

Profiling and soil identification and CPTU derived parameters in sand



Interpretation of CPTU data in terms of soil layering, soil classification and design parameters

- Stratification
- Soil classification
- Soil design parameters
 - Sand
 - Clay

CPT/CPTU Interpretation of Stratigraphy: Soil Layering and Soil Classification

1. Stratigraphy – Key signatures of soil layering from CPT/CPTU data at all levels
2. Soil Classification - development and application of soil classification charts

Stratigraphic Profiling

Excellent application for the CPT and especially the CPTU

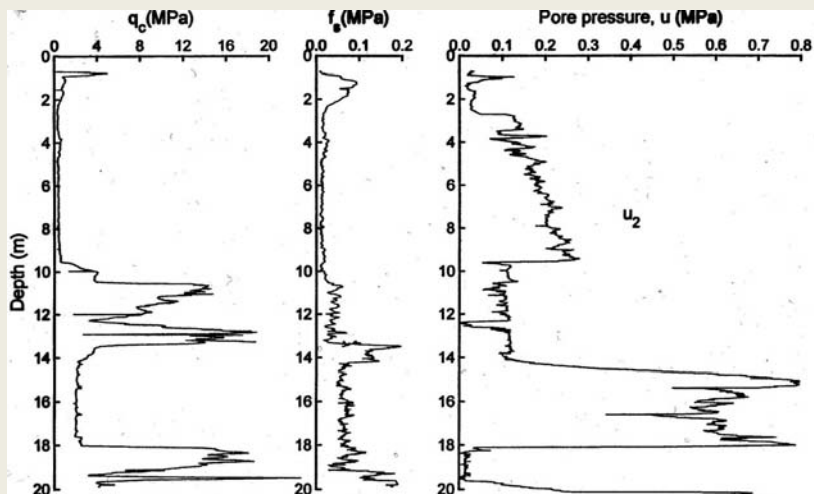
1. Reply on fundamentals of soil behavior, i.e., stiffness (e.g., dense sand vs. soft clay) and drainage (drained behavior during shear in sand vs. undrained behavior during shear in clay).
2. Use all information available – q_c or q_t , f_s , u , Q_t , R_f , B_q (+ other sensors when available).

Stratigraphic Profiling

Key Signatures to look for in measured data:

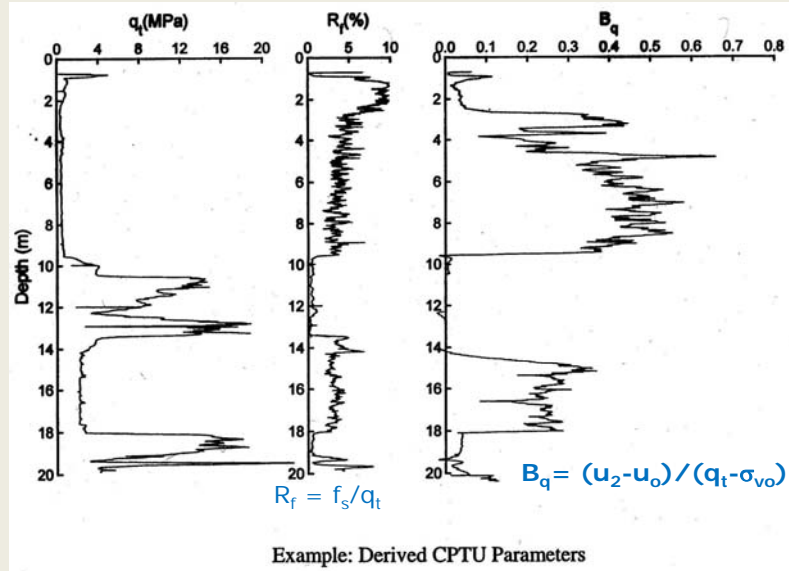
1. Shape and magnitude of q_t profile – e.g. high in dense sand, low in soft clay
2. Shape of u profile and magnitude, especially relative to equilibrium pore pressure profile – e.g., high in soft clay, $\Delta u = 0$ in medium density sand
3. Magnitude of R_f relative to that of q_t – e.g., if high and coupled with low q_t = soft clay.

Example North Sea – clay and sand layers

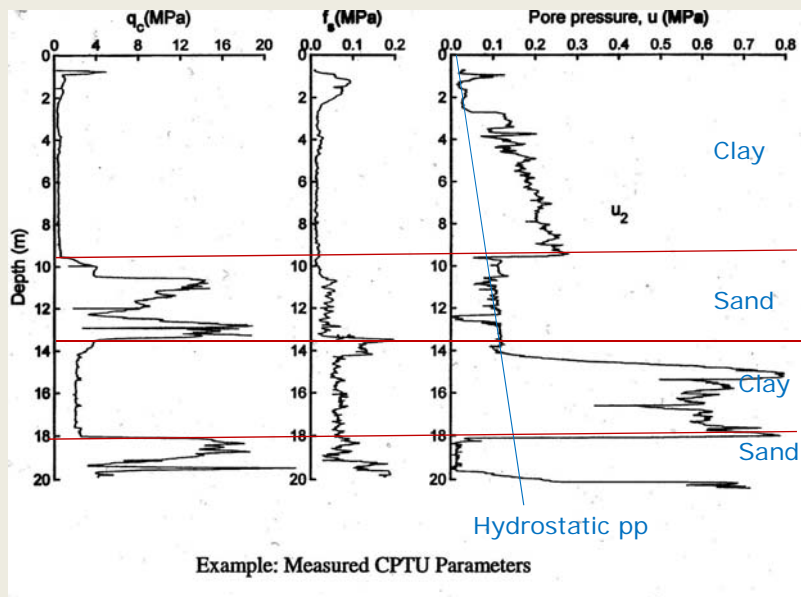


Example: Measured CPTU Parameters

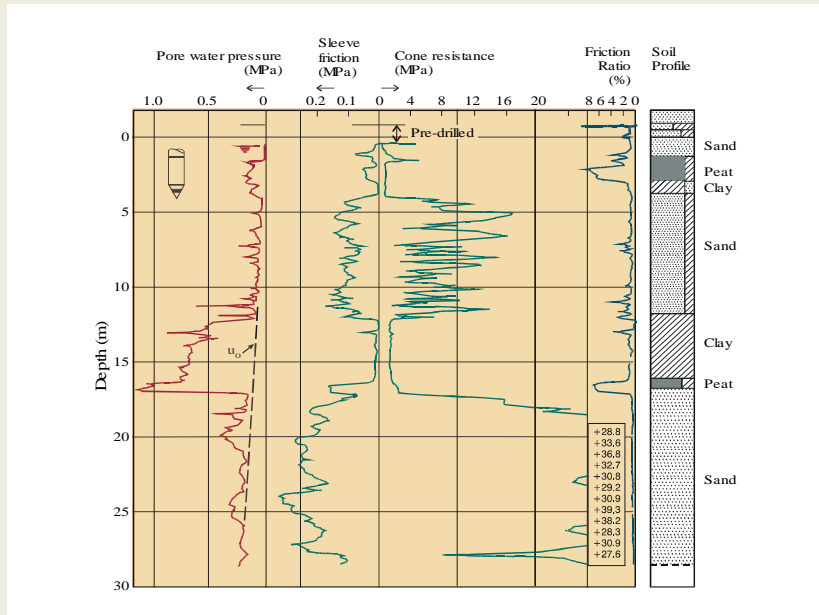
Example North Sea – clay and sand layers



