2nd Int. Conf. Deep Foundations, Field Testing & Construction

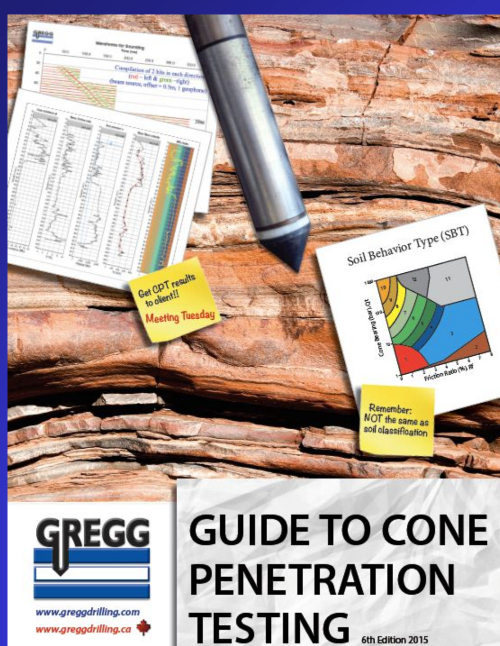
GREGG

Seismic CPT (SCPT)

Peter K. Robertson

Santa Cruz, Bolvia

May.2015



Robertson
& Cabal (Robertson)

CPT Guide

6th Edition
2015

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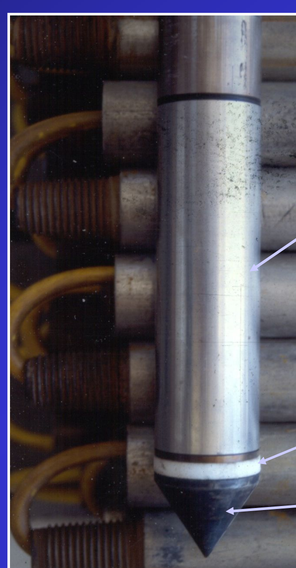
Robertson, 2015

History of CPT

- First developed in 1930's as mechanical cone
- Electric cones developed in 1960's
- Primary device for off-shore investigations since 1970's
- Major advancements since 1970:
  - Pore pressure measurements *(CPTu)*
  - More reliable load cells & electronics
  - Addition of seismic for shear wave velocity *(SCPTu)*
  - Additional sensors for environmental applications
  - Significant increase in documented case histories

Basic Cone Parameters



Sleeve Friction
$f_s = {}^{load}/_{2\pi rh}$

Pore Pressure, u_2

Tip Resistance
$q_c = {}^{load}/_{\pi r^2}$

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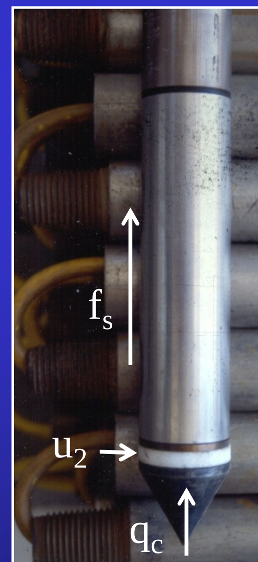
Cone Penetration Test (CPT)

ADVANTAGES:

- Fast and continuous profiling
- Repeatable and reliable data
- Economical and productive
- Strong theoretical basis for interpretation
- More than one measurement (q_c, f_s, u)
- Additional sensors (e.g. seismic V_s & V_p)

LIMITATIONS:

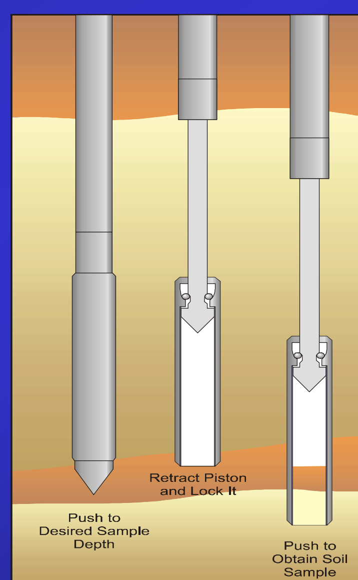
- Somewhat high capital investment
- Somewhat skilled operators
- No soil sample (during CPT)
- Penetration restricted in gravels/cemented layers (same as SPT)



Example CPT Soil Sampling

CPT (Piston-Type) Sampler

- Single-Tube System
- 30cm (12") long by 25mm (1 ") diameter



Example CPT pushing equipment

CPTu Interpretation

Soil Type

– Soil behavior type (*SBT*)

In-situ State

– Relative density (D_r) or State Parameter (ψ) and *OCR*

Strength

– Peak friction angle (ϕ') and undrained strength (s_u)

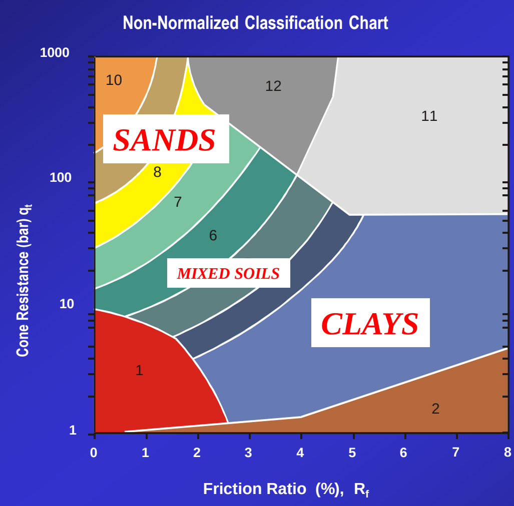
Stiffness/compressibility

– Shear (G_o), Young's (E') and 1-D constrained (M)

Consolidation/permeability

– Coeff of consolidation (c_v) and permeability (k)

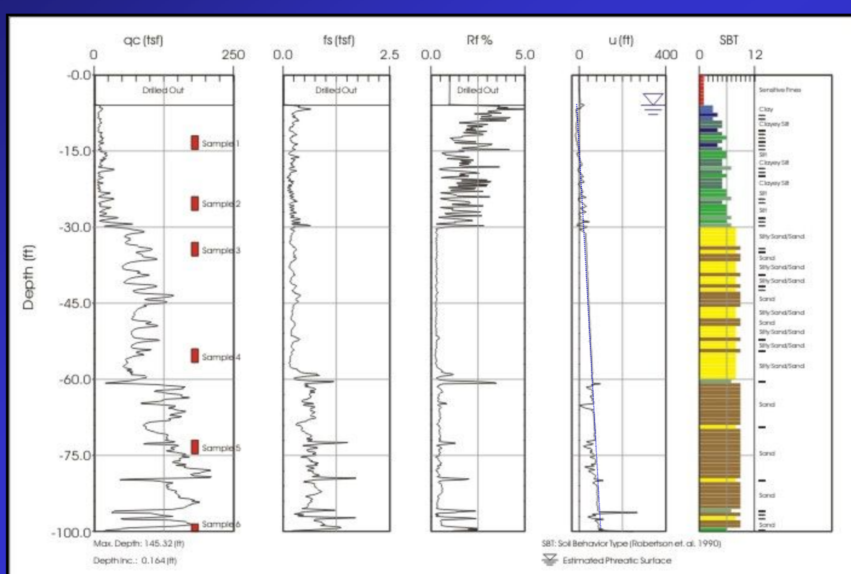
CPT - Soil Behavior Type (SBT)



CPT SBT based on *in-situ soil behavior characteristics (i.e. strength, stiffness & compressibility)* - not the same as traditional classification based on *physical characteristics (i.e. Atterberg Limits and grain size distribution)* carried out on disturbed samples

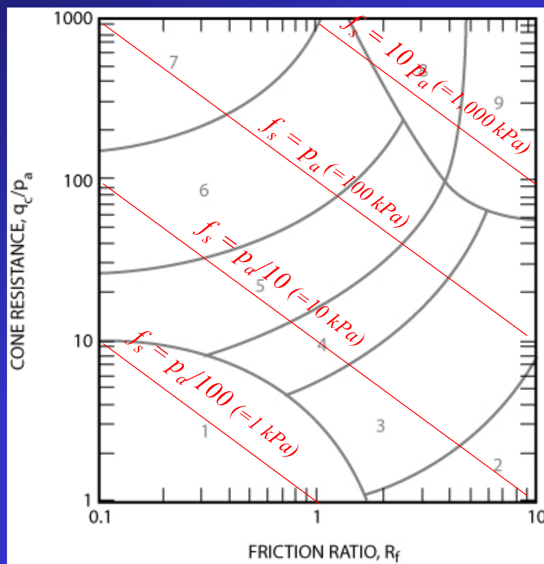
After Robertson & Campanella, 1986

Example CPT Data Presentation



Example CPTu Plot

Dimensionless SBT chart

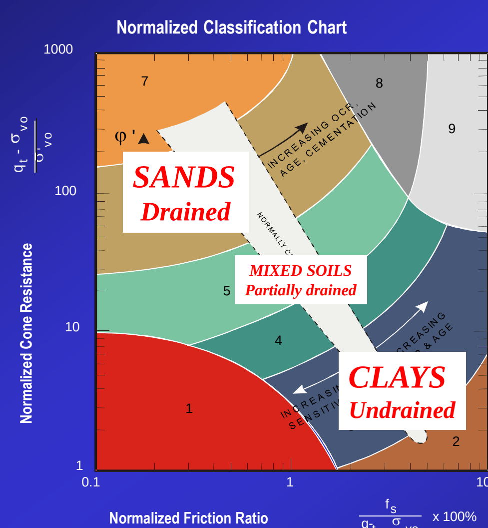


In 2010 Robertson (CPT'10) updated the SBT chart to use dimensionless parameters and to simplify the chart to 9 zones to be consistent with the normalized SBT chart (Robertson, 1990)

