CPT/CPTU Additional Sensors

1. Allows for obtaining additional measurements to supplement CPT/CPTU data

2. Modern electronics, sensor technology and data acquisition systems made this possible

3. Two primary objectives of additional sensors
   - Soil structural properties
   - Geoenvironmental application (not covered here)

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Additional CPT/CPTU Sesors

1. Seismic Cone
2. Resistivity
3. Cone Pressuremeter
4. Density Probes
5. Vision Cone
6. Full Flow Penetrometers (Ball, T-bar)

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

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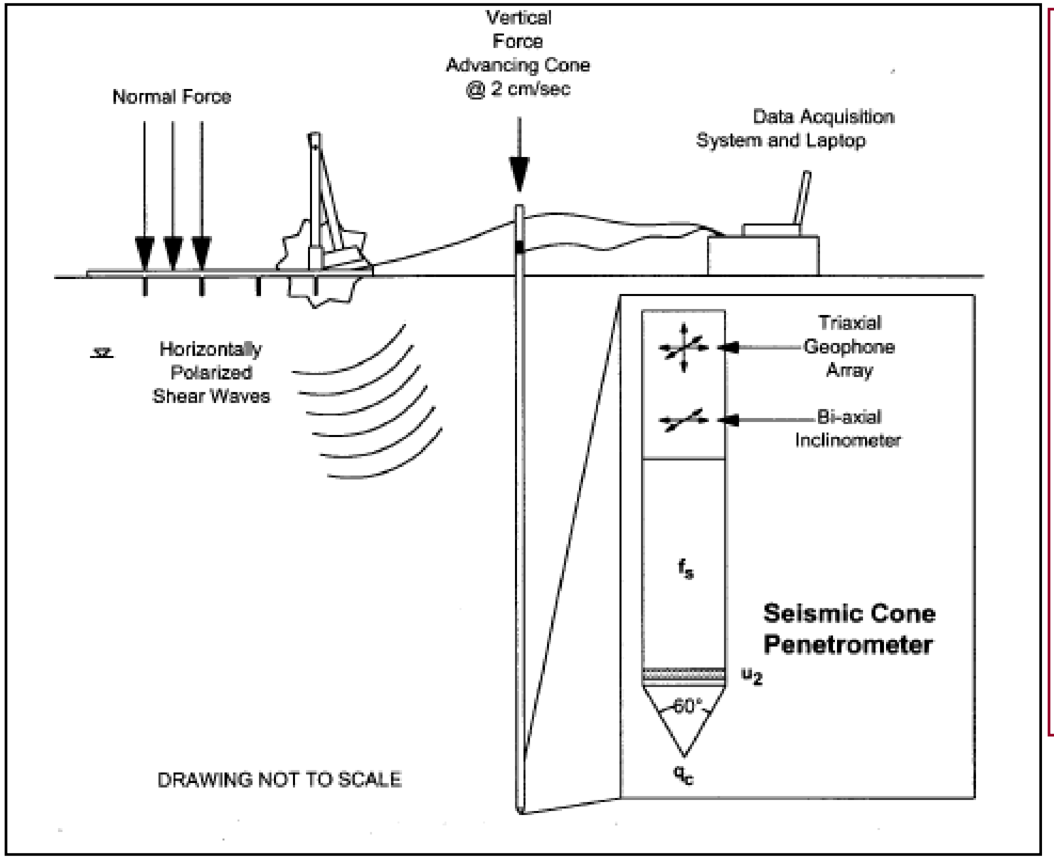
SCPTU – Basic Principle



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).

Mechanical Seismic Source – Cone Truck

Normal force applied to beam for good contact with ground surface

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

Trigger for recording of t = 0

Set-up allows for reverse strikes

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

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

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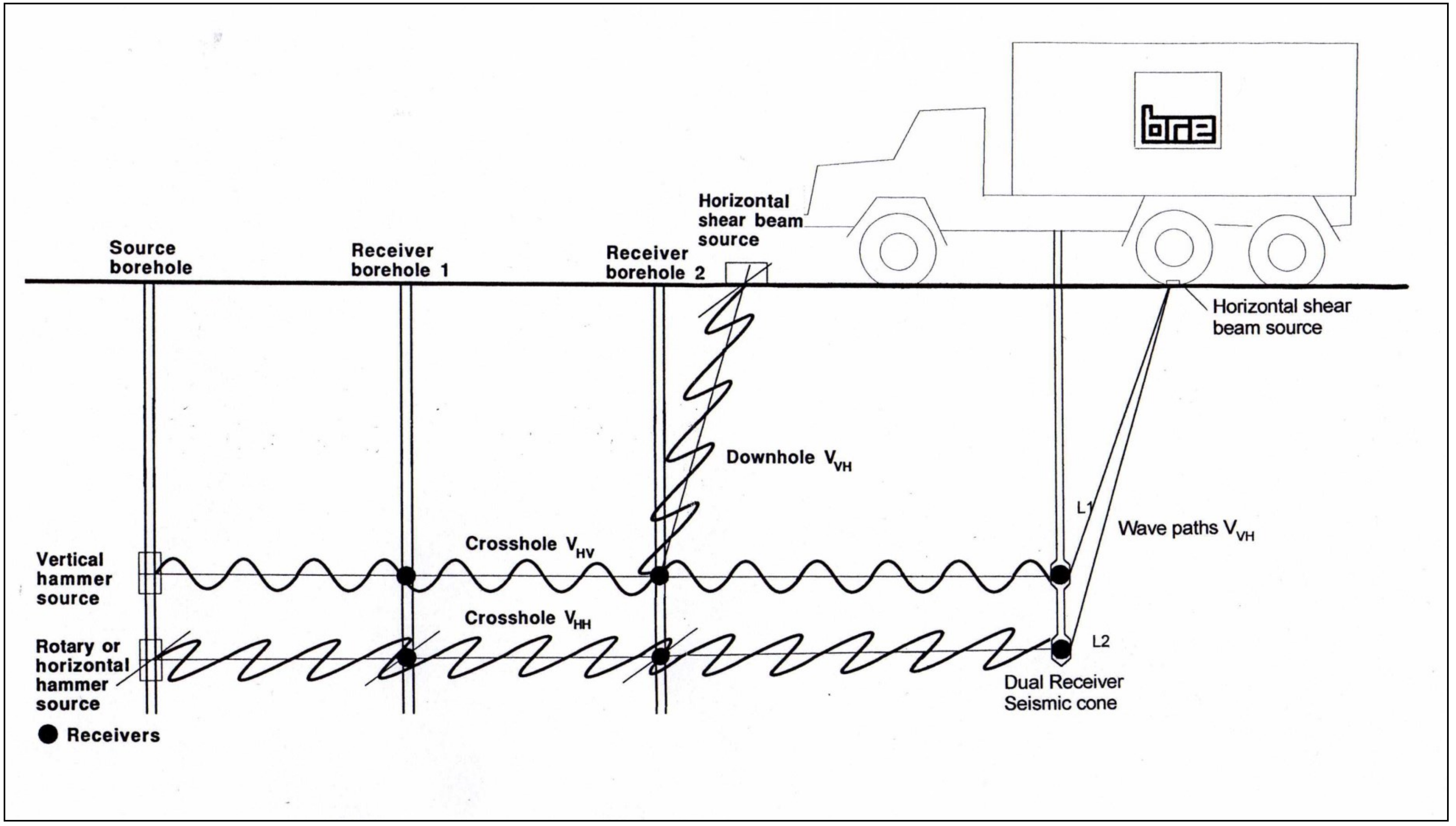
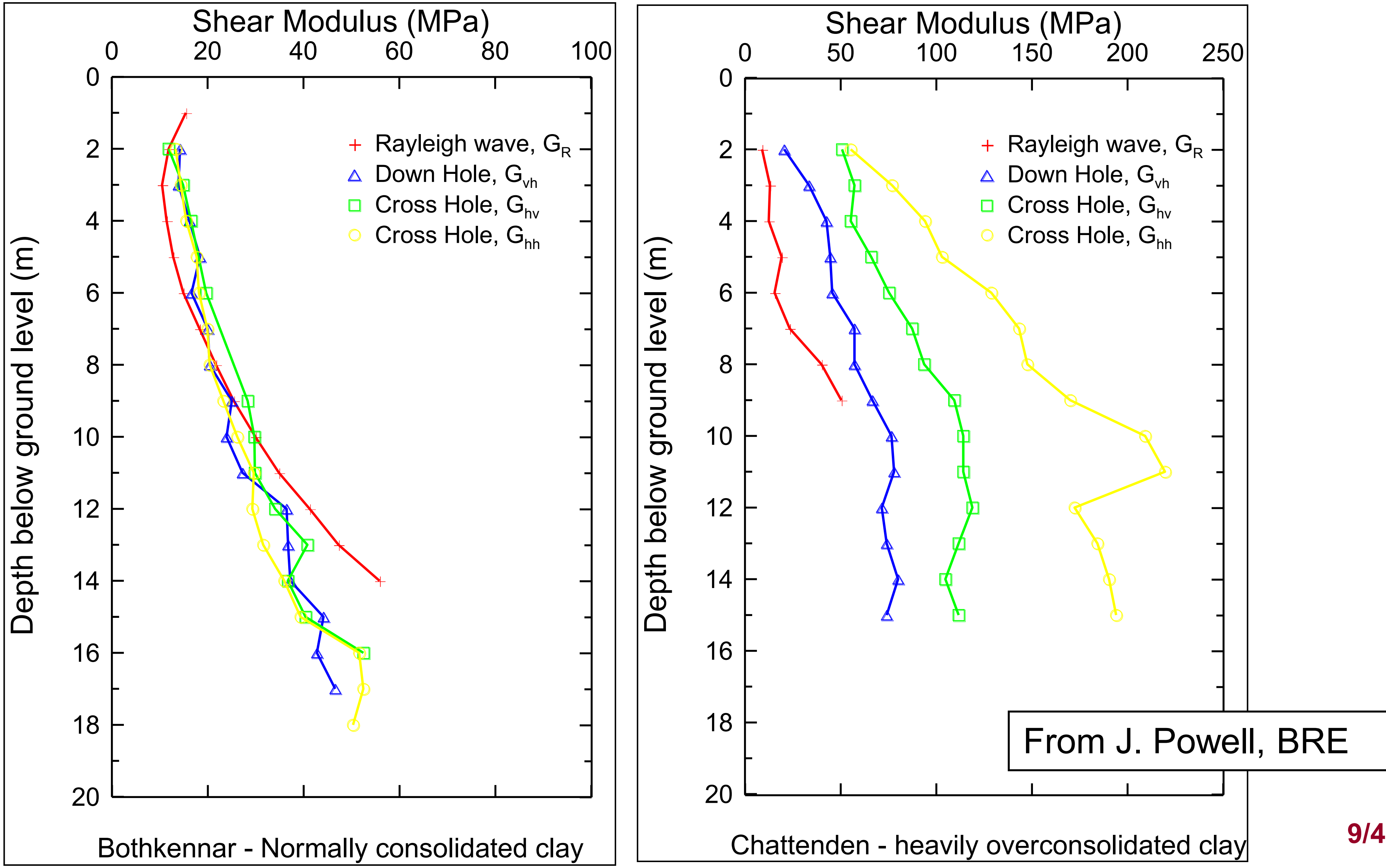
Downhole and Crosshole Seismic Waves