Example North Sea – clay and sand layers

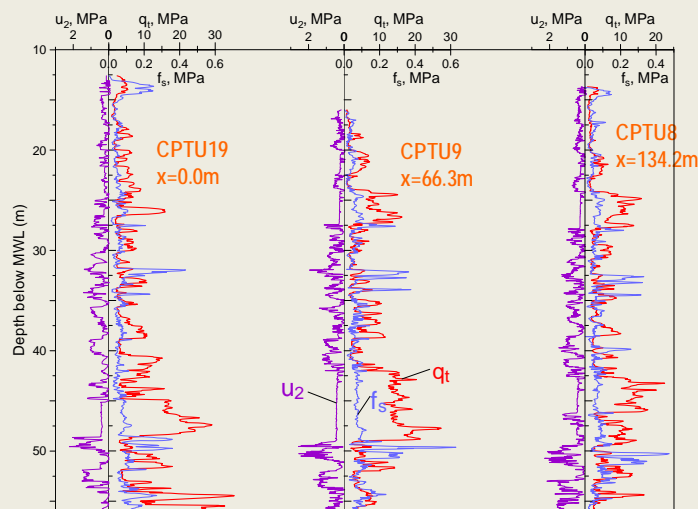


Example CPTU profile from Holland



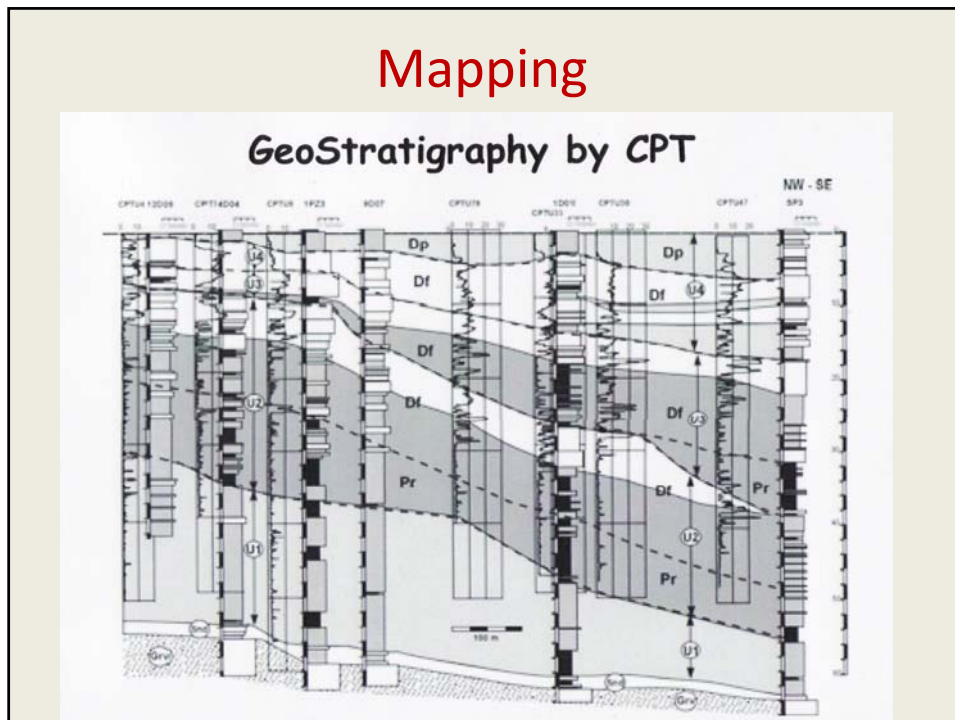
CPTU profiles in Venetian soils

High interbedding of soils from sands to silty clays



Venetian Soils (after S. Cola, 2001)

Mapping

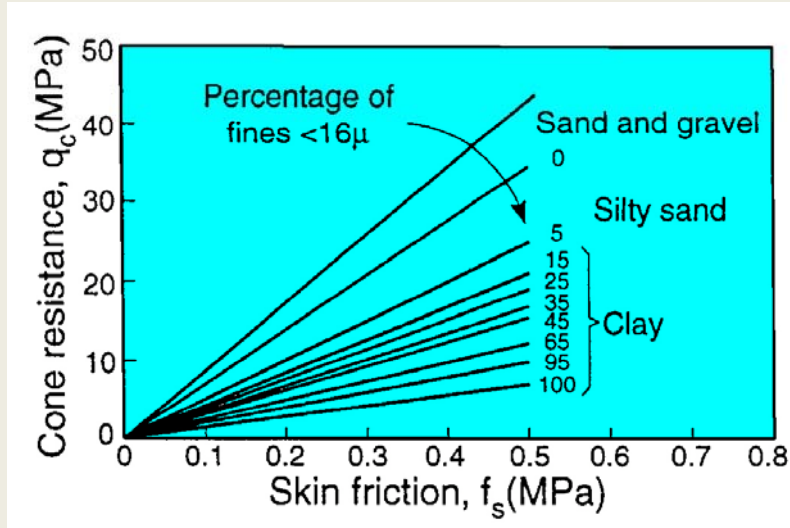


Soil Classification from CPT/CPTU data

Methodology:

1. Quantify observations used to identify soil stratigraphy.
2. Empirically based, i.e. measured CPT/CPTU data are correlated with known soil profiles.
3. Early charts relied on direct use of reduced data, e.g. q_c or q_t and f_s or R_f .
4. Later charts make use of normalized parameters to account for increasing overburden stress with depth, e.g. Q_t , B_q .

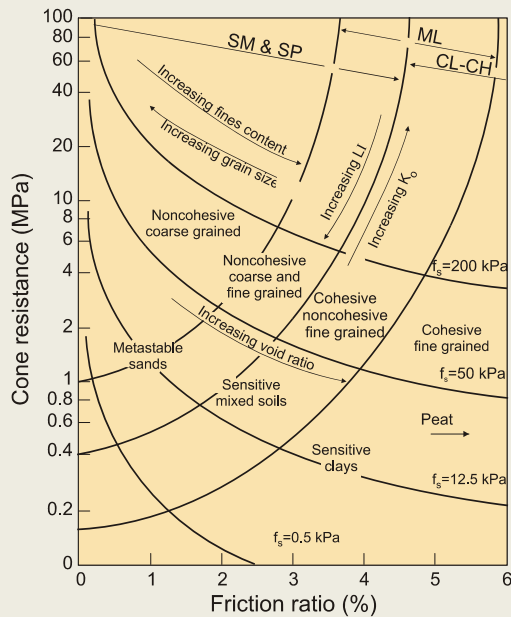
First CPT 'classification' chart



For mechanical cone

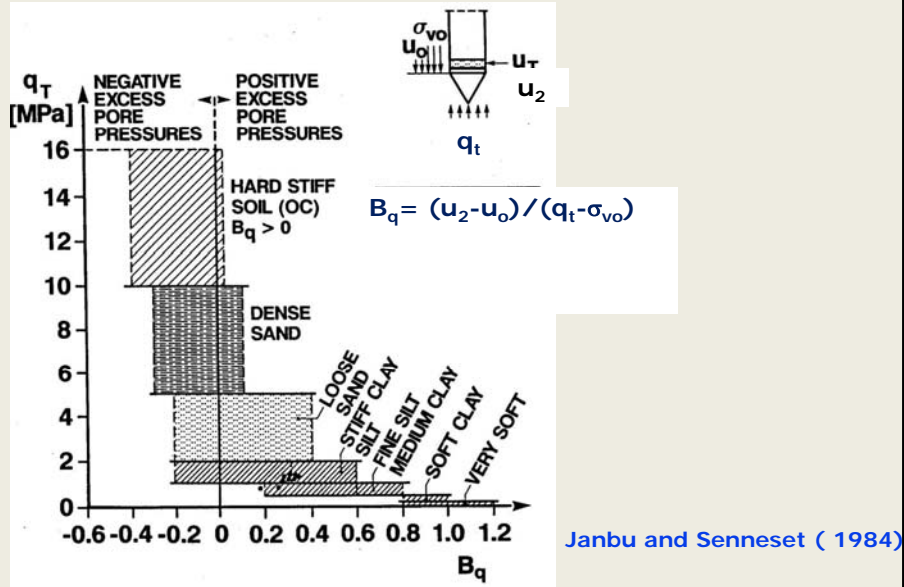
(Begemann, 1965)

Electrical friction CPT soil classification diagram

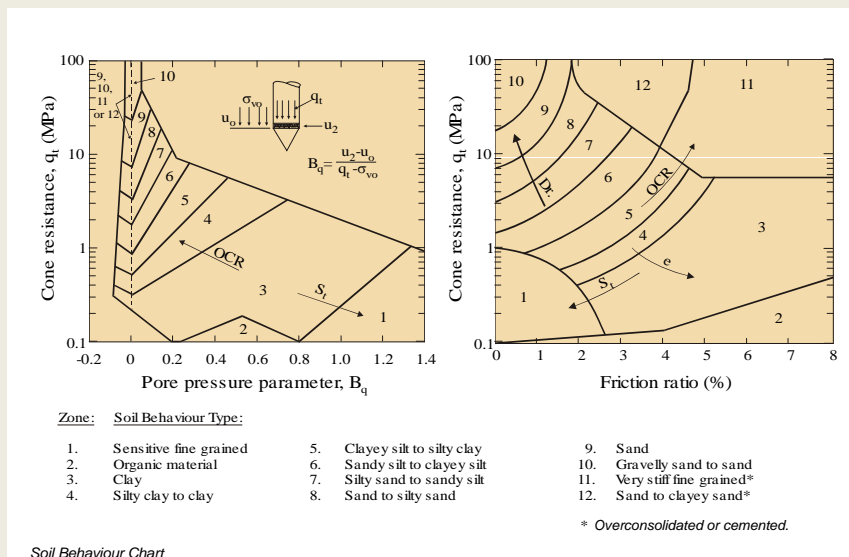


Douglas and Olsen (1981)

First soil classification chart using pore pressure

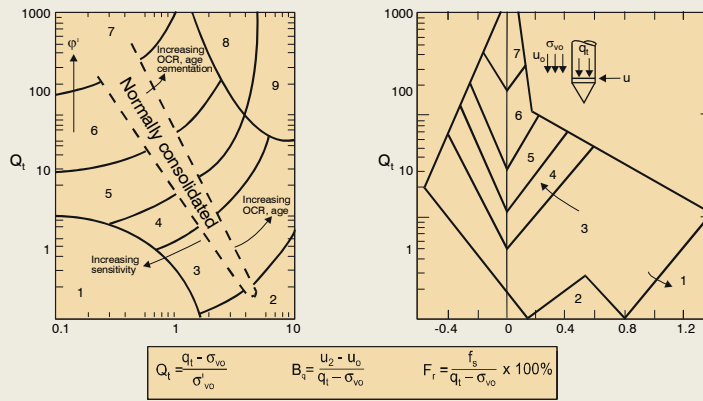


Soil behaviour classification chart



Robertson et al., 1986

Normalized soil behaviour classification chart



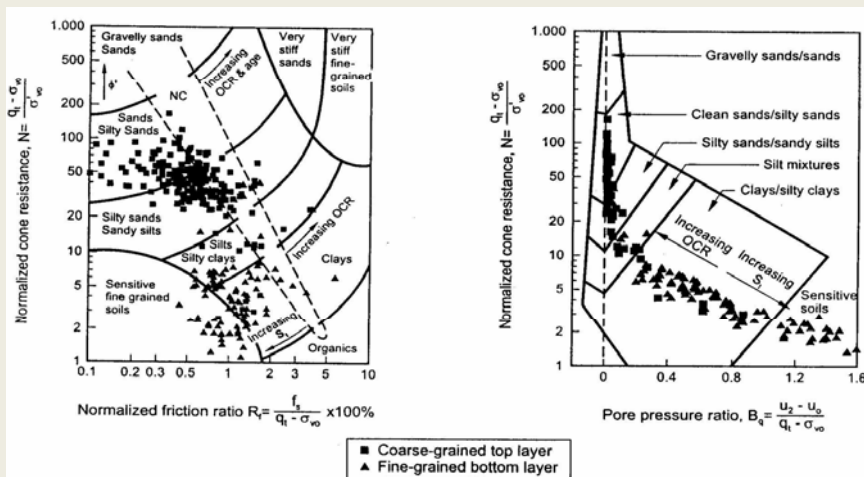
- Zone Soil behaviour type**
1. Sensitive, fine grained
 2. Organic soils-peats
 3. Clays-clay to silty clay

