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TRANSPORTATION RESEARCH BOARD

One Pack to Rule Them All– The Cone Penetration Test Expansion Pack

June 29, 2021

@NASEMTRB
#TRBwebinar

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•1.5 Professional Development Hour (PDH) – see follow-up email for instructions
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REGISTERED CONTINUING EDUCATION PROGRAM

#TRBwebinar

Learning Objectives

1. Explain advantages of CPT for certain geologies and design applications
2. Discuss how to improve seismic testing with CPT
3. Recover additional field data and compare it with other in-situ or laboratory tests

#TRBwebinar

The CPT Expansion Pack: One Probe - More Tools:
CPT Modules for Site Characterization

Diane Moug
Assistant Professor, Portland State University

June 29th, 2021

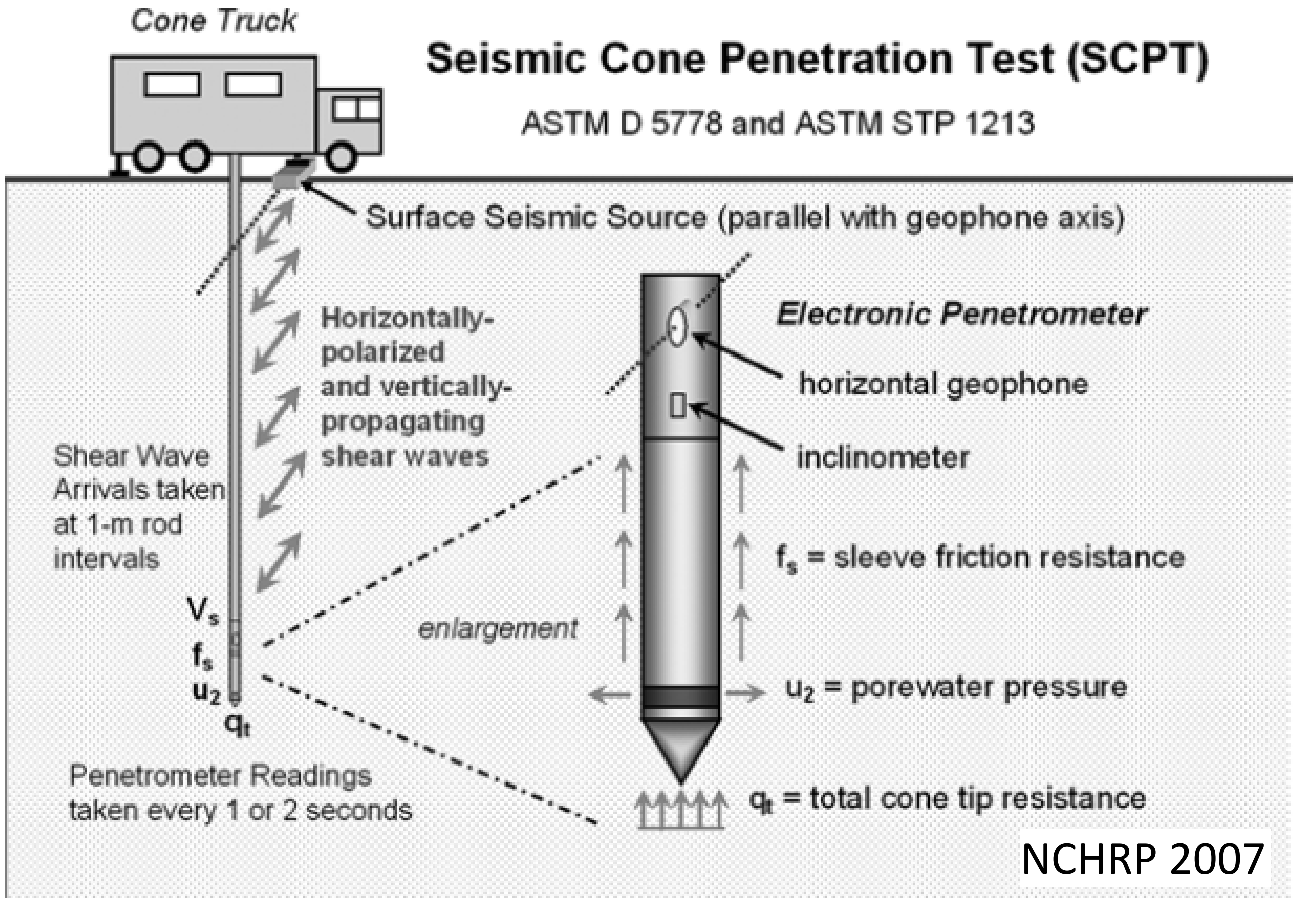
Contents:

- *Standard cone penetration test (CPT) operation, instrumentation & data*
- *Examples of CPT-based interpretation*
- *CPT in non-standard soils*
- *Expansion pack CPT modules*

Standard CPT Operation, Instrumentation & Data

CPT equipment and operation

- Hydraulically advanced at 20mm/s
- Data readings every 2 to 5 cm
- Primary measurements for the cone penetration test:
  - q_c – penetration resistance
  - f_s – sleeve friction
  - u_2 – porewater pressure at the cone shoulder (CPTu)
  - Inclination
- Additional instrumentation and modules are part of the CPT toolbox

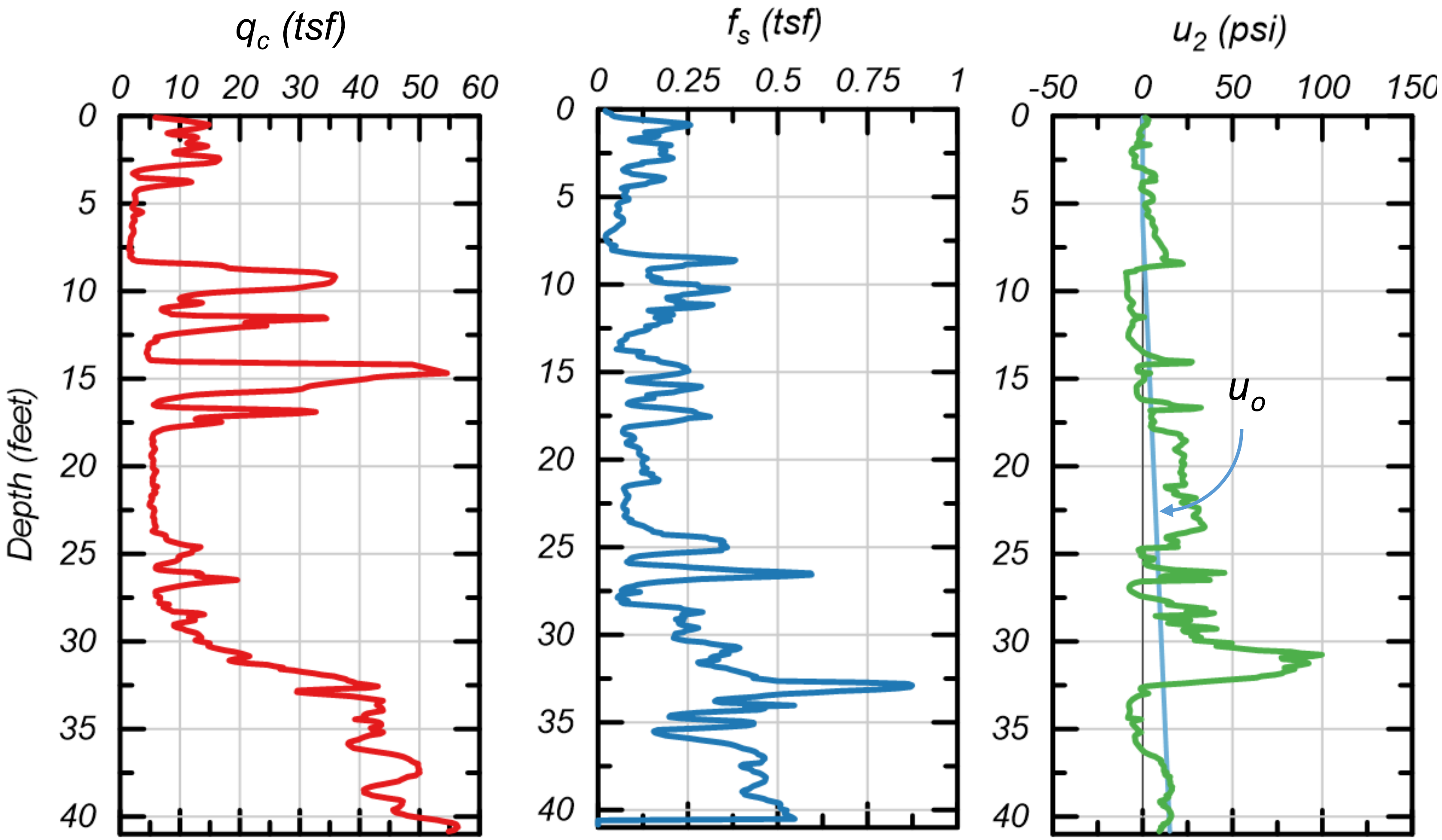


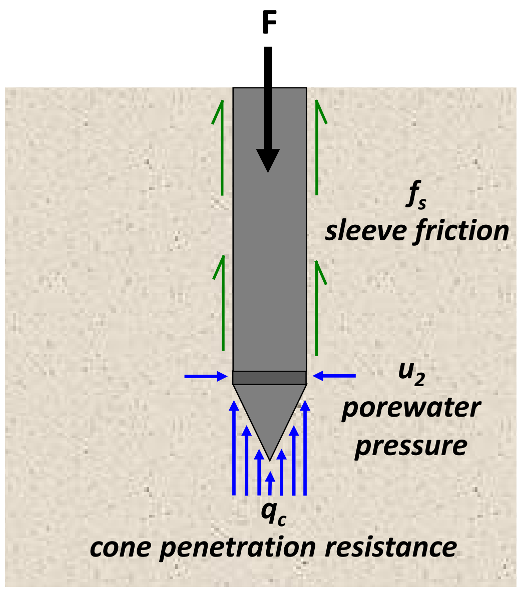
NCHRP 2007

Some advantage & limitations

- *Digital read outs in the field with relatively fast data processing*
- *Profile depths more than 100 feet depending on hydraulic capacity*
- *Fast and inexpensive compared to boring and sampling*
- *No soil sample obtained*
- *Applicable for clays to sand soils*


Example data profiles



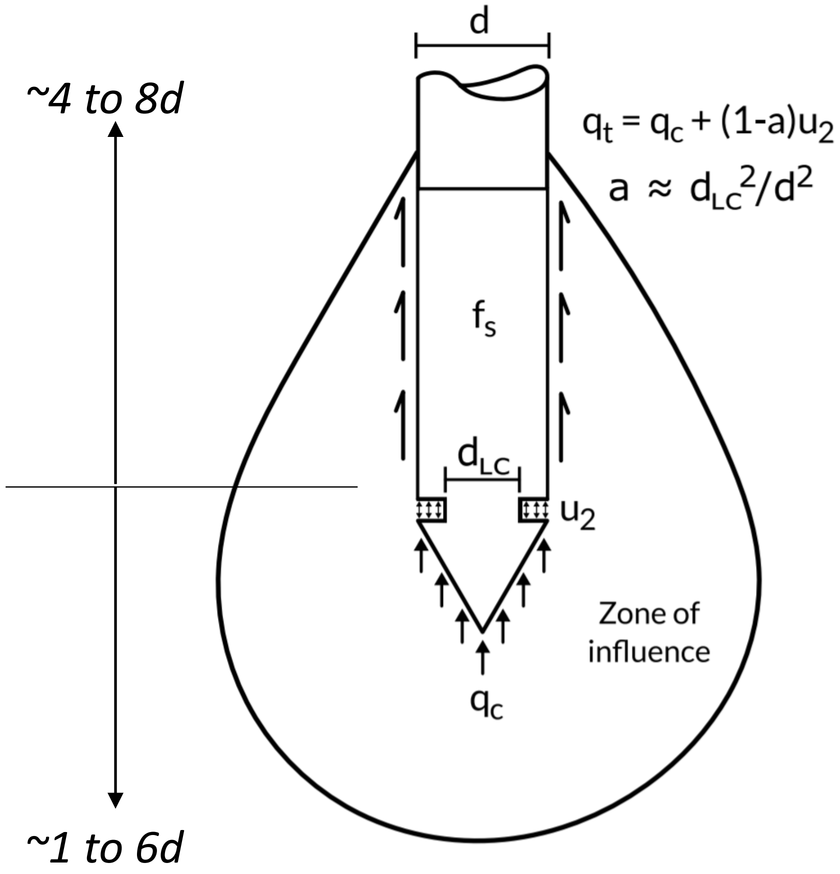


data from northwest Portland, OR

From Contec Inc.

Cone penetration loading mechanisms

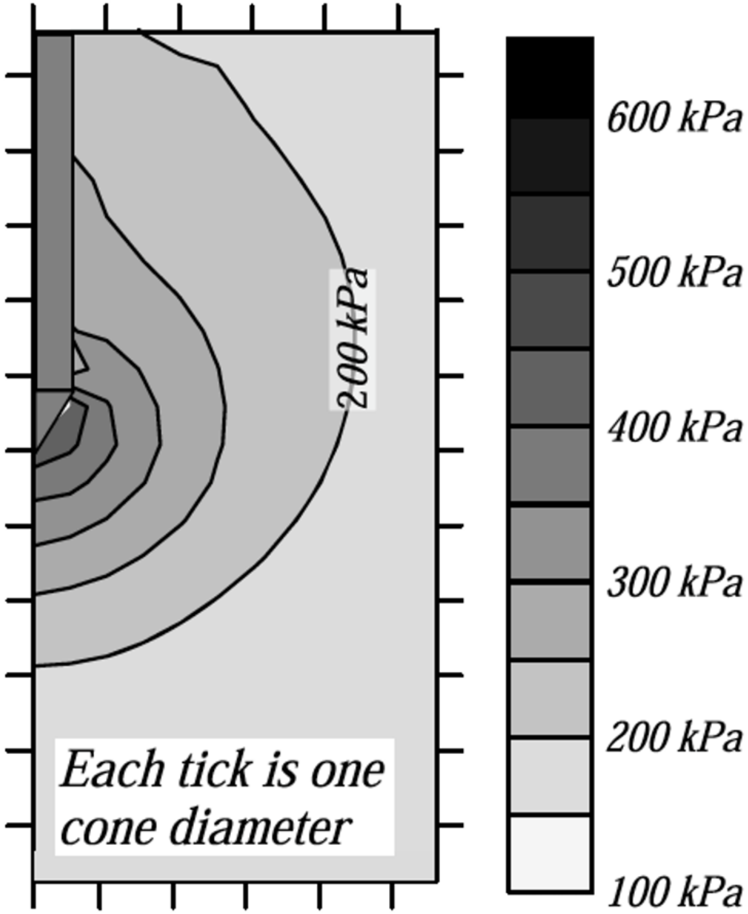
- Loading condition around the penetrating cone is a combination of compression, shearing, unloading, and cavity expansion
- Measured q_c, f_s, and u_2 are the response of soil behavior and properties to loading.



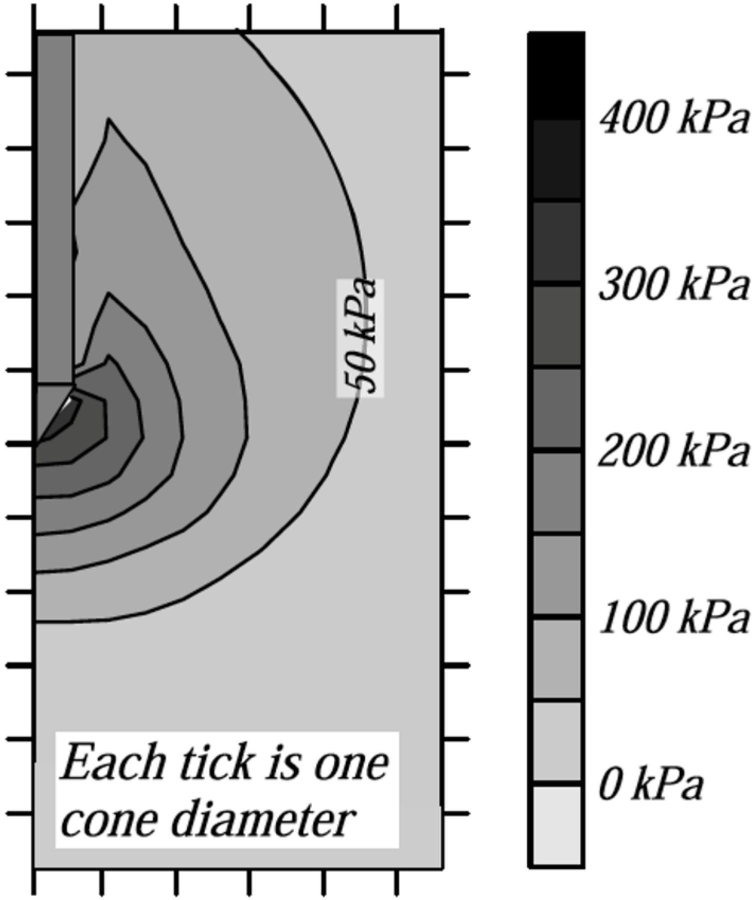
from Price et al. (2019)

- Compression loading:
  - Increases mean stress and pore pressure
- Shear:
  - Increases or decreases pore pressure
- $\Delta u = u_o + \Delta u_{compression} +/- \Delta u_{shear}$

Example: cone penetration in Boston blue clay



Simulated total mean stress distribution



Excess pore pressure (Δu) distribution

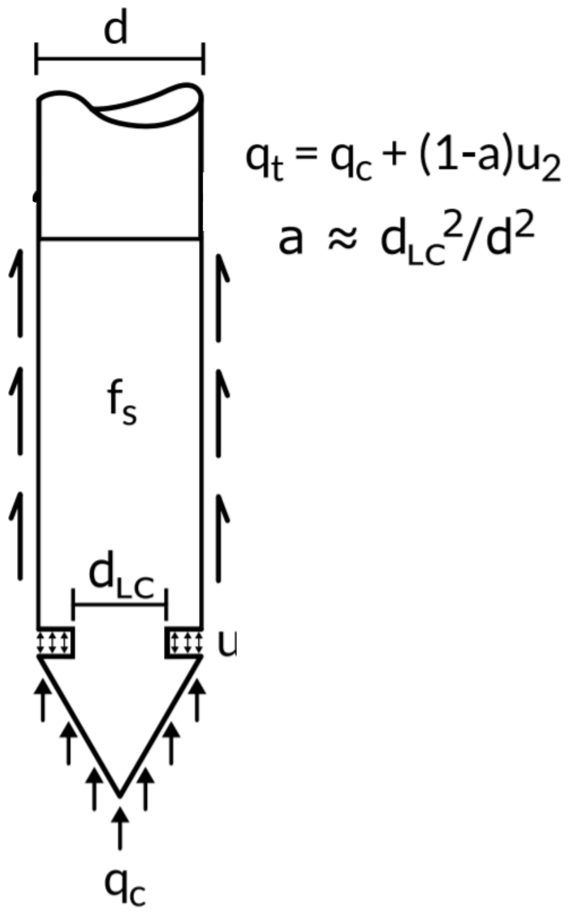
from Moug et al. (2019)

Examples of CPT-based interpretation with standard data

CPT variables

Measured Data
Cone tip resistance, q_c
Sleeve friction, f_s
Cone shoulder pore pressure, u_2
Others (u_1, V_s, etc.)

