Gregg Drilling & Testing, Inc.

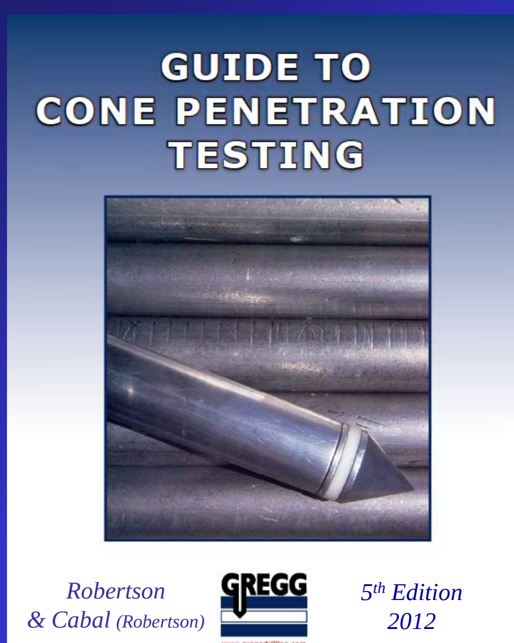
Site Investigation Experts

Seismic CPT (SCPT)

Peter K. Robertson

Webinar #12

Sept.2014



CPT Guide

5th Edition

Download ***FREE*** copy from:

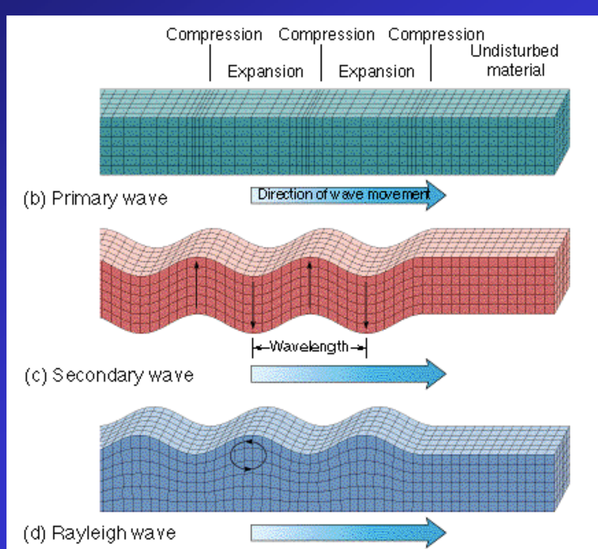
www.greggdrilling.com
www.cpt-robertson.com
www.geologismiki.gr

Robertson, 2013

Geophysical Testing

- Seismic
- Electrical
- Gravity
- Magnetic
- Nuclear
- Electromagnetic (GPR)

Main seismic waves



P-waves (compression)

S-waves (shear)

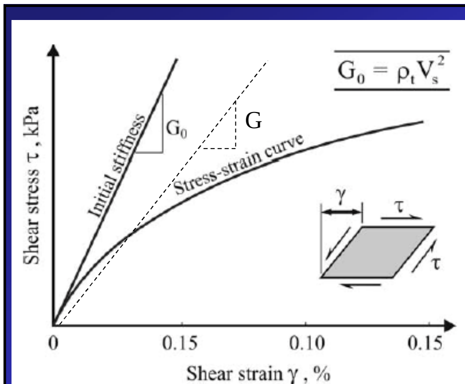
Rayleigh surface-waves (mostly shear)

Why are seismic velocities helpful?

Wave type	Propagation mode	Shape change	Wave velocity	Small-strain modulus
P		Compression	V_P (V) V_P (H)	$M_o = \rho_t V_P^2$ — M_o(V), M_o(H)
S		Distorsion	V_S (VH) V_S (HH)	$G_o = \rho_t V_S^2$ — G_o(VH), G_o(HH)

Wave propagation (green arrow)
Particle motion (red arrow)

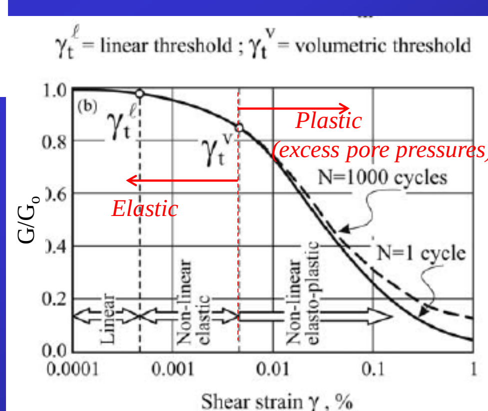
After Jamiolkowski, 2012



V_s is direct measure of small strain shear modulus, G_o (or G_{max})

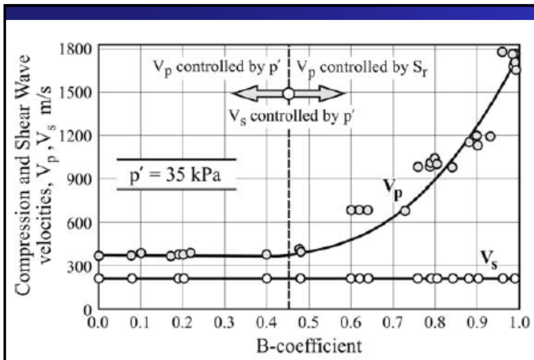
$$G_o = \rho_t (V_s)^2$$

$$\rho_t = \gamma/g$$



Small strain (elastic) shear modulus, G_o (or G_{max}) is a fundamental soil parameter ($\gamma < 10^{-4}$ %)

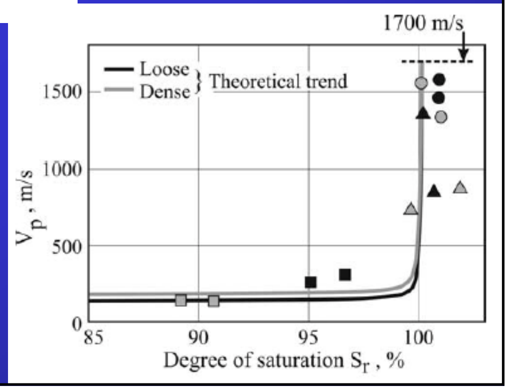
After Jamiolkowski, 2012



- V_p contolled by degree of saturation in most soils
- V_p ~ 1500 m/s (5000ft/s) in saturated soil
- V_p can be used to detect S_r < 100%

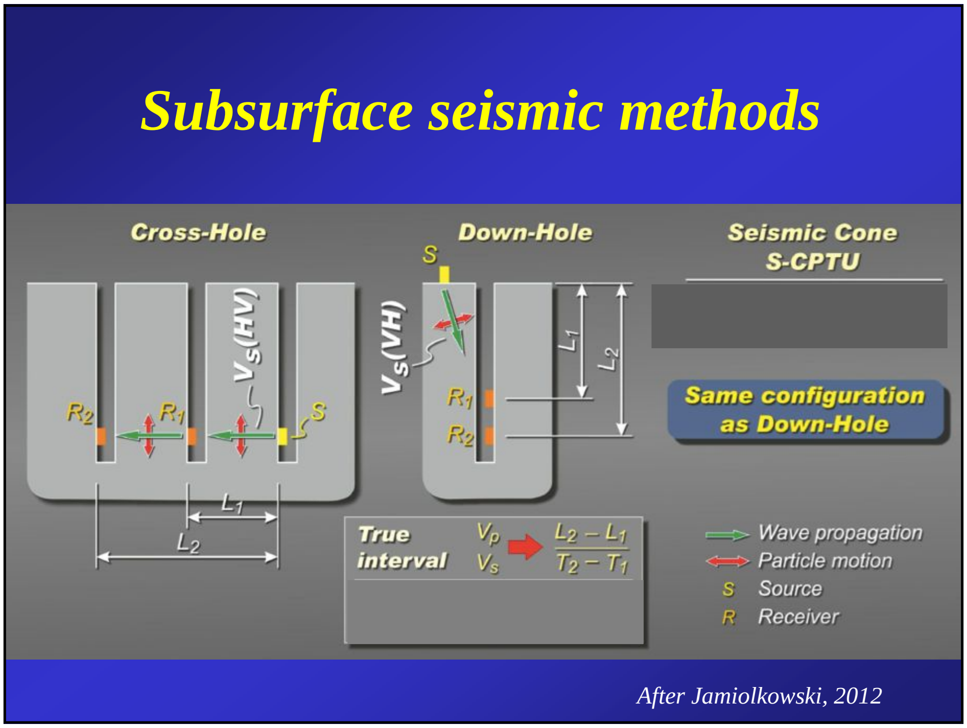
- V_s independent of saturation and GWL
- V_s controlled by in-situ effective stresses, density, age & cementation