p_a = atmospheric pressure = 100 kPa = 1 tsf

Robertson, 2015

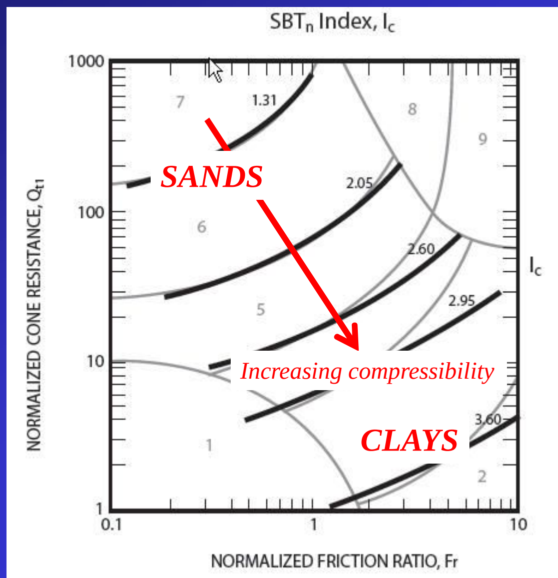
CPT- Normalized SBT Chart



Zone	Normalized Soil Behavior Type
1	sensitive fine grained
2	organic material
3	clay to silty clay
4	clayey silt to silty clay
5	silty sand to sandy silt
6	clean sands to silty sands
7	gravelly sand to sand
8	very stiff sand to clayey sand
9	very stiff fine grained

After Robertson, 1990

CPT SBT Index, I_c



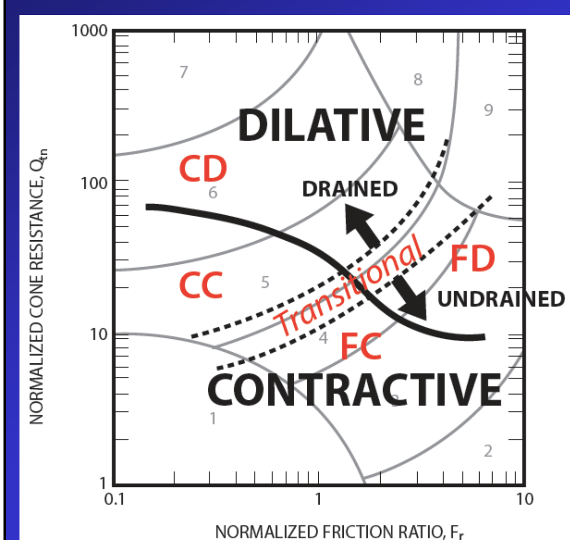
Soil Behavior Type Index, I_c

$Ic = [(3.47 – \log Q)^2 + (\log F+1.22)^2]^{0.5}$

Function primarily of Soil Compressibility

Compressibility linked to soil plasticity & amount/type of fines

Generalized CPT Soil Behaviour Type

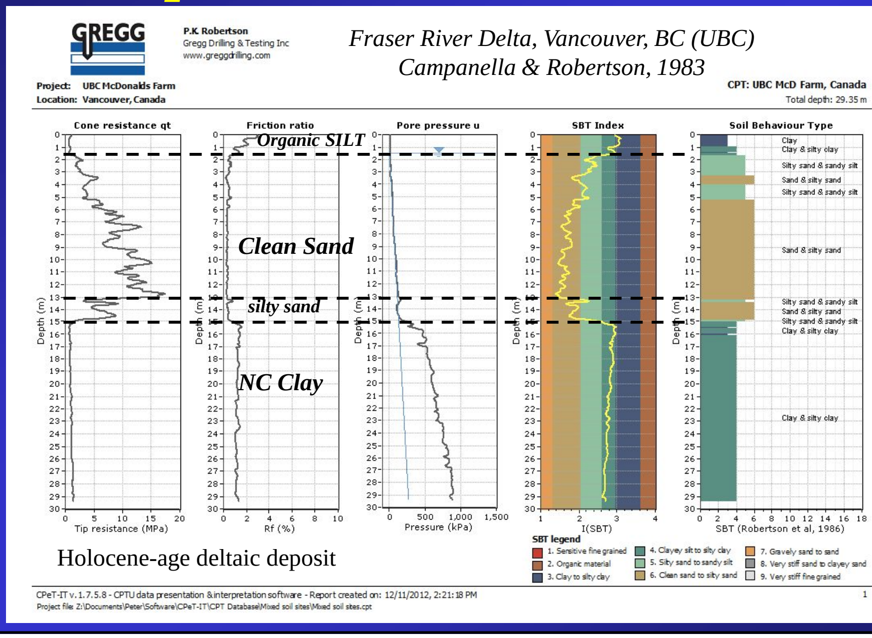


CPT Soil Behaviour

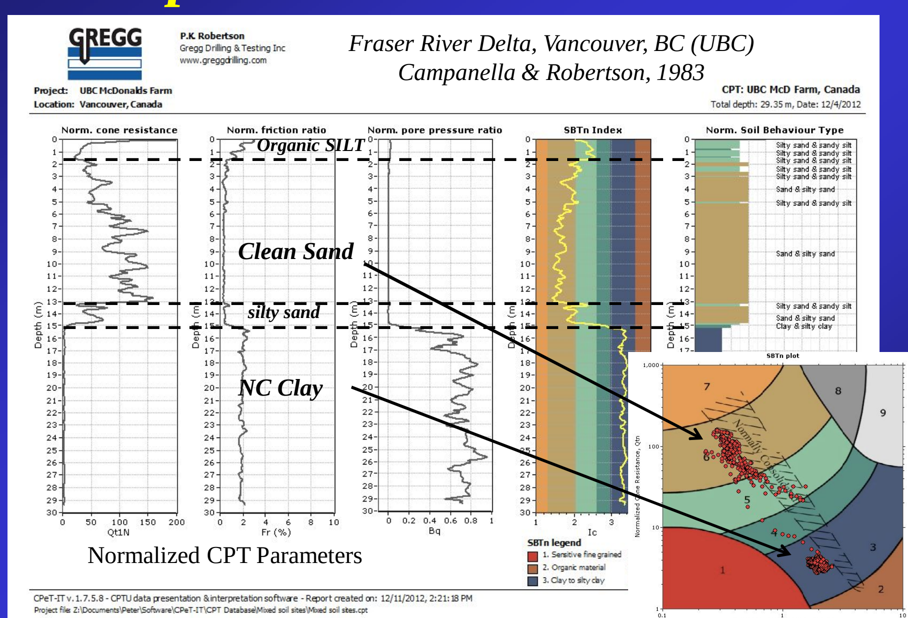
CD: Coarse-grain-Dilative (mostly drained)
CC: Coarse-grain-Contractive (mostly drained)
FD: Fine-grain-Dilative (mostly undrained)
FC: Fine-grain-Contractive (mostly undrained)