- Zone Soil behaviour type**
4. Silt mixtures clayey silt to silty clay
 5. Sand mixtures; silty sand to sand silty
 6. Sands; clean sands to silty sands

- Zone Soil behaviour type**
7. Gravely sand to sand
 8. Very stiff sand to clayey sand
 9. Very stiff fine grained

Robertson, 1990

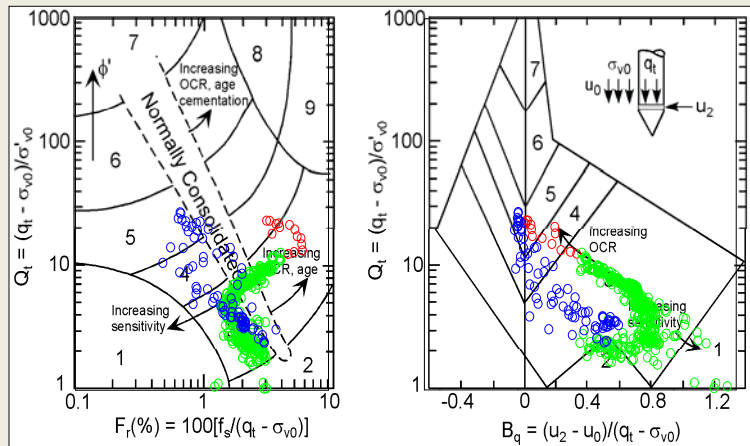
Example of use of soil classification chart for Oslo airport



Sandven et al., 1998

Example CPTU Soil Classification – Boston Blue clay

○ = "crust" ○ = Soft, moderately sensitive Clay ○ = "Interbedded silt, clay, sand"



Soil Behavior Type by Zone Number

- | | | |
|-----------------------------|--|-----------------------------------|
| 1. Sensitive, fine grained | 4. Silt mixtures clayey silt to silty clay | 7. Gravely sand to sand |
| 2. Organic soils-peats | 5. Sand mixtures; silty sand to sand silty | 8. Very stiff sand to clayey sand |
| 3. Clays-clay to silty clay | 6. Sands; clean sands to silty sands | 9. Very stiff fine grained |

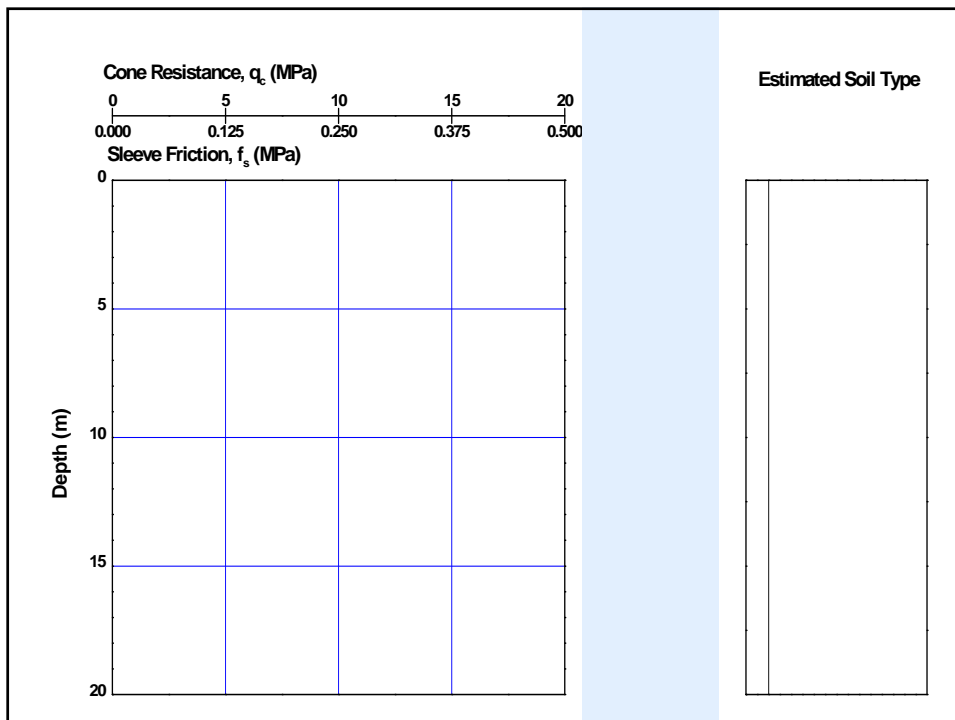
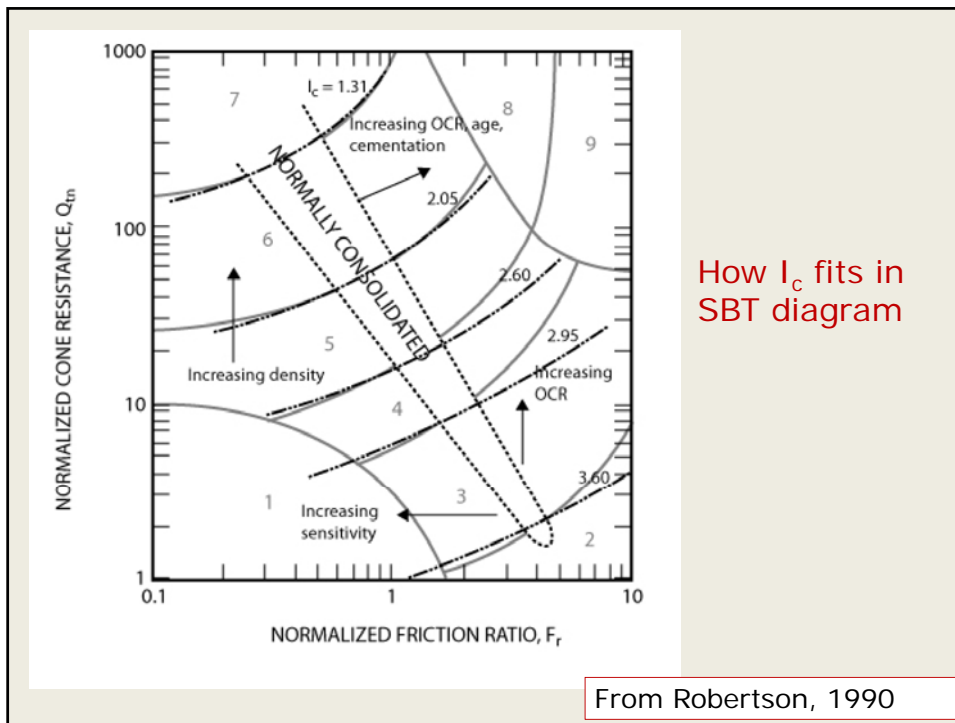
Definition of soil behaviour index, I_c

