory testing**
2. Verify reliability of results and that undrained conditions prevail
3. With increasing experience modify correlations for local conditions

Good CPTU Interpretation methods exist for:

- Soil Unit Weight (γ_w)
- Stress History: OCR or σ'_p
- Undrained Shear Strength for s_u(CAUC) and s_u(ave)
- Small strain shear modulus (G_{max})
- Coefficient of Consolidation (c_h)

Approximate estimates can be made from CPTU data for:

1. In Situ horizontal effective stress (σ'_{h0} or K_0)
2. Remolded undrained shear strength (s_{ur}) or Sensitivity (S_t)
3. Hydraulic Conductivity (k_h)