Modified from Robertson, 2012

Example CPT - UBC Fraser River

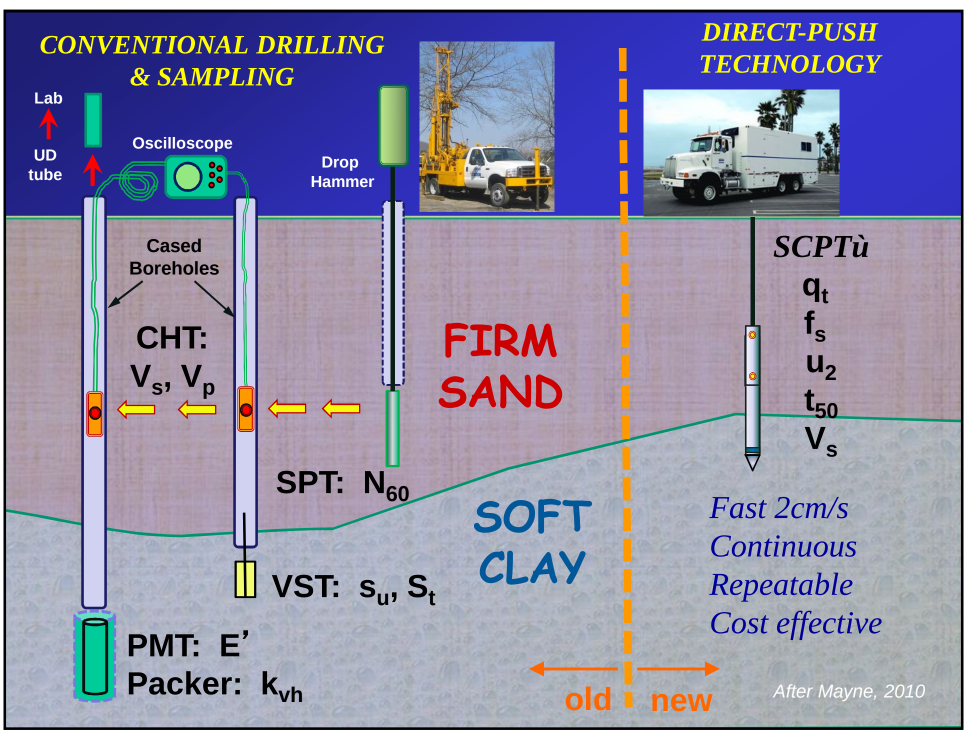


Example CPT - UBC Fraser River

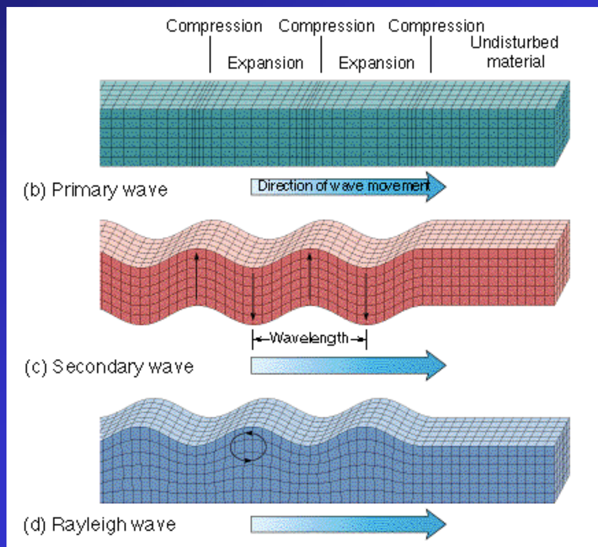


Seismic CPT

- >30 years experience (1983)
- Simple, reliable, and inexpensive
- Direct measure of soil stiffness
  - Small strain value, $G_o = \rho \cdot V_s^2$
- Typically 1 meter intervals
- Combines q_c and V_s profile in same soil



Main seismic waves



P-waves (compression)

S-waves (shear)

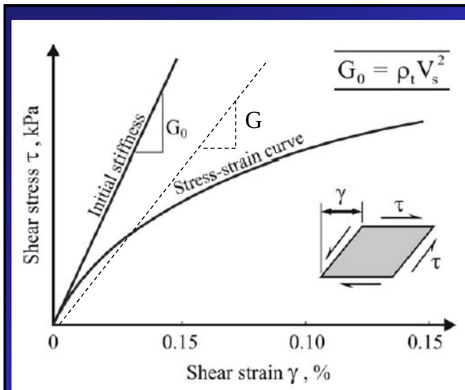
Rayleigh surface-waves (mostly shear)

Why are seismic velocities helpful?

Wave type	Propagation mode	Shape change	Wave velocity	Small-strain modulus
P		Compression	V_P (V) V_P (H)	$M_0 = \rho_t V_P^2$ M_0(V) M_0(H)
S		Distorsion	V_S (VH) V_S (HH)	$G_0 = \rho_t V_S^2$ G_0(VH) G_0(HH)

Wave propagation
Particle motion

After Jamiolkowski, 2012

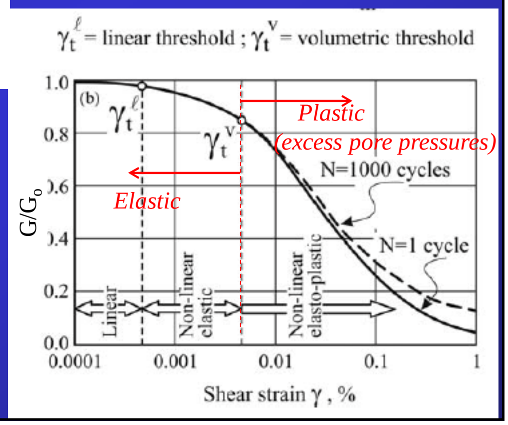


V_s is direct measure of small strain shear modulus, G_o (or G_{max})

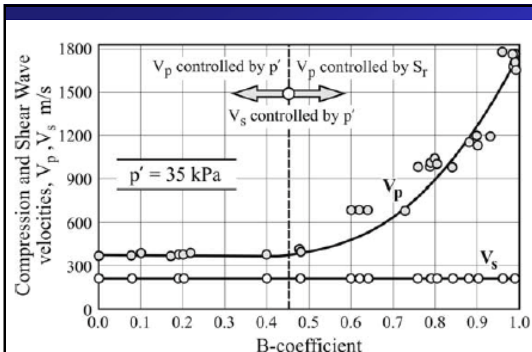
$G_o = \rho_t (V_s)^2$

$\rho_t = \gamma/g$

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

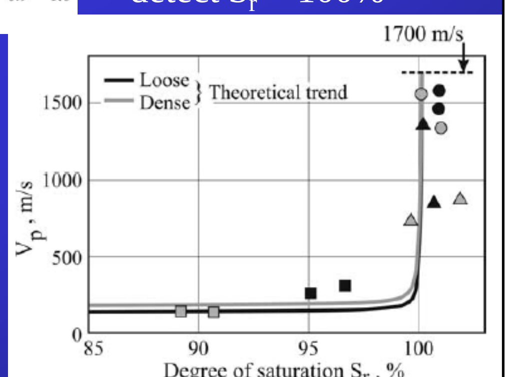


After Jamiolkowski, 2012



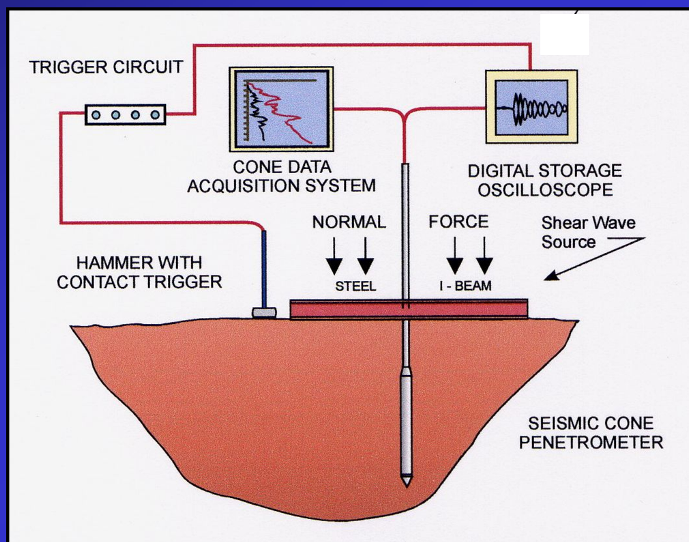
- V_p contolled by degree of saturation in most soils
- V_p ~ 1500 m/s (5000ft/s) in saturated soil
- V_p can be used to detect S_r < 100%

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



After Jamiolkowski, 2012

Basic Seismic CPT Configuration



Seismic CPT using a Drill-rig

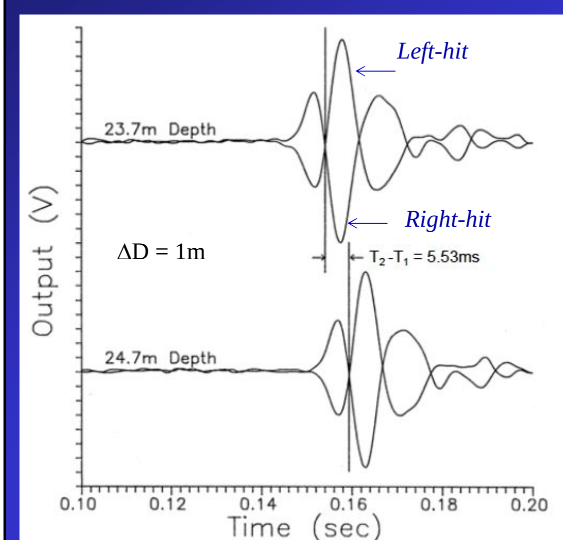
1990 U of Alberta

Modern CPT Trucks

Trucks with build-in seismic beam

Seismic beam

Polarized shear wave traces

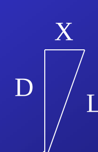


After Butcher et al 2005 (ISSMGE TC 10)