Example Small Shear Modulus Plots



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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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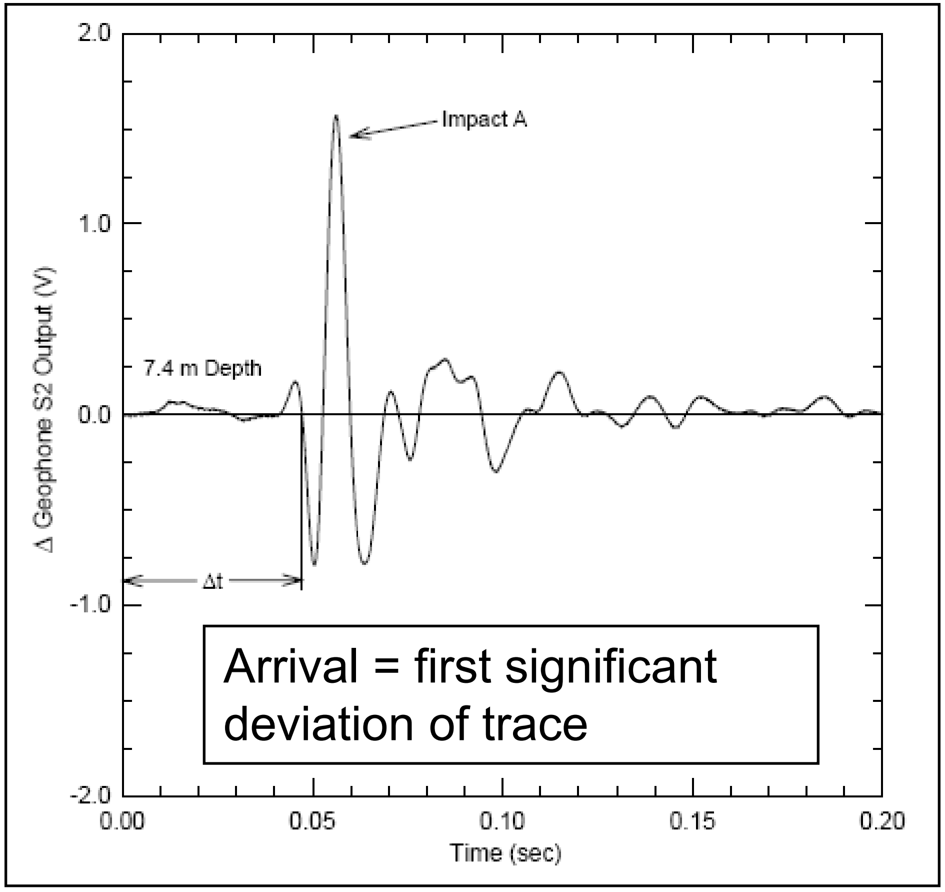
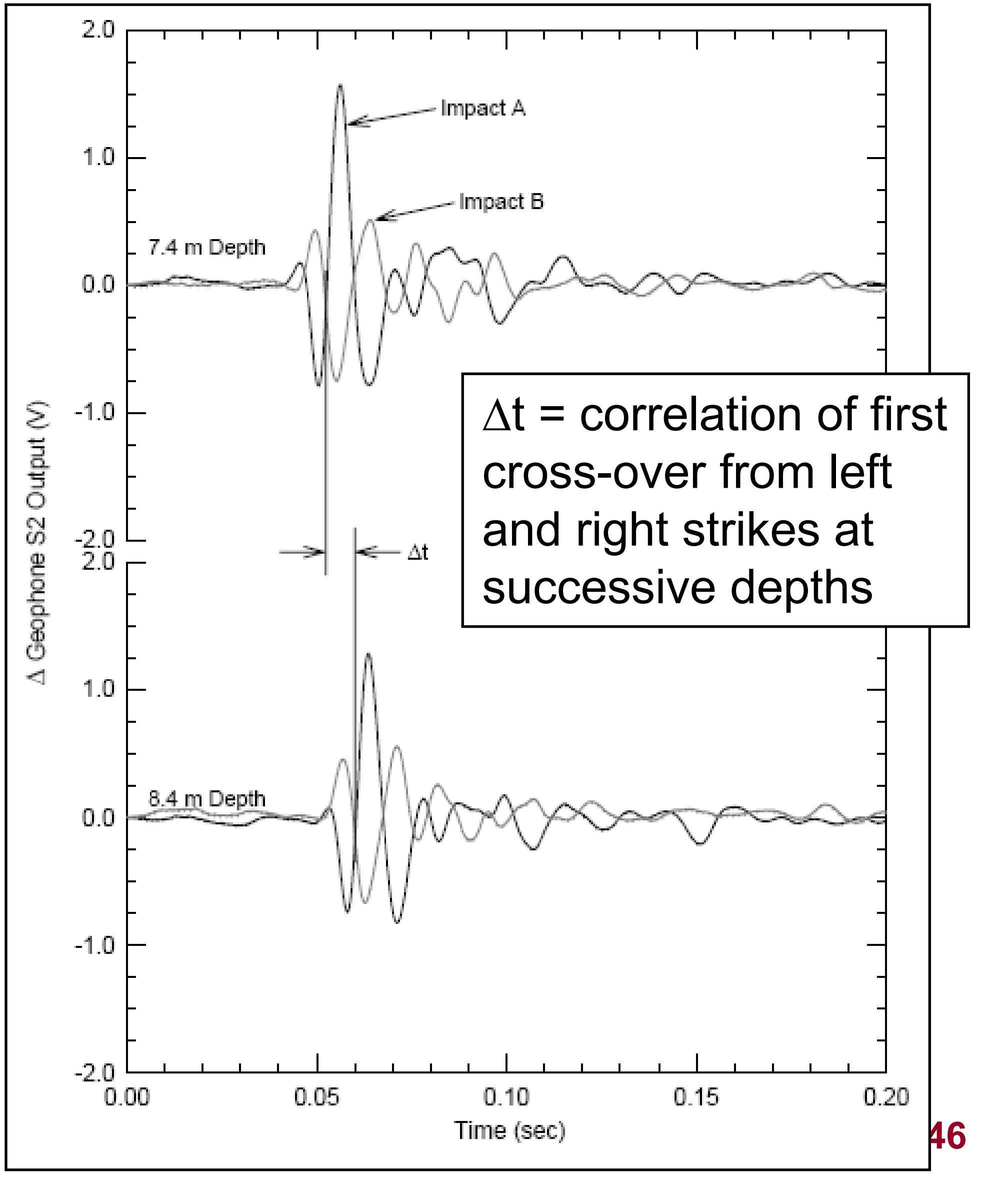
Example SCPTU Traces – Boston Blue Clay





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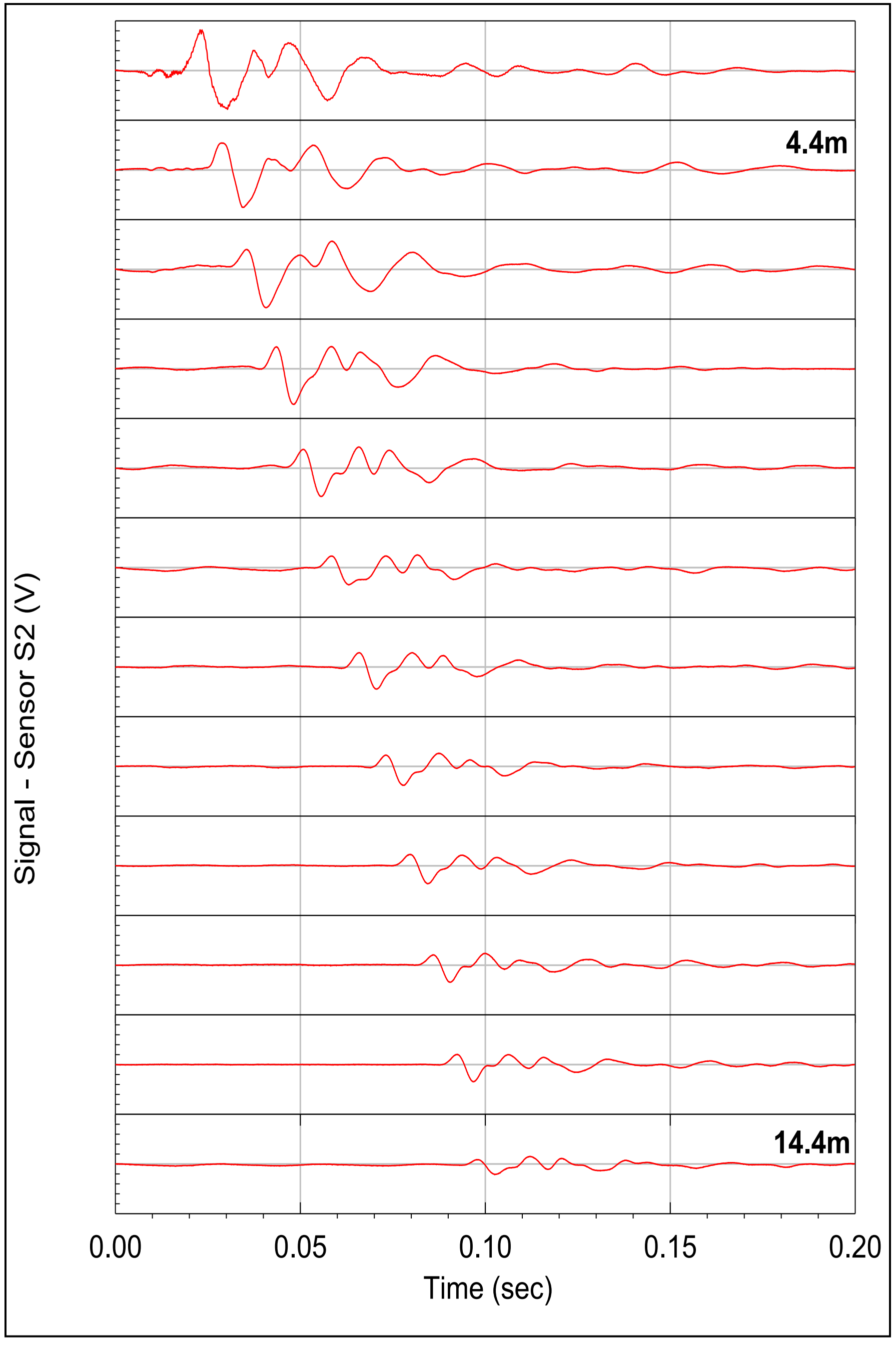
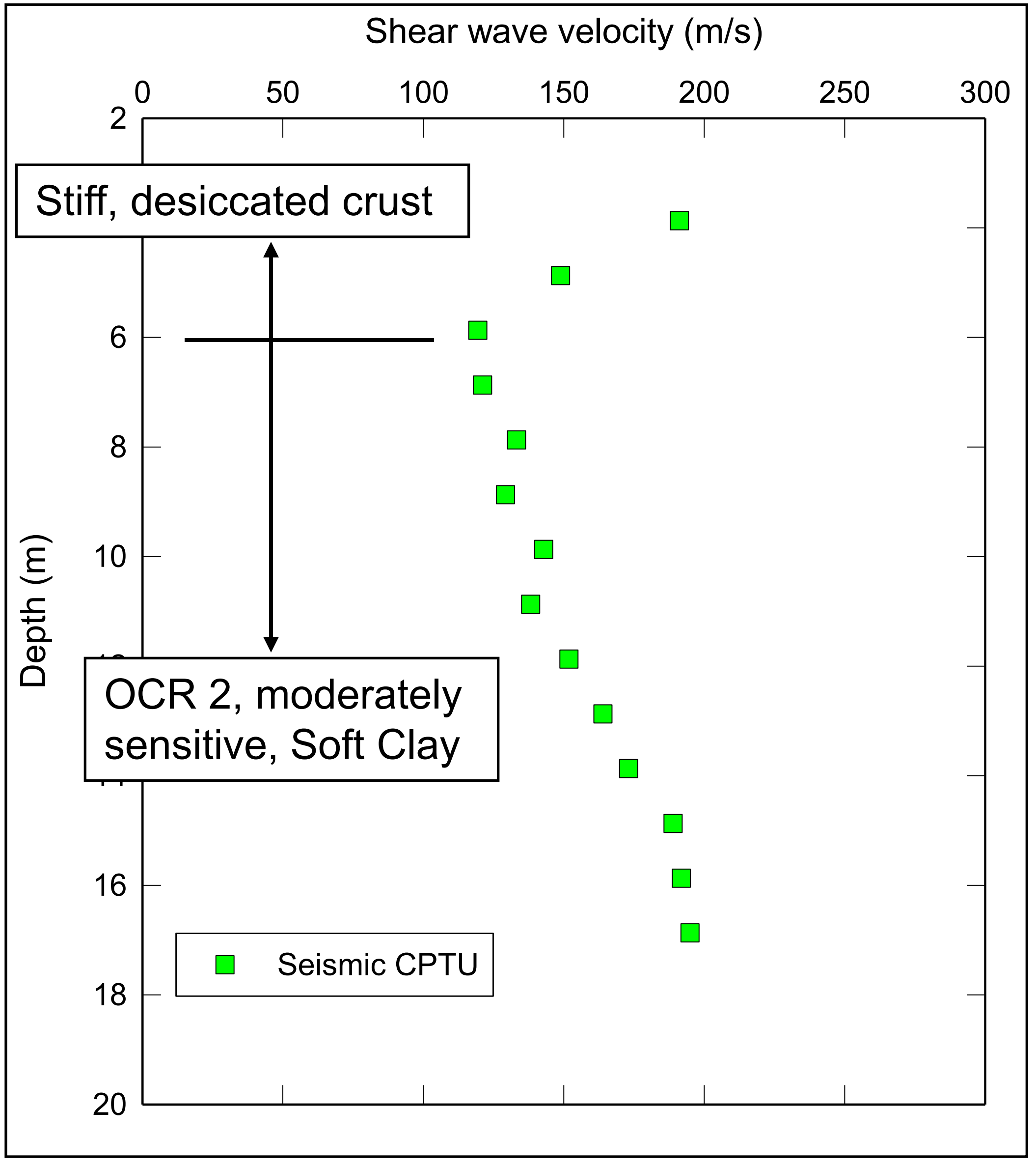
Example SCPTU Data



