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Offices Covering all USA

FHWA CPT Workshop

Goal

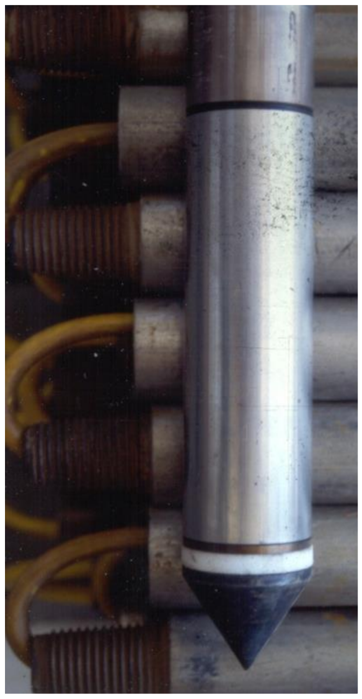
Assist DOT’s to start and increase use of CPT in Highway applications by developing, presenting and discussion information on CPT

Introduction to CPT

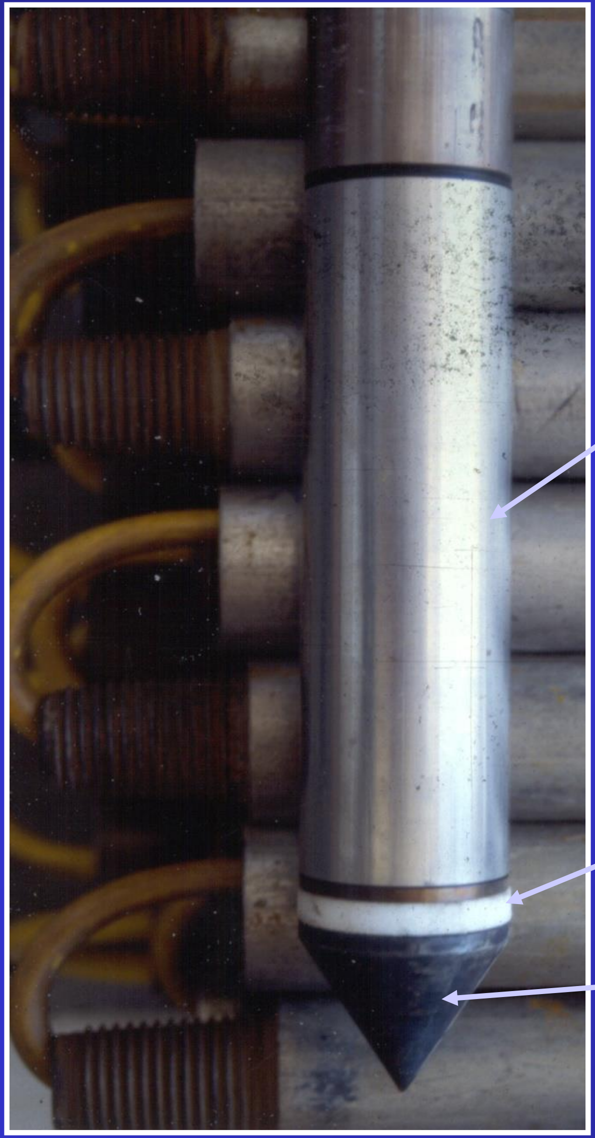
Peter K. Robertson

FHWA CPT Workshop

Sept. 2015



Basic Cone Parameters



Sleeve Friction

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

Pore Pressure, u_2

Tip Resistance

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

Robertson, 2015

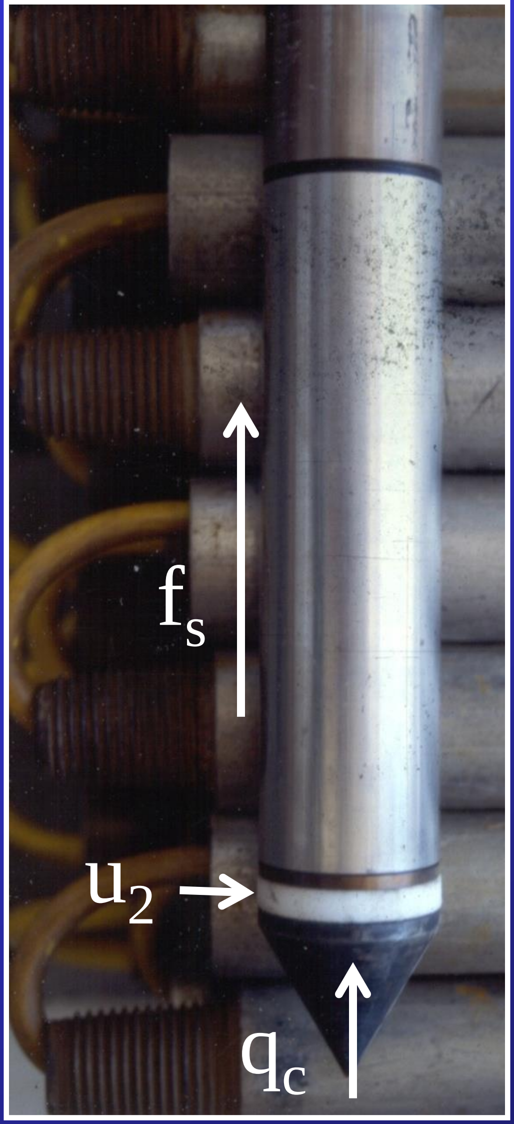
Cone Penetration Test (CPT)

ADVANTAGES:

- Fast and continuous profiling
- Repeatable 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)



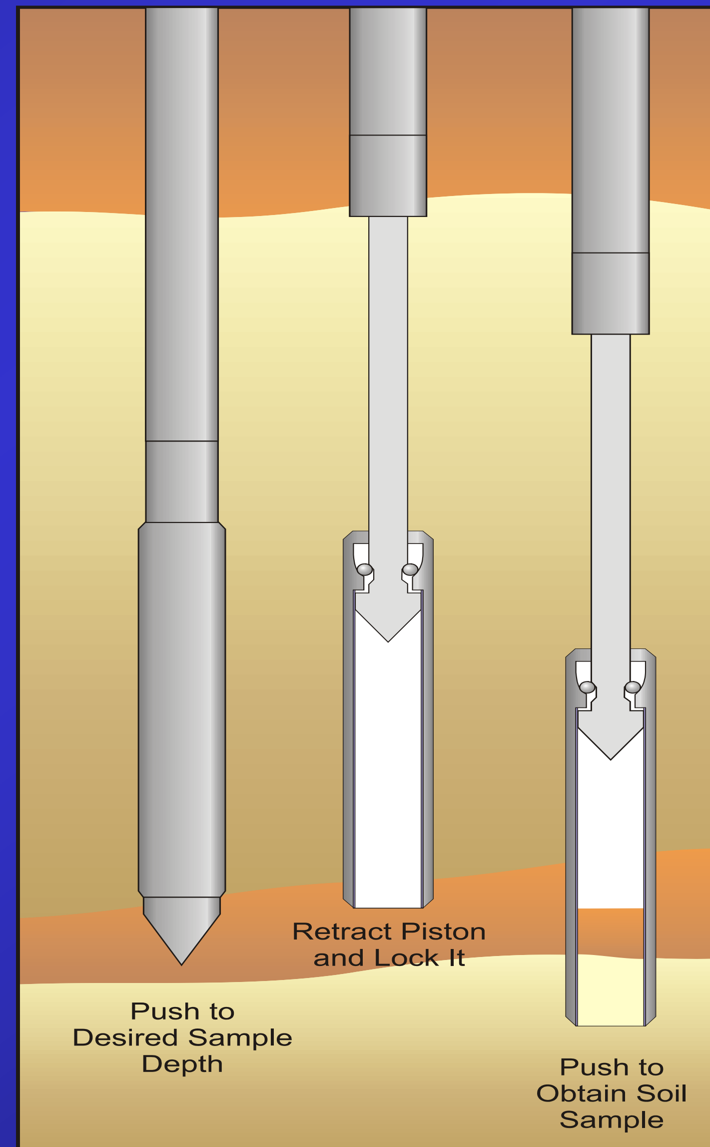
Typical approach using CPT

- CPT first
  - Reliable and fast (~600 ft/day)
  - Continuous profile (vert. & horiz. variability)
  - Preliminary interpretation (stratigraphy and parameters)
  - Small number of disturbed samples using CPT (classification purposes)
- Small number of boreholes to obtain good quality samples
  - Small number of good quality samples in layers that are critical to project

Example CPT Soil Sampling

CPT (Piston-Type) Sampler

- Simple single-tube system
- 30cm (12”) long by 25mm (1 ”) diameter
- Similar size as SPT sampler
- Good for classification purposes



Ground Investigation

To investigate ground and groundwater conditions in and around site consistent with project requirements

- Nature, sequence and variability of strata
- Groundwater conditions
- Physical, chemical and mechanical characteristics of strata

Field work designed to test and evaluate geologic model

Geotechnical Risk

Sum of:

- Hazards (What can go wrong?)
  - including geologic complexity
- Probability of occurrence (How likely is it?)
- Consequences (What are the consequences?)
- Experience of engineer (What is local experience?)

What level of sophistication is appropriate for site investigation & analyses?

GOOD	**Precedent & local experience**	*POOR*
SIMPLE	**Design objectives**	*COMPLEX*
LOW	**Level of geotechnical risk**	*HIGH*
LOW	**Potential for cost savings**	*HIGH*

↓ ***Traditional Methods*** — ***Simplified***

↓ ***Advanced Methods*** — ***Complex***

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

Example CPT pushing equipment

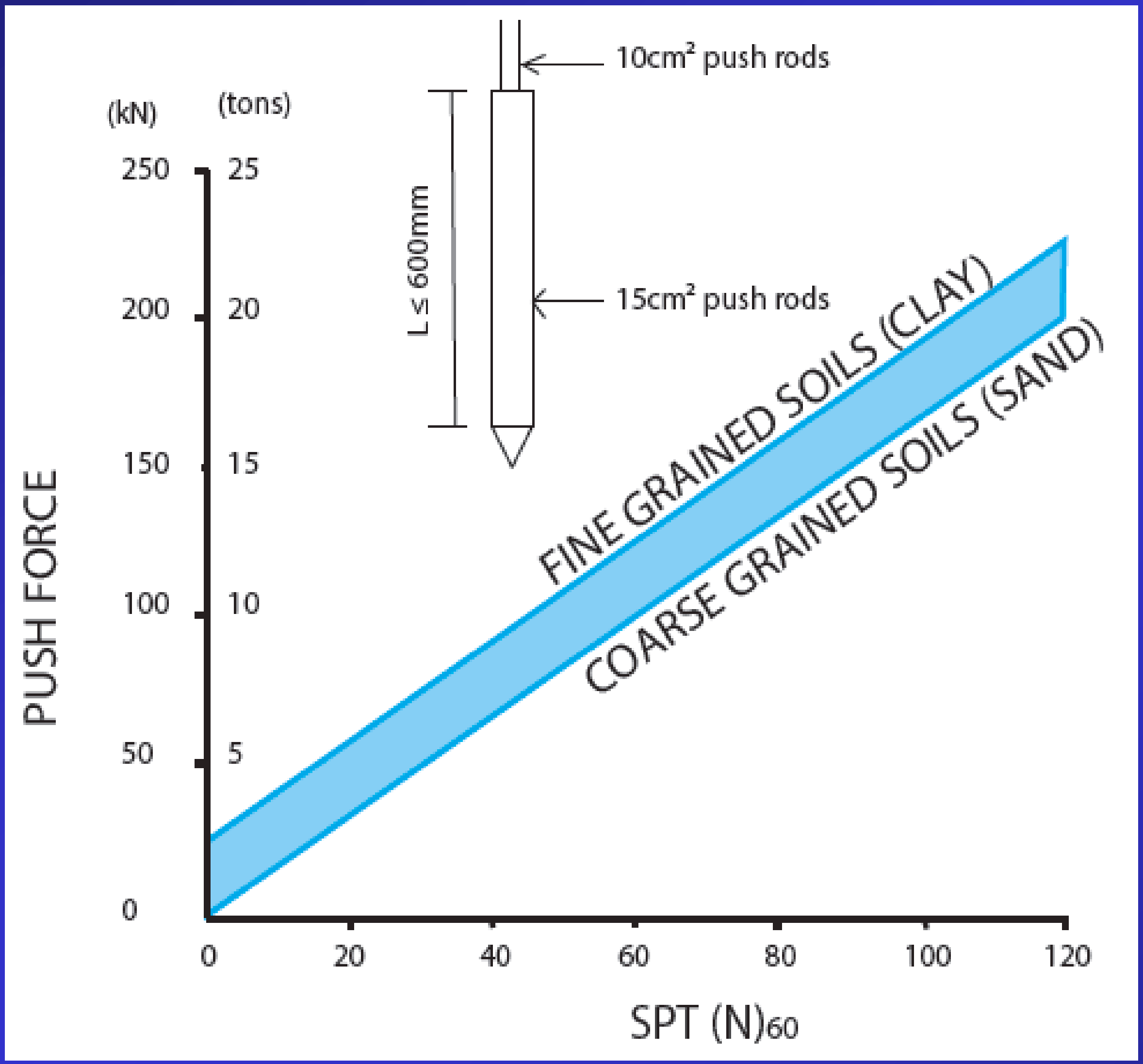
Example CPT pushing equipment

Small drill-rig to push CPT using anchor (1 flight of auger)

Improvements in CPT Equipment

- Robust designs
- Improved sensitivity
- Digital data collection and processing
- Equal end area friction sleeve
- New sensors:
  - Verticality (i)
  - Pore pressure (u)
  - Seismic (V_s)

How deep can you push the CPT?



