Additional Sensors

ADDITIONAL SENSORS THAT CAN BE INCORPORATED

- Modern electronics, sensor technology and data acquisition systems have opened up a whole new world for 'add-on' devices to the CPT/CPTU.
-
- We can now supplement the information from a CPT or CPTU by adding additional sensors.

- Can be dealt with in two parts
  - Engineering
  - Geoenvironmental – not today and a very specialist and powerful area

Add on devices

- Lateral stress measurements
- Cone Pressuremeter
- Seismic measurement
- Electrical resistivity
- Heat flow
- Density probes
- Acoustic noise
- Vision/video cone
- Gamma cone
- Magnetometer

- Full Flow devices

Add on devices

- Lateral stress measurements
- Cone Pressuremeter
- Seismic measurement
- Electrical resistivity
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- Gamma cone
- Magnetometer

- Full Flow devices

Seismic cone

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Or

Small strain shear modulus and the CPT

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Small strain shear modulus

- The shear modulus is largest at very low strains and has received particular attention in recent time.
- This initial, small strain modulus is often often denoted G_o or G_{max} (this may lead to some confusion as will be discussed later)

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Small strain shear modulus

$$G_o = 99.5\,(p_a)^{0.305}\,\frac{(q_{t/c})^{0.695}}{(e)^{1.130}}$$

where:
p_a = atmospheric reference stress in the same units as G_o and q_t.

NOTE much of the original scatter could also have related to the use of q_c and not q_t

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Seismic measurements

Seismic Piezocone = SCPTU

Add geophones and/or accelerometers to CPTU to measure arrival of compression wave (P) and shear wave (S) to compute the compression wave velocity (V_p) and the shear wave velocity (V_s)

Elastic theory (since strains induced in the soil by the waves are very small) allows for computation of the modulus parameters:

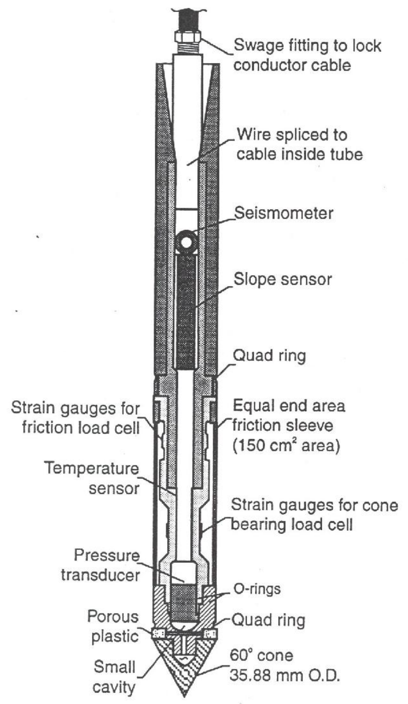
- Small Strain Shear Modulus = G_0 = G_{max} = $\rho_t(V_s)^2$

- Constrained Modulus = M_0 = $\rho_t(V_p)^2$

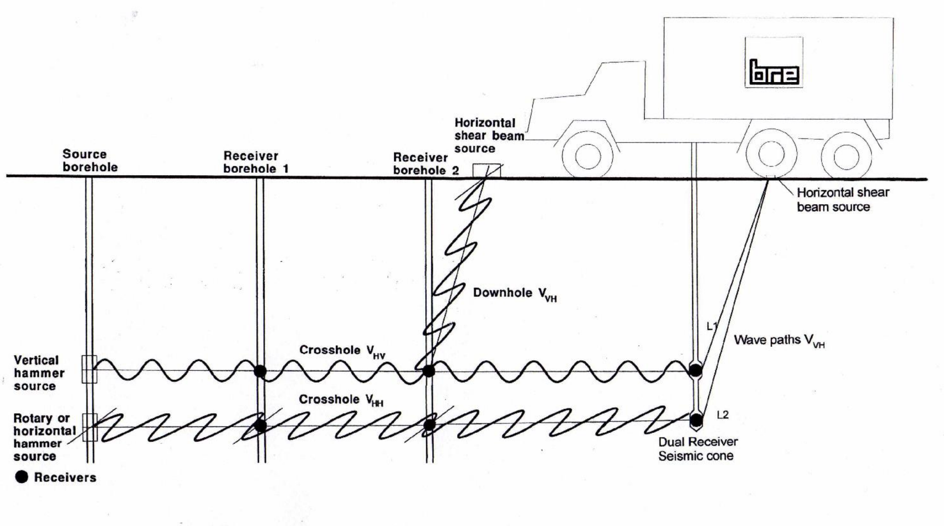
ρ_t = total unit weight

Seismic Cone

Can be 3D arrays



Geophysical testing



Shear Wave Velocity - Fundaments

The in situ shear wave velocity, V_s (and hence small strain shear modulus G_{max}) can be highly anisotropic. Thus direction of travel and polarization of wave is important.

V_{vh} – vertically propagating, horizontally polarized wave
V_{hh} – horizontally propagating, horizontally polarized wave
V_{hv} – horizontally propagating, vertically polarized wave.

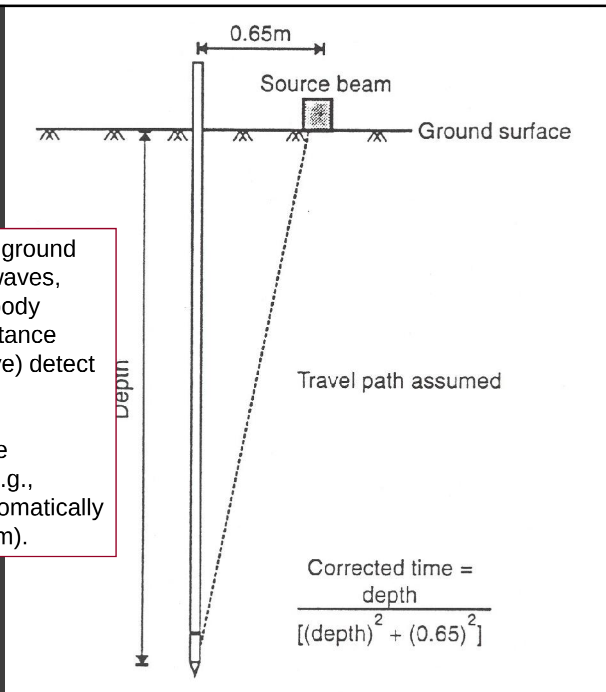
In some soils $V_{vh} \approx V_{hv}$; in most soils $V_{vh} \neq V_{hh}$.

SCPTU is a downhole method and thus measures V_{vh} or gives G_{vh}
(although most refer to SCPTU shear wave velocity as V_s)

SCPT test

Energy source at the ground surface initiates the waves, sensors in the cone body (usually just short distance after the friction sleeve) detect the wave arrival.

Source energy can be activated manually (e.g., hammer) or semi-automatically (e.g., hydraulic system).



Dual element option etc

Mechanical Seismic Source – Cone Truck

Normal force applied to beam for good contact with ground surface

Mechanical Seismic Source – Cone Truck

Normal force applied to beam for good contact with ground surface

SCPTU – "Portable" Source Beam for use with Drill Rigs

Trigger for recording of t = 0

Set-up allows for reverse strikes

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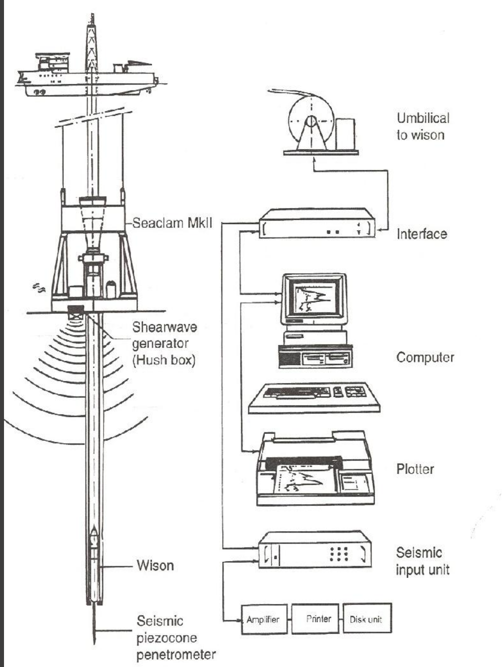
Seismic Cone



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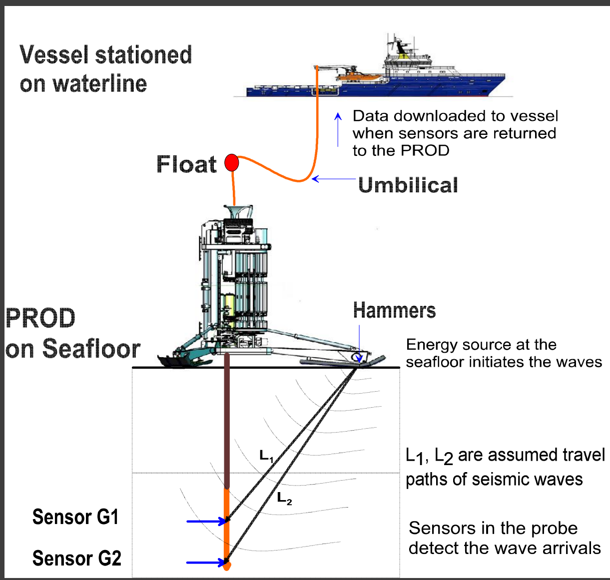
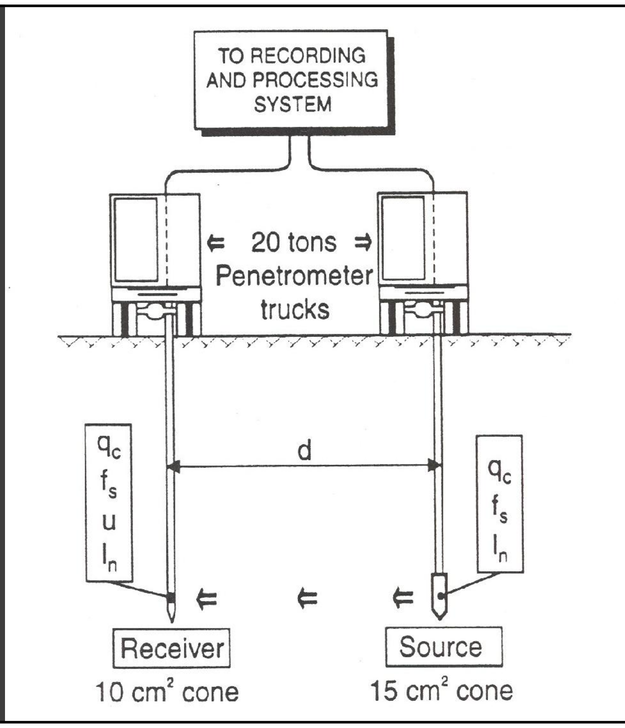
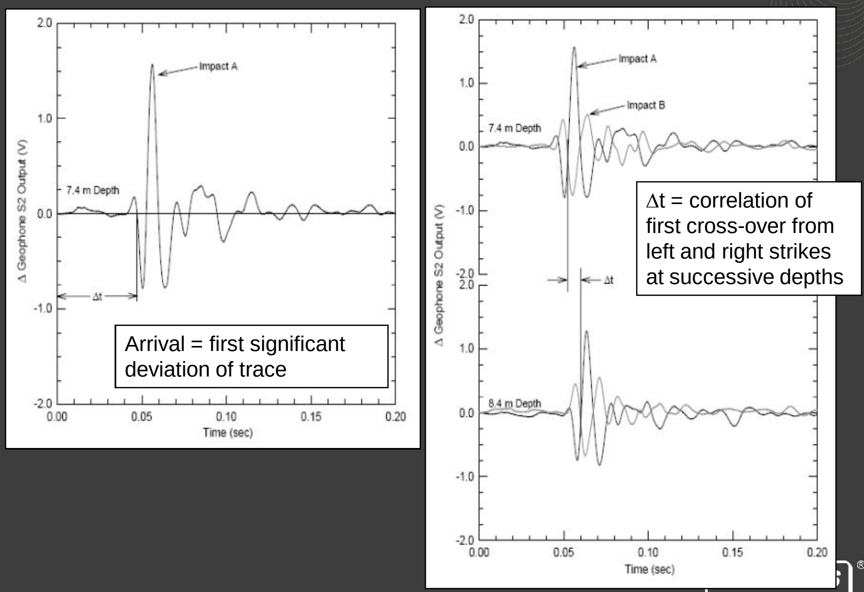
PROD SEISMIC PROBE