Calculated Variables	
Corrected tip resistance, q_t	$q_t = q_c + u_2(1-a)$
Excess cone shoulder pore pressure, Δu_2	$\Delta u_2 = u_2 - u_o$
Friction ratio, R_f	$R_f = f_s/q_t$
Normalized corrected tip resistance, Q_t	$Q_t = (q_t - \sigma_{vo})/\sigma'_{vo}$
Normalized sleeve resistance, F_r	$F_r = f_s/(q_t - \sigma_{vo})$
Pore pressure parameter, B_q	$B_q = \Delta u_2/(q_t - \sigma_{vo})$

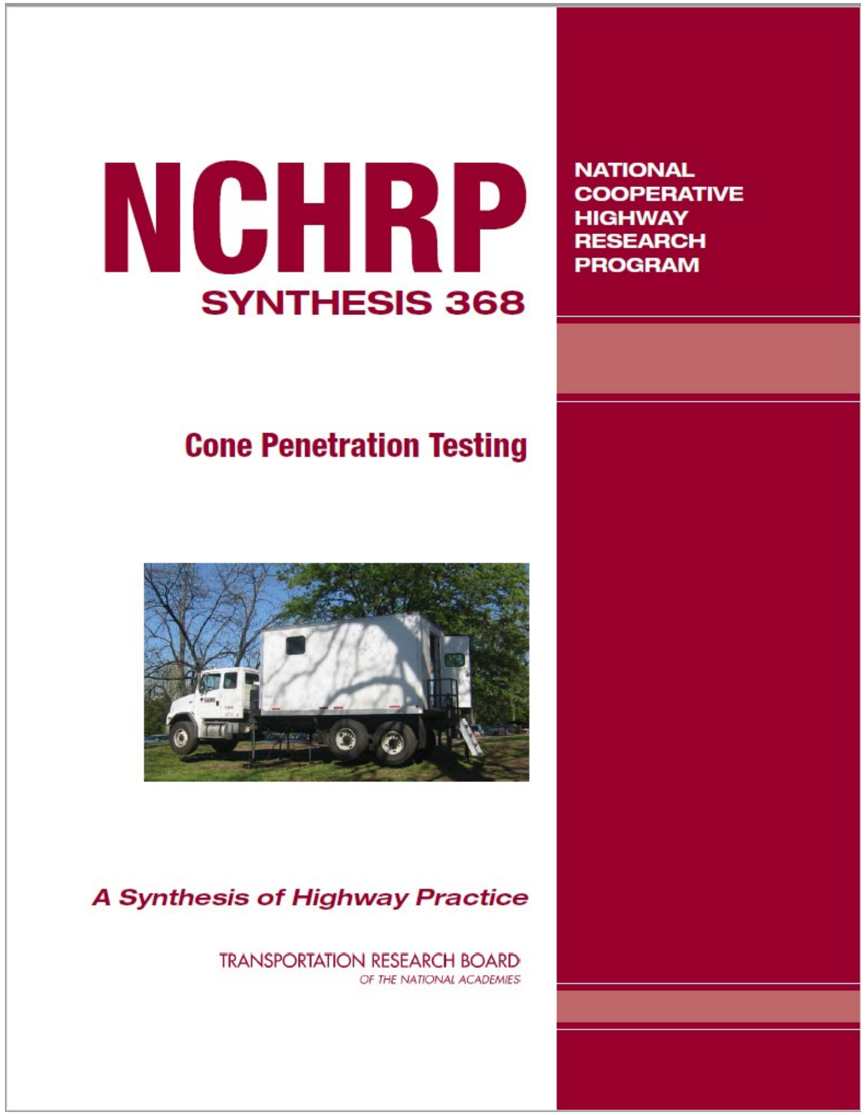


CPT-based interpretation

- Interpret stratigraphy and soil behavior type for clays, silts, and sands

- Interpretation for sand-like soils
  - Friction angle (ϕ’)
  - Relative density (D_R)
  - Unit weight (γ)
  - more…

- Interpretation for clay-like soils
  - Undrained shear strength (s_u)
  - Sensitivity (S_t)
  - Stress history (OCR) / pre-consolidation stress (σ'_p)
  - Unit weight (γ)
  - Coefficient of consolidation (c_h)
  - more…



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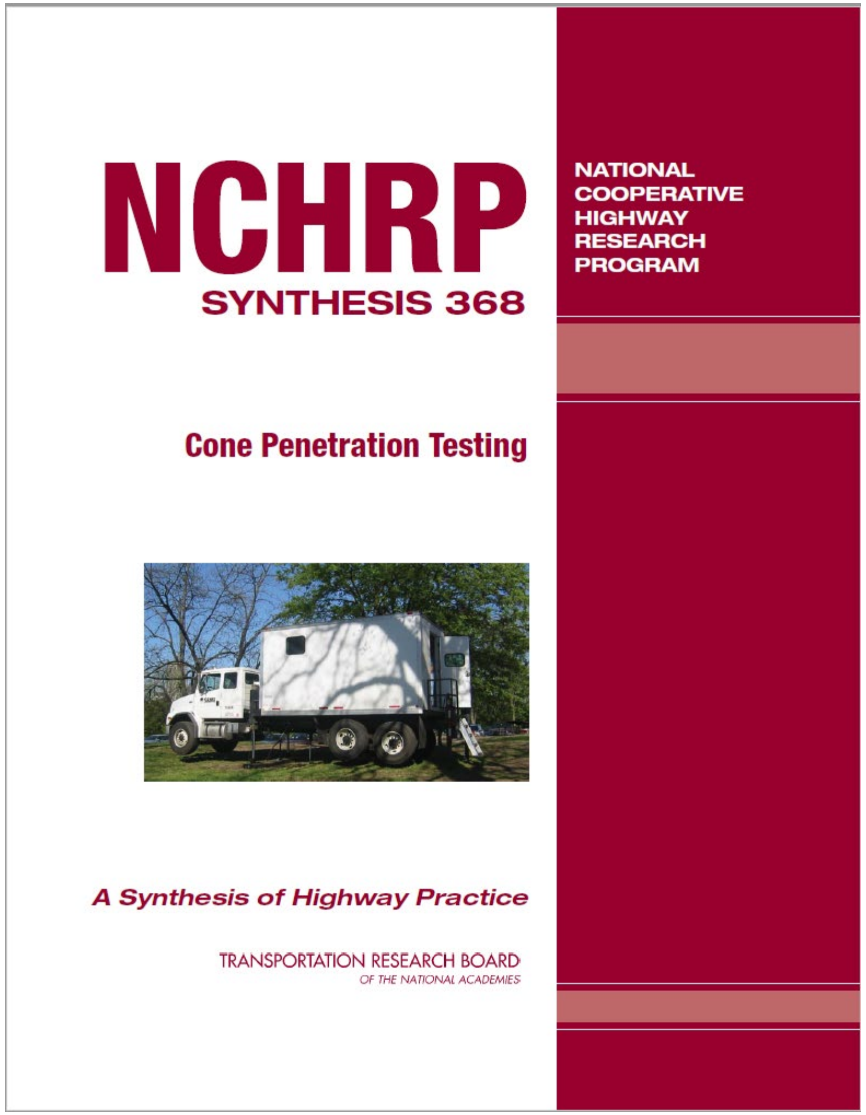


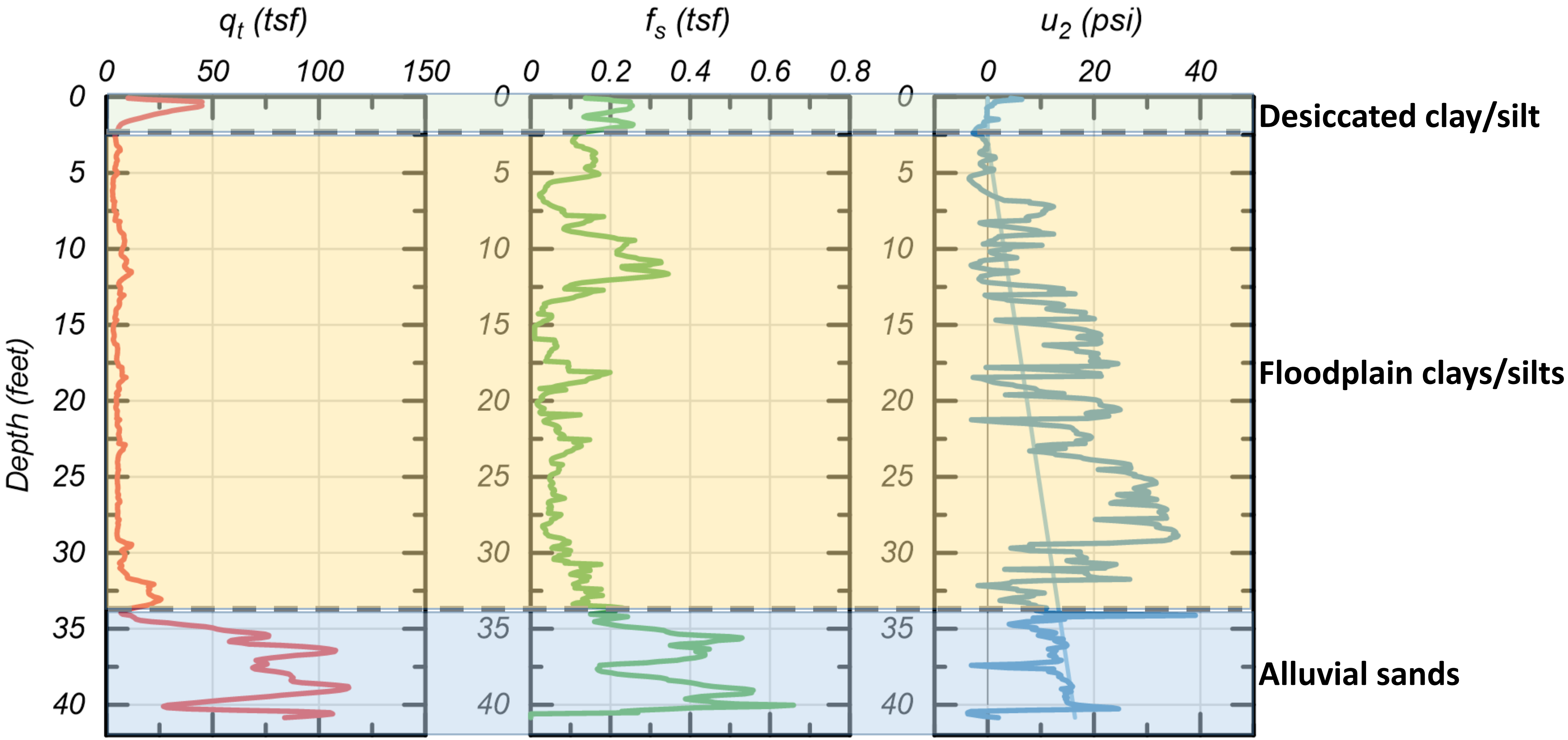
- Nearly continuous data profile is useful for detecting stratigraphic boundaries
  - Look at changes in q_t and Δu_2 magnitude
- Estimate groundwater table with u_2 measurements

<u>Rules of thumb:</u>

- Clean silica sand:
  - $q_c \approx q_t > 50$ tsf
  - $u_2 = u_o$ (near hydrostatic for drained penetration)

- Soft to firm to stiff intact clays:
  - $q_t < 50$ tsf
  - $\Delta u_2 = u_2 – u_o \neq 0$
  - $u_2 \sim 3\text{-}4u_o$ for normally consolidated clay
  - f_s is large relative to q_t

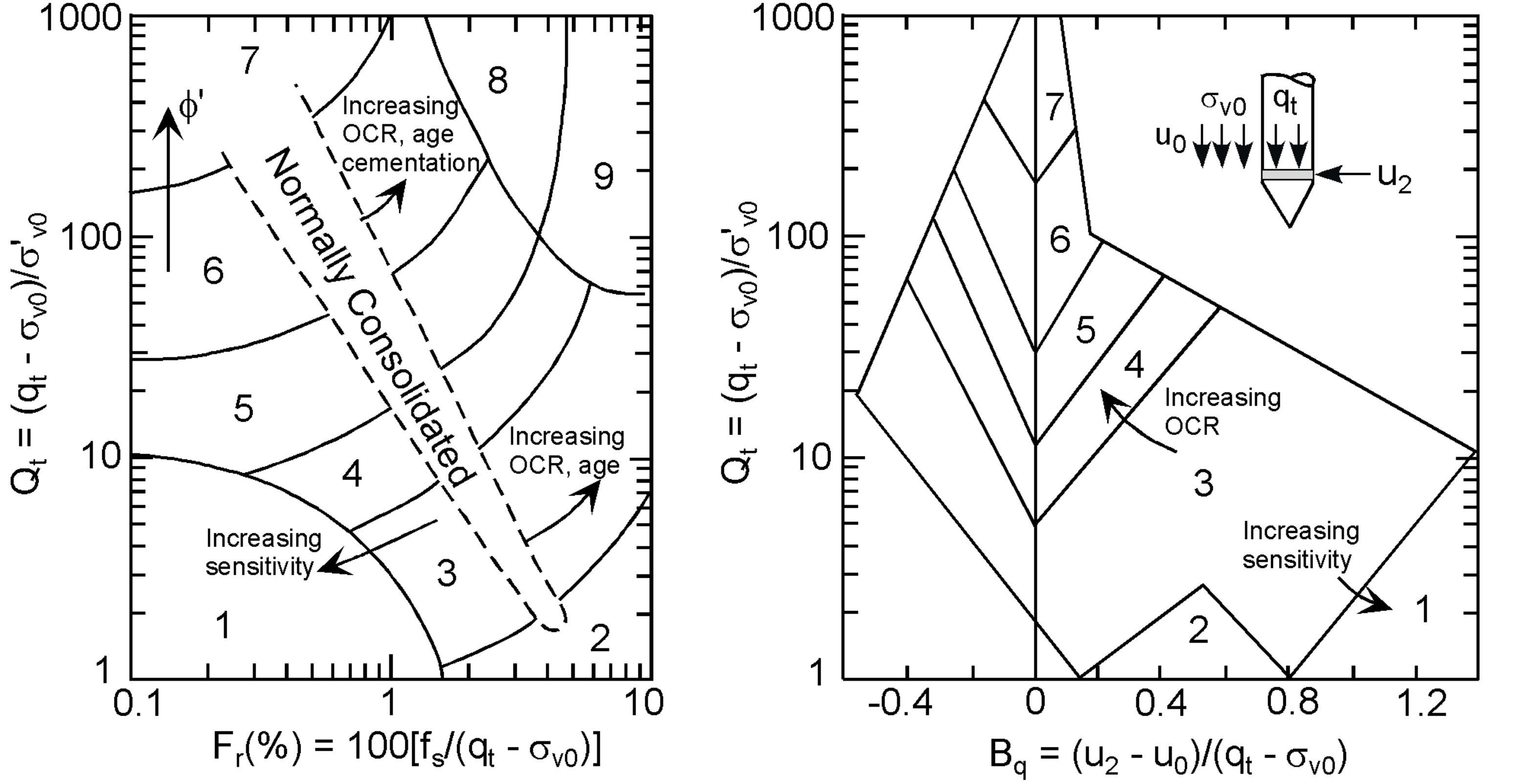
Example of CPT-based stratigraphy



Data from northeast Portland, OR

CPT-based soil behavior type

- No soil sample obtained (see samples in expansion pack) → interpret soil behavior type (SBT)
- Identify the most likely SBT based on empirical relationships to CPTu data.

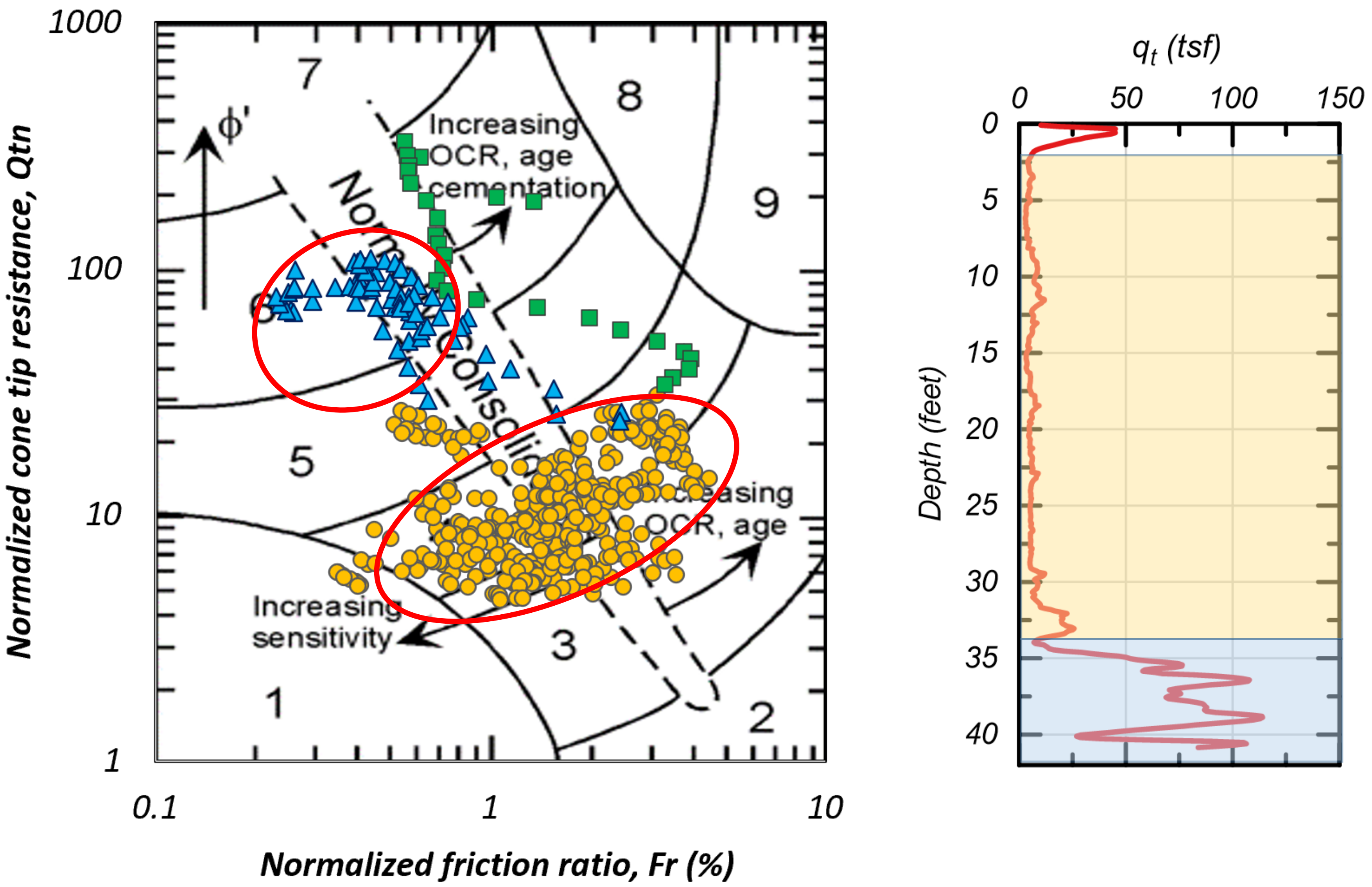


Soil Behavior Type by Zone Number

1. Sensitive, fine grained
2. Organic soils-peats
3. Clays-clay to silty clay
4. Silt mixtures clayey silt to silty clay
5. Sand mixtures; silty sand to sand silty
6. Sands; clean sands to silty sands
7. Gravelly sand to sand
8. Very stiff sand to clayey sand
9. Very stiff fine grained

Robertson (1990)

Example – northeast Portland, Oregon site



Robertson (1990) soil behavior type:

Silt mixtures; clayey silt to silty clay

Sands; clean sands to silty sands

- Undrained shear strength (s_u) interpretation based on pile base undrained bearing capacity:

$$q_b = s_u N_k + \sigma_{vo} \rightarrow q_t = s_u N_{kt} + \sigma_{vo}$$

$$s_u = \frac{q_t - \sigma_{vo}}{N_{kt}}$$

Options for selecting N_{kt}

- Experimentally: N_{KT} = 10 to 20 with 15 as average
  - Option 1: assume N_{kt} ~15 to 20 (conservative)
  - Option 2: correlate N_{kt} to plasticity index and OCR (e.g,. Karlsrud et al. 2005)
  - Option 3: use geologic and regional knowledge of N_{kt}
  - Option 4: calibrate against field or laboratory data to obtain site/geologic specific value.