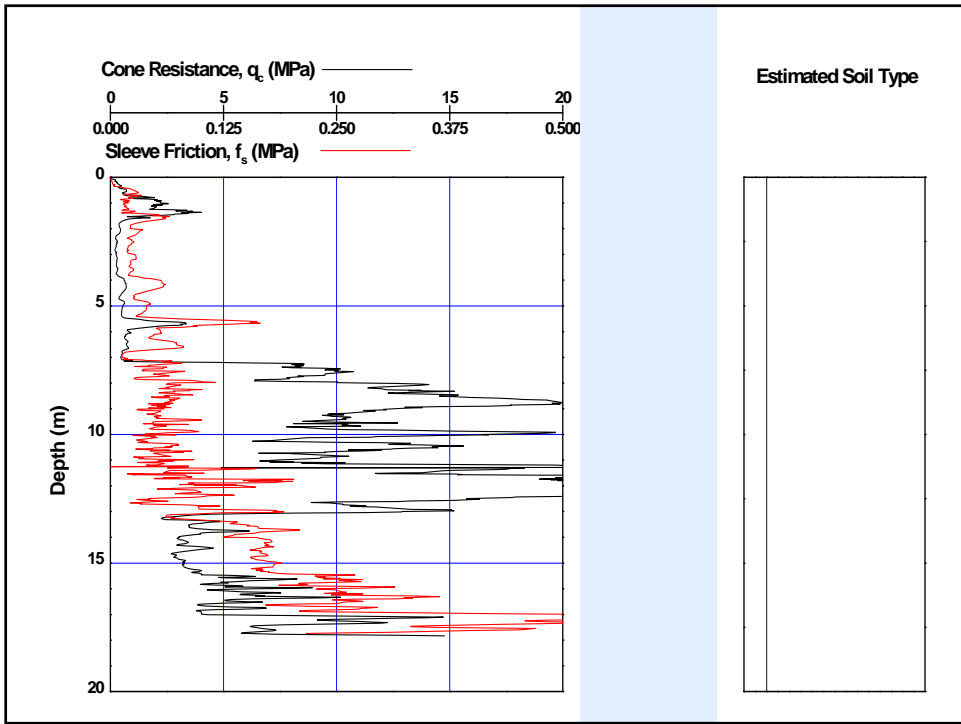
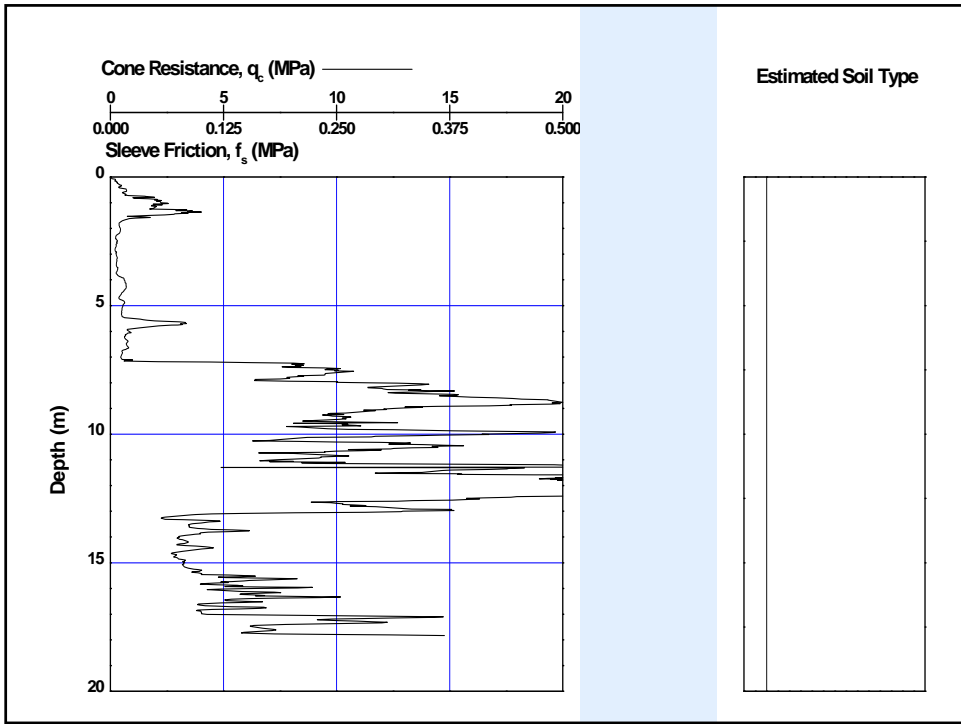
Robertson, 1990 defined I_c based on normalized parameters

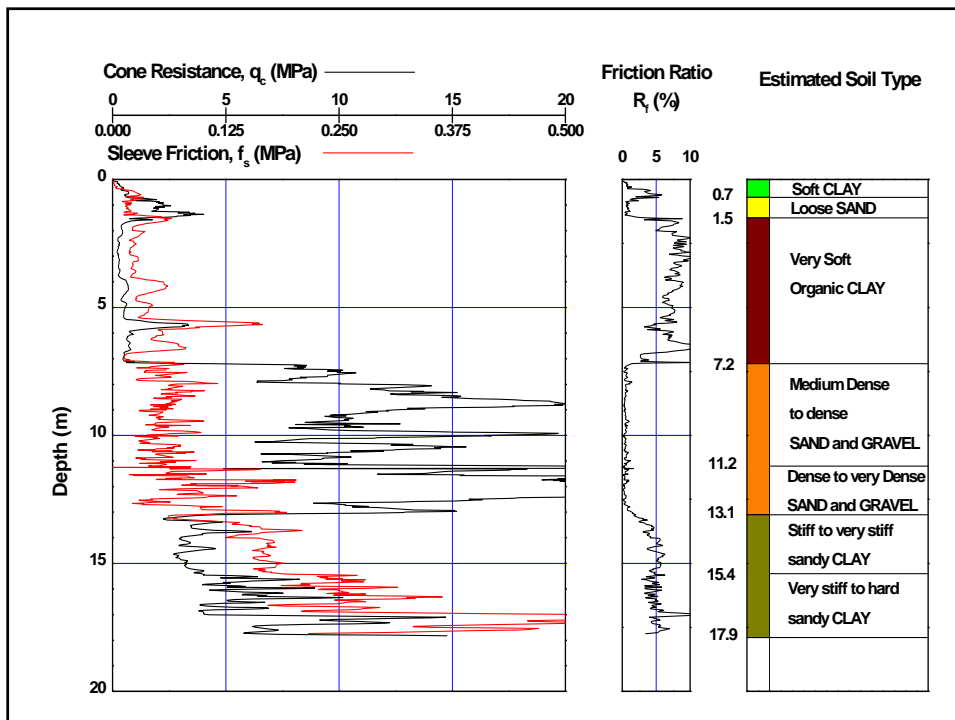
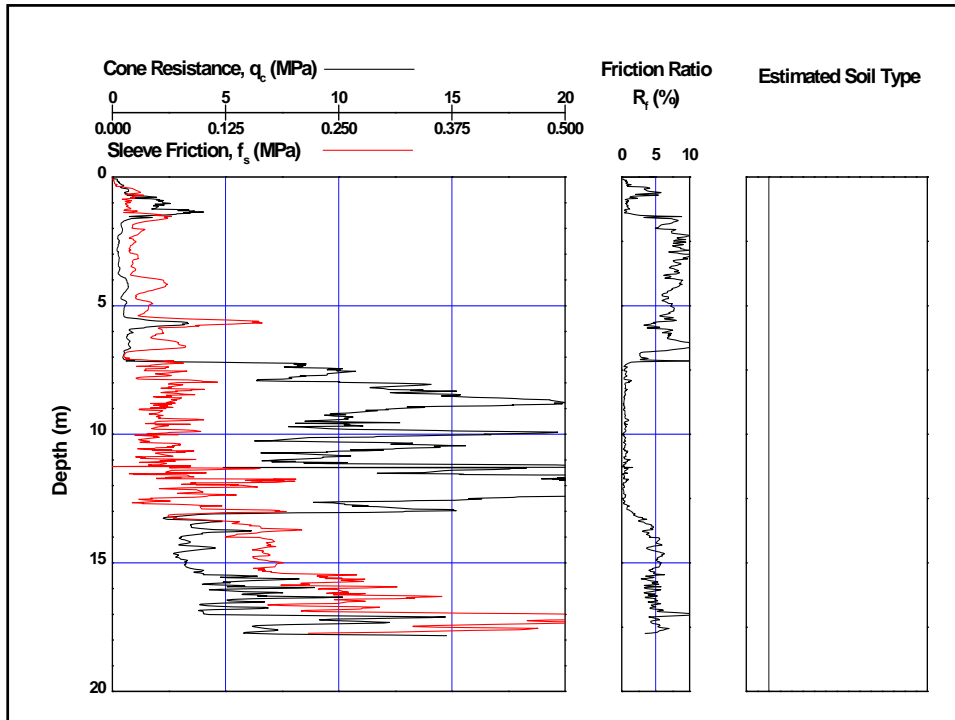
$$I_c = \left((3.47 - \log Q_t)^2 + (\log F_r + 1.22)^2 \right)^{0.5}$$

$$Q_t = \frac{q_t - \sigma_{v0}}{\sigma'_{v0}}, \quad F_r = \frac{f_s}{q_t - \sigma_{v0}}$$