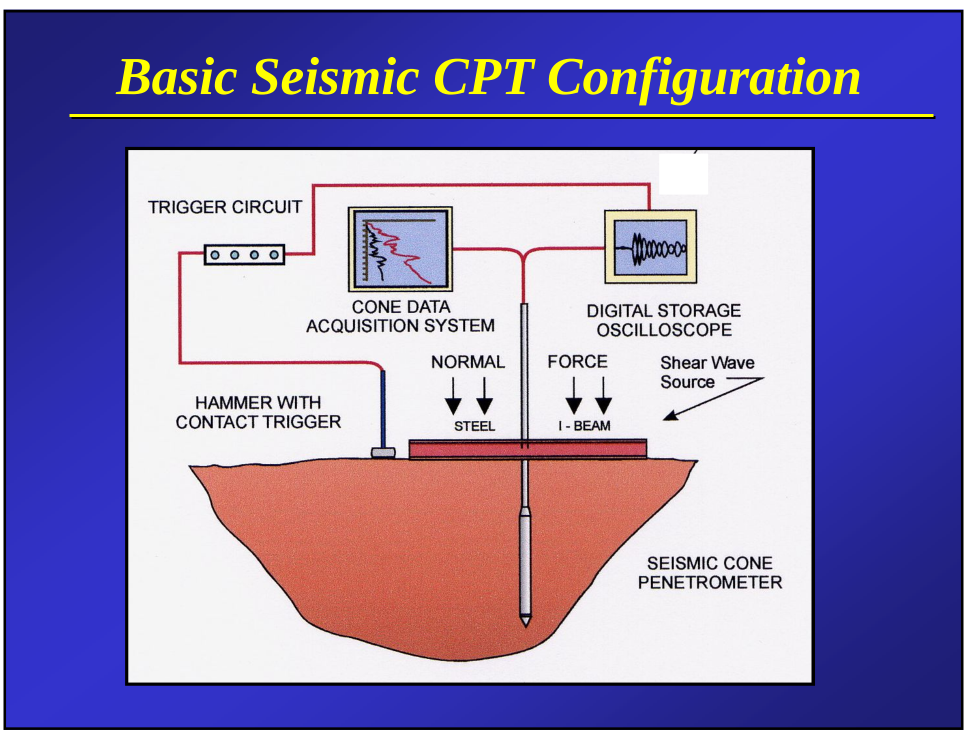
After Jamiolkowski, 2012



Seismic Testing Methods

- ***Surface-based (non-invasive)***
  - – Refraction/reflection
  - – Active (SASW, MASW)
  - – Passive (ReMi, etc.)
- ***Subsurface-based (invasive)***
  - – Down-hole/up-hole/cross-hole
    - *SCPT (down-hole) – mostly Vs*
  - – Borehole logging (e.g. P-S logging)

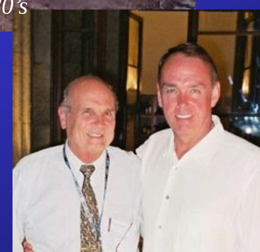

Subsurface seismic methods
Cross-Hole
Down-Hole
Seismic Cone S-CPTU
Same configuration as Down-Hole
True interval
Vp Vs
L2 – L1 / T2 – T1
Wave propagation
Particle motion
S Source
R Receiver
After Jamiolkowski, 2012


Basic Seismic CPT Configuration
TRIGGER CIRCUIT
CONE DATA ACQUISITION SYSTEM
DIGITAL STORAGE OSCILLOSCOPE
NORMAL
FORCE
Shear Wave Source
HAMMER WITH CONTACT TRIGGER
STEEL
I - BEAM
SEISMIC CONE PENETROMETER

Early days of SCPT *(UBC)*

Imperial Valley, CA, early 1980's

First SCPT in early 1980's
Prof Campanella, UBC



Seismic CPT using a Drill-rig

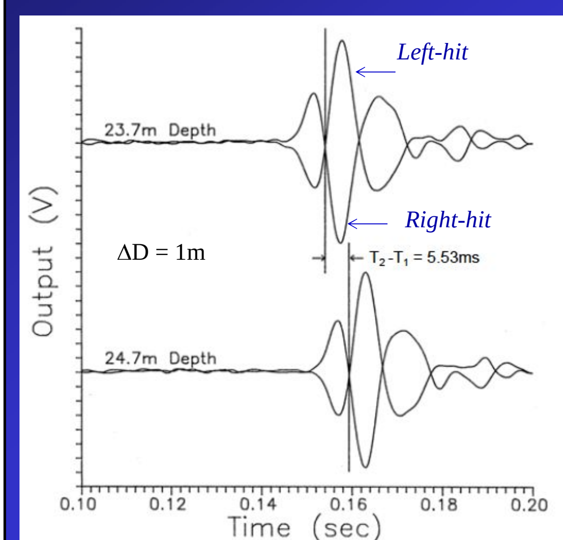
1990 U of Alberta

Modern CPT Trucks

Trucks with build-in seismic beam

Seismic beam

Polarized shear wave traces

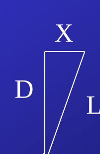


After Butcher et al 2005 (ISSMGE TC 10)

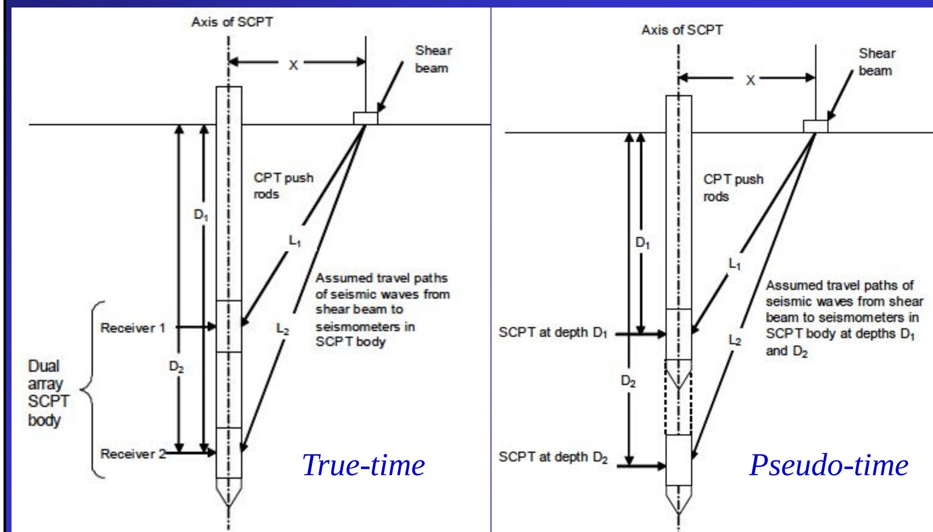
$$V_s = \frac{(L_2 - L_1)}{(T_2 - T_1)}$$

L = calculated straight path distance from source to receiver (use horizontal offset X & vertical depth D)

