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})*

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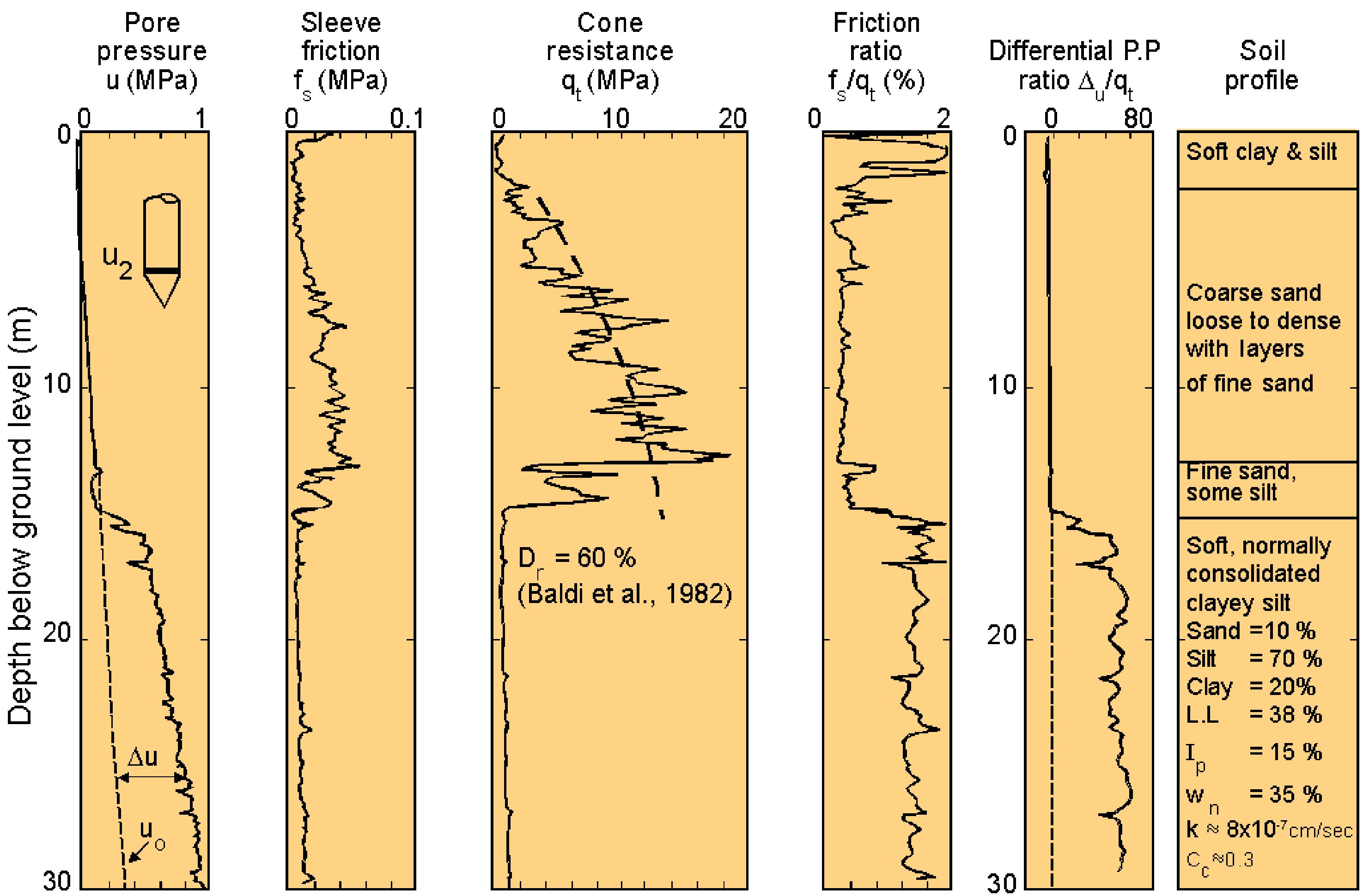
Example CPTU profile in sand



McDonald's Farm, Vancouver, Canada

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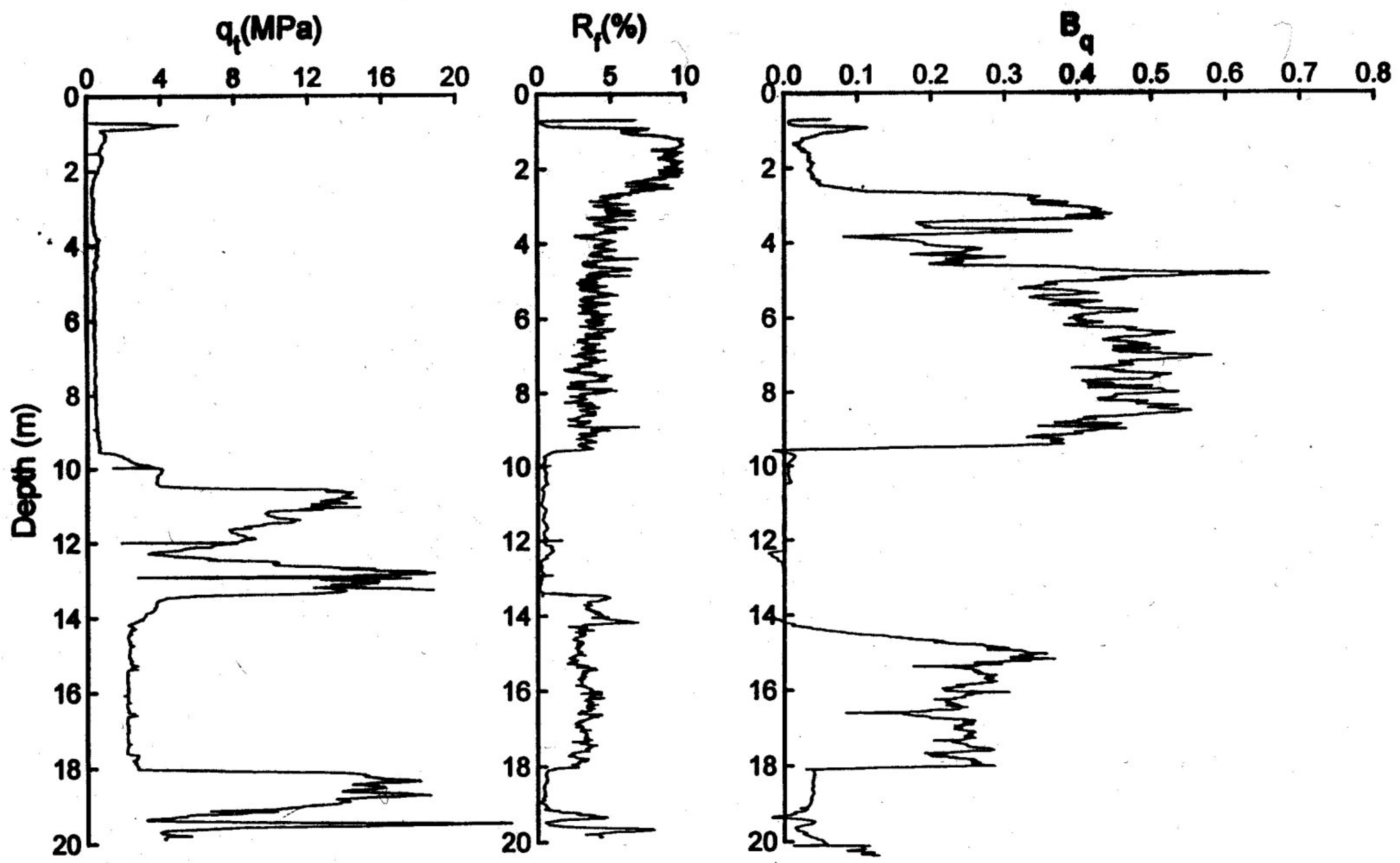
Example derived CPTU parameters



Example: Derived CPTU Parameters

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 laboratoy tests on high quality samples. Field CPT/CPTU data**

- **Sand: CPT/CPTU measurements in large calibration chambers. Parallel laboratory tests on similar samples**

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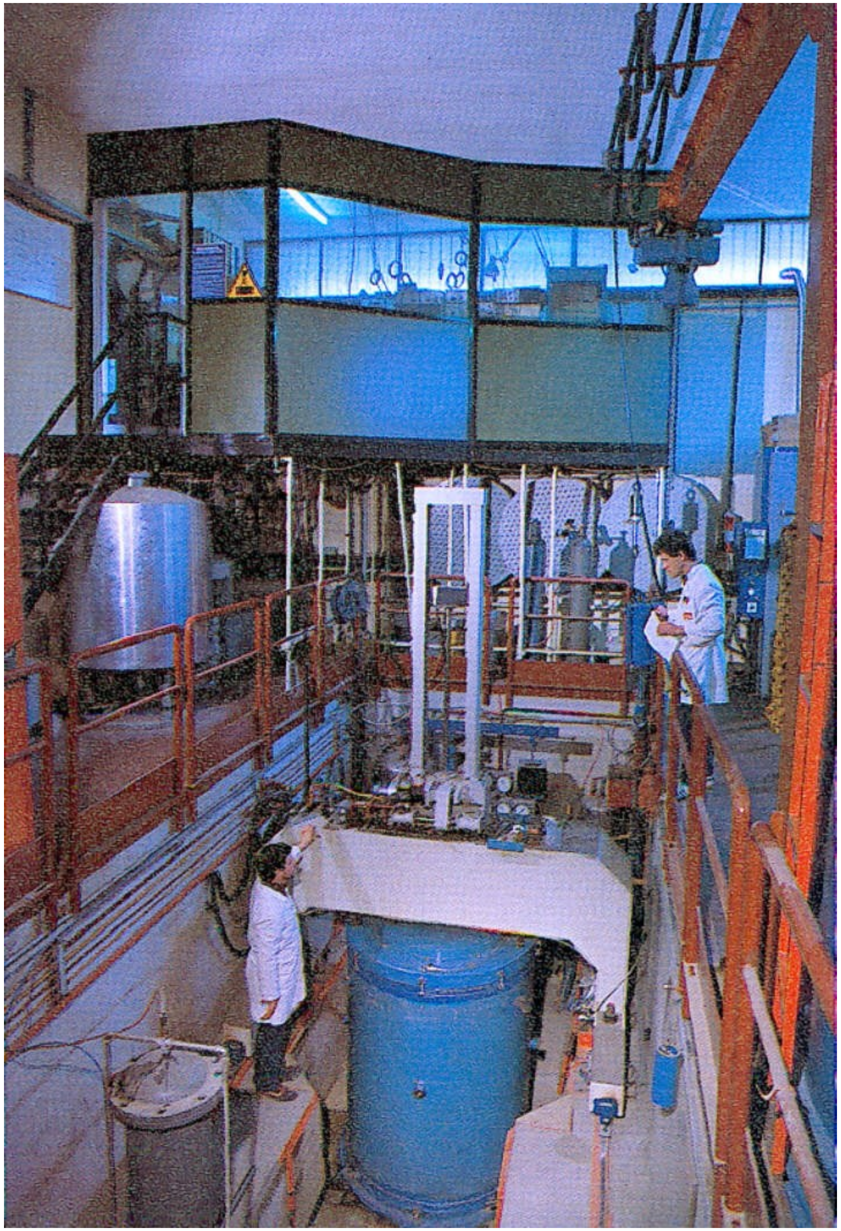


Large Calibration Chamber

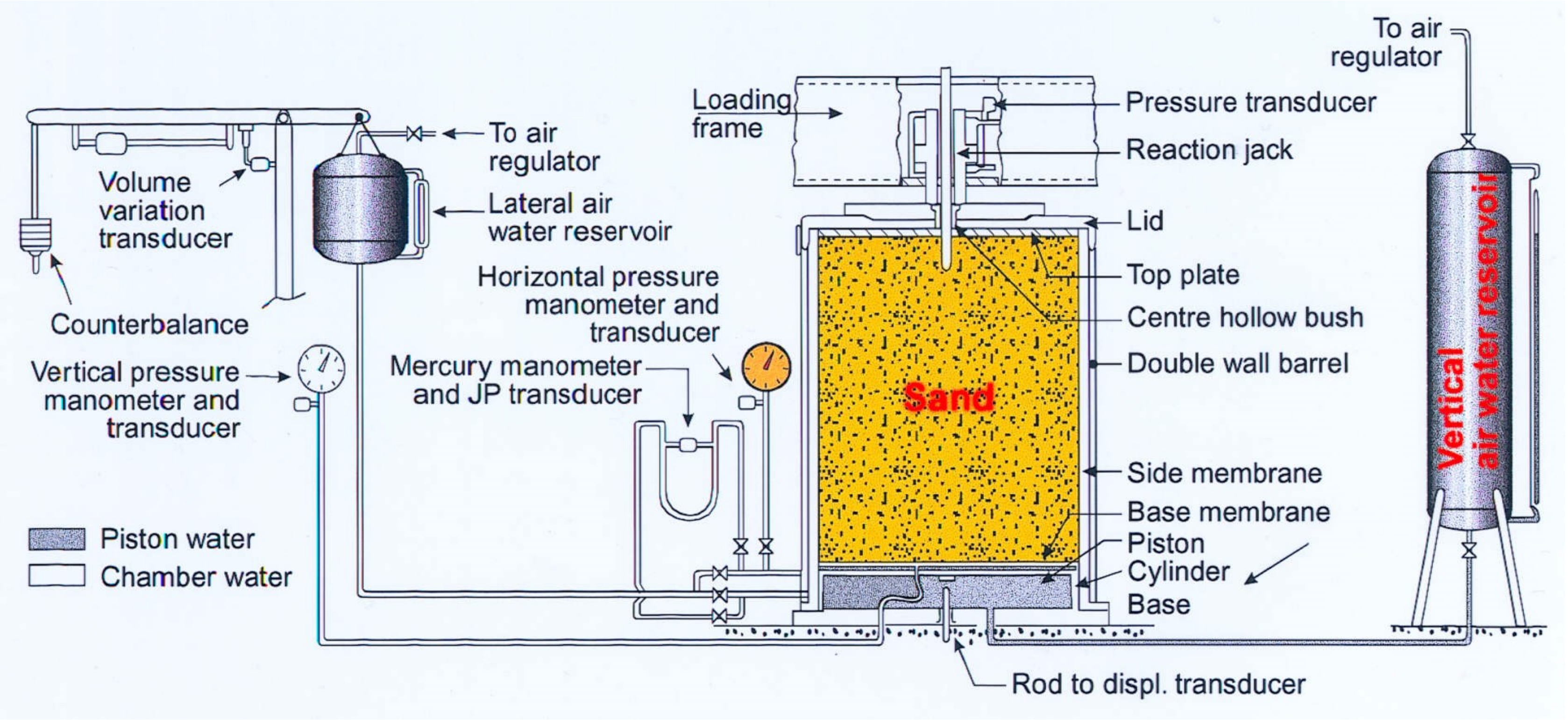
ENEL Italy

Sand sample :