Depends on:

- Reaction/push force
- Rod friction
- Density of ground

With 15 cm^2 cone (& 10cm^2 push rods) and *20 tons* reaction – can penetrate soil with SPT $(N)_{60} > 100$ (i.e. soft rock)

How accurate is the CPT?

- Most commercial cones are designed to measure max. full-scale output (FSO) tip stress, q_c = 1,000tsf (100 MPa)
- Most strain gauge load cells have accuracy of ± 0.1% FSO, i.e. accuracy ~ ± 1tsf (0.1 MPa)
  - Sands (q_c > 100tsf) - accuracy better than 1% of measured value
  - Soft clays (q_c < 10tsf) - accuracy maybe less than 10% of measured value

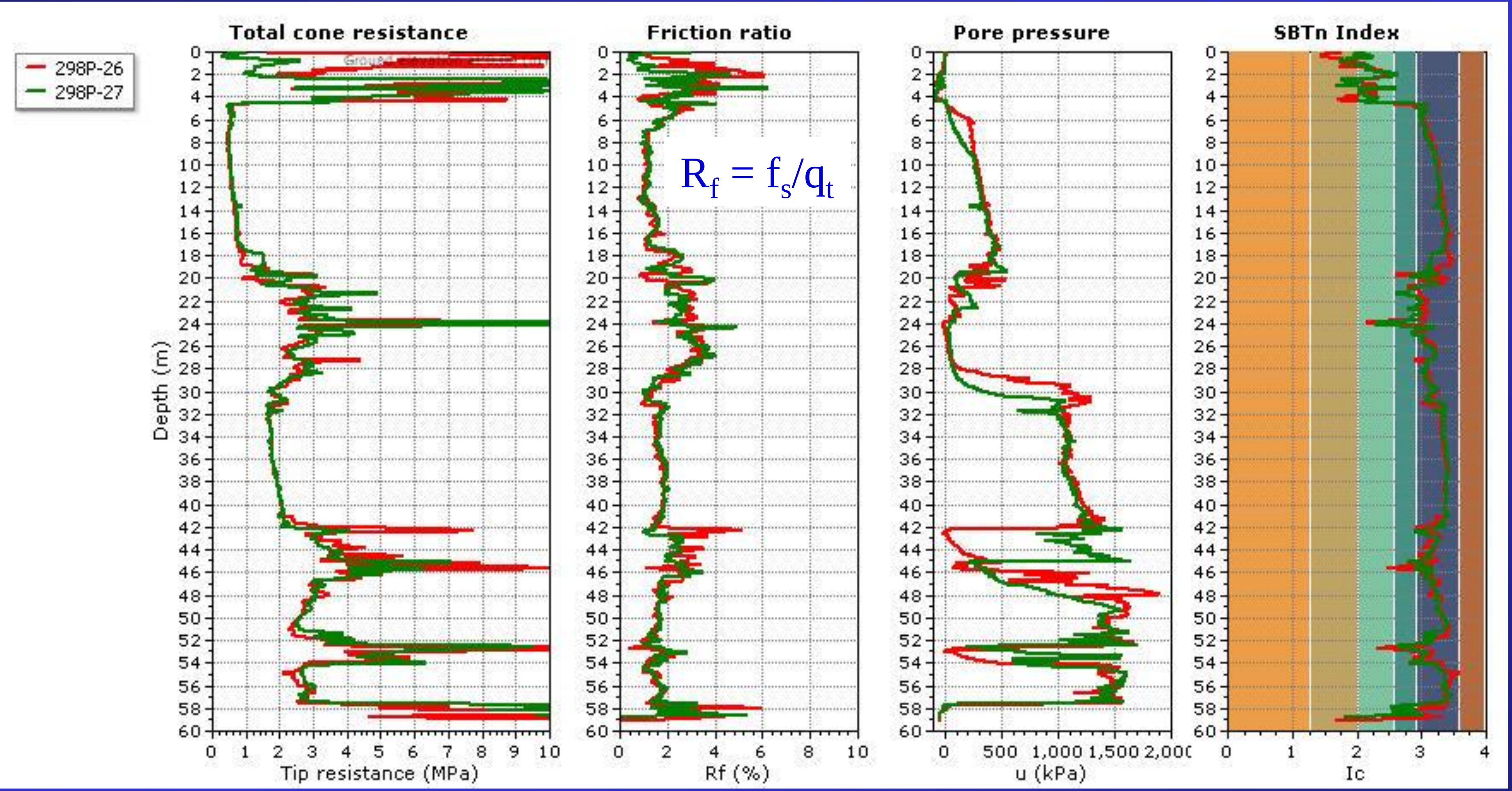
Need low capacity cones for soft clays

Accuracy - Repeatability

- In general:
  - Tip (q_t) is more accurate & repeatable than sleeve (f_s)
    - Prefer separate load cells to improve accuracy of f_s
    - Equal end area sleeves to minimize water effects on f_s
    - Check dimensional tolerance on sleeve
  - Tip (q_t) is more accurate & repeatable than u_2
    - *Except in very soft fine-grained soils (where q_c can be very small and u_2 can be very large)*
    - Potential loss of saturation in stiff dilative soils (negative values for u_2)

Robertson, 2015

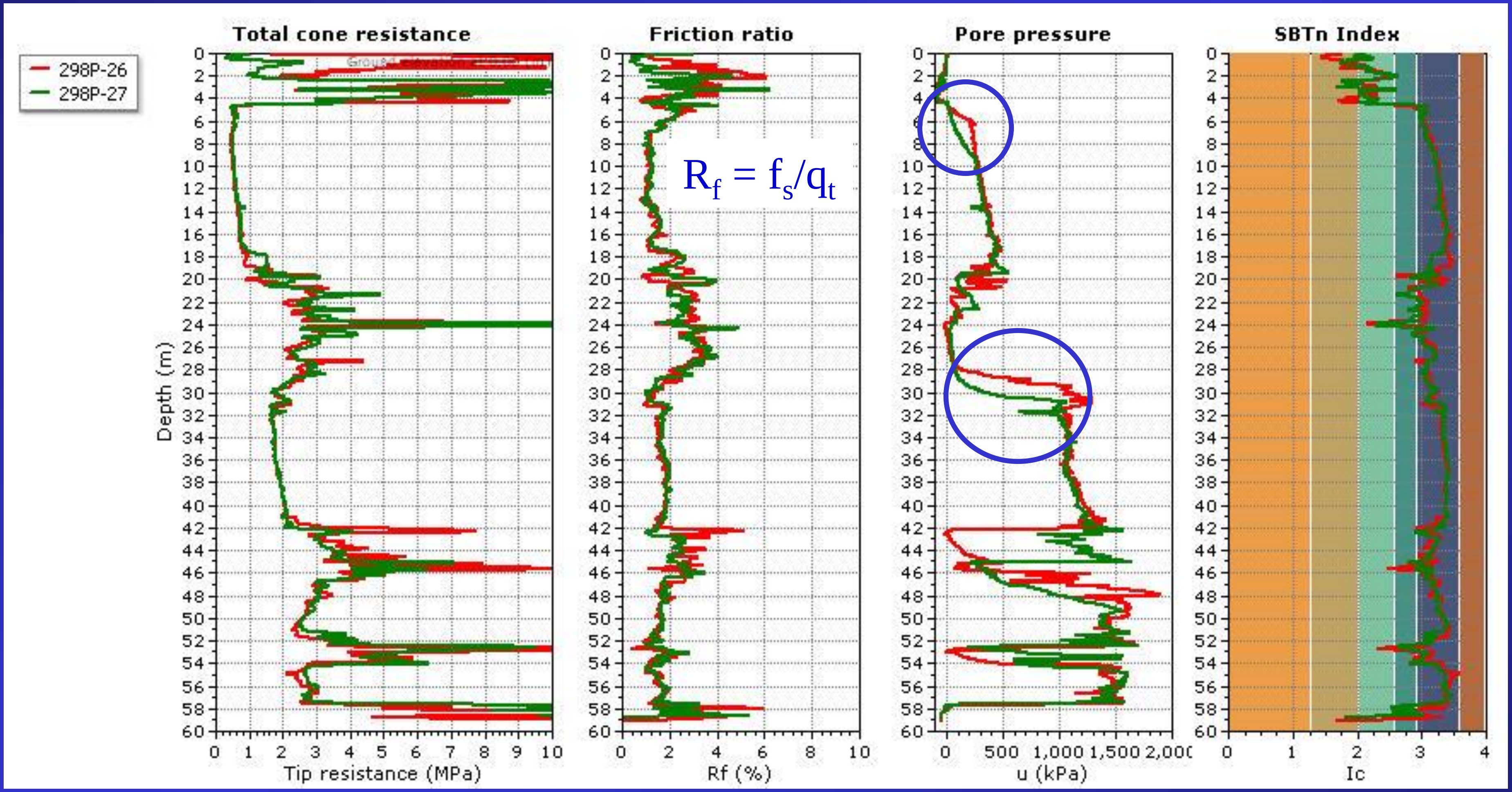
Repeatability - example



High level of repeatability

Robertson, 2015

Repeatability - example



Loss of saturation can produce 'sluggish' pore pressure response

Robertson, 2015

Repeatability of pore pressures data?

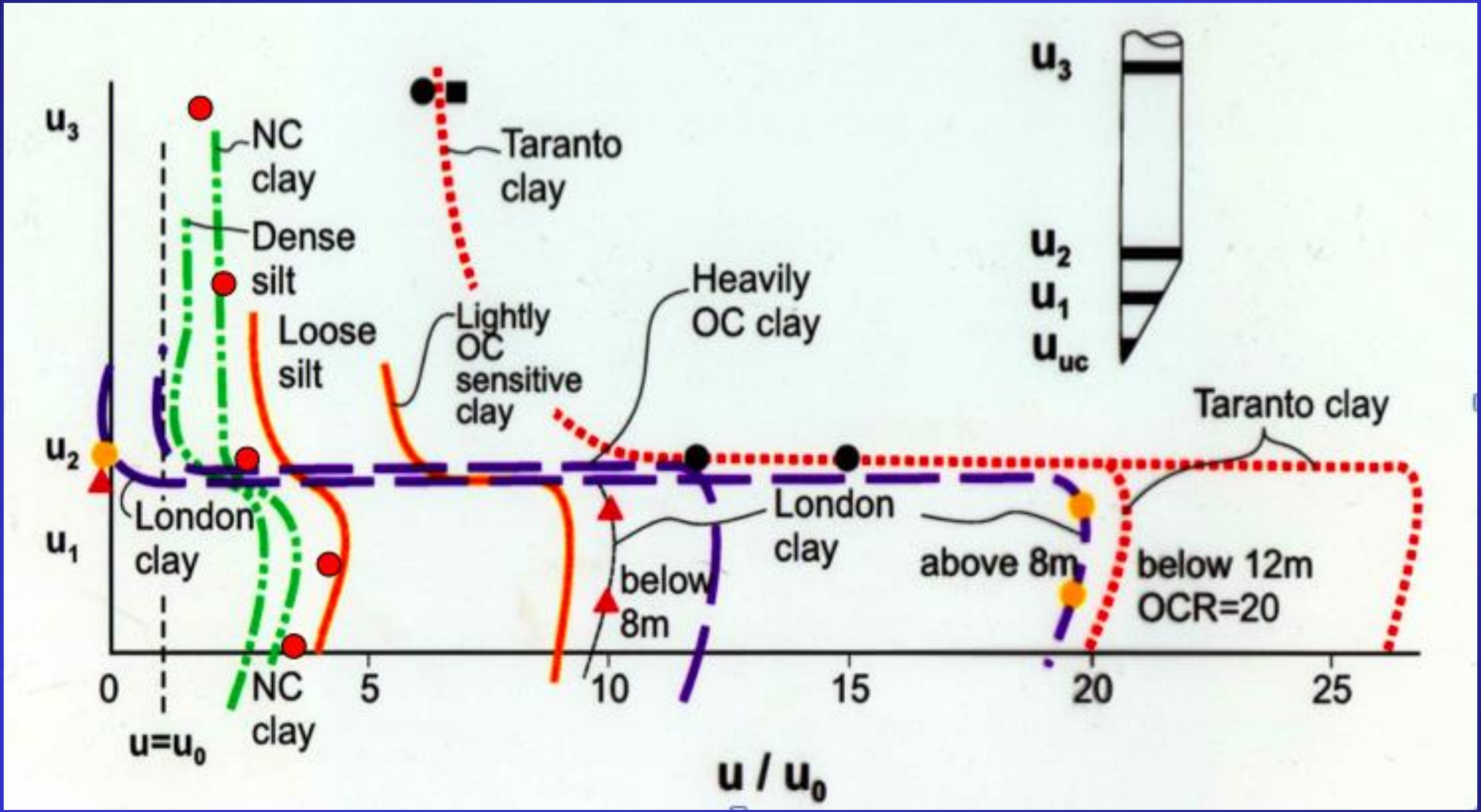
Why is pore pressure data so complex and often lacks repeatability?