$(T_2 - T_1)$ = time difference

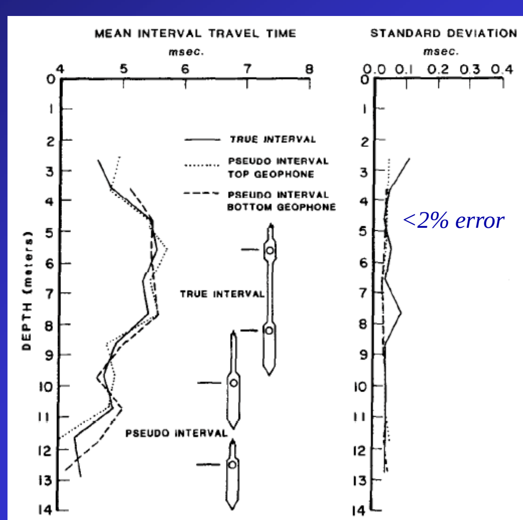


True & Pseudo-time interval



After Butcher et al 2005 (ISSMGE TC 10)

True & Pseudo-time interval



- In general, little difference between true- and pseudo-time interval methods
- Pseudo-time interval requires only 1 seismic sensor
- True-time allows real-time automatic velocity calculation

After Robertson et al, 1986

SCPT Equipment & Procedures

- Key elements:
  - True-time (dual-array) or pseudo-time (single-array)
  - Sensors
    - Type – geophones or accelerometers
    - Number – 1, 2, 3 (single, dual-, triaxial-)
  - Seismic source
    - Beam, auto-hammers
  - Trigger
    - Contact or sensor
      - Contact trigger preferred and commonly used

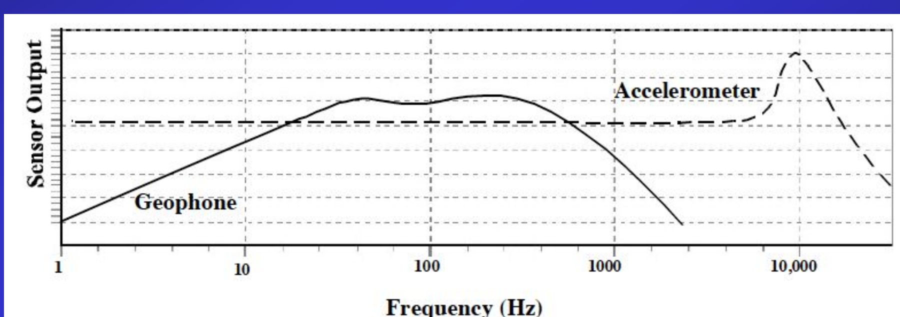
Sensors

See BCE Technical Note 10 (Baziw/Verbeek)

http://www.bcengineers.com/images/BCE_Technical_Note_10.pdf

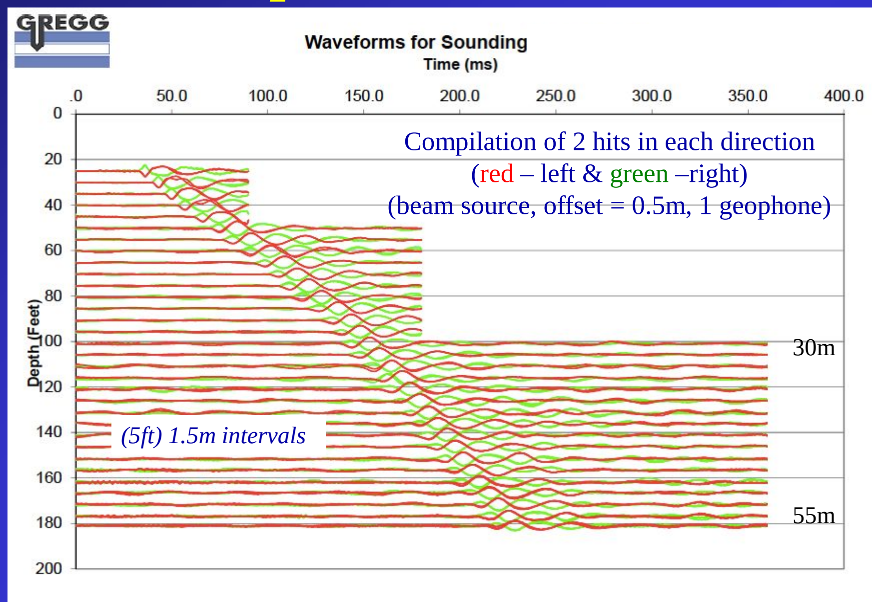
High resolution piezoelectric accelerometers – minimal sensor distortion