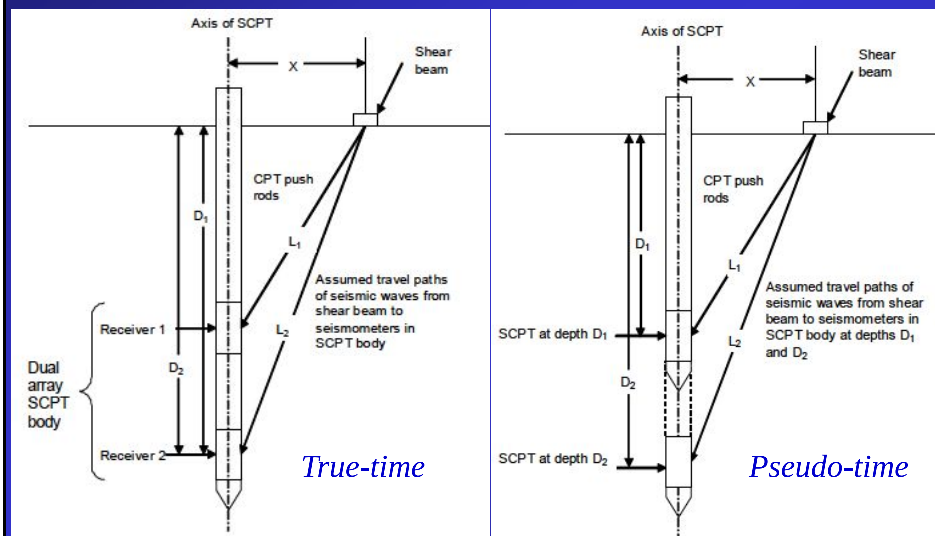
$$V_s = \frac{(L_2 - L_1)}{(T_2 - T_1)}$$

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

$(T_2 - T_1)$ = time difference

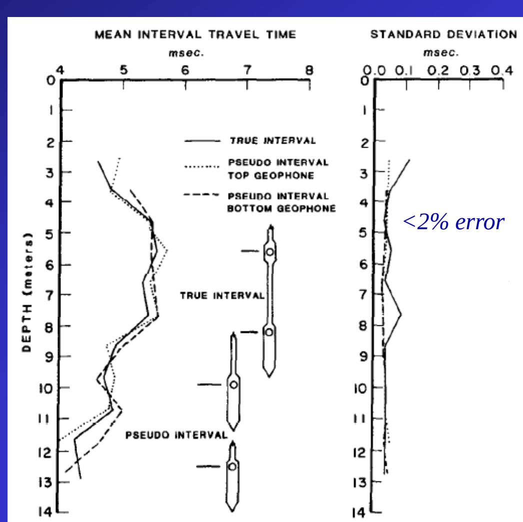


True & Pseudo-time interval



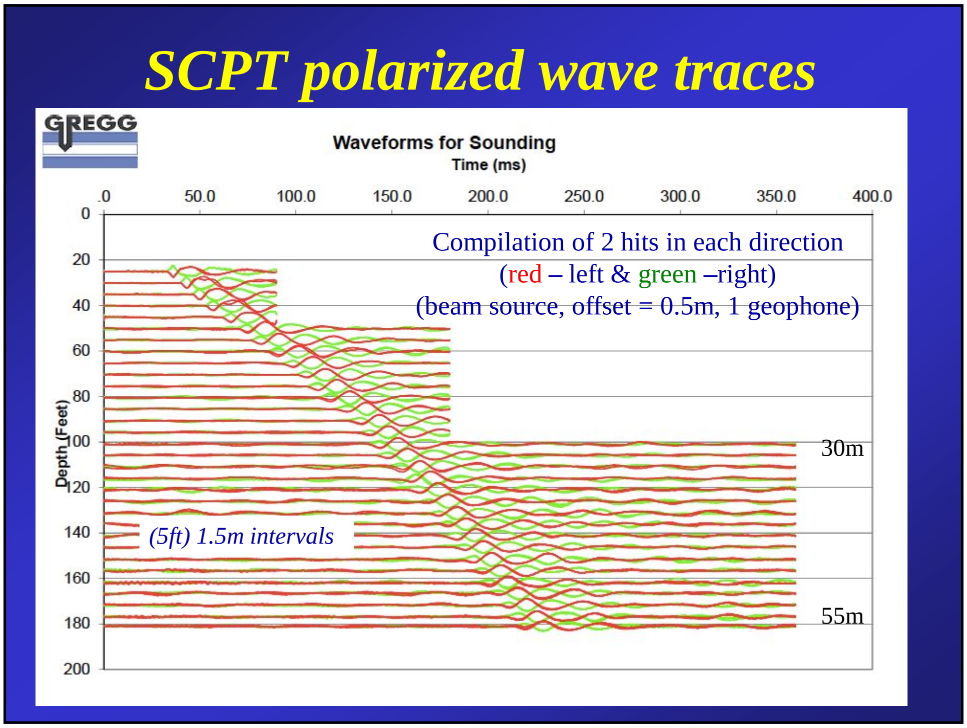
After Butcher et al 2005 (ISSMGE TC 10)

True & Pseudo-time interval

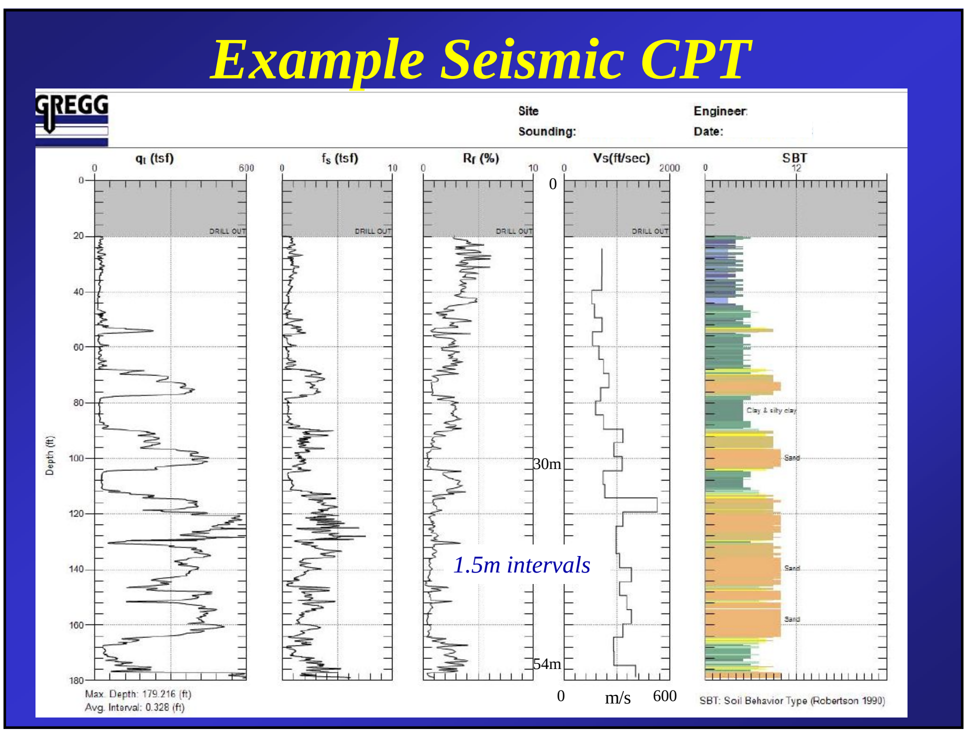


- In general, little difference between true- and pseudo-time interval methods
- Pseudo-time interval requires only 1 seismic sensor
- True-time allows real-time automatic velocity calculation

After Robertson et al, 1986

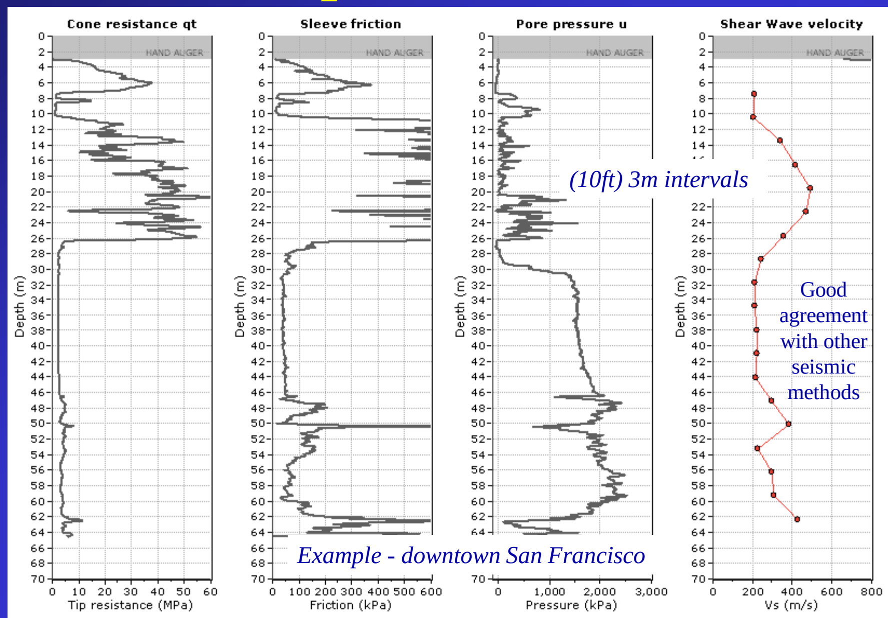


SCPT polarized wave traces
GREGG
Waveforms for Sounding
Time (ms)
.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
Depth (Feet)
0
20
40
60
80
100
120
140
160
180
200
Compilation of 2 hits in each direction
(red – left & green –right)
(beam source, offset = 0.5m, 1 geophone)
30m
(5ft) 1.5m intervals
55m



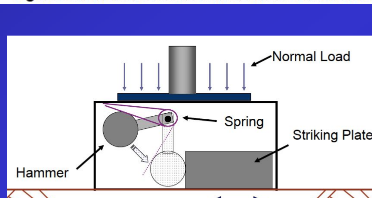
Example Seismic CPT
GREGG
Site
Sounding:
Engineer:
Date:
qt (tsf)
fs (tsf)
Rf (%)
Vs(ft/sec)
SBT
DRILL OUT
Depth (ft)
0
30m
54m
0
m/s
600
1.5m intervals
Clay & silty clay
Sand
Max. Depth: 179.216 (ft)
Avg. Interval: 0.328 (ft)
SBT: Soil Behavior Type (Robertson 1990)

Example Seismic CPT



Automatic seismic source

Figure 1. AutoSeis shear wave seismic source.



