The CPT and some additional Sensors

John J M Powell

Pisa 14th June 2016

JJMP GEOLABS®

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.

JJMP GEOLABS®

Add on devices

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

Add on devices

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

Seismic Measurements

- Martin Fahey (2001) said that the addition of seismic measurements to the CPTU should become the next standard/routine form of the CPTU.

Seismic Measurements

- Martin Fahey (2001) said that the addition of seismic measurements to the CPTU should become the next standard/routine form of the CPTU.

- We have come a long way and I think this is now proving to be the case

Seismic cone

Or
Small strain shear modulus and the CPT

Small strain shear modulus

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

JJMP GEOLABS®

Seismic measurements

JJMP GEOLABS®

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:

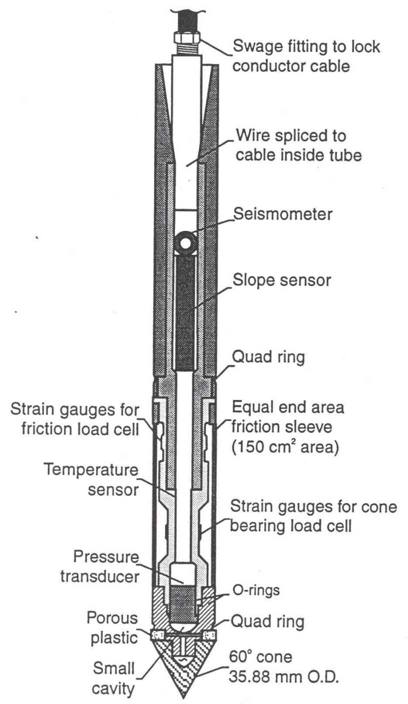
- Small Strain Shear Modulus = $G_0 = G_{max} = \rho_t (V_s)^2$

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

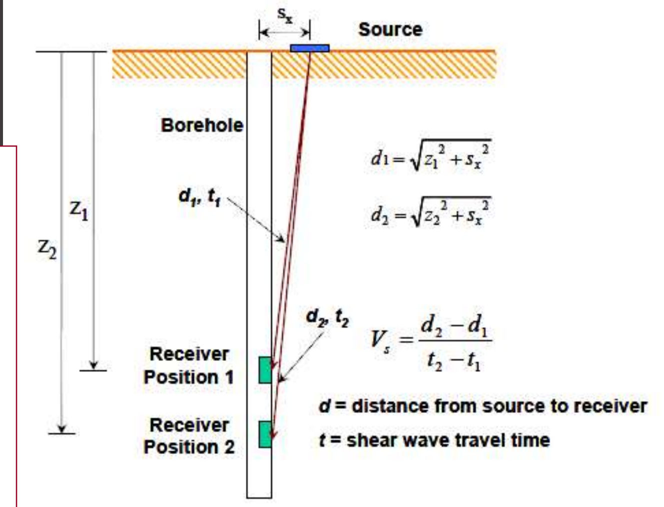
ρ_t = total unit weight

Seismic Cone

Can be 3D arrays



SCPT test

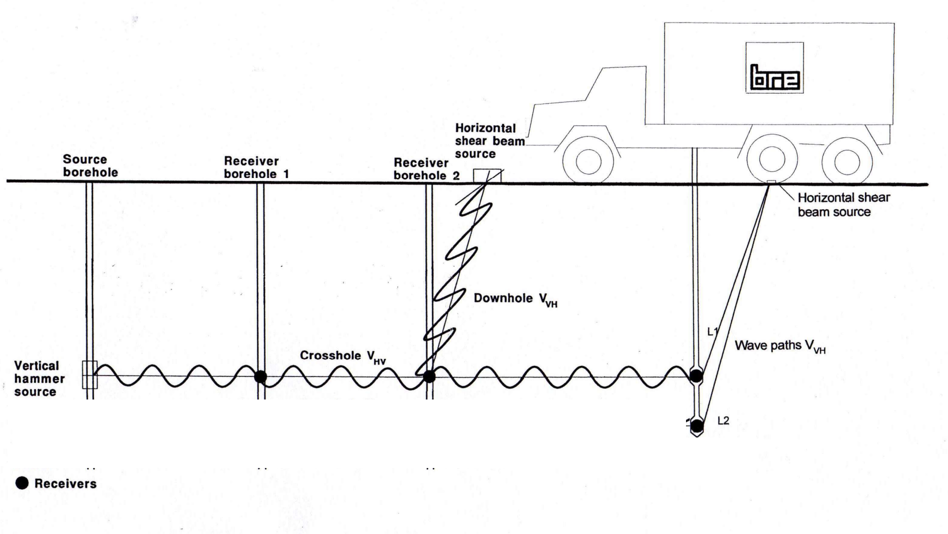


Energy source at the ground surface initiates the waves, sensors in the cone body (usually just short distance after the friction sleeve) detect the wave arrival.

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

JJMP GEOLABS®

Geophysical testing



Mechanical Seismic Source – Cone Truck

Normal force applied to beam for good contact with ground surface

JJMP

GEOLABS®

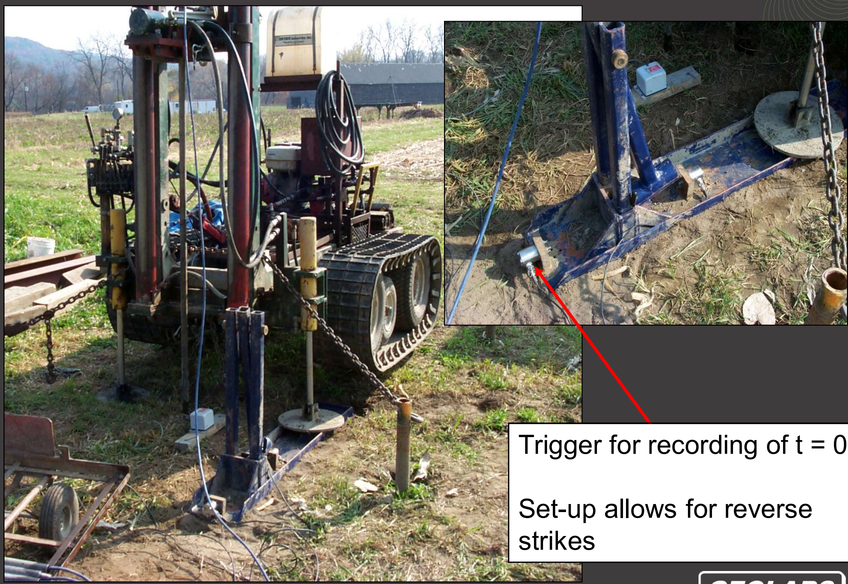
Mechanical Seismic Source – Cone Truck - Automated

Normal force applied to beam for good contact with ground surface

JJMP

GEOLABS®

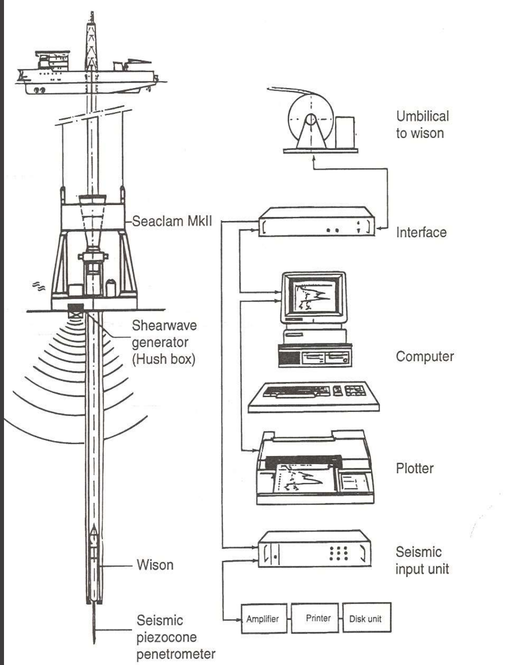
SCPTU – "Portable" Source Beam for use with Drill Rigs