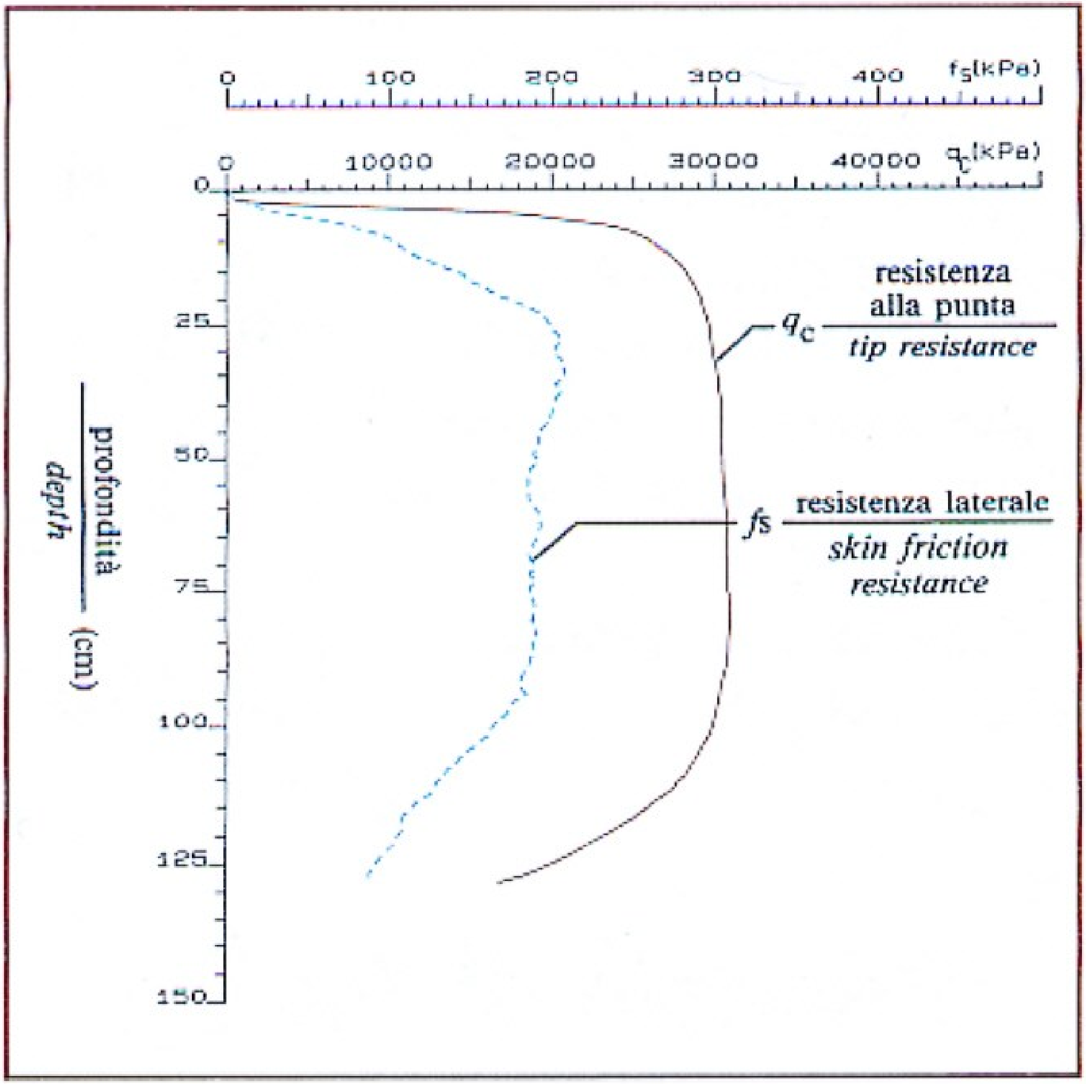
-diam. = 1.22 m

-hight = 1.5 m

ENEL Calibration Chamber - Schematic working principle

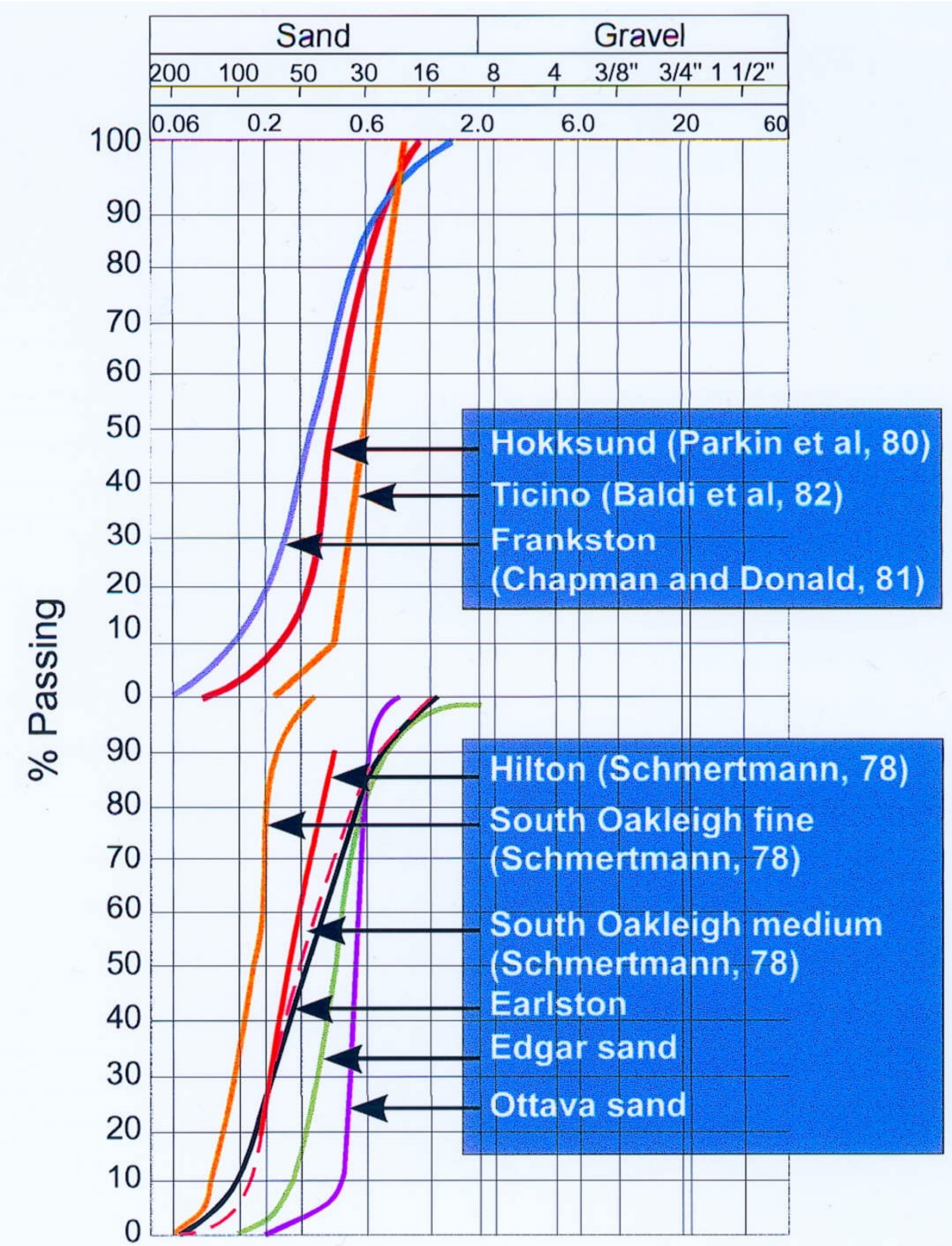


From Belotti et al.(1988)



Calibration Chamber

Typical result from one test at ISMES, Italy



Calibration Chamber Tests

Grain size distribution curves of some sands used

Correlations based on CC tests on these sands valid for young, uncemented, fine to medium, uniform, predominnatly quartz sands

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CPT/CPTU INTERPRETATION IN SITU STATE

- **Relative density/soil unit weight**
- **Effective stresses; vertical and horizontal**
- **Stress history**

Illustrate interpretation by two examples:

-Loose Drammen sand

-Very dense North Sea Sleipner sand

Alternative for sands:State parameter - Combining in situ stress and void ratio

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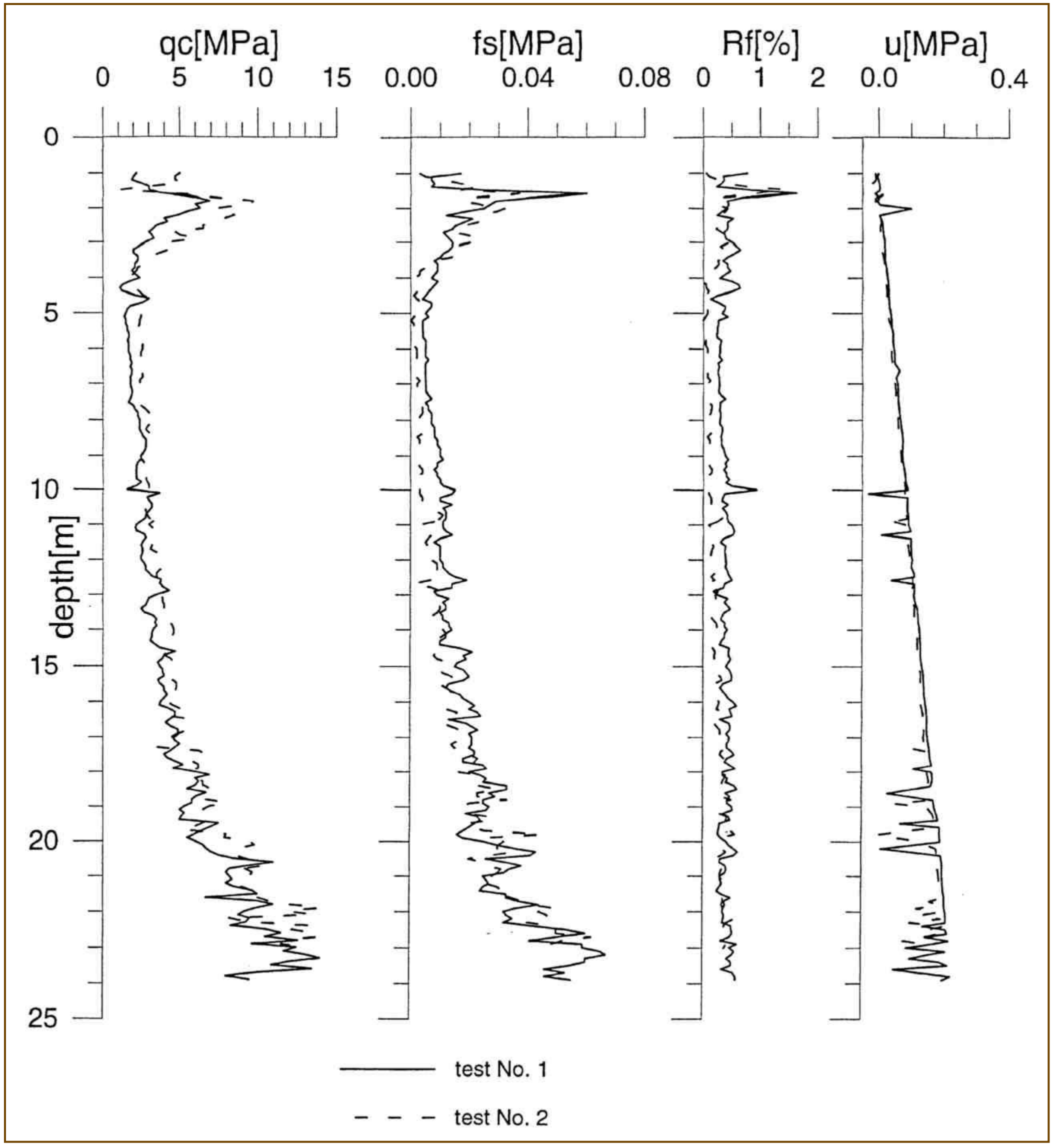
Aerial photo of Holmen Island in Drammen Fjord/River

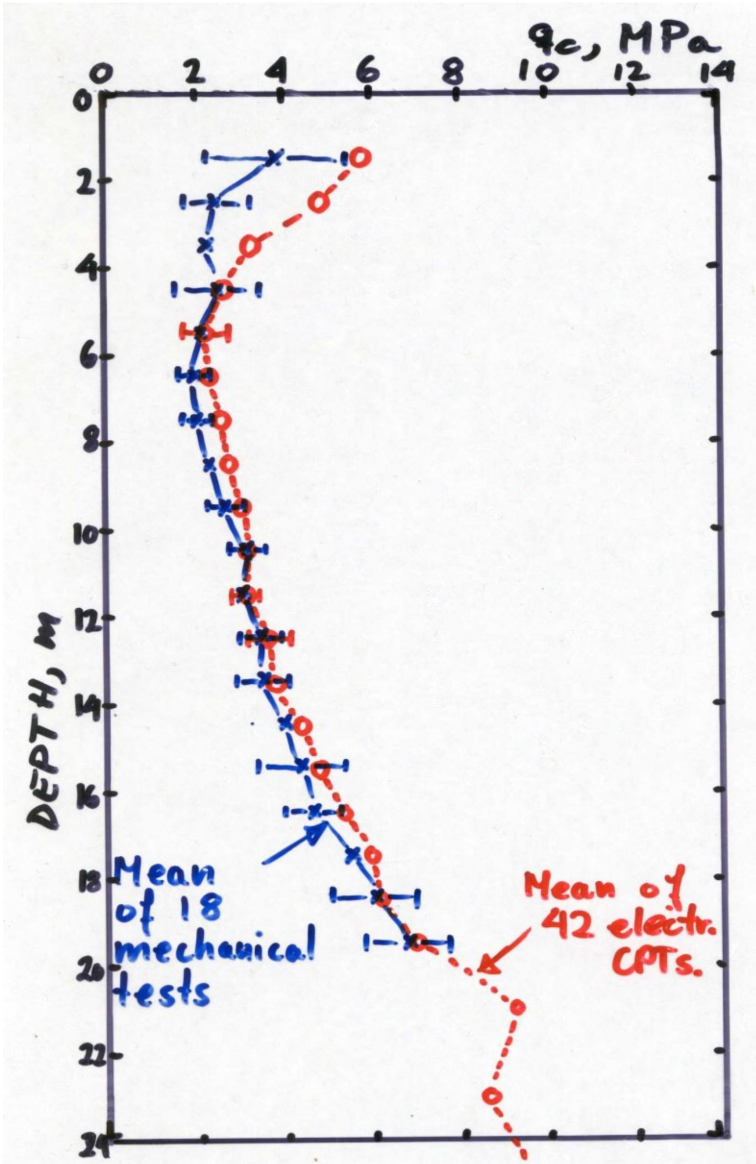
DRAMMEN SAND,Norway

- Very uniform layer 2-22m below GL
- WL ≅ 1.5m below GL
- Deposited 2-4000 years ago
- Not overconsolidated
- Comparable origin to Hokksund sand (20 km away)
- Dilatometer test indicate $K_0 \cong 0.4$
- Used by NGI for in situ testing and other research for 40 years

Drammen sand : Results of 2 CPTUs



Drammen sand test site



Comparison of mechanical CPTs carried out in 1950's compared with more recent electrical CPT/CPTU profiles

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SLEIPNER SAND

- Located in 80m depth in North Sea
- Deposited less then 100,000 years ago
- Not believed to be preloaded by ice
- Very high density postulated to be result of compaction by wave activity at shallow water depth
- State of the art offshore soil investigations for installation of large gravity base structure