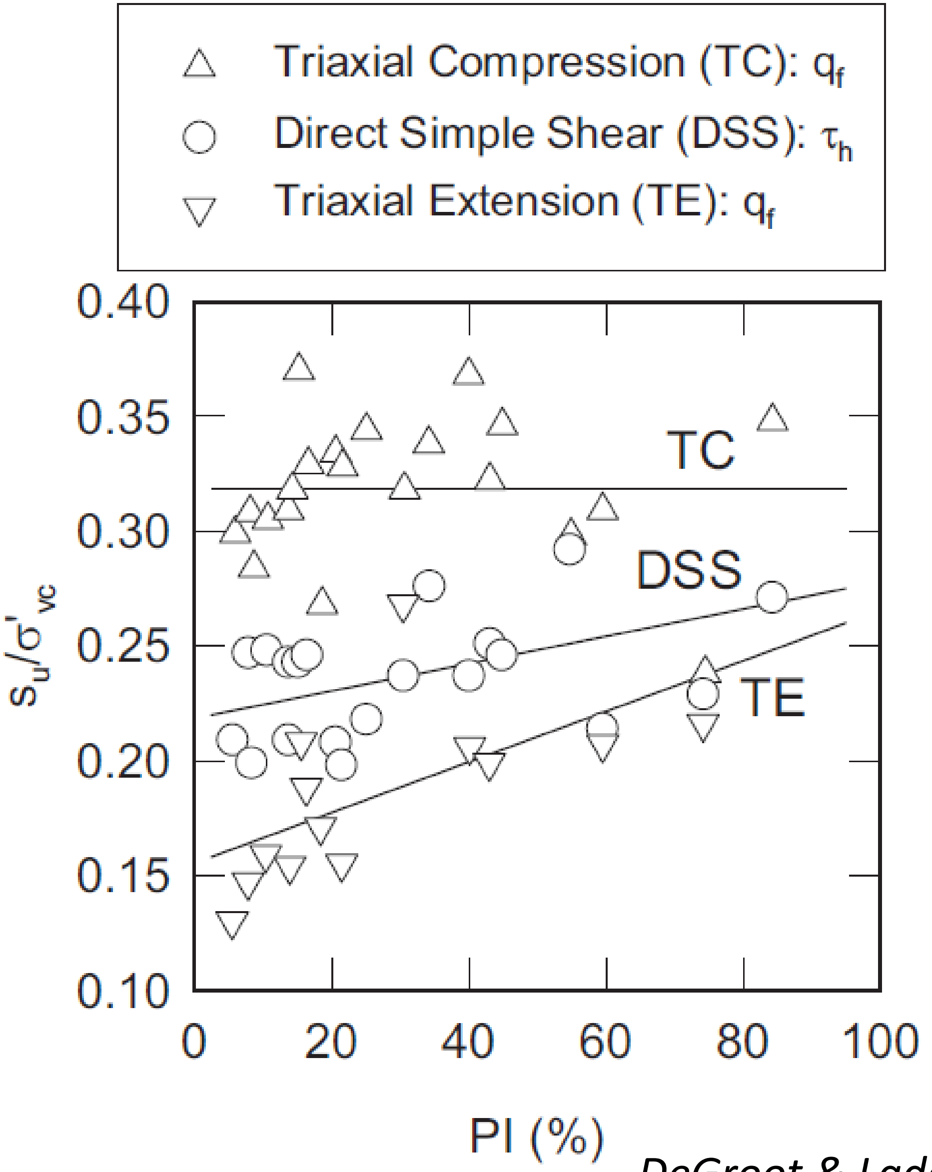
s_u anisotropy and N_{kt} values

- N_{kt} and s_u should be indexed to specific loading conditions

$$s_{u,TC} = \frac{q_t - \sigma_{vo}}{N_{kt,TC}}$$

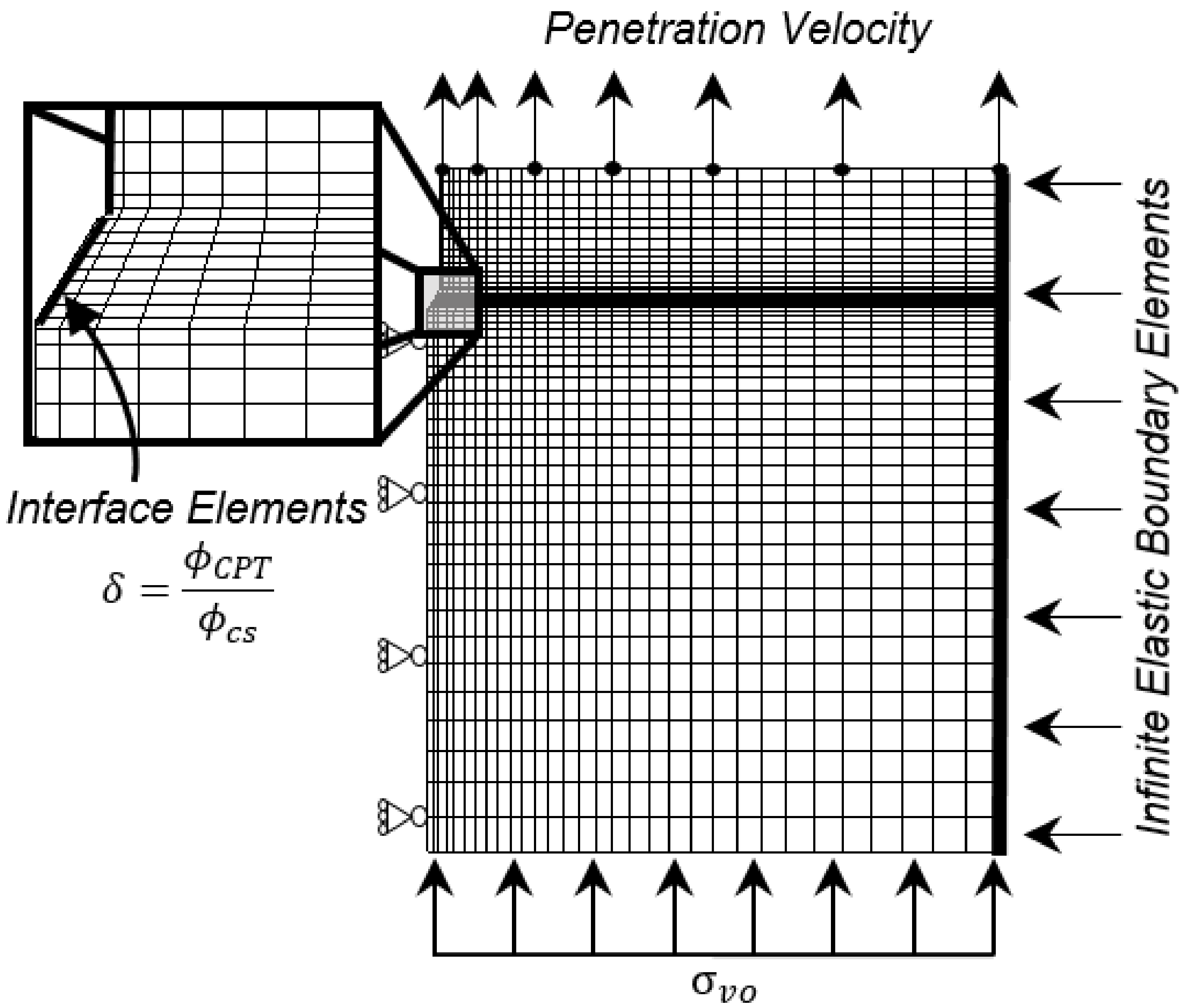
$$s_{u,DSS} = \frac{q_t - \sigma_{vo}}{N_{kt,DSS}}$$

$$s_{u,TE} = \frac{q_t - \sigma_{vo}}{N_{kt,TE}}$$

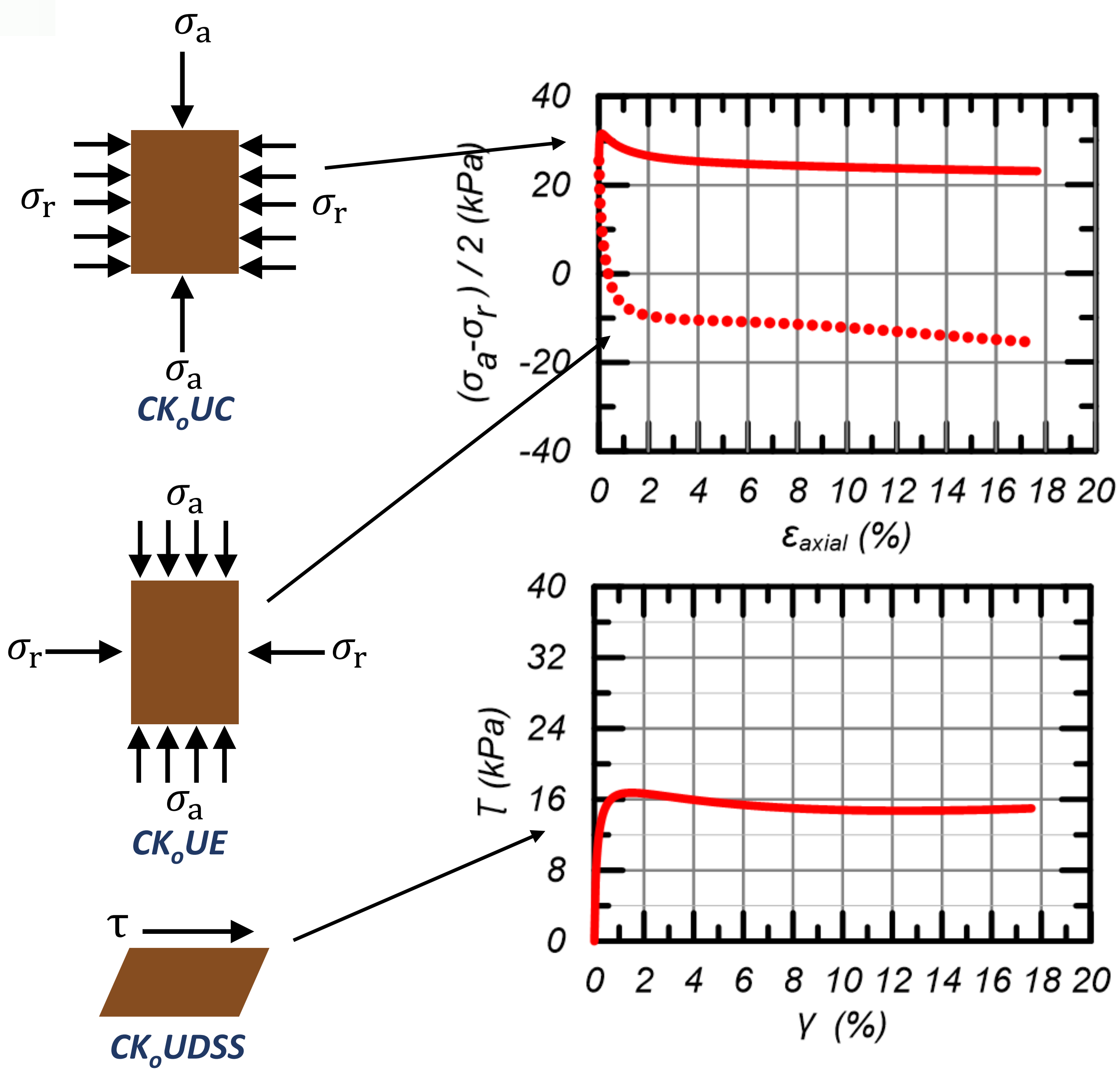


DeGroot & Ladd 2012

- *Moug et al. (2019):*
  - Simulate cone penetration in clay to study s_u anisotropy, N_{kt} and q_t



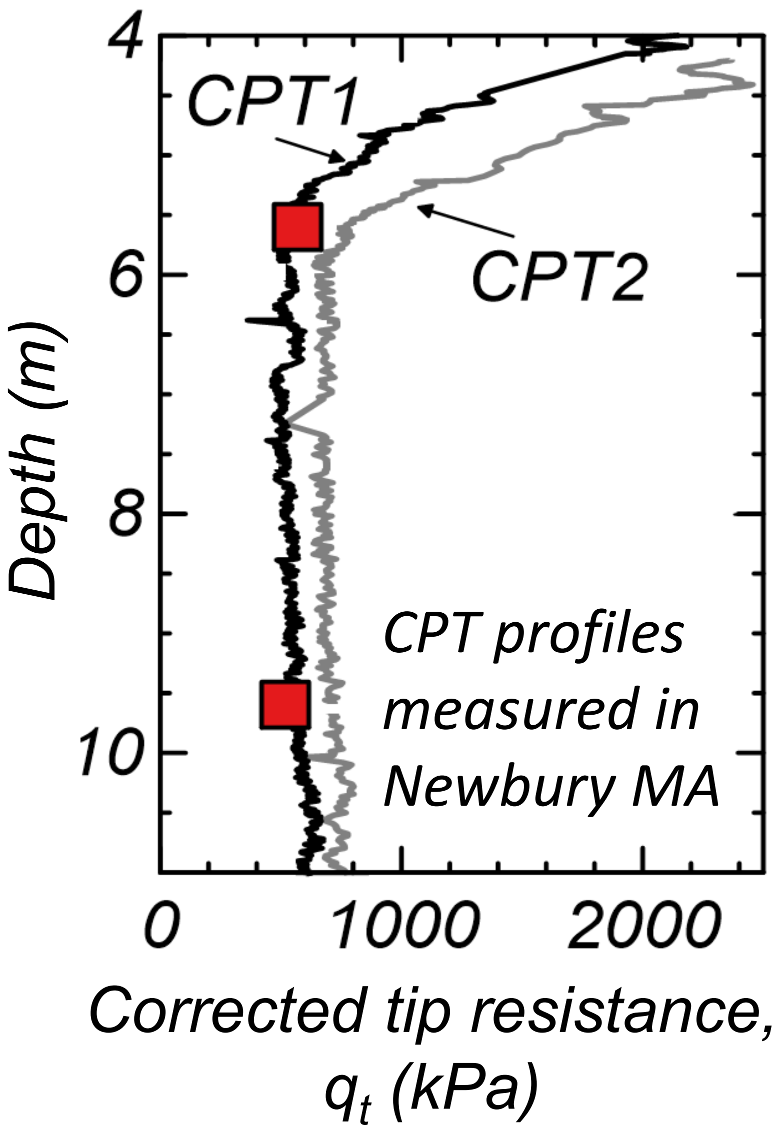
Anisotropic soil model for simulated cone penetration



	MIT-S1	Resedimented Lab Tests
OCR 1	s_u/σ'_{vo}	
CK_OUC	0.32	0.33
CK_OUE	0.18	0.14
CK_OUDSS	0.17	0.2

Moug et al. (2019)

Example: simulated penetration in Boston Blue Clay



e.g., interpreting s_u at 9.6 m:

$$s_u = \frac{q_t - \sigma_{vo}}{N_{kt}}$$

N_{kt} by loading condition:

$N_{kt,TC} = 6.5$ $N_{kt,DSS} = 9.8$

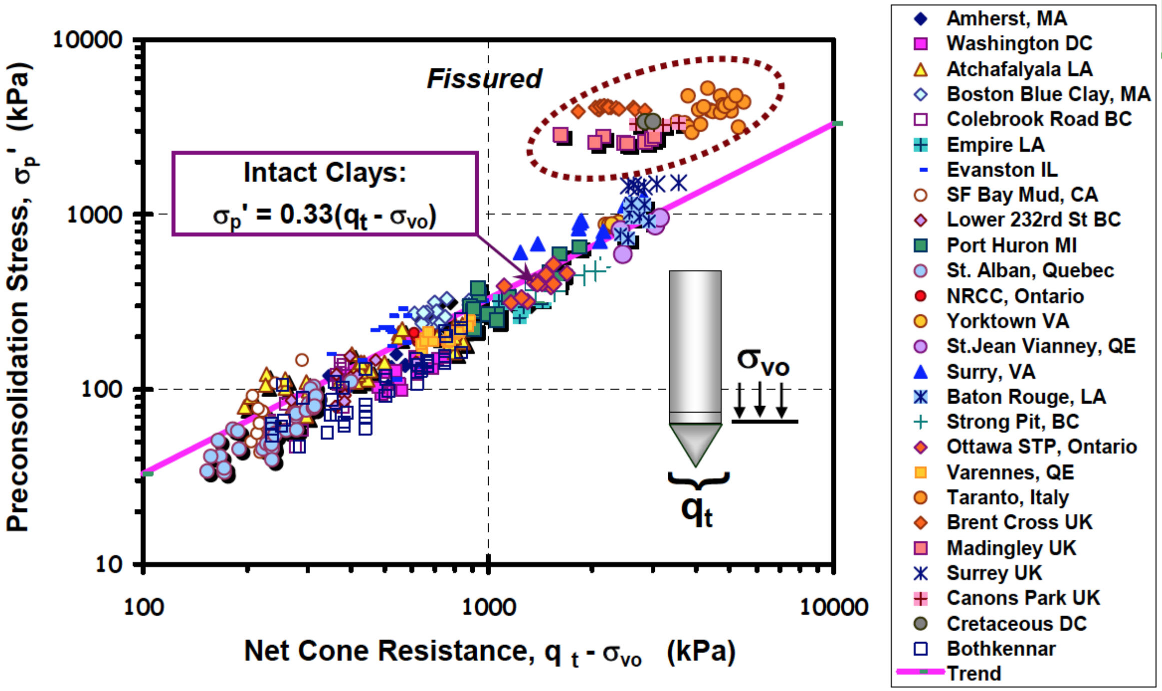
$N_{kt,TE} = 9.3$ $N_{kt,ave} = 8.5$

Moug et al. (2019)