Trigger for recording of t = 0

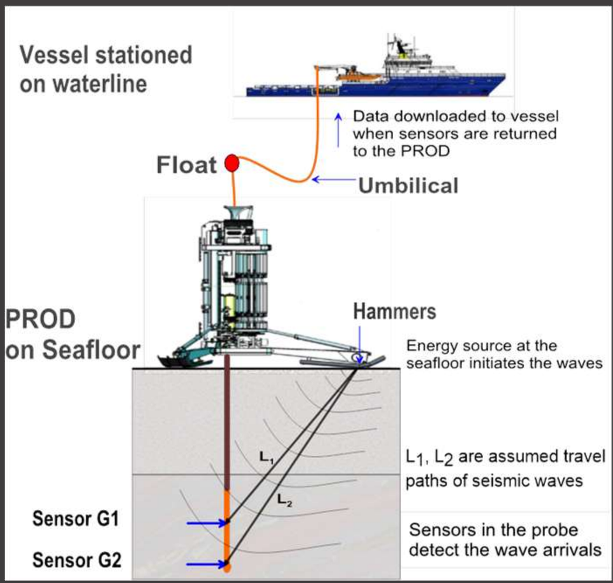
Set-up allows for reverse strikes

Seismic Cone



Slide 20

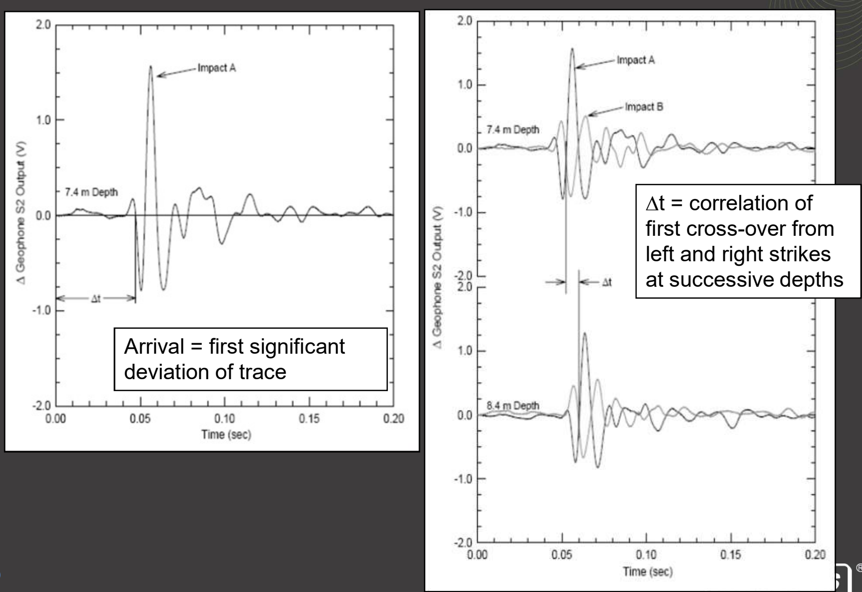
PROD SEISMIC PROBE



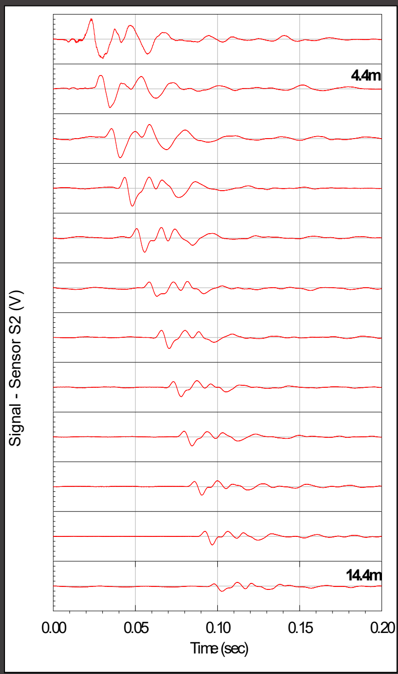
Courtesy of Hoang, Benthic

GEOLABS®

Example SCPTU Traces – Boston Blue Clay



Example SCPTU Data

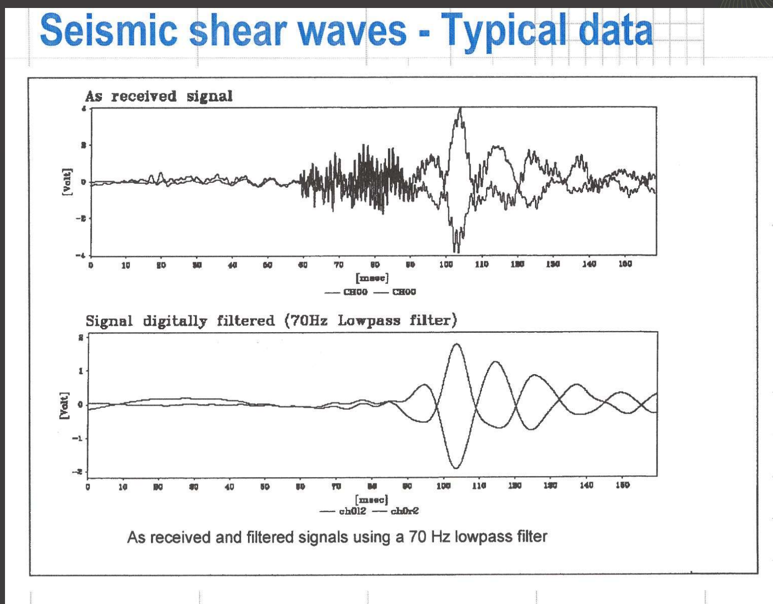


Boston Blue Clay – Newbury, MA

Seismic tests done at each 1 m rod change

GEOLABS

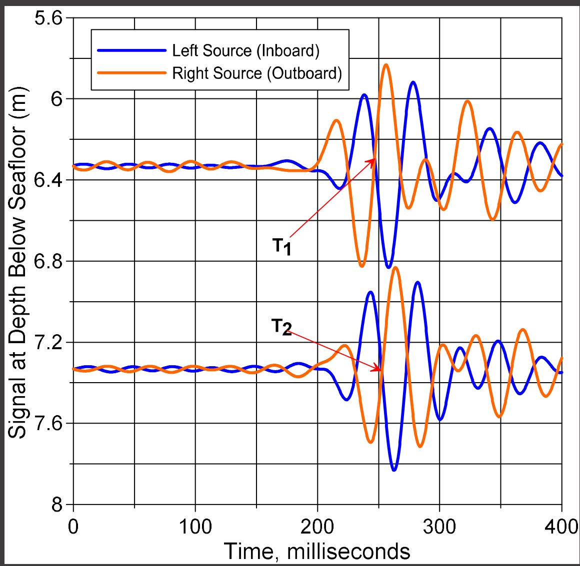
Reversal



As received and filtered signals using a 70 Hz lowpass filter

Slide 28

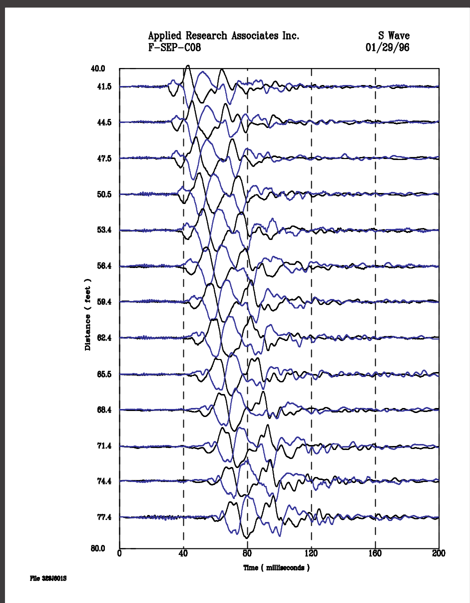
DATA REDUCTION: Filtered Data - Offshore