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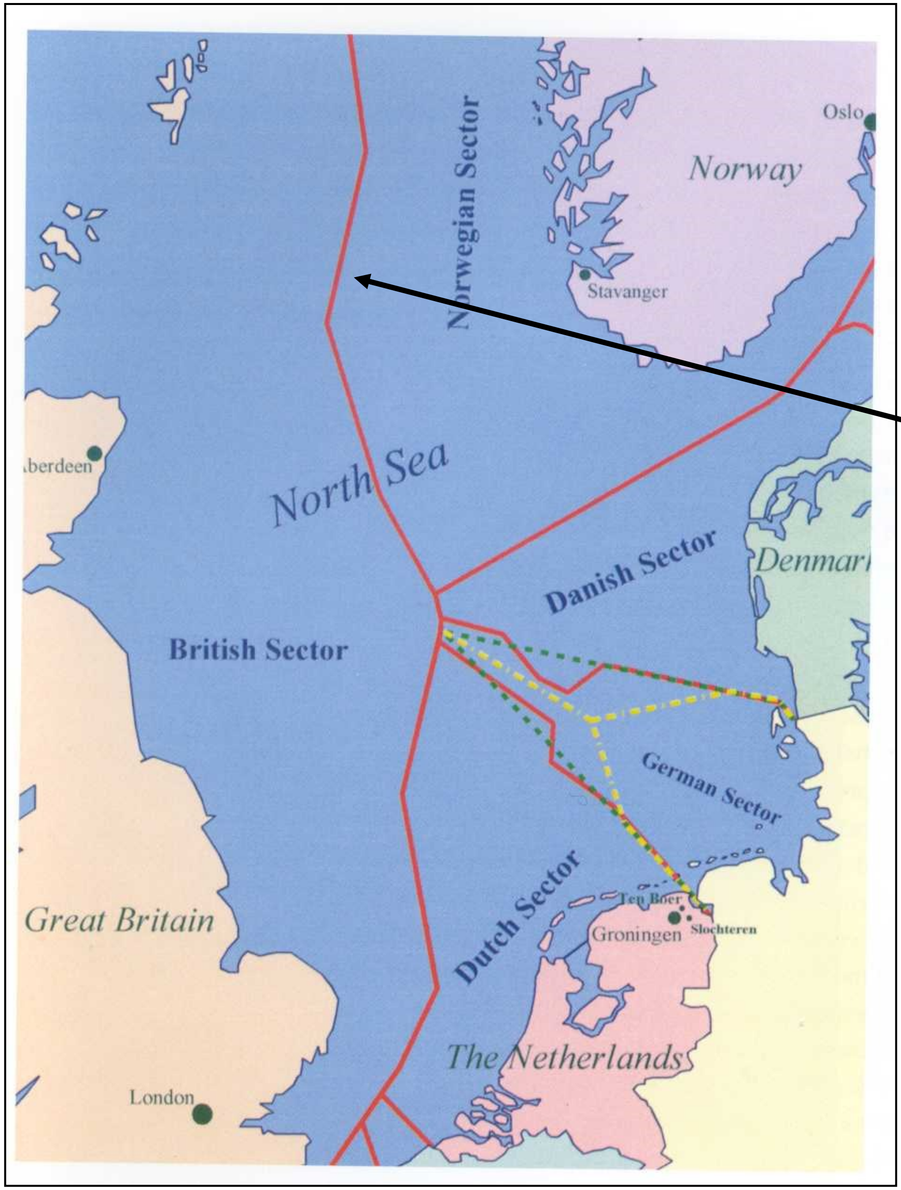
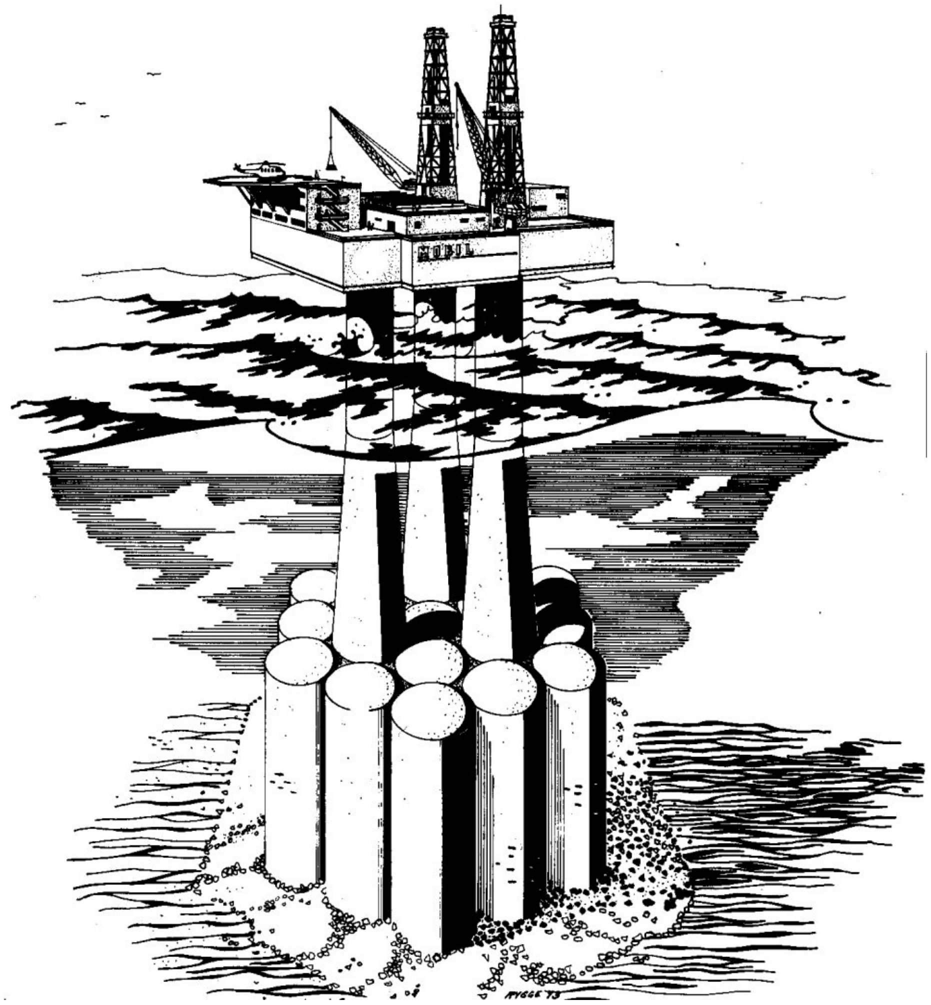
Sleipner Field in North Sea



Sleipner Gas Field 110 m water depth

Artist's view of large Gravity Base platform : CONDEEP



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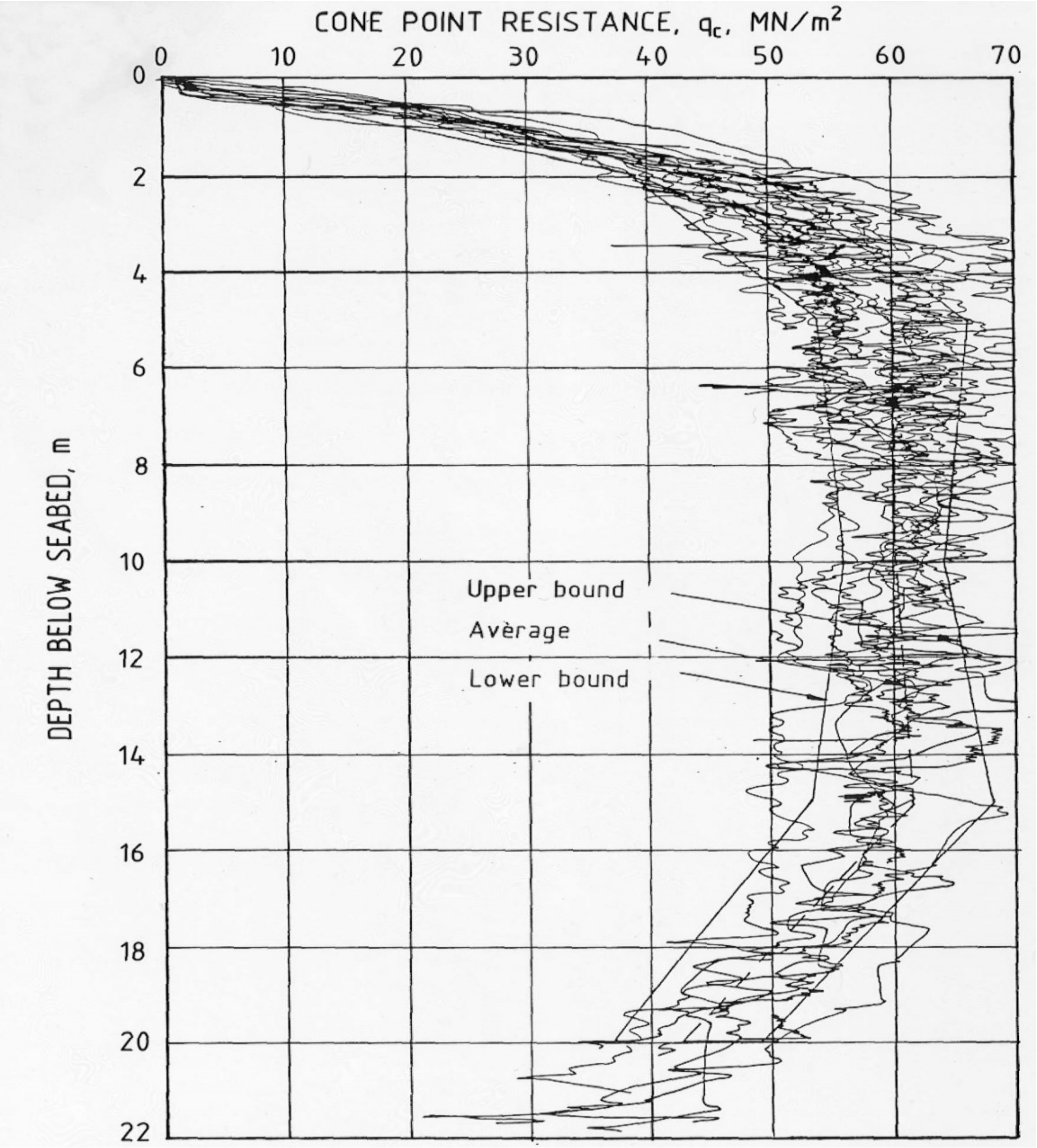
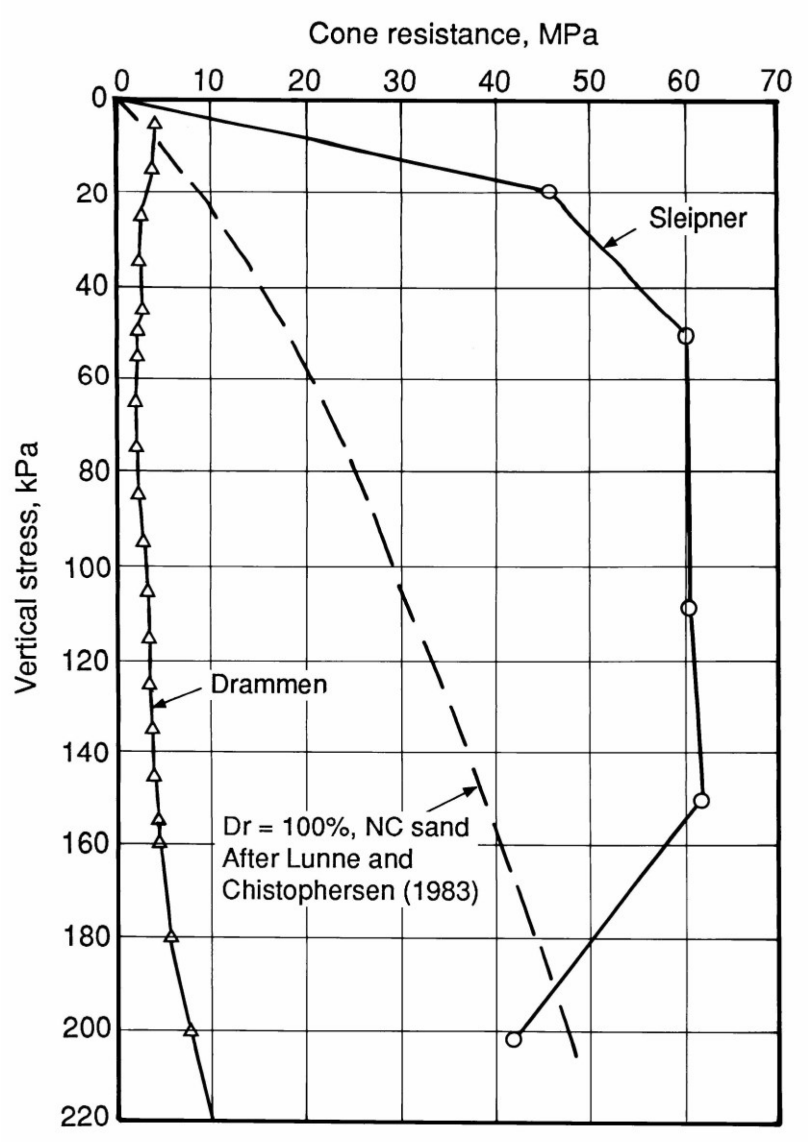
Sleipner North Sea : Results of 15 CPTs



Examples CPTs in Sand : Drammen, Norway; Sleipner, North Sea and Hokksund Calibration Chamber Tests : Dr = 100 %, NC



CLASSIFICATION PROPERTIES OF CC AND "REAL" SANDS

Sand property	Hokksund	Ticino	Drammen	Slepner
Mineralogy	35% quartz 45% feldspar 10% mica	30% quartz 5% mica	55%quartz 35% feldspar	90% quartz 9% feldspar
Angularity	Subrounded	Subrounded	Subrounded	Subrounded
d60, mm	0.50	0.60	0.63 (0.55-0.80)	0.14 (0.12-0.16)
d10, mm	0.27	0.32	0.23 (0.16-0.30)	0.09 (0.08-0.11)
cu	1.85	1.88	2.7 (2.0-3.4)	1.56 (1.45-1.60)
emax	0.92	0.89	0.87 (0.82-0.91)	1.05 (1.00-1.12)
emin	0.56	0.52	0.43 (0.41-0.49)	0.54 (0.50-0.58)
Gs	2.70	2.67	2.68	2.62

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Relative density, D_r

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

e = in situ void ratio

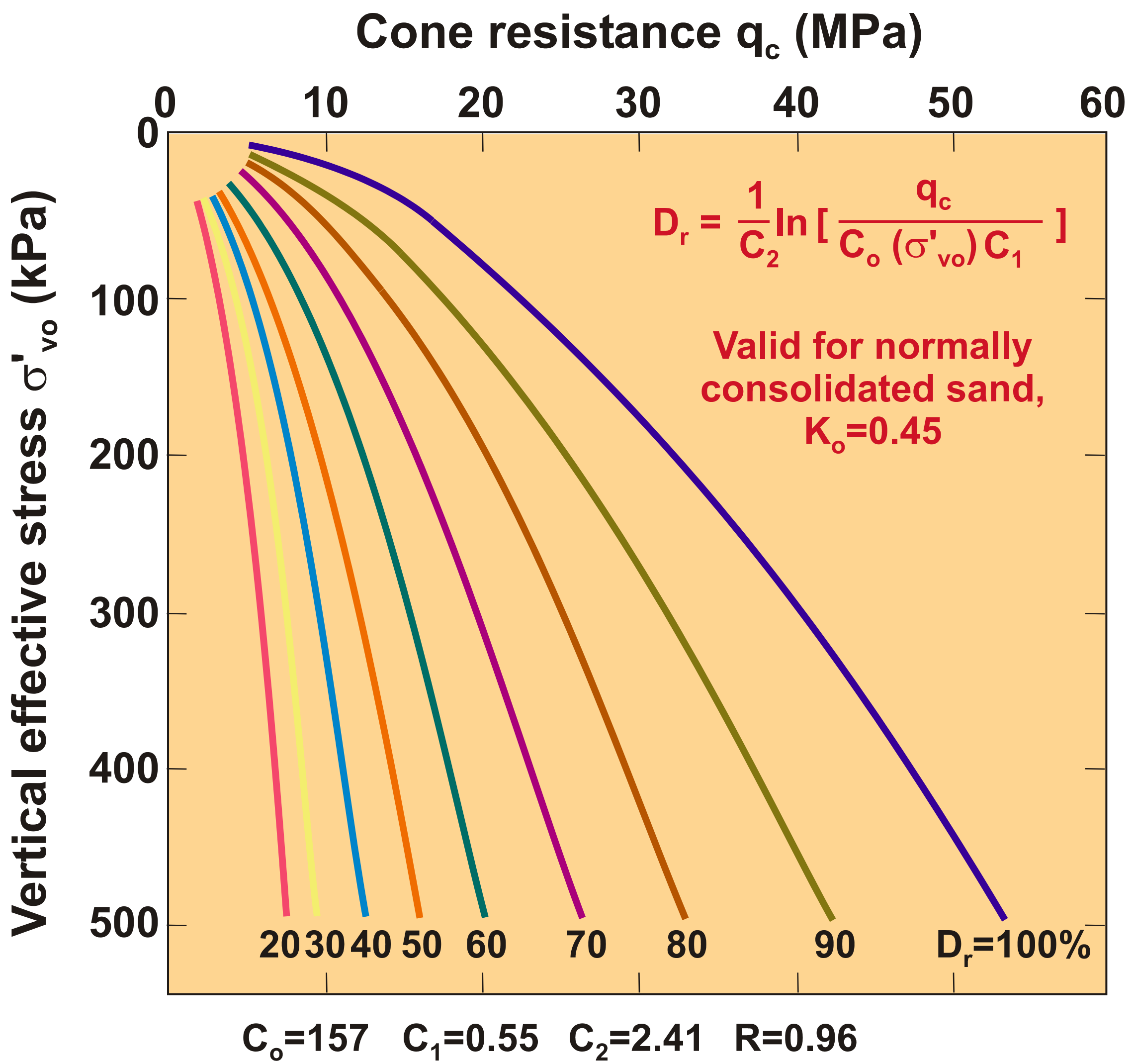
e_{max} = max. porosity (loosest state)