Simple repeatable source

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

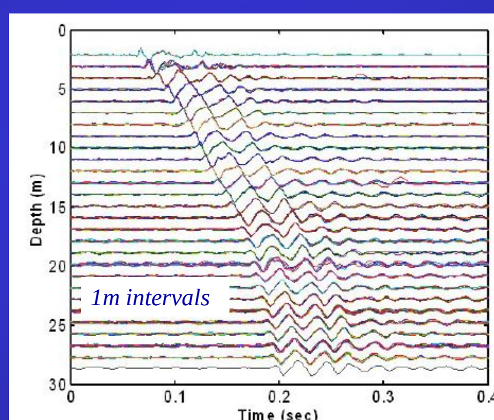
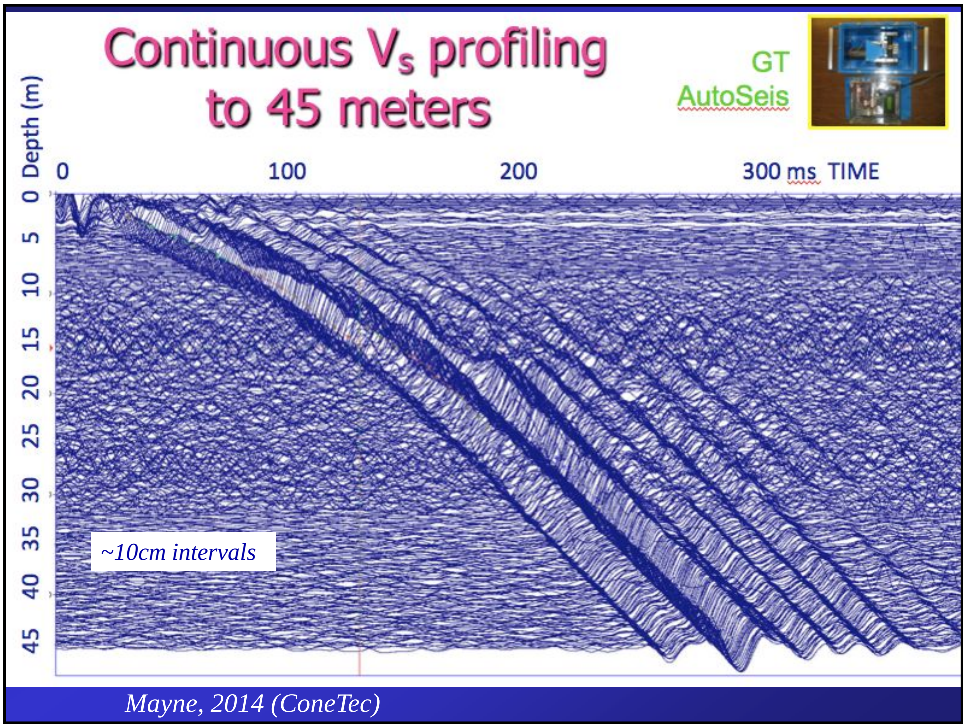
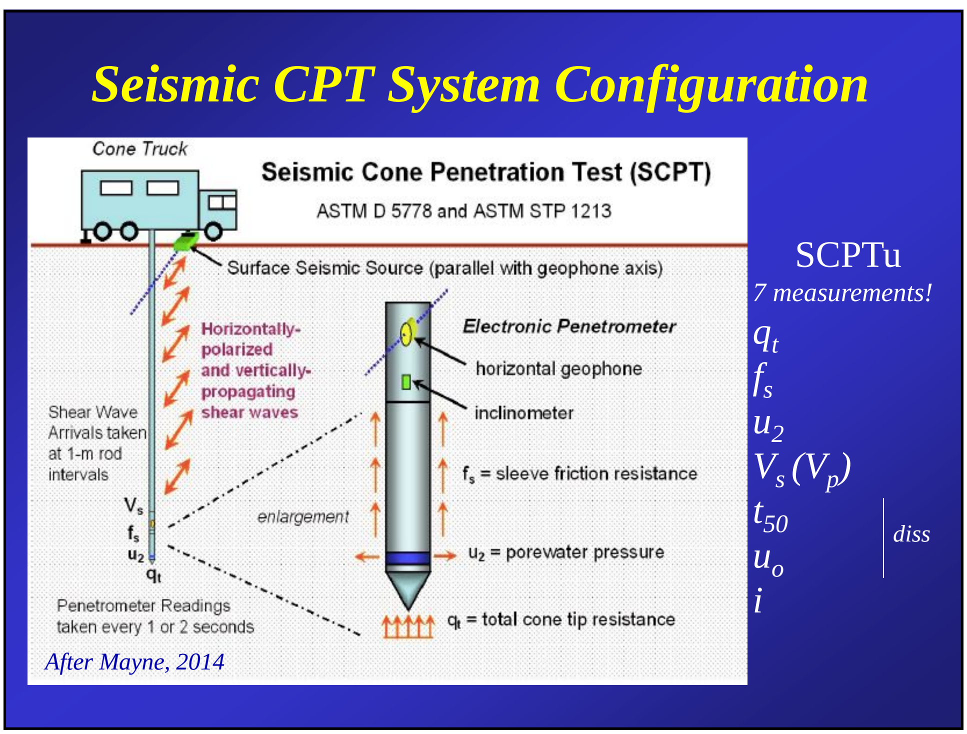


Figure 2. AutoSeis traces. *Single hammer*


Continuous V_s profiling to 45 meters
GT AutoSeis
Depth (m)
0 5 10 15 20 25 30 35 40 45
0 100 200 300 ms TIME
~10cm intervals
Mayne, 2014 (ConeTec)


Seismic CPT System Configuration
Cone Truck
Seismic Cone Penetration Test (SCPT)
ASTM D 5778 and ASTM STP 1213
Surface Seismic Source (parallel with geophone axis)
Horizontally-polarized and vertically-propagating shear waves
Shear Wave Arrivals taken at 1-m rod intervals
V_s
f_s
u_2
q_t
enlargement
Electronic Penetrometer
horizontal geophone
inclinometer
f_s = sleeve friction resistance
u_2 = porewater pressure
q_t = total cone tip resistance
Penetrometer Readings taken every 1 or 2 seconds
After Mayne, 2014
SCPTu
7 measurements!
q_t
f_s
u_2
V_s (V_p)
t_{50}
u_o
i
diss

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

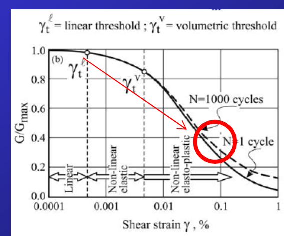
- Direct measure of soil stiffness
  - Settlement calculations
  - Input for numerical modeling (stress-strain)
- Estimation of soil parameters based on V_s
- Evaluation of soil liquefaction based on V_s
- Determination of saturation based on V_p
- Identification of '*unusual*' soils
  - i.e. soils with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

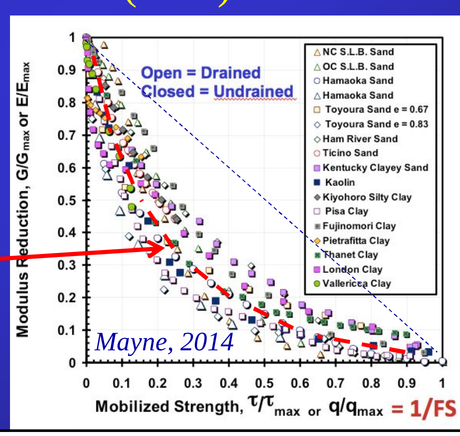
$$G/G_o = 1 - f\ (\tau/\tau_{max})^g = 1\text{-}f\ (1/FS)^g$$

where FS (factor of safety)