JJMP Courtesy of Hoang, Benthic

GEOLABS®

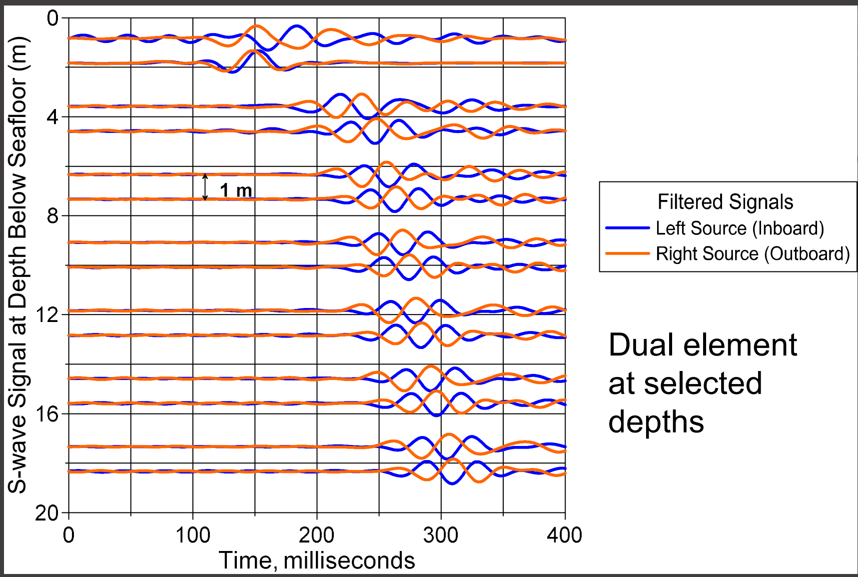
Example of Seismic-CPT Data



JJMP

GEOLABS®

DATA REDUCTION: Filtered Data



ea,

Dual element at selected depths

Courtesy of Hoang, Benthic

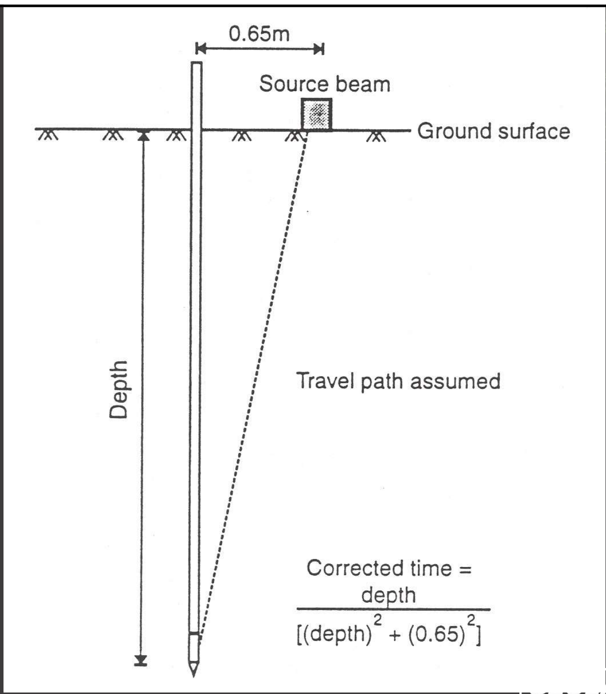
GEOLABS®

Potential Errors/problems

- Time
- Distance

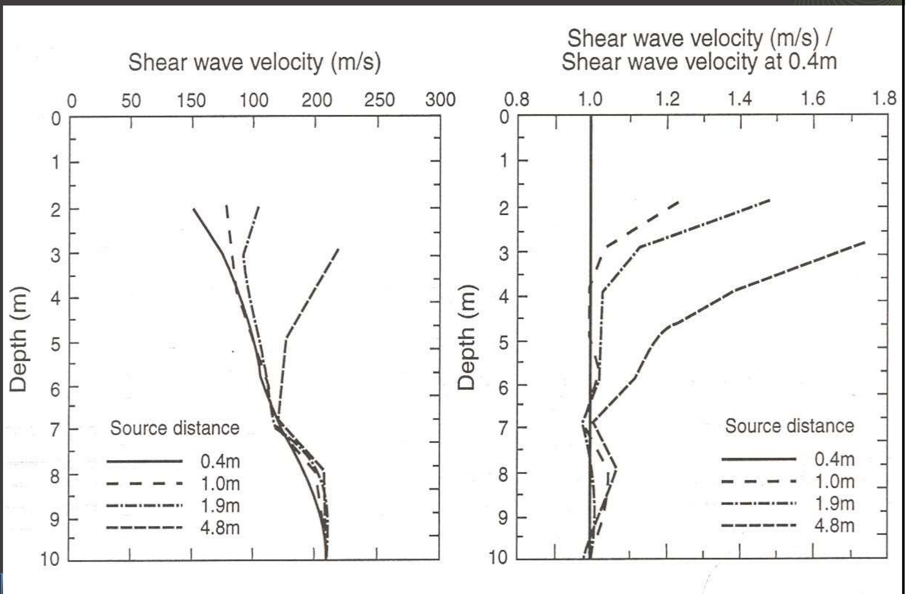
GEOLABS®

SCPT test

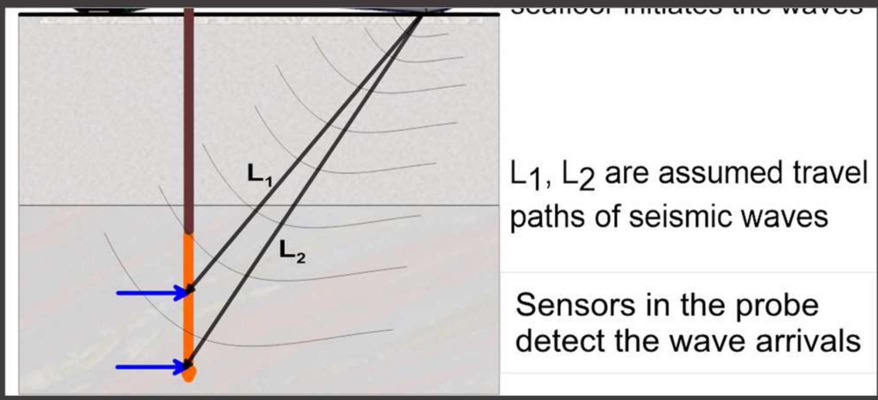


Dual element option etc

Potential Errors



PROD SEISMIC PROBE



GEOLABS®

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

GEOLABS®

Seismic Cone Testing

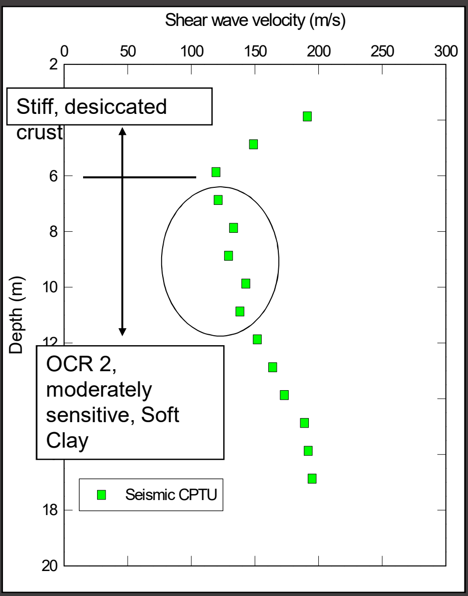
- Dual vs Single element

Dual	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

JJMP

GEOLABS®

Example vs Profile from SCPTU



Boston Blue Clay, Newbury, MA

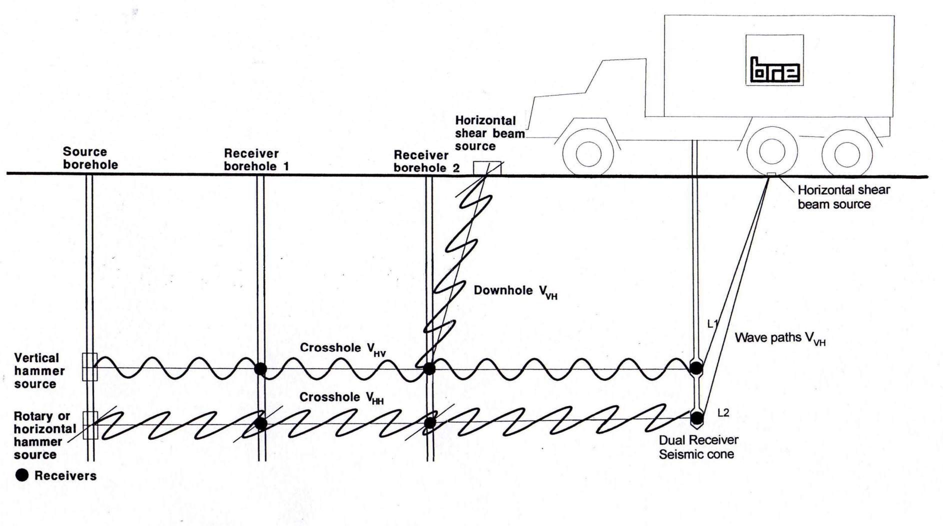
Used pseudo interval method; analyzed data via crossover and cross-correlation methods

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

JJMP

GEOLABS®

Geophysical testing - Anistropy



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.

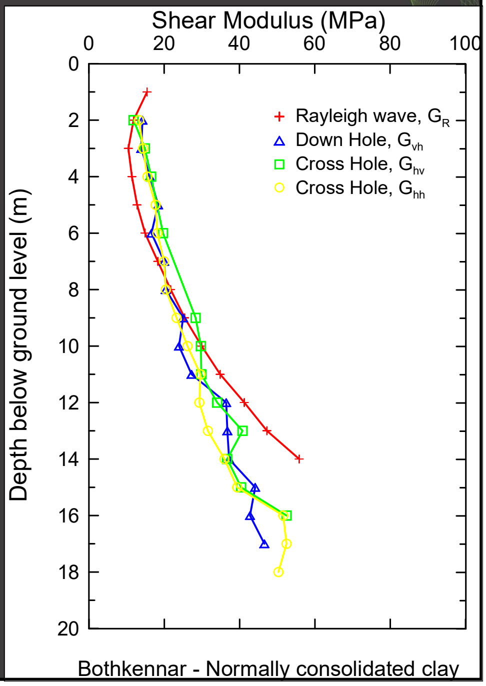
In some soils $V_{vh} \approx V_{hv}$; in most soils $V_{vh} \neq V_{hh}$.

