cfms
COMITÉ FRANÇAIS DE MÉCANIQUE DES SOLS ET DE GÉOTECHNIQUE

ACADÉMIE DES SCIENCES
INSTITUT DE FRANCE

ACADÉMIE DES TECHNOLOGIES
POUR UN PROGRÈS RAISONNÉ, CHOISI ET PARTAGÉ

SIMSG ISSMGE

LES TRAVAUX PUBLICS FÉDÉRATION NATIONALE

Charles-Augustin COULOMB - A geotechnical tribute

Paris, september 25 & 26, 2023

Developments in Seismic CPT and links to the Ménard Pressuremeter Test

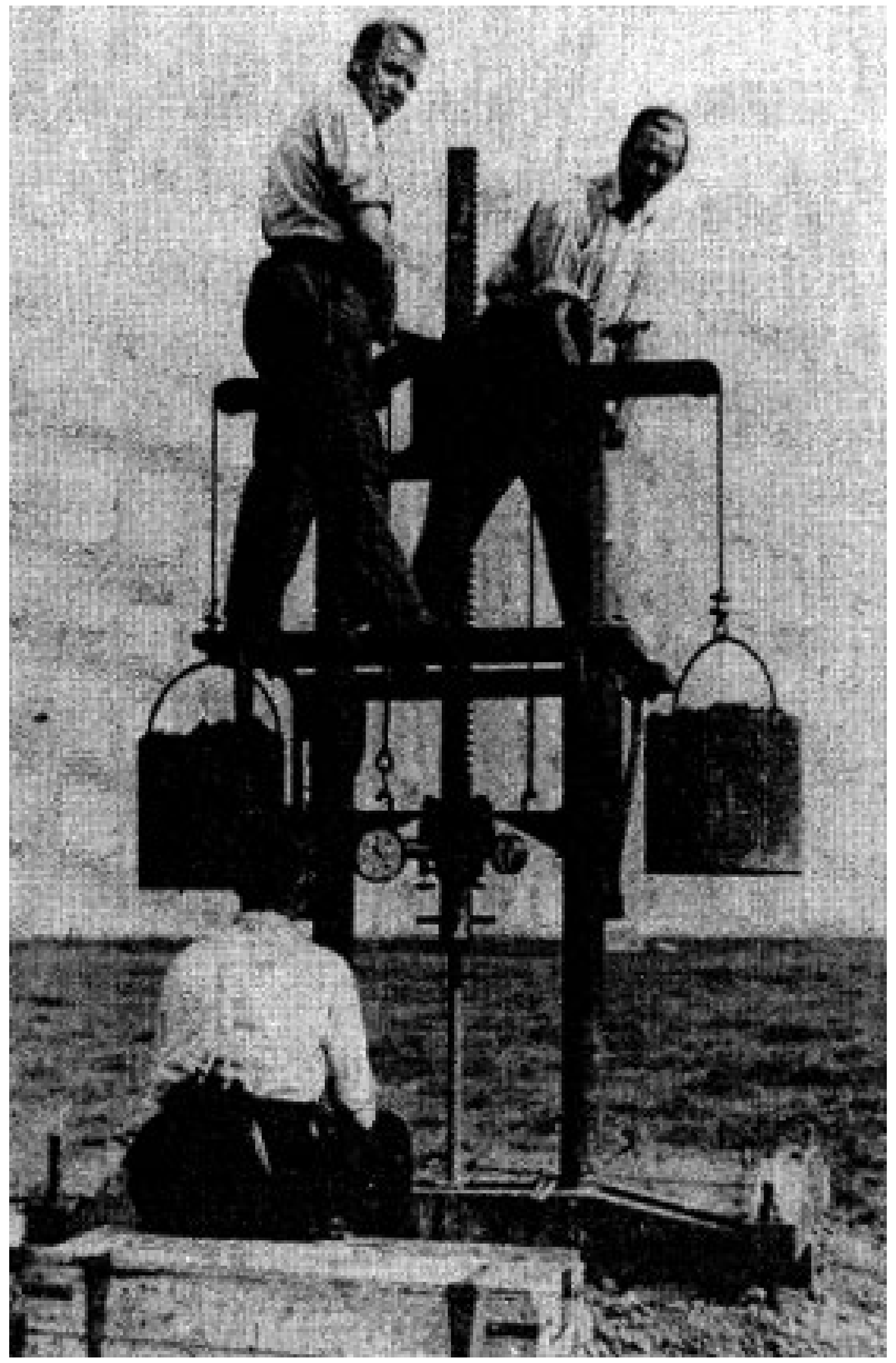
P.K. Robertson

Gregg Drilling & Testing, Inc.