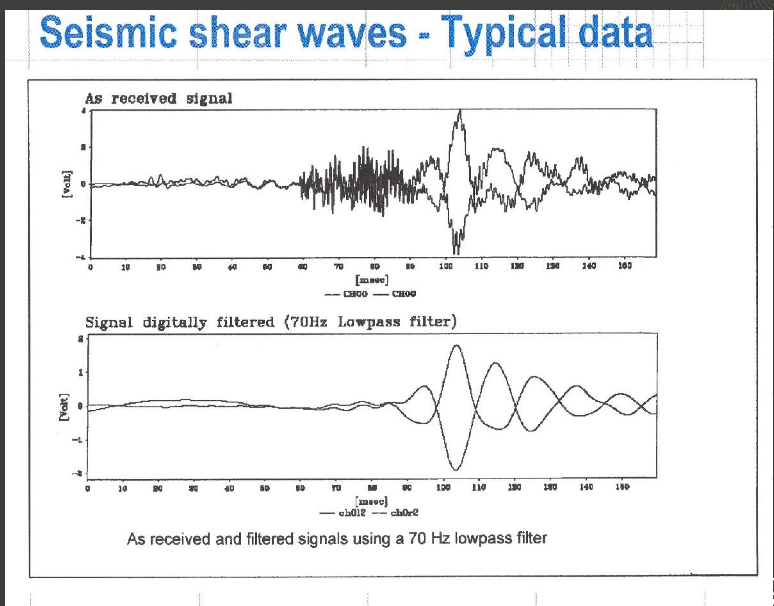
Courtesy of Hoang, Benthic



Example SCPTU Traces – Boston Blue Clay



Reversal



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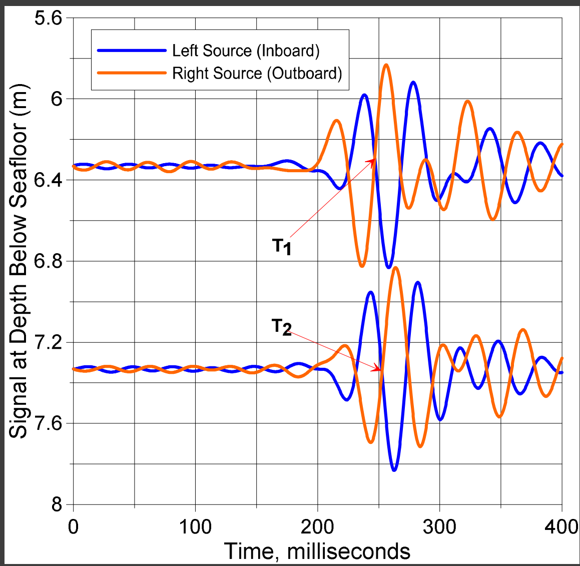
DATA REDUCTION: Filtered Data



Courtesy of Hoang, Benthic

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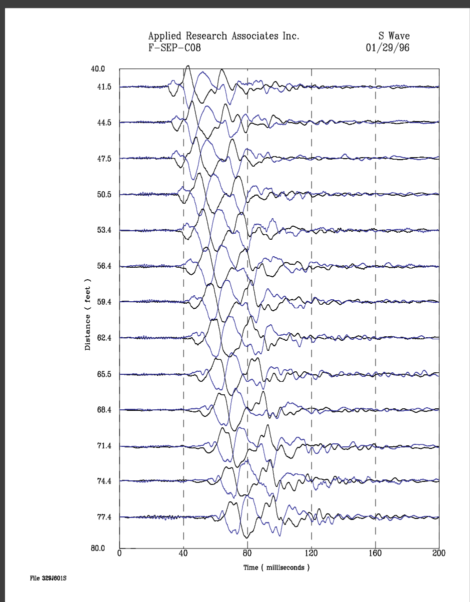
Example of Seismic-CPT Data



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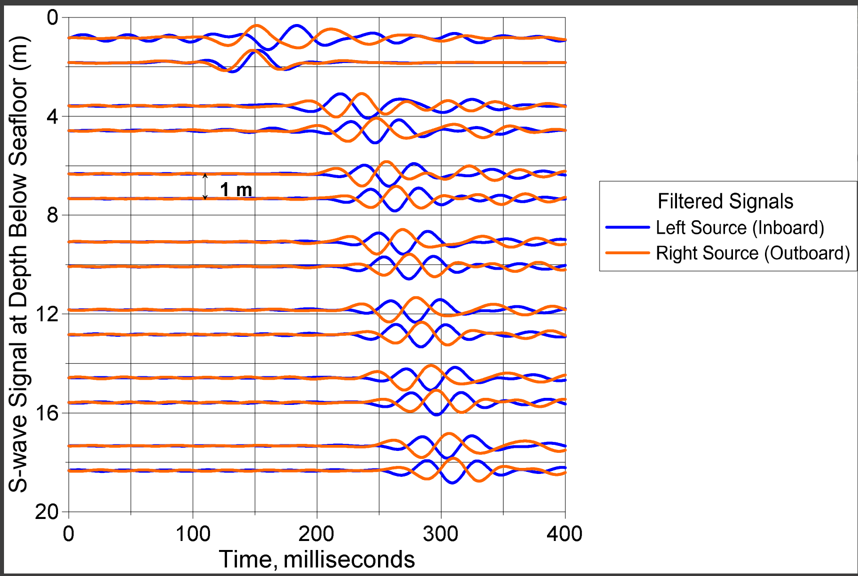
DATA REDUCTION: Filtered Data



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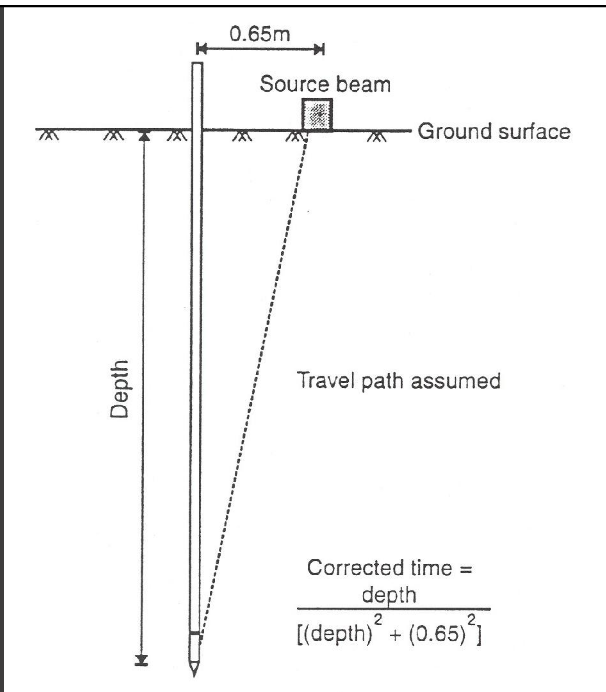
Courtesy of Hoang, Benthic

SCPT test



Dual element option etc

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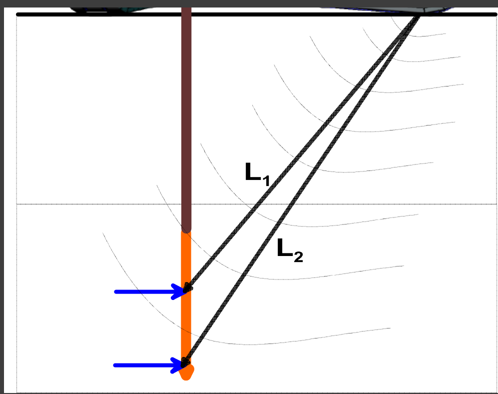
PROD SEISMIC PROBE



L_1, L_2 are assumed travel paths of seismic waves

Sensors in the probe detect the wave arrivals

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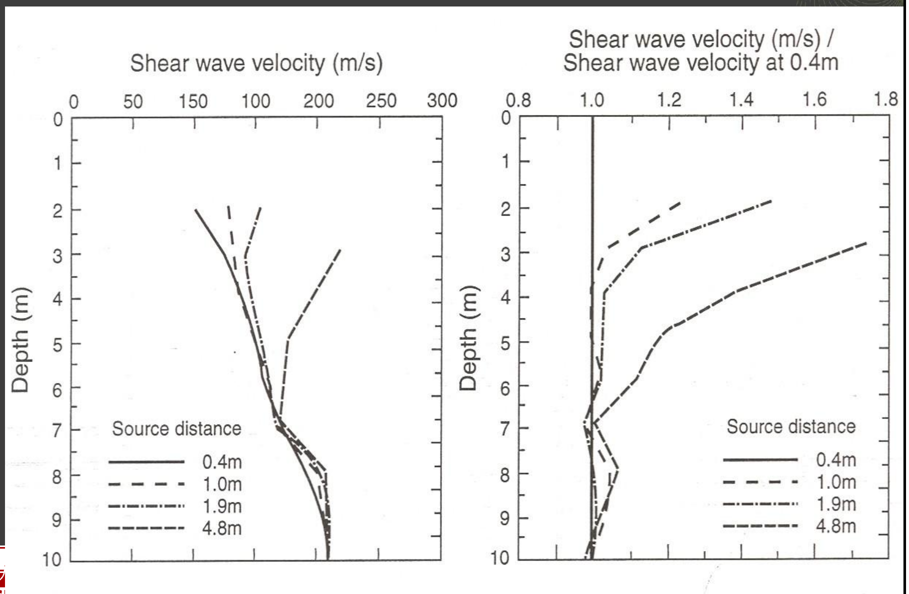
Potential Errors



Data Reduction

Shear Wave Velocity: $V_s = \Delta L/\Delta t$

Measurement Methods:

1. Pseudo Interval – difference in arrival time between successive depths using single set of geophones
2. True Interval – two sets of geophones in the cone, measure arrive of same wave to directly determine Δt

Determination of Arrival time:

1. First deviation of the trace
2. Cross-correlation between successive depths
3. First cross over of wave traces when using left and right strikes

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Seismic Cone Testing

Dual	vs	Single element
Spacing fixed typically 0.5 -1m		dependent on push interval accuracy of depth measurement
Triggering same		can have differences
Generally more reliable **Level of uncertainty removed**		peaks and troughs in data

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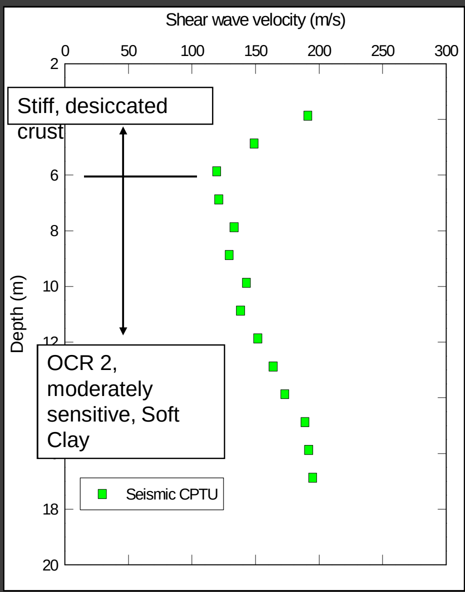
Example vs Profile from SCPTU



Boston Blue Clay, Newbury, MA

Used pseudo interval method; analyzed data via crossover and cross-correlation methods

With estimate ρ_t can then convert to G_{max} profile

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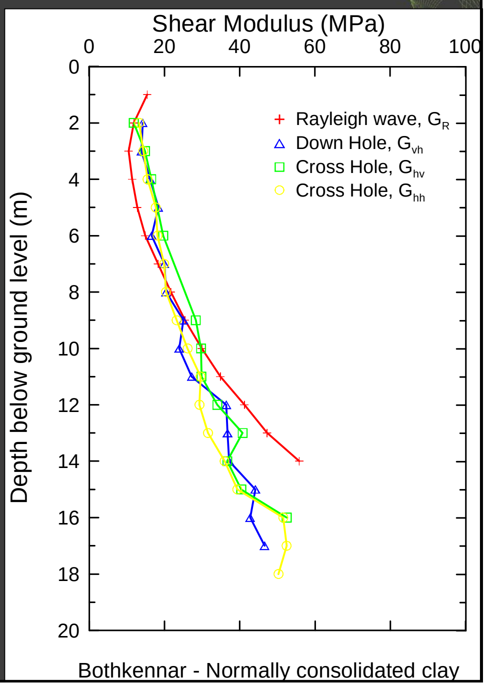
Geophysics - Bothkennar

(so G_o unique???)



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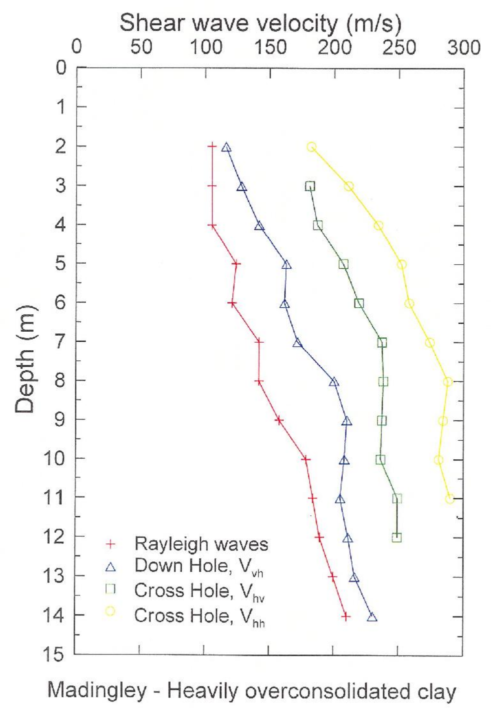
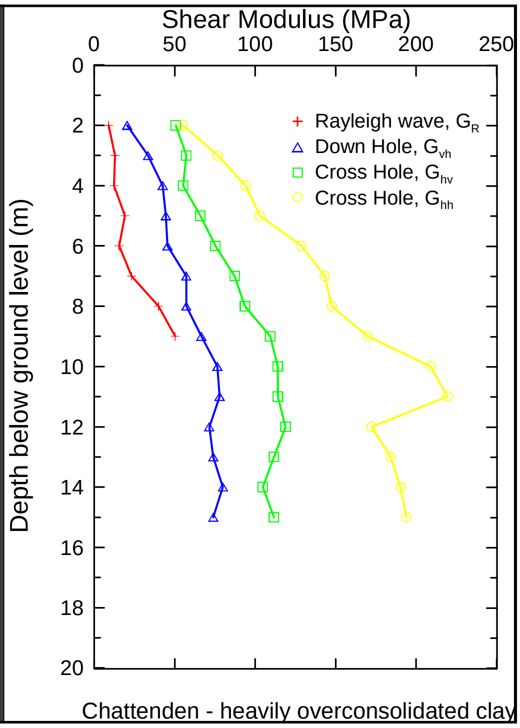
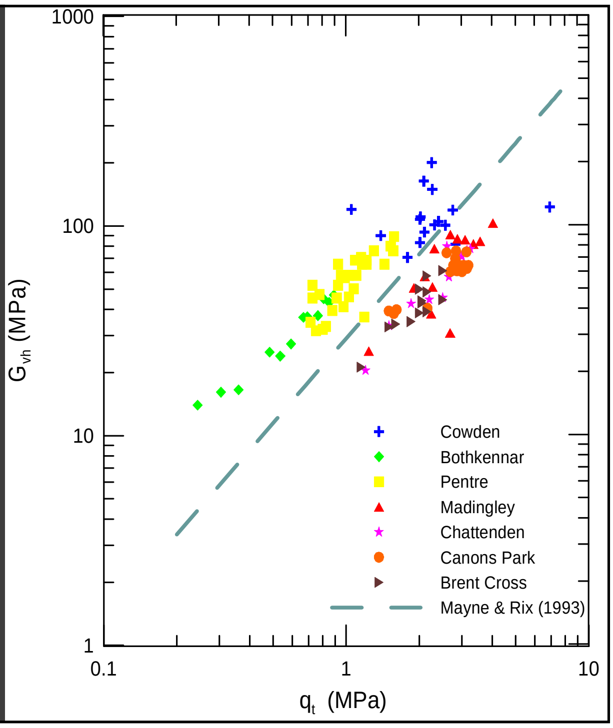
Shear wave velocities - stiff clay



Geophysics - Heavily OC clay

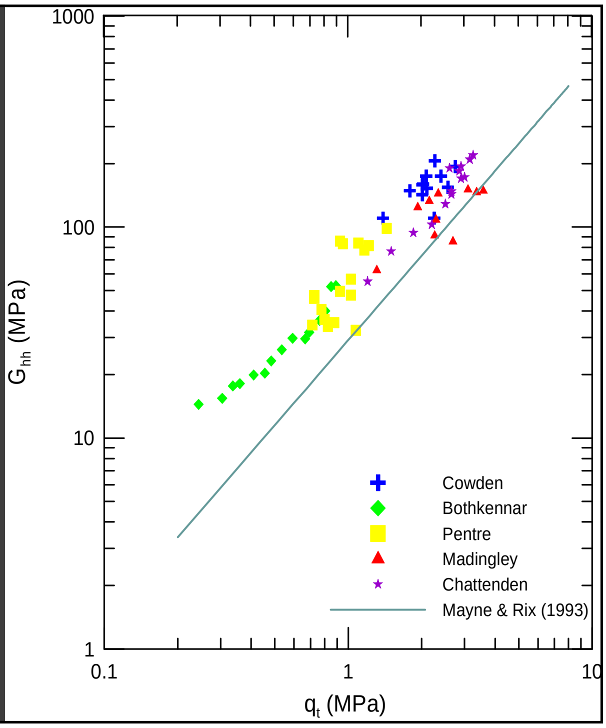


G_{VH} in UK soils



G_{HH} in UK soils

what you correlate with



Seismic Measurements

- Fahey (2001) said that the addition of seismic measurements to the CPTU should become the next standard/routine form of the CPTU and I think this is proving to be the case (Is G_o a fundamental soil parameter)
- Certainly the addition of geophones to the CPT enables downhole seismic testing to be undertaken in a very cost effective way, but remember that it is V_{vh} that is being measured
- If it is that q_t correlates with G_{hh} then, as we are actually deriving G_{vh} from the seismic cone, is there potential here for assessment of stiffness anisotropy?? Needs much more work!

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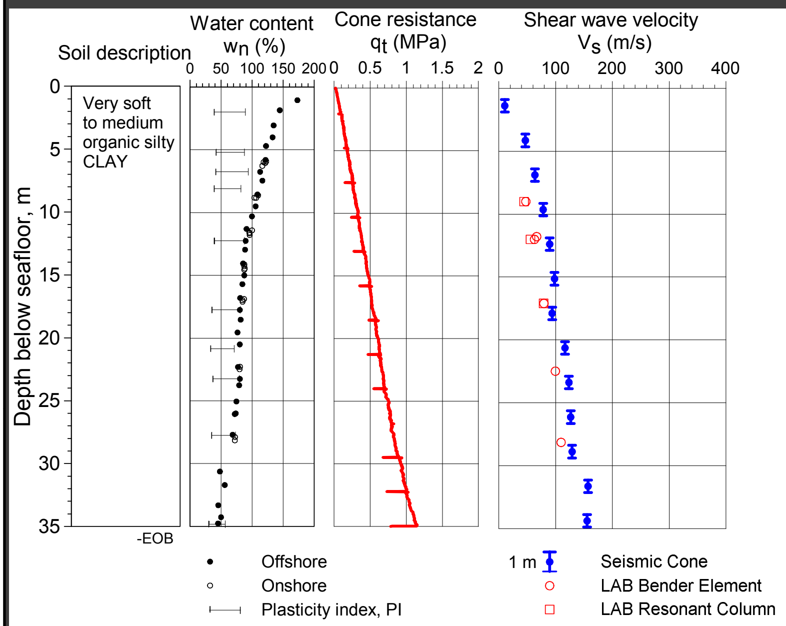
CASPIAN SEA SOFT CLAY



$G_{max} = \rho_t V_s^2$

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CASPIAN SEA SOFT CLAY

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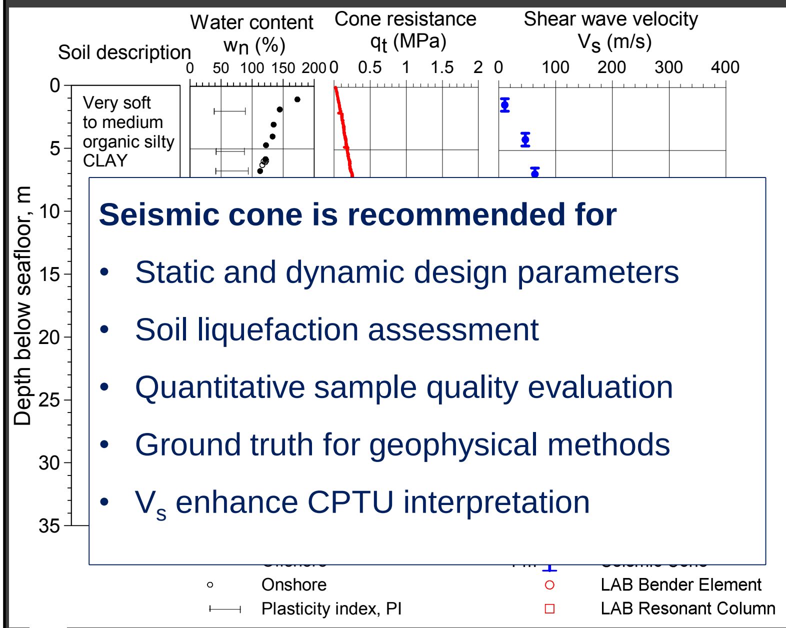

Seismic cone is recommended for

- Static and dynamic design parameters
- Soil liquefaction assessment
- Quantitative sample quality evaluation
- Ground truth for geophysical methods
- V_s enhance CPTU interpretation

$G_{max} = \rho_t V_s^2$

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Anisotropy of Stiffness

Possibly if there is a correlation between q_t and G_{hh} then as we are actually deriving G_{vh} from the seismic cone is there potential here for assessment of anisotropy?? Needs much more work!