Boston Blue Clay – Newbury, MA

Seismic tests done at each 1 m rod change

Example V_s Profile from SCPTU

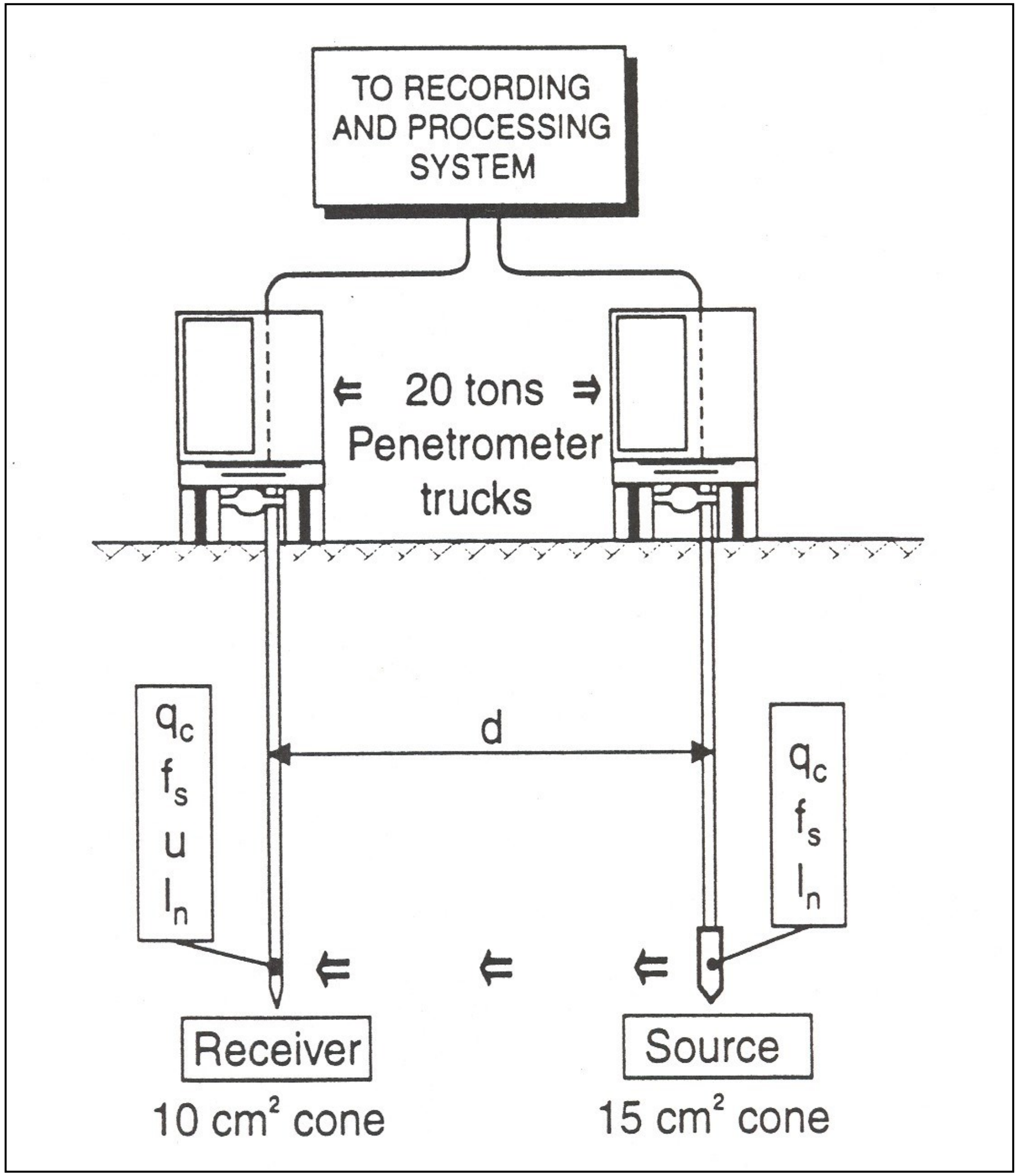


Boston Blue Clay, Newbury, MA

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

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

SCPTU System for Downhole and Crosshole Testing.



[Baldi et al. 1988]

Electrical Resistivity

Purpose of Electrical Resistivity Measurements

- Estimating the in situ porosity or density.

- Indication of in situ soil contamination [Separate lecture and case history].

- Provide input data for evaluation of the corrosive potential of soils (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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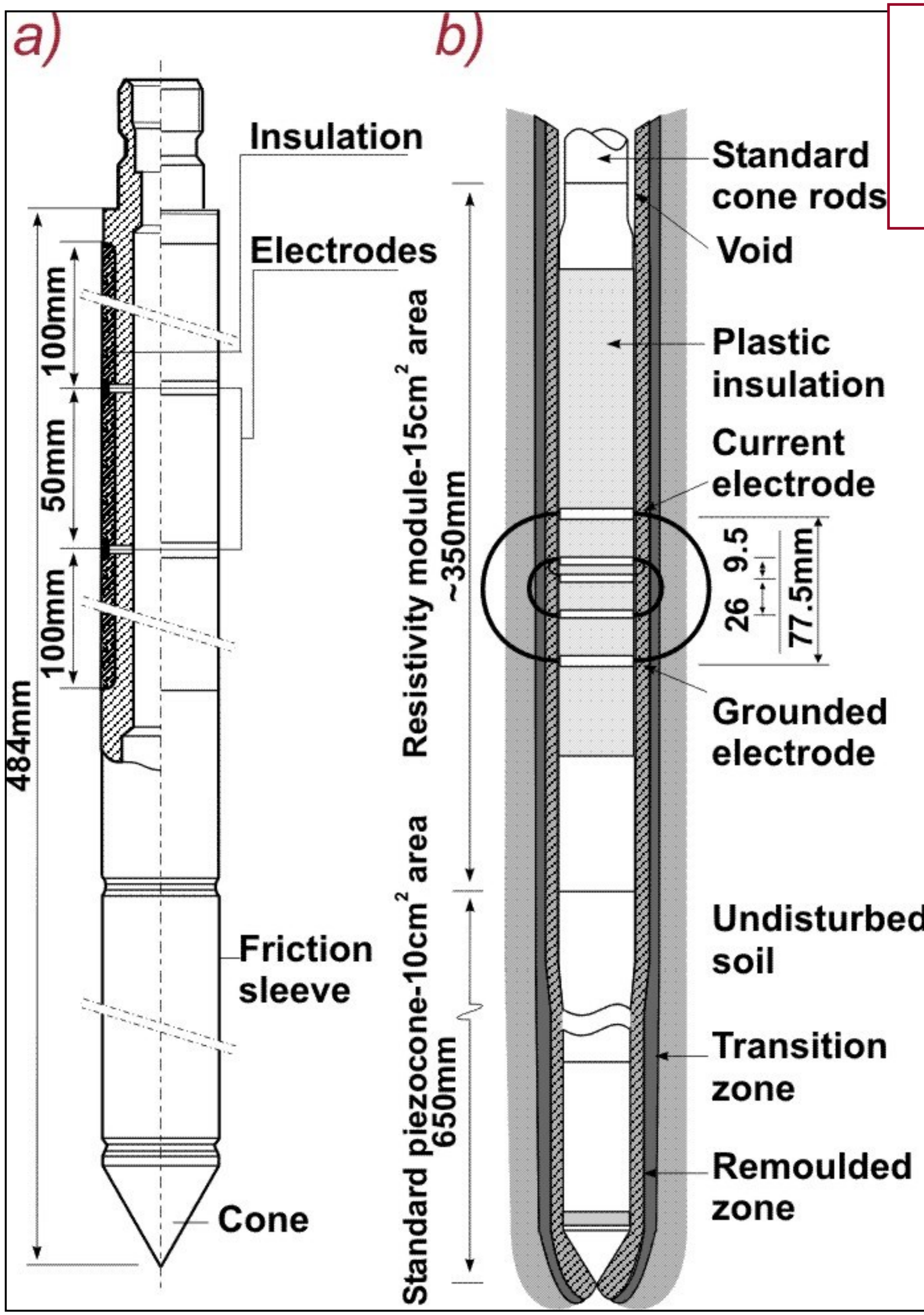
CPT/CPTU Resistivity Cones



a) Single electrode probe (Zuidberg et al.1987)

b) Double electrode probe (Campanella and Kokan1993)

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.

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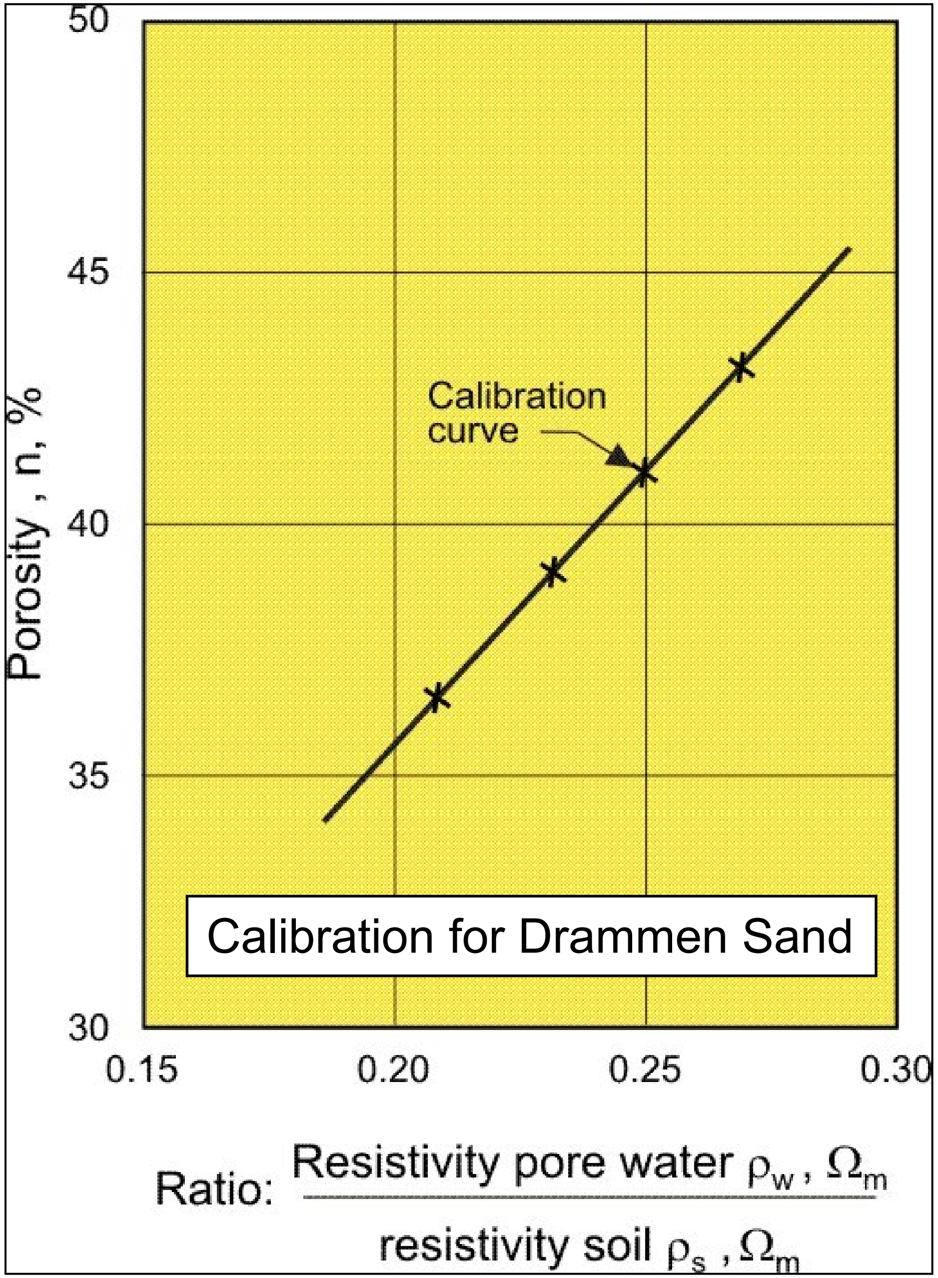
Resistivity Calibration – Formation Factor