Both geophones and accelerometers can be effective

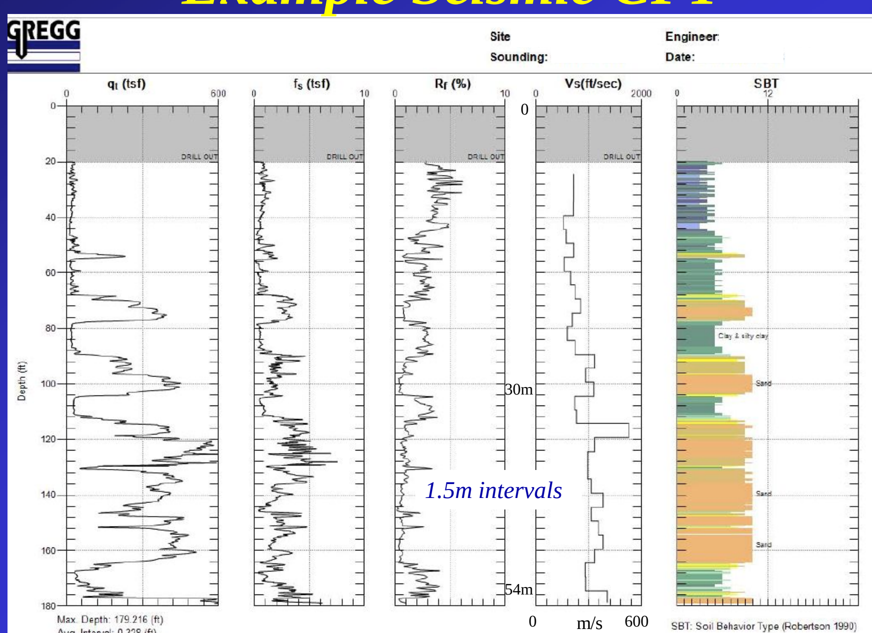


Typical frequency response curves for geophones and accelerometers

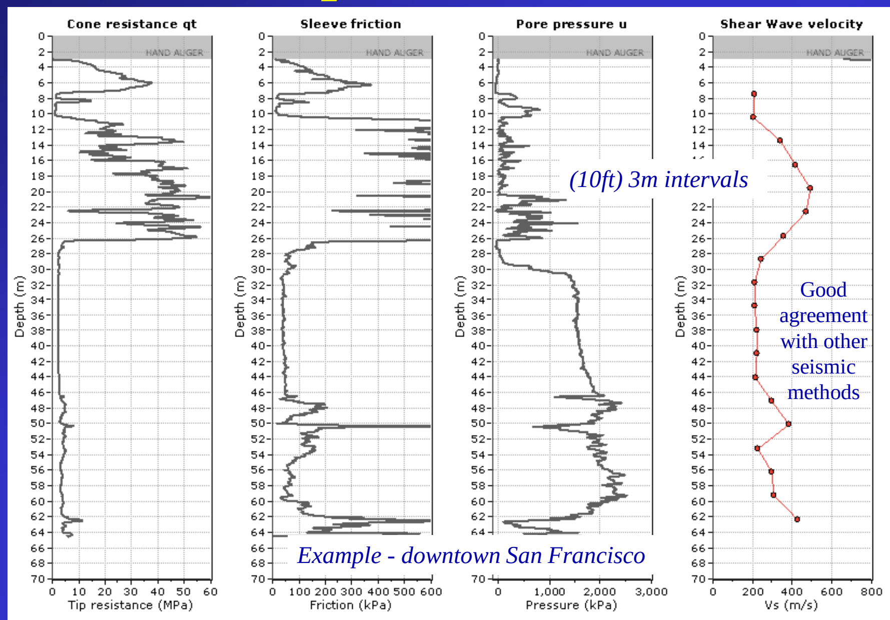
SCPT polarized wave traces



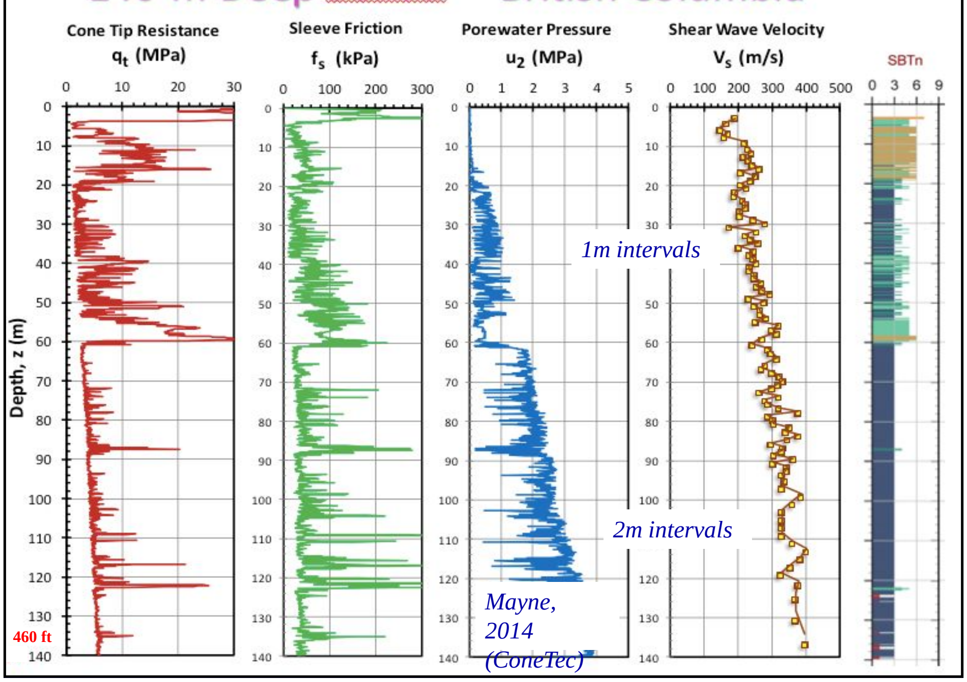
Example Seismic CPT



Example Seismic CPT



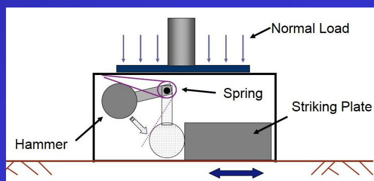
140-m Deep SCPTu - British Columbia



Automatic seismic source

Figure 1. AutoSeis shear wave seismic source.

Automatic hammer source
"*AutoSeis*" – Georgia Tech
(Mayne & McGillivray, 2005)



Simple repeatable source

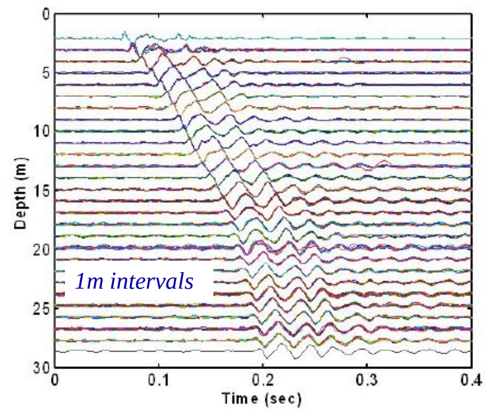
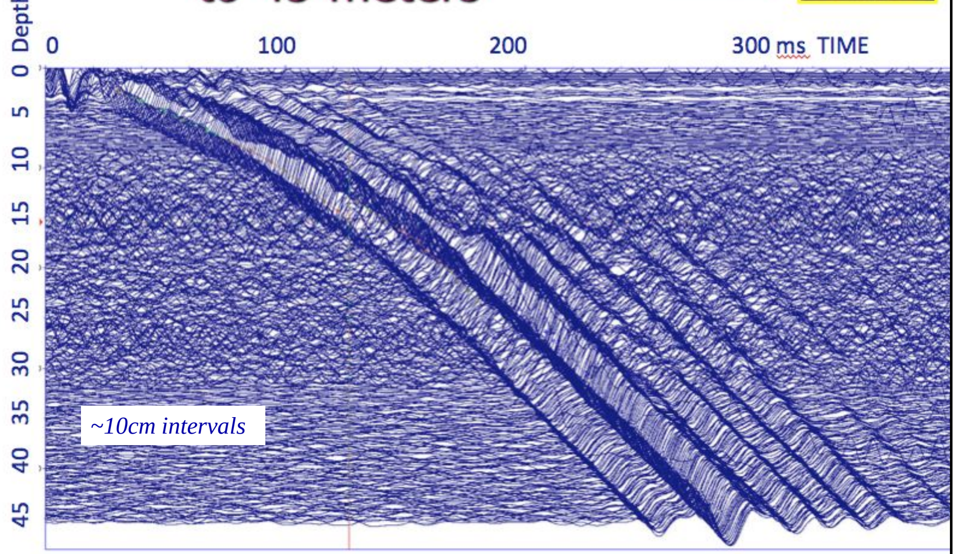


Figure 2. AutoSeis traces. *Single hammer*

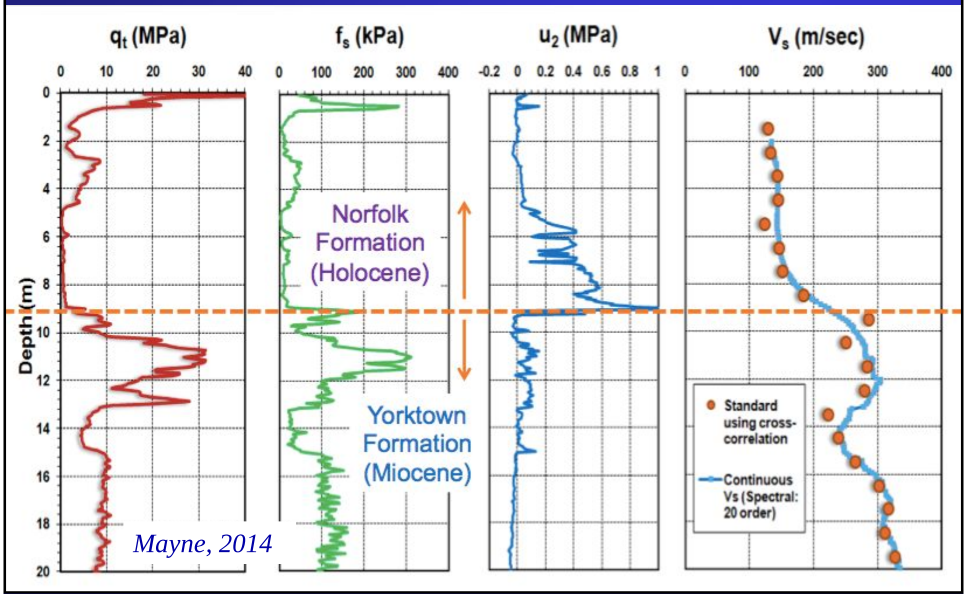
Continuous V_s profiling to 45 meters

GT AutoSeis

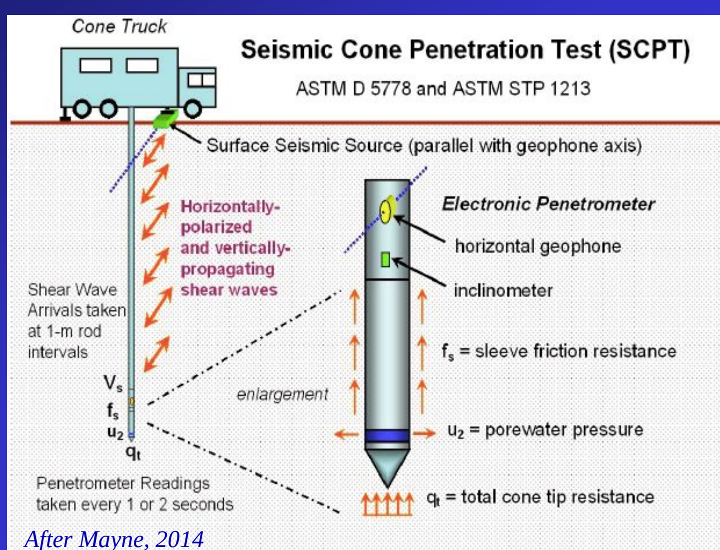


Mayne, 2014 (ConeTec)