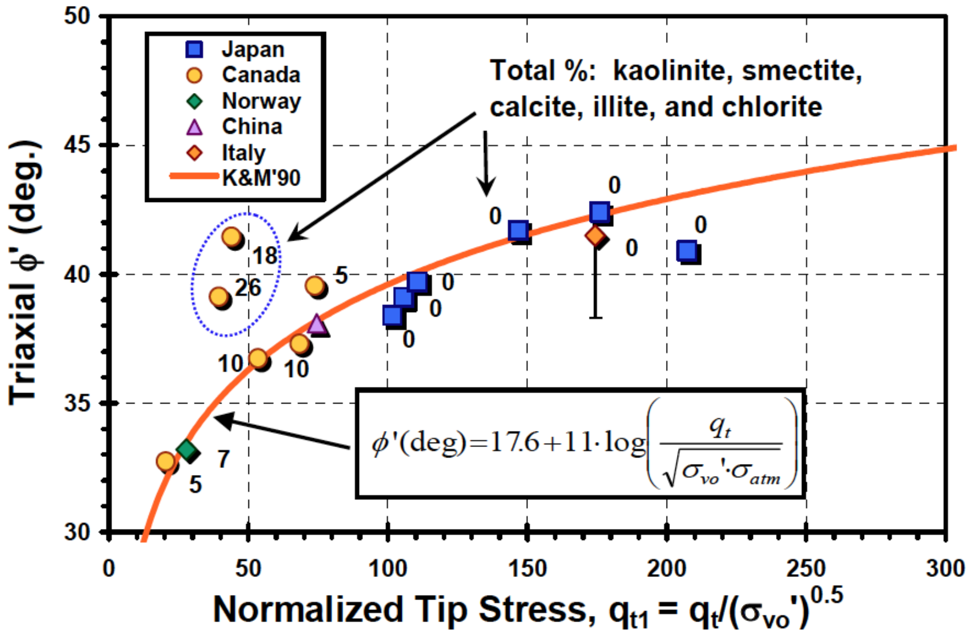
CPT in non-standard soils

CPT-based interpretations for clay-like and sand-like soils

- Interpretation methods for clays were primarily developed with:
  - Undrained penetration conditions
  - Normal, sedimentary clays



- Interpretation methods for sands were primarily developed with:
  - Drained penetration conditions
  - Fine to medium clean silica sands
  - Uniform soil units



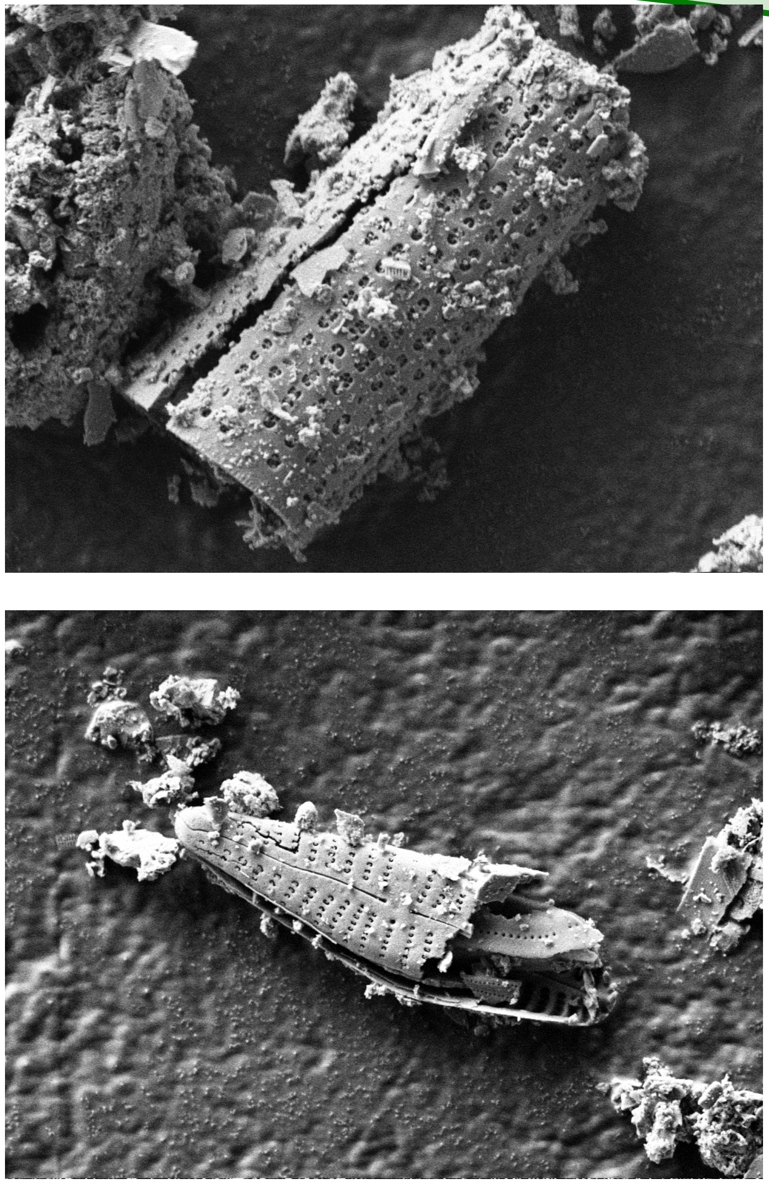
(NCHRP 2007)

What about when the soils are not silica sands or normal clays?

- ➢ Evaluate the assumptions that interpretations rely upon against site soils and conditions.
- ➢ Can adjustments be made to data?
  - Fines content corrections
  - Layered soil corrections
  - Variable penetration rate
- ➢ Can supplemental data be collected?
  - Consider sampling and laboratory testing to further inform CPT data and potentially develop site-specific interpretations.

Non-standard soil example: diatomaceous soils

- Diatoms are silt-sized silica skeletons from ancient algae blooms
- Diatom particles are intricately patterned particles with high intraskeletal porosity
- Diatomaceous soils have “non-standard” geotechnical behavior:
  - High liquid limit and plastic limit
  - Highly compressible
  - High apparent preconsolidation stresses
  - And more…

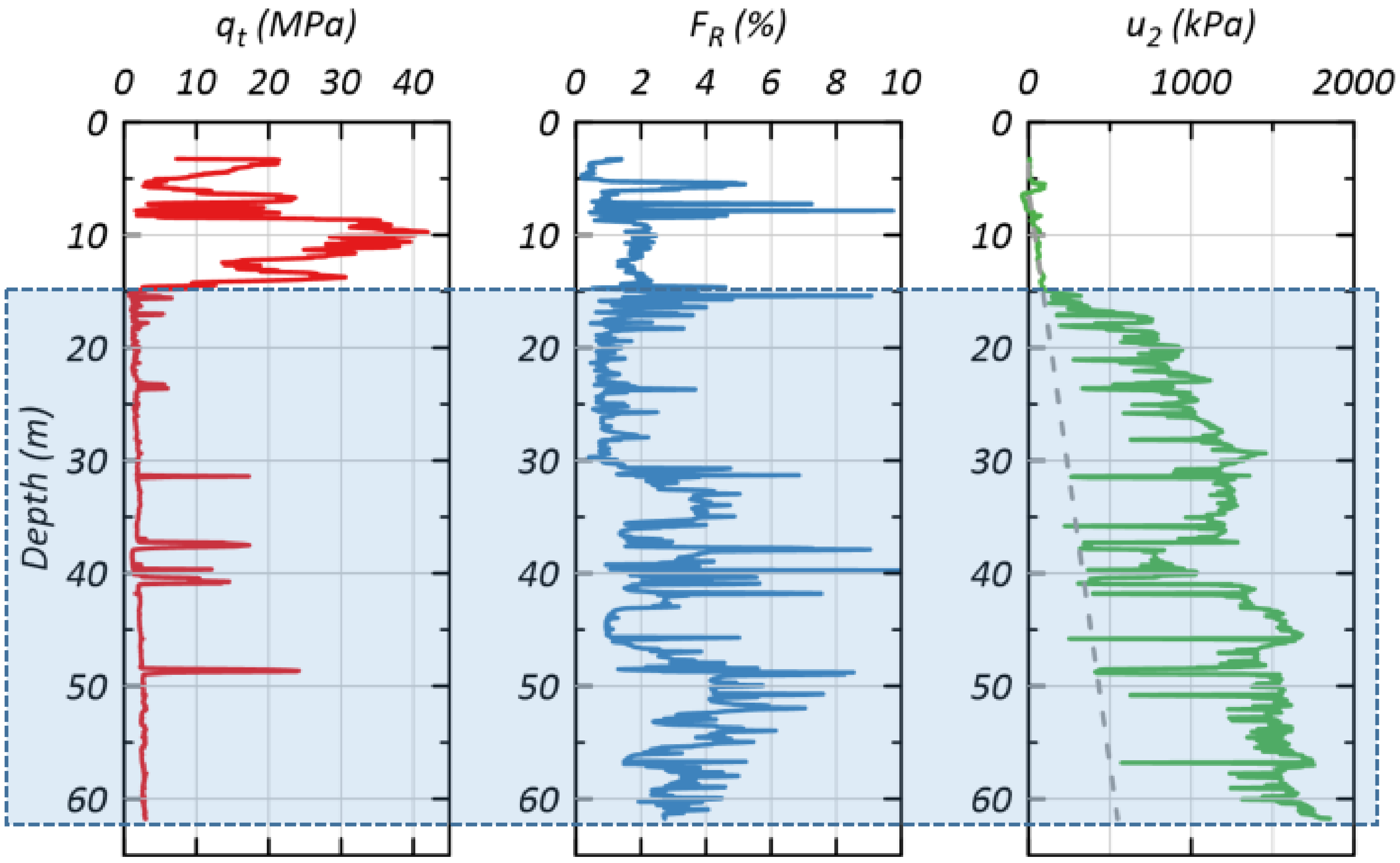


Diatomaceous soils from an Oregon site

CPT profiles in diatomaceous soils

- Generally, CPT data from diatomaceous soils (Evans & Moug 2020):
  - Low q_t
  - High u_2

- *Can standard CPTu interpretation methods be applied to diatomaceous soils?*



CPT data from diatomaceous soil site in Oregon

ODOT SPR820: Development of Reliable Geotechnical Methods and Standards for Design and Construction over Diatomaceous Deposits

Project approach:

- Drilling and sampling at four diatomaceous soil site in Oregon.
- Laboratory measurement of engineering properties: undrained shear strength (s_u), friction angle (ϕ'), compressibility (C_c and C_r), cyclic strength (CRR), and more.
- In-situ testing: SCPTu, VST, SPT.
- Synthesis and analysis of data for geotechnical design recommendations.

Expansion Pack CPT modules

- Many applications of standard CPT data: q_c, f_s, u_2
  - s_u, OCR, unit weight, relative density, friction angle, and more…

- Can expand use of standard CPT data
  - u_2 dissipation tests

- Additional modules offer further expansion:
  - Seismic
  - Magnetometer
  - Video
  - Electrical conductivity
  - Sampling

Overview of additional CPT modules

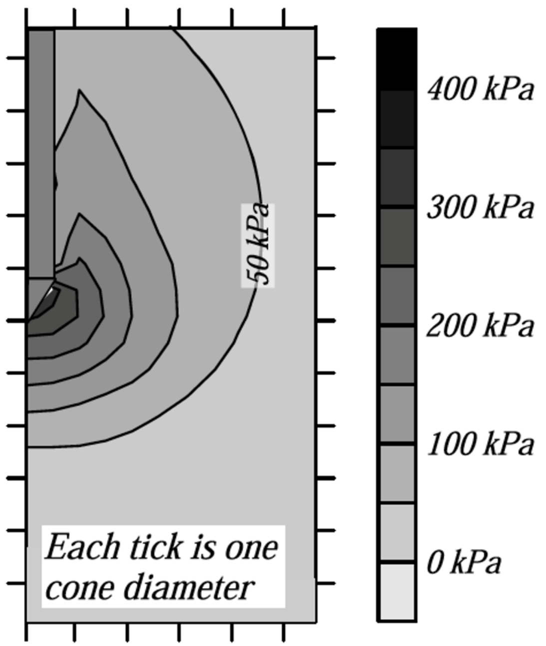
- Many applications of standard CPT data: q_c, f_s, u_2
  - s_u, OCR, unit weight, relative density, friction angle, and more…

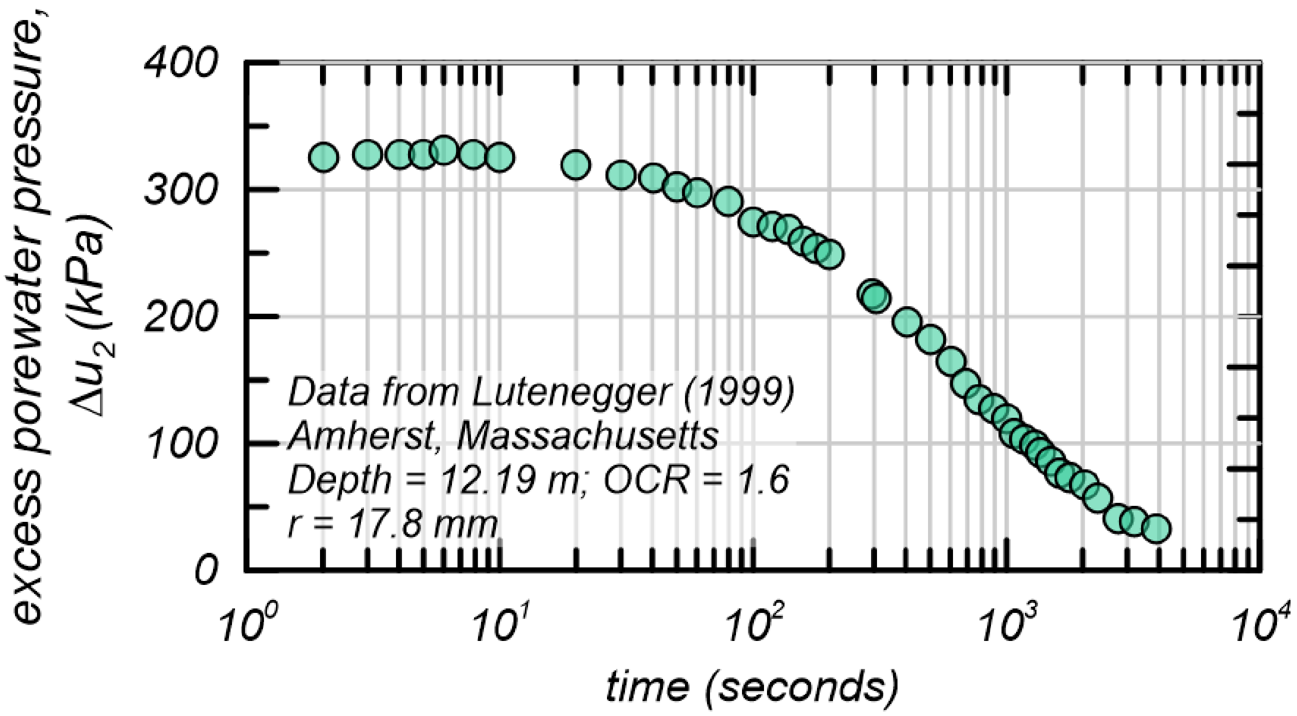
- Can expand use of standard CPT data
  - **u_2 dissipation tests**

- Additional modules offer further expansion:
  - *Seismic (G. Verbeerk will cover)*
  - **Magnetometer**
  - **Video**
  - **Electrical conductivity**
  - **Sampling**

CPTu dissipation test overview

- Interpret horizontal coefficient of consolidation (c_h) and permeability (k_h) of clay-like soils
- Consolidation of Δu occurs during pauses in cone penetration
- Record rate of u_2 dissipation to u_o





Estimating c_h from CPTu dissipation test

- Teh & Houlsby (1991):

$$c_h = \frac{0.245 * r^2 \sqrt{I_r}}{t_{50}}$$

r = cone penetrometer radius

$I_r = \frac{G}{s_u}$ = soil rigidity index

t_{50} = time to 50% dissipation

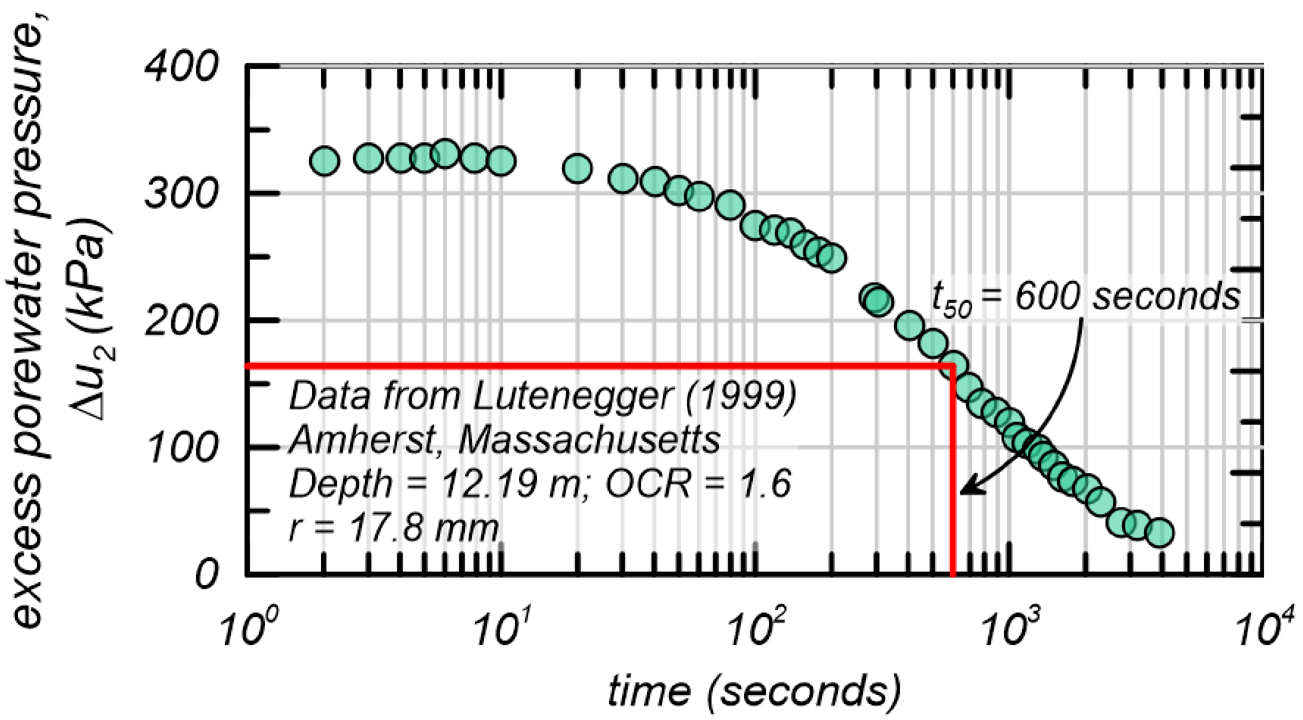
- Example from Lutenegger (1999):