- complex stress and strain field around cone
- strongly dilative soils can produce negative pore pressures at u_2 location

Pore pressure data can be very good in soft fine-grained soils with high GWL

- high positive pore pressures throughout
- short depth to saturated soils

Complex distribution of pore pressures



Modified from Campanella et al. 1985

Robertson, 2015

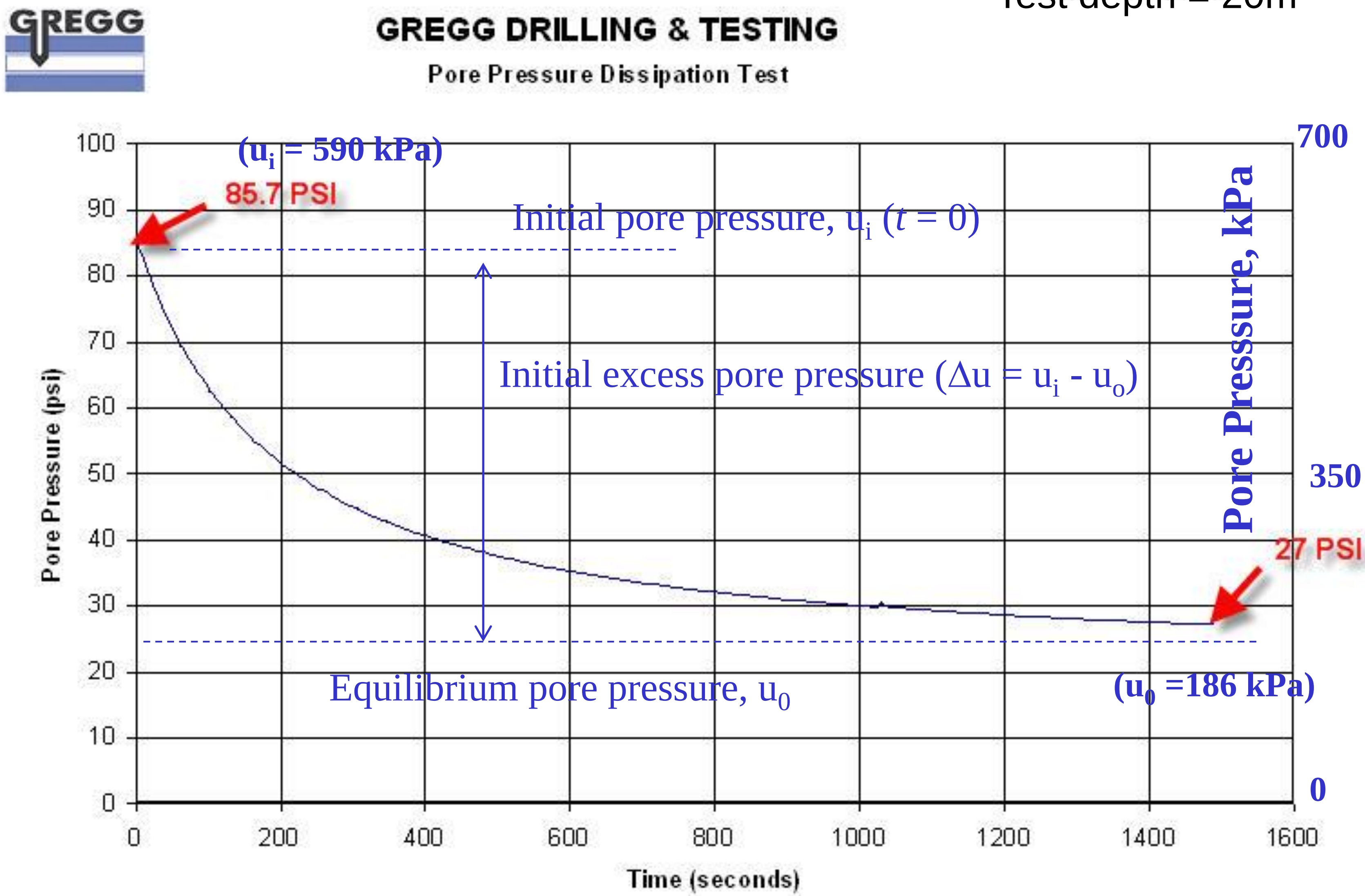
Dissipation test

- Provides information on:
  - Equilibrium pore pressure, u_0 (at that location and time)
    - piezometric profile (is it hydrostatic?)
    - piezometric surface (i.e. GWL)
  - Rate of dissipation
    - Controlled primarily by coefficient of consolidation (c_h) and permeability (hydraulic conductivity, k_h)
    - Varies by orders of magnitude (very fast to very slow)