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

For uncemented, unstructured soils

f ~ 1.0 and g ~ 0.3

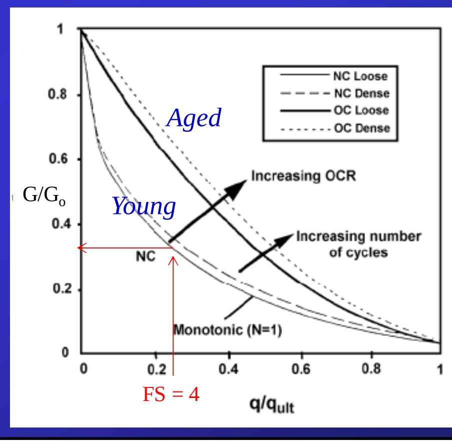


Mobilized stiffness for design

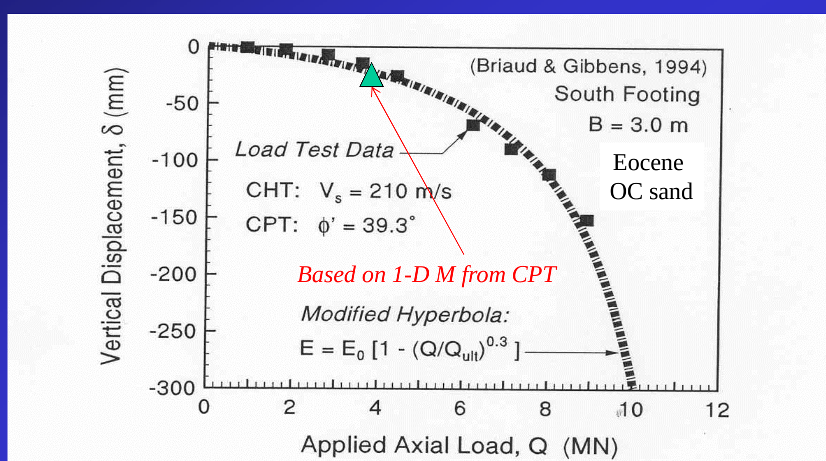
Mobilized modulus for footing design

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

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

Load-settlement – elastic solution

- Poulos and Davis, 1990 (see Mayne, 2000)
- Soil modulus either constant or linearly increasing with depth

Axial pile settlement, s (both shaft and base)

$$s = Q\, I_p / E_{sl}\, D_p$$

where: $E_{sl} = E_o\,(1 - Q/Q_{ult})^{0.3})$

and $E_o = 2.5\, G_o$ and $G_o = \rho\, V_s^2$

Case History - Drilled Shaft

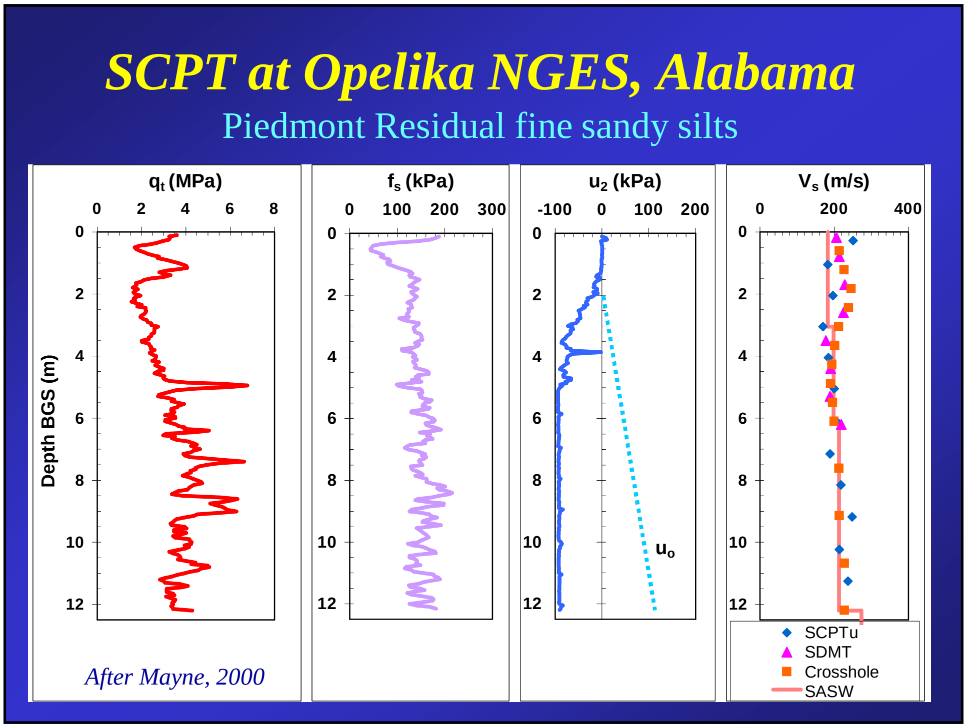
Opelika NGES, Alabama

(Brown, ASCE JGGE, Dec. 2002)

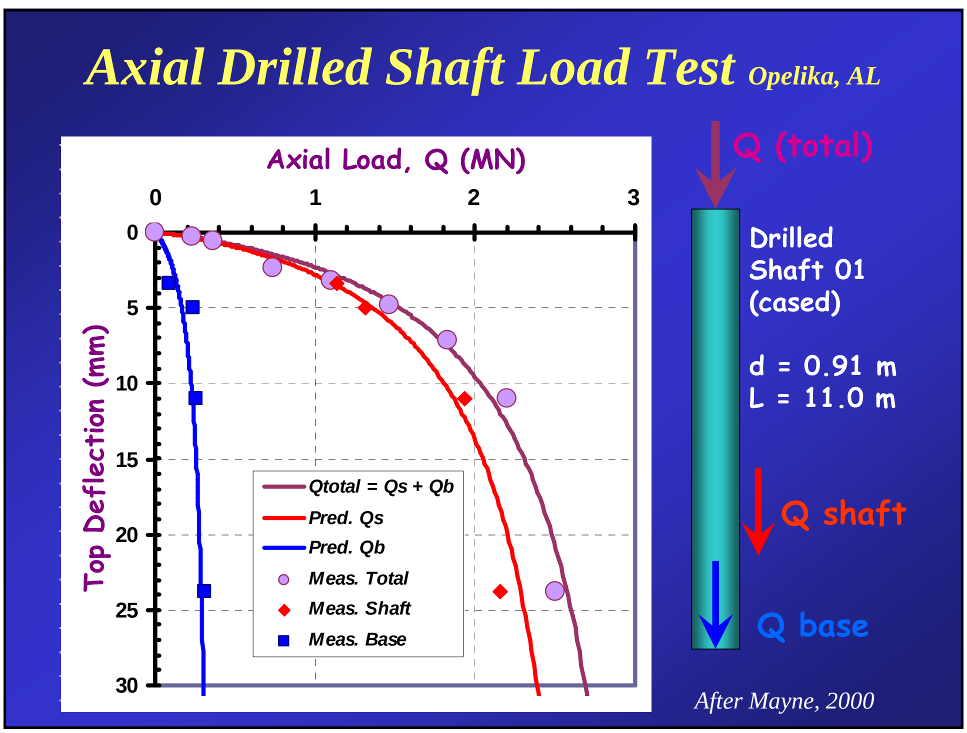
Eight Drilled Shafts:
d = 3 feet
L = 36 feet

Construction Methods
- ❑ Dry (Cased)
- ❑ Bentonite
- ❑ Dry Polymer Slurry
- ❑ Liquid Polymer Slurry

After Mayne, 2000

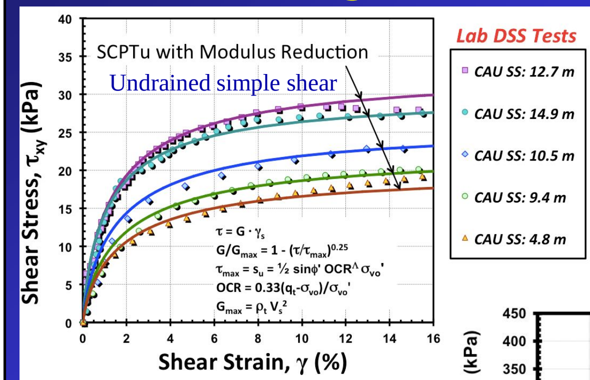


SCPT at Opelika NGES, Alabama
Piedmont Residual fine sandy silts
q_t (MPa)
f_s (kPa)
u_2 (kPa)
V_s (m/s)
Depth BGS (m)
u_o
SCPTu
SDMT
Crosshole
SASW
After Mayne, 2000



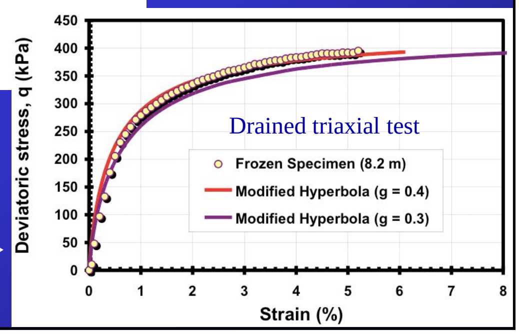
Axial Drilled Shaft Load Test Opelika, AL
Axial Load, Q (MN)
Top Deflection (mm)
Qtotal = Qs + Qb
Pred. Qs
Pred. Qb
Meas. Total
Meas. Shaft
Meas. Base
Q (total)
Drilled Shaft 01 (cased)
d = 0.91 m
L = 11.0 m
Q shaft
Q base
After Mayne, 2000

Estimating stress-strain curves



Soft clay
Burswood, Perth,
Australia (Chung, 2005)

Natori river sand
(young, uncemented)
Japan (Mimura, 2003)



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)