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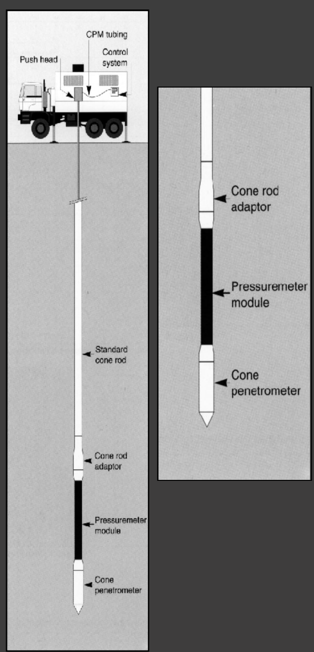
Cone Pressuremeter

Cone Pressuremeter (CPM)

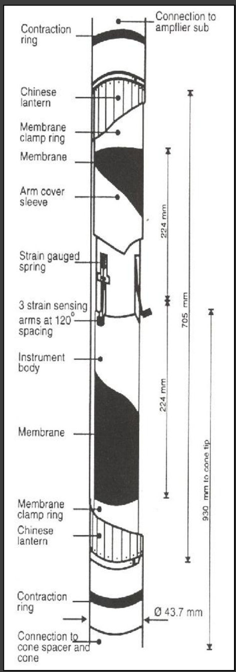


Cone Pressuremeter (CPM) = Pressuremeter module mounted behind a standard electrical cone penetrometer.

Advantages over conventional pressuremeters:

1. Uses standard CPT rigs
2. Operator independent, thus very repeatable
3. Clear ID of soils to be tested via CPT data
4. Know where in soil profile you are based on results of CPTU
5. Can combine with results of CPTU at same depth and same location

CPM – Mechanical Details



The Pressuremeter module: 43.7 mm diameter, L/D = 10, attached behind 15 m^2 CPT or CPTU.

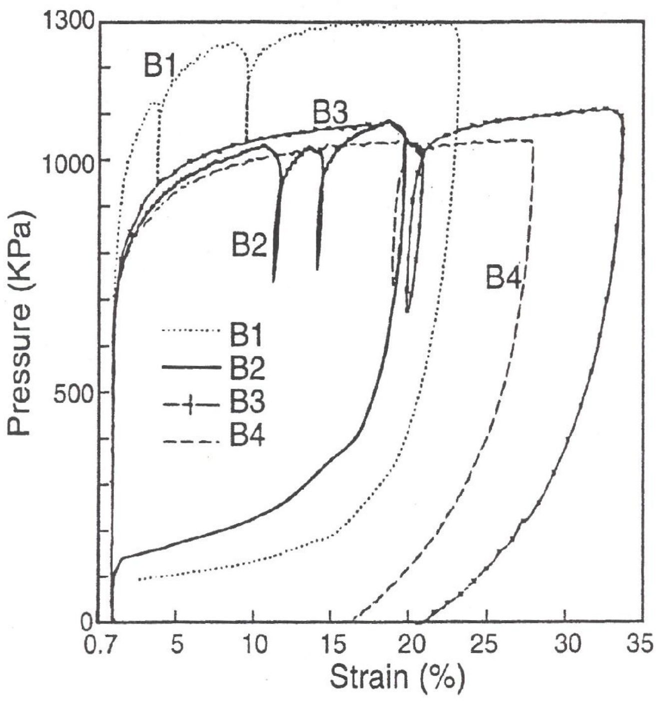
The Pressuremeter cell = cylindrical rubber membrane inflated by nitrogen gas. Membrane is protected during insertion by an additional steel reinforced rubber membrane

Measurements of inflation pressure and cavity strain are recorded at mid-height of the module by instrumentation at three locations, 120° apart. The maximum radial strain is 50%.

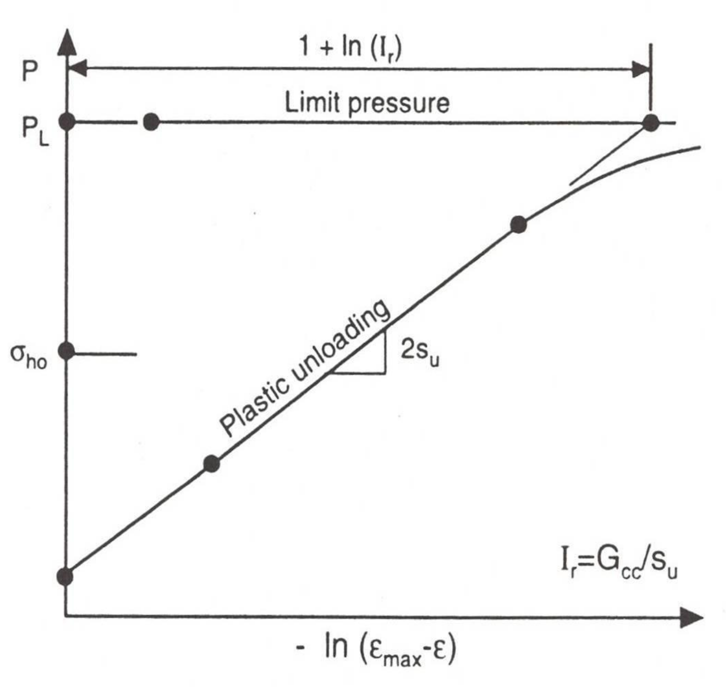
Cone Pressuremeter

Tests in Clays

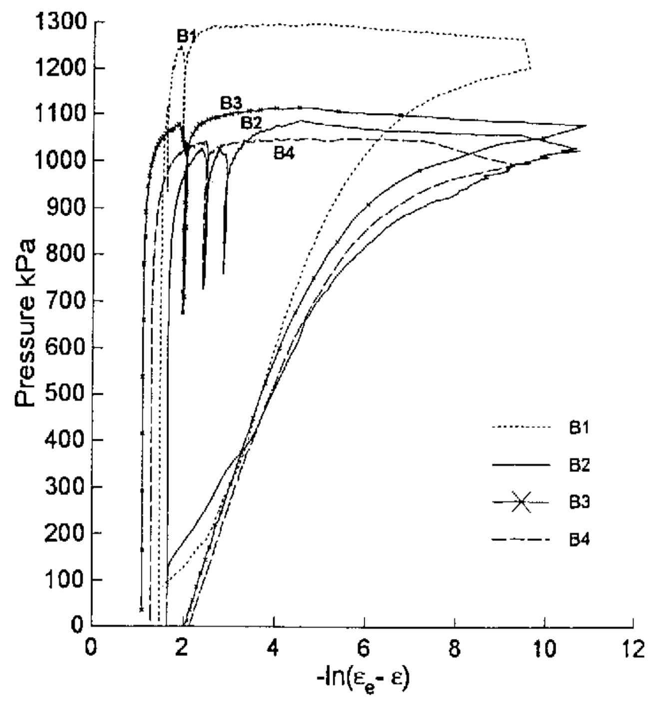
Typical CPM tests with unload reload loops