Formation Factor F is defined as the ratio of the bulk resistivity of the soil (ρ_b) and the pore fluid (ρ_f), i.e.,

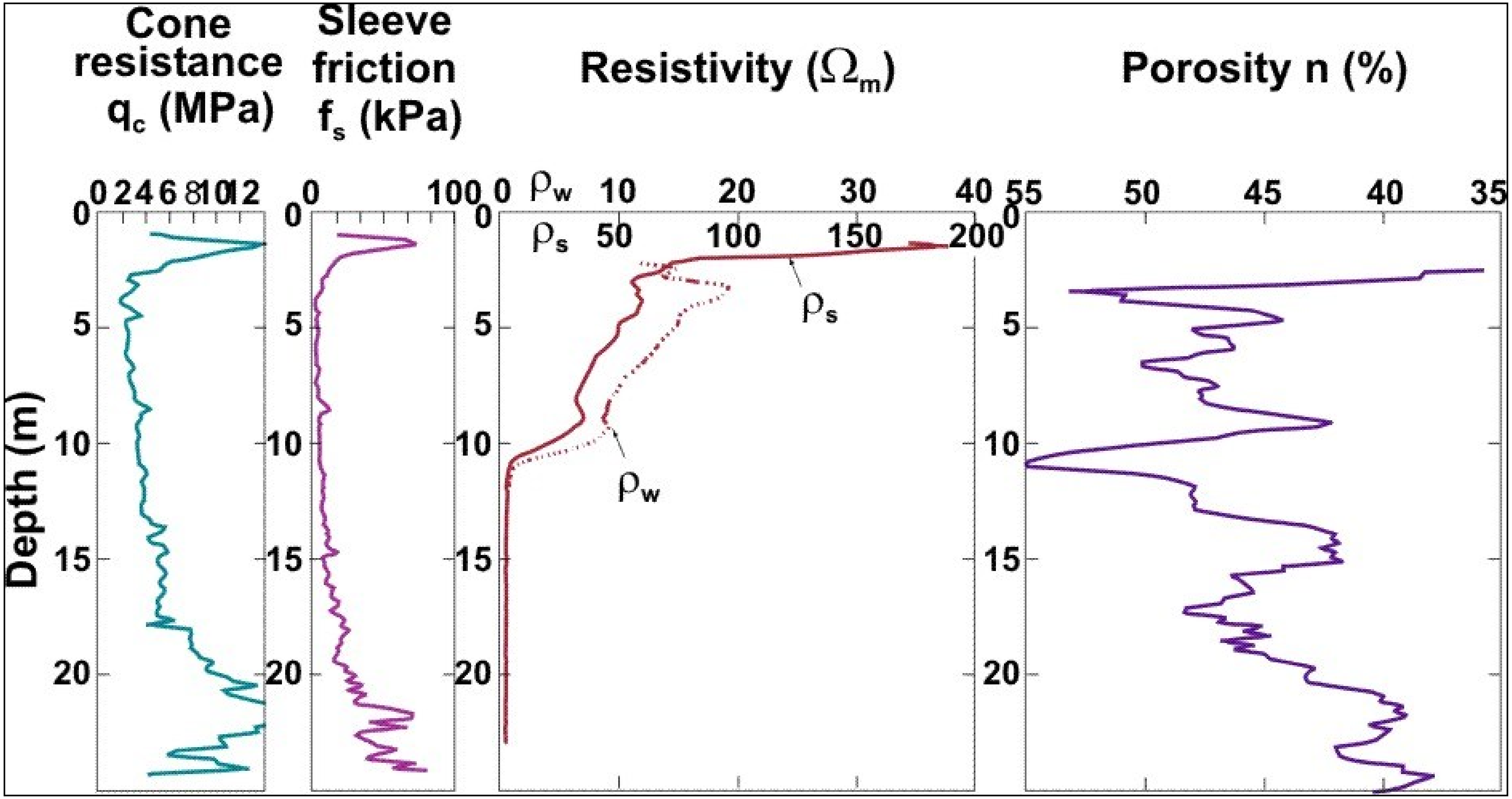
$$F = \rho_b/\rho_f$$

Archie (1942) linked the formation factor to soil porosity n as

$$F = An^{-m}$$

A and m are calibration constants, ideally determined using soil and pore fluid of known resistivity and prepared to known porosity.

Example of Porosity from CPT Resistivity



Tests by GeoDelft and NGI (1982)

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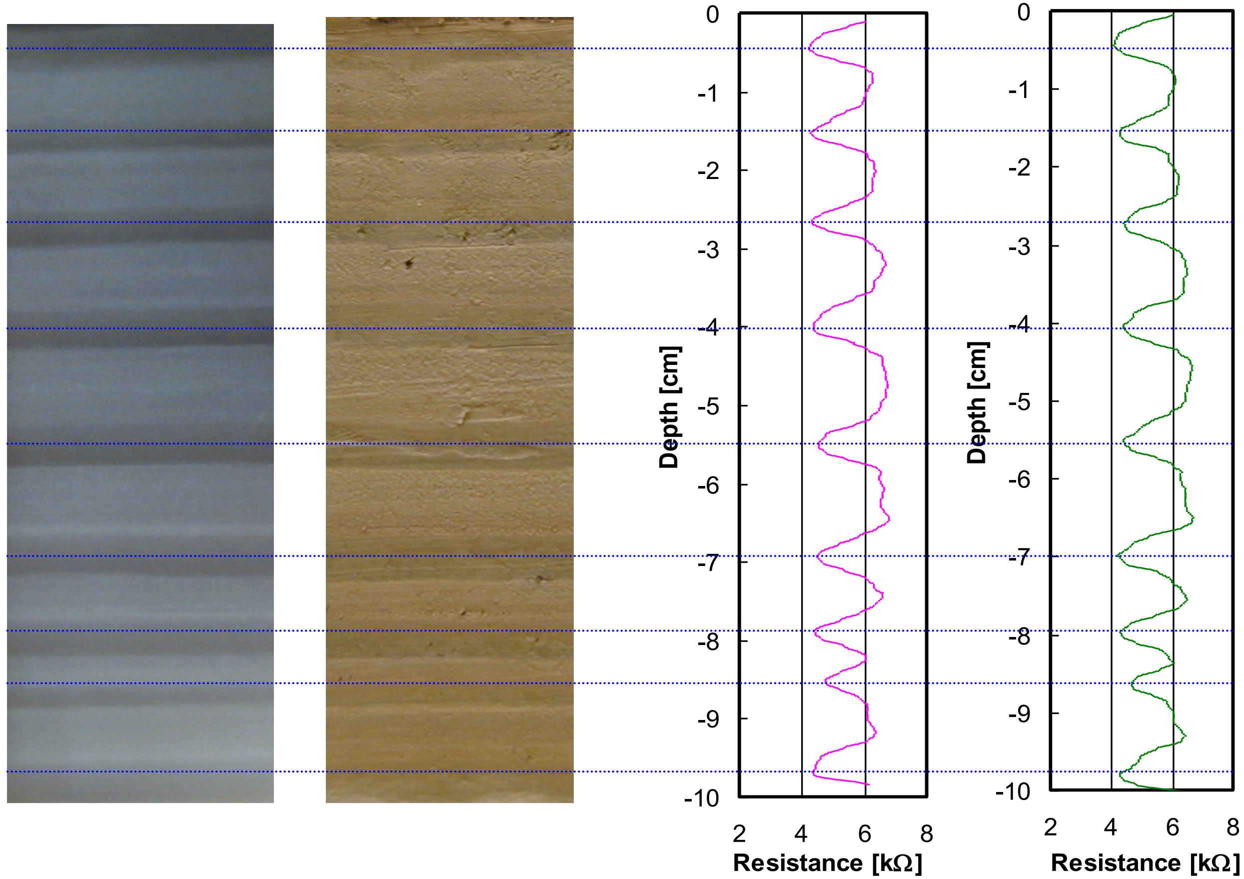
Miniature Needle Probe Resistivity Measurements for Stratigraphy



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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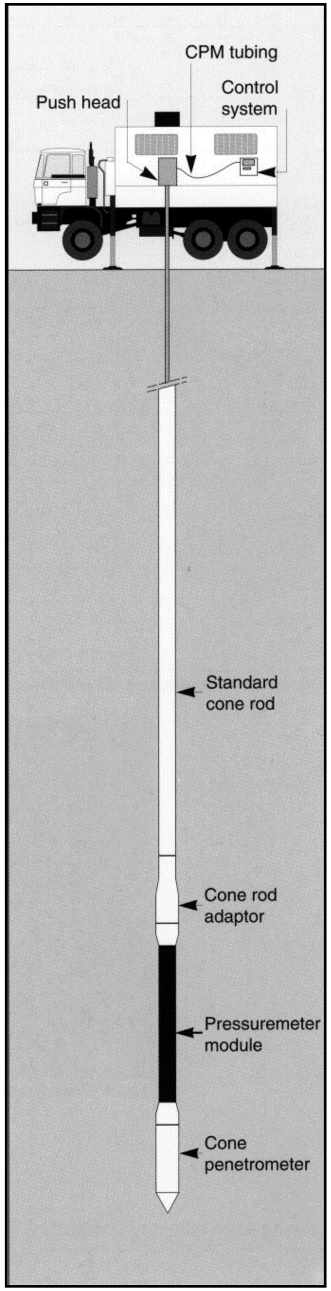
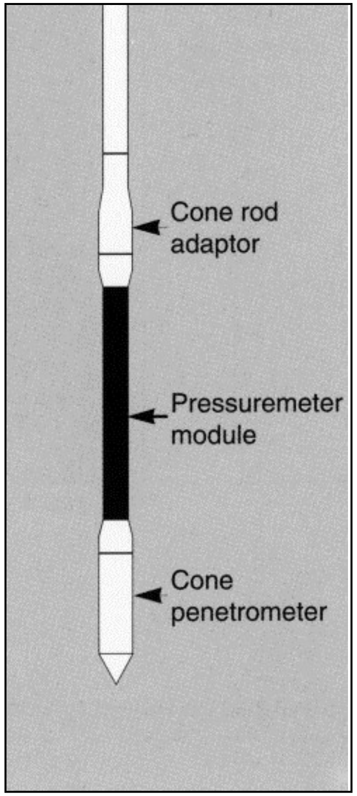
Cone Pressuremeter (CPM)





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

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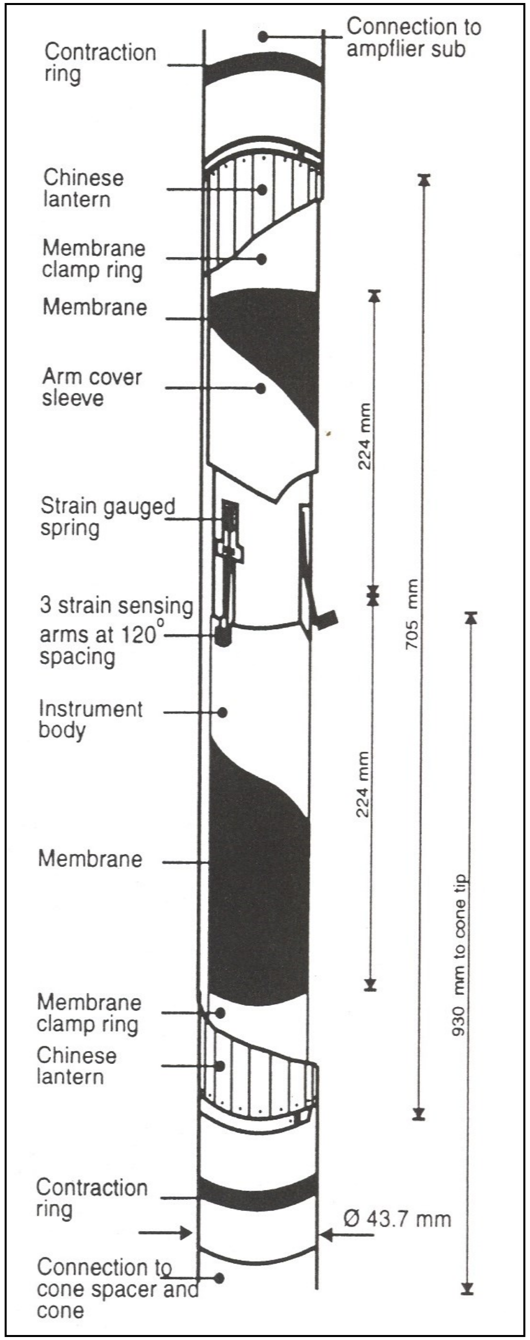

CPM – Mechanical Details

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%.