t_{50} = 600 seconds

I_r = 175

r = 17.8 mm

c_h = 1 cm²/min

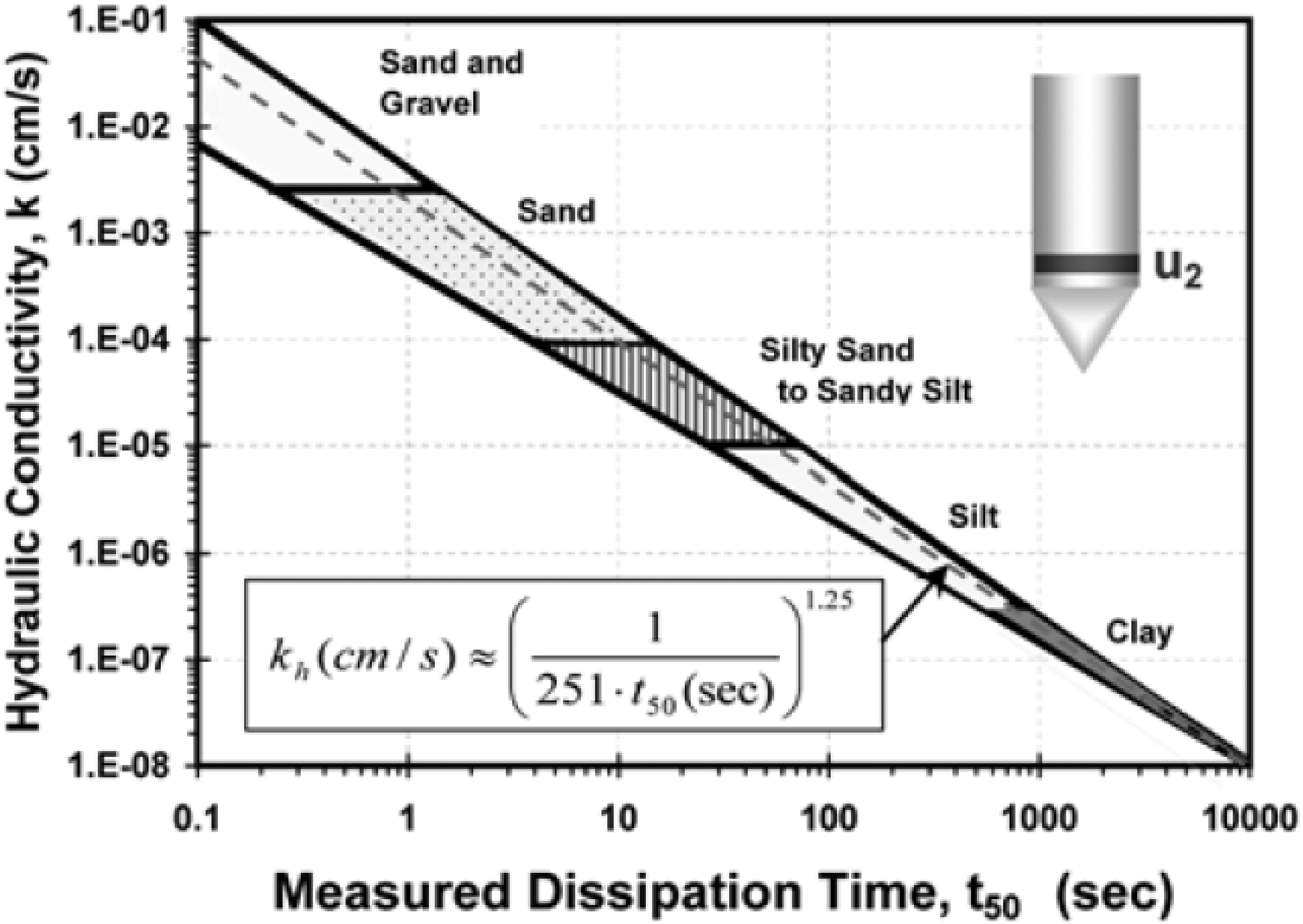


Estimating k_h from CPTu dissipation test

$$k_h = \frac{c_h \gamma_w}{D'}$$

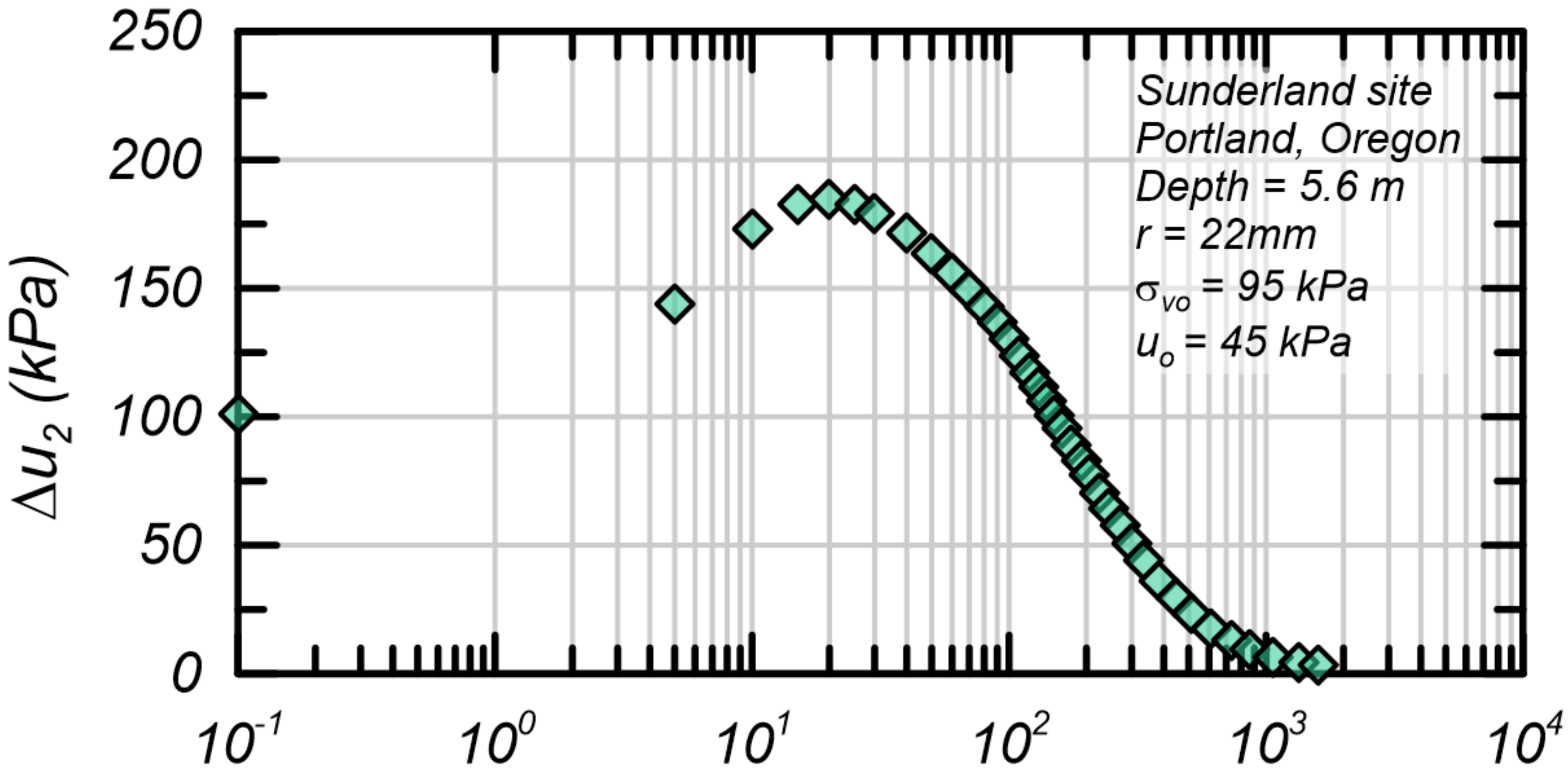
D' = constrained modulus

$D' \cong 5(q_t - \sigma_{vo})$ for normal clays and silica sands

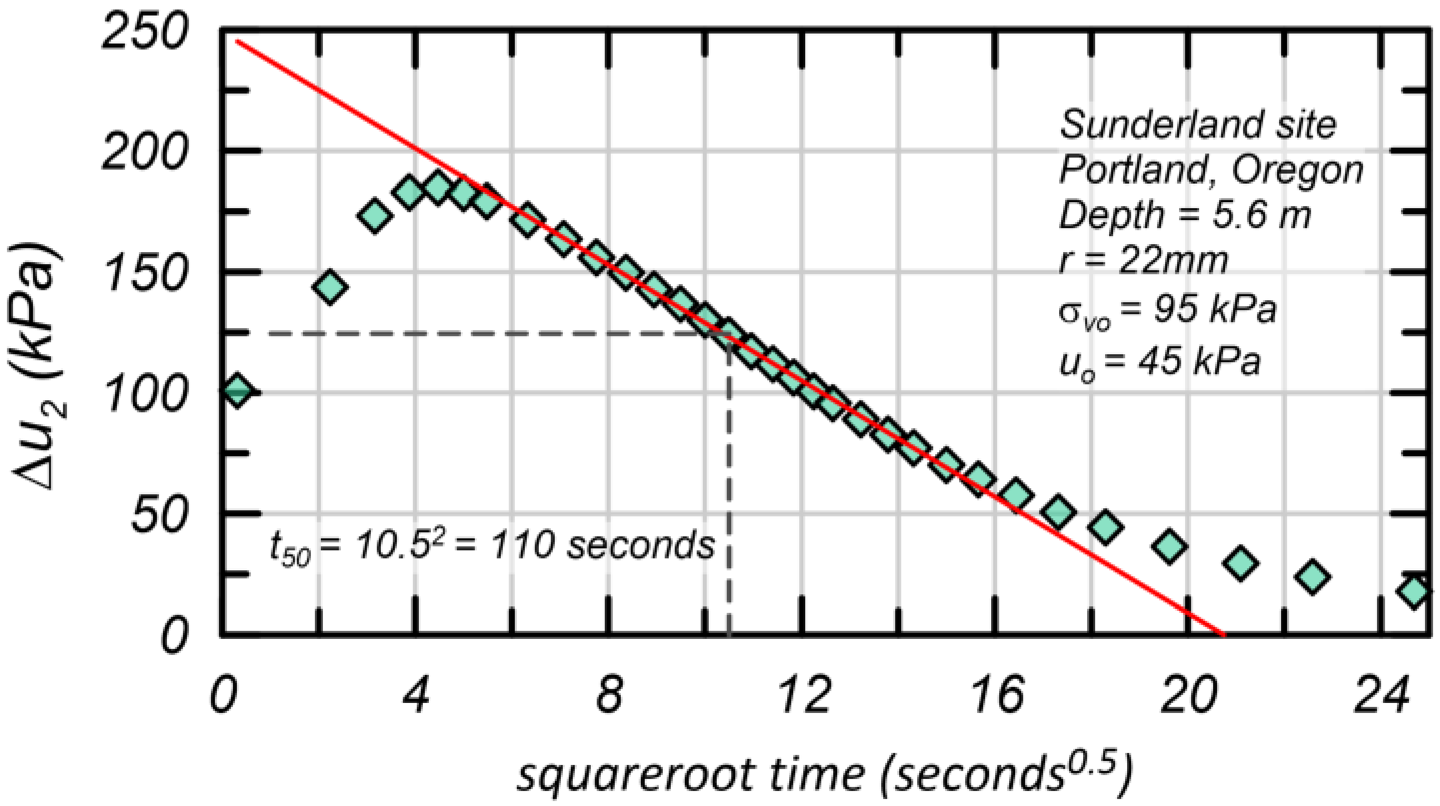


NCHRP (2007)

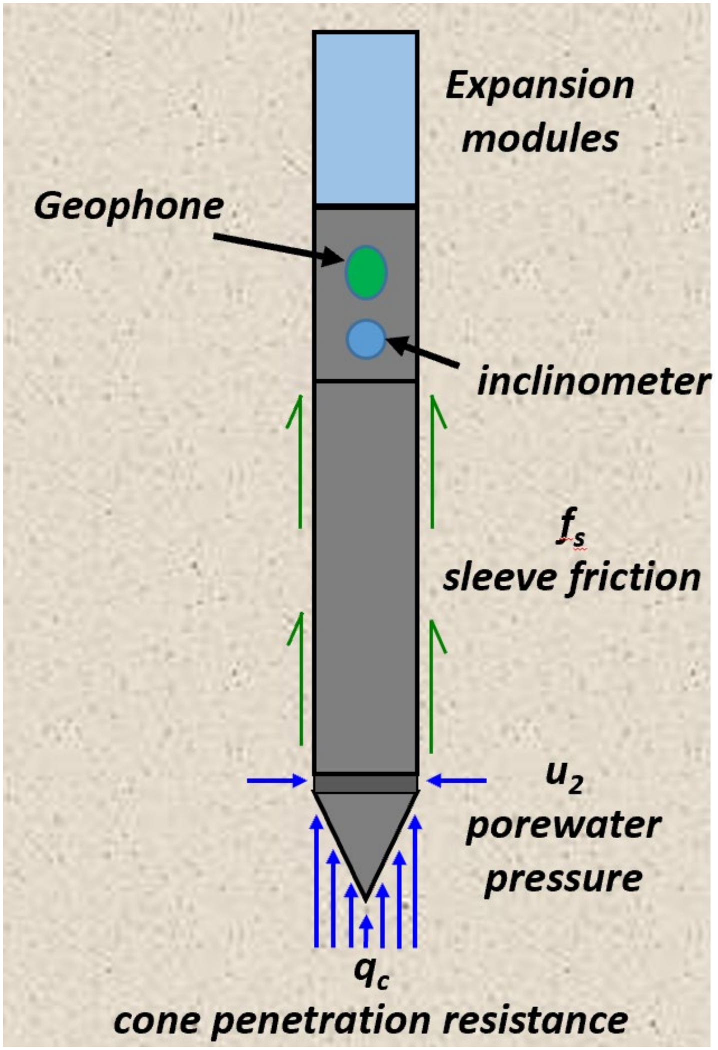
- Non-monotonic u_2 dissipation tests possible in overconsolidated clays or dilatory soils



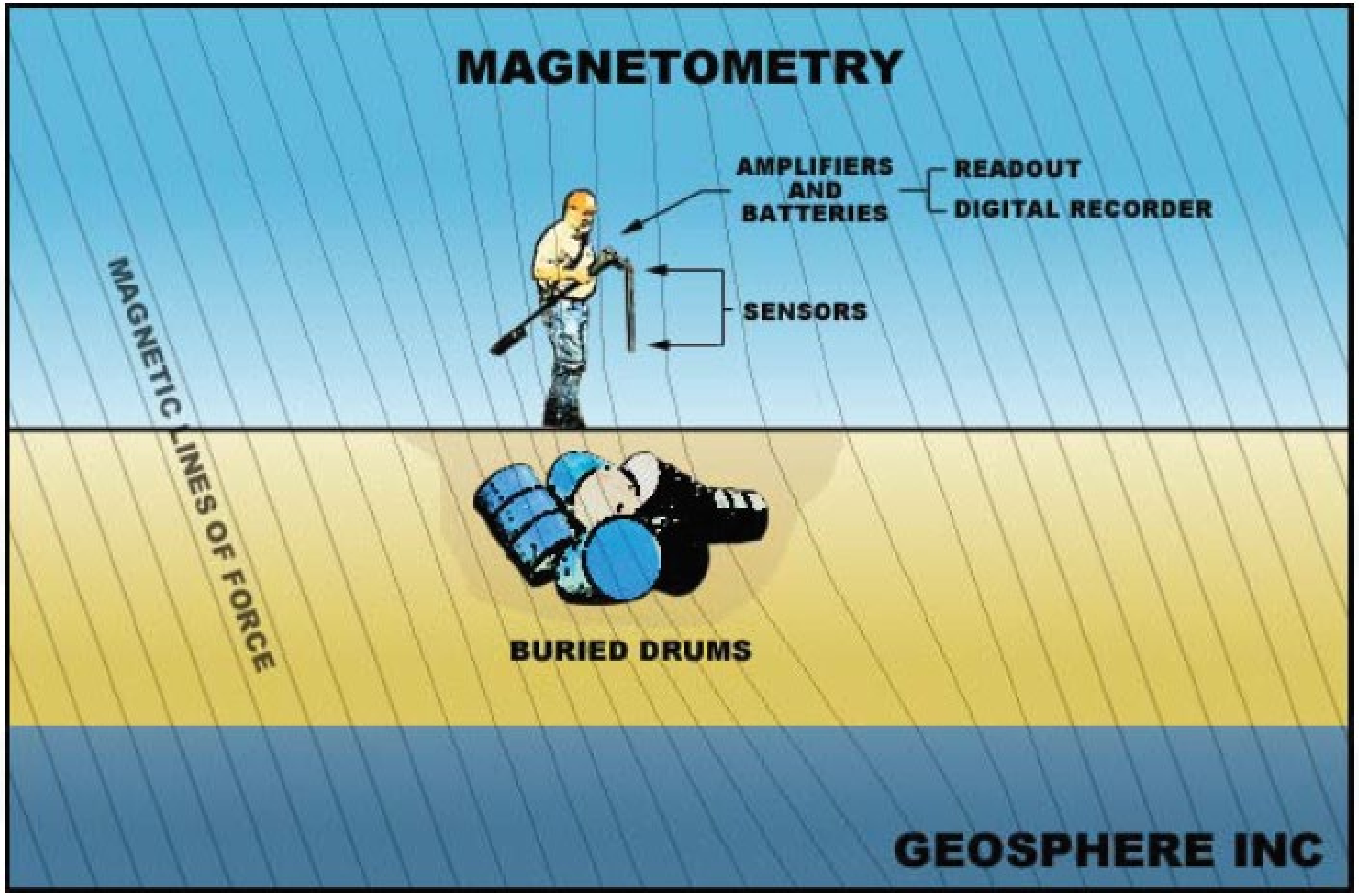
- Various approaches to non-monotonic tests available
- E.g., Sully et al. (1999) square root-time method:
  - Use Teh & Houlsby interpretation with t_{50} estimated from square-root time



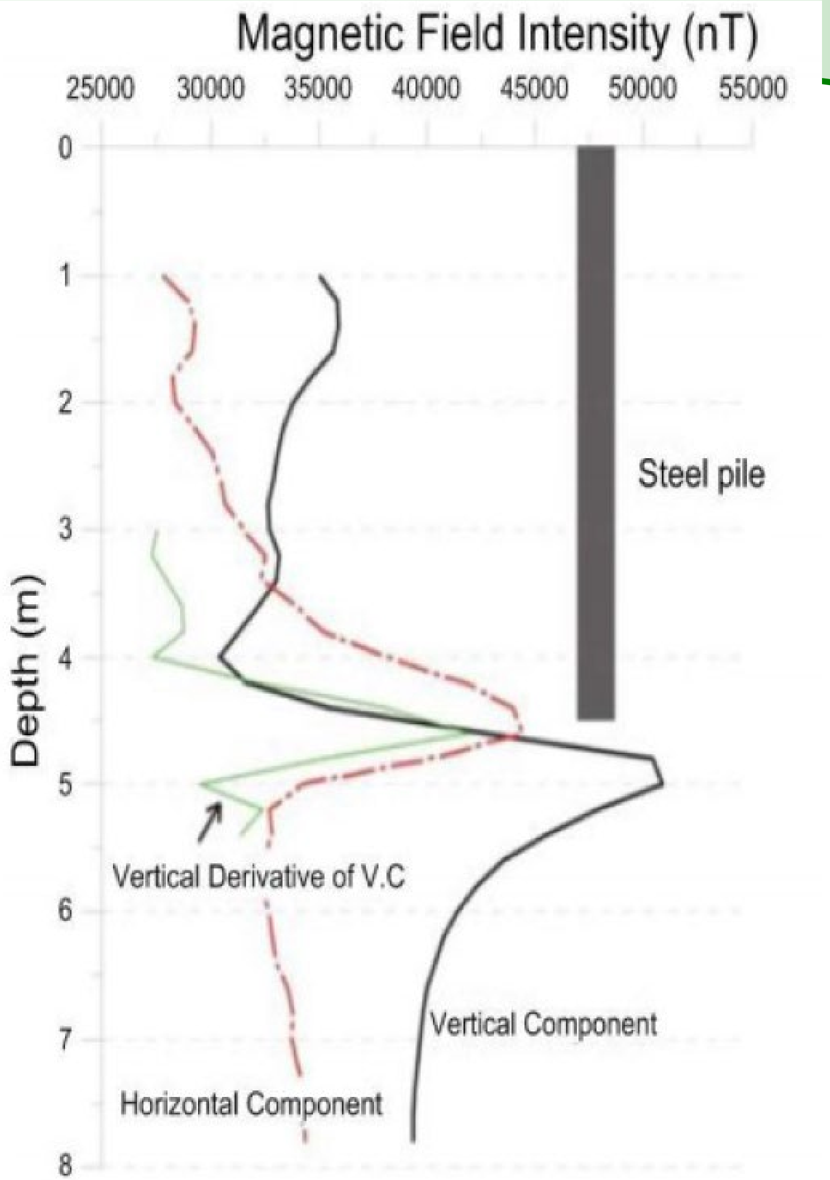
- Additional instrumentation modules for the "CPT expansion pack"
- Generally added to a standard 15 cm^2 cone
- Basic CPT data are still collected