Contiuous source – Norfolk (USA)



Seismic CPT System Configuration



SCPTu

7 measurements!

q_t

f_s

u_2

V_s (V_p)

t_{50} | *diss*

u_o

i

Seismic CPT - Advantages

- 30 years experience (~1983)
- Simple, reliable, and inexpensive
- Direct measure of small strain soil stiffness
- Typically 1 meter intervals
- Combines CPT measurements (q_c, f_s, u) and seismic V_s (V_p) profile in same soil (very cost effective)

SCPT Applications

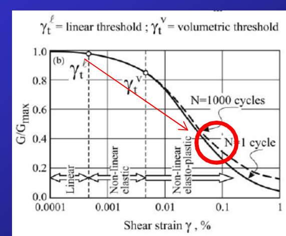
- Direct measure of soil stiffness
  - Settlement calculations
  - Input for numerical modeling (stress-strain)
- Estimation of soil parameters based on V_s
- Evaluation of soil liquefaction based on V_s
- Determination of saturation based on V_p
- Identification of '*unusual*' soils
  - i.e. soils with microstructure
- Link to lab testing (V_s in-situ and lab)

Direct measure of soil stiffness

- Small strain shear modulus, $G_o = \rho (V_s)^2$
  - key parameter in soil dynamics ($G_o = G_{max}$)
- Link to small strain Young's modulus, E_o

  $E_o = 2G_o (1+\upsilon) \sim 2.4\ G_o$

  υ = poisson's ratio ~ 0.2 (drained small strains)
- Soften to strain level of interest
  - for γ ~ 0.1%, soften by ~ 0.4
  - $E'_{0.1\%} \sim G_o$



Mobilized stiffness for design

Modified hyperbola based on mobilized stress level (Fahey, 1998)

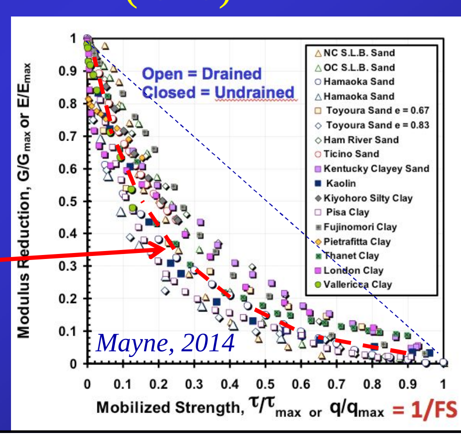
$$G/G_o = 1 - f\ (\tau/\tau_{max})^g = 1\text{-}f\ (1/FS)^g$$

where FS (factor of safety)

$FS = \tau/\tau_{max} = q/q_{ult}$

For uncemented, unstructured soils

f ~ 1.0 and g ~ 0.3

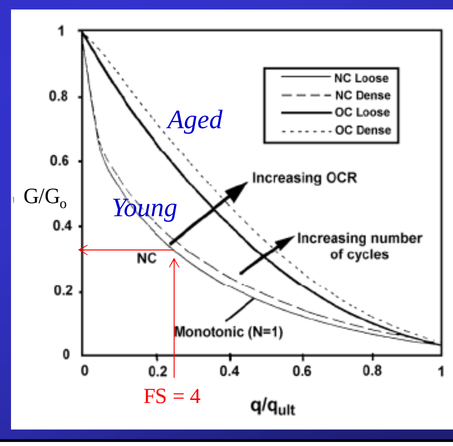


Mobilized stiffness for design

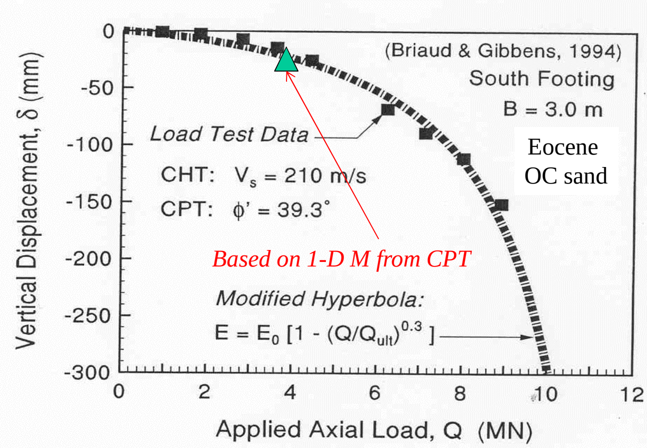
Mobilized modulus for footing design

$$E' = 2.4\, G_o\, [1 - (q/q_{ult})^{0.3}]$$

Modulus can be varied as a function of degree of loading to produce full load-settlement curve



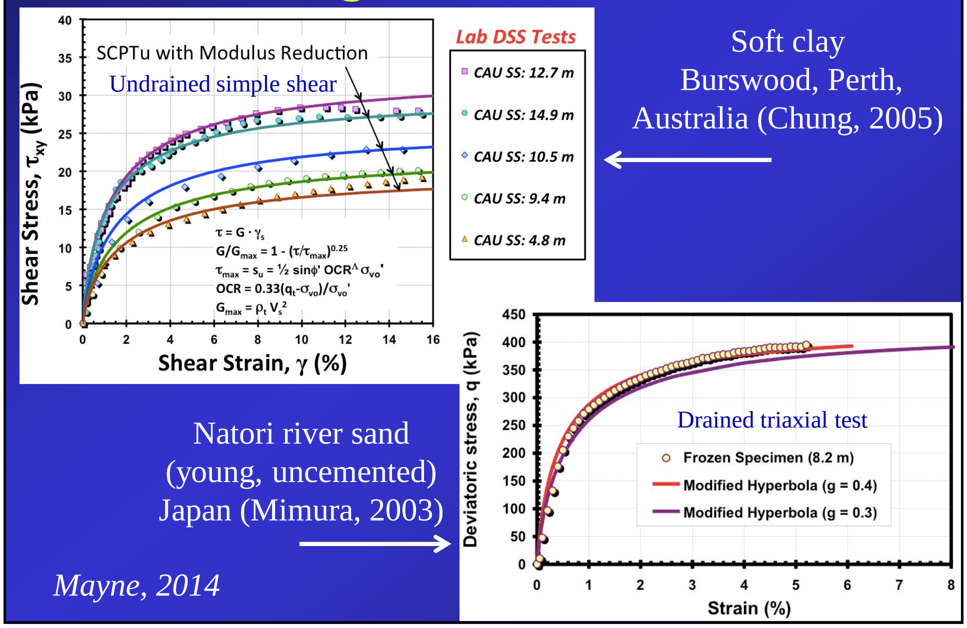
Texas A & M Footing - sand



Nonlinear Footing Settlement: $\delta = \dfrac{Q \cdot I_{hrv}}{B \cdot E_0 [1 - (Q/Q_u)^{0.3}]}$

After Mayne, 2000

Estimating stress-strain curves



Mayne, 2014

Estimating soil parameters

Summary by Mayne (2014) – www.cpt14.com

•Independent estimate based on V_s:

Young, uncemented soils

–Soil unit weight,

□ γ_t (KN/m^3) = 8.32 log (V_s) 1.61z V_s(m/s) & z (m)

–Peak friction angle (sands)

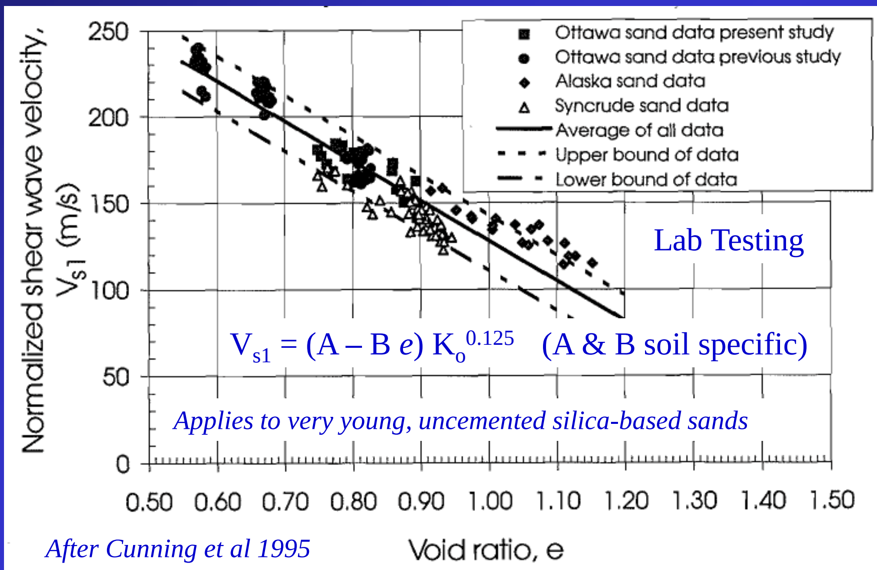
□ $\phi' = 3.9 (V_{s1})^{0.44}$ $V_{s1} = V_s (\sigma'_{vo}/p_a)^{0.25}$ m/s

–Undrained shear strength, s_u (clays)

- s_u (kPa) = $(V_s/7.93)^{1.59}$ V_s (m/s)

Careful with units - not commonly used

Estimating void ratio (e) from V_s



$V_{s1} = (A - B\,e)\,K_o^{0.125}$ (A & B soil specific)

Applies to very young, uncemented silica-based sands

After Cunning et al 1995

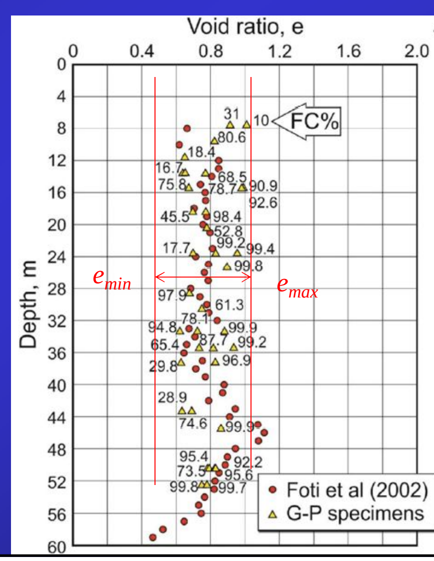
Estimating porosity (n) from V_s & V_p

$$n = \frac{\rho_s - \left[\rho_s^2 - \dfrac{4(\rho_s - \rho_f)B_f}{V_p^2 - 2\left(\dfrac{1-\nu_s}{1-2\nu_s}\right)V_s^2}\right]}{2(\rho_s - \rho_f)}$$

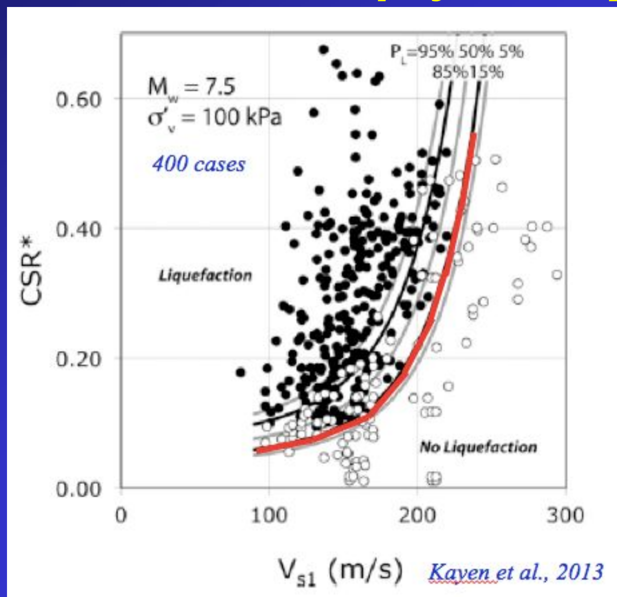
ρ_s = soil particles mass density
ρ_f = pore fluid mass density
B_f = bulk modulus of pore fluid
ν_s = Poisson ratio of soil skeleton

Very sensitive to accuracy of V_s & V_p

After Jamiolkowski (2014) & Foti et al (2002)



Evaluation of cyclic liquefaction



Cyclic Liquefaction:

100 < V_{s1} < 230 m/s

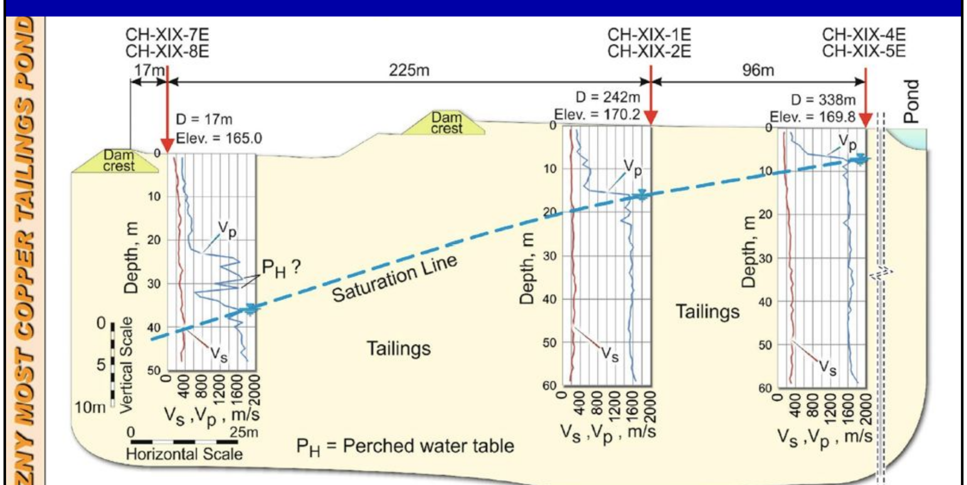
No liquefaction:

V_{s1} > 250 m/s

Young, uncemented soils

No effect of 'fines'

Estimating saturation from V_p measurements



Zelazny-Most Copper tailings pond – After Jamiolkowski, 2014 (CPT14)

G-266 LVE-11

Non-textbook – 'unusual' soil

- Most existing published experience/research based on typical "*ideal*" ground
  - *Young, uncemented: soft clay and clean silica sand*
- Limited published experience/research on non-textbook "*unusual*" ground
  - stiff fissured clays, soft rock, intermediate soils (silts), calcareous soils, man-made ground, tailings, older and/or cemented soils
- *Microstructure* often used to describe soils with '*unusual*' characteristics