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

D_r = 100% densest state

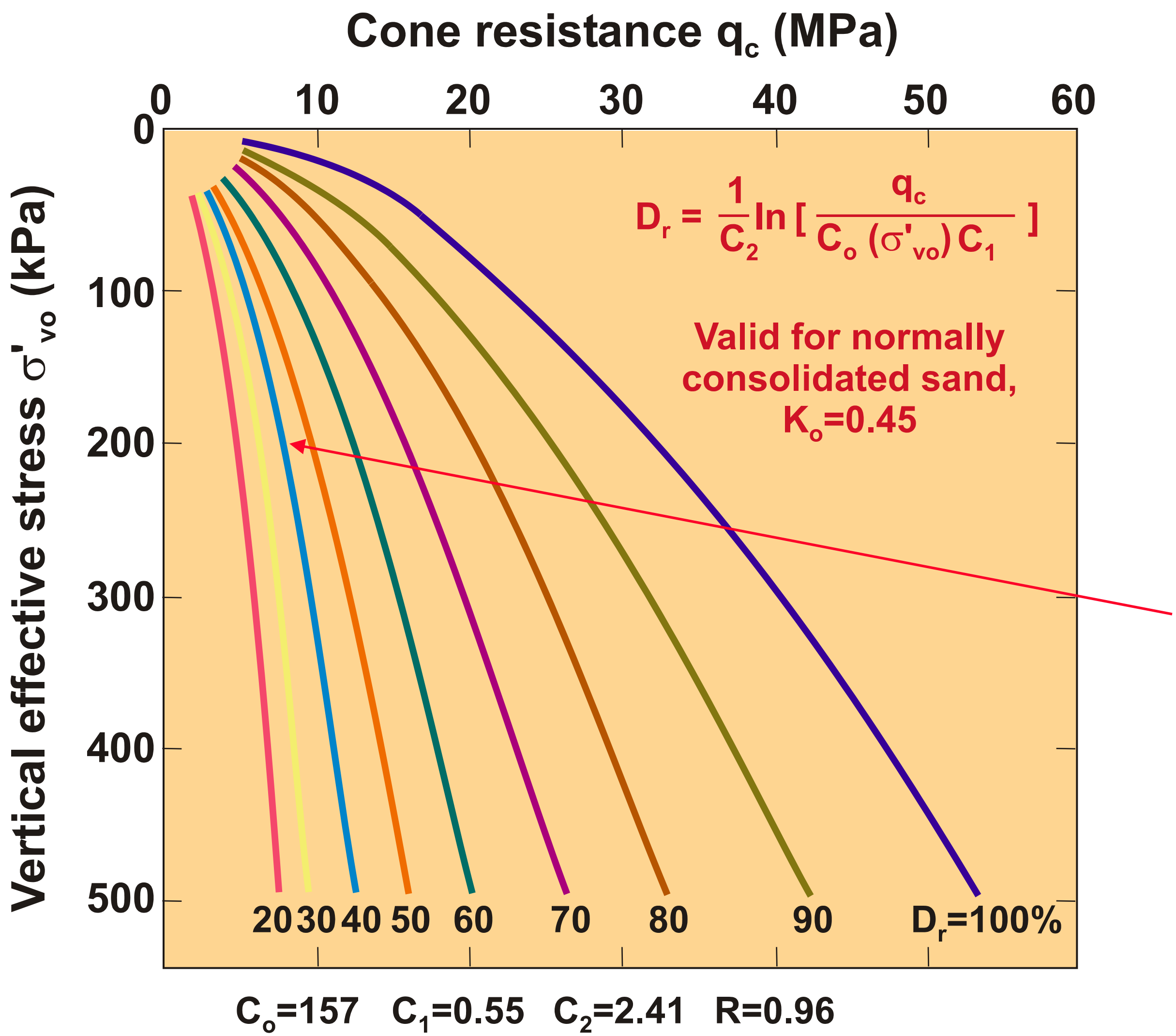
D_r = 0 % most loose state (in practice in field 20 – 25 %)

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



After Baldi et al.(1986)

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



Drammen sand :

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

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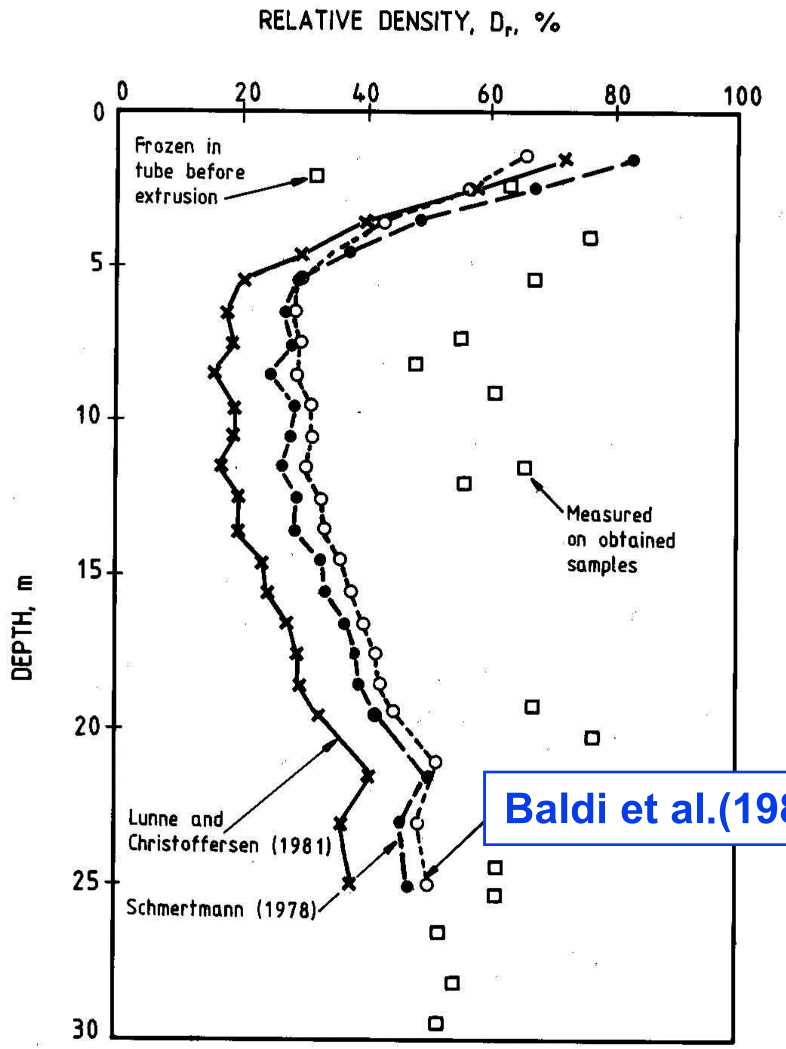
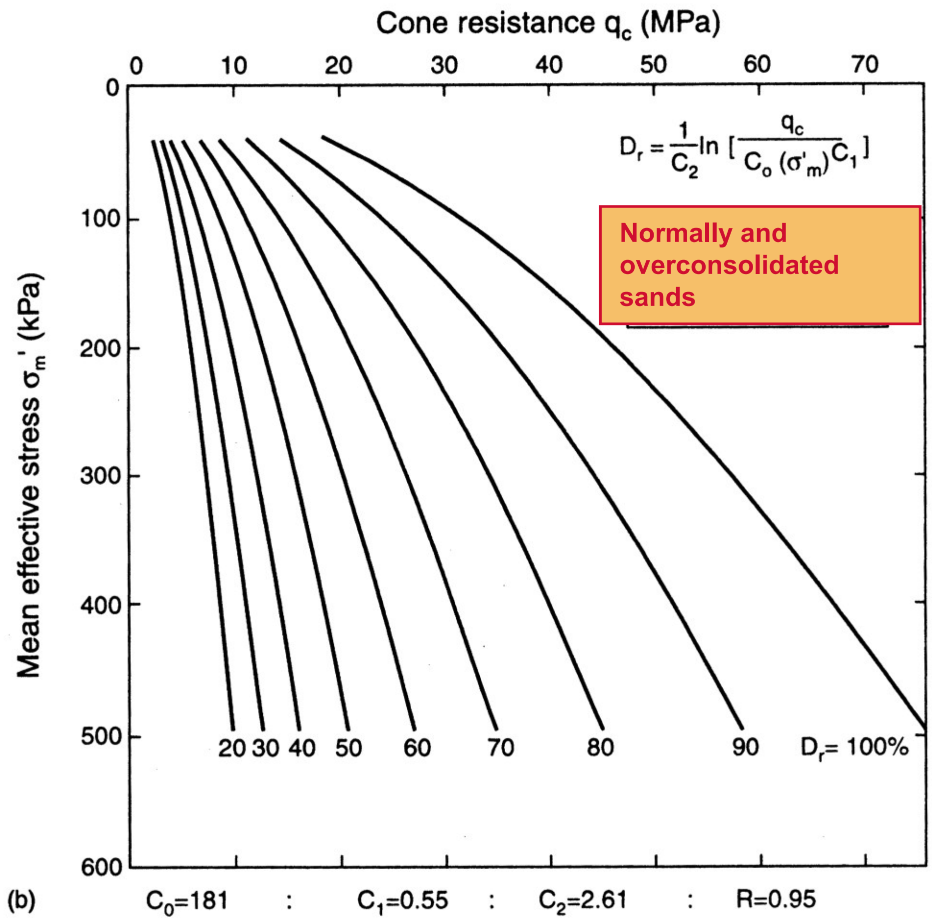
Drammen sand : D_r from CPT correlations and measured on obtained samples



Baldi et al.(1986)

q_c, σ_m', D_r relation for Ticino OC and NC sand

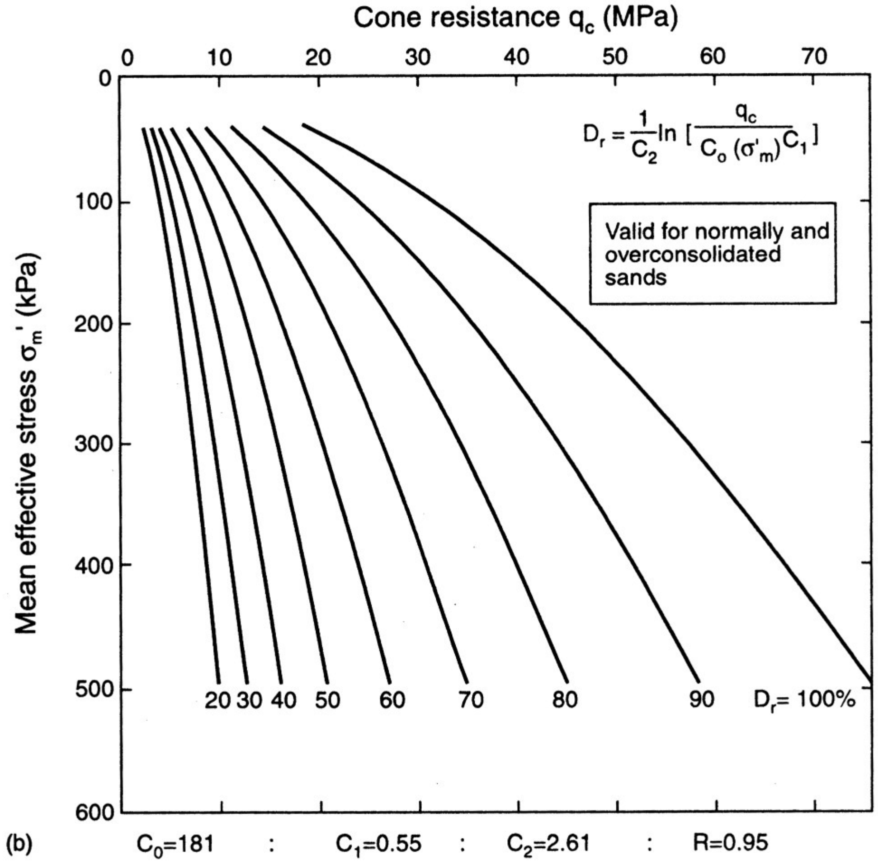


$\sigma_m' = 1/3(\sigma_{vo}' + 2\,\sigma_{ho}')$

Need to estimate K_o

After Baldi et al.(1986)

q_c,σ_m',D_r relationship for OC and NC sand



σ_m'= 1/3(σ_{vo}' + 2 σ_{ho}')

Seipner sand

Z,m	q_c,MPa	K_o	σ_m',kPa	D_r,%
10	60	0.6	80	>100
		1.2	124	>100
15	55	0.4	99	>100
		1.1	176	>100
22	40	0.4	132	>100
		0.8	151	98

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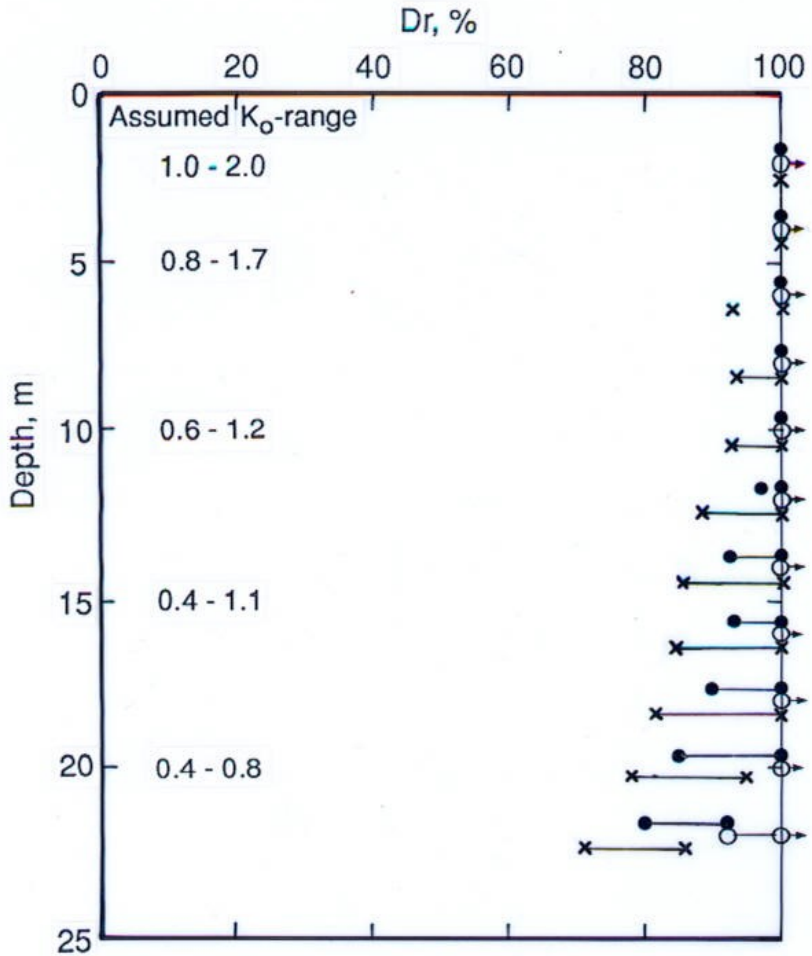
Relative density of Sleipner sand



Legend:

- ● From CPT (Schmertmann, 1978)
- × From CPT (Lunne and Christophersen, 1983)
- ○ From CPT (Baldi et al., 1986)

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
- *Fines content* will reduce q_c and D_r can be underestimated; if FC > 5% be careful with using D_r concept
- In interbedded sand layers where q_c have not reached full value within a thin layer D_r may be underestimated
- Aging increase cone resistance

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

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EVALUATION OF STRESS HISTORY, OCR, AND K_0 IN SANDS

In general no reliable methods exist, but estimates can be made:

OCR

- from geological evidence
- from neighbouring clay layers (odeometer tests)
- from K_0 (if already assessed – eg. SBP)

K_0

- from OCR if known: $K_0(oc) = K_0(nc) \times OCR^m$

  $K_0(nc) = 1 - \sin\phi'$ (Jaky, 1944)
- based on calibration chamber data

  Mayne (1991) $K_0 = f(q_t, \sigma_{vo}', OCR)$

  Iteration procedure is required

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K_0 IN SANDS

Based on calibration chamber data, Mayne (1991) proposed a modified form of the above by combining the calibration chamber test results to produce the following:

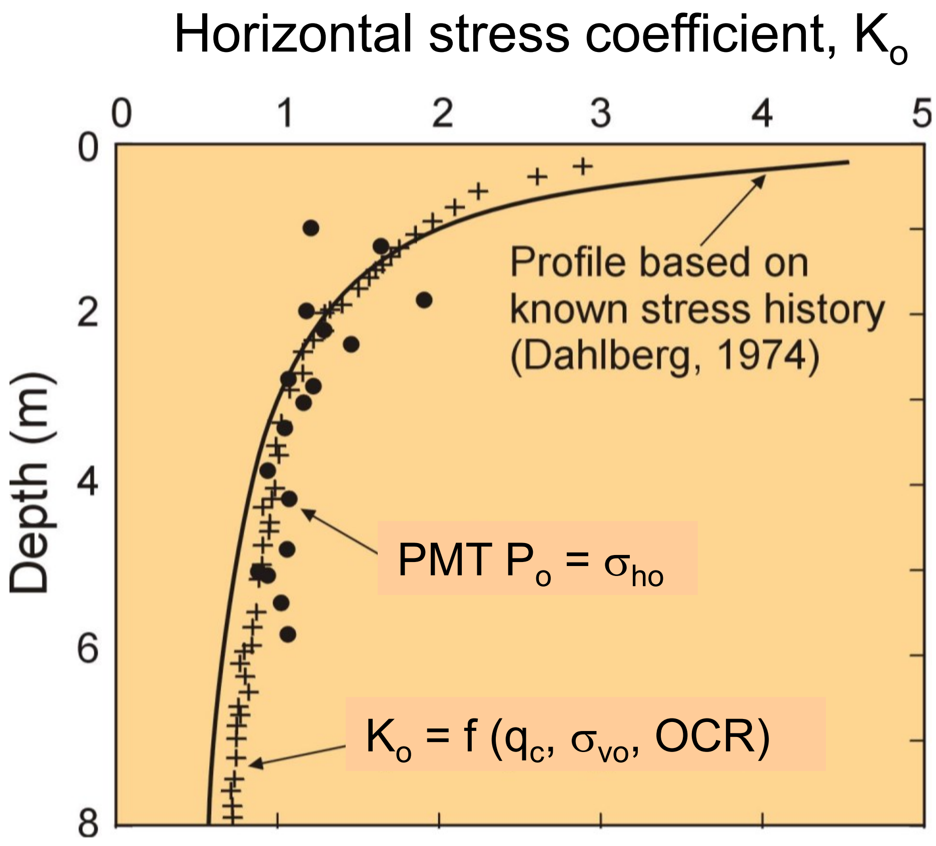
$$K_0 = \frac{\sigma'_{h0}}{\sigma'_{v0}} = \frac{\left(p_a/\sigma'_{vo}\right)\bullet\left(q_c/p_a\right)^{1.6}}{145\exp\left[\left(\frac{\left(q_c/p_a\right)/\left(\sigma'_{v0}/p_a\right)^{0.5}}{12.2\left(OCR\right)^{0.18}}\right)^{0.5}\right]} \quad (5.56)$$

The above equation requires iteration until a matching value of K_0 is obtained. Need also correlation between K_o and OCR.