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CPM – Potential Soil Properties

CPM can provide following soil properties – although additional research is still required to improve interpretation of results:

1. Clays
    - undrained shear strength
    - Horizontal stress
    - Stress-strain curve and thus stiffness as f(strain)

2. Sands
    - initial state parameter → need q_c
    - relative density → need q_c
    - Stiffness
    - friction angle → may need q_c
    - horizontal stress → need q_c

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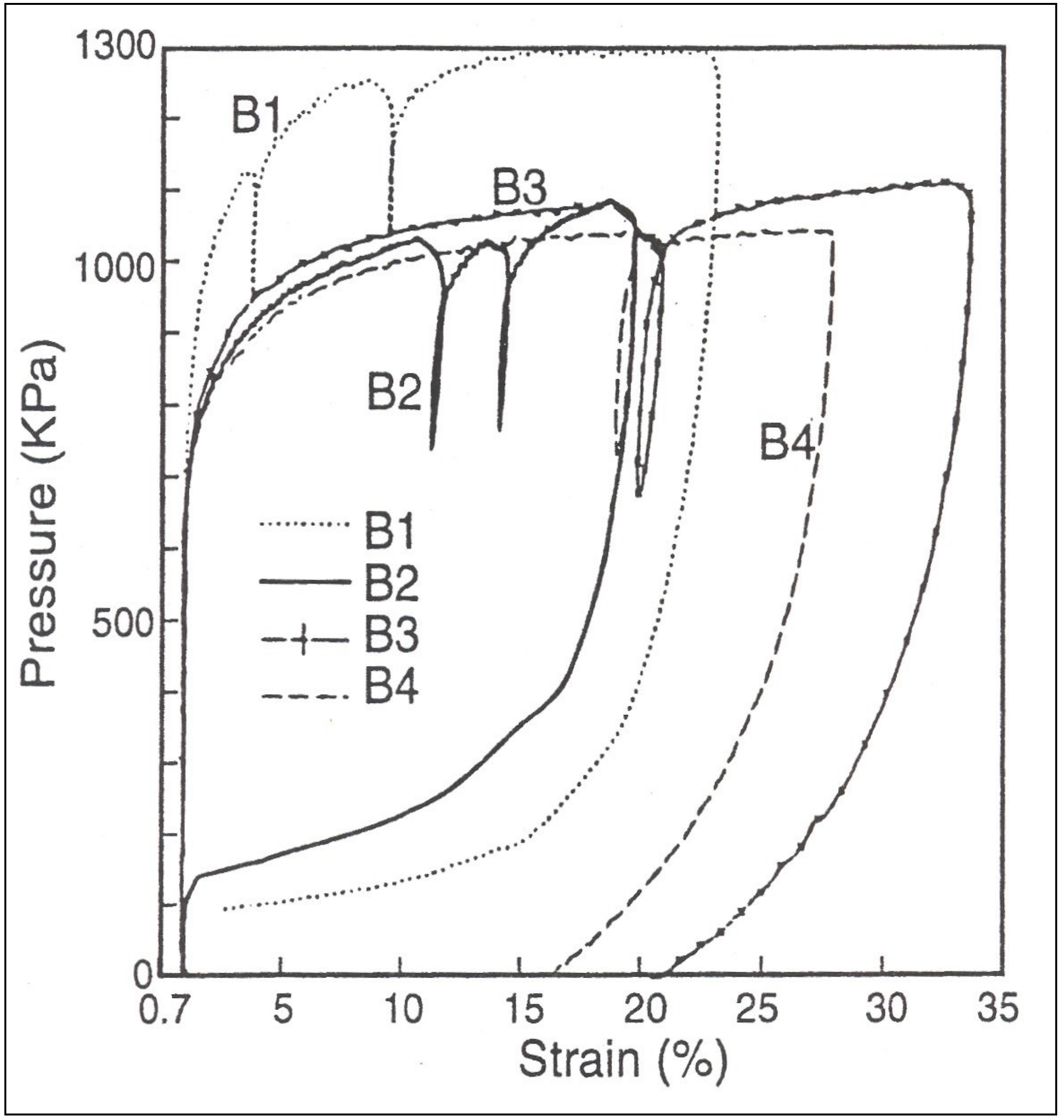
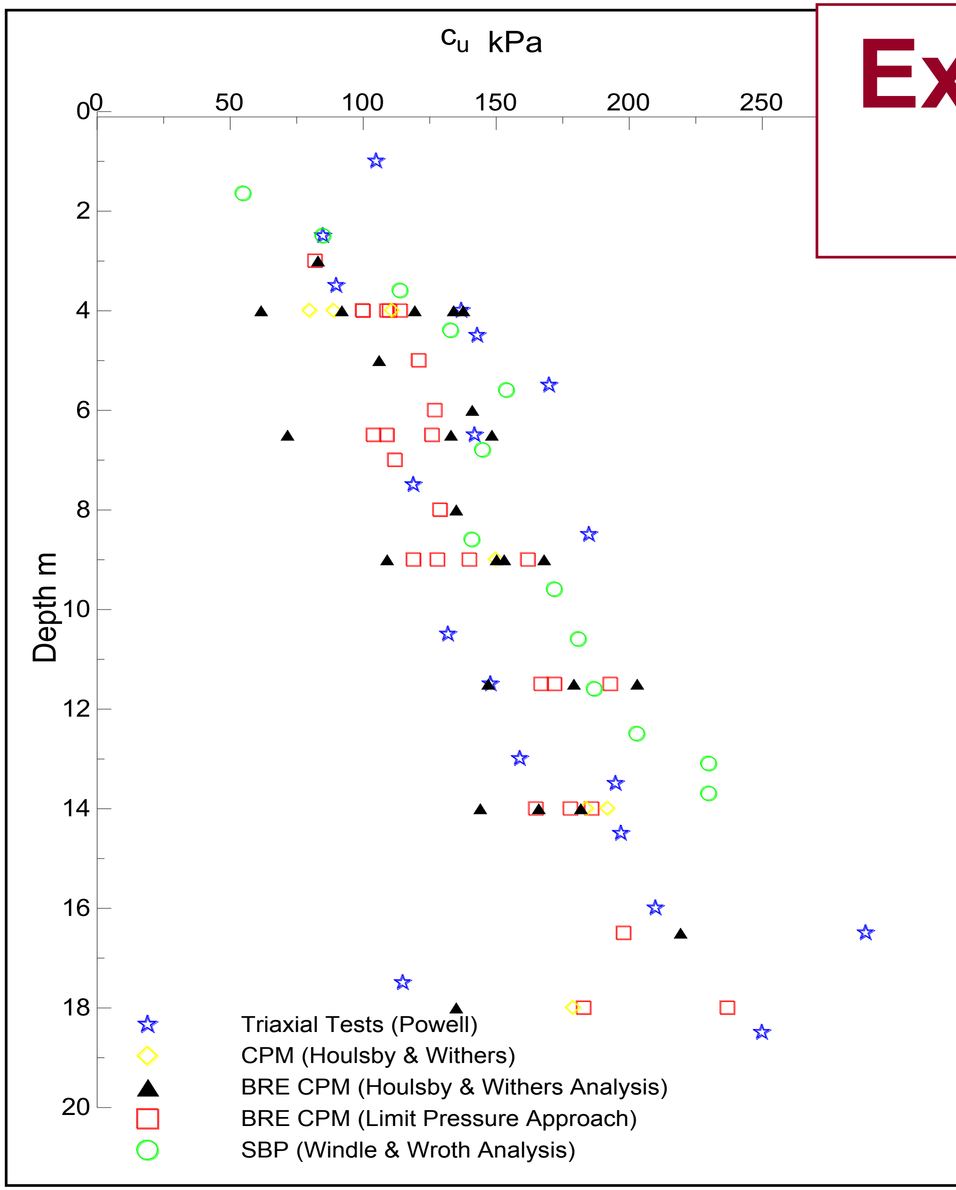
Example CPM Results in Clay



Measured data converted to pressure versus time. Unload-reload loops allow for more accurate determination of small strain modulus

There are several interpretation theories used in research and practice.

Example CPM Results in Stiff Clay

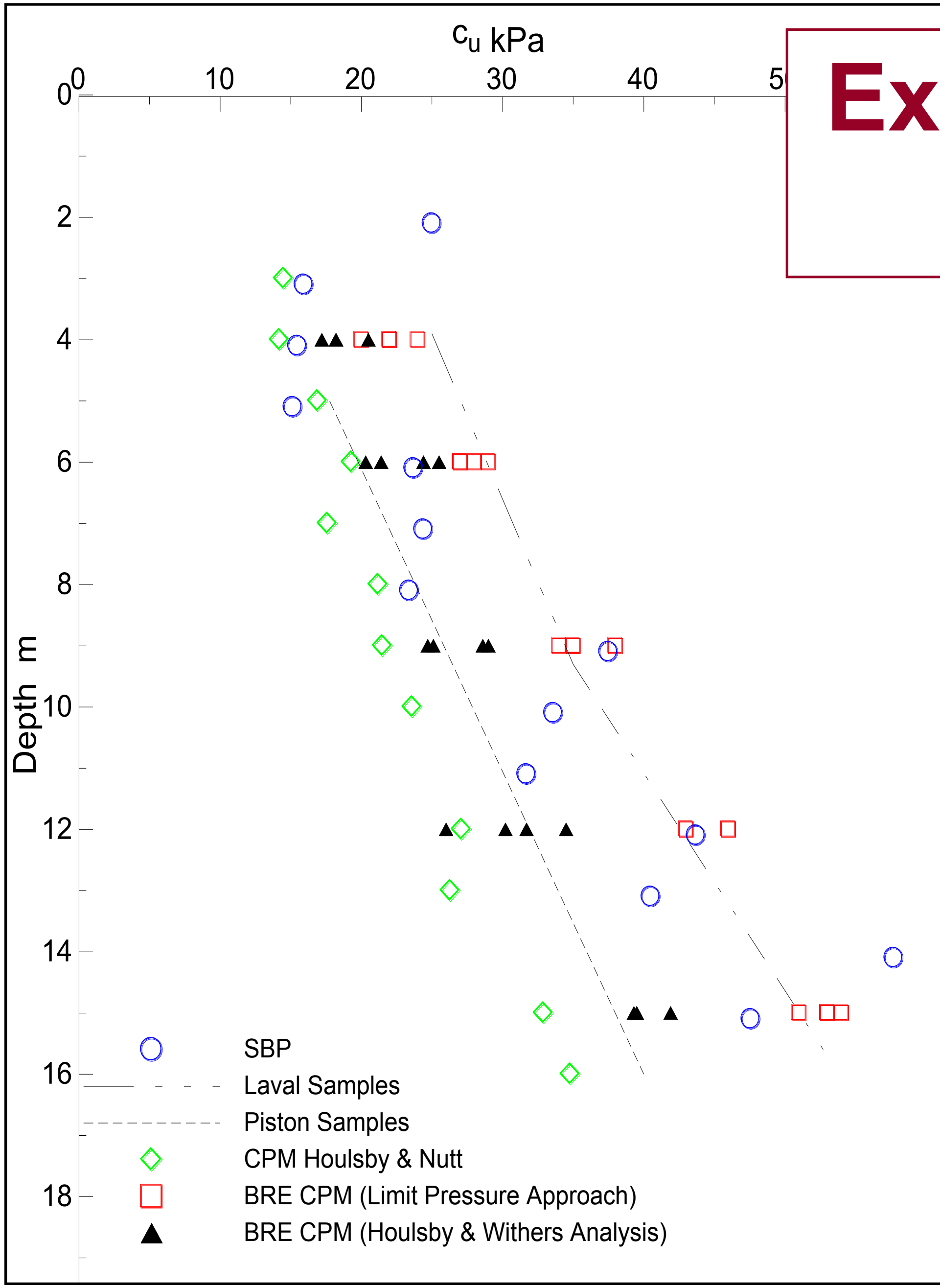


Madingley clay, UK

Undrained shear strength from CPM, SBP and laboratory triaxial tests

From Powell (BRE)