Theory

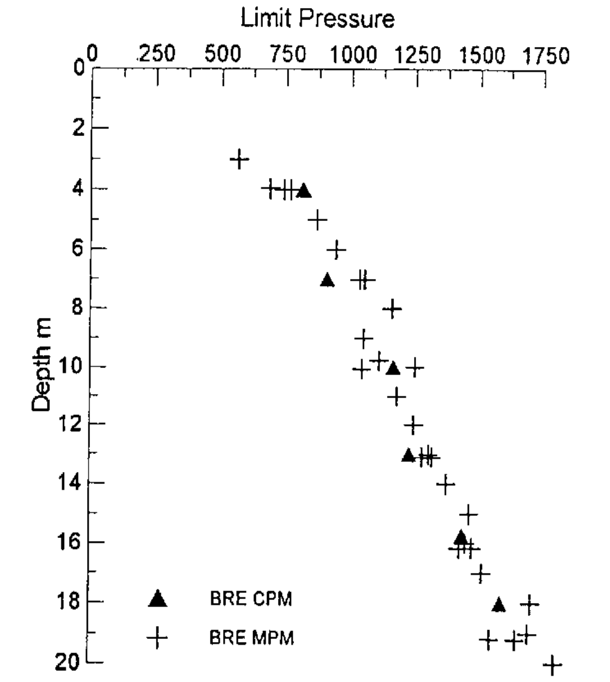


Interpretation



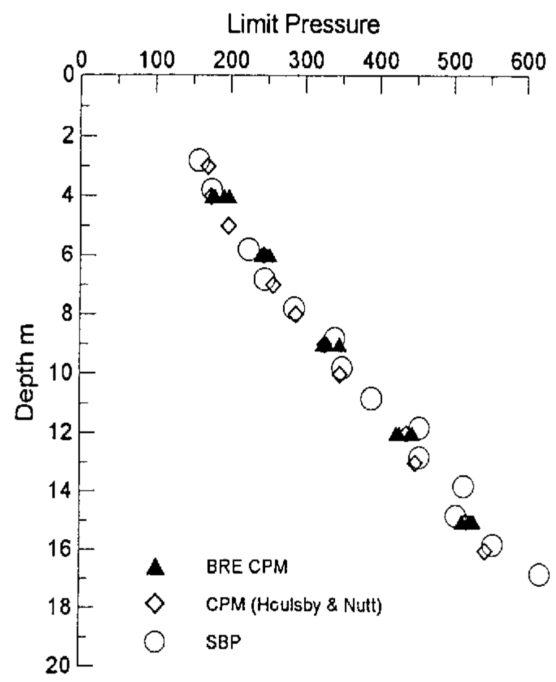
Limit Pressure

repeat



Limit Pressure

devices

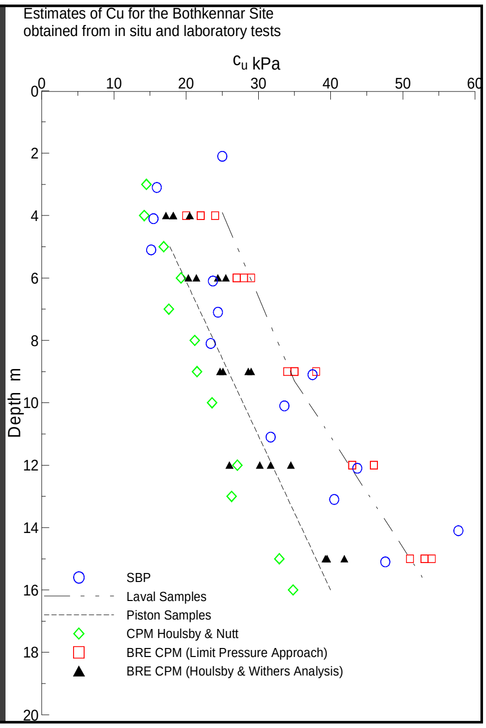


CPM shear strength soft clay

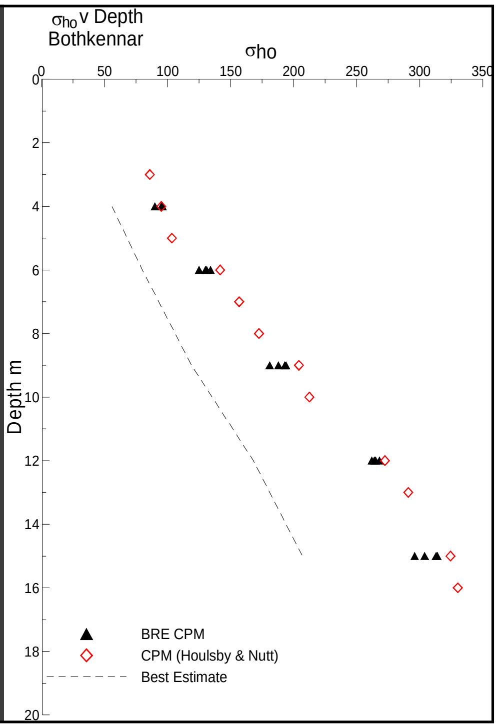
Bothkennar, UK

Undrained shear strength from CPM, SBP and laboratory triaxial tests

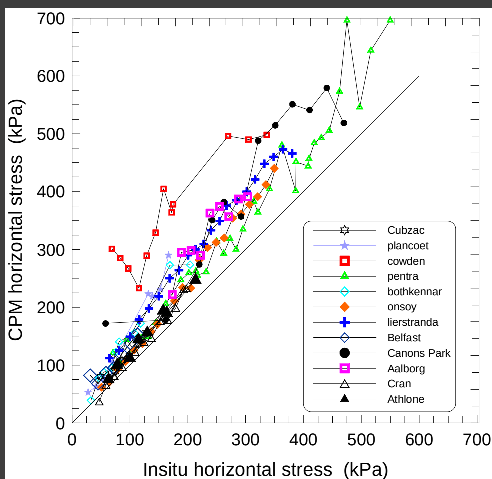
There are variations in s_u from different interpreation methods – continued topic of research



Bothkennar - σ_{ho}



σ_{ho} vs best estimate all sites



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Yu correction (for length to diameter 10:1)

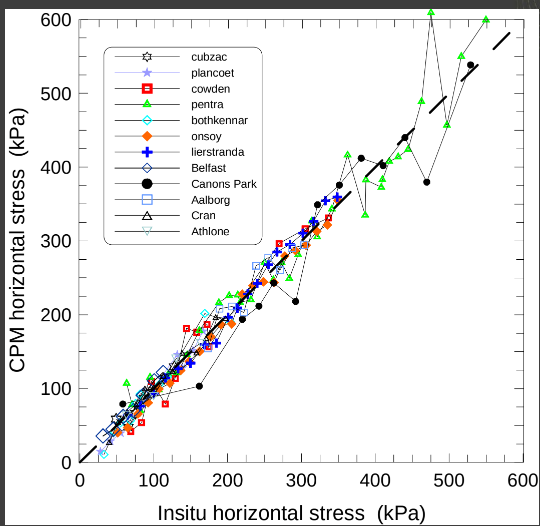
$$\sigma_{hoc} = \sigma_{hohw} - c_u \left[0.63 + 0.0733 \ln(I_r)\right]$$

σ_{hoc} is the corrected horizontal stress
σ_{hohw} is the Houlsby and Withers derived value
c_u is the strength of the soil
I_r is the rigidity index for the soil

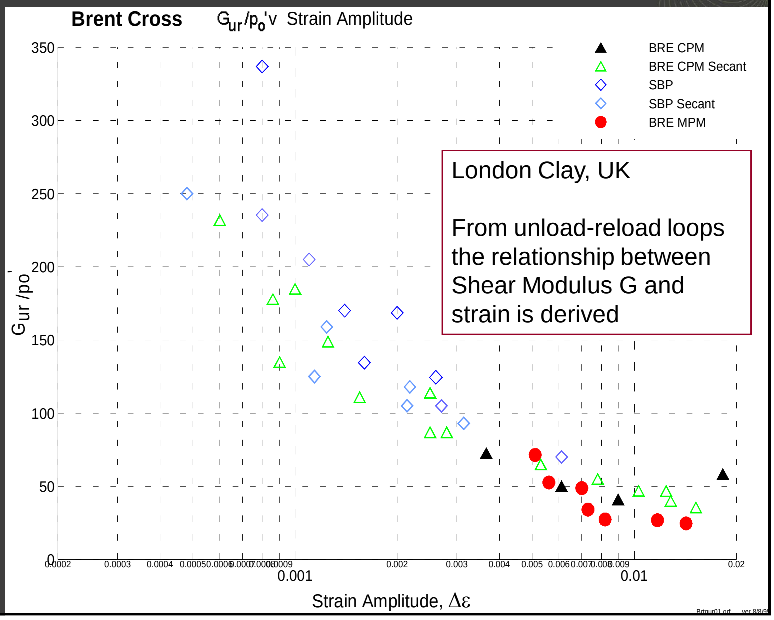
Basically c_u related correction

$\sigma_{hoyumod}$ vs best estimate all sites

Using the modified Yu correction



London Clay typical



Bothkennar stiffness non typical

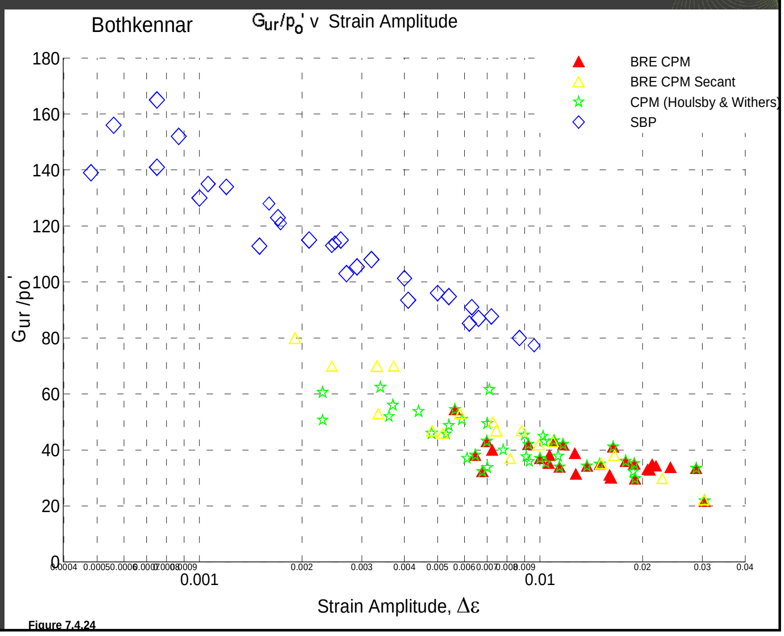


Figure 7.4.24

Cone pressuremeter - can give us

Clays:

- assessment/measurement of shear strength
- stress/ strain and hence stiffness with strain
- potential for assessment of horizontal stress – much improved

Sands:

clean sands

- initial state parameter — needs q_c
- relative density — needs q_c
- **stiffness**
- friction angle — may need q_c
- horizontal stress — needs q_c

Is there potential for better combined assessments?

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Linking the two

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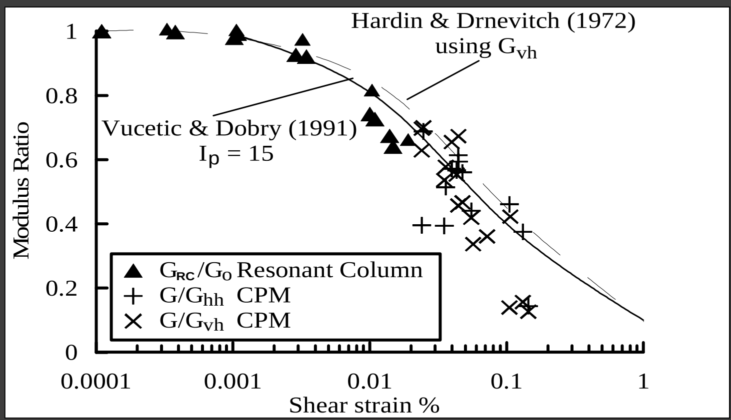
Non linear models of shear modulus and shear strain



Resonant column and CPM data from Pentre site

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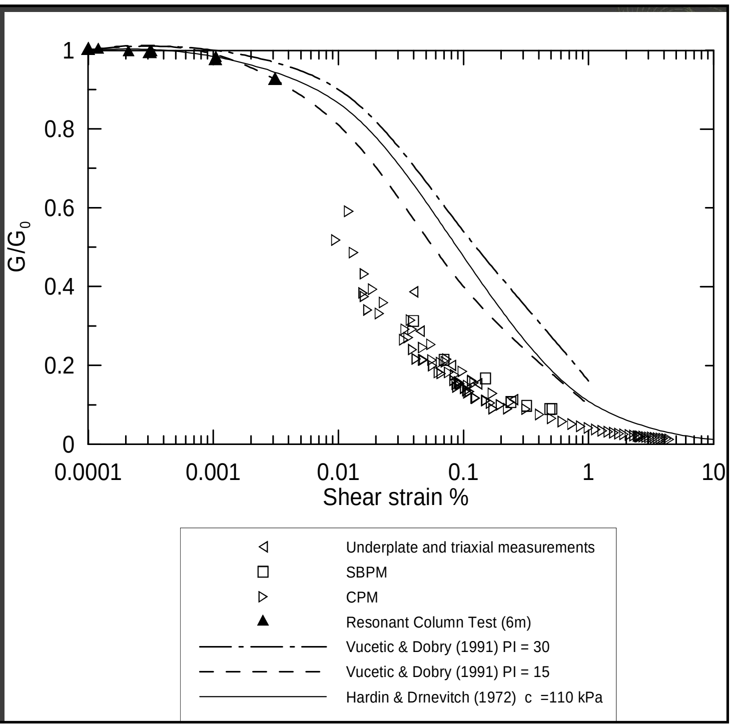

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Seismic and CPM Measurements

- Developments in procedures to extrapolate from small strain stiffness to larger strains will make the use of both tools increasingly powerful.