OCR = 5.04* K_o1.54 (Mayne, 1992)

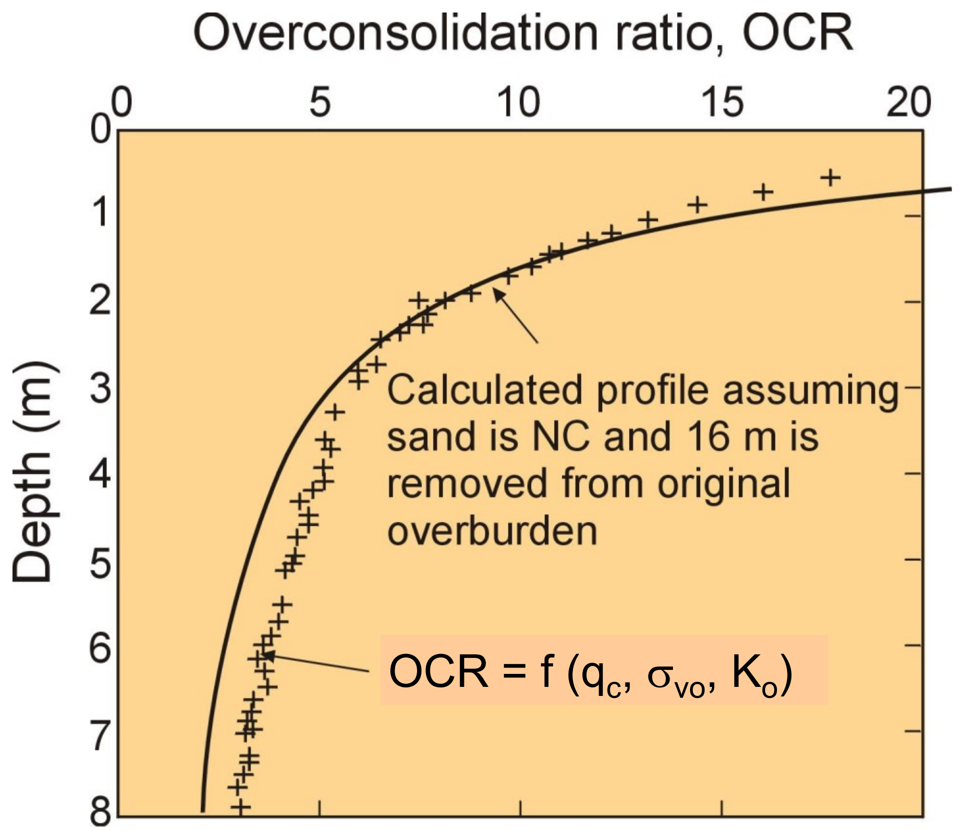
Valid for medium to fine quarts sands not cemented.

Example of K_o and OCR interpretation after Mayne (1991)



Stockholm sand

Example of K_o and OCR interpretation after Mayne (1991)



Stockholm sand

DRAINED SHEAR STRENGTH, ϕ_D', FROM CPT

Three most common methods:

1 **Empirical D_r approach**

- ***use estimated D_r and then correlation $(\phi_D'/D_r)/\sigma_{vm}'$***
- ***or carry out triaxial tests reconstituted to D_r from CPT***

2 **Empirical calibration chamber correlation**

3 **Bearing capacity method**

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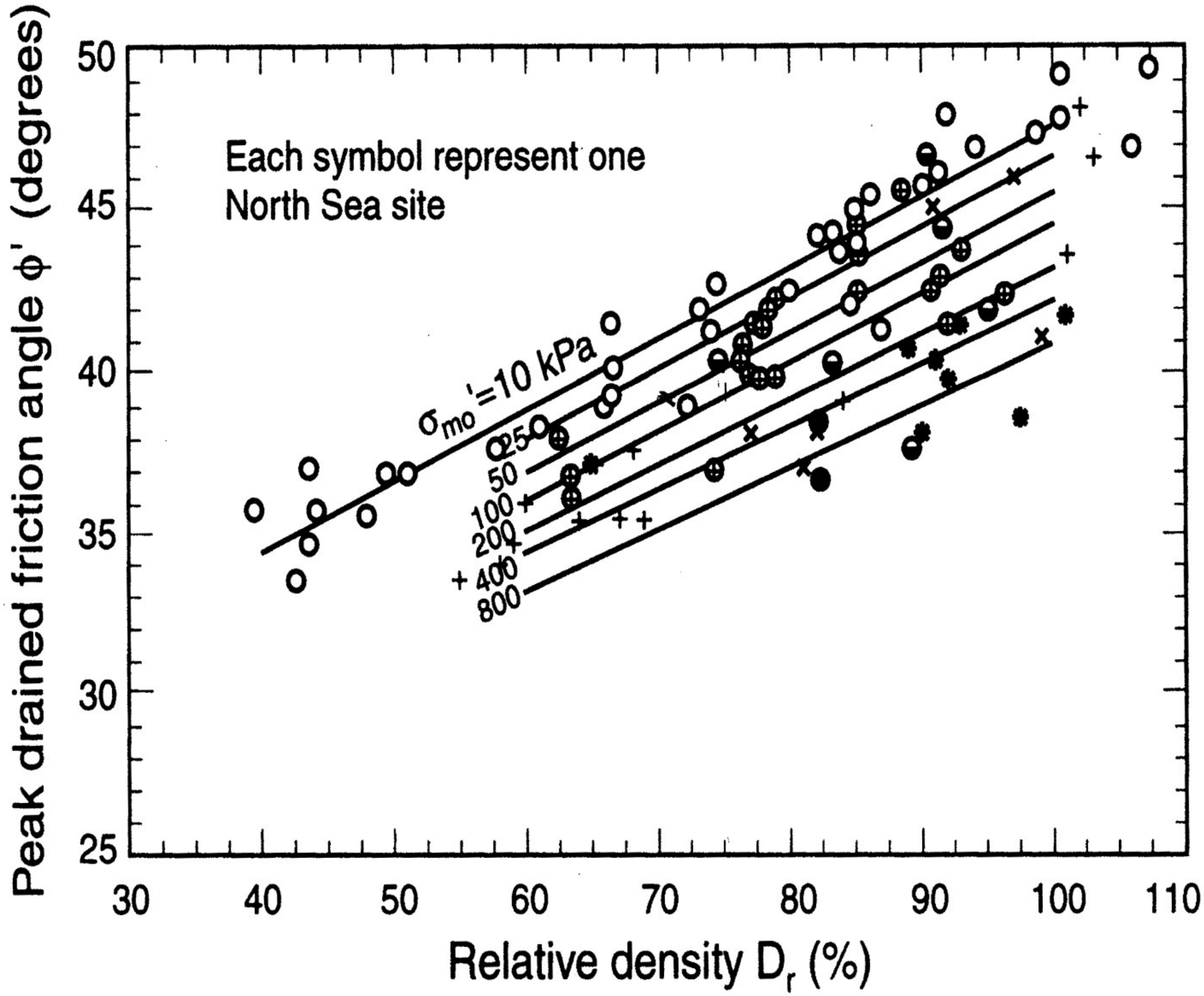
Correlations between ϕ', D_r and σ_{mo}' for fine medium, uniform quartz sand



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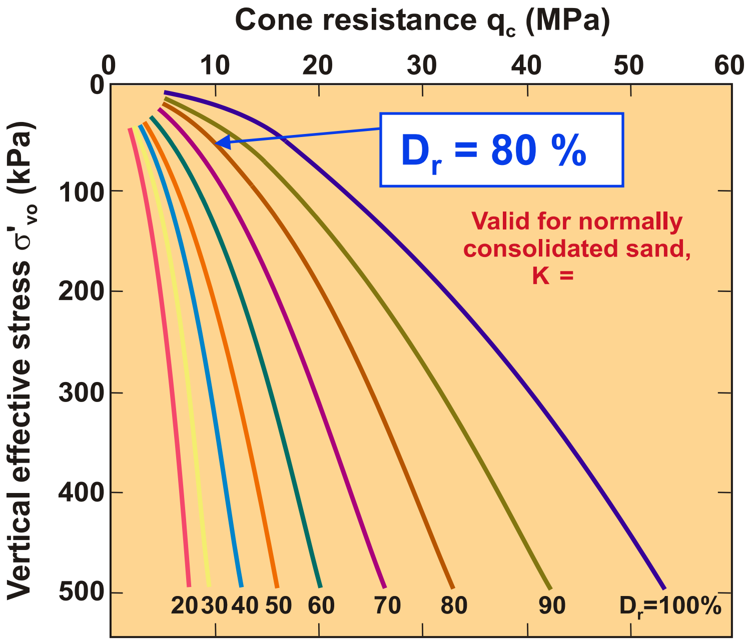
ϕ' in sands

EXAMPLE :

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

- **ϕ' = f (D_r, σ_{mo}') gives ϕ' = 40°** **Fig. 5.54**



C_o=157 C_1=0.55 C_2=2.41 R=0.96

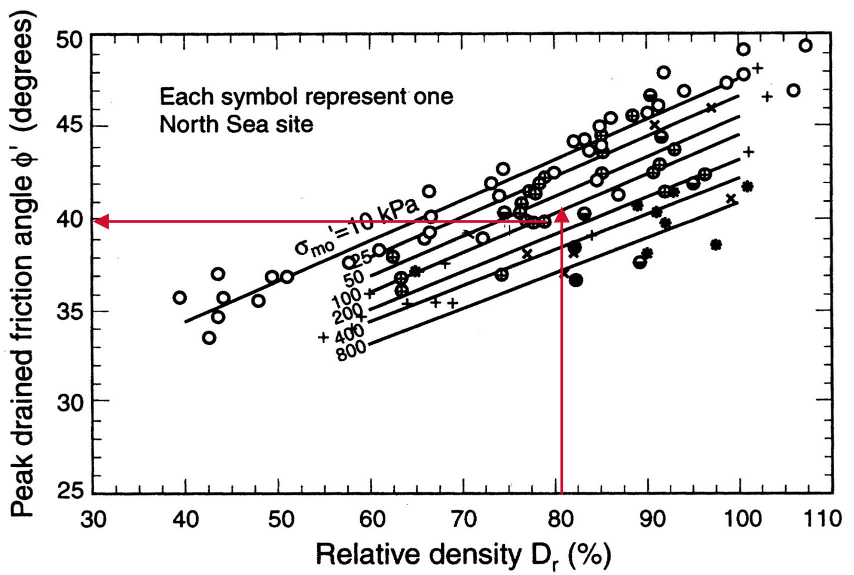


Fig. 5.54

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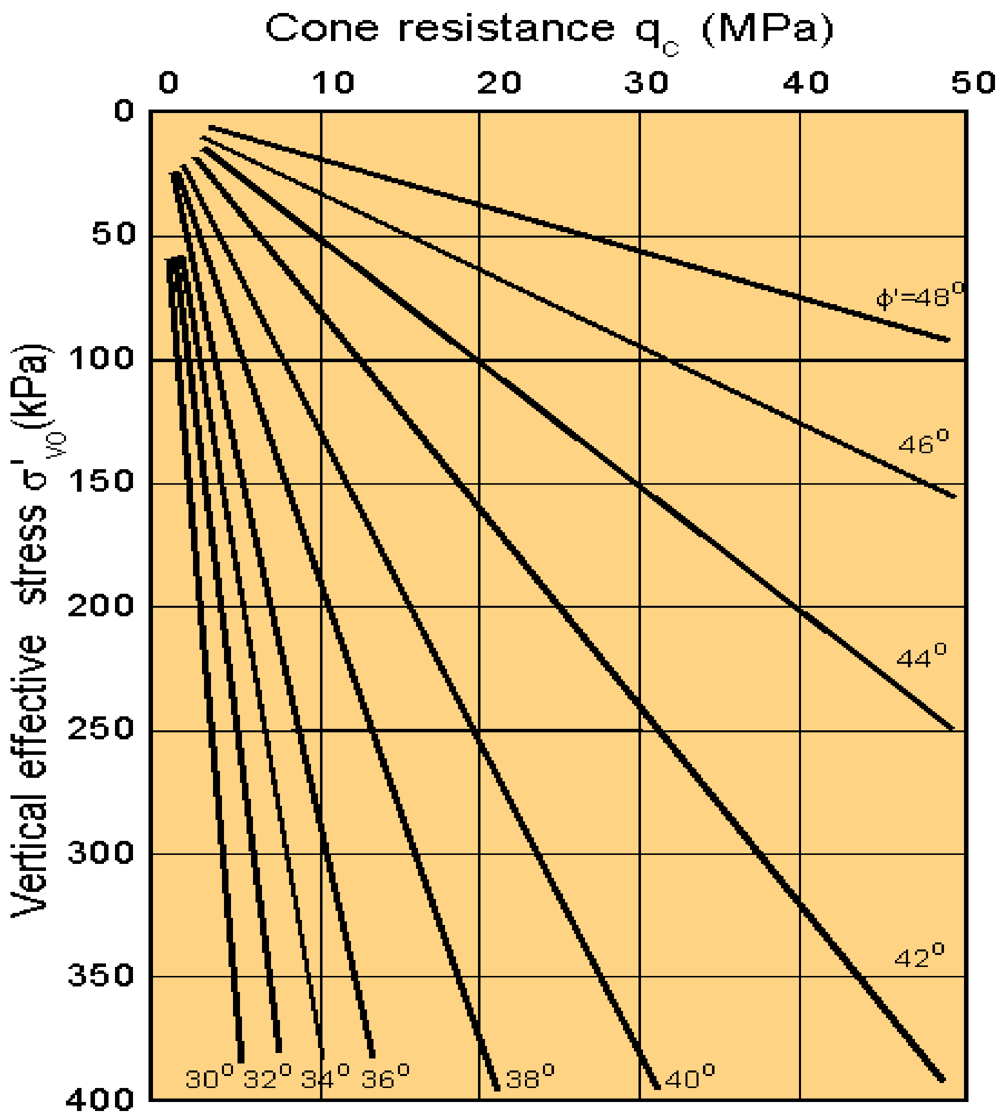
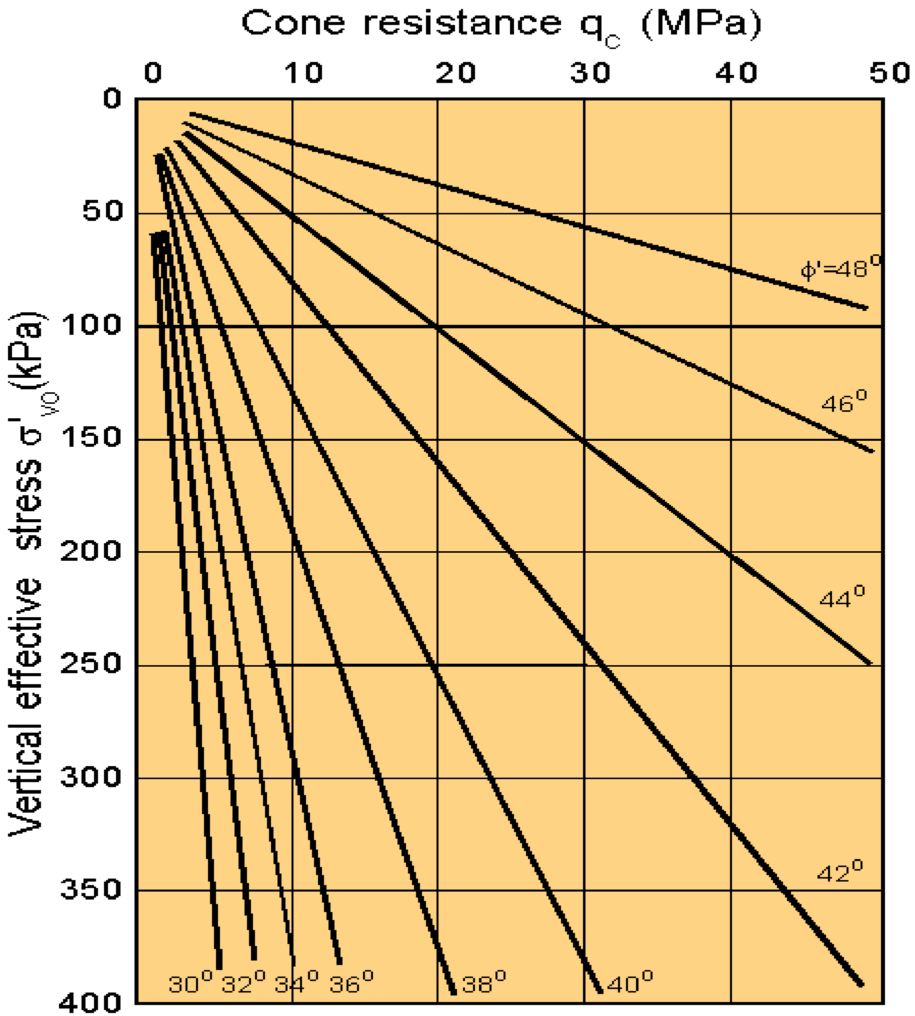
σ_v', q_c, ϕ' relationships