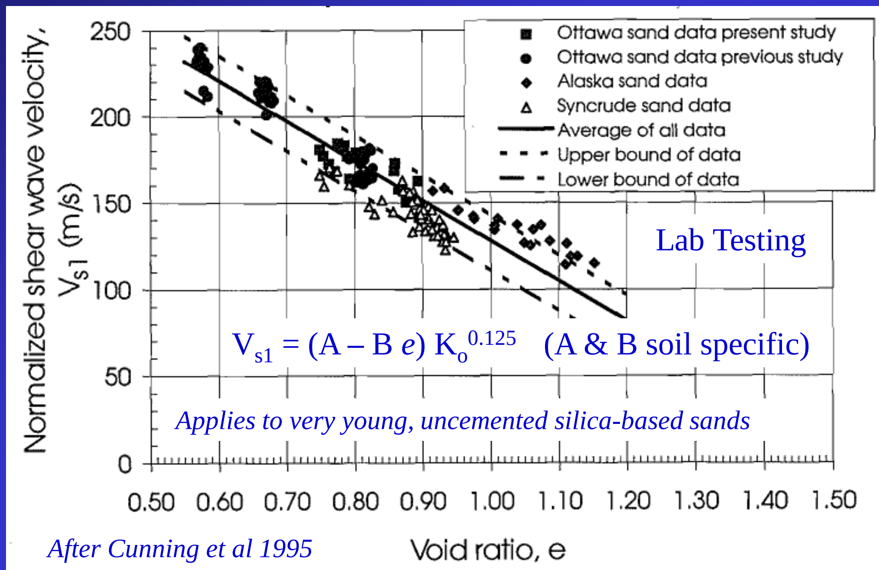
$\phi' = 3.9 (V_{s1})^{0.44}$ $V_{s1} = V_s (\sigma'_{vo}/p_a)^{0.25}$ m/s

–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

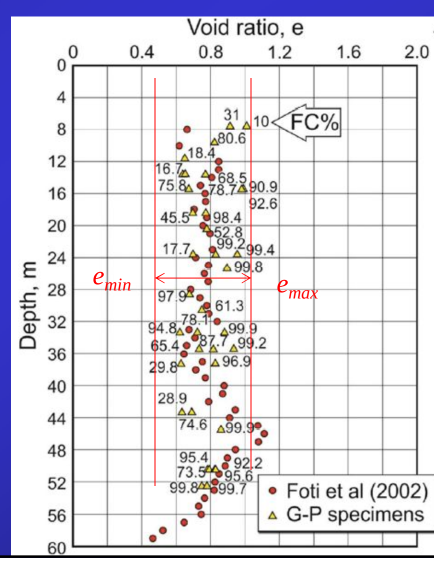
Estimating porosity (n) from V_s & V_p

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

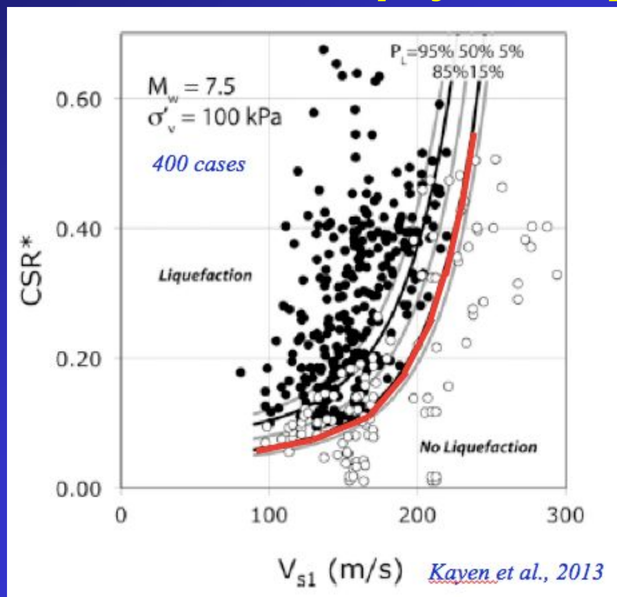
ρ_s = soil particles mass density
ρ_f = pore fluid mass density
B_f = bulk modulus of pore fluid
ν_s = Poisson ratio of soil skeleton

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:

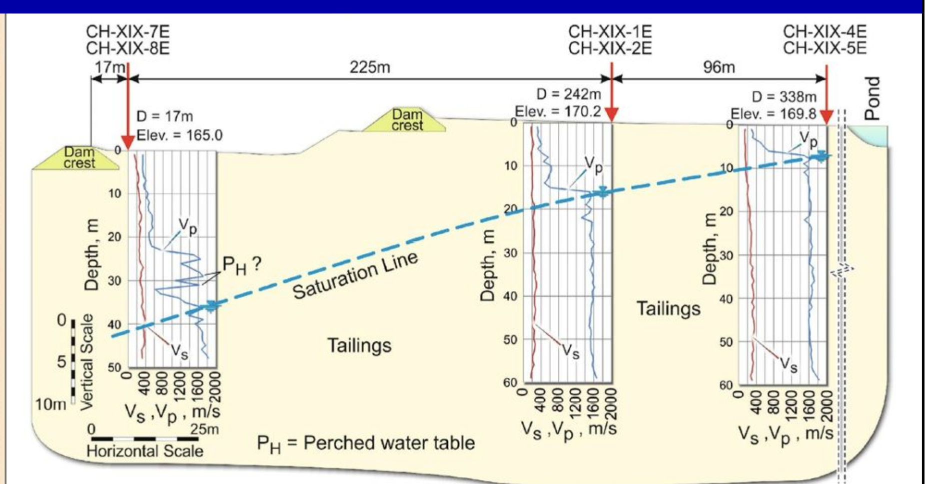
V_{s1} > 250 m/s

Young, uncemented soils

No effect of 'fines'

Estimating saturation from V_p measurements

ZELAZNY MOST COPPER TAILINGS POND



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

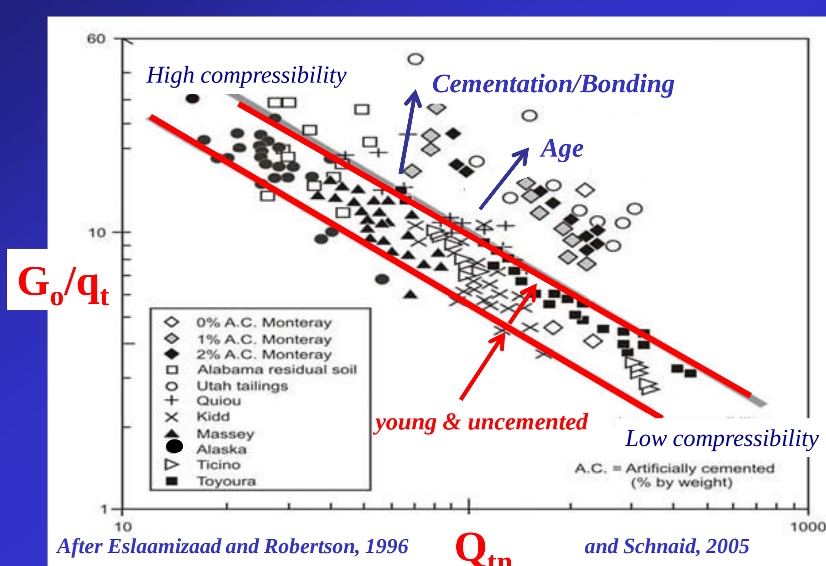
Identification of 'unusual' soils

- 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

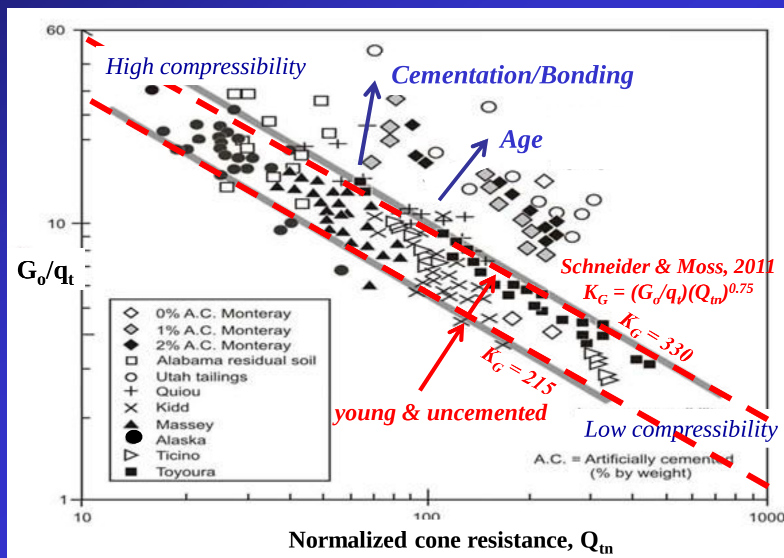
V_s and CPT

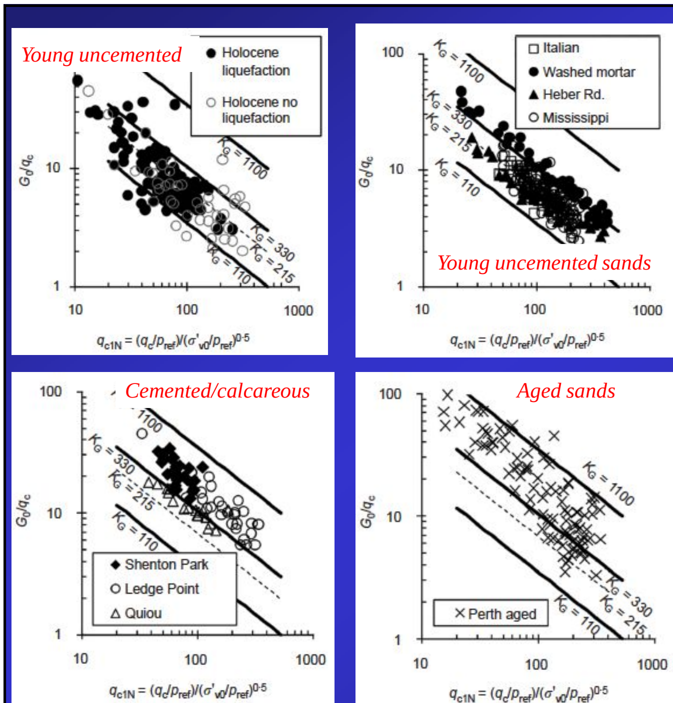
- V_s controlled mainly by: state (relative density & OCR), effective stresses, age and cementation
- CPT tip resistance, q_t, controlled mainly by: state (relative density & OCR), effective stresses, and to lesser degree by age and cementation
- Strong relationship between q_t and V_s, but depends mainly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