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)

JJMP GEOLABS®

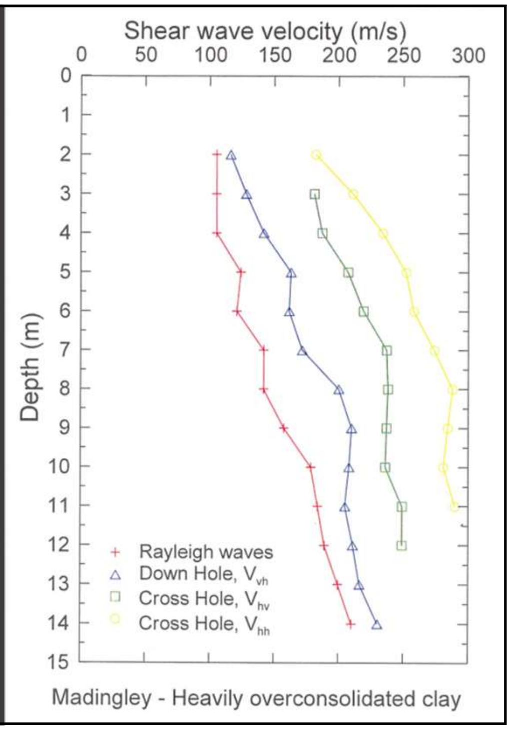
Geophysics - Bothkennar

(so G_o unique???)



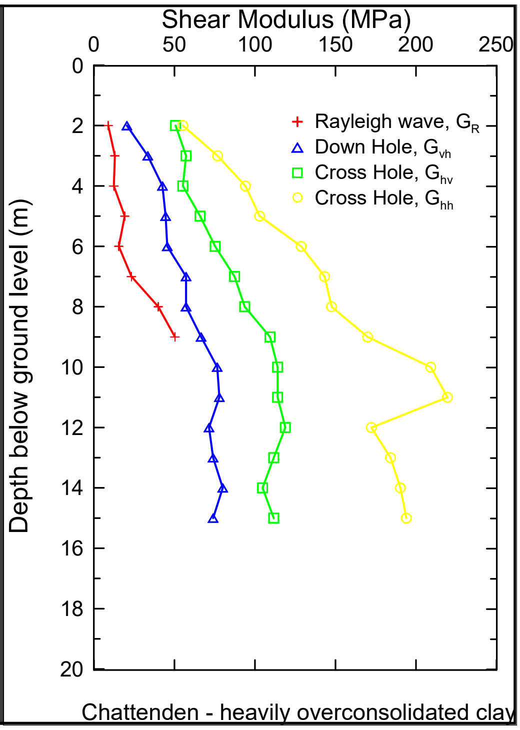
JJMP

Shear wave velocities - stiff clay



JJMP

Geophysics - Heavily OC clay



JJMP

Seismic Cone

- But we know what we are measuring!! VH

JJMP

GEOLABS®

BUT !!!!!

- We always seem to like to find otherways of getting the same information from other data
- OR
- We like to better understand interactions in our parameters

Basic Equation

- Correlations between index parameters and V_s or G_{max} can provide rapid estimates useful for preliminary design and for verifying *in situ* and laboratory results.
- (Hardin, 1978) suggested that Gmax for clays depends on the *in situ* (or applied) stress (σ'), void ratio (e), and OCR.
- The empirical equation describing the influence of the controlling factors on Gmax can then be written as follows:
- $G_{max} = SF(e)(\sigma_v' \sigma_h')^n \, p_a^{(1-2n)}$

- where *S* is a dimensionless parameter characterizing the considered soil;
- *F*(*e*) is a void ratio function;
- σ'_v and σ'_h are the vertical and horizontal effective stresses, respectively;
- *n* is a parameter indicating the influence of stress; and *p*
- is the atmospheric pressure

BUT

- People seem to have tried to link G_0 with many other CPT parameters:

- q_c
- q_t
- q_{net}
- B_q
- f_s
- etc

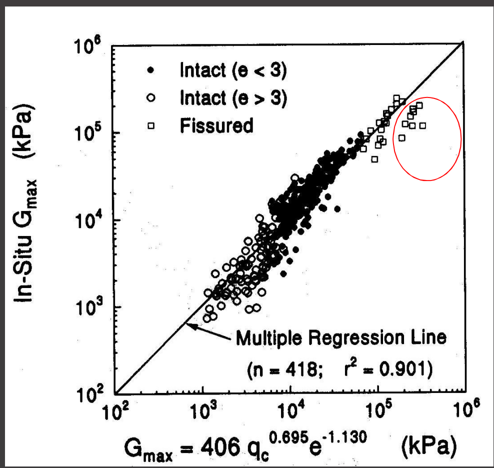
Small strain shear modulus

$$G_o = 99.5\,(p_a)^{0.305}\,\frac{(q_c)^{0.695}}{(e)^{1.130}}$$

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

Small strain shear modulus from CPTU data



From Mayne and Rix (1993)

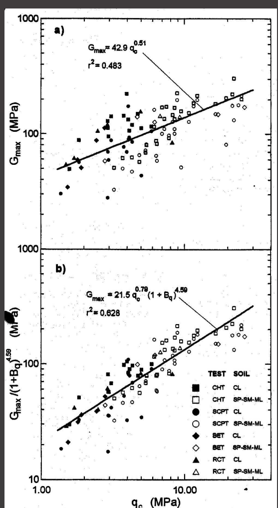
What G??

Do we believe?

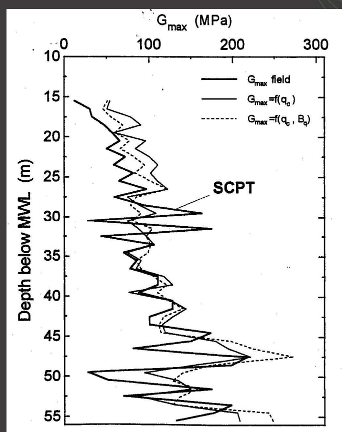
See later

$(r_2 = 0.901)\quad G_{max} = 406(q_c)^{0.695}/e_o^{\ 1.130}$

CPTU - G_{max} correlations for Venetian soils -



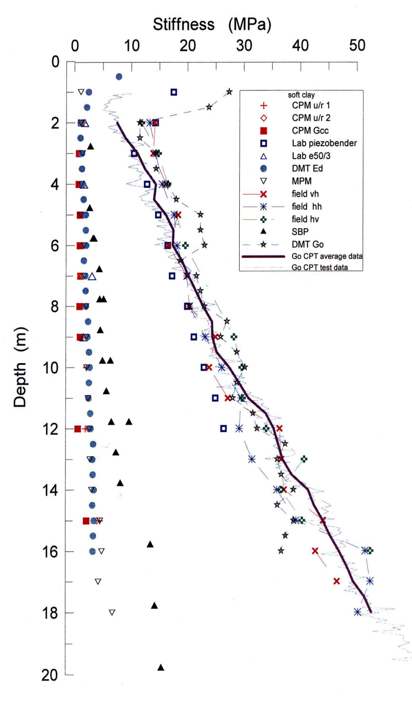
Correlations form Simonini and Cola,2000



Comparison with Gmax measured with seismic cone

GEOLABS

Stiffness Bothkennar

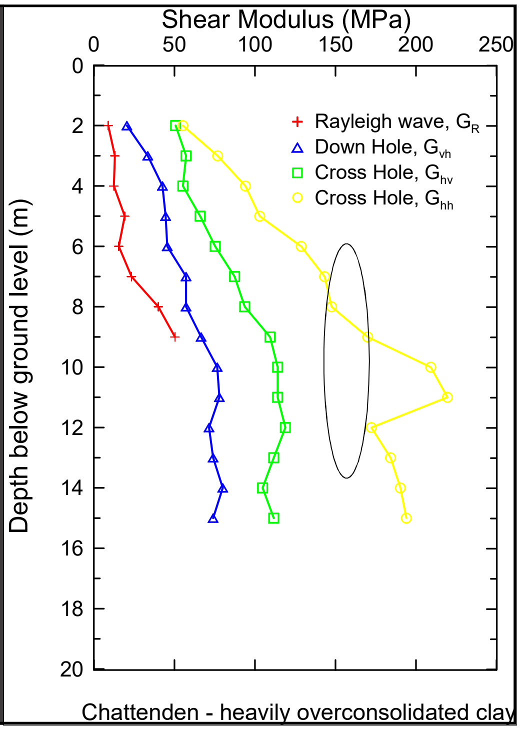


Powell 2001

Equations

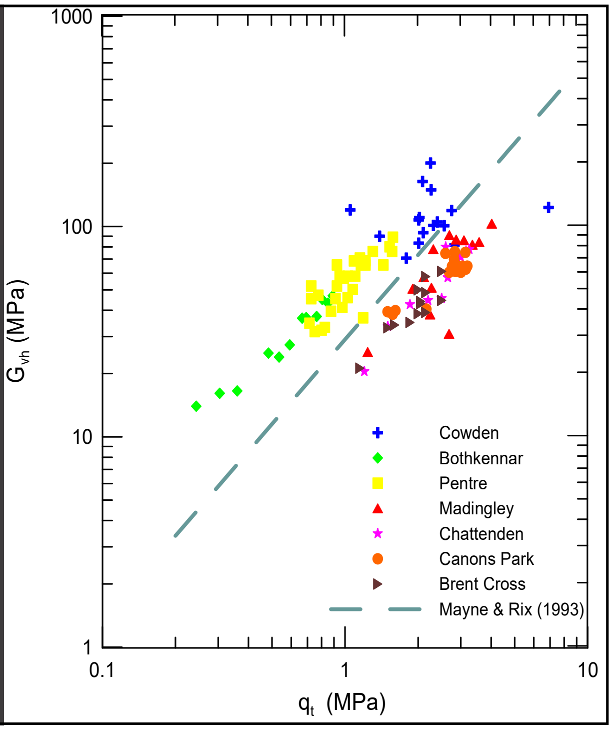
- All looks great
- But you find the same equations being modified for different sets of solis
- Eg. Recent Long and Donohue used the Simonini and Cola (2000) but had to modify it to get better fit for Norwegian soils (nc to lightly oc!!!)
- Care needs to be taken if correlations are used in different situations