Based on Calibration Chamber Data

From Robertson and Campanella(1983)

Relationship between bearing capacity number and friction angle from large calibration tests



Drammen sand

Z,m	q_c,MPa	σ_{v0}',kPa	φ °
6	2.1	60	33
10	3.0	100	32

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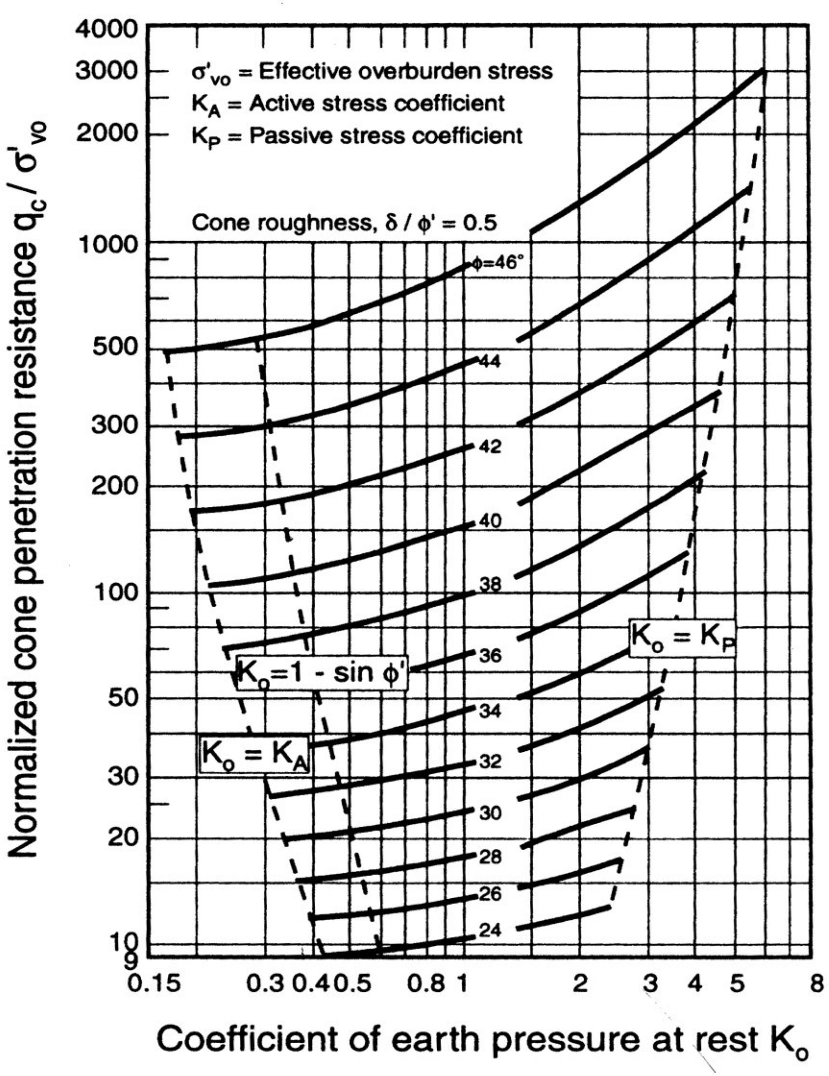
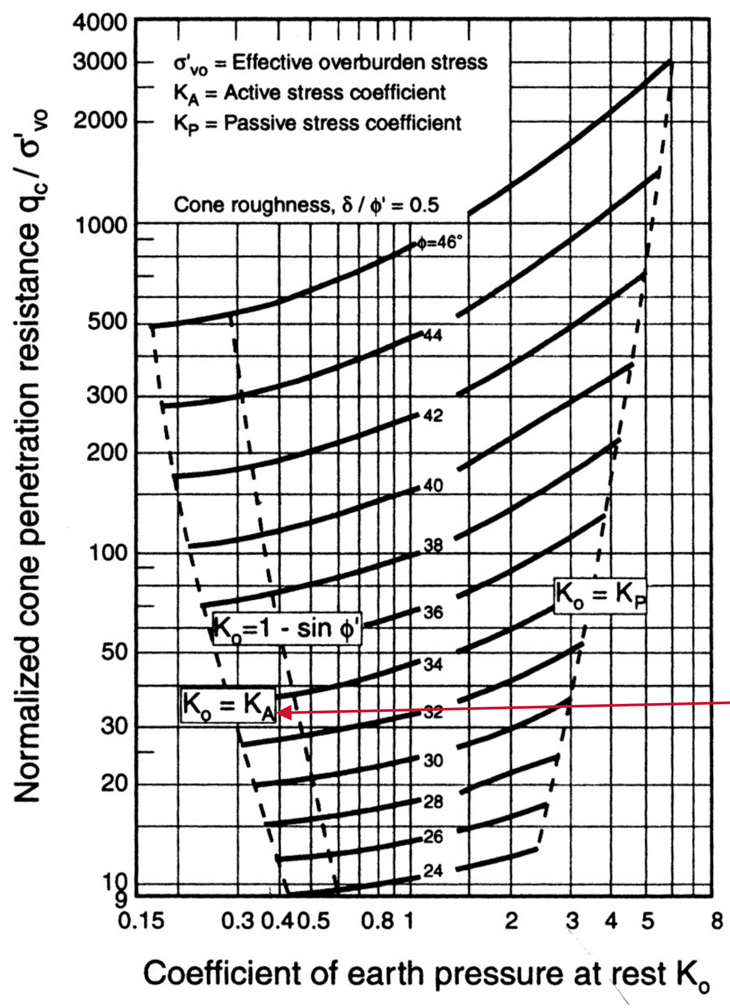
Chart for predicting peak friction angle from q_c , σ_{vo}' ,K_o



Dorgunoglu and Micthell bearing capacity theory (after Marchetti(1988)

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



Drammen sand 6m,

q_c = 2.1 kPa

q_c/σ_{vo}'= 35

NC sand : ϕ = 33 °

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ϕ' in Drammen sand

Depth=10 m ; q_c = 2.1 MPa ; σ_{vo}'=100 kPa; K_o = 0.4; σ_{mo}' = 60 kPa

- $\phi' = f(D_r, \sigma_{mo}')$ gives $\phi' = 30^o$ Fig. 5.54
- $\phi' = f(q_c/\sigma_{vo}')$ gives $\phi' = 32^o$ Fig. 5.56
- $\phi' = f(q_c/\sigma_{vo}', K_o)$ gives $\phi' = 33^o$ Fig. 5.58

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

- For bearing capacity use $\phi' = 30^o$
- For pile driving resistance use $\phi' = 33^o$

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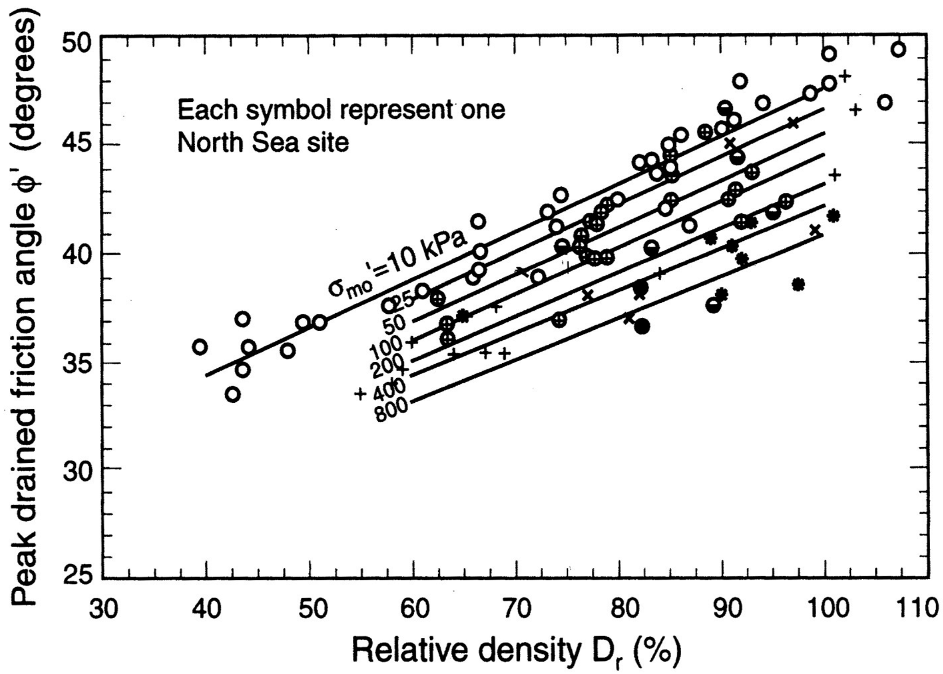
Correlations between ϕ', D_r and σ_{mo}' for fine medium, uniform quartz sand



Seipner sand

Z,m	K_o	σ_m',kPa	D_r,%	ϕ °
10	0.6	80	>100	45
	1.2	124	>100	44.5
15	0.4	99	>100	44.5
	1.1	176	>100	44
22	0.4	132	>100	44.5
	0.8	151	98	44

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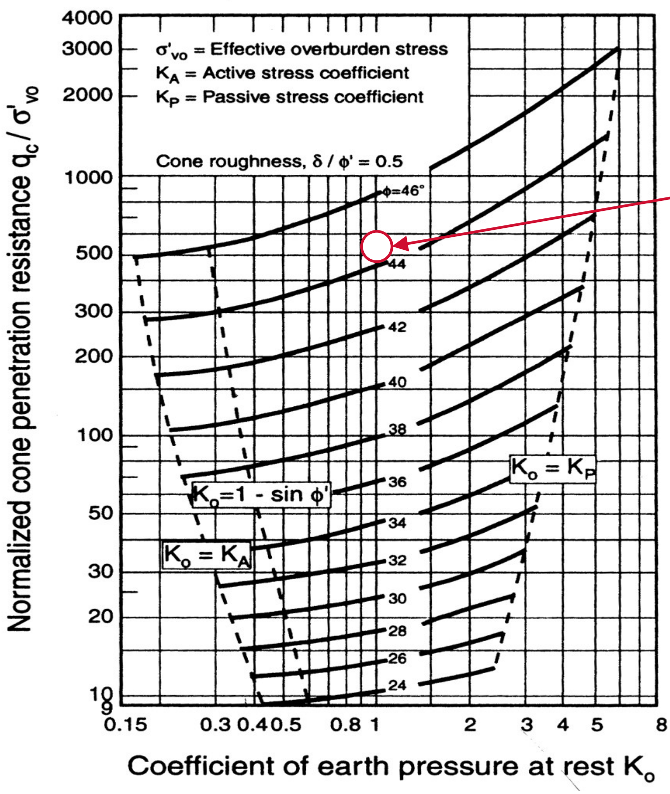
ϕ' in Sleipner sand

Depth=10 m ; q_c = 60 MPa ; σ_{vo}'=110 kPa; K_o = 1.0; q_c/ σ_{vo}'=545

ϕ' = f (q_c/σ_{vo}',K_o) gives ϕ' = 44.5°



ϕ' = 44.5°

ϕ_d in Sleipner sand

Depth=10 m ; q_c = 60 MPa ; σ_{vo}'=110 kPa; K_o = 1.0; q_c/ σ_{vo}'=545

- **$\phi' = f (D_r, \sigma_{mo}')$ gives $\phi_d = 45^o$** Fig. 5.54
- **$\phi' = f (q_c/\sigma_{vo}')$ gives $\phi_d = 44.5^o$** Fig. 5.56
- ***CID triaxial tests at D_r=100 % gives ϕ_d = 43 - 45^o***

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

- **For bearing capacity use $\phi' = 43^o$**
- **For pile driving resistance use $\phi' = 45^o$**

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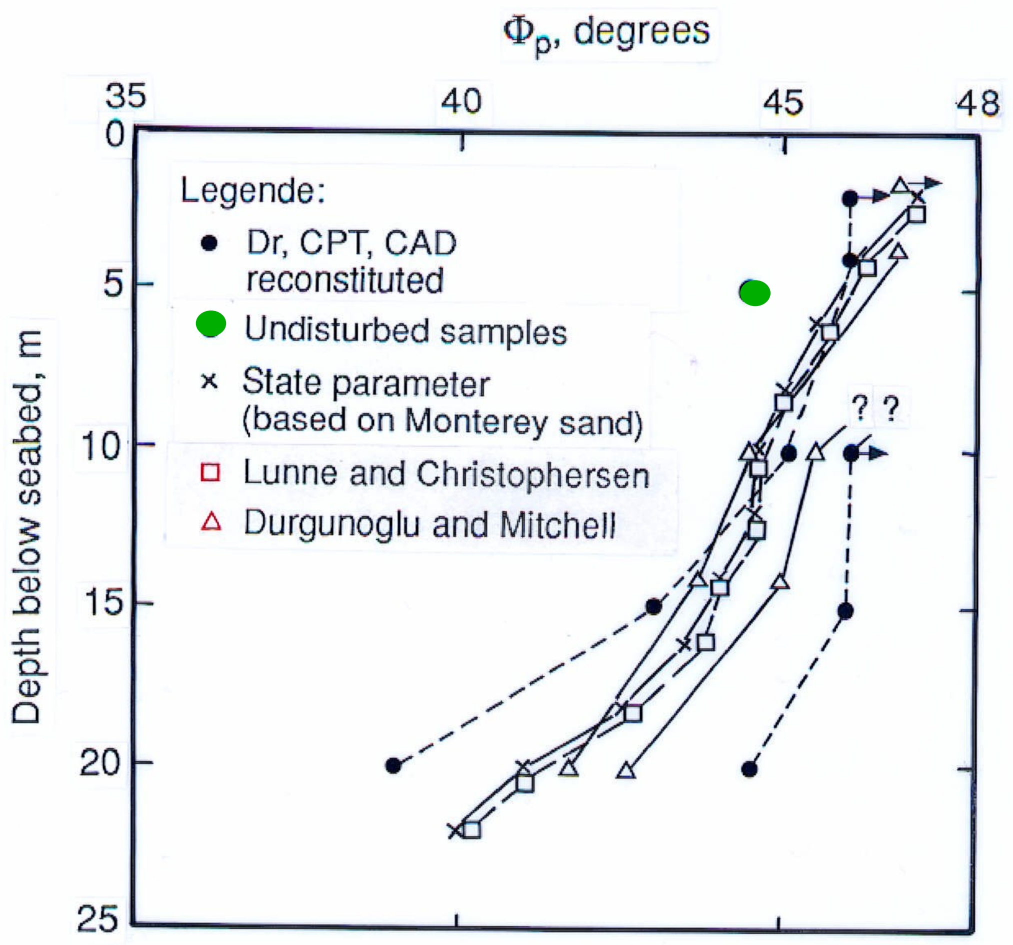
Sleipner sand : friction angle from CPT and from triaxial tests



INTERPRETATION OF CPT IN TERMS OF DEFORMATION PARAMETERS IN SAND

Correlations available to get

- Constrained (oedometer modulus) M
- Young's Modulus, E
- Small strain shear modulus; G_{max}

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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

[redacted]

In laboratory ⇒ triaxial test

2 *Constrained modulus, M*

Applicable when there are no lateral deformations.