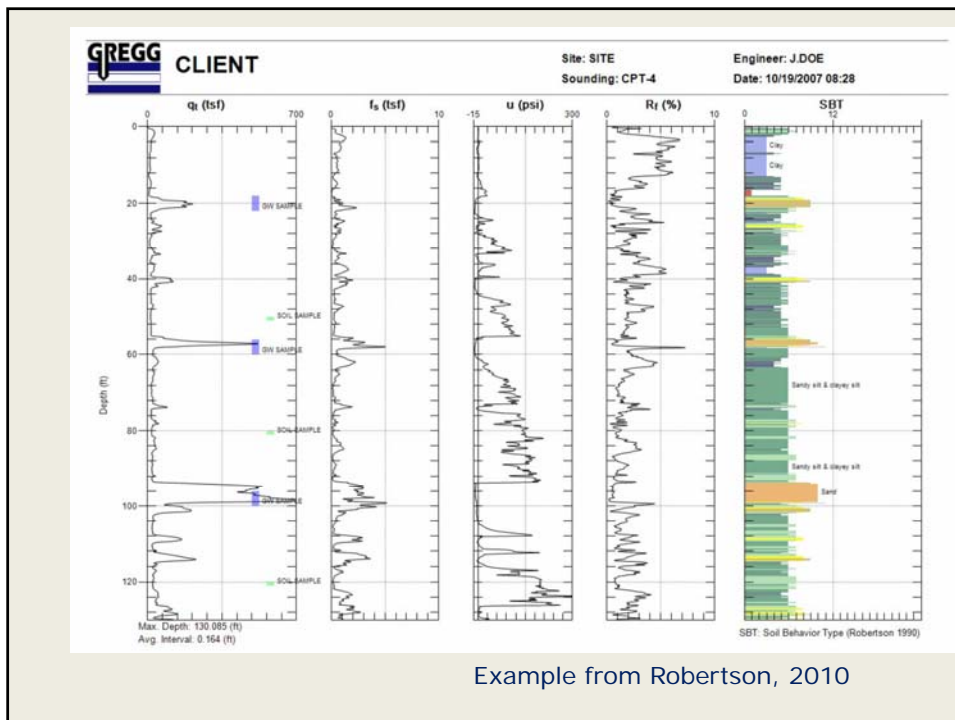
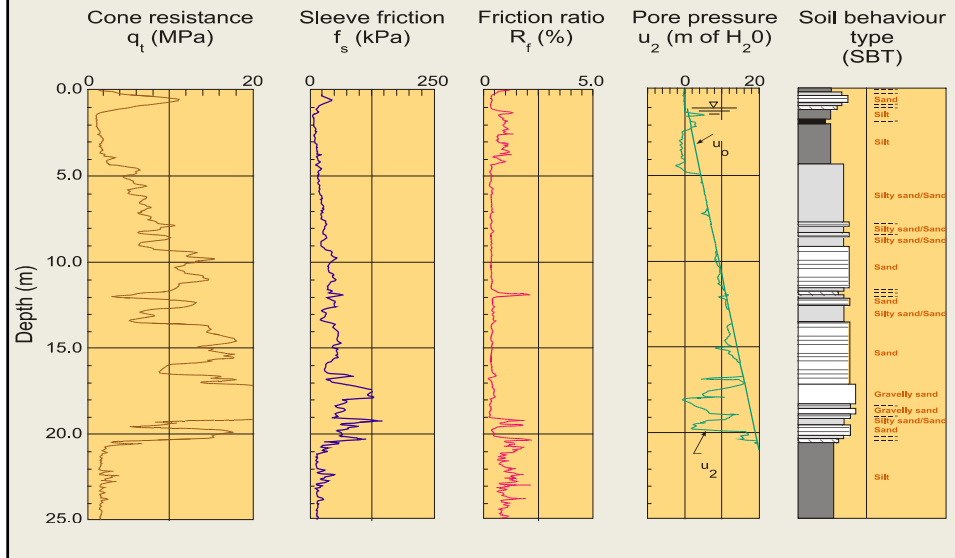
Can be used for a first computerized soil identification in field or in office



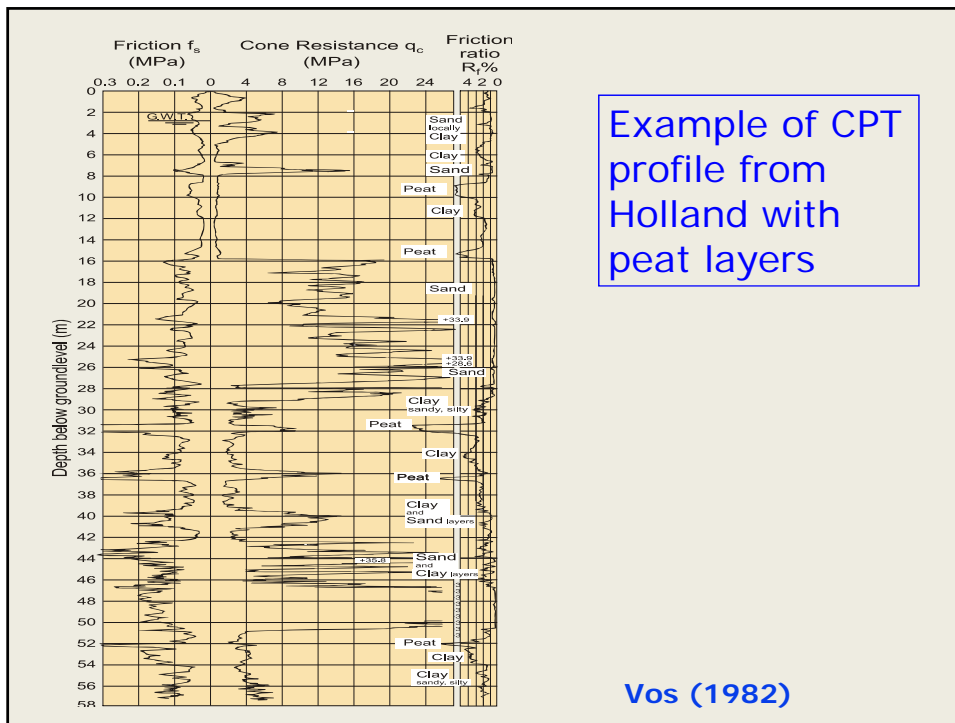




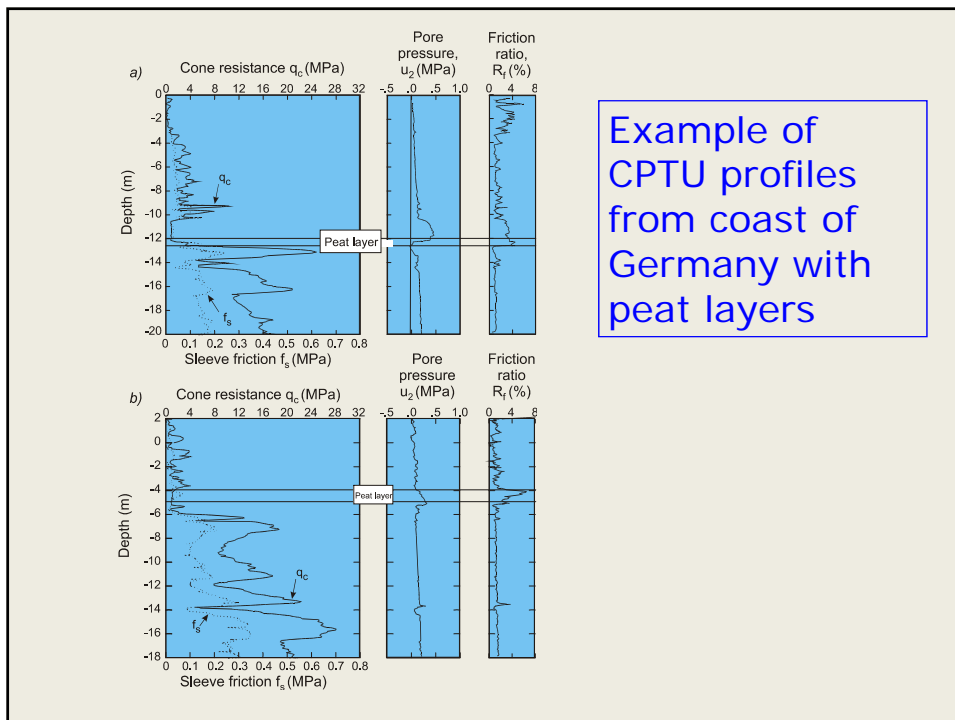
Example computerized soil identification from R_f charts



Example from Robertson, 2010



Example of CPT profile from Holland with peat layers



Example of CPTU profiles from coast of Germany with peat layers

Recommendations: CPT/CPTU based Soil Identification/Classification

- Use all information available, e.g., q_c or q_t , f_s , u , F_r , B_q
- Shape and magnitude of q_t profile gives indication on whether you are in uniform clay layer, sand layer, etc.
- Pore pressure profile readily indicates a drained condition (e.g., sand with $\Delta u = 0$) or undrained (e.g., clay with $\Delta u > 0$)
- Use $q_t - R_f - B_q$ and/or $Q_t - F_r - B_q$ diagrams to identify soil type. Accumulate local experience to create/modify diagrams.

Recommendations: CPT/CPTU based Soil Identification/Classification

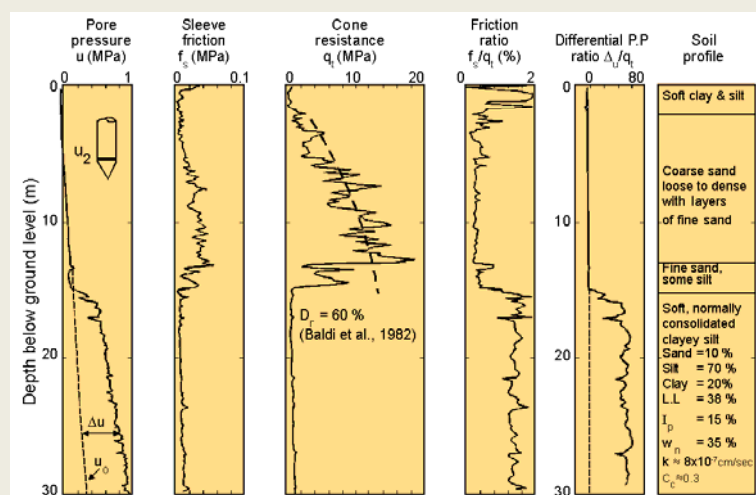
- Correlate 'signatures' with sampled borehole logs for 'local' classification
- Short dissipation tests can help in identifying soil type
- Measurements using other sensors can enhance soil identification (see later lecture also):

Seismic cone to get V_s
Electrical conductivity (or resistivity)
Nuclear density/Gamma con
Video cone

INTERPRETATION IN SAND - DRAINED CONDITIONS

- In situ state
 - relative density; porosity
 - in situ stresses, stress history
- Drained shear strength
- Deformation characteristics
 - constrained modulus (M)
 - Young's modulus (E_D)
 - Small strain or maximum shear modulus (G_{max})