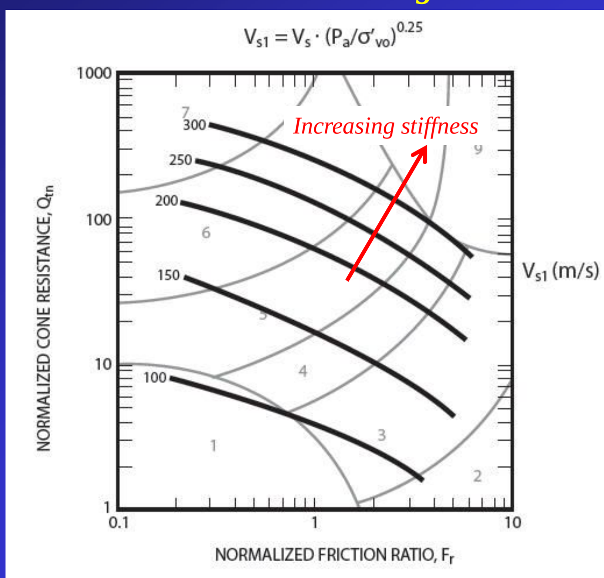
–If $K^*_G < 200$ potentially very young & uncemented

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

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

(also - Andrus et al, 2007)

Estimated V_s based on CPT



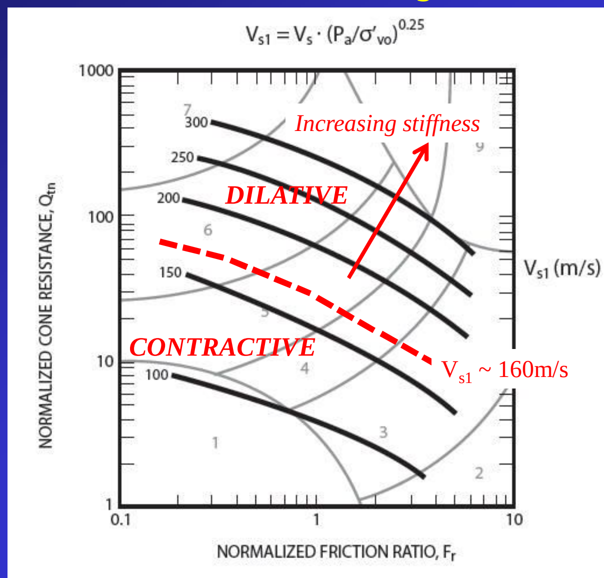
Soils with same V_{s1} have similar (small strain) behavior

Young (Holocene to Pleistocene-age) uncemented soils

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

Robertson, 2009

Estimated V_s based on CPT



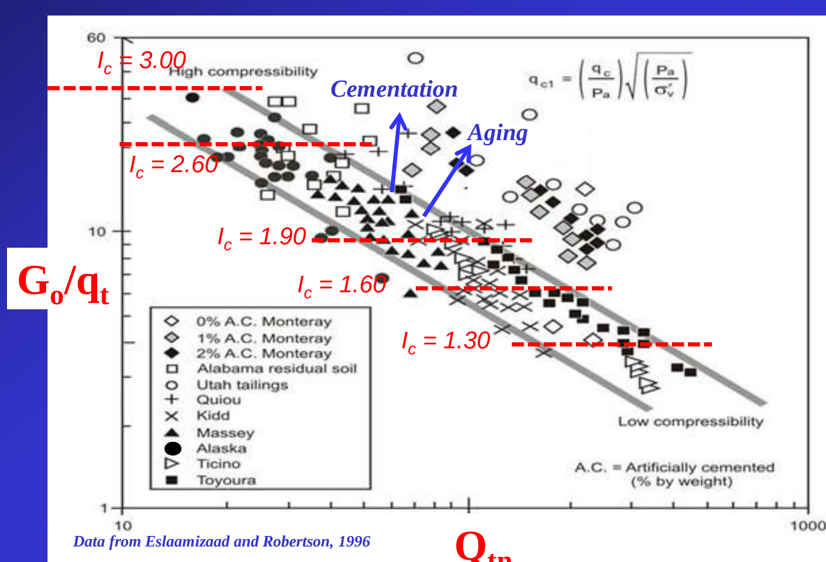
Soils with same V_{s1} have similar (small strain) behavior

Young (Holocene to Pleistocene-age) uncemented soils

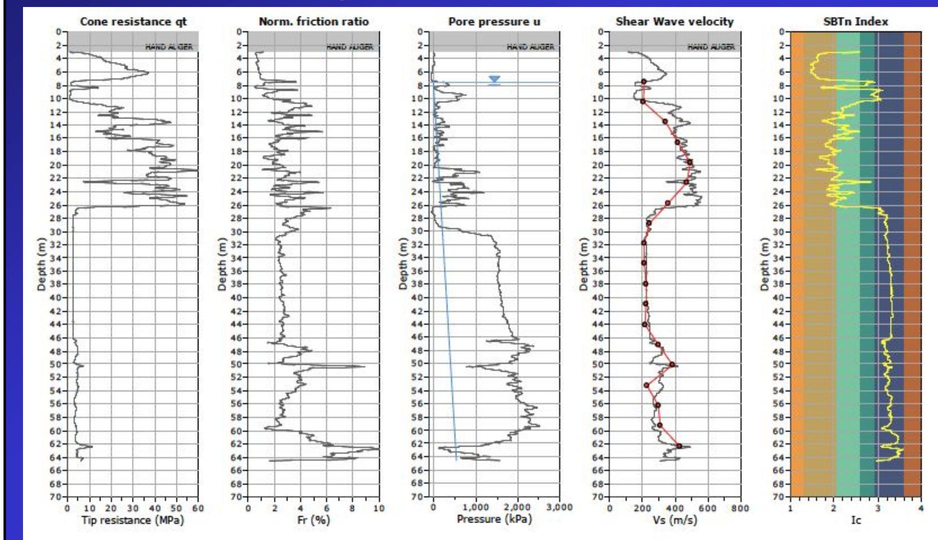
Based on case histories of flow liquefaction & lab results

Robertson, 2010

Estimating age and/or cementation

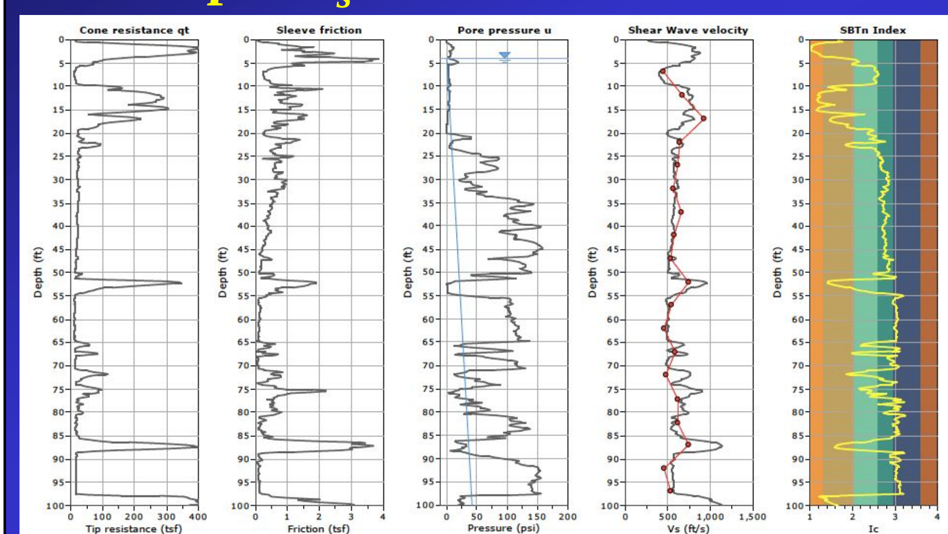


Example V_s measured vs estimated



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-behaved’* or *‘unusual’*
  - e,g, will traditional correlations (based on ‘well-behaved’ soils) apply?

Continued growth in use and application of SCPTu

Questions?