Robertson, 2015

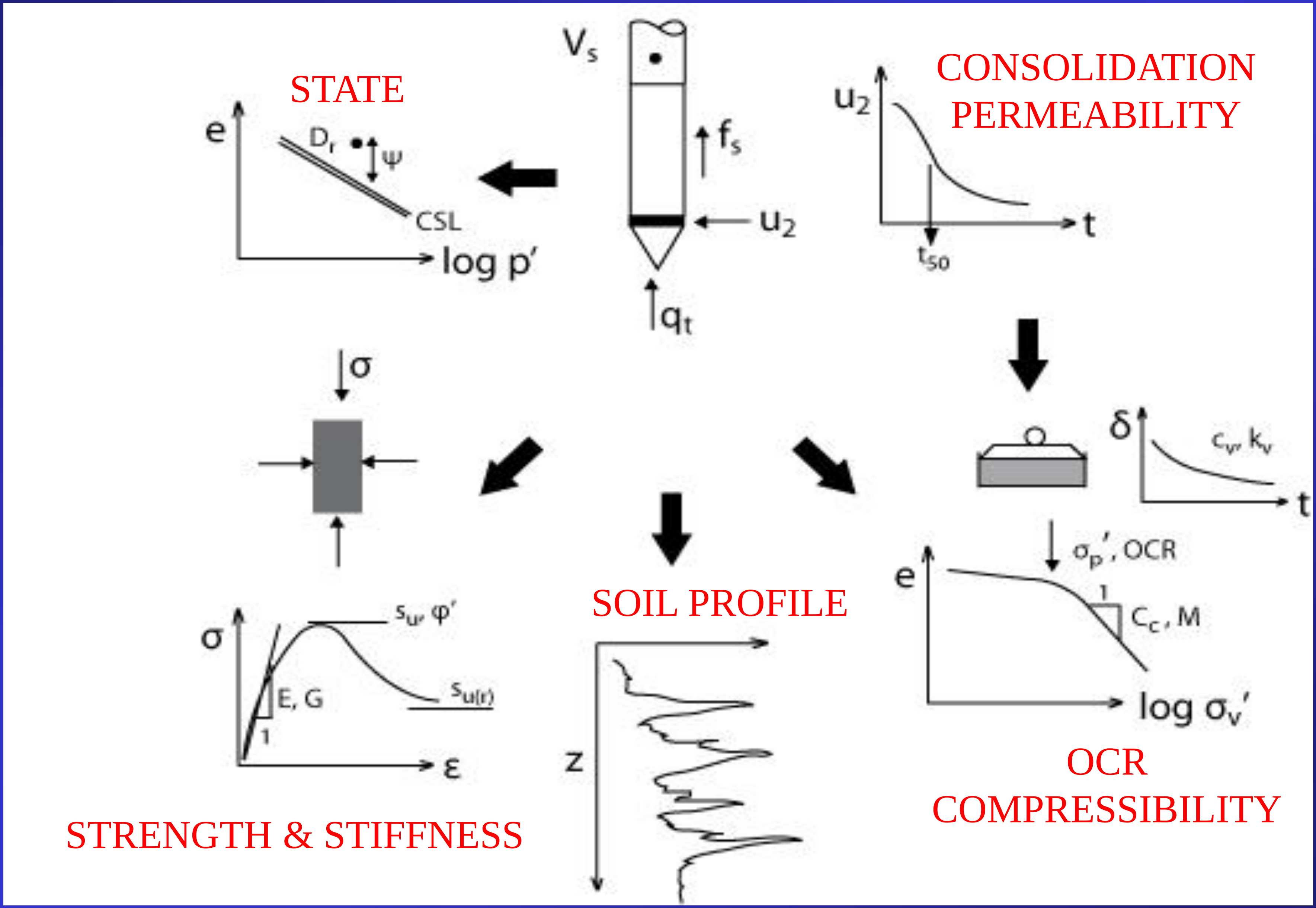
Dissipation Test

Test depth = 20m

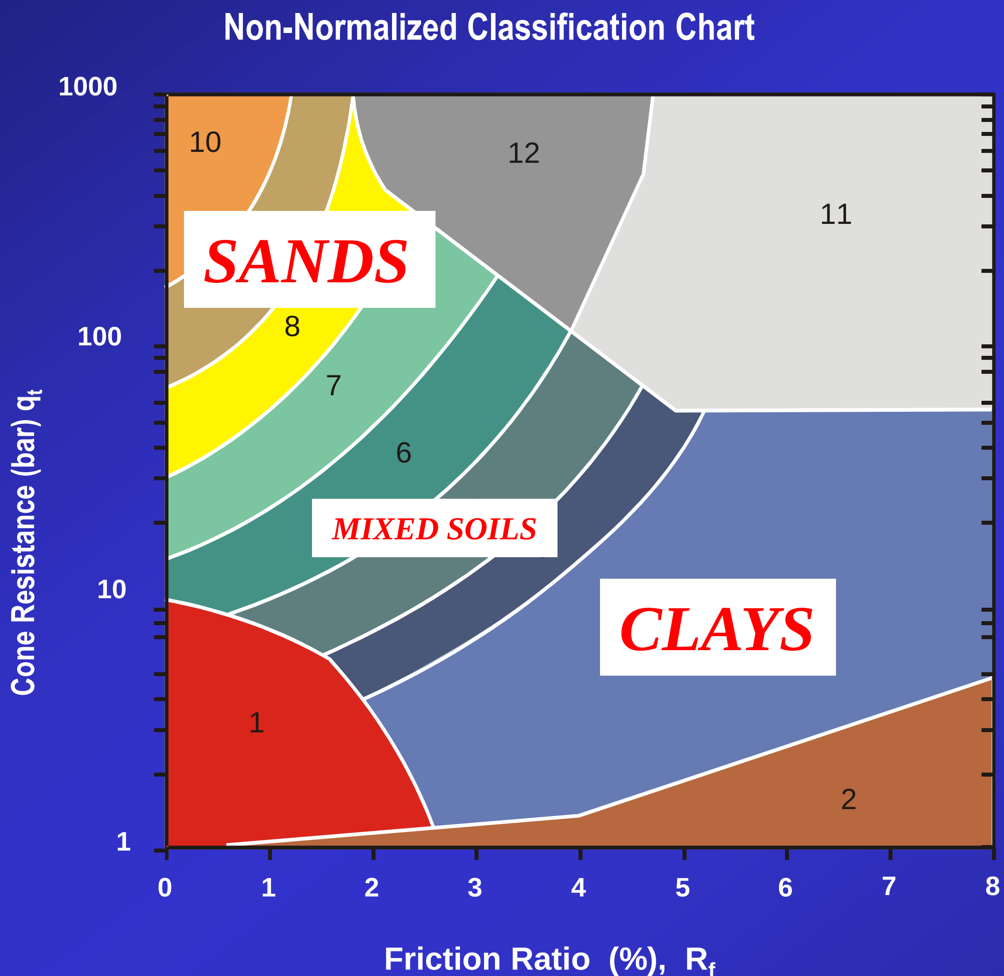


Depth to piezometric surface (GWL) = 20 – (186/9.81) = 1.04m

CPTu Interpretation



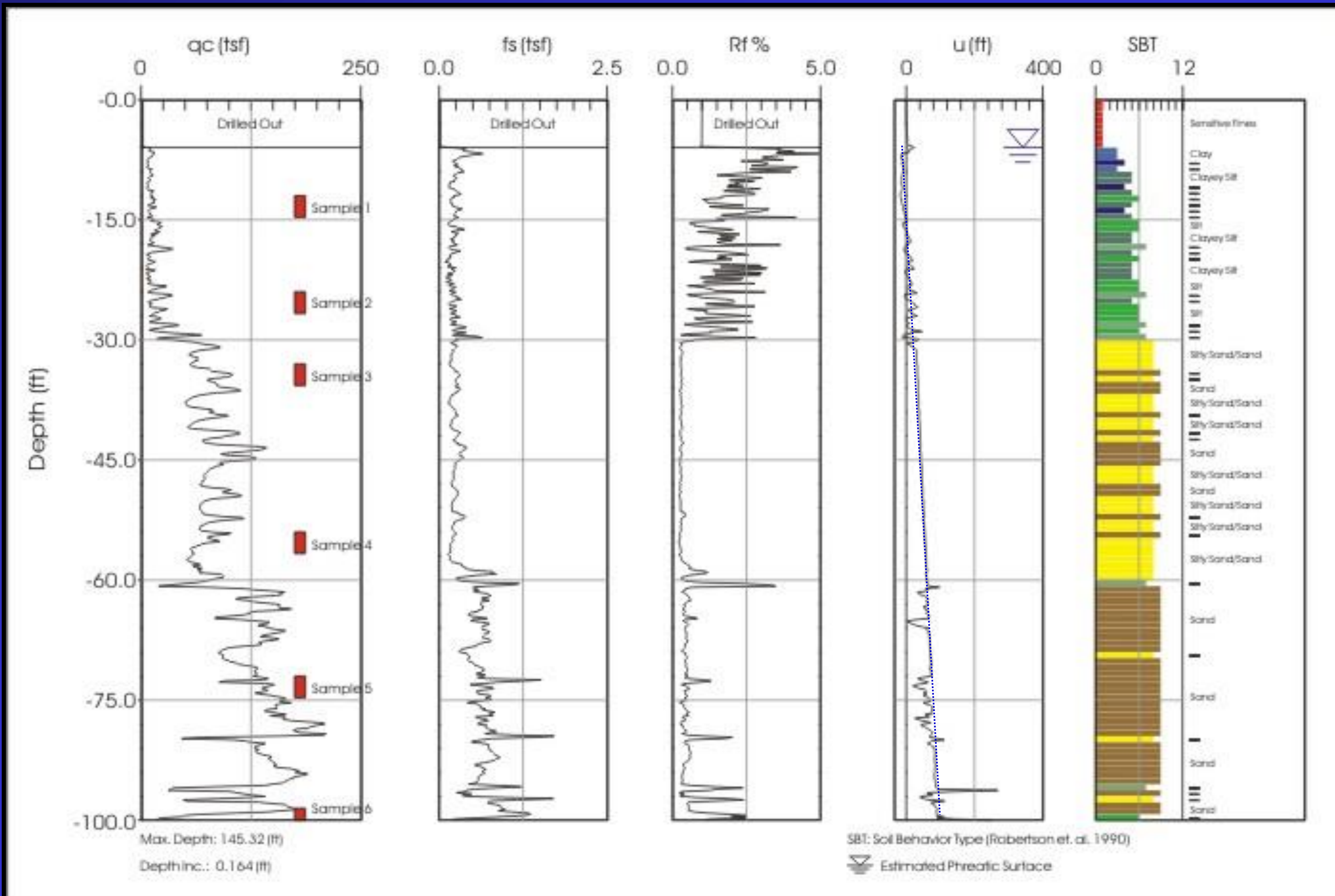
CPT - Soil Behavior Type (SBT)



After Robertson & Campanella, 1986

CPT *SBT* based on *in-situ mechanical 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

Example CPT Data Presentation



Example CPTu Plot

CPT – Normalization

CPT:

$$Q_t = (q_t - \sigma_v) / \sigma'_{vo}$$

$$F = f_s / \sigma'_{vo}$$

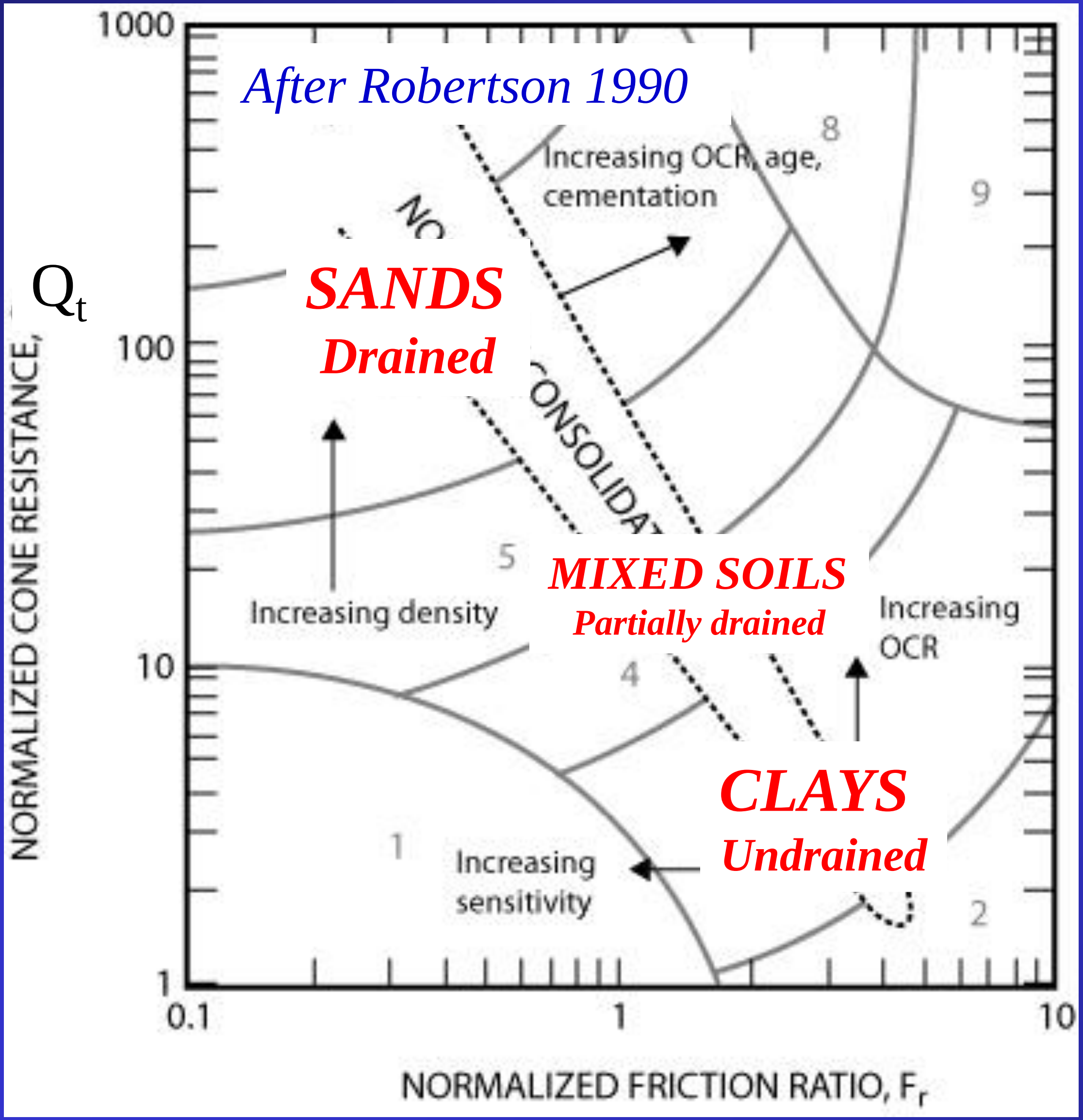
$$F_r = [f_s / (q_t - \sigma_v)]100\ (\%)$$

CPTu:

$$B_q = (u_2 - u_0) / (q_t - \sigma_v)$$

$$U = (u_2 - u_0) / \sigma'_{vo}$$

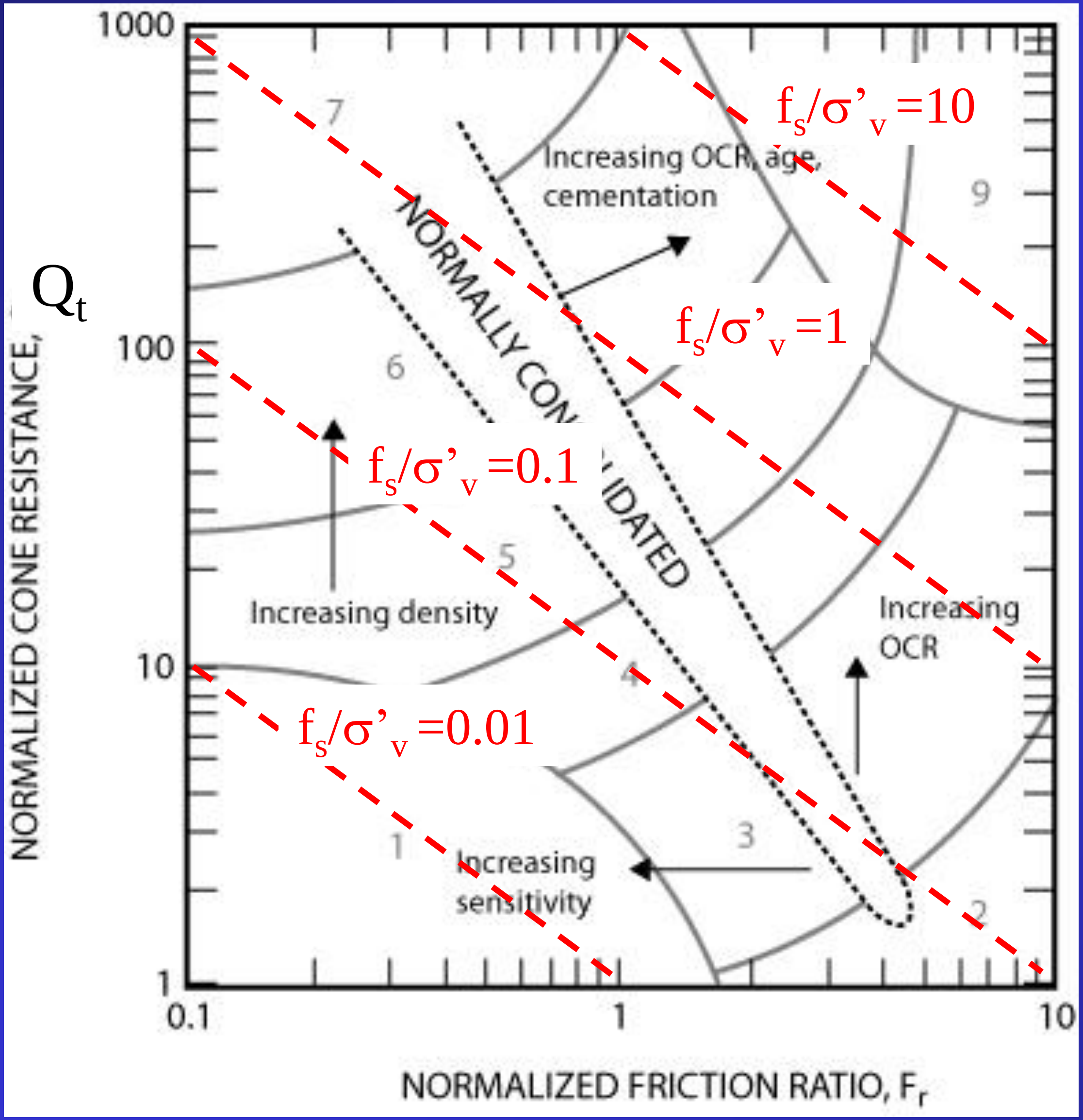
CPT Normalized SBT



CPT *SBT* based on *in-situ mechanical behavior* (*strength, stiffness, compressibility*)