Geophysics - Heavily OC clay



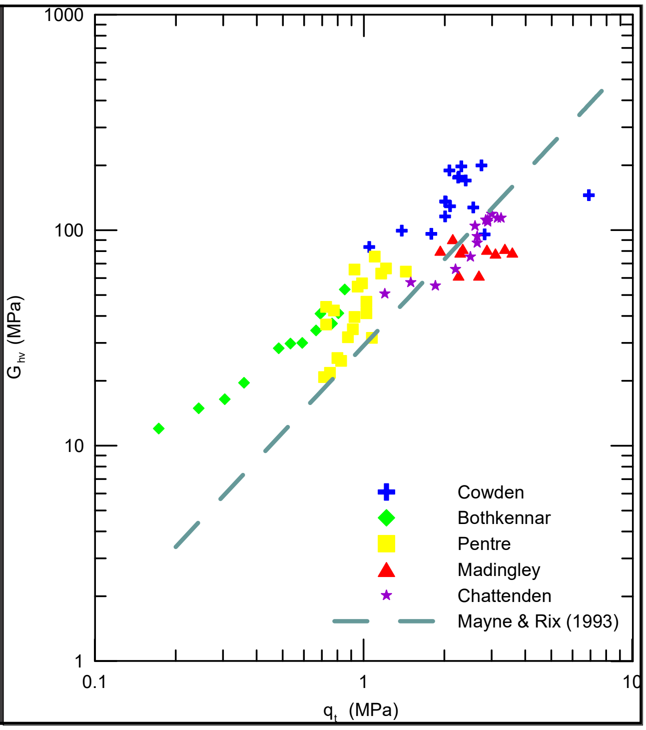
JJMP

G_{VH} in UK soils



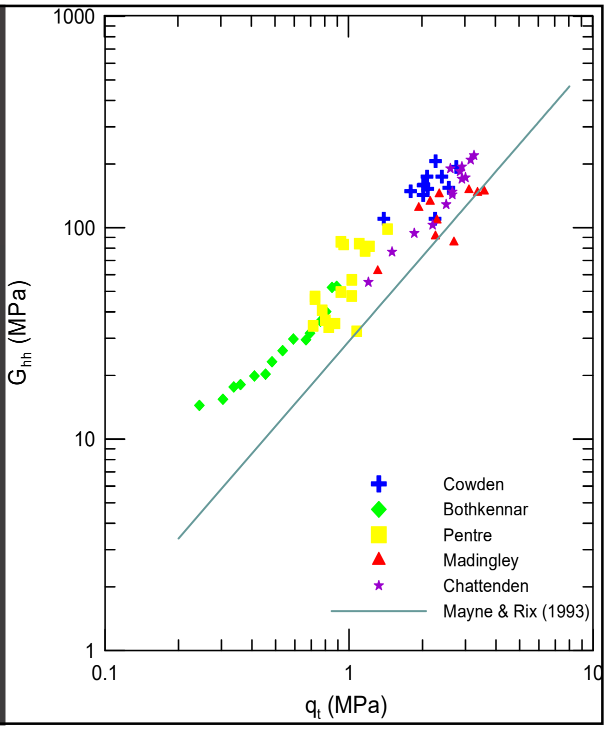
JJMP

G_{HV} in UK soils



G_{HH} in UK soils

what you correlate with

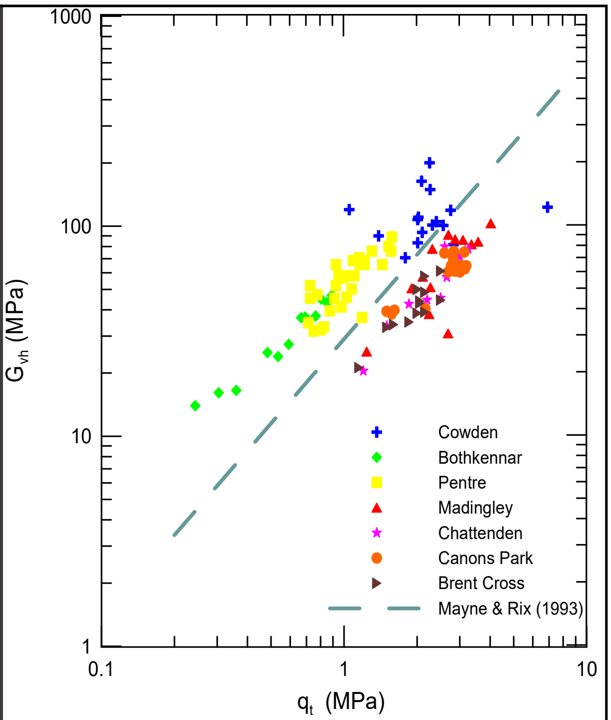


An UPDATE!

JJMP

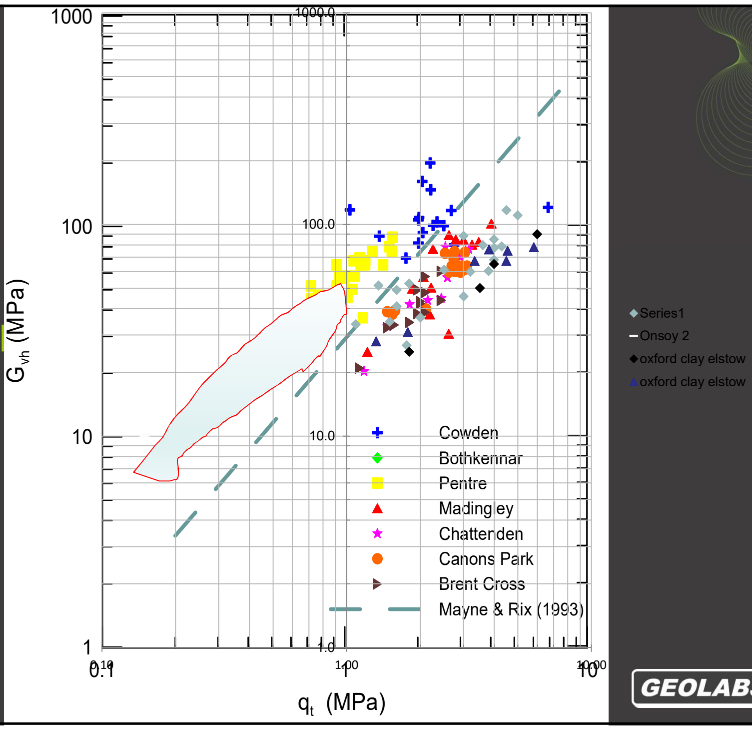
GEOLABS ®

G_{VH} in UK soils



JJMP

G_{VH} in UI



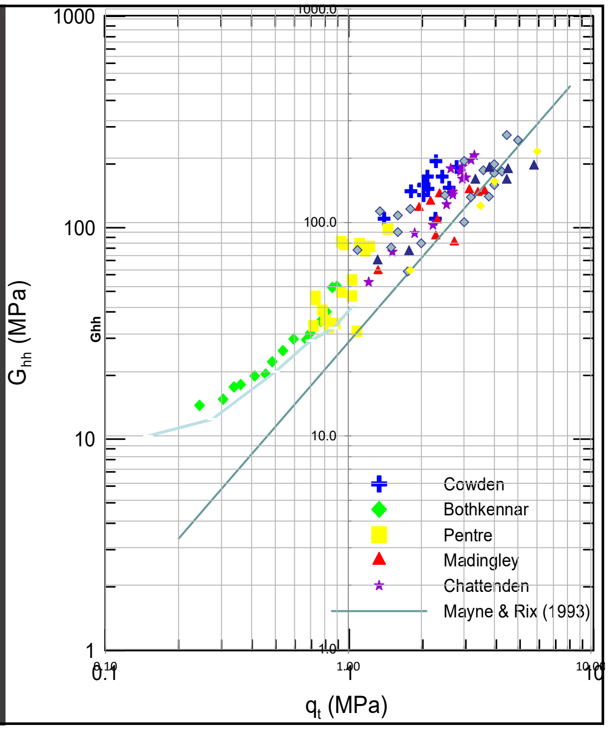
JJMP

GEOLABS®

G_{HH} in UK soils

what you correlate with

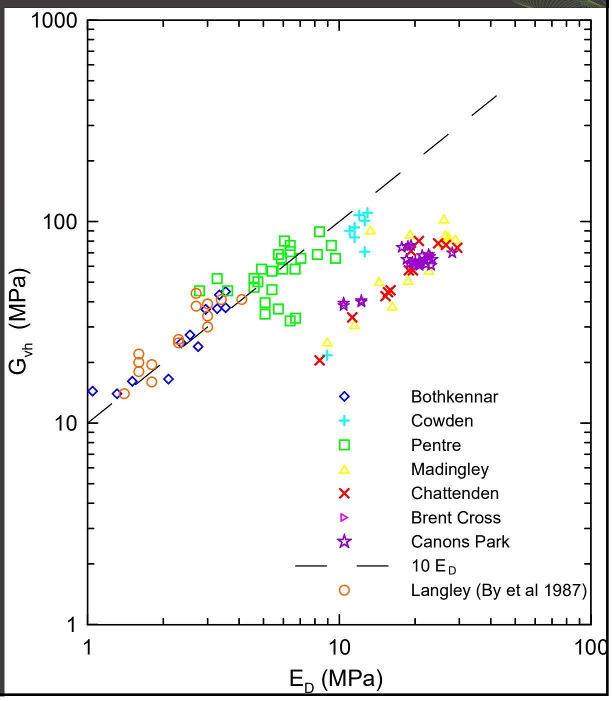
So which Stiffness would you want to correlate q_t with???