Example CPM Results – Soft Clay



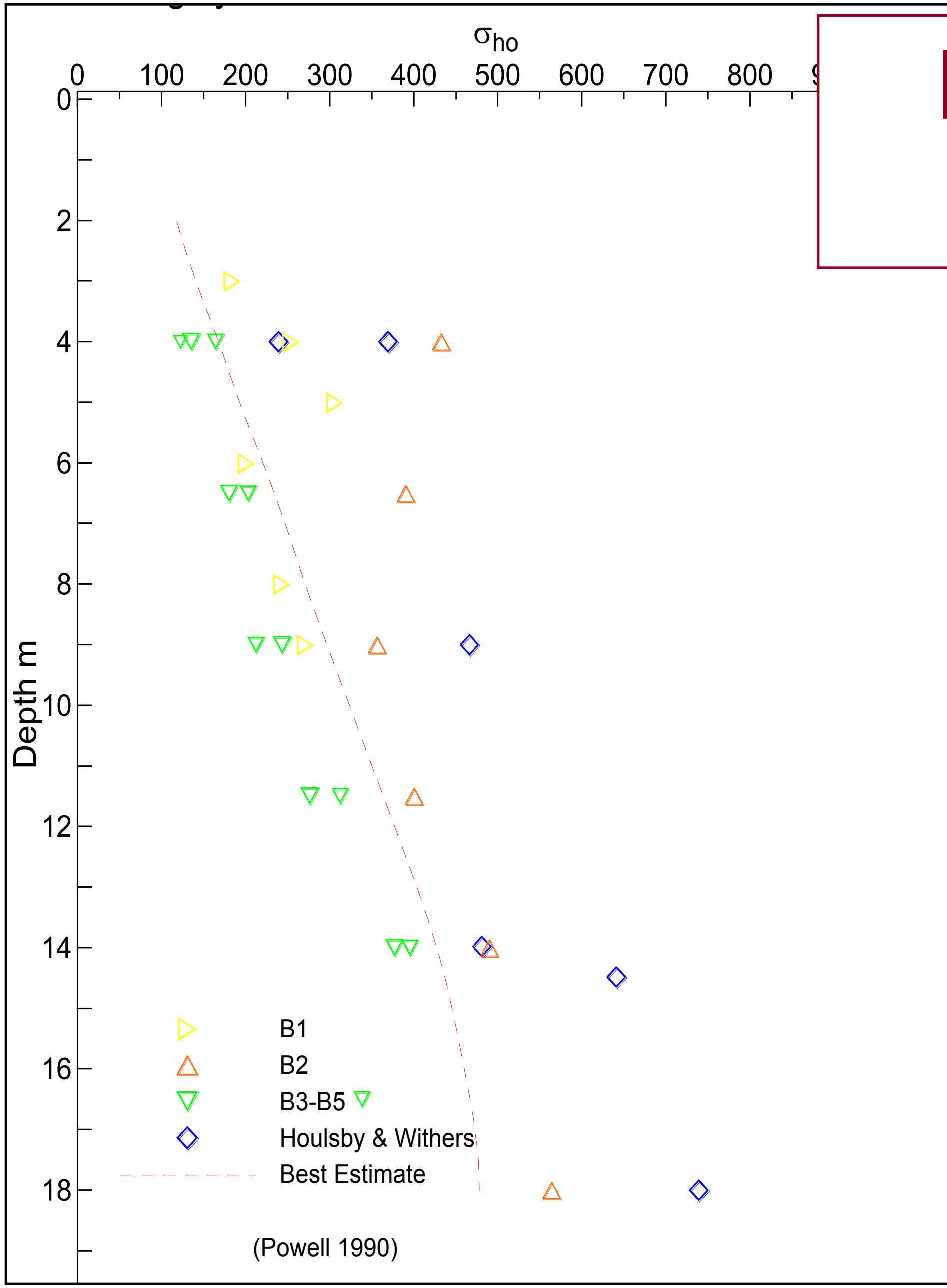
Bothkennar, UK

Undrained shear strength from CPM, SBP and laboratory triaxial tests

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

From Powell (BRE)

Horizontal Stress from CPM

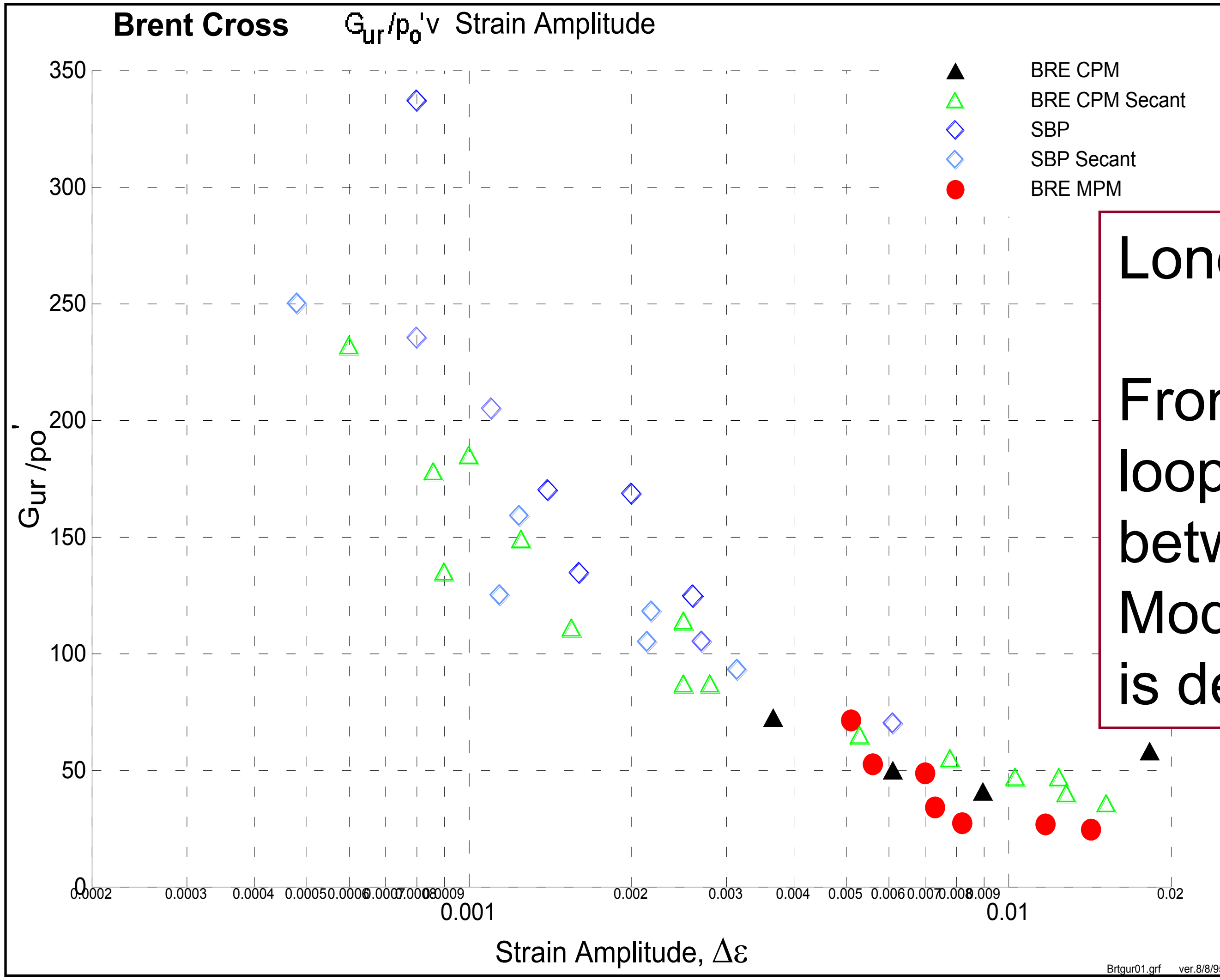


Gault Clay, UK

Estimation of σ_{h0} from CPM data, when combined with u_0 data then gives σ'_{h0} and hence K_0 → this is major advantage of traditional pressuremeters → CPM couples this with advantage of collecting CPTU data at same time

From Powell (BRE)

Modulus Degradation Curve from CPM



London Clay, UK

From unload-reload loops the relationship between Shear Modulus G and strain is derived

From Powell (BRE)

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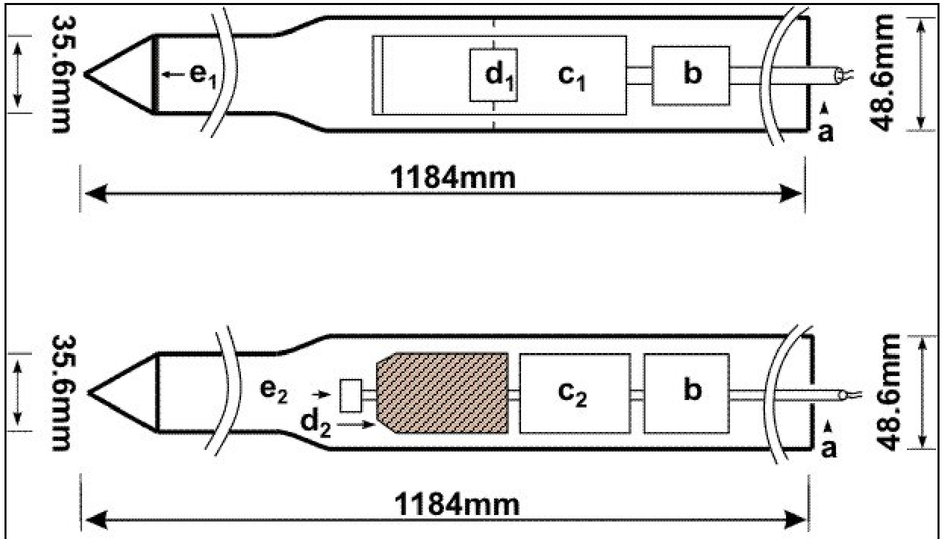
Special Density Probes – Kyoto University



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

<u>Neutron Moisture</u> (NM) probe – for water content determination

<u>Neutron Density</u> (ND) probe – for soil density determination

Allows for profiling of water content and soil density.