Not same as traditional '*classification*' based *physical characteristics* (*Atterberg limits, grain size*) on *disturbed samples*

CPT Soil Behavior Type SBT



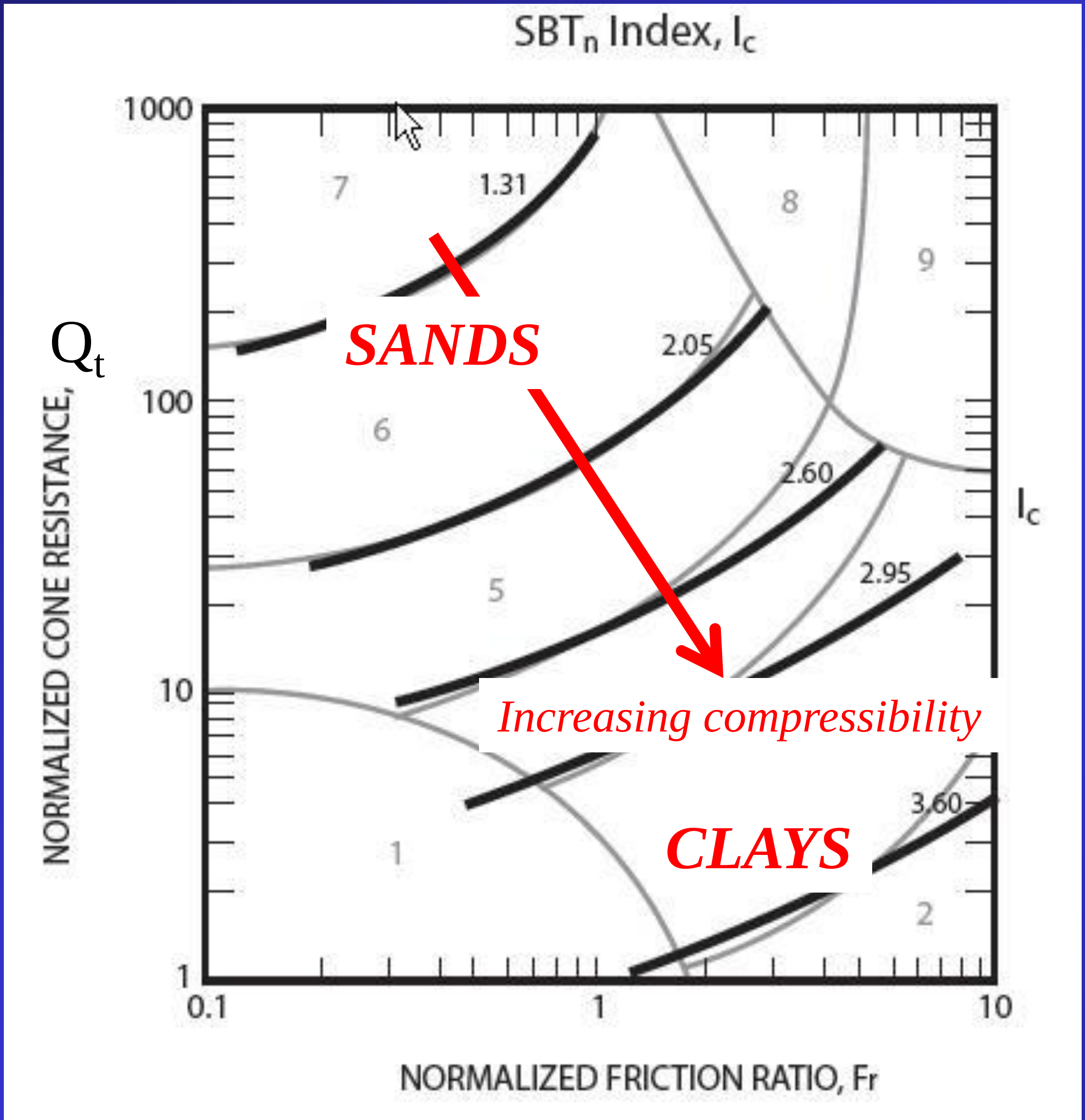
Normalized CPT sleeve resistance

$$F = f_s / \sigma'_{vo}$$

also a measure of stress history (similar to K_D)

Varies by 3 orders of magnitude!

CPT SBT Index, I_c



Soil Behavior Type Index, I_c

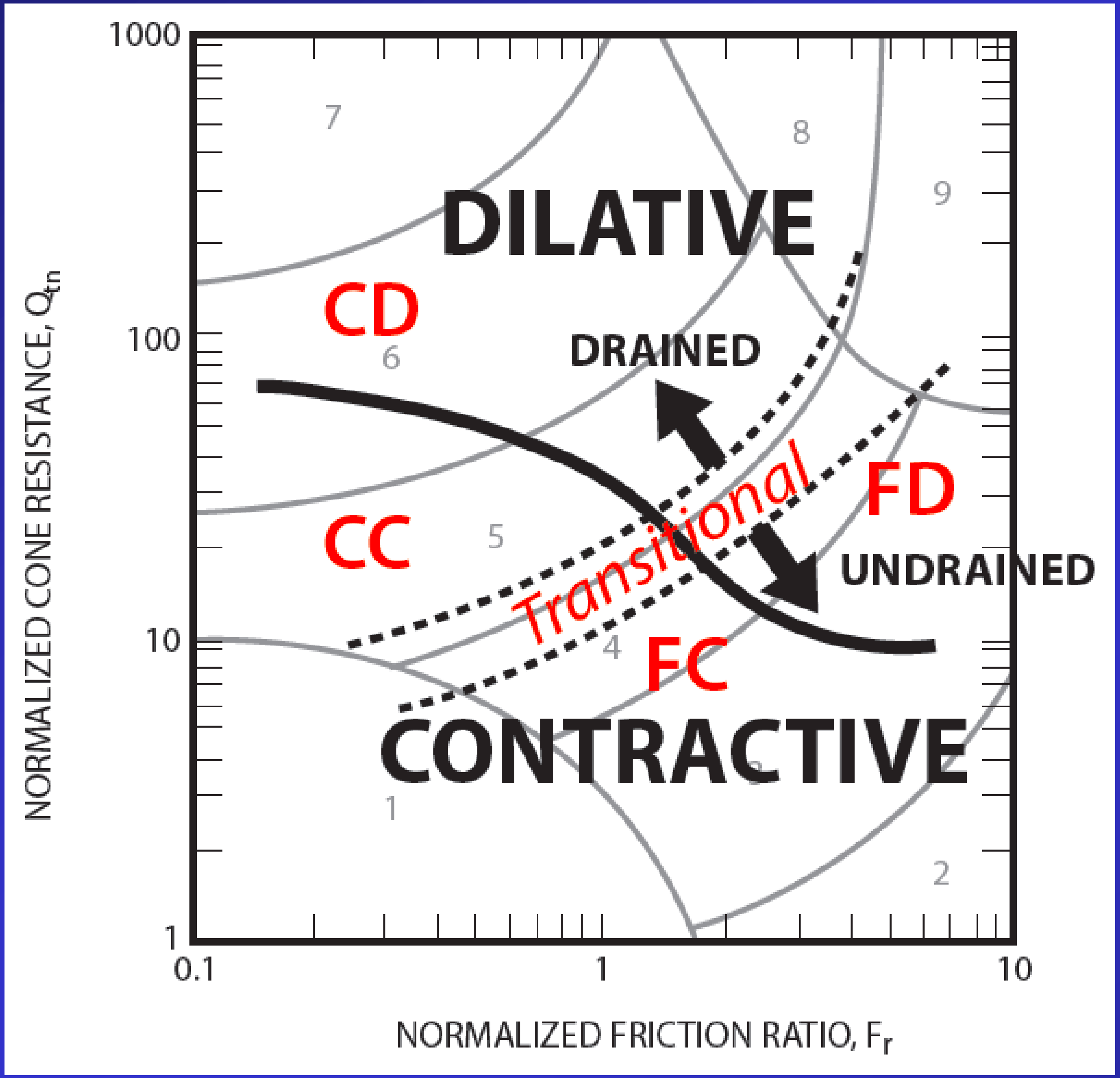
(first proposed by Jefferies & Davies, 1993)

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

Function primarily of Soil Compressibility

Note:
Q_t plays larger role than F_r

Generalized CPT Soil Behaviour Type



CPT Soil Behaviour

CD: Coarse-grain-Dilative (mostly drained)

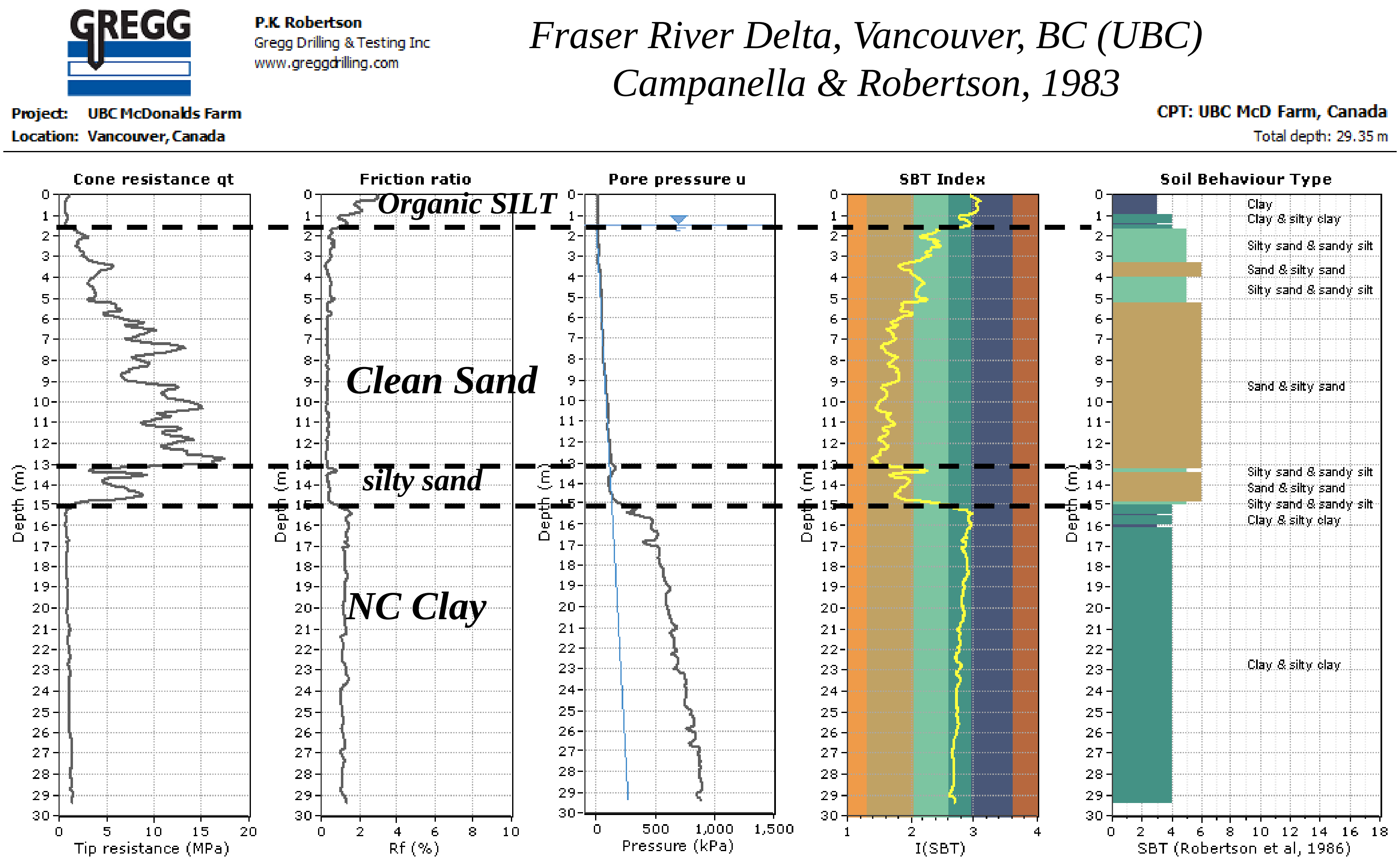
CC: Coarse-grain-Contractive (mostly drained)

FD: Fine-grain-Dilative (mostly undrained)

FC: Fine-grain-Contractive (mostly undrained)