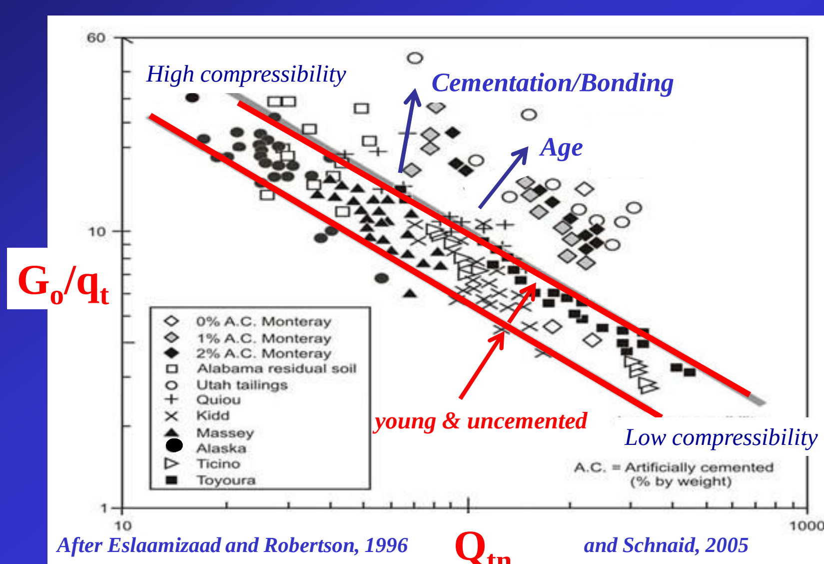
Identification of 'unusual' soils

- CPT penetration resistance, q_t – *mostly large strain response* – mostly controlled by peak strength
- Shear wave velocity, V_s – *small strain response* – controlled by small strain stiffness
- Potential to identify '*unusual*' soils from SCPT by measuring both small and large strain response

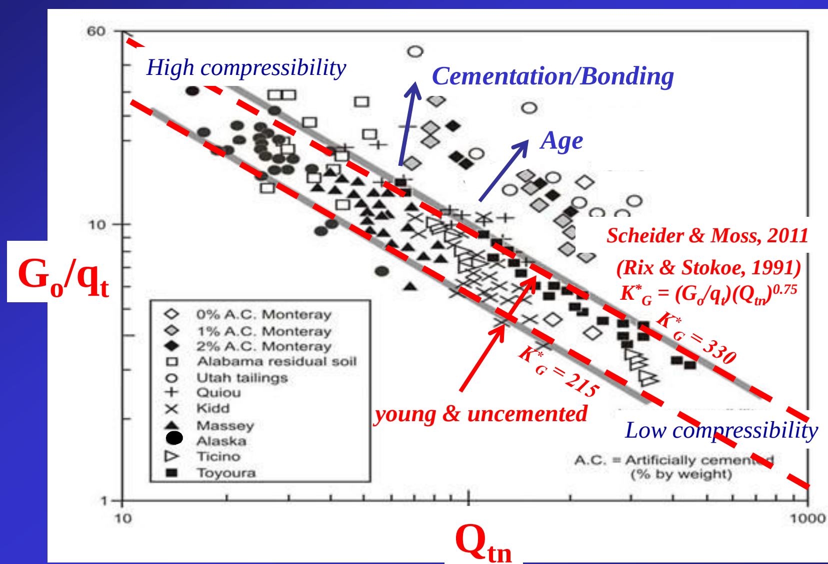
V_s and CPT

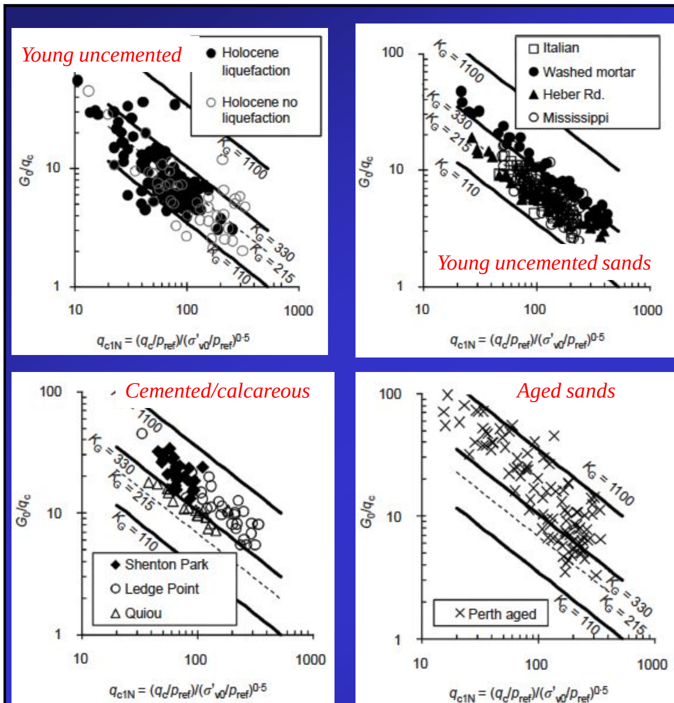
- V_s controlled mainly by: state (relative density & OCR), effective stresses, age and cementation
- CPT tip resistance, q_t, controlled mainly by: state (relative density & OCR), effective stresses, and to lesser degree by age and cementation
- Strong relationship between q_t and V_s, but depends mainly on *age and cementation* (i.e. microstructure)

Estimating age and/or cementation



Estimating age and/or cementation





SCPT data in sands

$K^*_G = (G_o/q_t)(Q_{tn})^{0.75}$

Scheider & Moss, 2011

Estimating age and/or cementation

Schneider & Moss, 2011

$$K^*_G = (G_o/q_t)(Q_{tn})^{0.7}$$

–If $K^*_G > 330$ potentially aged and/or cemented

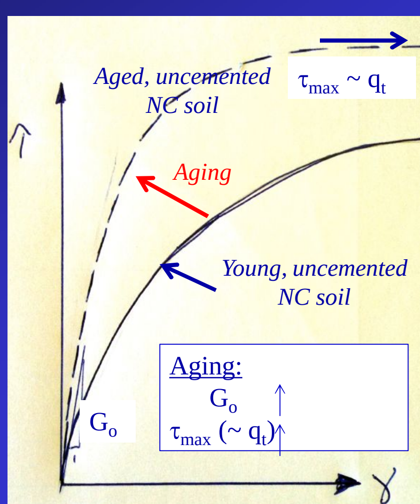
–If $K^*_G < 200$ potentially very young & uncemented

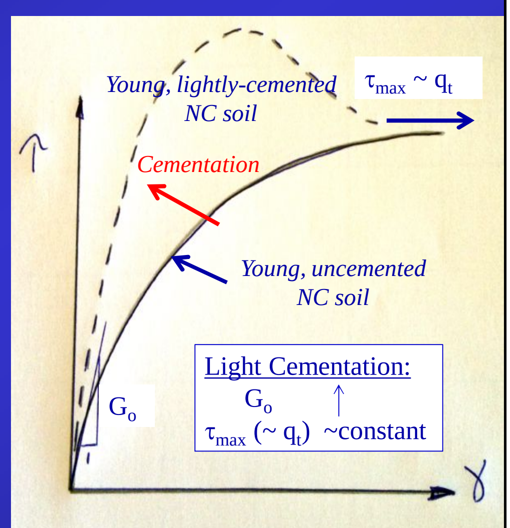
Difference between 'geologic-age' and 'behaviour-age'

–e.g. past soil liquefaction events can re-set age clock?