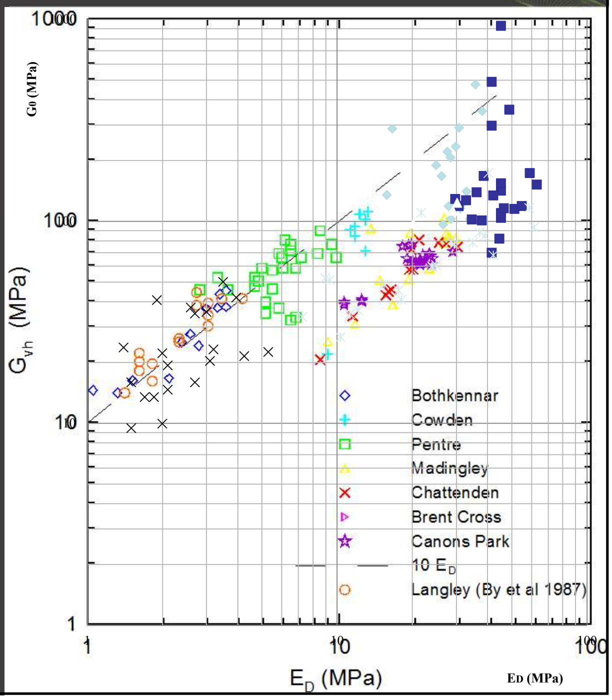
JJMP

And another CONSIDERATION

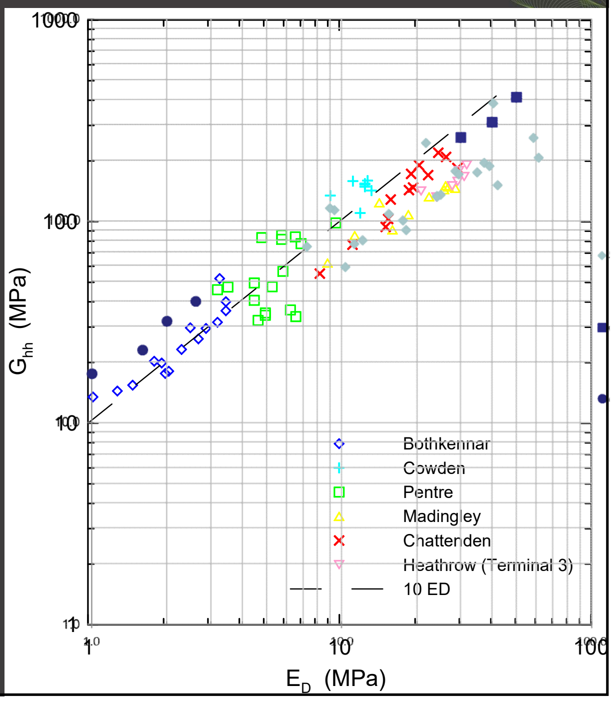
G_{vh} and E_D



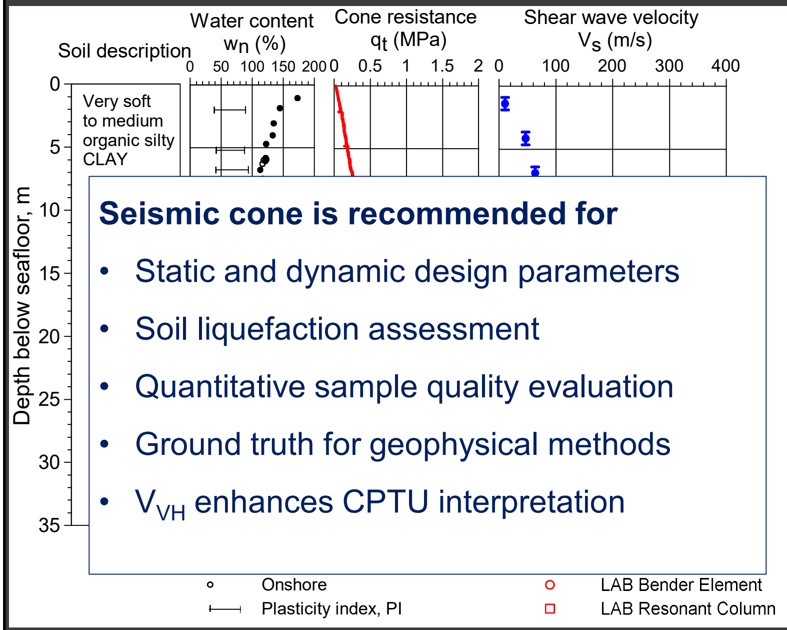
G_{vh} and E_D



G_{hh} and E_D



CASPIAN SEA SOFT CLAY



Seismic cone is recommended for

- Static and dynamic design parameters
- Soil liquefaction assessment
- Quantitative sample quality evaluation
- Ground truth for geophysical methods
- V_{VH} enhances CPTU interpretation

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

!!!!!!!!!!!!!!

GEOLABS®

What with what

- q_t seems to link best with G_{hh}
- q_t seems to link best with E_D
- E_D seems to link best with G_{hh}

JJMP

GEOLABS®

Seismic Measurements

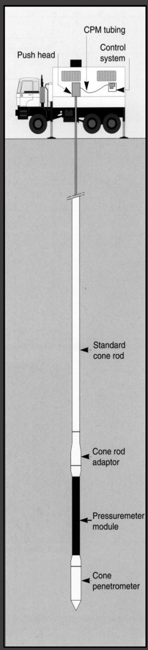
- Martin Fahey (2001) said that the addition of seismic measurements to the CPTU should become the next standard/routine form of the CPTU.
- We have come a long way and I think this is now proving to be the case
- Certainly the addition of geophones to the CPT enables downhole seismic testing to be undertaken 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!

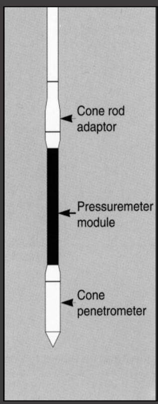
JJMP GEOLABS®

Cone Pressuremeter

JJMP GEOLABS®

Cone Pressuremeter (CPM)



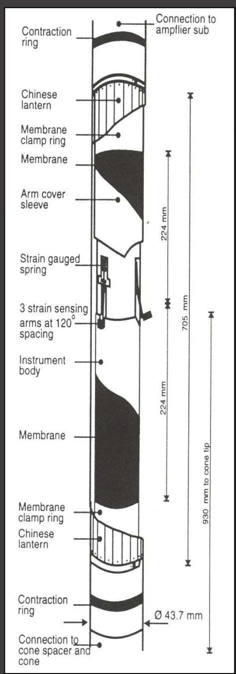


Cone Pressuremeter (CPM) = Pressuremeter module mounted behind a standard electrical cone penetrometer.

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%.