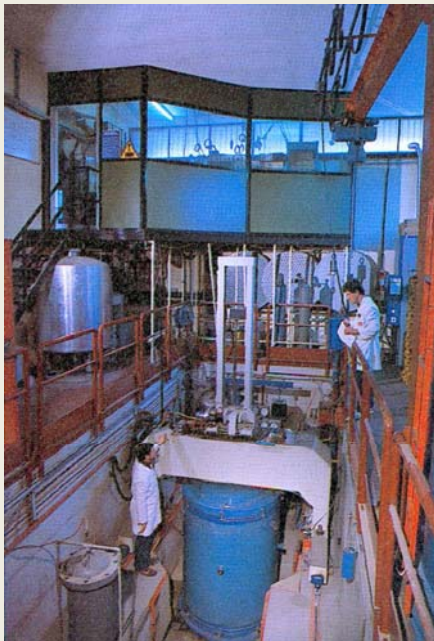
Example CPTU profile in sand



McDonald's Farm, Vancouver, Canada

CPT/CPTU INTERPRETATION

- Theories exist for modelling penetration of a cone for both drained and undrained conditions. Several simplifications and assumptions need to be made to use the different theories.
- Need to calibrate theories with experimental results from real soil.
- Key issue is to obtain realistic reference soil parameters
- Clay: Use laboratory tests on high quality samples. Field CPT/CPTU data
- Sand: CPT/CPTU measurements in large calibration chambers. Parallel laboratory tests on similar samples



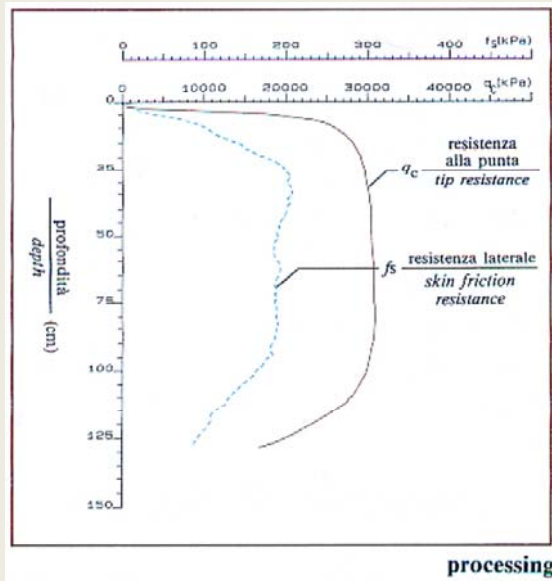
Large
Calibration
Chamber

ENEL Italy

Sand sample :

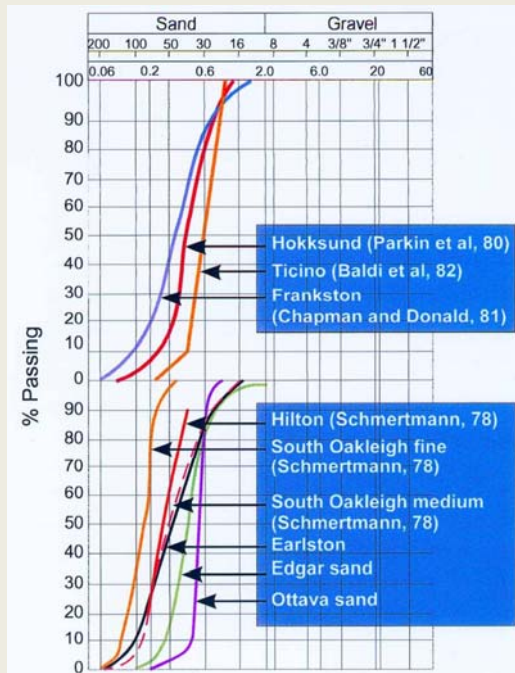
-diam. = 1.22 m

-height = 1.5 m



Calibration Chamber

Typical result from one test at ISMES, Italy



Calibration Chamber Tests

Grain size distribution curves of some sands used

Relative density, D_r (I_D)

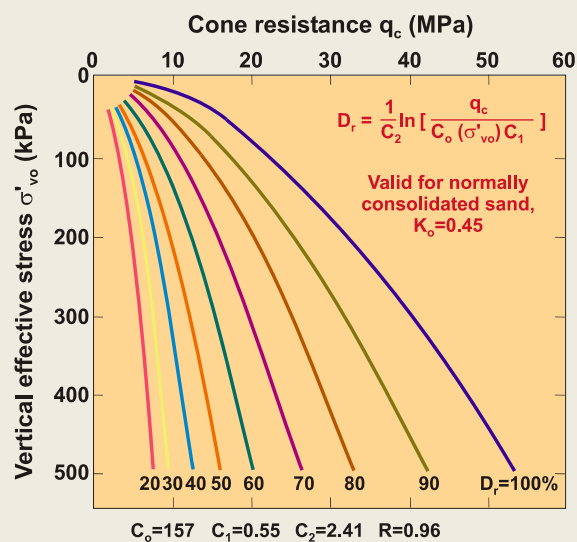
$$D_r(I_D) = \frac{e_{max} - e}{e_{max} - e_{min}}$$

e = in situ void ratio = volume of voids/volume of solids

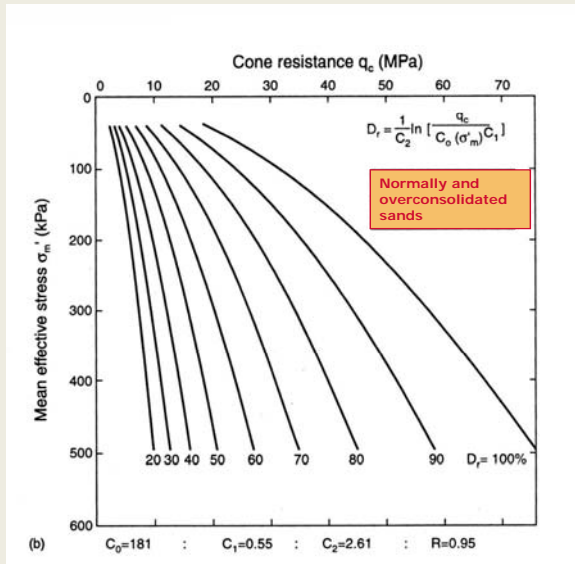
e_{max} = max. porosity (loosest state)

e_{min} = min. porosity (densest state)

q_c, σ'_{vo}, D_r relationship for Ticino NC sand



q_c, σ'_m, D_r relationship for Ticino OC and NC sand



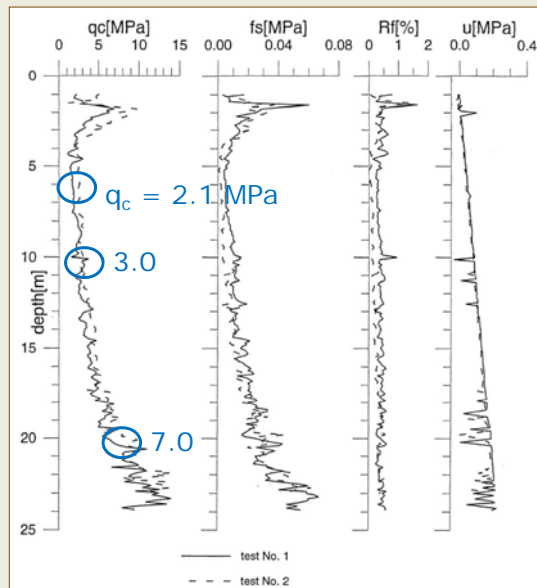
$$\sigma'_m = 1/3(\sigma'_{vo} + 2 \sigma'_{ho})$$

Need to estimate

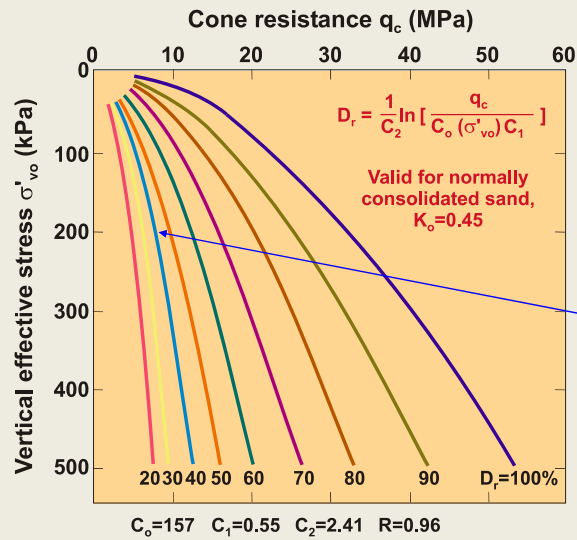
$$K_o = \sigma'_{ho} / \sigma'_{vo}$$

After Baldi et al. (1986)