Modified from Robertson, 2012

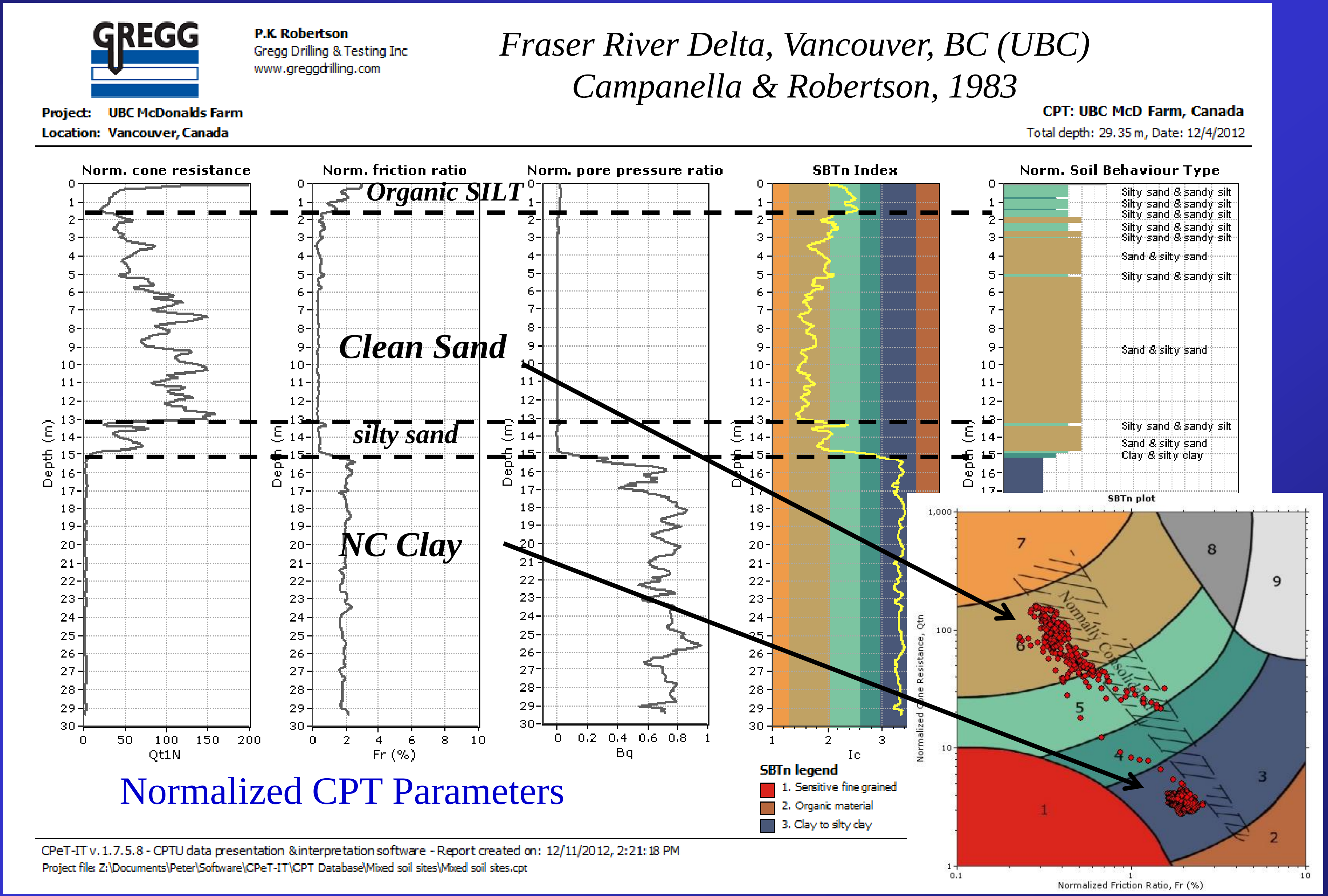
Example CPT - UBC Fraser River



Holocene-age deltaic deposit

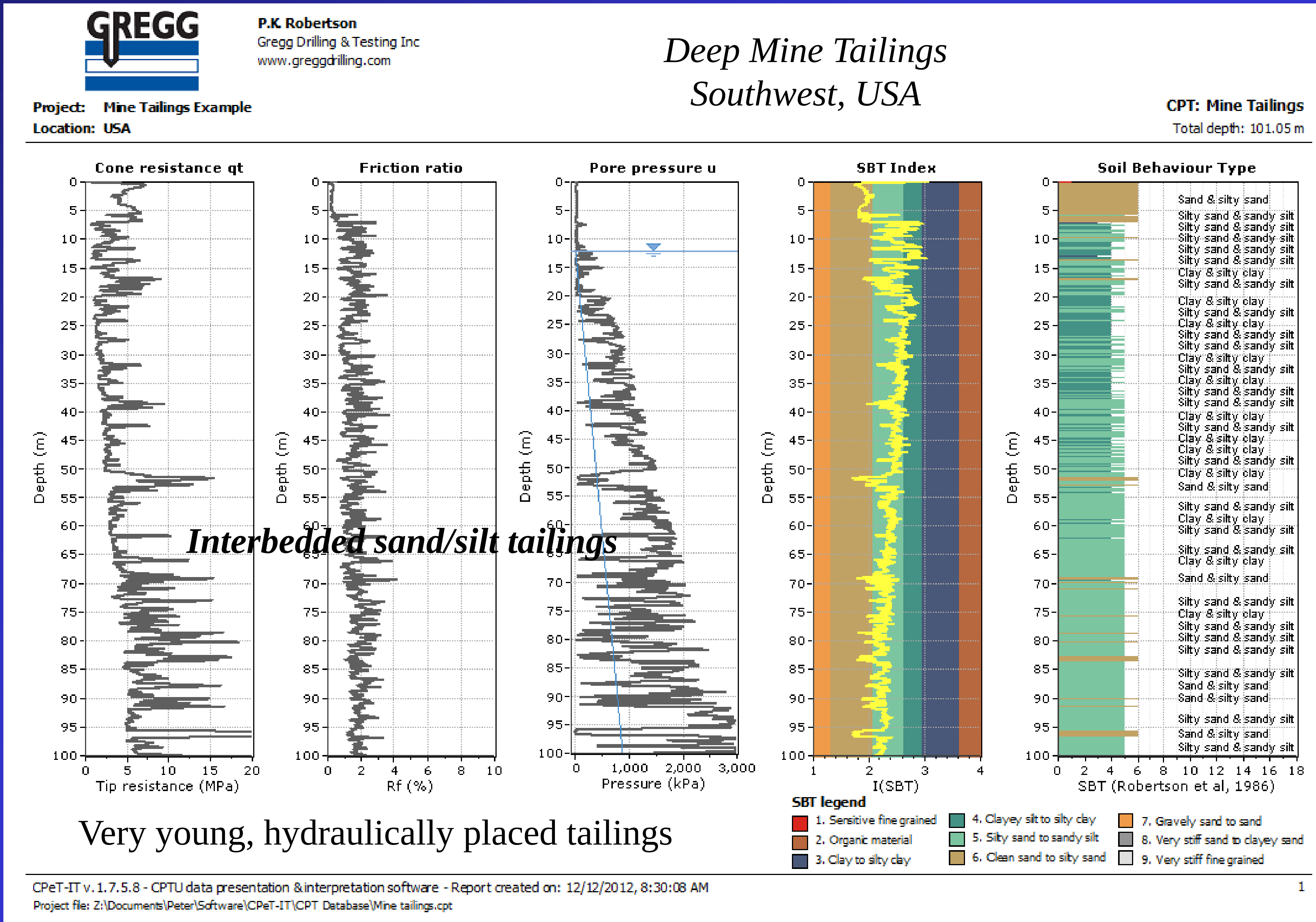
CPeT-IT v.1.7.5.8 - CPTU data presentation & interpretation software - Report created on: 12/11/2012, 2:21:18 PM
Project file: Z:\Documents\Peter\Software\CPeT-IT\CPT Database\Mixed soil sites\Mixed soil sites.cpt

Example CPT - UBC Fraser River



Normalized CPT Parameters

Example 100m CPT – Tailings

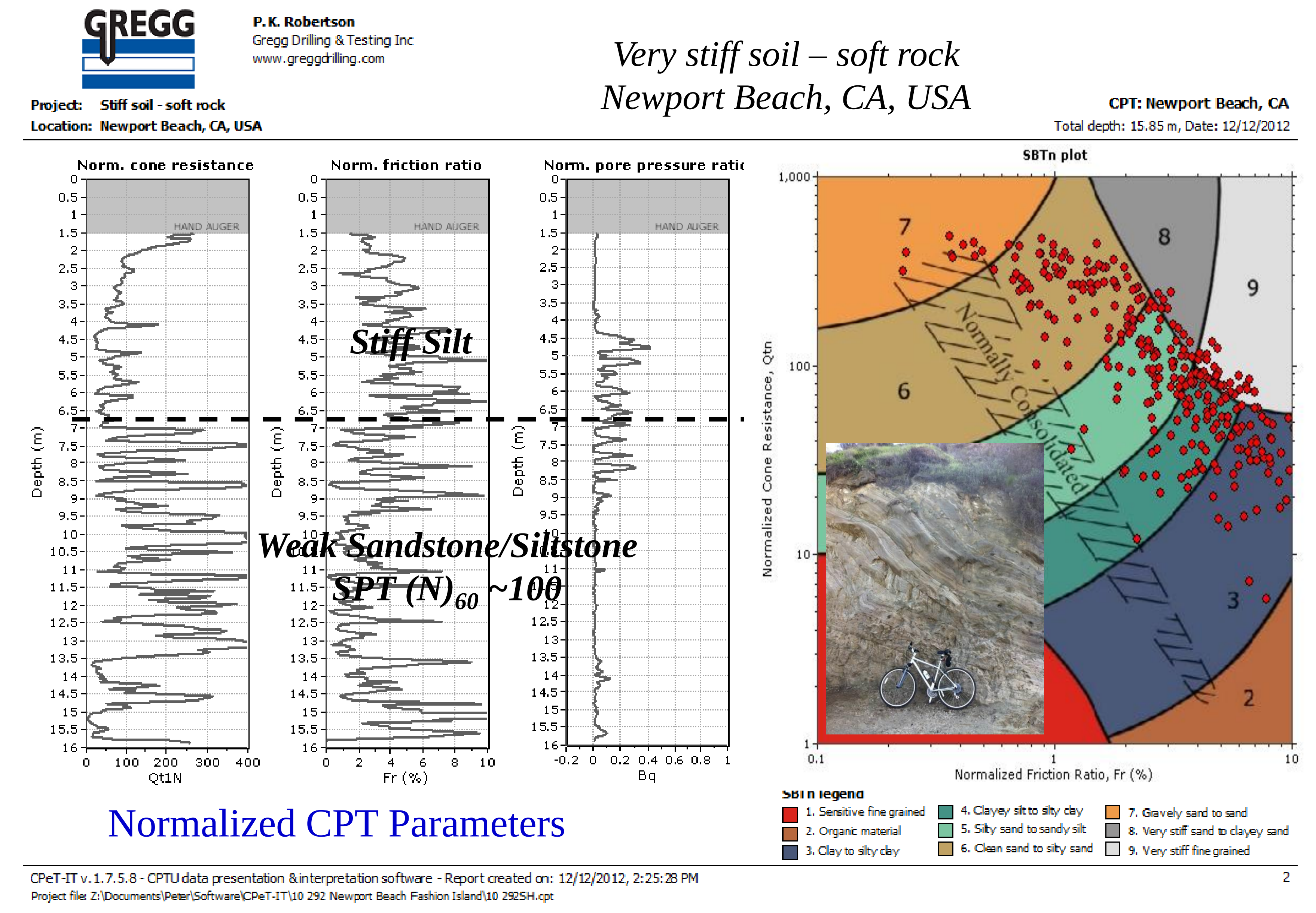


Deep Mine Tailings
Southwest, USA

Interbedded sand/silt tailings

Very young, hydraulically placed tailings

Example CPT – Soft Rock



Requirements for a Good Insitu Test

- Reliable, operator independent measurements
  - Examples: CPT, CPTu, SCPTu, DMT
- Repeatable disturbance of surrounding soil
  - Examples: CPT, CPTu, SCPTu, DMT
- Measurement of more than one independent variable
  - Example: CPTu, SCPTu, SDMT