[redacted]

In laboratory ⇒ 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.

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CORRELATIONS BETWEEN CONE RESISTANCE AND CONSTRAINED MODULUS, M FOR SANDS

Rough estimate from calibration chamber tests:

NC sands: $M_0 = 4\ q_c$ — $q_c < 10$ MPa

$M_0 = 2\ q_c + 20$ (MPa) for $10\ \text{MPa} < q_c < 50$ MPa

$M_0 = 120$ MPa — $q_c > 50$ MPa

OC sands: $M_0 = 5\ q_c$ — $q_c < 50$ MPa

$M_0 = 250$ Mpa — $q_c > 50$ MPa

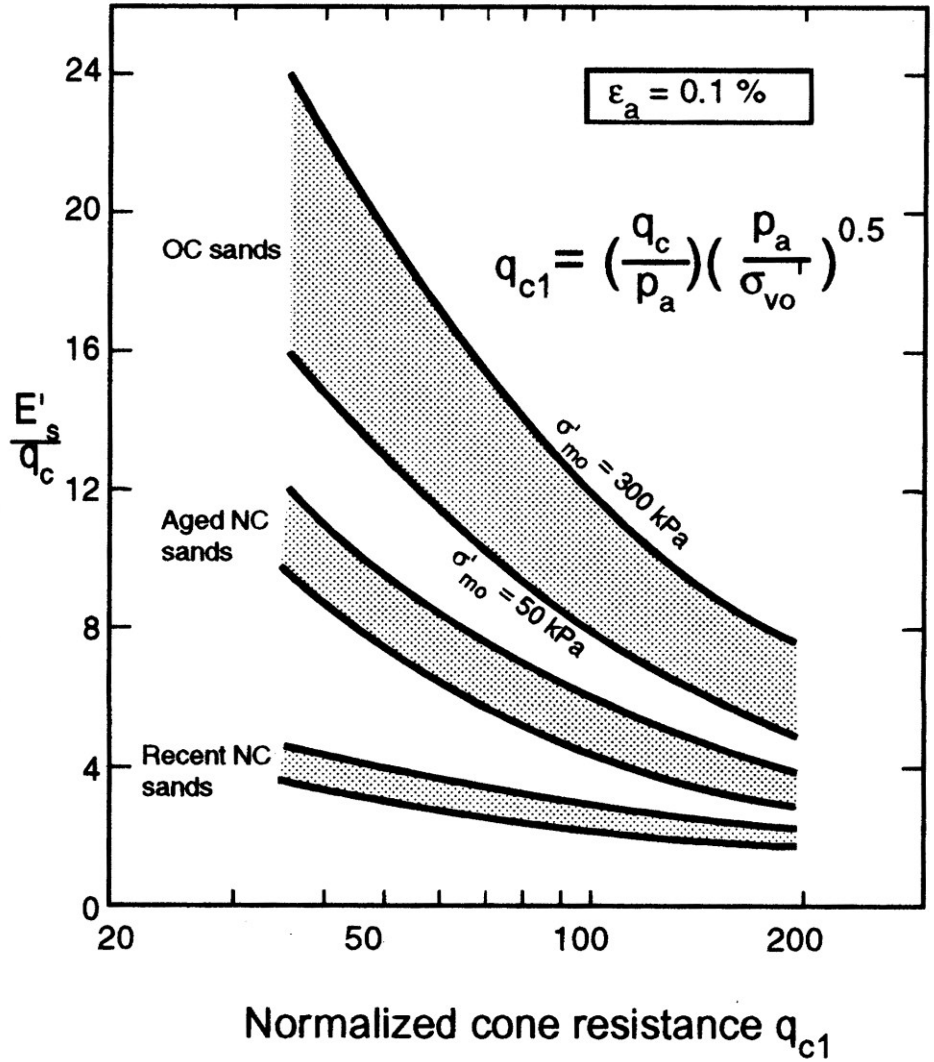
Ref. Lunne and Christophersen (1983)

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:

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

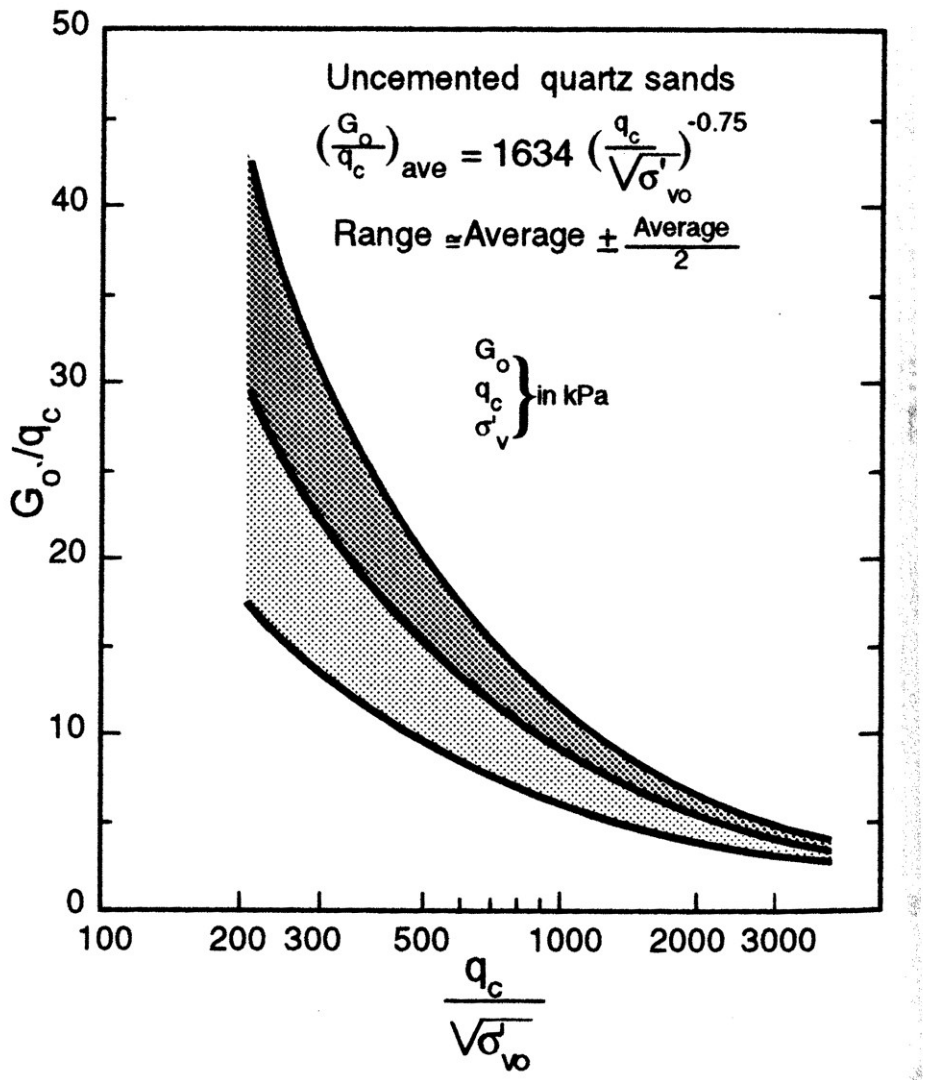
Ref. Modulus concept by Janbu(1969)

Evaluation of drained Young's modulus from CPT



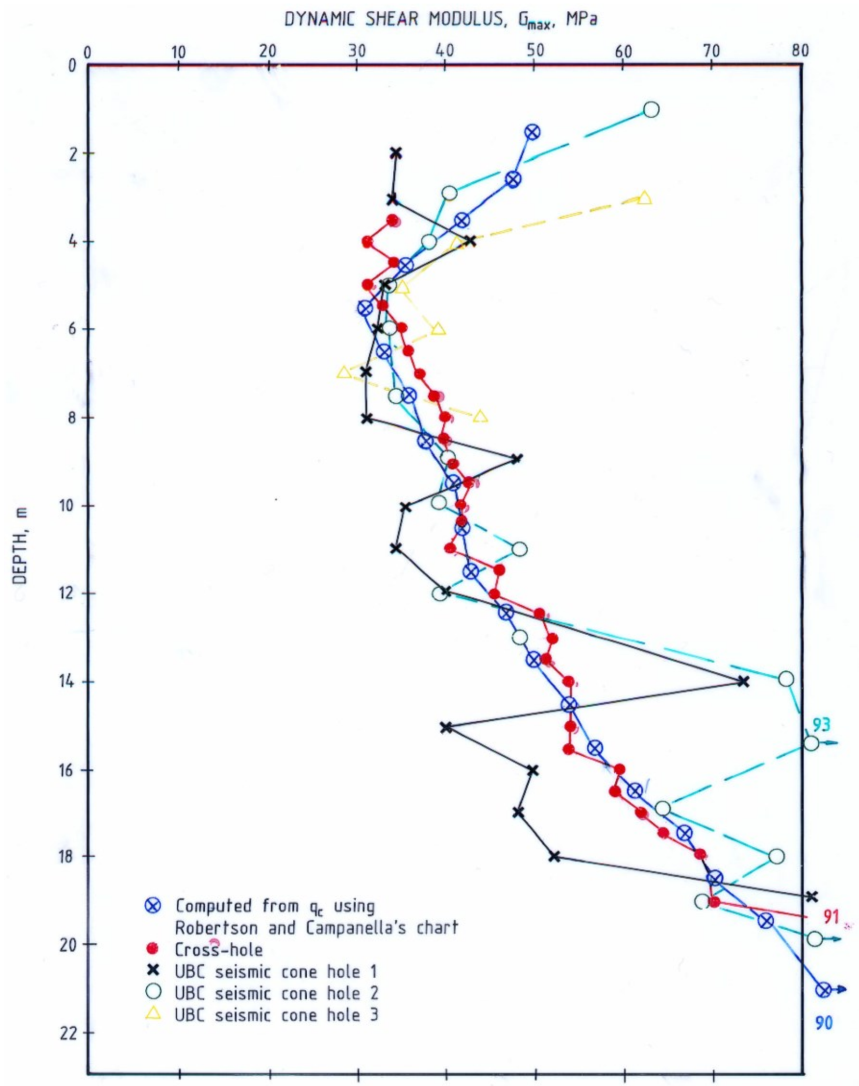
From Baldi et al. (1989)

Small strain shear modulus G_{max} from q_c and σ_{vo}'



After Rix and Stokoe(1992)

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



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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 if sand is different to Hokksund 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
- Effect of aging is to increase cone resistance

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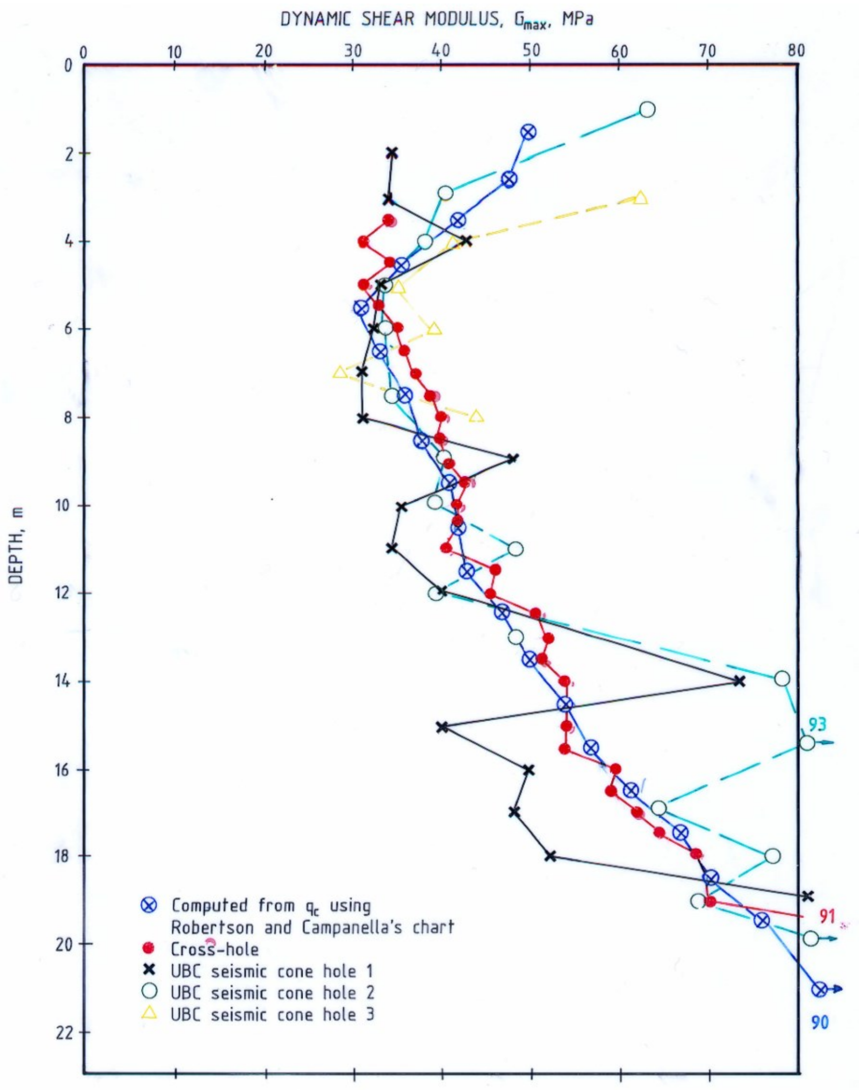
Interpretation in sand

- **Reserve overheads**

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



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DISCUSSION ON RELATIVE DENSITY APPROACH

Relative density (D_r) is a very much used parameter in engineering practice. Several engineering parameters are linked to D_r through empirical correlations:

- ***strength, deformation, dynamic parameters.***

Also D_r is used for controlling/specifying density of built in laboratory specimens from disturbed specimen

However, there are also uncertainties with D_r due to problems of determining maximum and minimum densities (porosities). Due to non-standardization of these measurements different laboratories can get significantly different values.

It is also generally recognized that the behaviour of sand is a function not only of density (or porosity) but of present stress state, stress and strain history, ageing, cementation, sand structure and anisotropy.