[Mimura et al. 1995]

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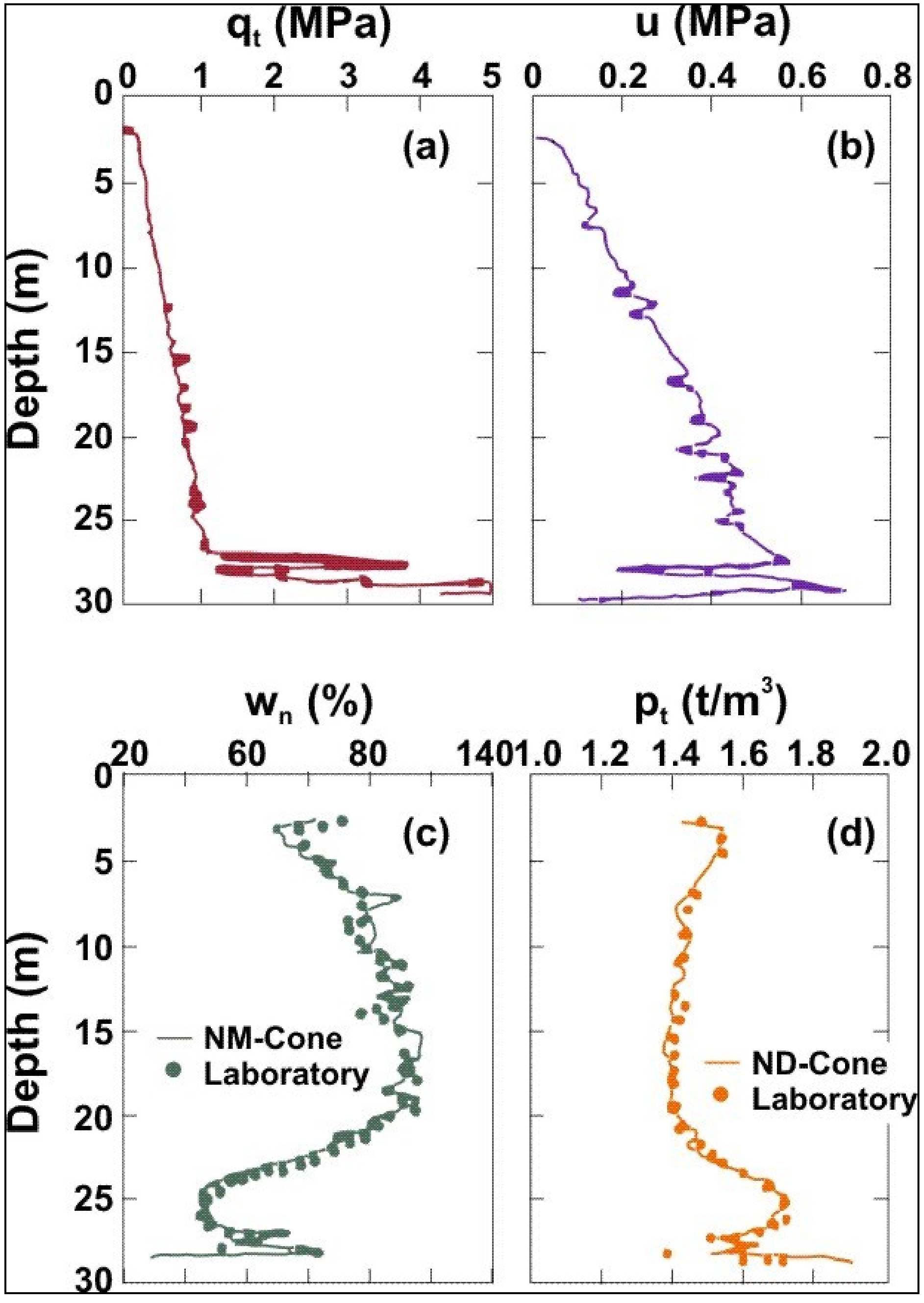
Example – Kyoto University Density Probes



Kinkay Bay clay, Japan

Verification of probe measurements via laoratory tests on collected samples

Shibata et al. (1994)

Other Sensors – add on devices

Other sensors researchers have tried:

1. Acoustic noise
2. Vision Cone
3. Lateral stress sleeve
4. Thermal conductivity probe
5. Full flow penetrometers

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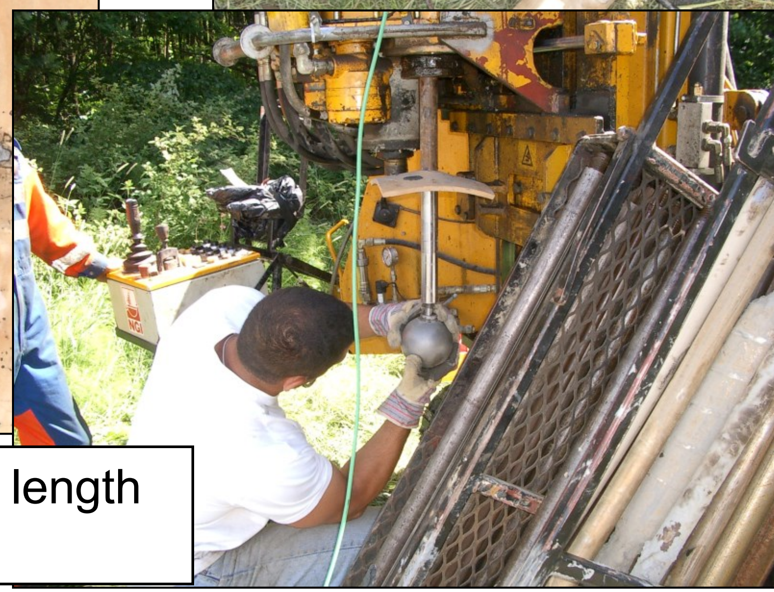
Full Flow Penetrometers – T-bar and Ball



T-bar: 40 mm diameter by 250 mm length
Ball: 113 mm diameter

T-bar and Ball Full Flow Penetrometers

Developed at University of Western Australia with advantages including (Randolph et al. 1998):

1. Overburden stress is (theoretically) in equilibrium above and below T-bar/Ball and thus no need to subtract overburden as for CPT

2. Due to larger area results more sensitive

3. T-bar/Ball resistance can be measured also during extraction to get some measure of remoulded shear strength and sensitivity

4. Cyclic tests can be done to estimate remoulded shear strength

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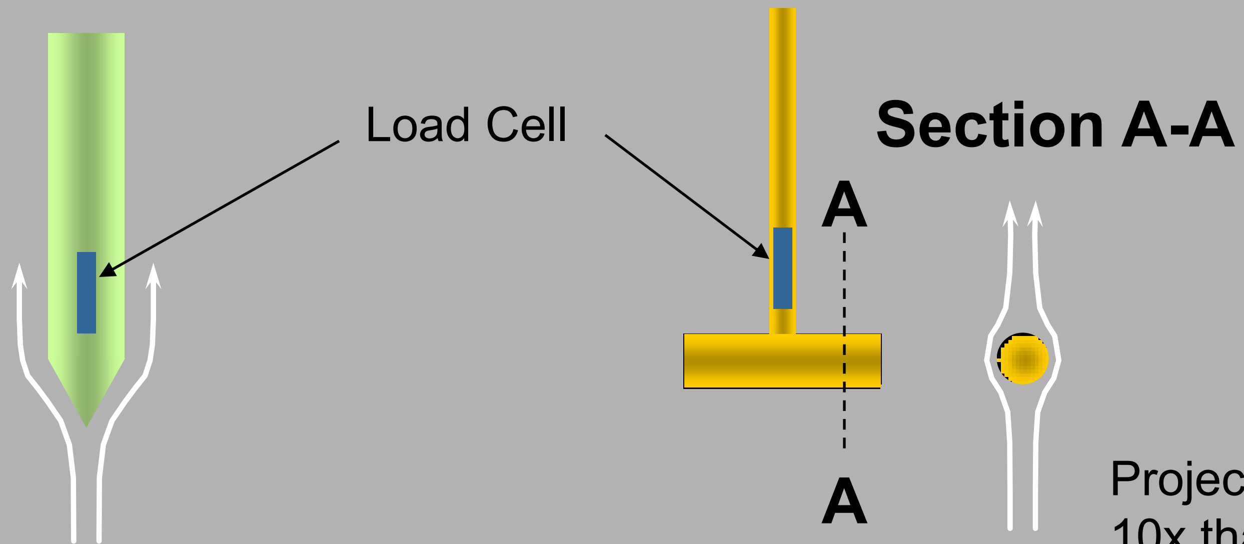
Full Flow Mechanism

CPTU	T-bar/Ball



Projected area T-bar = 10x that of push rod

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

$$s_u = q/N_t$$

Example of deployment of T-bar offshore using seabed CPT Rig

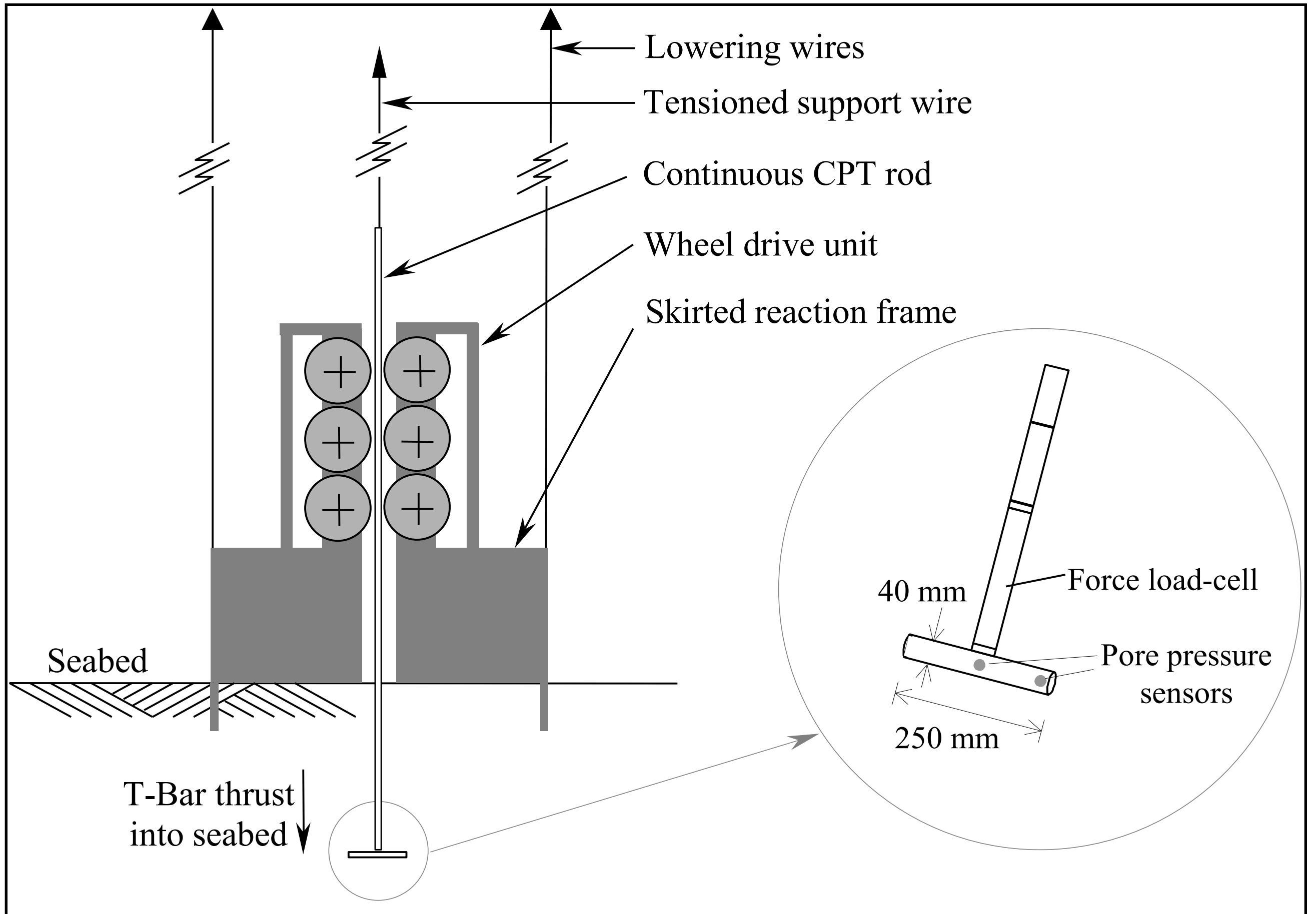


Figure A1. Seabed Wheel Drive Unit and T-Bar General

T-bar and Ball can be threaded onto conventional CPT/CPTU load cell and regular cone rods can be used for push

[Randolph et al. 1998]