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Summary – Additional CPTU Sensors

1. Seismic CPTU – well proven technology, becoming increasingly popular.
2. Cone Pressuremeter – limited availability, research in progress on interpretation procedures. Greatest potential is for estimating K_0 and shear stress-strain degradation curve. But there is also potential for better combined parametrer assessments in sands?

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Full flow situ tests: T-bar and Ball tests

- Test methodology developed by University of Western Australia ; Prof. Mark Randolph and colleagues
- Mainly use offshore in very soft clays; but can also be used onshore

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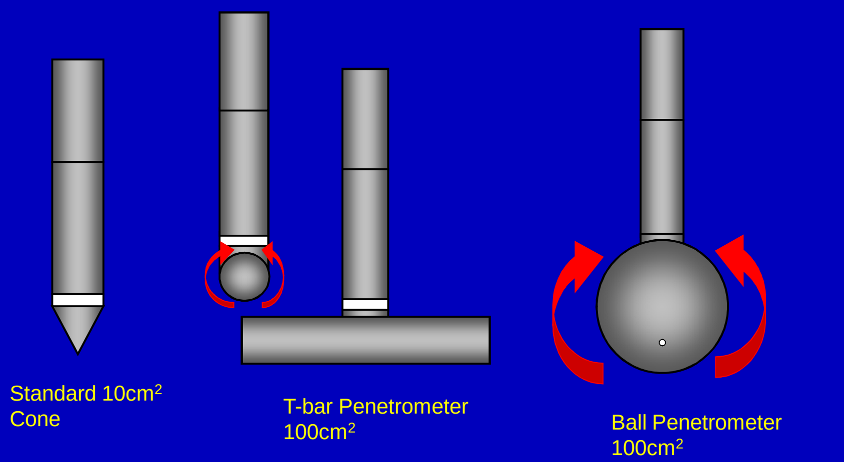
Full flow penetrometers



- Minimal correction for pore pressure effects
- Greater bearing area
- Measurements made during extraction
- Availability of simplified bearing capacity solutions

T-bar, ball and cone penetrometers

Use same load cell as for cone resistance

Aspects of T-bar and ball tests

- Equipment and procedures so far only covered in **NORSOK standard** used in North Sea; but work is ongoing to make this ISO Standard
- According to NORSOK :
  - T- bar Diameter = 40 mm; length = 250 mm
  - Ball diameter = 117 mm
  - Area = 100 cm^2
  - Speed of penetration as CPT = 20 mm/sec
  - Penetration resistance measured also during extraction

- Cyclic testing can be done to get information on remoulded shear strength or sensitivity

Piezocone Testing in Clay

Correction for pore pressure effects on cone resistance:

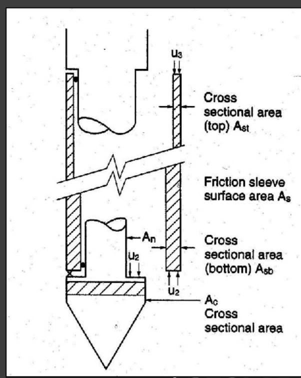
$q_t = q_c + (1-a)u_2$

q_c = measured cone resistance

$a = A_n/A_c$ = area ratio (0.3- 0.85)

u_2 = measured pore pressure behind cone

For very soft clay correction can be 25 – 40 %



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Undrained shear strength from CPTU data

In practice use : $q_t = N_{kt} * s_u + \sigma_{vo}$

Or : undrained shear strength, $s_u = (q_t - \sigma_{vo})/N_{kt}$

$= q_{net}/N_{kt}$

Where : q_{net} = net cone resistance

σ_{vo} = total vertical stress

N_{kt} = cone factor

Correction for vertical stress usually: 30 – 35 %

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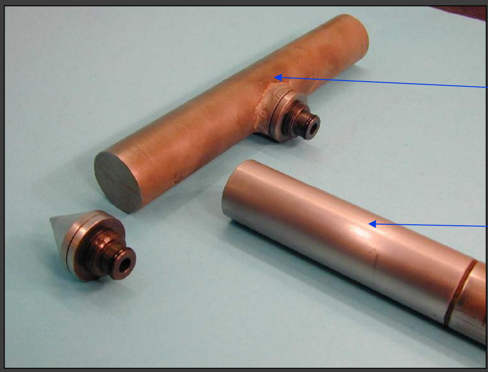
T-bar, ball and cone penetrometers



A_p

A_s

$(A_s/A_p) = 0.1$

T-bar corrections:

For pore pressure: $q_{T\text{-bar,cor}} = q_{T\text{-bar}} + (1 - a)u^* (A_s/A_p)$

For vertical stress: $q_{net} = q_{T\text{-bar,cor}} - \sigma_{vo} * (A_s/A_p)$

Normally u not measured, but $u < u_2$ (CPTU)

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Comparison CPT and T-bar and Ball

Corrections required before computing shear strength:

Correction effect	CPTU	T-bar and Ball
Pore water pressure	+ 20 – 40 % of q_c	< + 2 – 4 % of $q_{T\text{-bar}}$
Total vertical stress	- 30 – 35 % of q_c	- 3 – 3.5 % of $q_{T\text{-bar}}$

In addition area of T-bar 10 times larger than cone, so much better resolution

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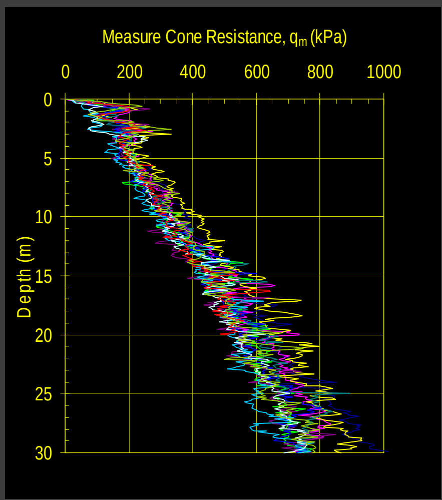
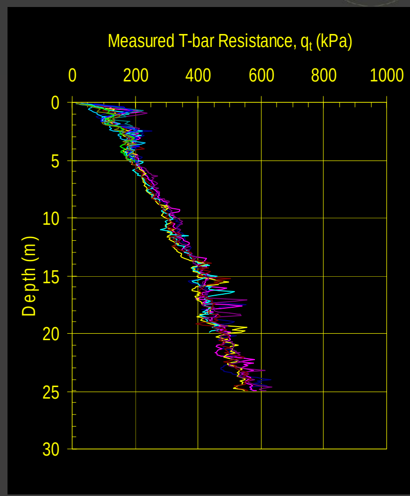
CPTU and T-Bar, offshore Australia

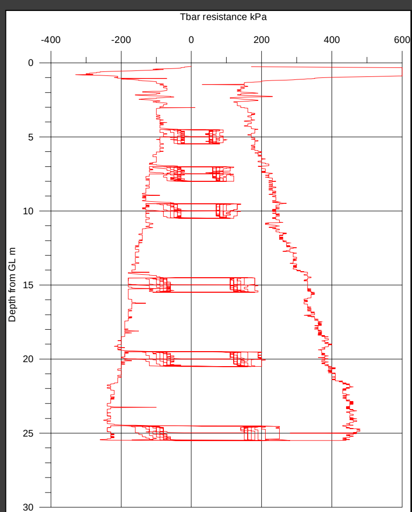




CPTUs at 11 locations

T-bar tests at 11 locations

Typical results from Onsøy clay (Norway)



Complete T-bar test at Onsøy site including extraction and cyclic tests

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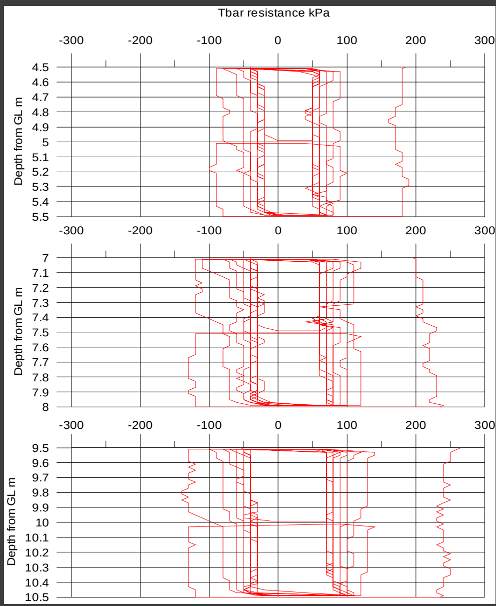
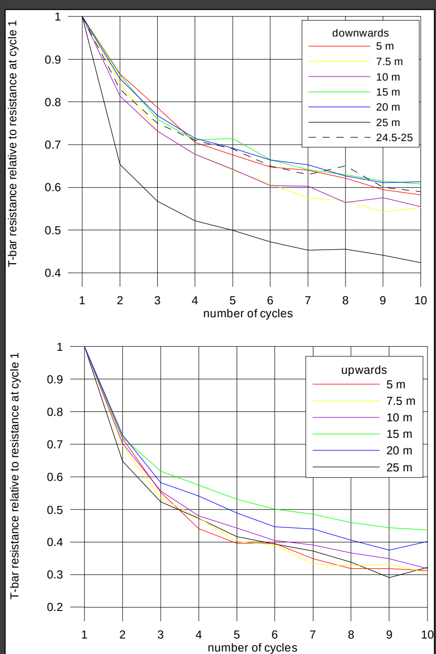


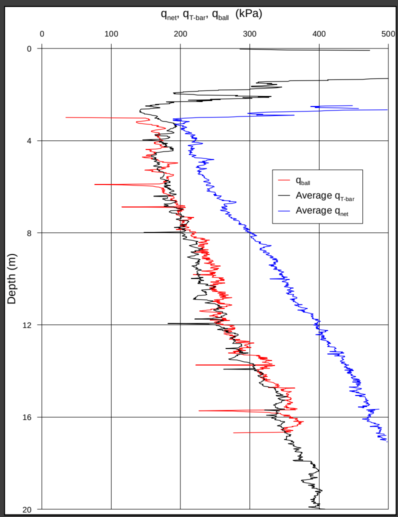
Results of cyclic T-bar tests, Onsøy clay



Results of cyclic T-bar tests, Onsøy clay, Degradation curves

For computation of remoulded shear strength, use average of penetration and extraction resistance after 10 cycles

Comparison results from CPT, T-bar and ball



q_{net}, $q_{T\text{-}bar}$ and q_{Ball} at Onsøy

Tests so far indicate T-bar and ball give very similar results

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Recommended N-factors from NGI/COFS JIP project