Drammen sand : Results of 2 CPTUs



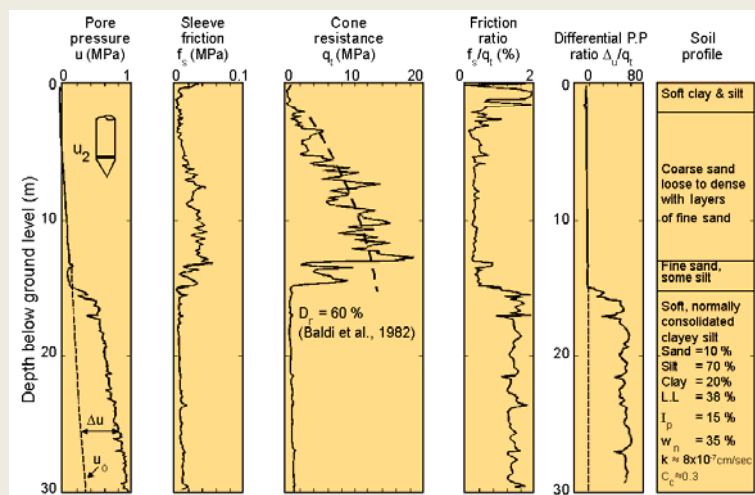
q_c, σ_{vo}', D_r relationship for NC sand



Drammen sand :

σ_{vo}, kPa	q_c, MPa	$D_r, \%$
60	2.1	27
100	3.0	28
200	7.0	43

Example estimating D_r in sand



McDonald's Farm, Vancouver, Canada

Factors that should be considered when estimating D_r in situ

- Charts valid for fine to medium uniform, moderately compressible, unaged and uncemented sands
- For compressible sands at a given D_r q_c will reduce, hence D_r may be underestimated
- Increase in grain size can increase cone resistance, hence D_r may be overestimated

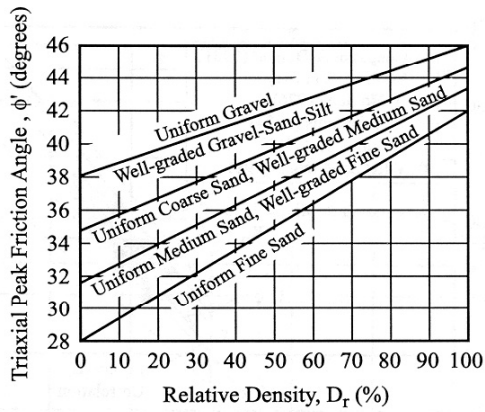
We should not consider the interpreted D_r values as absolute true values -- better to use NOMINAL (e.g. Schmertmann, 1991).

DRAINED SHEAR STRENGTH, ϕ_D' , FROM CPT

Four most common methods:

- 1 Empirical D_r approach
 - use estimated D_r and then correlation $(\phi_D'/D_r)/\sigma_{v0}'$
 - or carry out triaxial tests reconstituted to D_r from CPT
- 2 Empirical calibration chamber correlation
- 3 Empirical field and lab correlation
- 4 Bearing capacity method

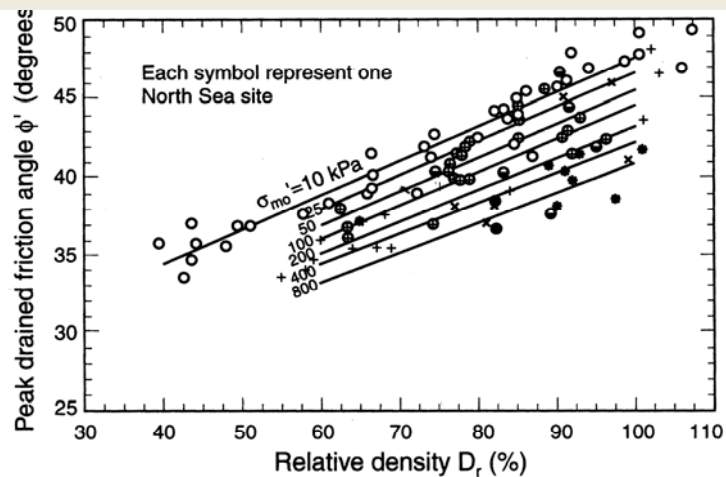
Simplified relationship between ϕ' and D_r



After
Schmertmann(1978)

Very rough correlation since $\phi' = f(D_r, \sigma_{vo}', \sigma_{ho}')$

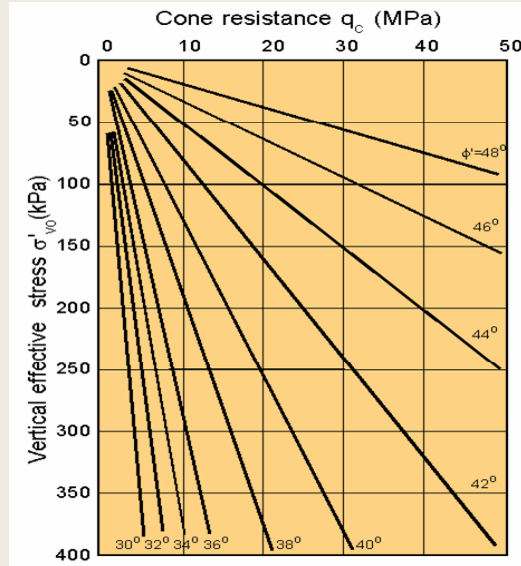
Correlations between ϕ' , D_r and σ_{mo}' for fine medium, uniform quartz sand



$$\sigma_{mo}' = (\sigma_{vo}' + 2 \cdot \sigma_{ho}') / 3 = \text{mean effective stress}$$

$$\sigma_{mo}' = \sigma_{vo}' \cdot (1 + 2 \cdot K_o) / 3 \quad K_o = \sigma_{ho}' / \sigma_{vo}'$$

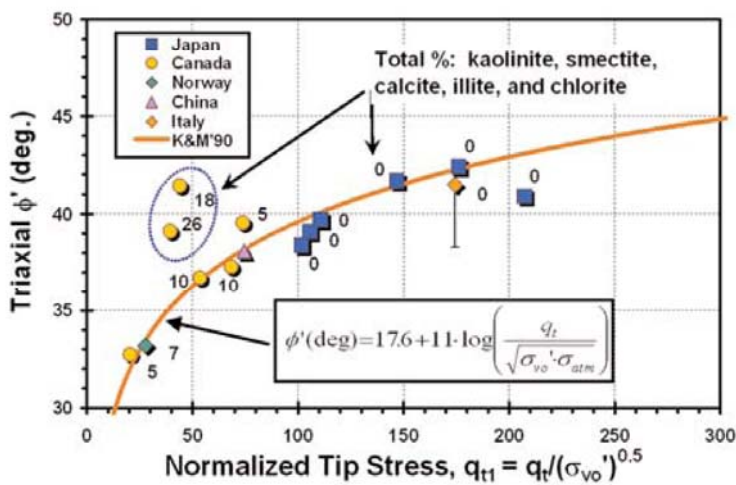
σ_v', q_c, ϕ' relationships



Based on
Calibration
Chamber Data

From Robertson and
Campanella(1983)

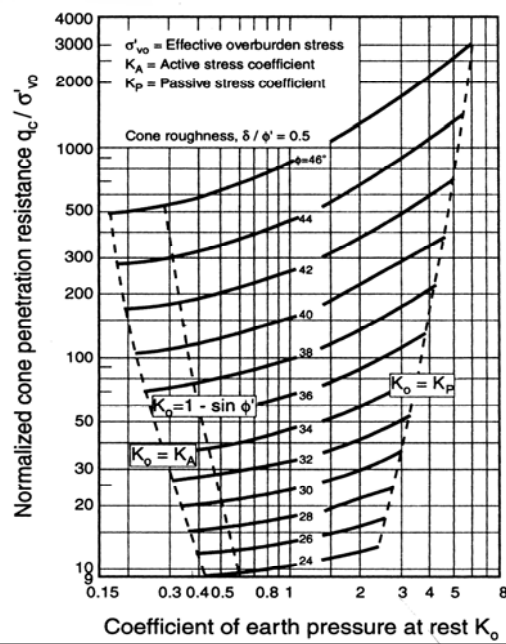
σ_v', q_t, ϕ' relationships



Based on
field and
lab data

From Mayne(2006)

Chart for predicting peak friction angle from q_c , σ_{vo}' , K_o



Dorgunoglu and Mitchell bearing capacity theory

(after Marchetti, 1988)

$$K_o = \sigma_{ho}' / \sigma_{vo}'$$

ϕ' in sands

EXAMPLE :

Depth=10 m ; $q_c = 10$ MPa ; $\sigma_{vo}' = 70$ kPa ; $K_o = 0.4$; $\sigma_{mo}' = 42$ kPa

- $\phi' = f(D_r, \sigma_{mo}')$ gives $\phi' = 40^\circ$

Fig. 5.54

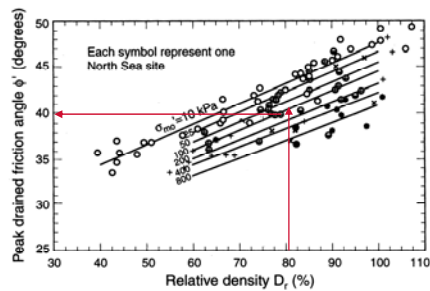
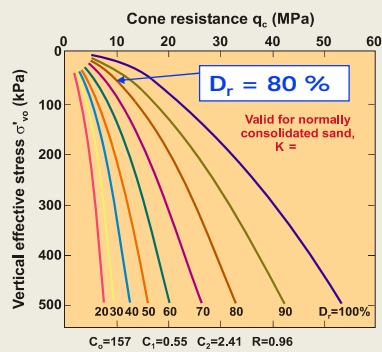