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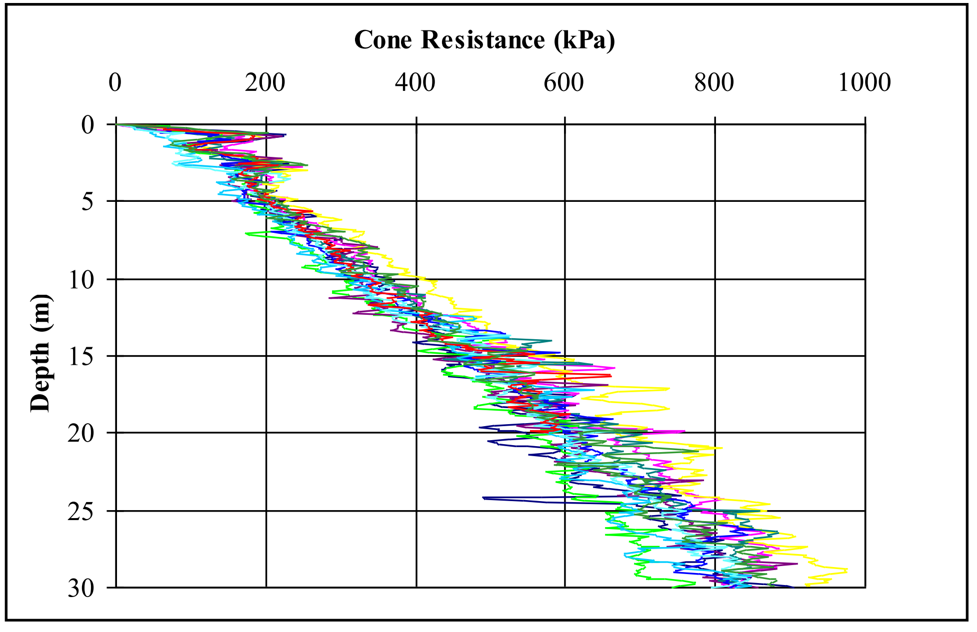
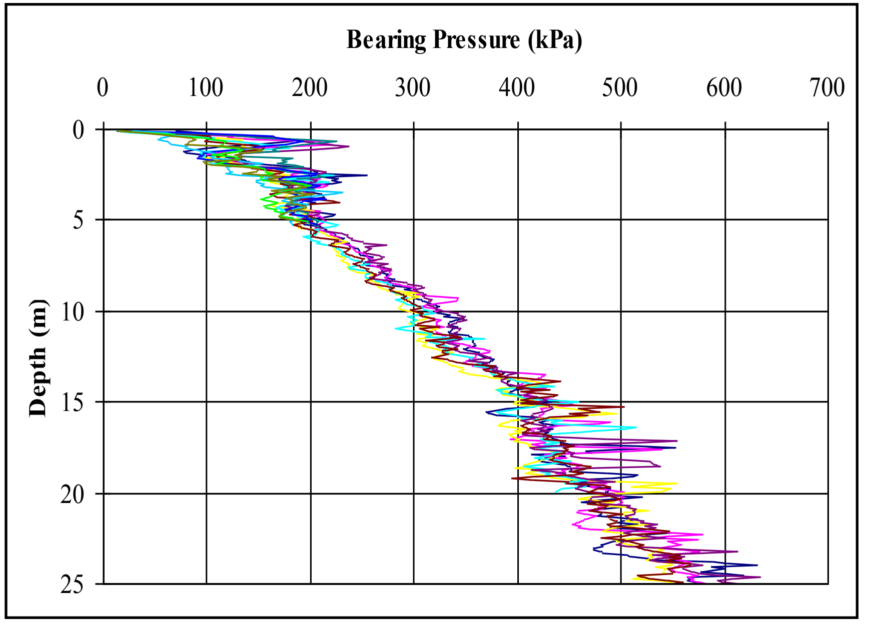
Example Results T-bar and CPTU – Offshore Australia

Results from CPTUs at 11 locations



Results of T-bar tests at 11 locations



[Randolph et al. 1998]

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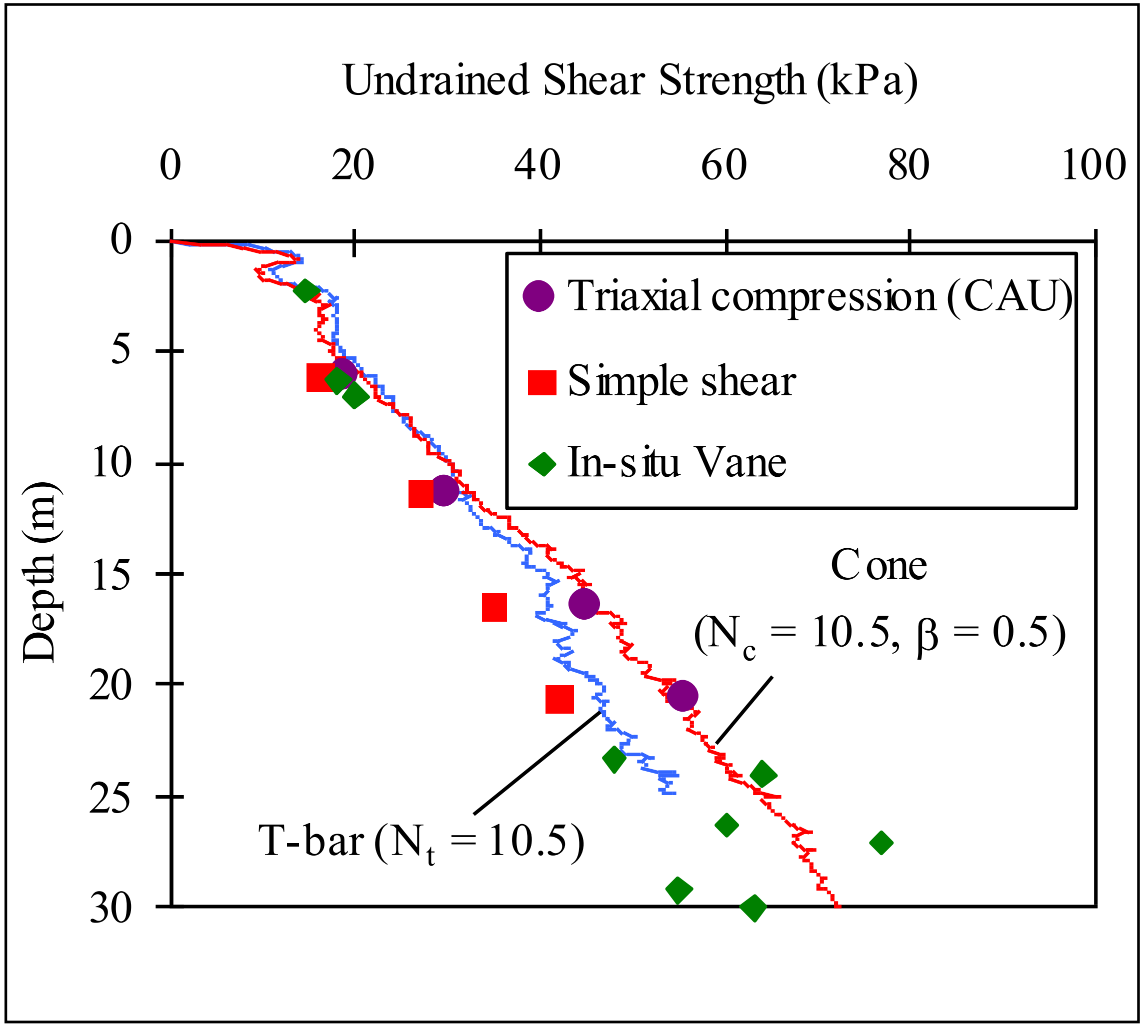
Example – Undrained shear strength interpreted from T-bar data



T-bar Factor N_{kt} = 10.5 to convert measured resistance to s_u

Comparison with in situ Field Vane Test and laboratory Triaxial Compression and Direct Simple Shear tests

[Randolph et al. 1998]

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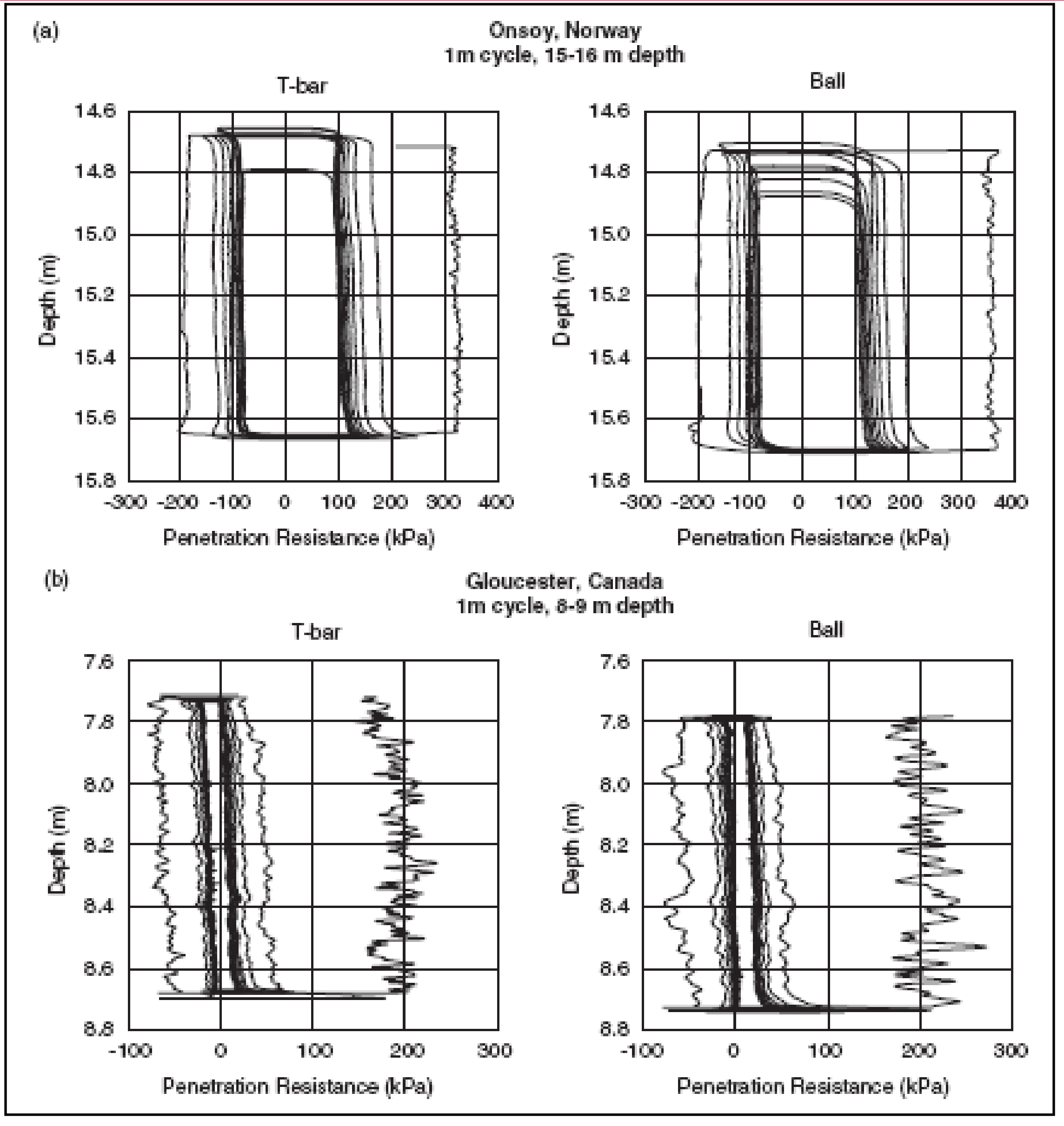
Example of Cyclic T-bar and Ball Tests



Tests performed in Onsøy Norway and Gloucester Canada.

Note:
Approx. symmetric cycles + approaching a steady state resistance → measure of remolded undrained shear strength

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Current Full Flow Penetrometer Research

A number of teams are conducting research into full flow penetrometers and their application in geotechnical engineering practice, including: 1) NGI (Lunne et al.) in cooperation with Univ. of Western Australia (Randolph et al.), and 2) UC Davis and UMass Amherst.

Some preliminary findings:

- T-bar/Ball profiles tend to have somewhat less scatter than CPTU profiles
- The T-bar/Ball factors (N_t or N_b) for conversion to s_u tend to be within a narrower range than the CPTU cone factor N_{kt}
- Appears to have good potential for estimating s_{ur} from cyclic testing.

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Example Comparison CPTU and T-bar Factors for s_u

Lunne et al. (2005) Range of Recommended CPTU and T-bar factors for s_u(CAUC) and s_u(ave)

Test	Factor	Range	
		s_u(CAUC)	s_u(ave)
CPTU	N_{kt}	9 - 13	12 – 17
	$N_{\Delta u}$	6 – 9	7 – 12.5
T-bar	N_t	8 - 11	10 - 13

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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 K0 and shear stress-strain degradation curve

3. 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.

4. Full Flow Penetrometer – appears to have good to excellent potential. Research still in progress

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