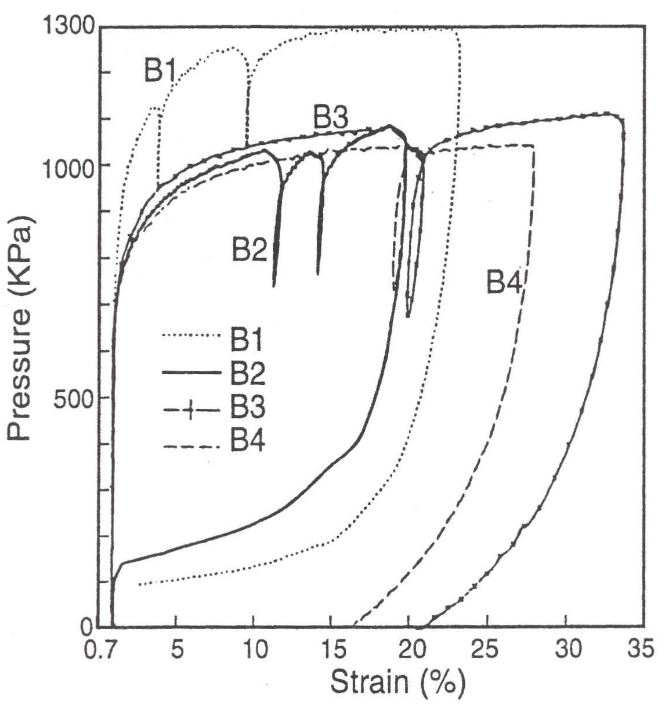
Cone Pressuremeter

Tests in Clays

JJMP

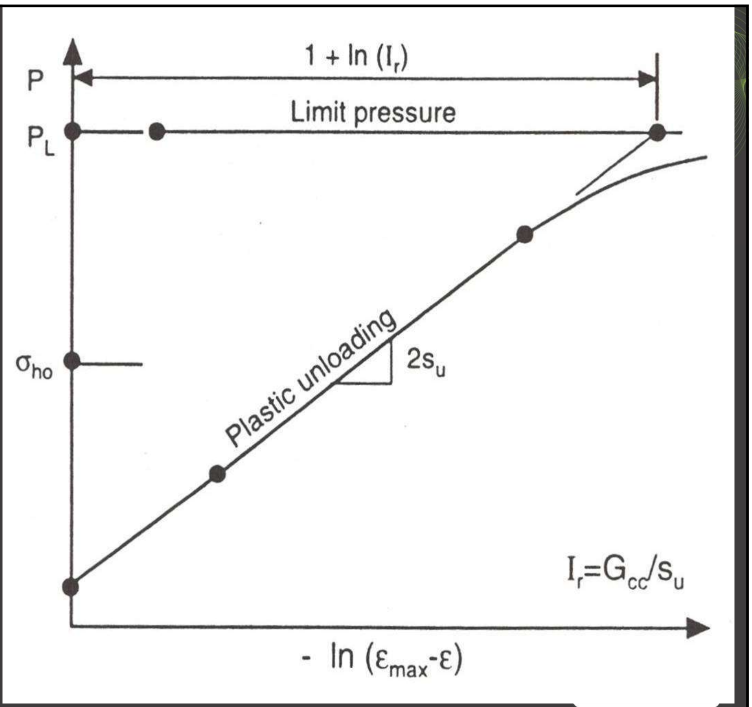
GEOLABS®

Typical CPM tests with unload reload loops

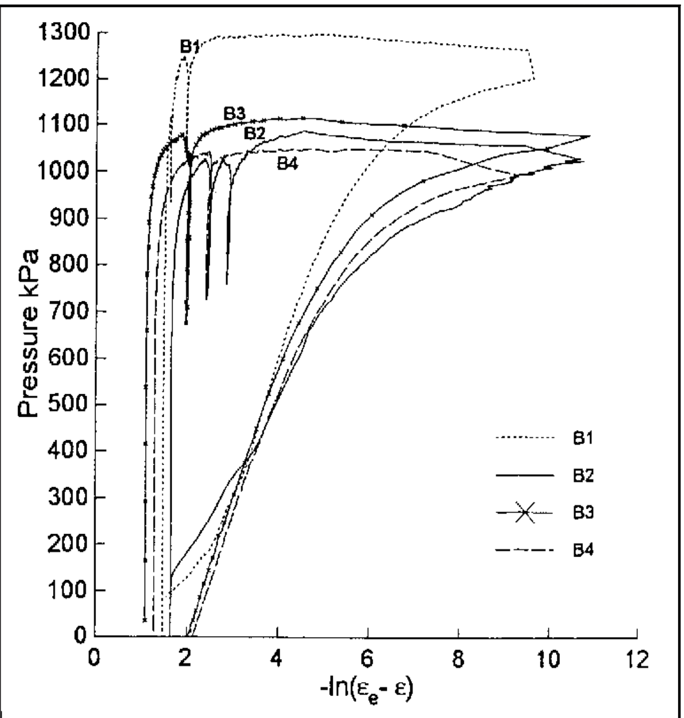


JJMP

Theory
(Houlsby
and Withers
1988)

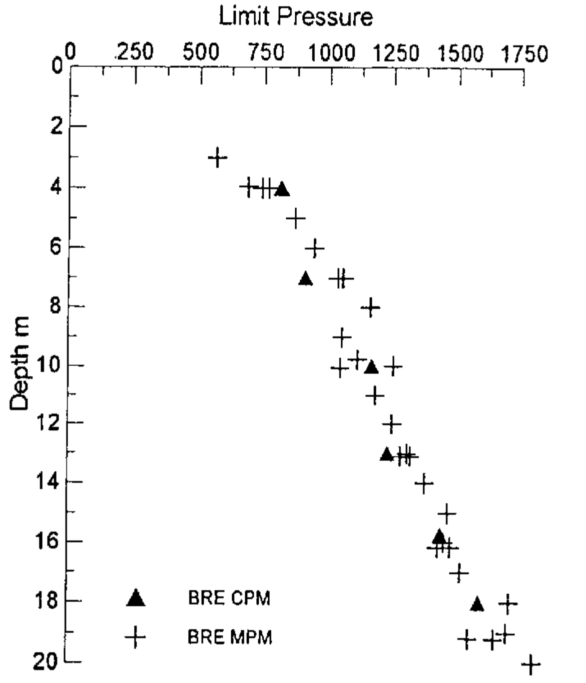


Interpretation



Limit Pressure

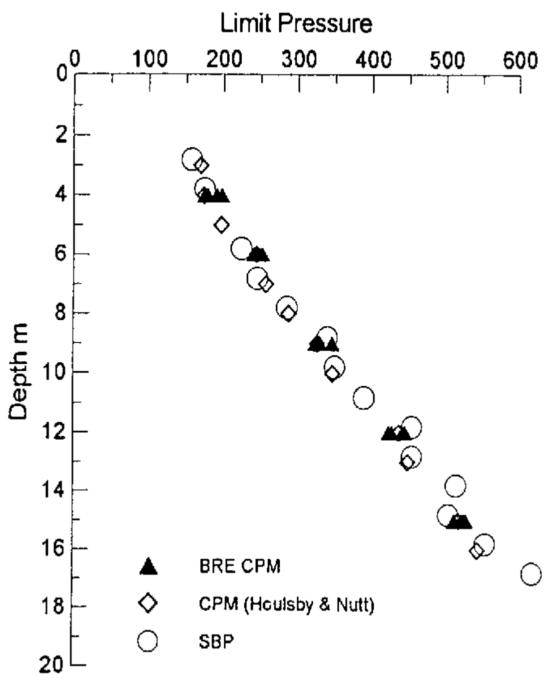
repeat



JJMP

Limit Pressure

devices



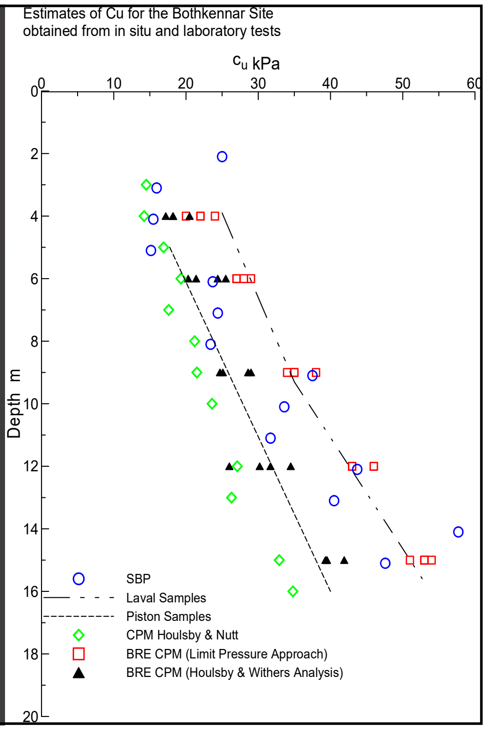
JJMP

CPM shear strength soft clay

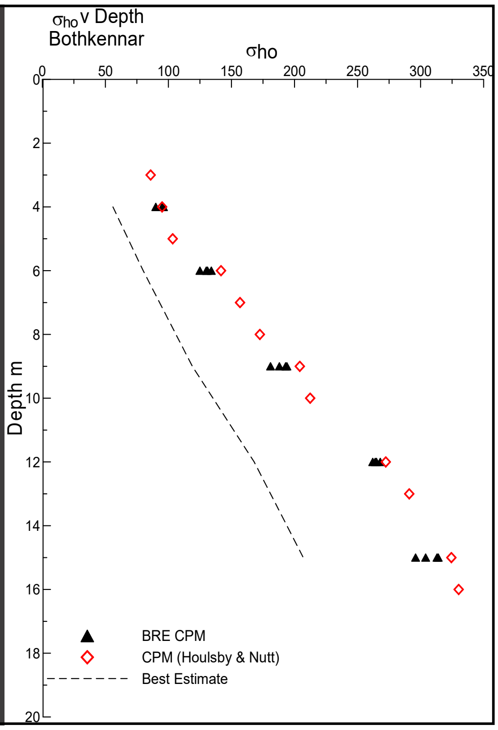
Bothkennar, UK

Undrained shear strength from CPM, SBP and laboratory triaxial tests

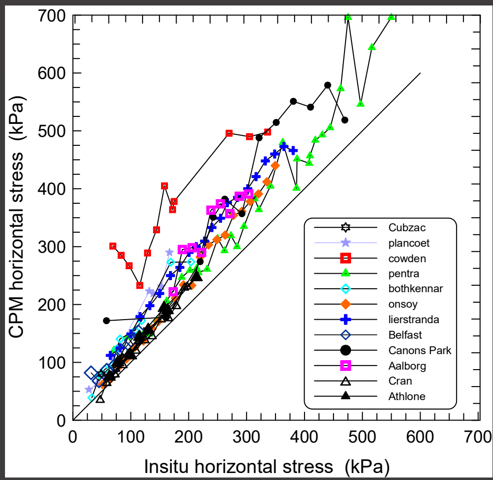
There are variations in s_u from different interpreation methods – continued topic of research