Real soil behavior complex – need to measure more than one in-situ response

Factors affecting CPT interpretation

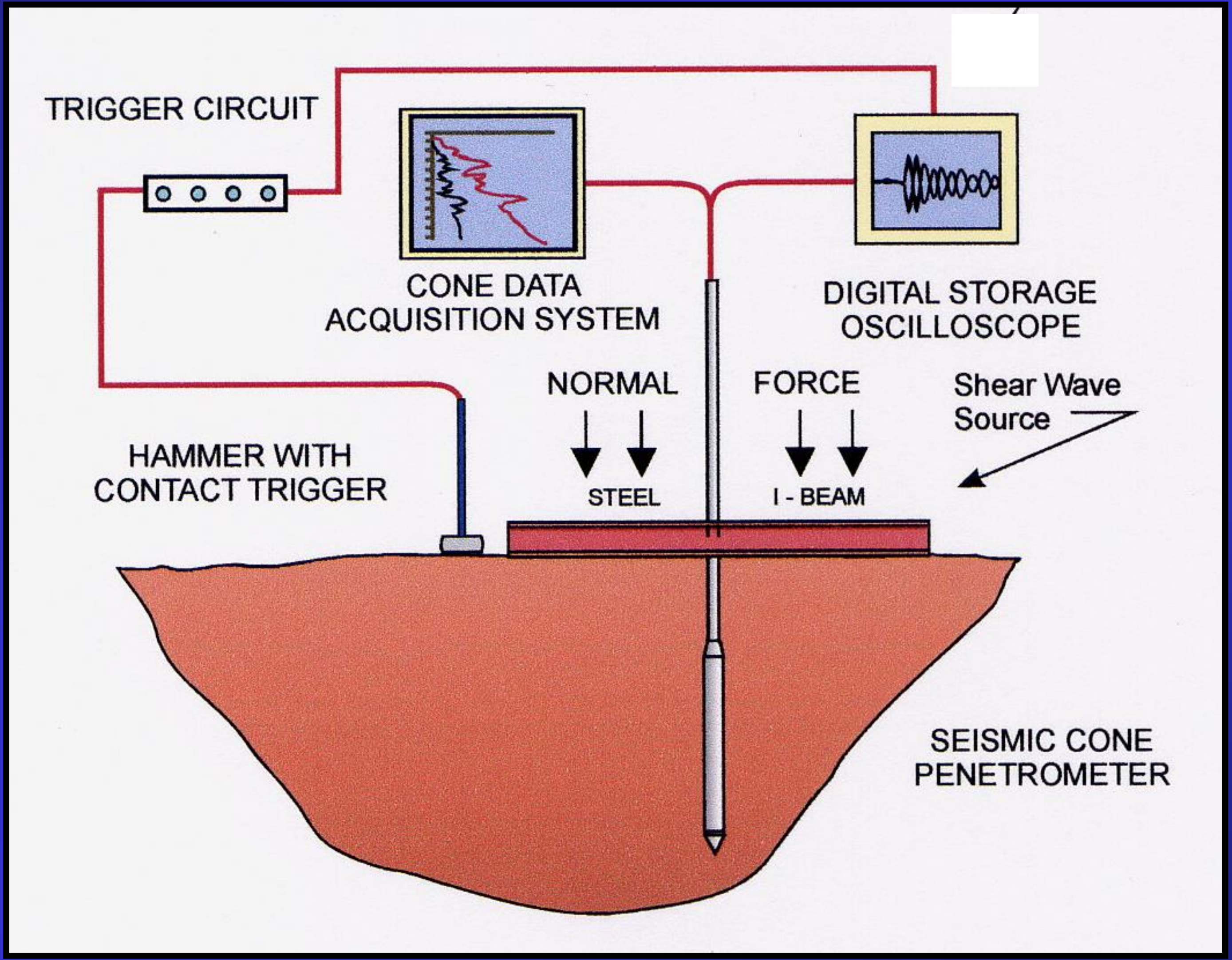
- Geology & geologic history
  - In-situ stresses (*importance of horizontal stresses*)
  - Soil compressibility (*mineralogy*)
  - Cementation
  - Particle size (*e.g. gravel size*)
  - Stratigraphy/layering

CPT should be interpreted within a geologic context

Seismic CPT (SCPT)

- >30 years experience (1983)
- Simple, reliable, and inexpensive
- Direct measure of soil stiffness
  - Small strain value, $G_o = \rho \cdot V_s^2$
- Typically 1m (~3ft) intervals
- Combines q_c and V_s profile in same soil

Basic SCPT Configuration



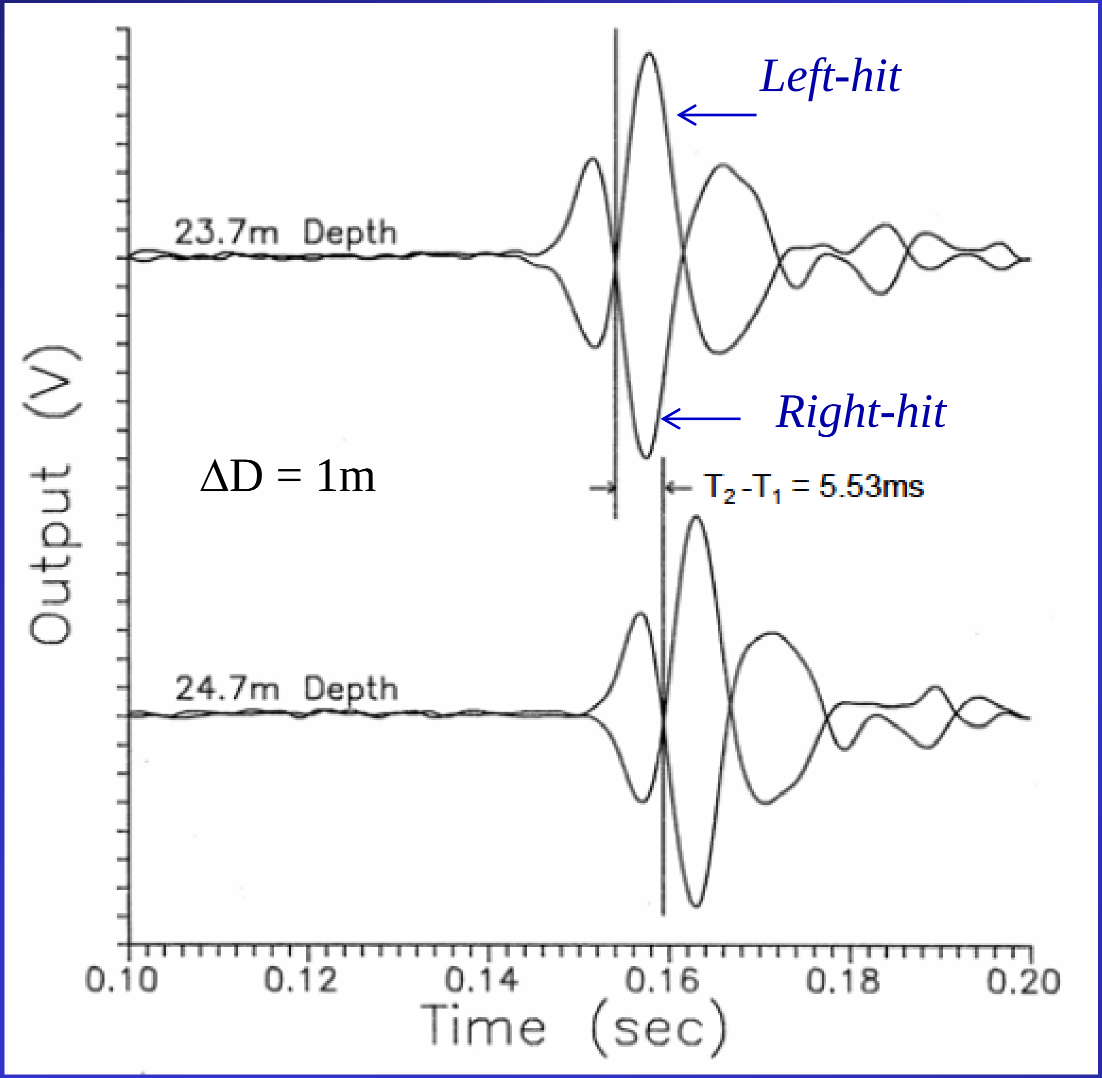
Seismic CPT

CPT truck/drill-rig with (build-in) seismic beam

Seismic beam

Figure 1. AutoSeis shear wave seismic source.

Polarized shear wave traces



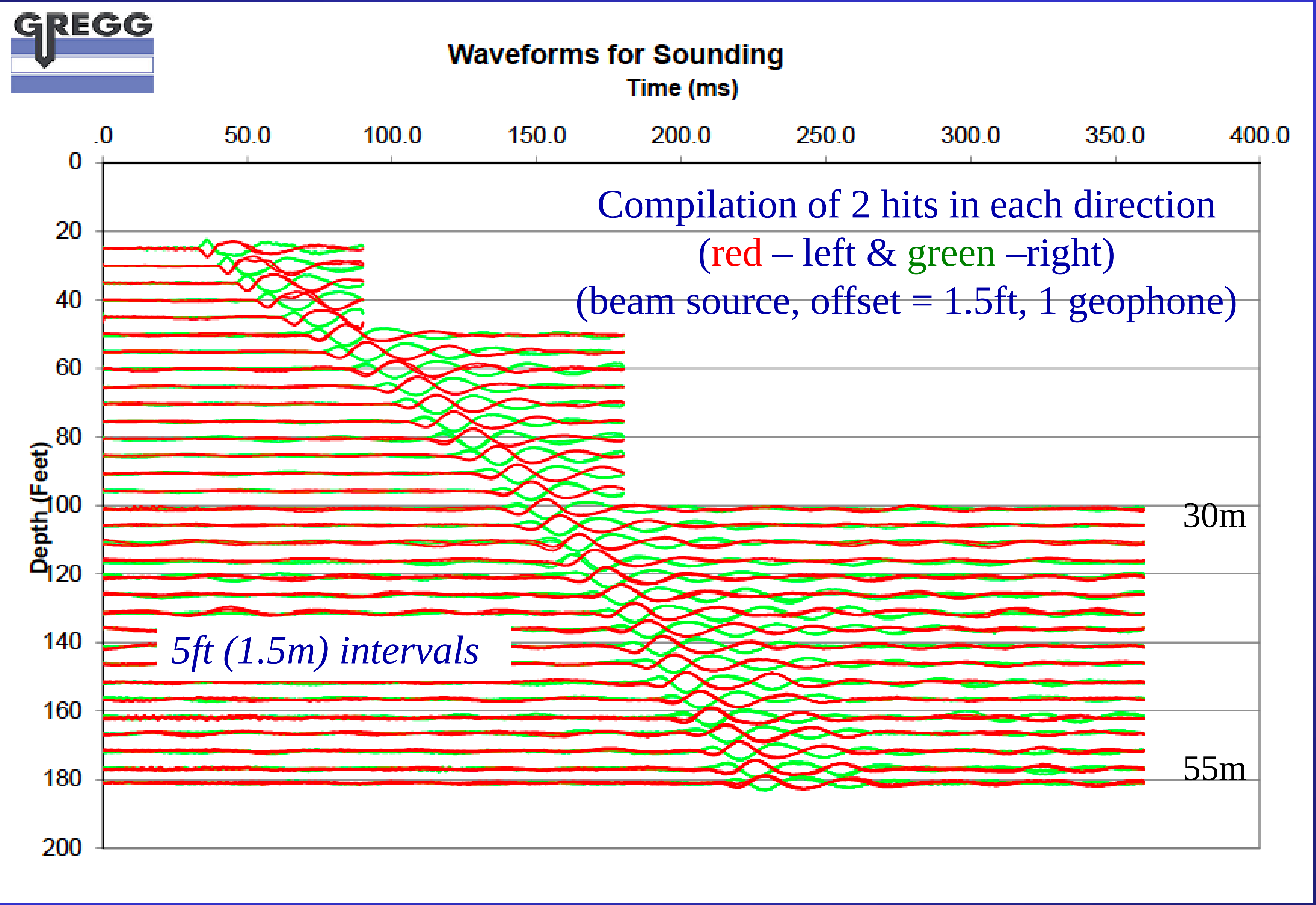
$$V_s = \frac{(L_2 - L_1)}{(T_2 - T_1)}$$