- Measure strength and/or direction of a magnetic field
- Detect buried or submerged objects, or metal objects installed sub-grade
- Detect objects within about 2 m of the profile



- **Example applications:**
  - Length of foundation/sheet piles
  - Position of retaining or tieback anchors
  - Position of power cables
  - Unexploded bomb/ordnance surveys

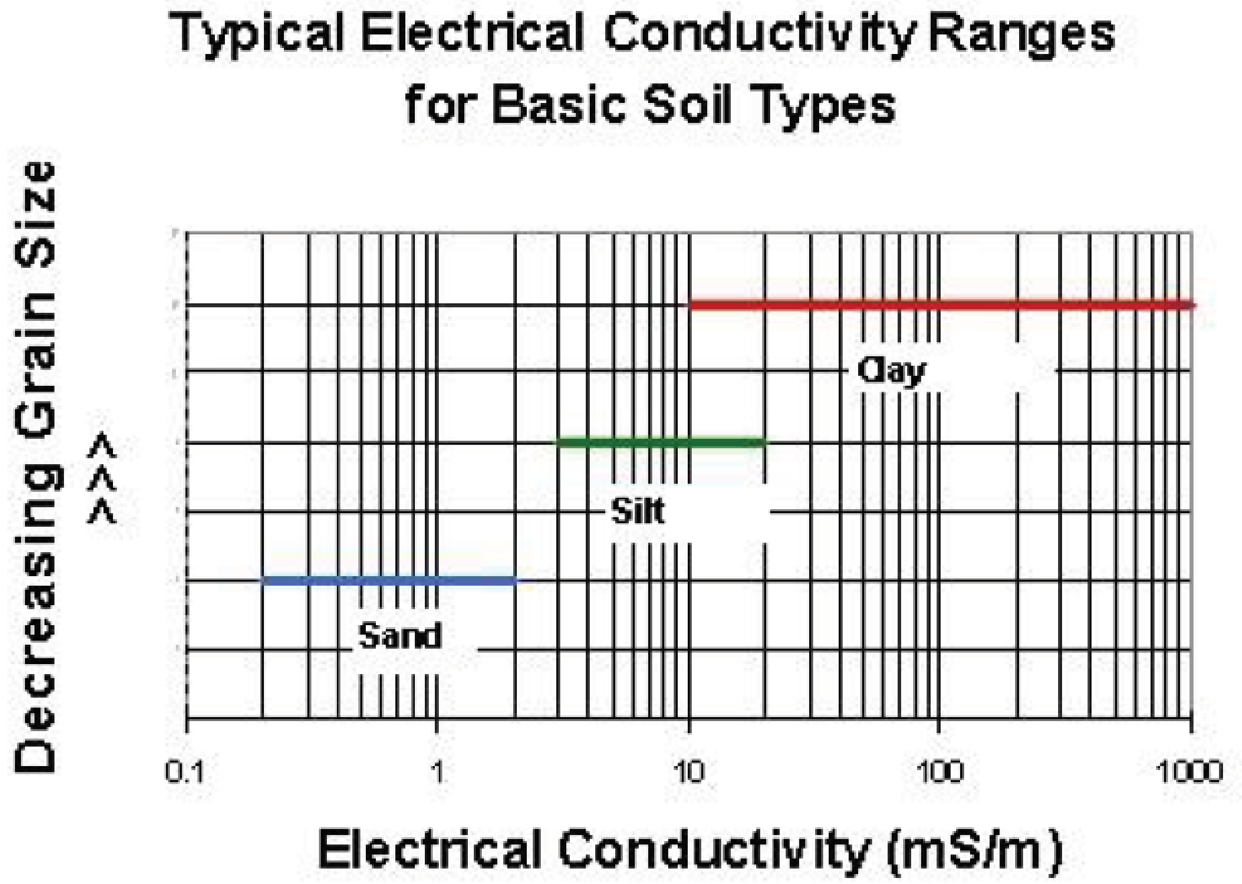


From G. Verbeek

Video Module

- Records images that show soil texture, color, grain size, etc. of the soil passing the camera
- UV light sources can be used to detect hydrocarbons
- Ideal for coarse grained soils

- Conductivity measured between two insulated electrodes
- Measured electrical conductivity related to soil water content, pore fluid conductivity, hydrocarbon contamination, and particle size

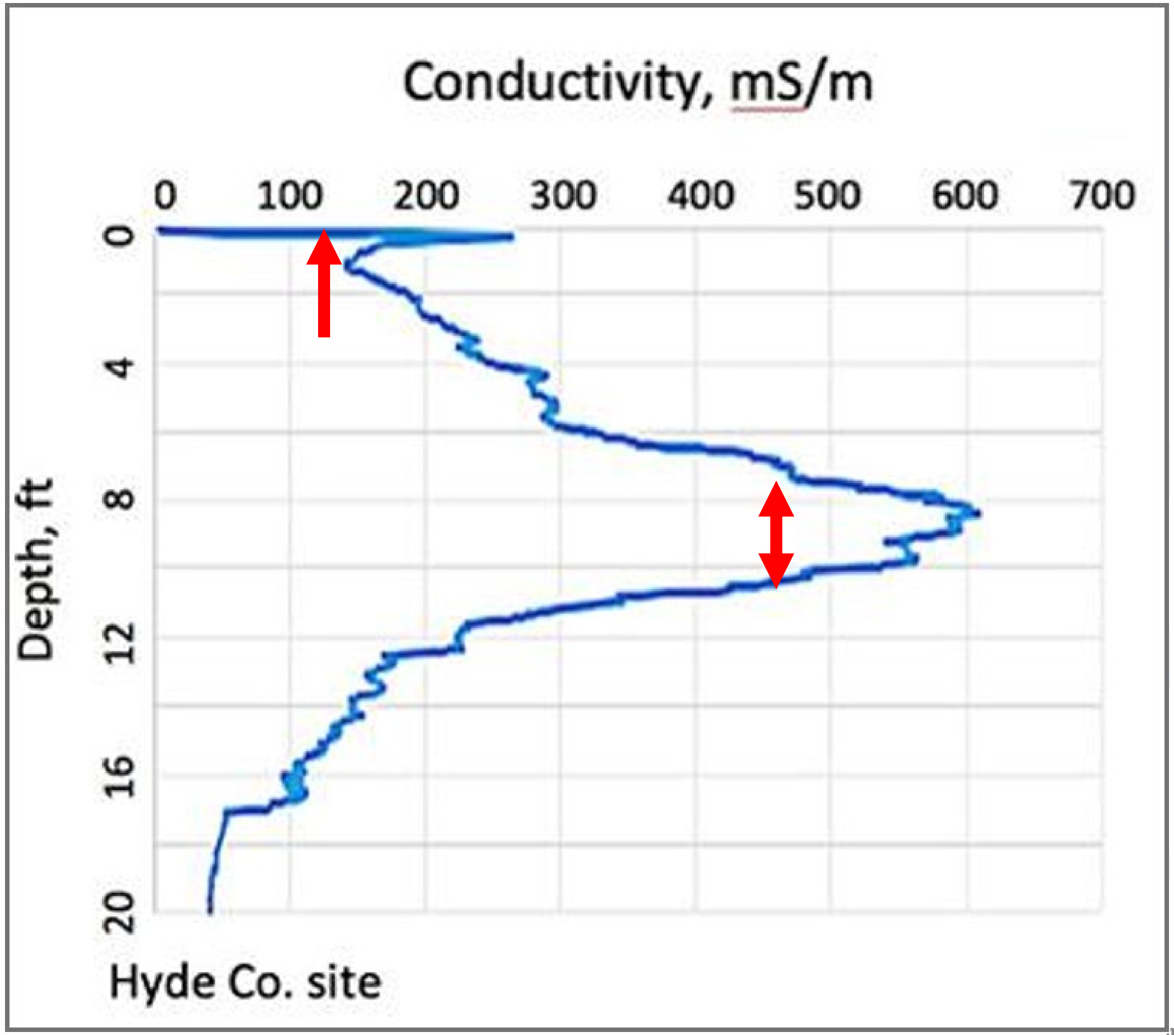


Conductivity of water (mS/m)

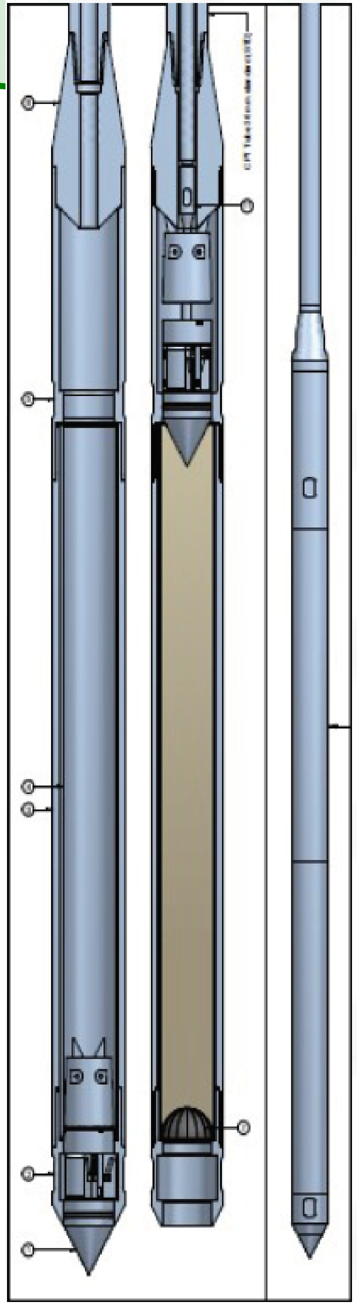
- pure water: 0.05 – 0.3
- drinking water: < 10
- lake / river water 5 – 150
- waste water > 1000
- sea water 5000
- Great Salt Lake 15800

From G. Verbeek

- **Example applications**
  - Grain sizes and soil characterization
  - Environmental applications



- Collect samples up to 2.5” diameter and 3’ long
- Sample after CPT profile with dummy cone
- Samples appropriate for soil classification and index properties



From G. Verbeek

- Additional modules available
  - u_1, u_3 pore pressure elements
  - Nuclear density / gamma cone
  - pH
  - and more…

- "Basic" CPTu can go far, while modules add cost and complexity, so only use modules as needed

Summary & Closure

Summary & Closure for CPT Overview

- Cone penetration testing measures a nearly-continuous data profile of standard data (q_c, f_s, and u_2).

- Soil behavior type and soil properties can be estimated from standard data measurements

- When soils or conditions deviate from base assumptions of interpretation methods, consider supplementary lab tests, data corrections, or adjustments to CPT procedures

- CPT capability can be expanded with additional modules
  - Vision cone, magnetometer, conductivity, sampling, among others

Additional resources and CPT standards

- NCHRP Synthesis 368 (2007) *"Cone Penetration Testing, A Synthesis of Highway Practice"*

American Society for Testing and Materials (ASTM) standards:

- D3441 "*Mechanical Cone Penetration Tests of Soil*"
- D5778 *"Performing Electric Friction Cone and Piezocone Penetration Testing of Soils"*
- D6067 *"Using the Electric Cone Penetrometer for Environmental Site Characterization"*

Example of Improving Practice
Seismic CPT Data Analysis to Derive Shear Wave Velocity Profiles

Gerald Verbeek

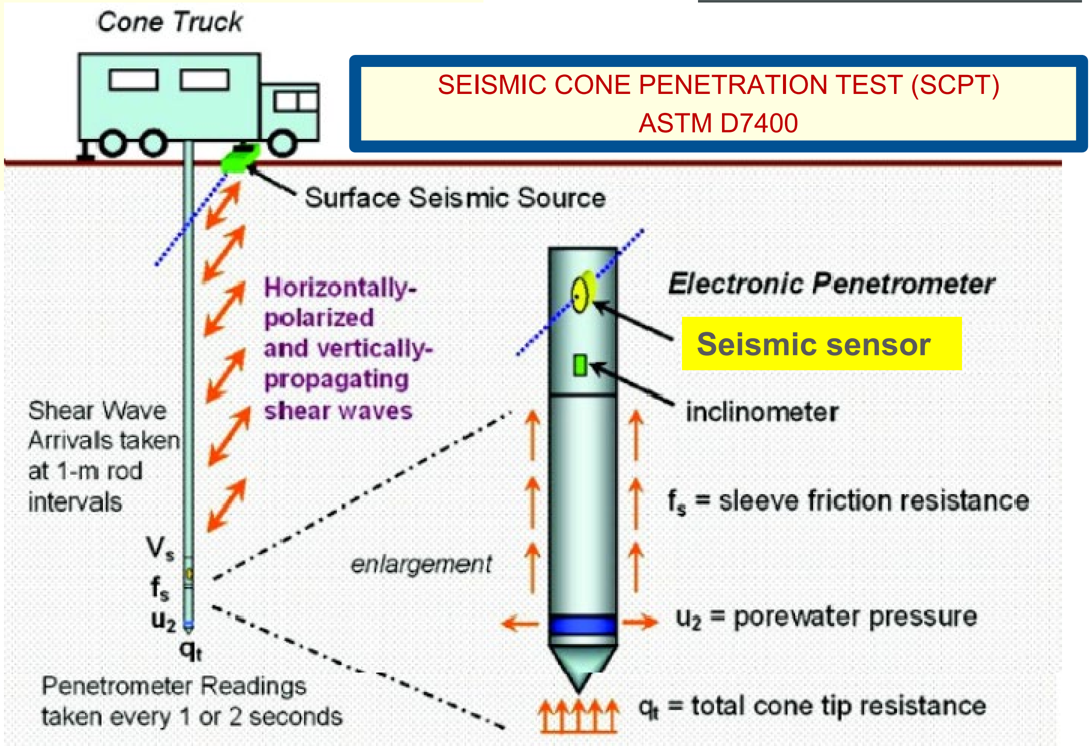
Baziw Consulting Engineers, Ltd.

Vancouver , BC - Canada

Tyler , TX - USA

Why Seismic Testing?

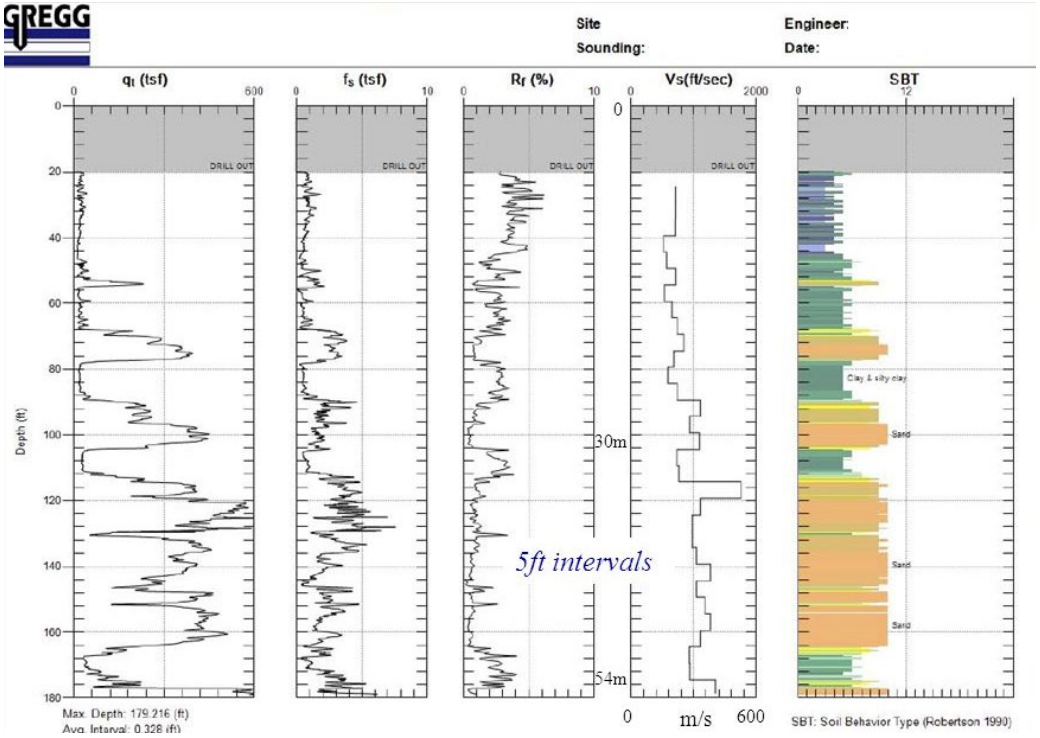
More information…..



After Ku, Mayne and Cargill, CGJ 2013

Why Seismic Testing?

More information…..



Why Seismic Testing?

That is very relevant.

- Direct measurement of the small strain Shear Modulus
  $G_0 = \rho\,(V_s)^2$
- Link to small strain Young's Modulus
  $E_0 = 2\,G_0\,(1 + \nu) \approx 2\,G_0$
- Direct measurement of the Poisson's Ratio
  $\nu = [\,V_p^2 - 2V_s^2\,] / 2\,(V_p^2 - V_s^2\,)$

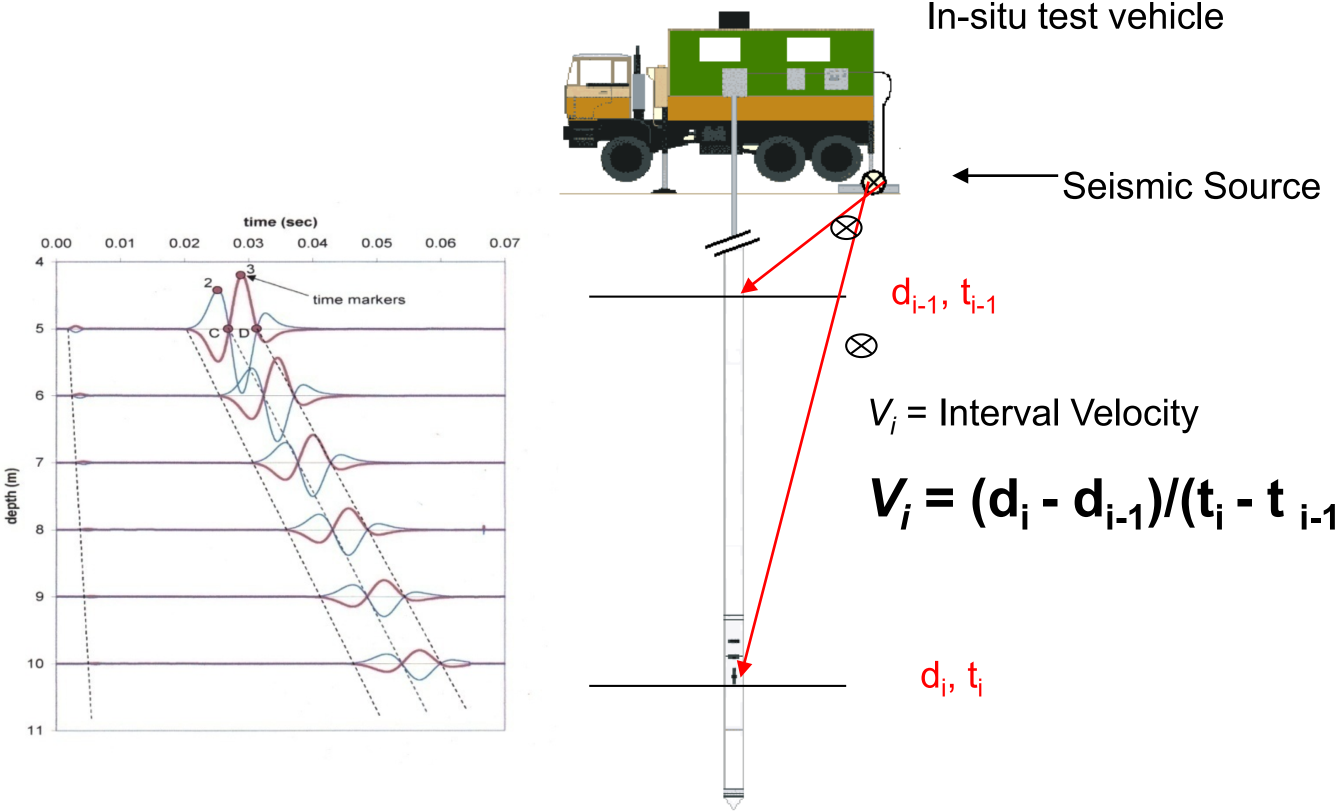
Why Seismic Testing?