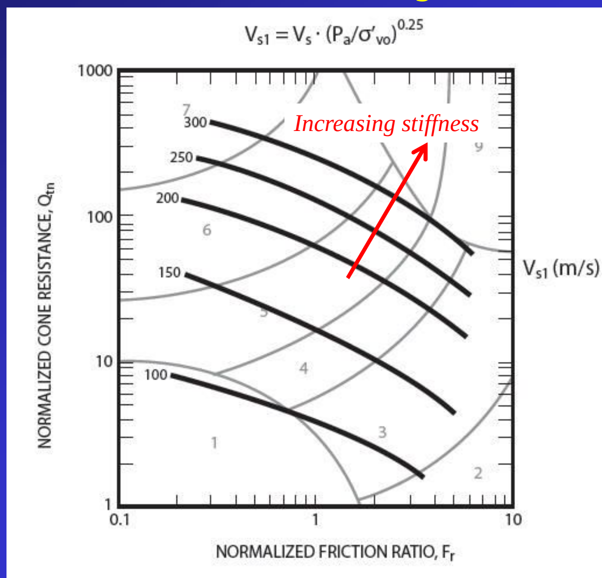
(also - Andrus et al, 2007)

Generalized influence of 'age' & 'cementation' on soil behaviour





Estimated V_s based on CPT



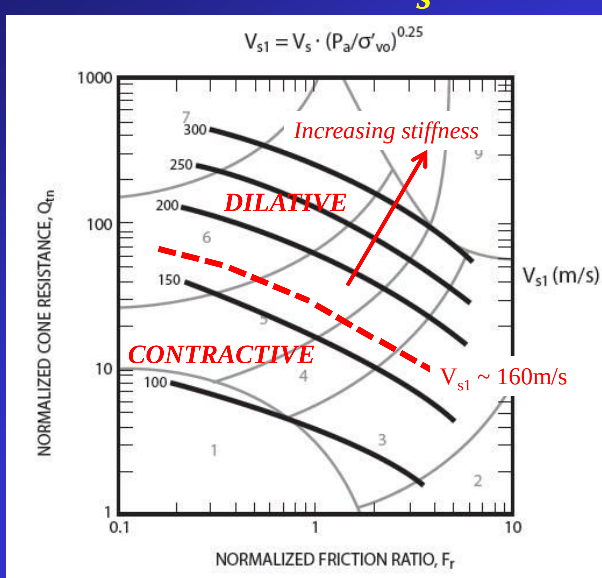
Soils with same V_{s1} have similar (small strain) behavior

Young (Holocene to Pleistocene-age) uncemented soils

Based on large SCPT database (>1,000 data points)

Robertson, 2009

Estimated V_s based on CPT



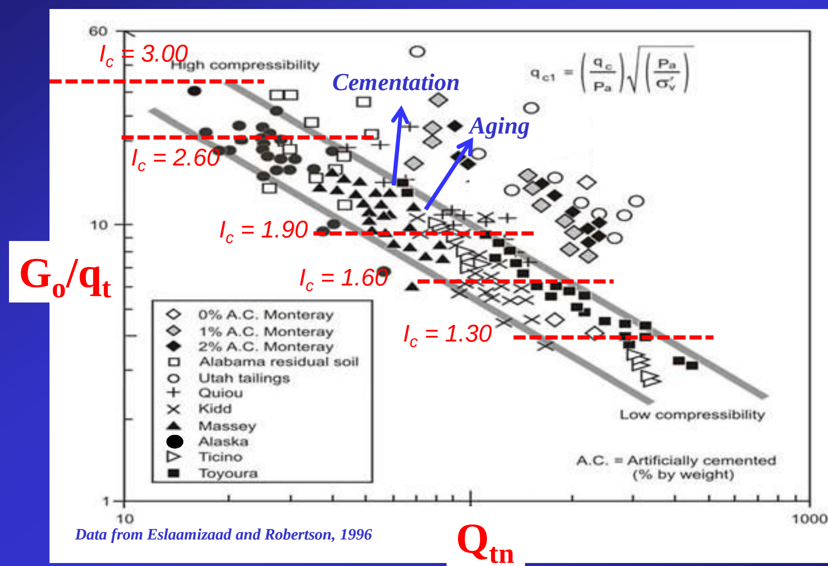
Soils with same V_{s1} have similar (small strain) behavior

Young (Holocene to Pleistocene-age) uncemented soils

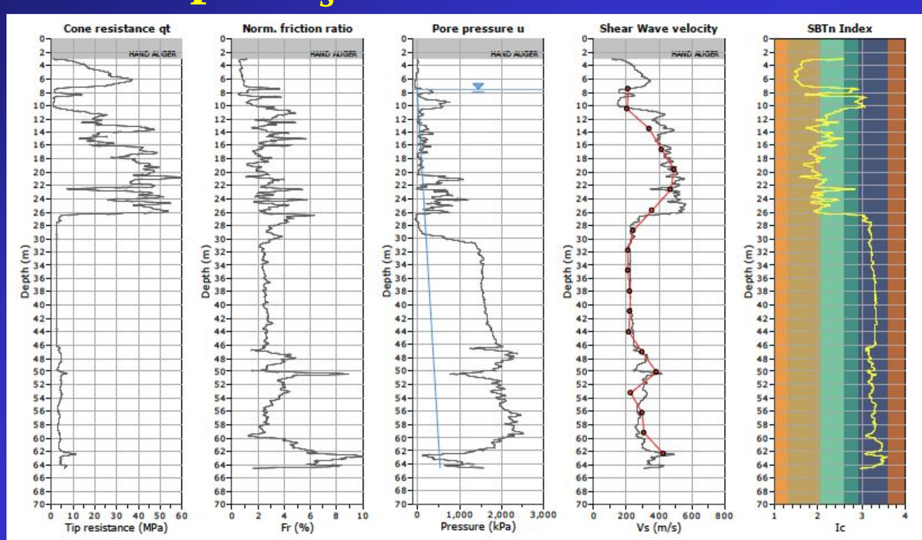
Based on case histories of flow liquefaction & lab results

Robertson, 2010

Estimating age and/or cementation

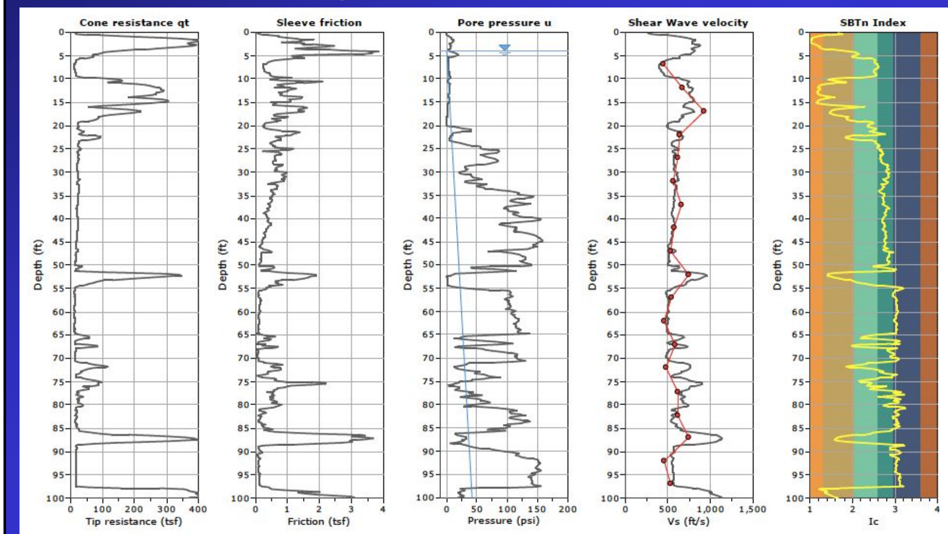


Example V_s measured vs estimated



Example - young, uncemented soils – downtown San Francisco

Example V_s measured vs estimated



Example – Nevada, USA

Summary

- SCPT is a very powerful in-situ test
  - Cost effective way to add V_s (V_p) to CPT
  - Up to 7 measurements in 1 test (q_t, f_s, u, V_s, t_{50}, u_o, i)
- V_s is a direct measure of soil stiffness
- Helpful for:
  - Settlement calculations & stress-strain relationship
  - Liquefaction evaluation
  - Identification of ‘unsual’ soil (age & cementation)
  - Saturation using V_p

Summary

Should all CPT's at a site be SCPTu?

- Common to make ~20 to 30% of CPT's using SCPT
- Identify site specific relationship between q_t and V_s
- Identify if soils are either *'well-bahaved'* or *'unusual'*
  - e,g, will traditional correlations (based on 'well-behaved' soils) apply?

Continued growth in use and application of SCPTu

Questions?