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

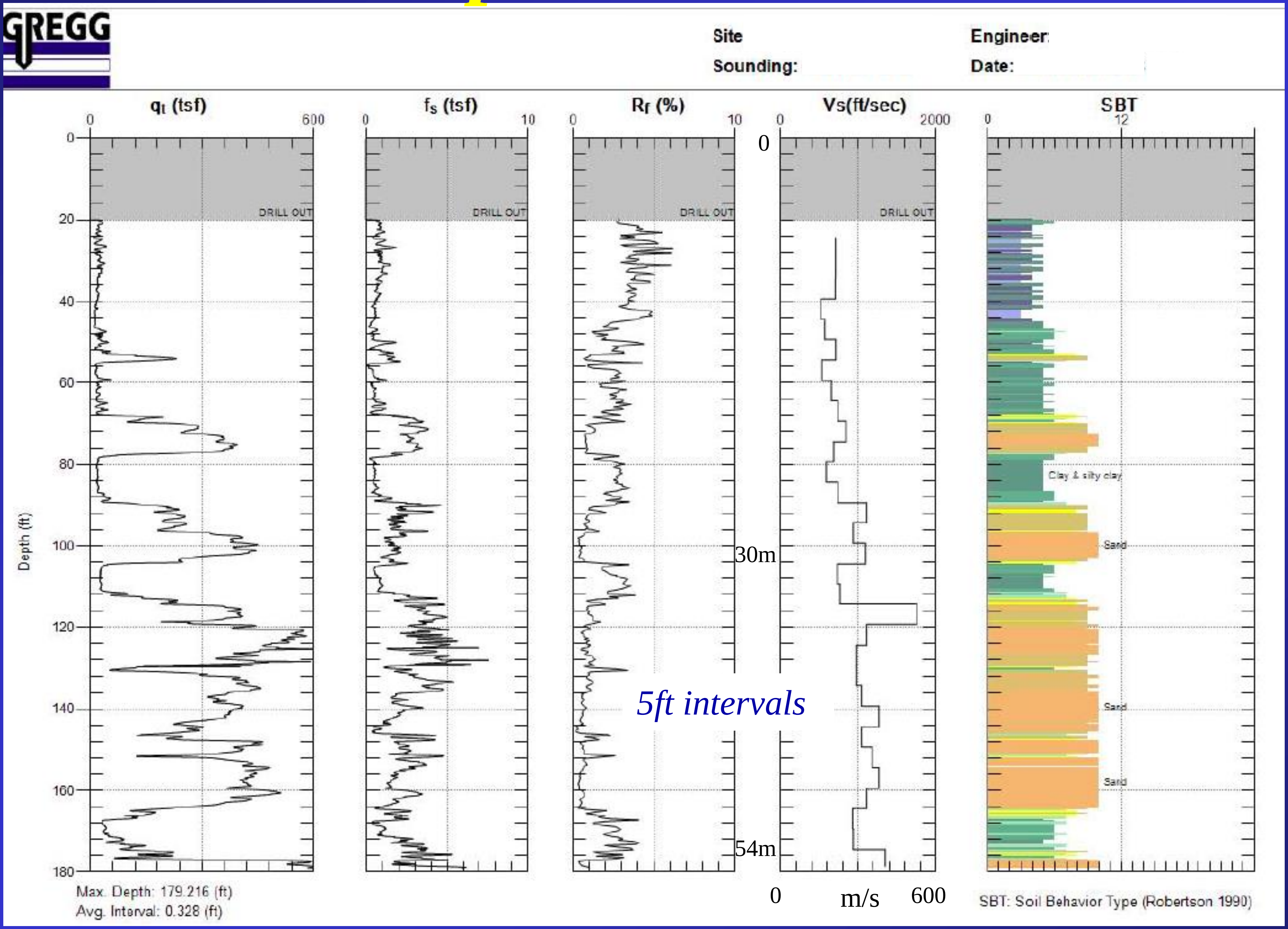
$(T_2 - T_1)$ = time difference

After Butcher et al 2005 (ISSMGE TC 10)

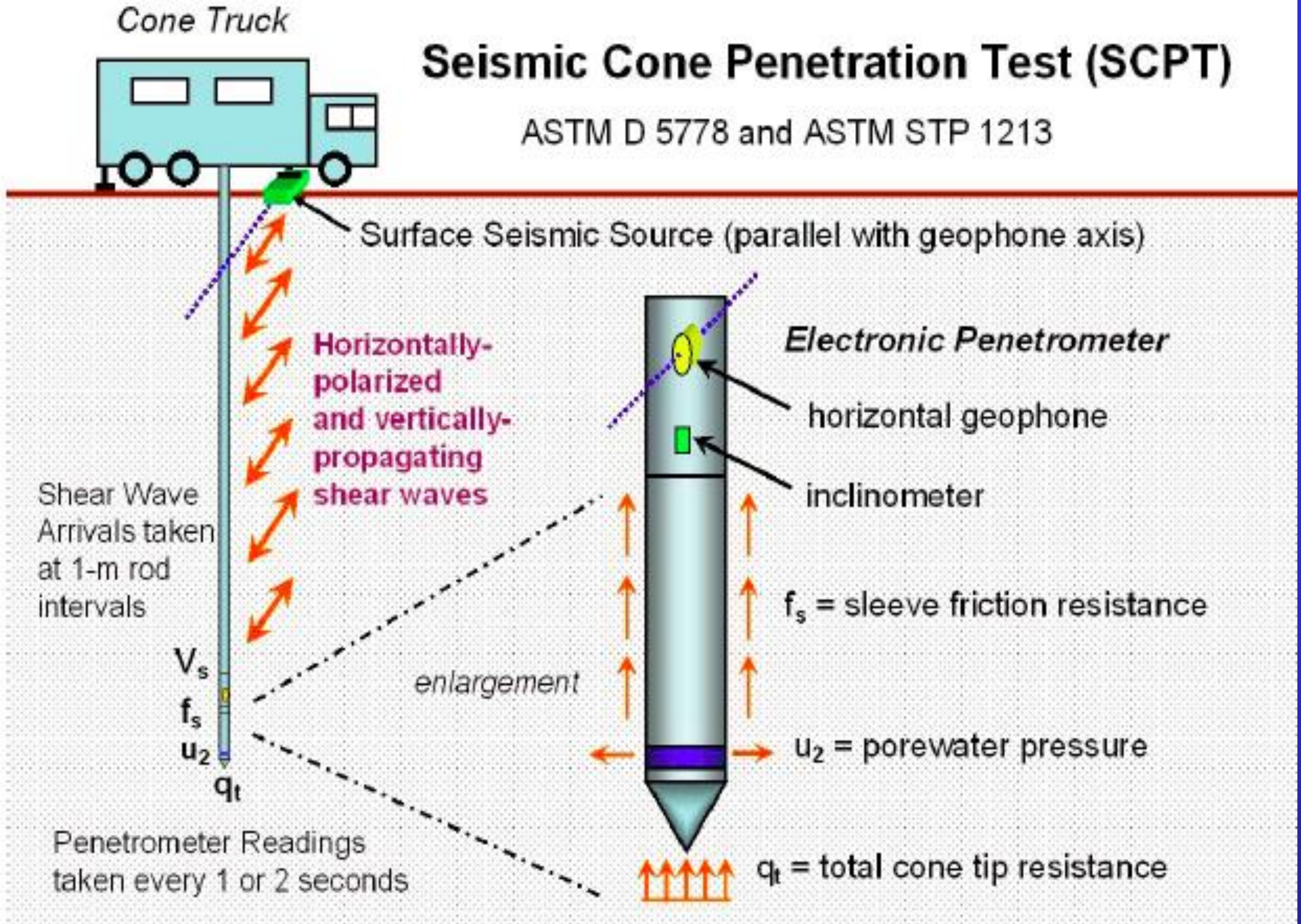
SCPT polarized wave traces



Example Seismic CPT



SCPTu - Advantages



After Mayne, 2014

SCPTu

7 measurements!

q_t

f_s

u_2

V_s (V_p)

t_{50}

u_o

i

diss

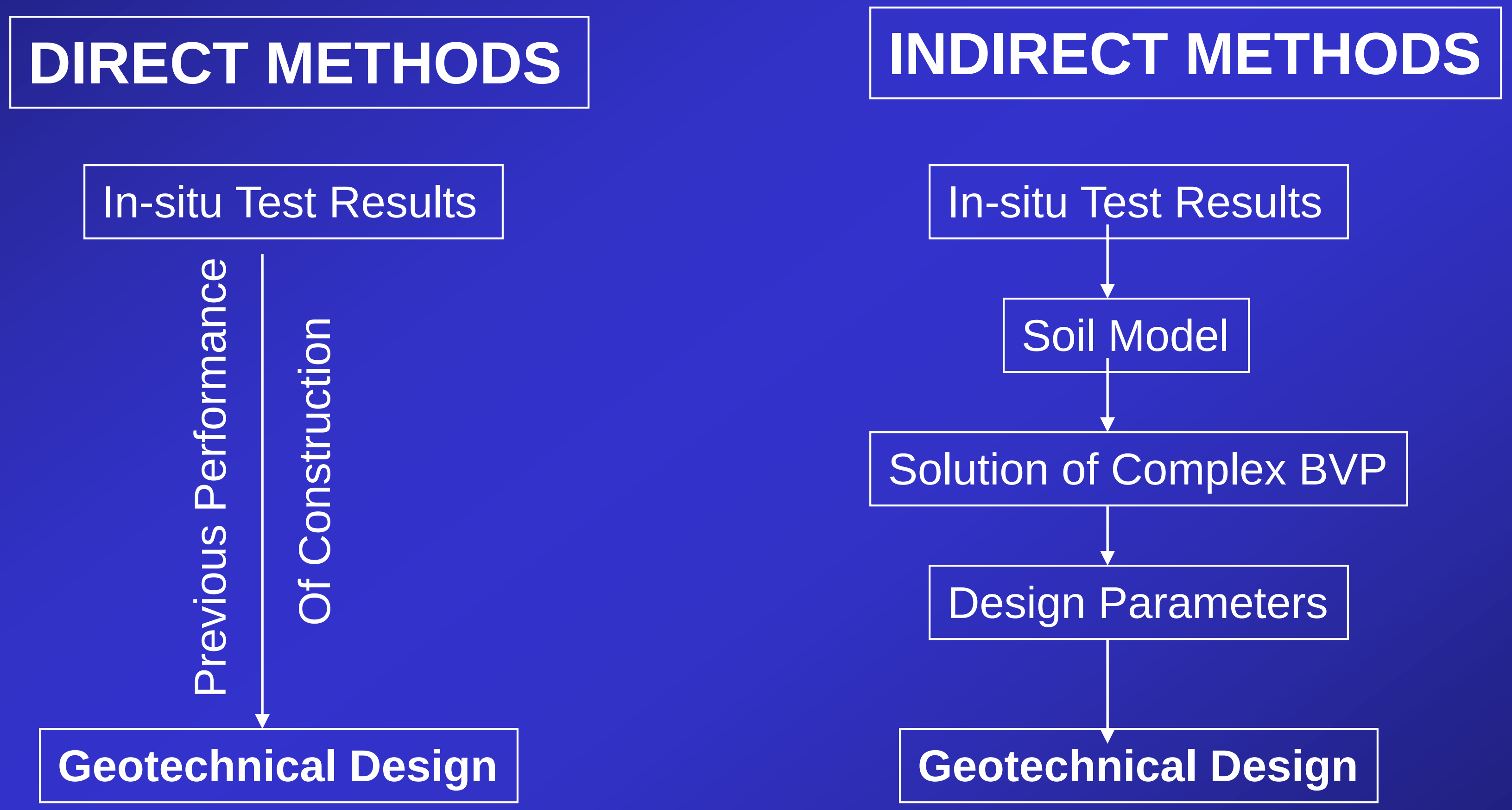
Perceived applicability of CPTu for Deriving Soil Parameters

	Initial state parameter				Strength Parameters			Deformation Characteristics*			Flow Charact.	
Soil Type	γ/D_r	ψ	K_o	OCR	S_t	s_u	Φ'	E	M	G_o	k	c_h
Clay	3-4		2	1-2	2-3	1-2	4	2-3	2-3	2-3	2-3	2-3
Sand	2-3	2-3	5	4-5			2-3	2-3	2-3	2-3	3	3-4

Applicability rating: 1 high reliability, 2 high to moderate, 3 moderate, 4 moderate to low, 5 low reliability.

** Improved when using SCPTu*

In-situ Testing and Geotechnical Design



Perceived Applicability

	Pile Design	Bearing Capacity	Settlement*	Compaction Control	Lique-faction
Sand	1-2	1-2	2-3	1-2	1-2
Clay	1-2	1-2	3-4	3-4	2-3
Intermediate Soils	1-2	2-3	3-4	2-3	2-3

Reliability rating: 1 = High, 2 = High to Moderate, 3 = Moderate,
4 = Moderate to Low, 5 = Low
** Higher when using SCPT*

Software Development

- PC based data acquisition systems
- Digital data
- Real-time interpretation
- Color presentation
  - Soil profile
  - Interpretation parameters
- Interpretation software *(e.g. CPeT-IT)*

Summary

- CPT is a fast, reliable, cost effective means to evaluate soil profile, geotechnical parameters, groundwater conditions and preliminary geotechnical design.
- Suitable for a wide range of soils, except for dense gravels and hard rock.
- SCPTu should be used for higher risk projects