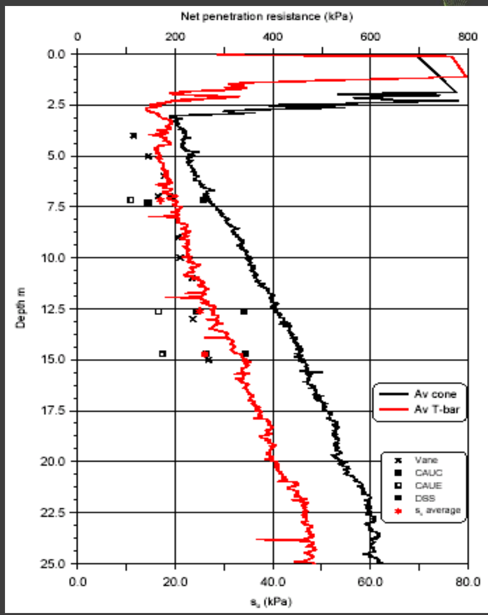
Data base established high quality data from 11 offshore and 3 onshore sites:
CPTU and T-bar/ball penetration test results
CAUC triaxial and DSS test results on good quality samples

Statistical evaluation of N_{kt},$N_{\Delta u}$ and $N_{T\text{-}bar}$ based on s_u from CAUC (and DSS and vane)

NGI Low et al. (2010) GEOLABS®

Penetration Resistance and Shear Strengths

Onsøy clay



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Recommended N-factors from NGI/COFS study

N factor	Definition	Recommended N-factor	
		Mean	Range
$N_{kt,suc}$	q_{net}/s_{uc}	**12.0**	**10.0 -14.0**
$N_{\Delta u}$	$(u_2 - u_0)/s_{uc}$	**6.0**	**4.0 - 9.0**
$N_{T\text{-}bar,suc}$	$q_{T\text{-}bar}/s_{uc}$	**10.5**	**8.5 - 12.5**

Similar variation in N_{kt} and $N_{T\text{-}bar}$ with s_u from CAUC triaxial strength (similar conclusions when using DSS s_u as reference)
Larger overall variation in $N_{\Delta u}$ but when good data are available for local correlation use of $N_{\Delta u}$ can be very useful. For Norwegian soft marine clays s_u is now computed from Δu_2 on regular basis

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T-bar and Ball for assessing undrained shear strength in soft clays

- Larger area gives better resolution of results
- Less correction due to pore pressure and vertical stress
- Need to determine T-bar (Ball) factor to determine undrained shear strength; wrt triaxial tests (CAUC)
- Potential to determine remoulded shear strength from cyclic tests (but $N_{T\text{-}bar}/N_{Ball}$ for remoulded strength > than for intact strength)
- T-bar/ball testing of offshore box cores have proved to be useful
- **For very soft clays where s_u is critical it is often recommended to do T-bar or ball in addition to CPTU offshore**

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Incentive for compensated cone penetrometers in deep waters

In 2000 m water depth a typical cone penetrometer will sense at the seafloor: u_2 = 20 MPa q_c = 15 MPa (with a = 0.75)

In a soft clay typical values *with reference to seafloor* will be at 10 m penetration:

u_2= 0.18 MPa and **q_c = 0.35** MPa, corresponding to undrained shear strength, s_u = 32 – 40 kPa.

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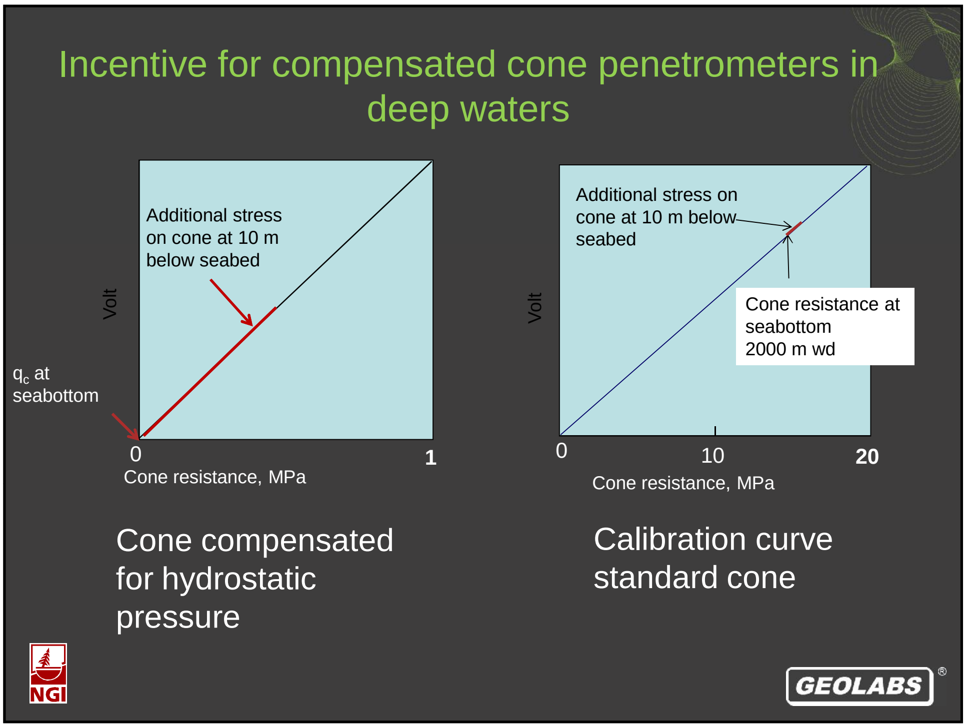
Incentive for compensated cone penetrometers in deep waters
Additional stress on cone at 10 m below seabed
Volt
qc at seabottom
0
1
Cone resistance, MPa
Cone compensated for hydrostatic pressure
Additional stress on cone at 10 m below seabed
Volt
Cone resistance at seabottom 2000 m wd
0
10
20
Cone resistance, MPa
Calibration curve standard cone
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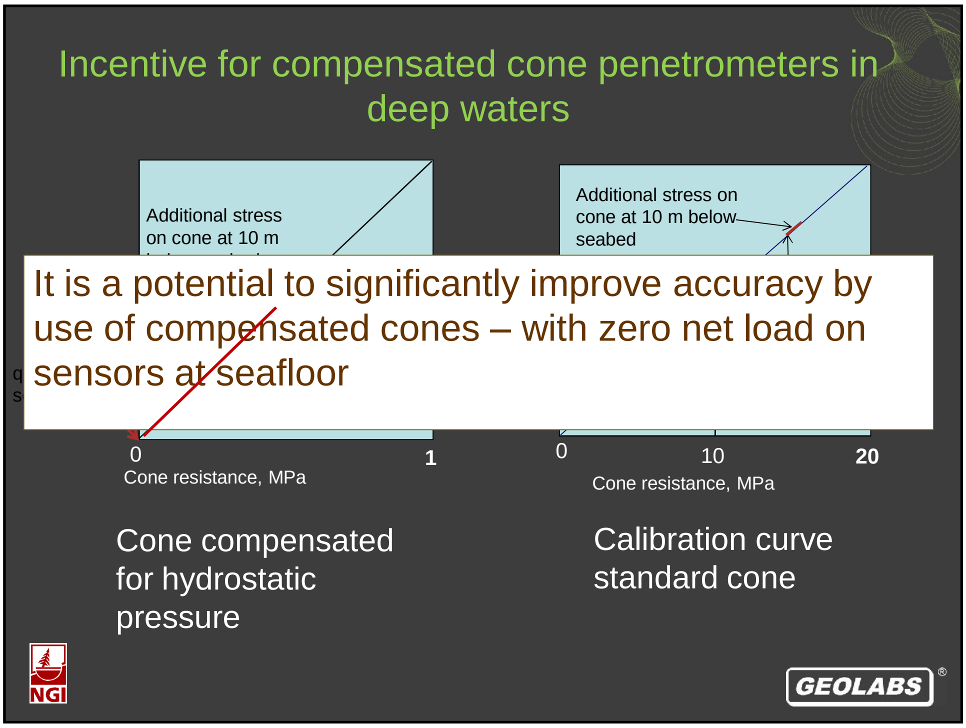
Incentive for compensated cone penetrometers in deep waters
Additional stress on cone at 10 m
Additional stress on cone at 10 m below seabed
It is a potential to significantly improve accuracy by use of compensated cones – with zero net load on sensors at seafloor
0
1
Cone resistance, MPa
0
10
20
Cone resistance, MPa
Cone compensated for hydrostatic pressure
Calibration curve standard cone
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Electrical Resistivity Measurements

- Measurement of electrical conductivity (resistivity = $(\text{conductivity})^{-1}$) in soils has been used for many years for the purpose of estimating in situ porosity or density.
- Electrical resistivity has also been used as an indicator of soil contamination.
- Electrical resistivity is also an important input for the evaluation of the corrosive potential of the soil (e.g. Bryhn, 1989).

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Electrical Resistivity - Fundamentals

Electrical resistivity of soil is not measured directly, but is inferred from the measured voltage (V) across an electrode pair at a constant supplied current (I).

According to Ohm's law, soil resistance, R, can then be computed as:

$R = V/I$

This is not a fundamental soil property because depends on current path length and cross sectional area of effective resistance unit. Can convert to Soil Resistivity (ρ) as,

$\rho = (A/L)R = KR = K(V/I)$, where obtain K via calibration

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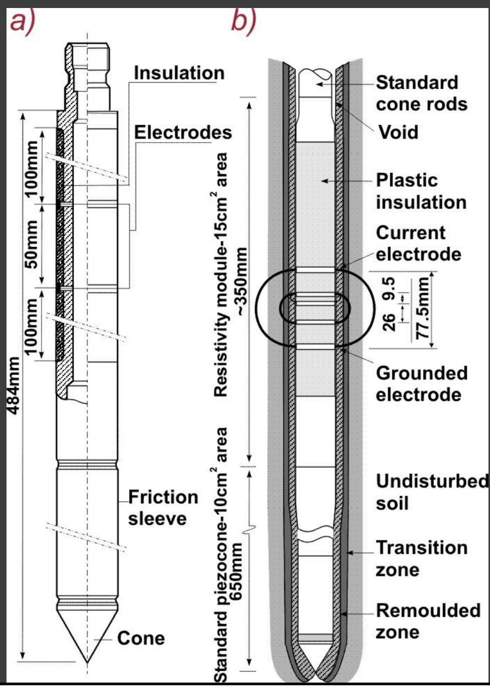


Electrical resistivity Probe

a) Single electrode

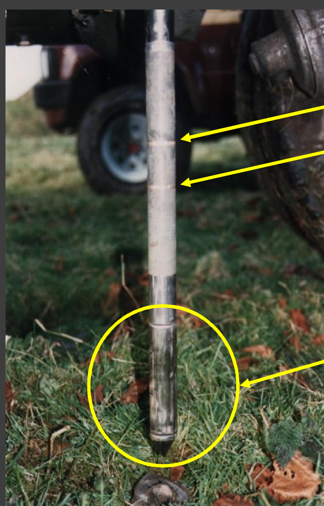
(Zuidberg et al.,1987)

b) Double electrode

(Campanella and Kokan,1993)

Spacing of electrodes ("dots" or rings) controls the effective zone of influence over which the resistivity is measured and also whether measurement is in disturbed or undisturbed zones.