Fig. 5.54

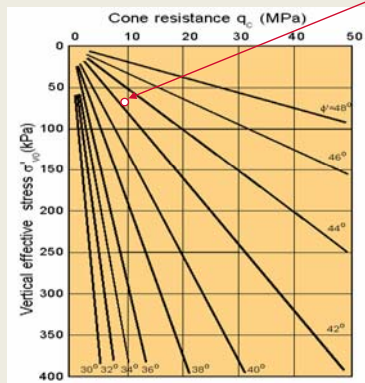
ϕ' in sands

EXAMPLE :

Depth=10 m ; $q_c = 10$ MPa ; $\sigma_{vo}' = 70$ kPa ; $K_o = 0.4$; $\sigma_{mo}' = 42$ kPa

- $\phi' = f(q_c/\sigma_{vo}')$ gives $\phi' = 43^\circ$

Fig. 5.56



ϕ' in sands

EXAMPLE :

Depth=10 m ; $q_t = 10$ MPa ; $\sigma_{vo}' = 70$ kPa ; $K_o = 0.4$; $\sigma_{mo}' = 42$ kPa

$$\phi' = 17.6^\circ + 11 \log \left(\frac{(q_t - \sigma_{vo}')}{(\sqrt{\sigma_{vo}' * \sigma_{atm}})} \right) \quad \phi' = 40.5^\circ$$

Mayne (2006)

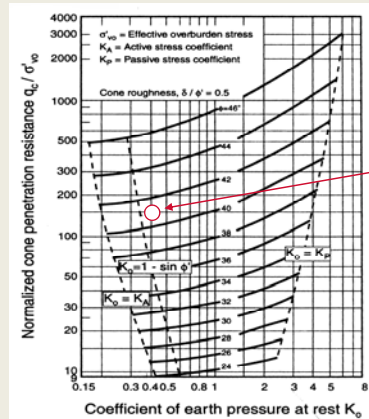
$$\sigma_{atm} = 100 \text{ kPa}$$

ϕ' in sands

EXAMPLE :

Depth=10 m ; $q_c = 10 \text{ MPa}$; $\sigma_{vo}' = 70 \text{ kPa}$; $K_o = 0.4$; $\sigma_{mo}' = 42 \text{ kPa}$

- $\phi' = f(q_c/\sigma_{vo}', K_o)$ gives $\phi' = 41^\circ$ Fig. 5.58



$\phi' = 41^\circ$

ϕ' in sands

EXAMPLE :

Depth=10 m ; $q_c = 10 \text{ MPa}$; $\sigma_{vo}' = 70 \text{ kPa}$;

$K_o = 0.4$ $\sigma_{mo}' = 42 \text{ kPa}$

- $\phi' = f(D_r, \sigma_{mo}')$ gives $\phi' = 40^\circ$ Fig. 5.54
- $\phi' = f(q_c/\sigma_{vo}')$ gives $\phi' = 43^\circ$ Fig. 5.56
- $\phi' = 17.6^\circ + 11 \log((q_t - \sigma_{vo}')/(\sqrt{\sigma_{vo}'} * \sigma_{atm}))$ $\phi' = 40.5^\circ$
- $\phi' = f(q_c/\sigma_{vo}', K_o)$ gives $\phi' = 41^\circ$ Fig. 5.58

Use the value of ϕ' that is most conservative for the design problem at hand:

- For bearing capacity use $\phi' = 40^\circ$
- For pile driving resistance use $\phi' = 43^\circ$

INTERPRETATION OF CPT IN TERMS OF DEFORMATION PARAMETERS IN SAND

Modulus to use depends on level of deformation, stress level and boundary conditions.

- 1 *Young's modulus, E*
Applicable where lateral deformations are possible



In laboratory \Rightarrow triaxial test

- 2 *Constrained modulus, M*
Applicable when there are no lateral deformations.



In laboratory \Rightarrow consolidation test

- 3 *Dynamic (or maximum shear modulus, G_{max})*
Required in analysis involving very small strain (e.g. 10^{-3}).
E.g. dynamic loading to wave action, earthquake or machine foundations.

CORRELATIONS BETWEEN CONE RESISTANCE AND CONSTRAINED MODULUS, M FOR SANDS

Rough estimate from calibration chamber tests:

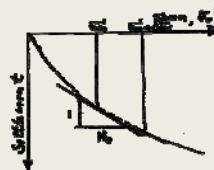
NC sands: $M_0 = 4 q_c$ $q_c < 10 \text{ MPa}$
 $M_0 = 2 q_c + 20 \text{ (MPa)}$ for $10 \text{ MPa} < q_c < 50 \text{ MPa}$
 $M_0 = 120 \text{ MPa}$ $q_c > 50 \text{ MPa}$
 OC sands: $M_0 = 5 q_c$ $q_c < 50 \text{ MPa}$
 $M_0 = 250 \text{ MPa}$ $q_c > 50 \text{ MPa}$

Ref. Lunne and Christophersen (1983)

M_0 is tangent modulus at in situ stress conditions, σ_{v0}' .

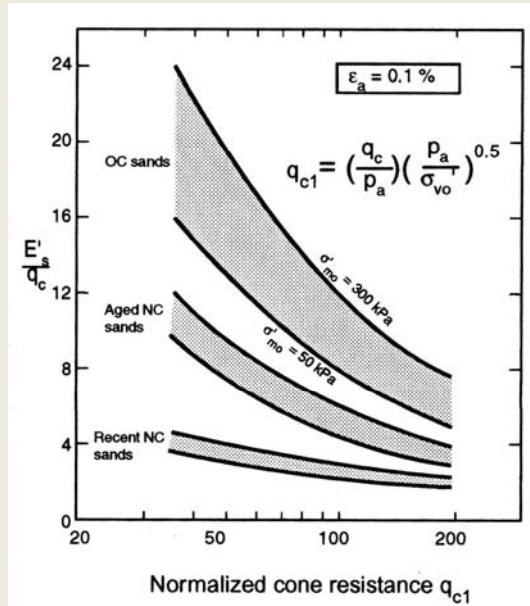
Tangent modulus applicable for stress range $\sigma_{v0}' + \Delta\sigma_v'$ is given as:

$$M = M_0 \sqrt{\frac{(\sigma_{v0}' + \Delta\sigma_{v0}')/2}{\sigma_{v0}'}}$$



Ref. Modulus concept by Janbu(1969)

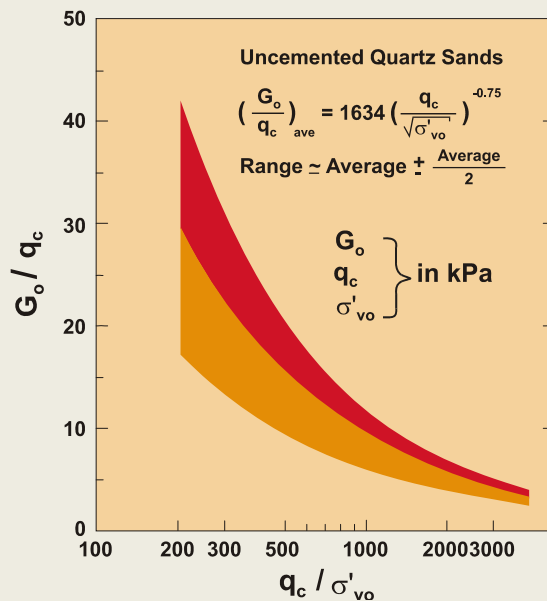
Evaluation of drained Young's modulus from CPT



E - modulus at 0.1 % axial strain

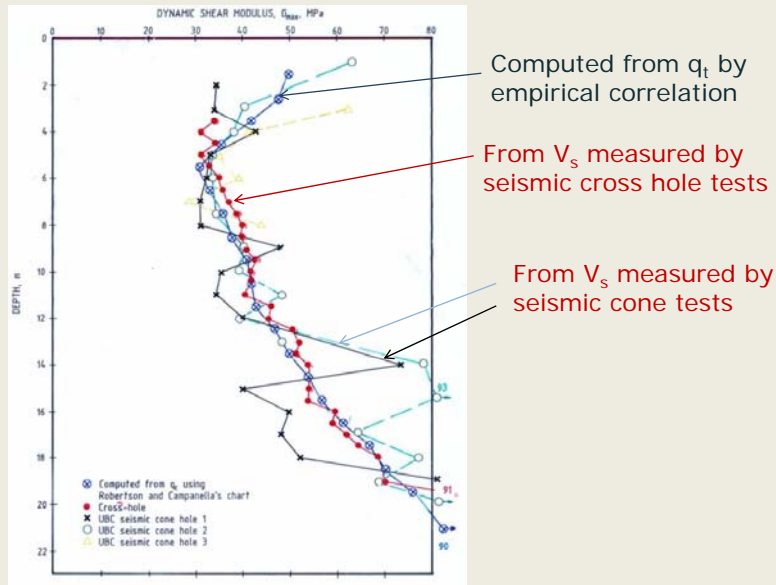
From Baldi et al. (1989)

Small strain shear modulus, G_{max}



After Rix and Stokoe (1992)

Drammen sand : G_{max} from CPT correlation, from seismic cone and from Cross Hole



Summary Interpretation in sand

- Check if drained conditions ($\Delta u = 0$)
- Estimate grain size (preferably from samples -- if not available from classification chart)
- Use correlations from Calibration Chamber tests. Modify if sand is different to Høksund and Ticino (grain size, mineralogy, compressibility)
- 'Nominal' D_r : Correlations to D_r are approximate and sensitive to variations in soil compressibility and horizontal stress. Correlations are uncertain at shallow depth. Use several correlations if available
- Reasonably good correlations exist for drained friction angle ϕ' and moduli M , E and G_{max}