Bothkennar - σ_{ho}



σ_{ho} vs best estimate all sites



JJMP

GEOLABS®

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

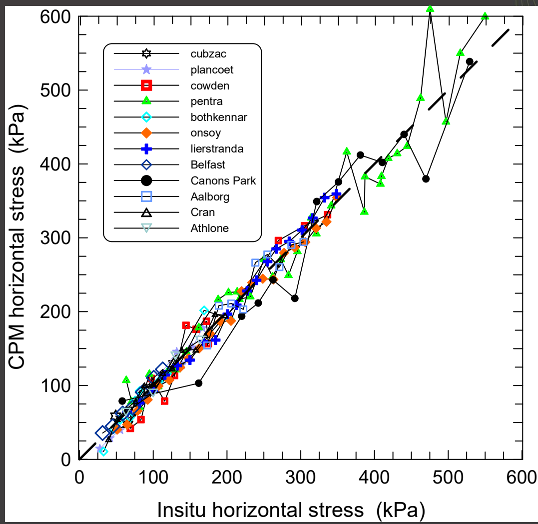
Basically c_u related correction

JJMP

GEOLABS®

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

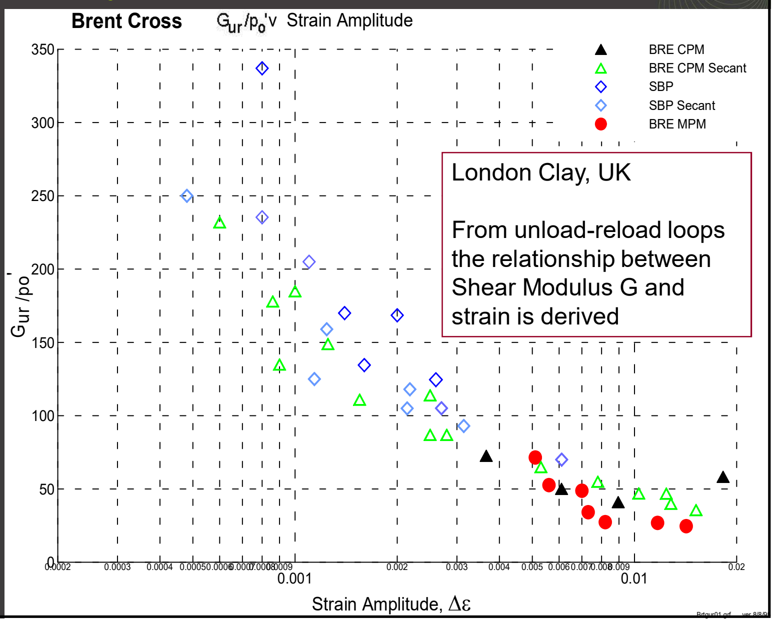
Using the modified Yu correction



JJMP

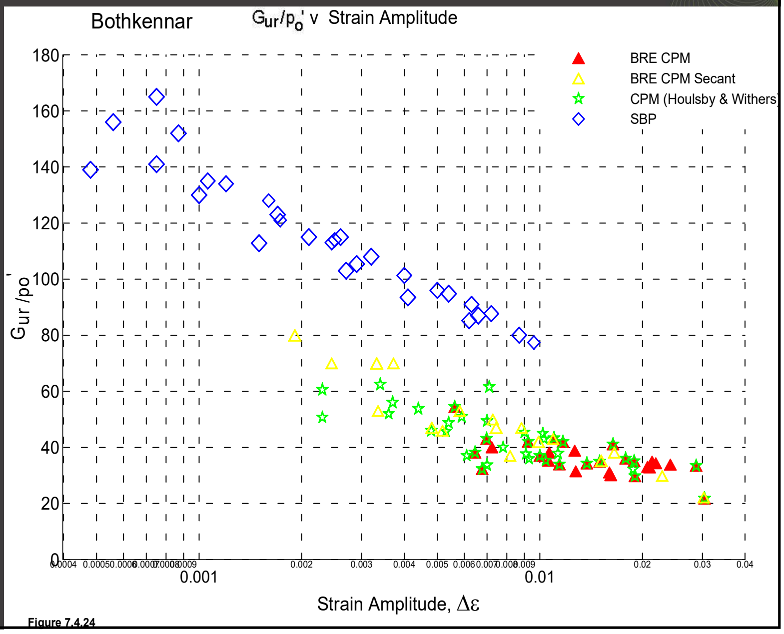
GEOLABS®

London Clay typical



JJMP

Bothkennar stiffness non typical



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

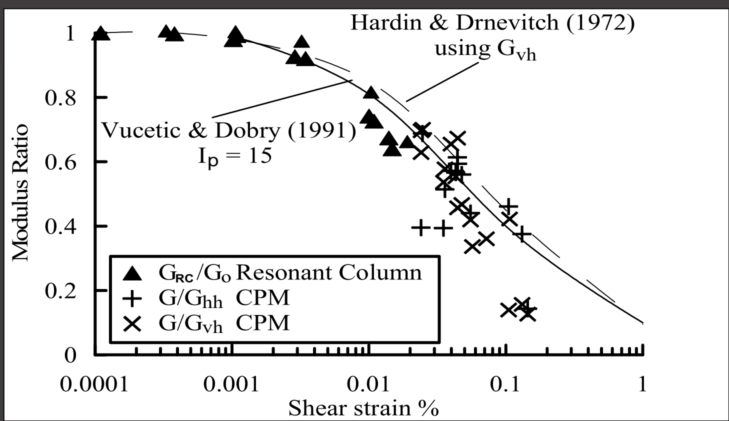
Is there potential for better combined assessments?

Linking the two

JJMP

GEOLABS®

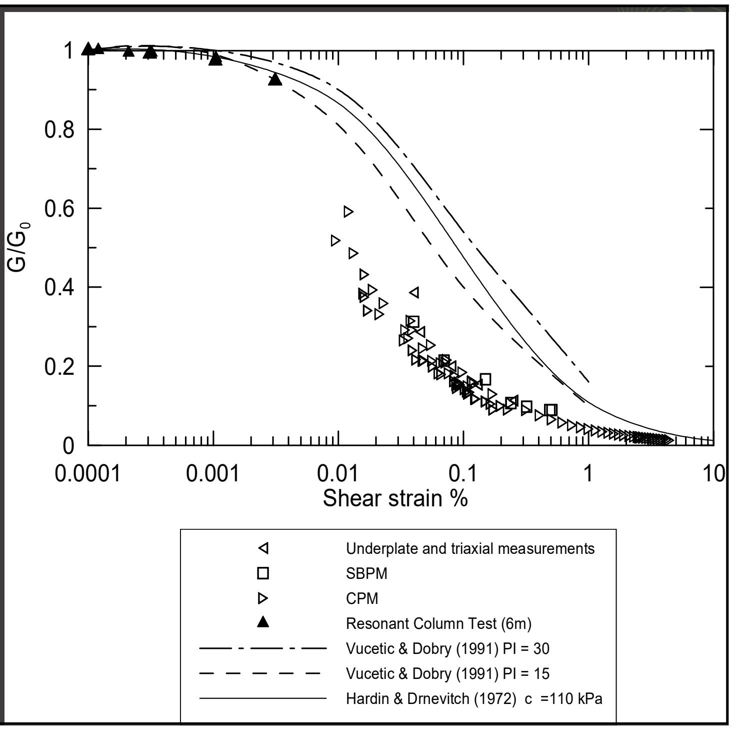
Non linear models of shear modulus and shear strain



Resonant column and CPM data from Pentre site

JJMP

GEOLABS®



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.

Summary – Additional CPTU Sensors

1. Seismic CPTU – well proven technology, becoming increasingly popular. But BE WARE
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?

.

JJMP GEOLABS®

Conclusions and finally

- Combination of tests can be most powerful and give much better characterisation of soils and sites,
- So if we use a Seismic Cone Pressuremeter we have everything and redundancy!!
- Life is wonderful

JJMP GEOLABS®

Thank you ?