An alternative approach is the STATE PARAMETER which combines void ratio (porosity) and stress level. Covered in CPT book

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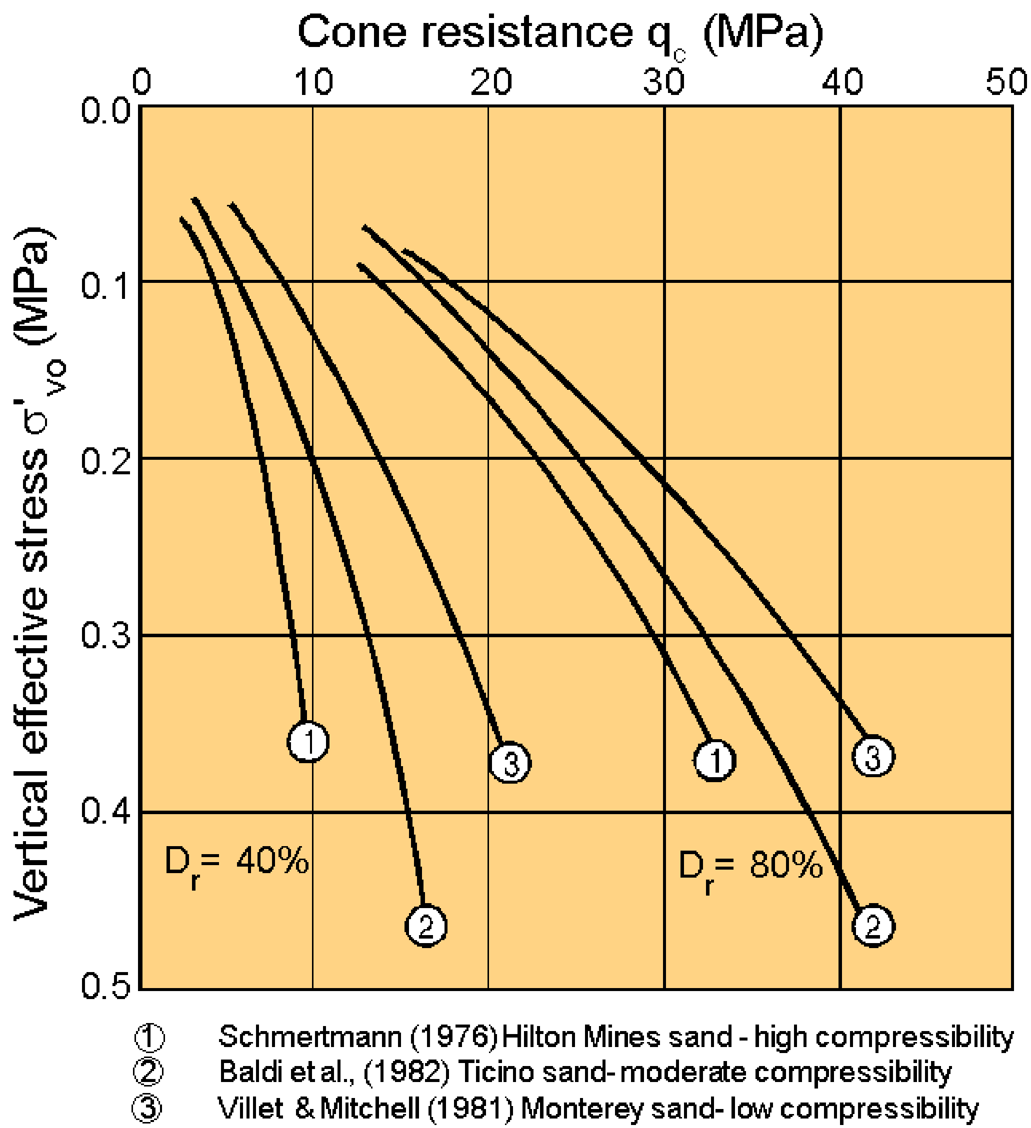
Effect of sand compressibility on q_c, σ_{vo}', D_r relationship



From Robertson and Campanella (1983)

Estimation of Ko and OCR from q_c and σ_{vo}'

- $K_o = f(q_c, \sigma_{vo}', OCR, p_a)$
- $OCR = 5.04 * K_o^{1.54}$ (Mayne, 1992)

E.g. Stockholm sand; at 4 m,

q_c = 11000 kPa, σ_{vo}' =64 kPa

First iteration : K_o = 1 gives OCR = 5.04 and K_o = 0.92

Second iteration : K_o = 0.92 gives OCR = 4.43 and K_o = 0.95

Third iteration : K_o = 0.95 gives OCR = 4.64 and K_o = 0.94

Fourth iteration : *K_o = 0.94 gives OCR = 4.55 and K_o = 0.94*

Know stress history since 16 m was removed by excavation

NGI

Drammen sand : friction angle from CPTU and triaxial tests

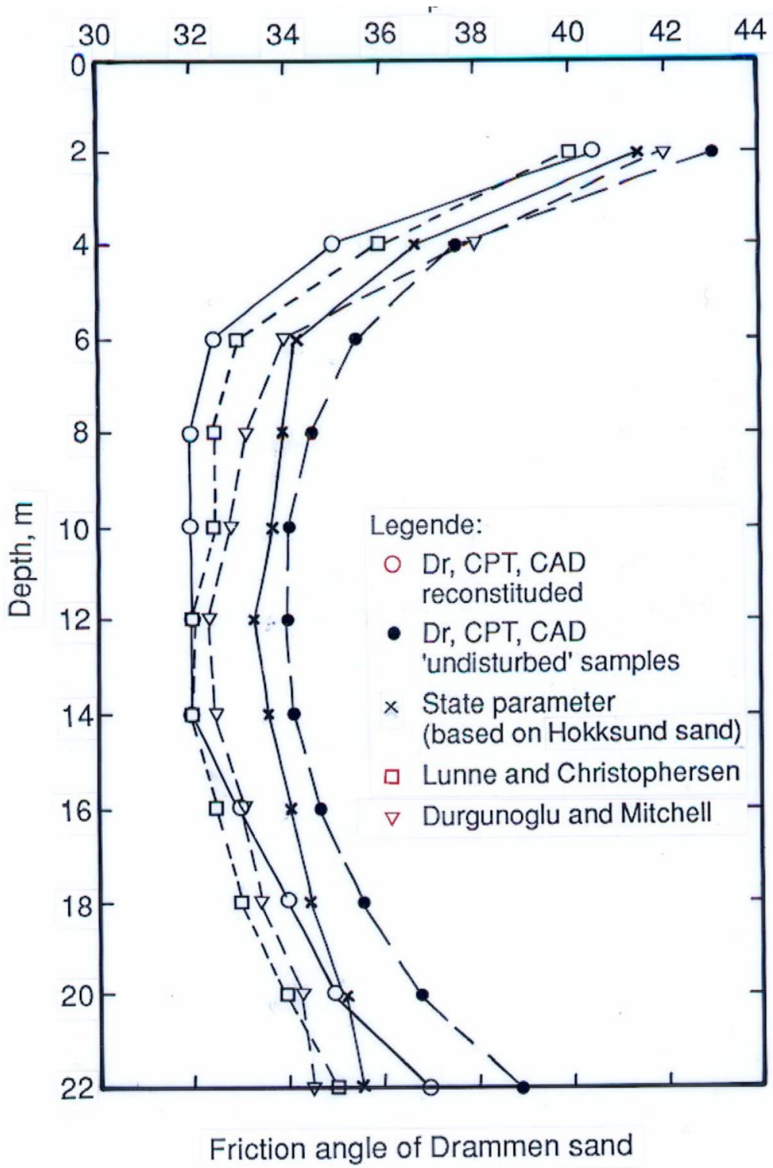


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Figure 3.2 Increment Δqc1 as a function of fines content (from Ishihara, 1993)

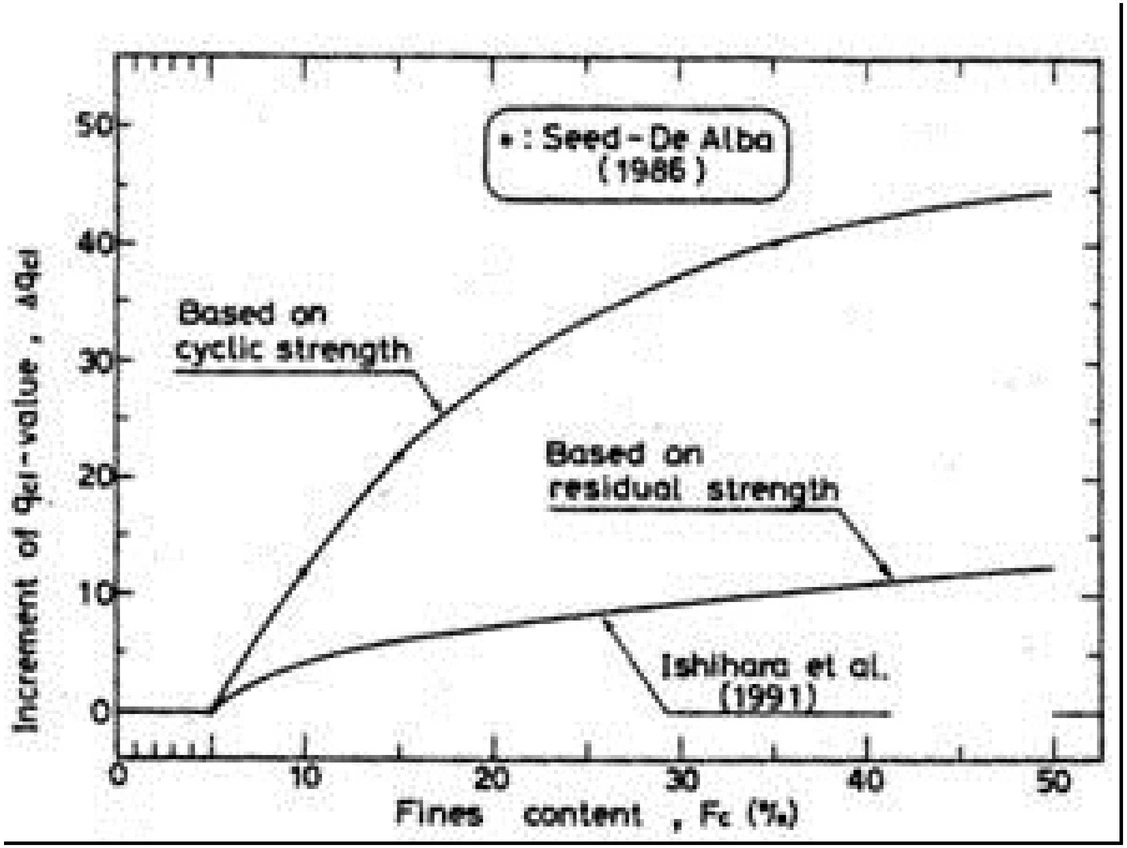
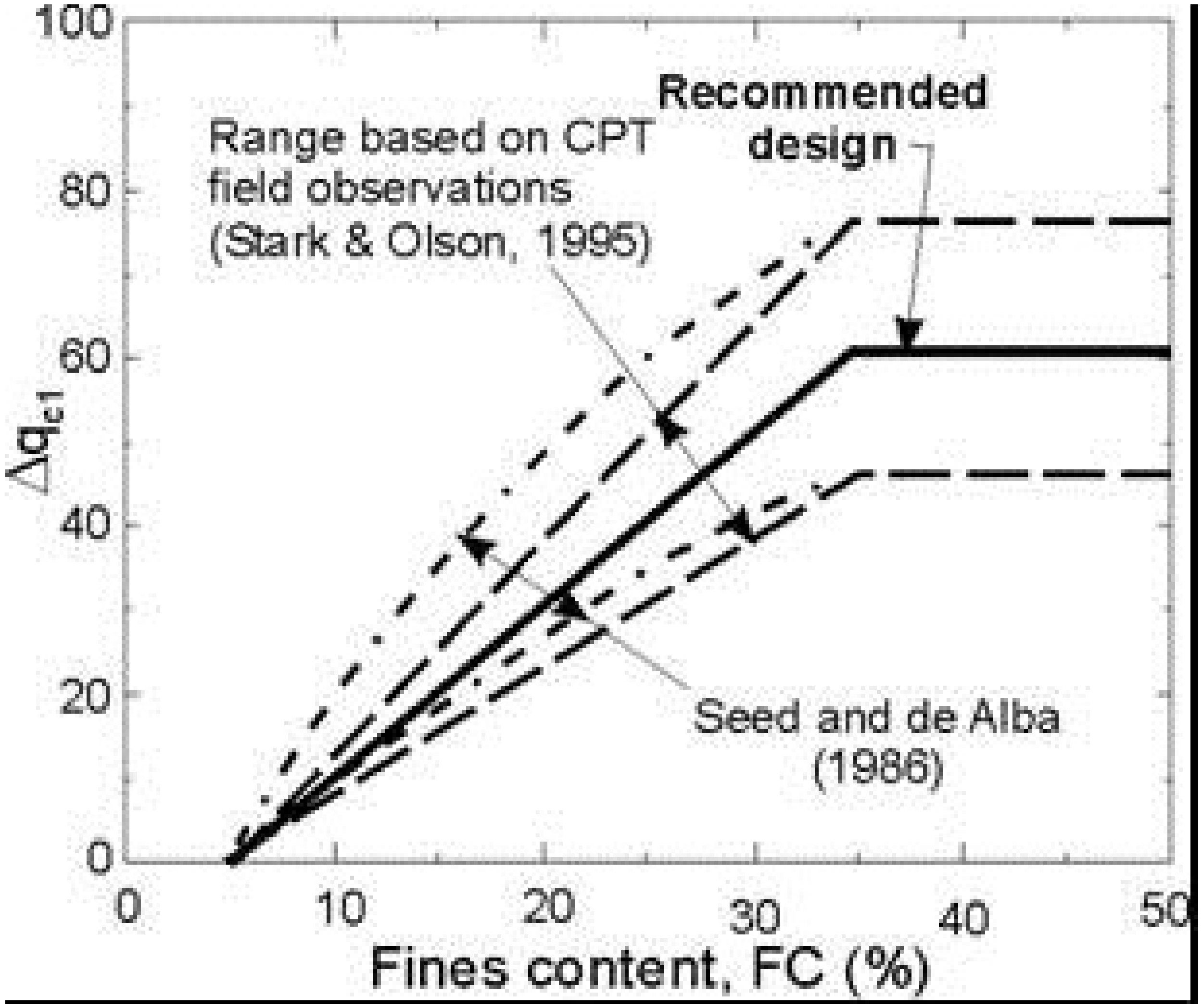
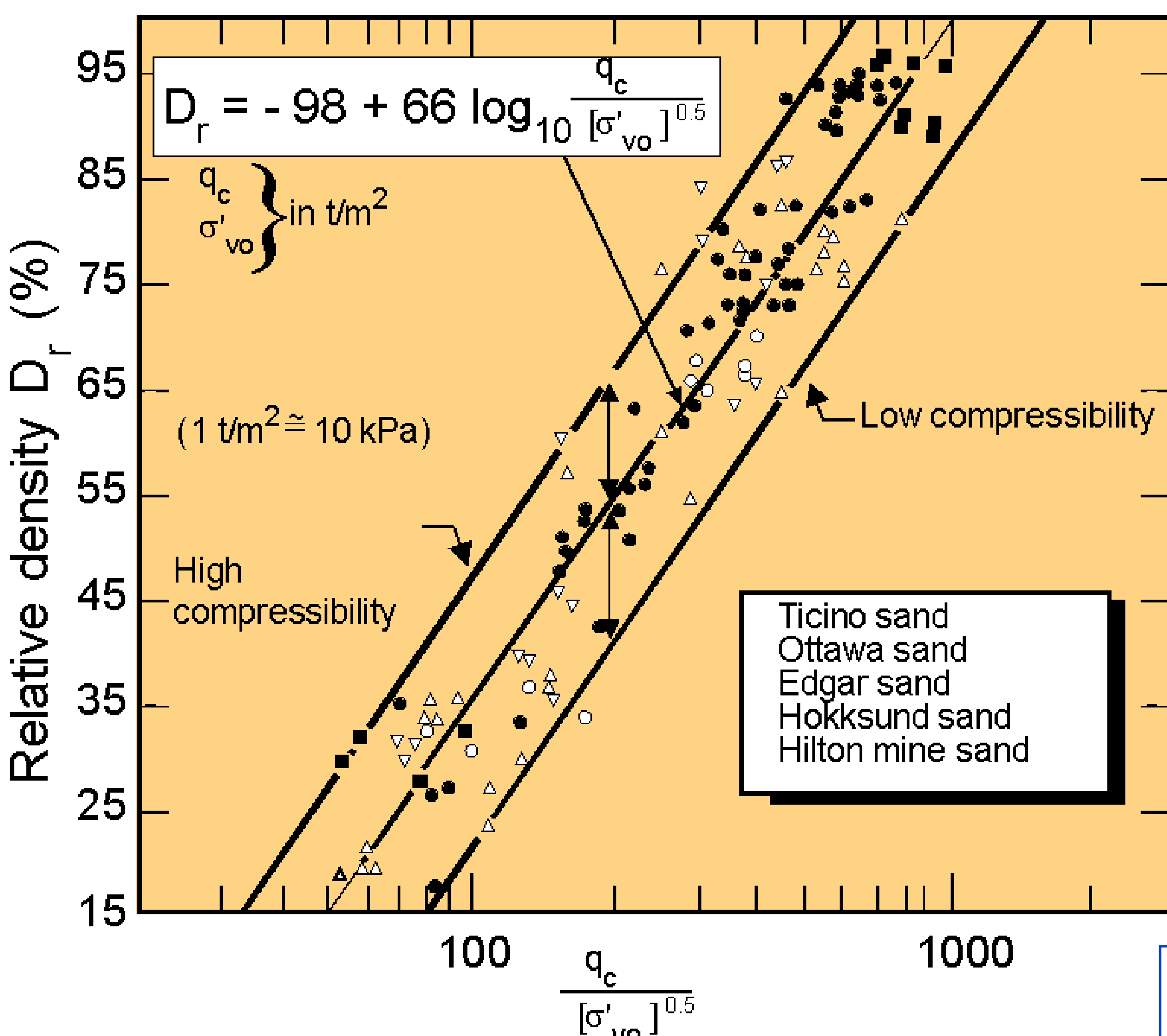


Figure 3.3 Correction for fines content for evaluation of liquefaction potential (after Lunne et al., 1997)



Influence of compressibilty on NC, uncemented, unaged, predominantly quartz sands



After Jamiolkowski et al., 1985

CONDEEP base being built in dry dock in Stavanger

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CONDEEP out of dry dock : construction continues in fjord

NGI

CONDEEP being floated to site

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