It is a good tool to assess liquefaction potential.

V_s is influenced by many of the variables that influence liquefaction (such as void ratio, soil density, confining stress, stress history, and geologic age)

Analyses on the catastrophic liquefaction in Christchurch, New Zealand in 2010 and 2011 showed very clearly that near-surface rather than deep liquefaction resulted in extensive foundation damage.

How do you perform SCPT

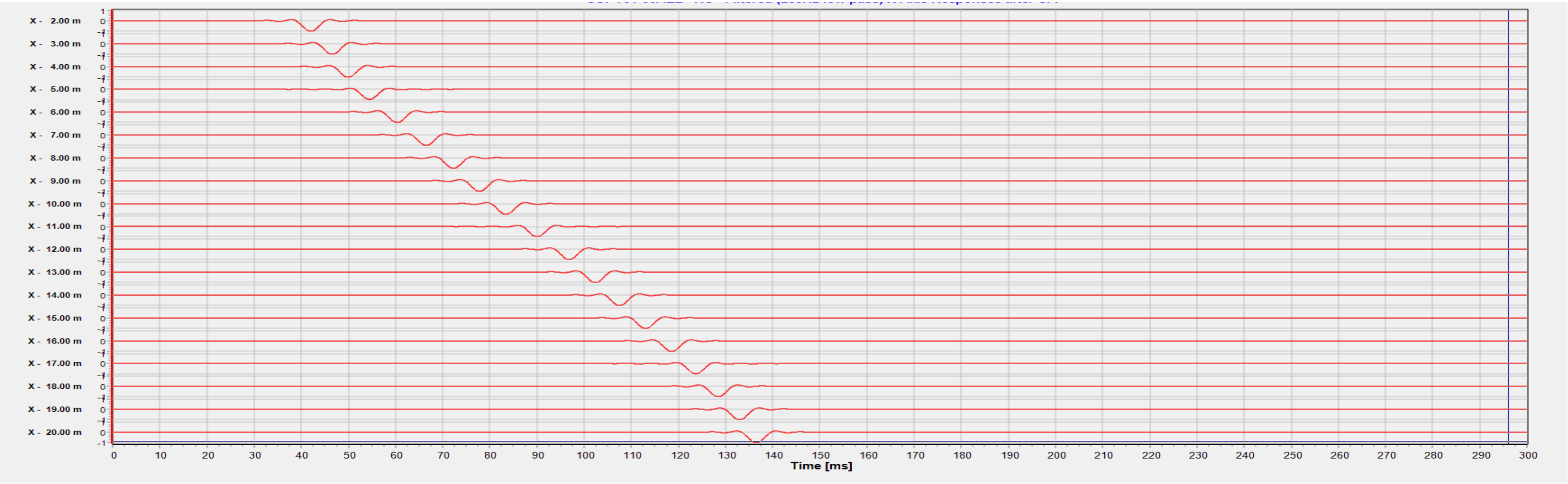


V_i = Interval Velocity

$$V_i = (d_i - d_{i-1})/(t_i - t_{i-1})$$

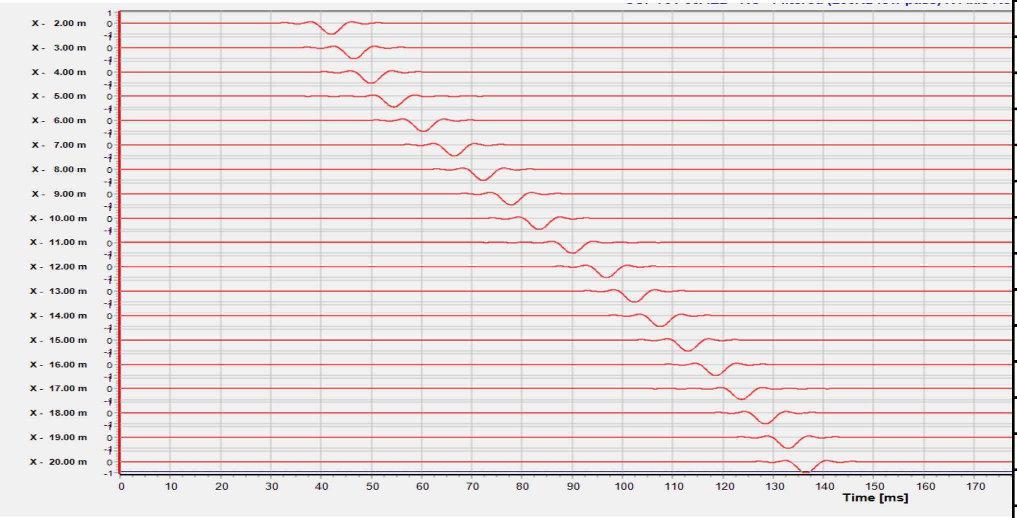
How do you perform SCPT

What you would expect and like to get ……



How do you analyze SCPT data

What you would expect and like to get ..



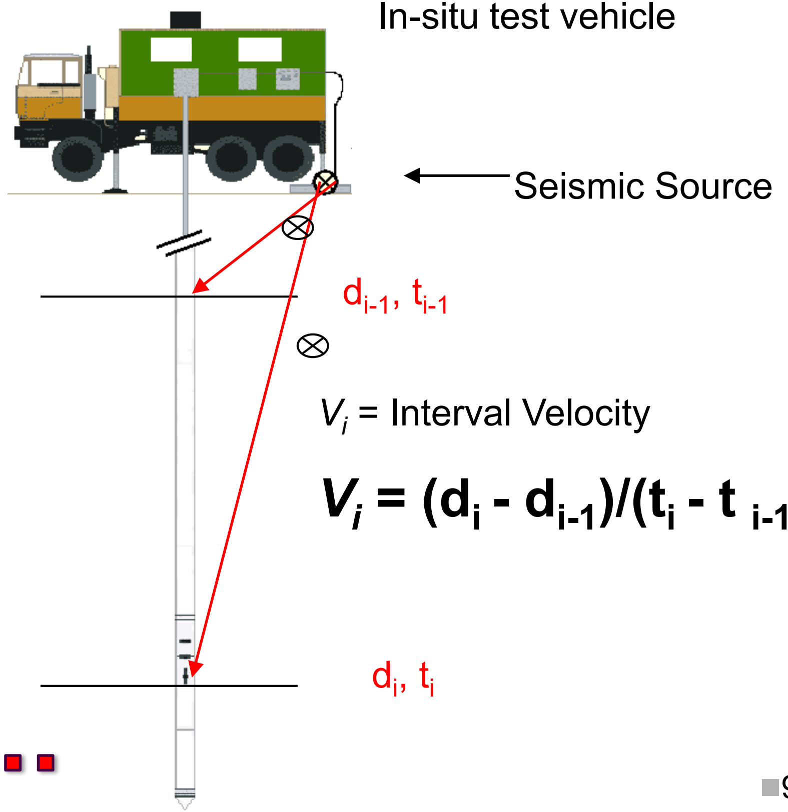
Depth [m]	Right Arrival Time [ms]
2	31.4582
3	36
4	39.3964
5	43.9182
6	49.7847
7	55.95
8	61.7268
9	67.2446
10	72.8621
11	79.4756
12	86.2683
13	91.816
14	96.9654
15	102.5032
16	108.021
17	113.1405
18	117.8715
19	122.4133
20	125.969

Offset 1.7 m

How do you analyze SCPT data

Layer 1: distance = 2.62 m
time = 31.4582 ms
velocity = 2.62/0.0314582
= 83.44 m/s

Layer 2: distance 2 = 3.45 m
change in distance = 0.83 m
time 2 = 36 ms
change in time = 4.5418 ms
velocity = 182.75 m/s

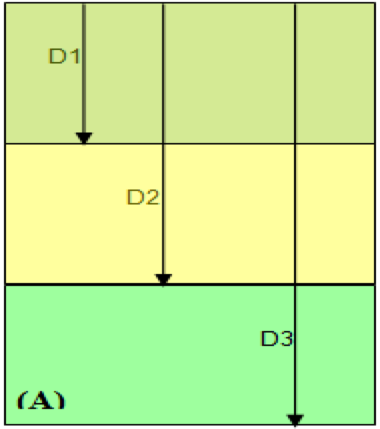


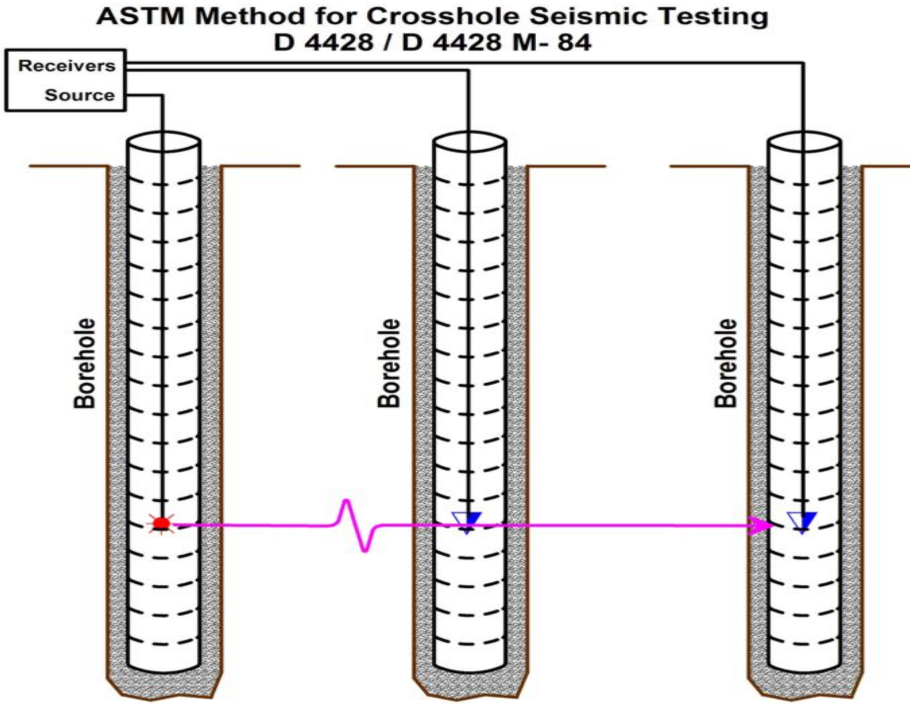
V_i = Interval Velocity

$$V_i = (d_i - d_{i-1})/(t_i - t_{i-1})$$

Not really, unless….

How do you analyze SCPT data





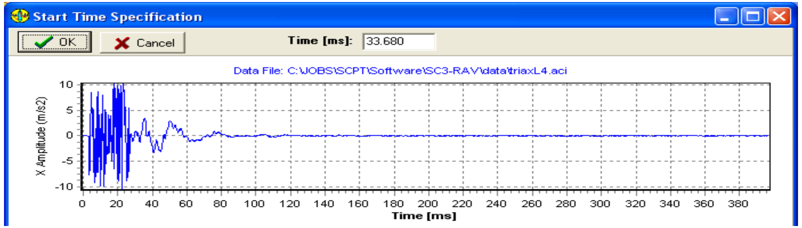
this requires a very small offset and that creates issues

You test like crosshole testing

Seismic Source Radial Offset

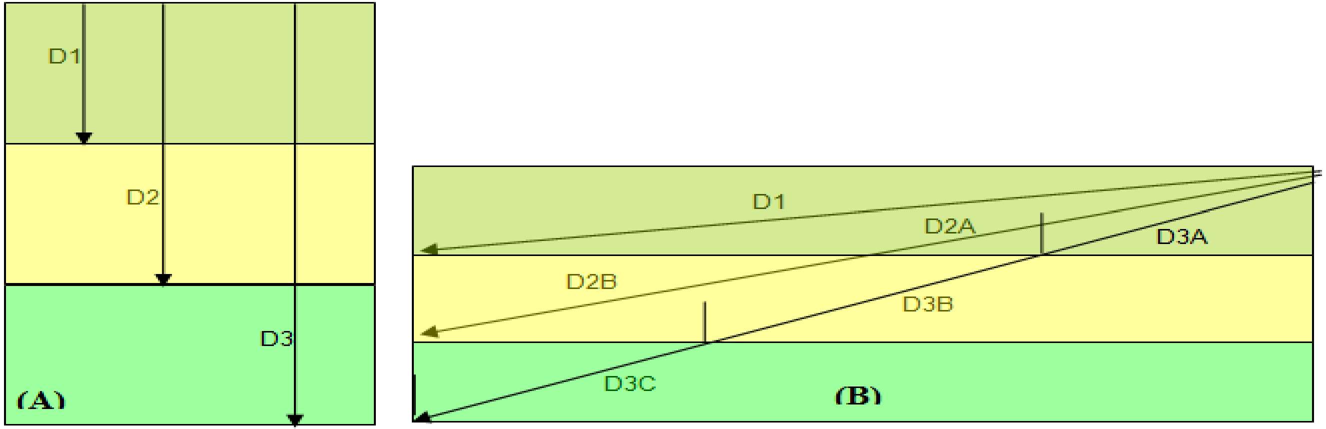
What is the "correct" SSRO?

- Rod noise interference.
- Near-field effects.
- Increased travel time through layers.



Offset: 1 m	Offset: 3 m	Offset: 5 m
Test depth: 2 m	Test depth: 2 m	Test depth: 2 m
Interval velocity: 150 m/s	Interval velocity: 150 m/s	Interval velocity: 150 m/s
Arrival time: 14.9 m/s	Arrival time: 24.0 ms	Arrival time: 35.9 ms
Δt of 1 ms ≈ 7 % error	Δt of 1 ms ≈ 4 %	Δt of 1 ms ≈ 3 %

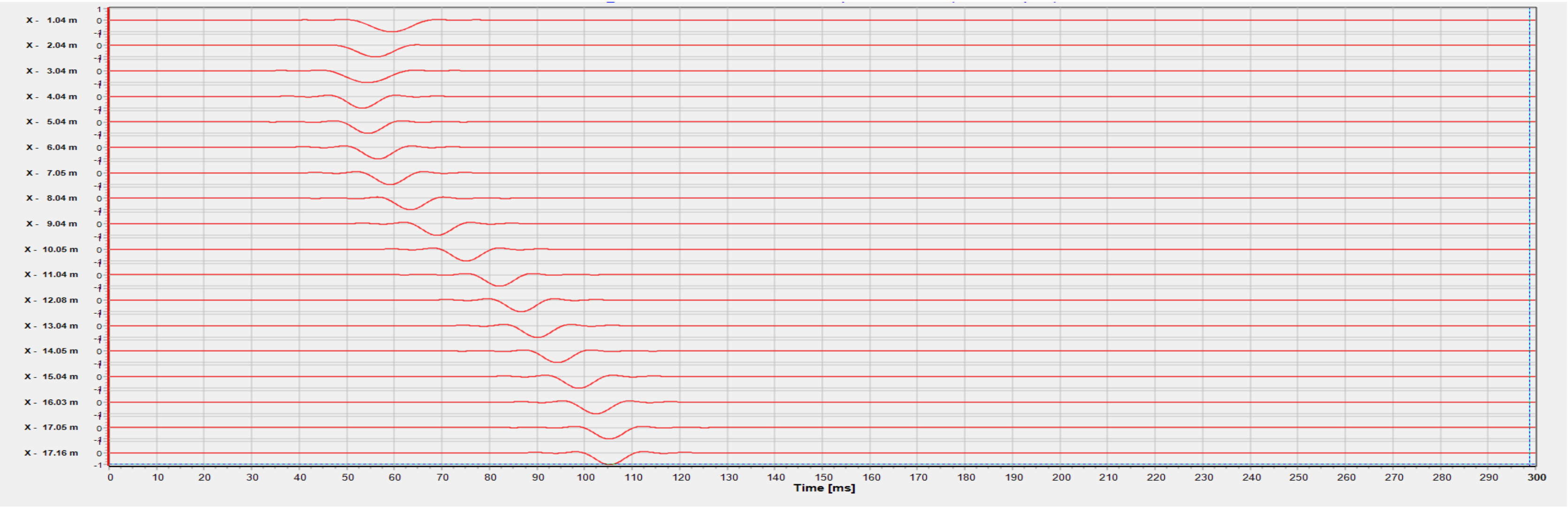
How do you analyze SCPT data



But now your math doesn't work and there is another issue

How do you analyze SCPT data

Sometimes you get profiles like this



How do you analyze SCPT data

And that is why people (might) say:

"Near surface estimates are difficult to obtain and subsequently interval velocity estimates are inaccurate“

But it all depends on how you analyze the data

How do you analyze SCPT data

Pierre de Fermat

1607 - 1665

A smart man:

Fermat's principle states that the path taken by a ray between two given points is the path that can be traversed in the *least time*

Proposed 1662

~~**Least distance**~~

Least Time

How do you analyze SCPT data

Willibrord Snellius

1580 - 1626

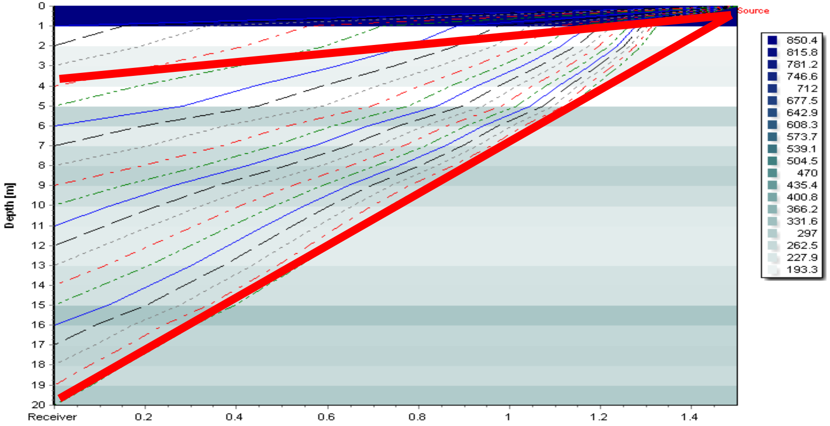
A Dutch man:

The law eventually named after Snell was first accurately described by the Persian scientist Ibn Sahl at the Baghdad court in 984.