Electrical Conductivity Cone



Electrical conductivity instrument (brass rings)

Standard friction cone

Resistivity/dielectric probes

(Georgia Tech - Mayne)

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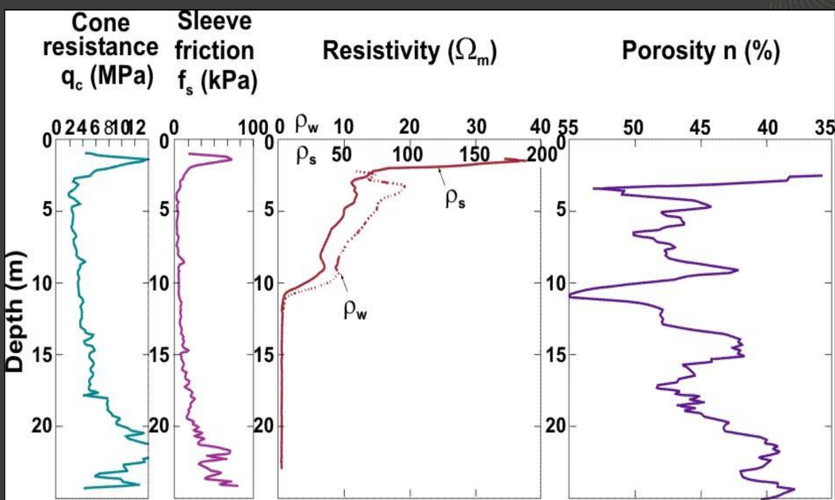
Example of Porosity from CPT Resistivity



Tests by GeoDelft and NGI (1982)

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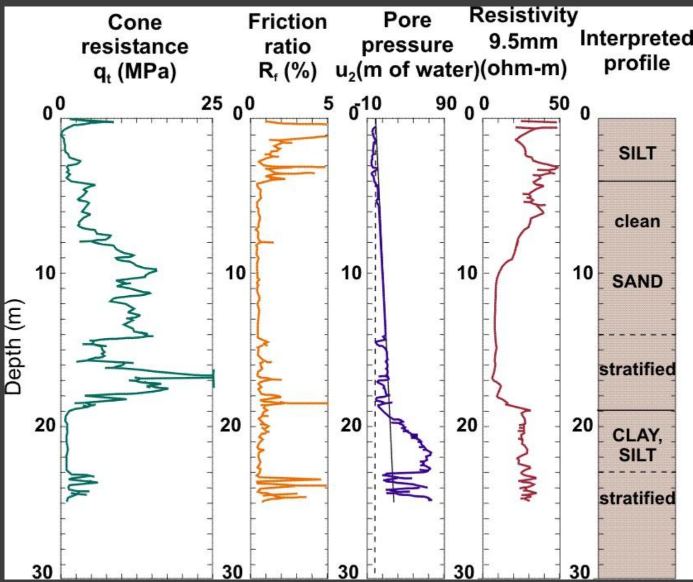
RCPTU results Laing Bridge, Vancouver



Campanella and Kokan(1993)

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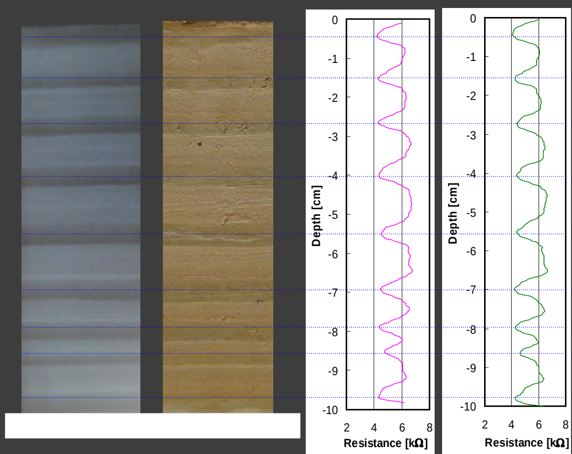
Miniature Needle Probe Resistivity Measurements for Stratigraphy



X-Ray
Photograph
Needle probe measurements

Measurements on sample of Connecticut Valley Varved Clay, Amherst, MA conducted by Santamarina (GT).

Measured resistance between small insulated wire inside hypodermic needle – awaits possible field development

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Possible approach to get Relative density, D_r form electrical resistivity CPT

- Campanella and Kokan (1993) suggested that ratio of electrical resistivity measured by closely spaced electrodes and widely spaced electrodes may be related to D_r
- $D_r = f(\rho_{closespacing} / \rho_{widespacing})$
- $D = (\rho_{closespacing} / \rho_{widespacing})$ = dilatancy parameter

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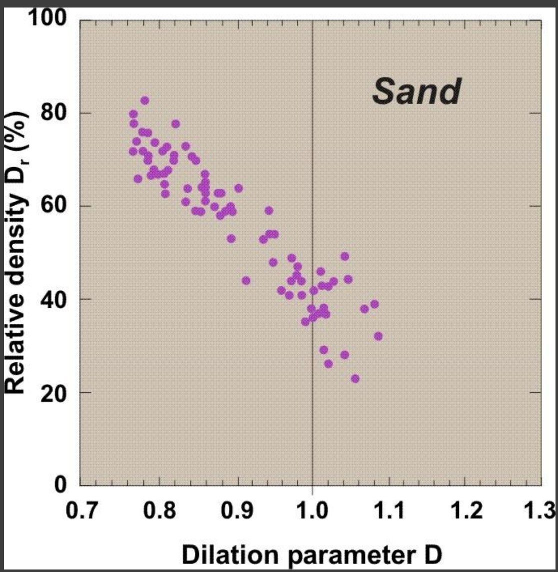
Possible approach to get Relative density, D_r form electrical resistivity CPT



Campanella and Kokan(1993)

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Special density probe from Kyoto University, Japan

- **Neutron moisture (NM) probe**
- **Neutron Density (ND) probe**

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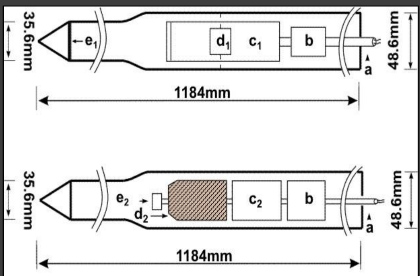
Special Density Probes – Kyoto University



a: cable leading to data collection system:
b: pre-amplifier,
c1: He^3-filled proportional tube
c2: photomultiplier tube
d1: Cf^{252} fast neutron source
d2: lead (Pb) shield
e1: porous ceramic filter
e2: Cs^{137} gamma-ray source

Neutron Moisture (NM) probe – for water content determination

Neutron Density (ND) probe – for soil density determination

Allows for profiling of water content and soil density.

[Mimura et al. 1995]

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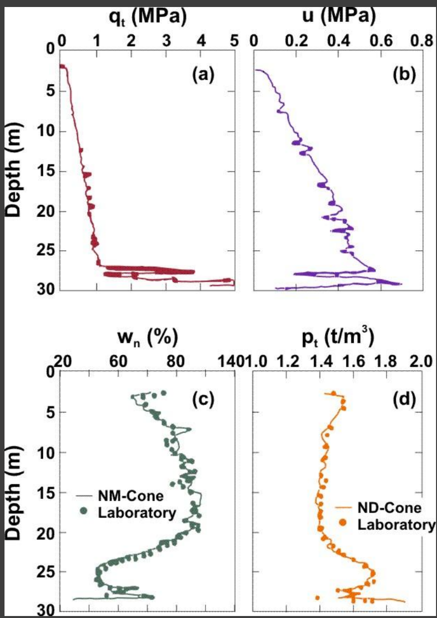

Results of Kyoto University density probes in Kinkay Bay clay, Japan

Very good!!

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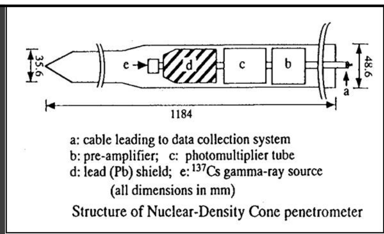
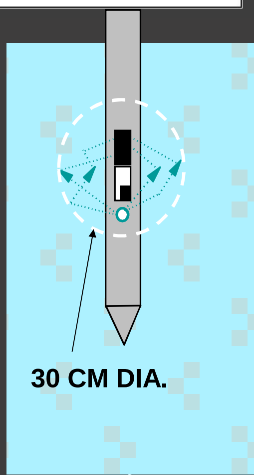
NUCLEAR DENSITY CONE ND-CPT



- DENSITY RELATED TO SCATTERING OF GAMMA RAY
- CESIUM SOURCE
- HOUSED IN STANDARD CPT:
  - DIAMETER = 35.6 mm
  - CONE ANGLE = 60°
  - CONE AREA = 10 cm²
  - AREA RATIO = 0.78
  - PENETRATION = 1 – 2 cm/sec



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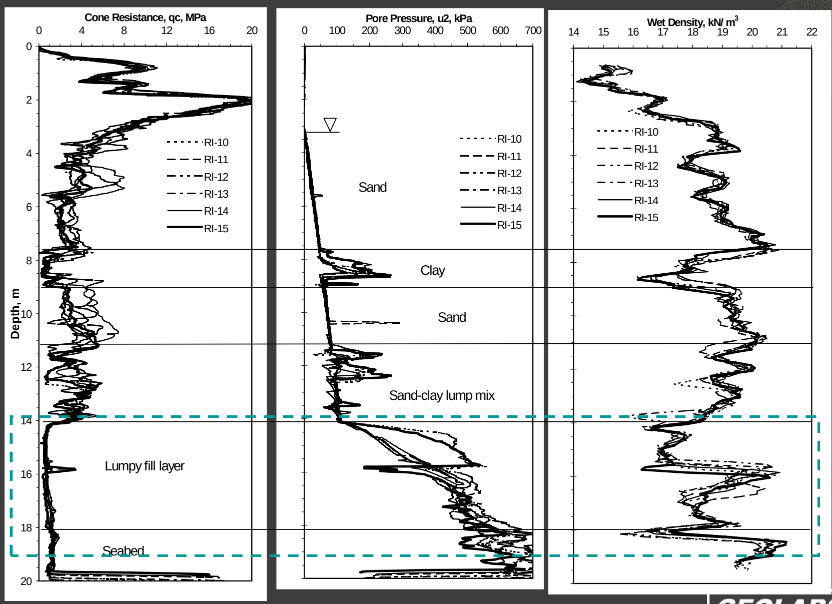
From Thiam Soon(2004)

Nuclear density probe in lumpy clay fill, Singapore



From Thiam Soon(2004)

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Summary – Additional CPTU Sensors

1. Seismic CPTU – well proven technology, becoming increasingly popular.

1. Cone Pressuremeter – limited availability, research in progress on interpretation procedures. Greatest potential is for estimating K_0 and shear stress-strain degradation curve. But there is also potential for better combined parametrer assessments in sands?

2. Resistivity Cone – okay for porosity profiling although requires prior calibration for given soil; excellent profiling tool for detecting spatial variability of salt concentration in pore water.

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Thank you ?

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