Snell's law states that the ratio of the sines of the angles of incidence and refraction is equivalent to the ratio of phase velocities in the two media

Derived 1621

How do you analyze SCPT data

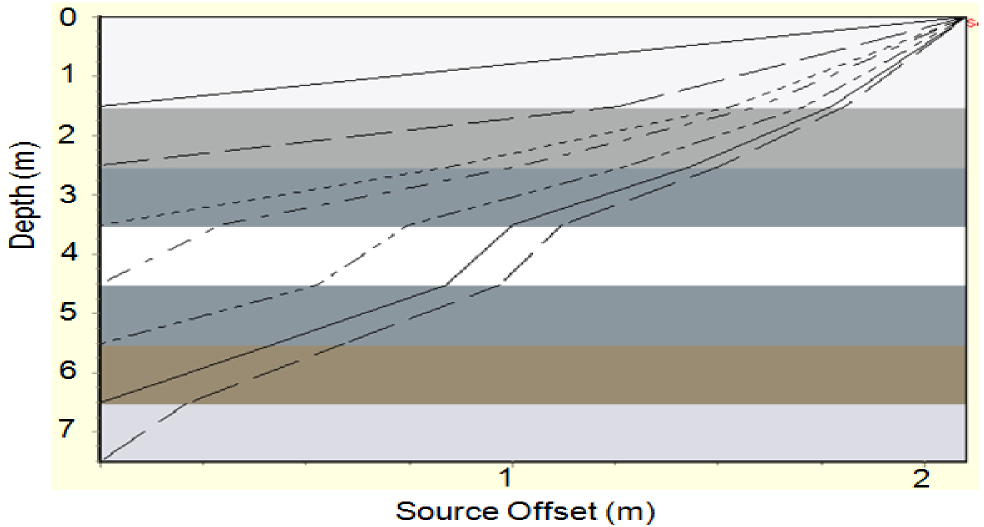


Interval Depth [m]	Interval Velocity Estimate [m/s]		**Difference average [%]**
	SRA	IFM	
0-1	850	850	0
1-2	114	160	34
2-3	167	195	16
3-4	184	198	7
4-5	152	159	4
5-6	262	270	3
6-7	206	210	2

How do you analyze SCPT data

Iterative Forward Modeling (IFM):

- Laterally homogeneous medium.
- Refraction at layer boundaries (Snell's Law).
- Fermat's principle of least time.



Some other suggestions

The first step is to derive the arrival times......

- Standard method is to pick first arrivals.
- An alternative is to use reverse polarity method.
- Or you can use markers and analyze each side independently.

Some other suggestions

Don't stack data during data acquisition:

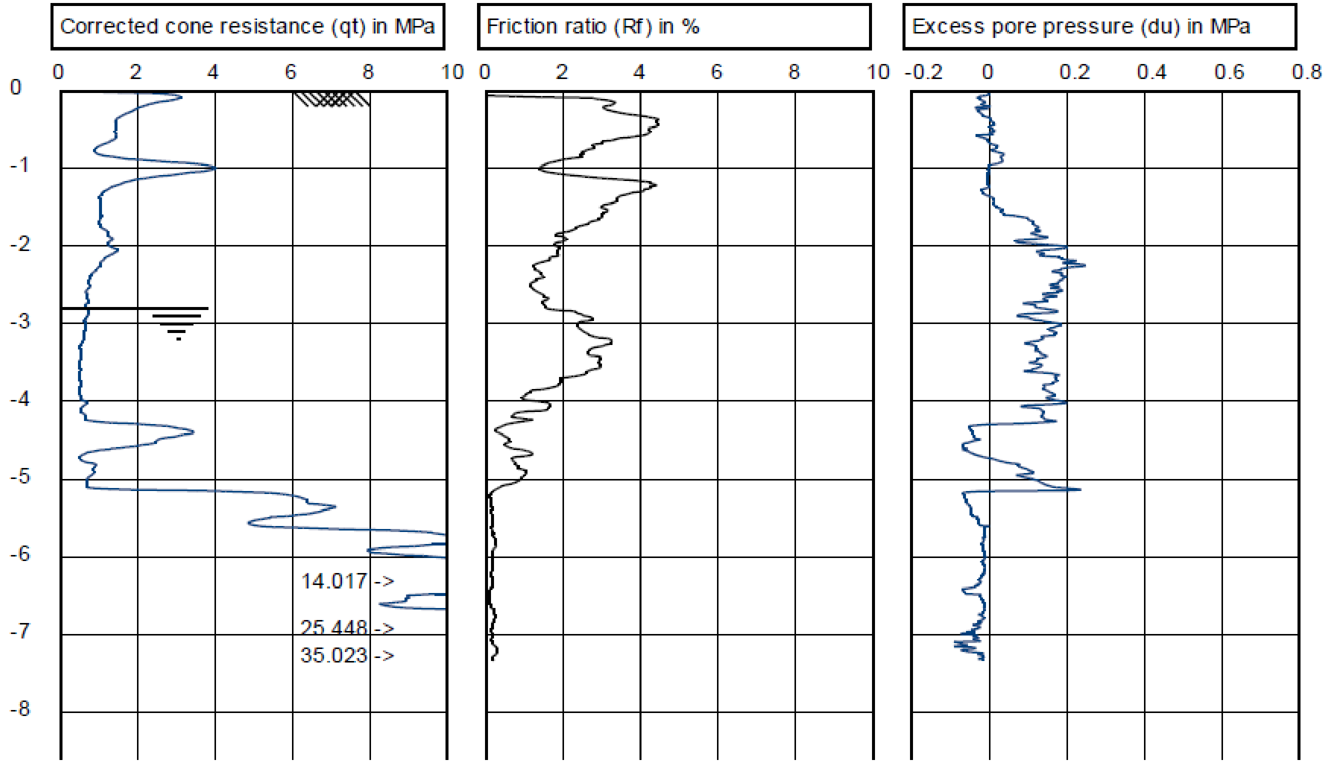
Data stacking is nothing more than averaging. Now consider the case of the statistician who drowns while fording a river that he calculates is, on average, three feet deep. If he were alive to tell the tale, he would expound on the "flaw of averages," which states, simply, that plans based on assumptions about average conditions usually go wrong. This basic but almost always unseen flaw shows up everywhere in business, distorting accounts, undermining forecasts, and dooming apparently well-considered projects to disappointing results.

Some other suggestions

Suggestions for a typical report:

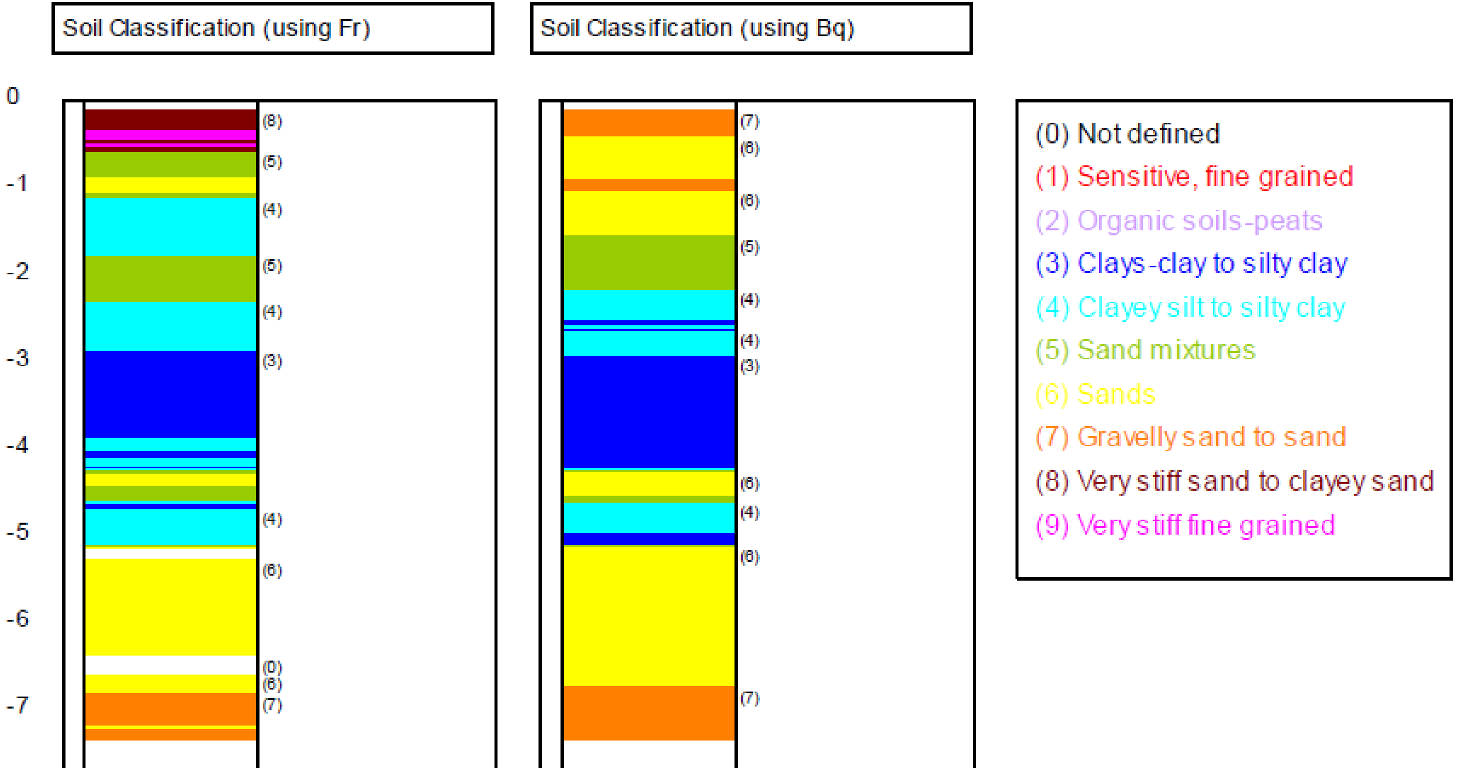
- Show each step in your report and not just the final result (be transparent)
- Show the results in such a way that the process can be duplicated (so decimal places do not necessarily imply accuracy)
- Structure your report the same every time (be consistent)
- Let the results be the results (be honest)
- Include, where appropriate, comments on the report (be an engineer)

Case Study



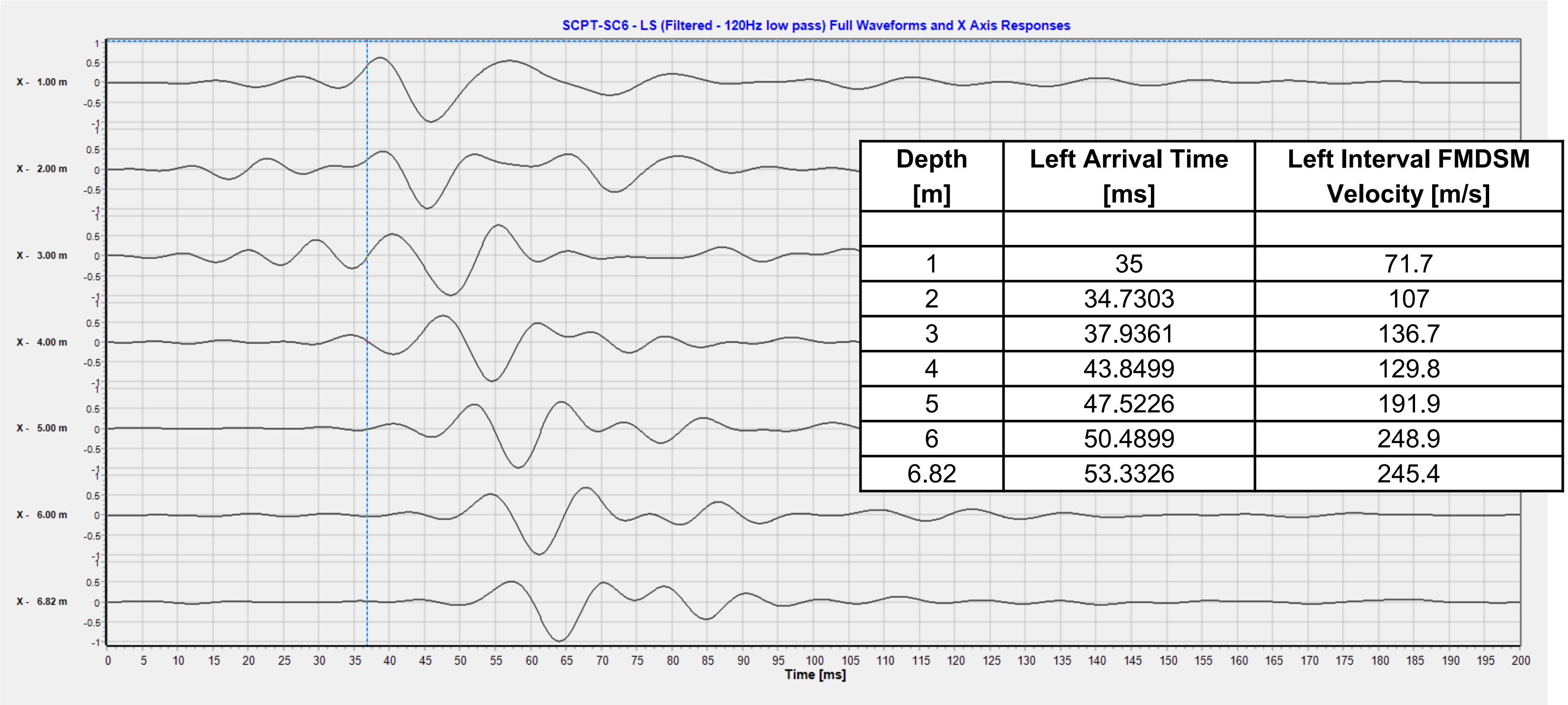
Corrected cone resistance (qt) in MPa
Friction ratio (Rf) in %
Excess pore pressure (du) in MPa
0 2 4 6 8 10
0 2 4 6 8 10
-0.2 0 0.2 0.4 0.6 0.8
0
-1
-2
-3
-4
-5
-6
-7
-8
14.017 ->
25.448 ->
35.023 ->

Case Study



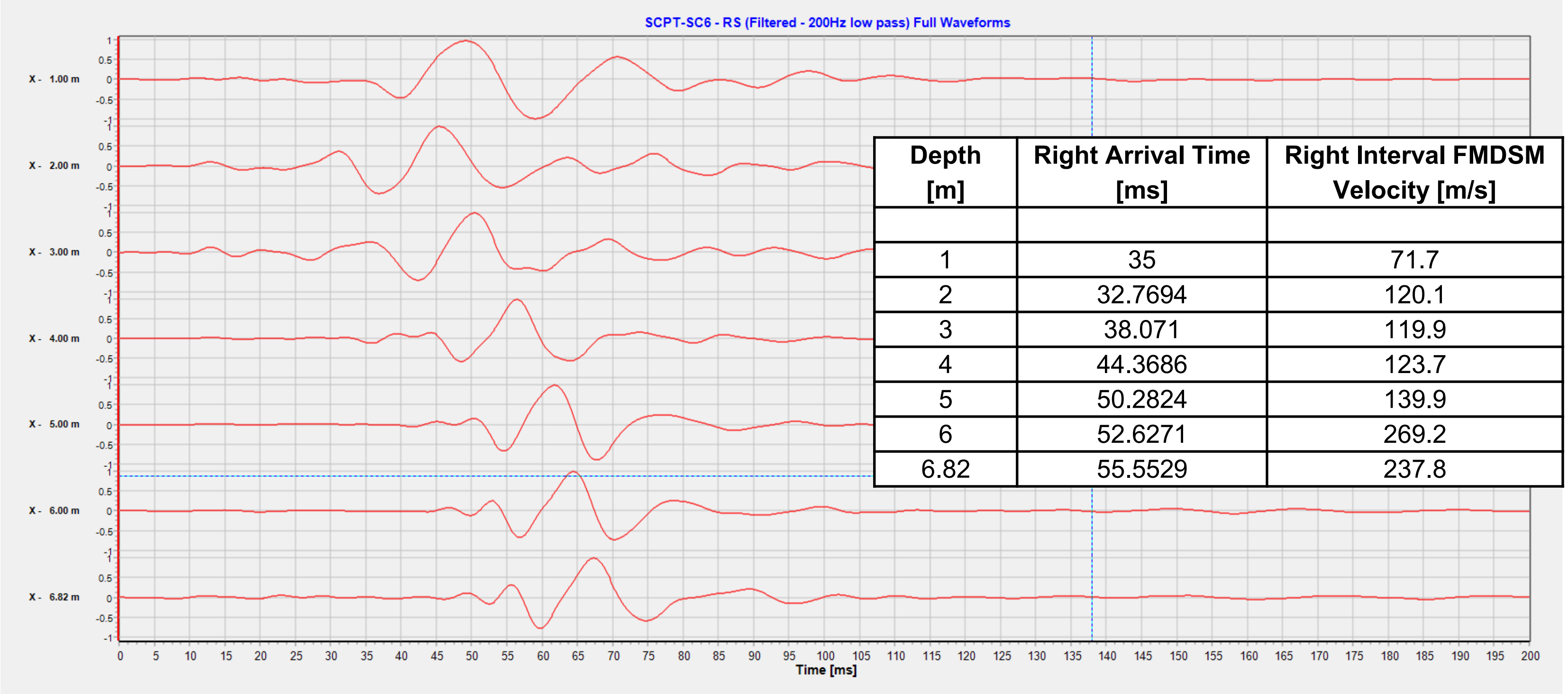
Soil Classification (using Fr)
Soil Classification (using Bq)
0
-1
-2
-3
-4
-5
-6
-7
(8)
(5)
(4)
(5)
(4)
(3)
(4)
(6)
(0)
(6)
(7)
(7)
(6)
(6)
(5)
(4)
(4)
(3)
(6)
(4)
(6)
(7)
(0) Not defined
(1) Sensitive, fine grained
(2) Organic soils-peats
(3) Clays-clay to silty clay
(4) Clayey silt to silty clay
(5) Sand mixtures
(6) Sands
(7) Gravelly sand to sand
(8) Very stiff sand to clayey sand
(9) Very stiff fine grained

Case Study



Depth [m]	Left Arrival Time [ms]	Left Interval FMDSM Velocity [m/s]
1	35	71.7
2	34.7303	107
3	37.9361	136.7
4	43.8499	129.8
5	47.5226	191.9
6	50.4899	248.9
6.82	53.3326	245.4

Case Study



Depth [m]	Right Arrival Time [ms]	Right Interval FMDSM Velocity [m/s]
1	35	71.7
2	32.7694	120.1
3	38.071	119.9
4	44.3686	123.7
5	50.2824	139.9
6	52.6271	269.2
6.82	55.5529	237.8

Case Study

Depth [m]		LS Interval Velocity [m/s]	RS Interval Velocity [m/s]	Avg. Interval Velocity [m/s]	Spread
0	1	71.7	71.7	71.7	0%
1	2	107	120.1	113.6	6%
2	3	136.7	119.9	128.3	7%
3	4	129.8	123.7	126.8	2%
4	5	191.9	139.9	165.9	16%
5	6	248.9	269.2	259.1	4%
6	6.82	245.4	237.8	241.6	2%

The end

Conclusion

Acquisition of seismic data to derive shear wave velocities is more complex than often realized, but there is a logic behind it provided you understand and respect how seismic waves travel through the soil

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Today's Panelists

Moderated by:
Derrick Dasenbrock,
FHWA

Gerald Verbeek,
Eijkelkamp North America

Diane Moug,
Portland State University

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