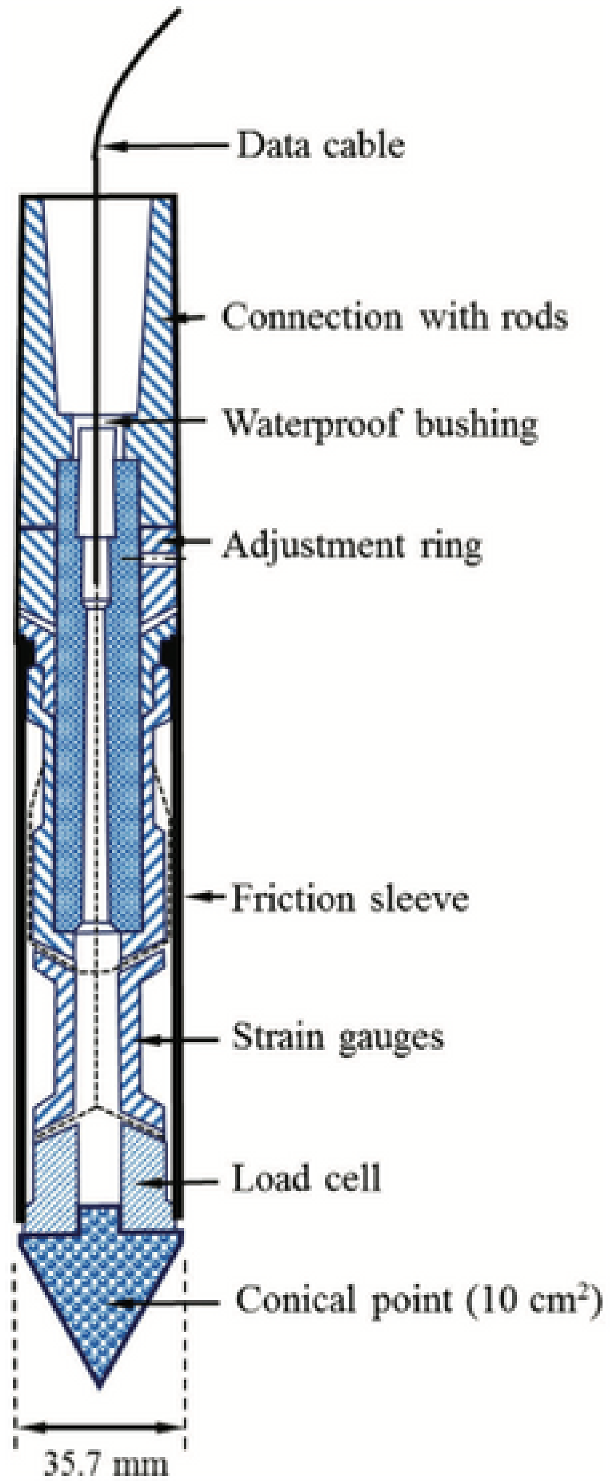
BUREAU VERITAS Shaping a World of Trust | Geos | SoilCloud | SOLETANCHE BACHY | spie batignolles / fondations | SSI 2U | terrasol setec

HISTORY OF CPT

1930s
First Mechanical Cones

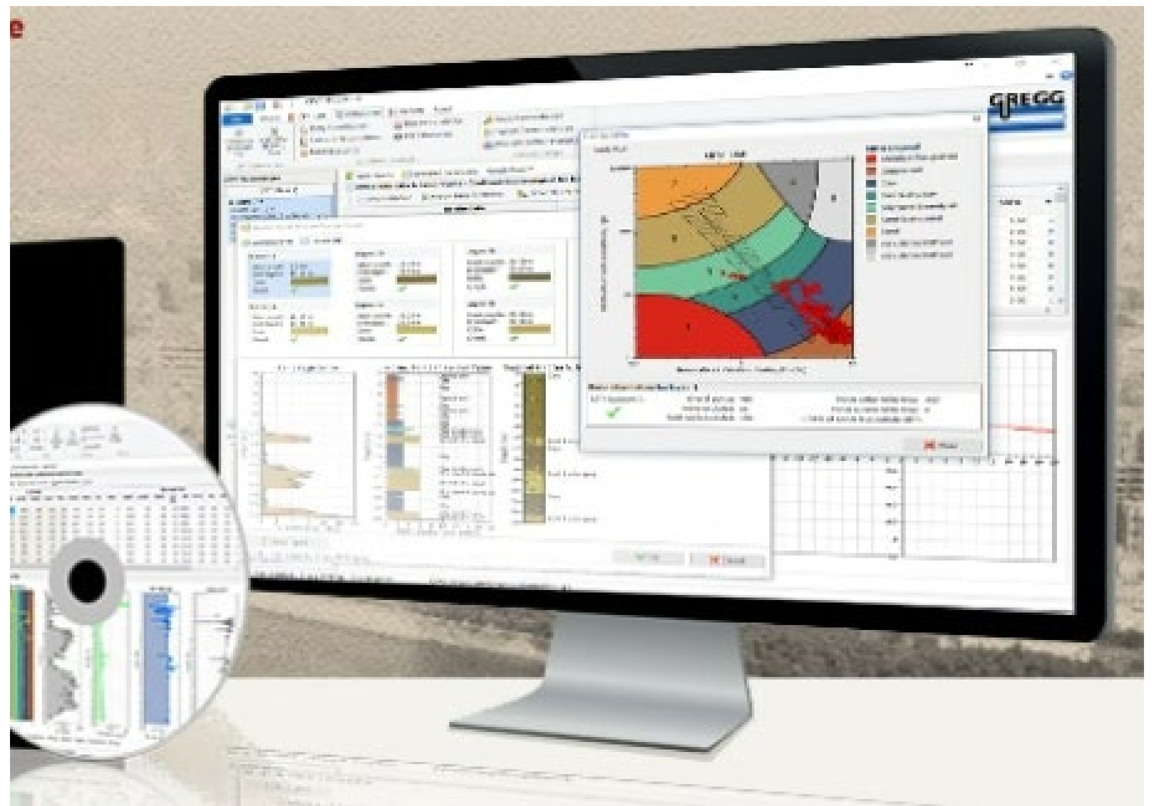


1960s
Electric Cones Developed

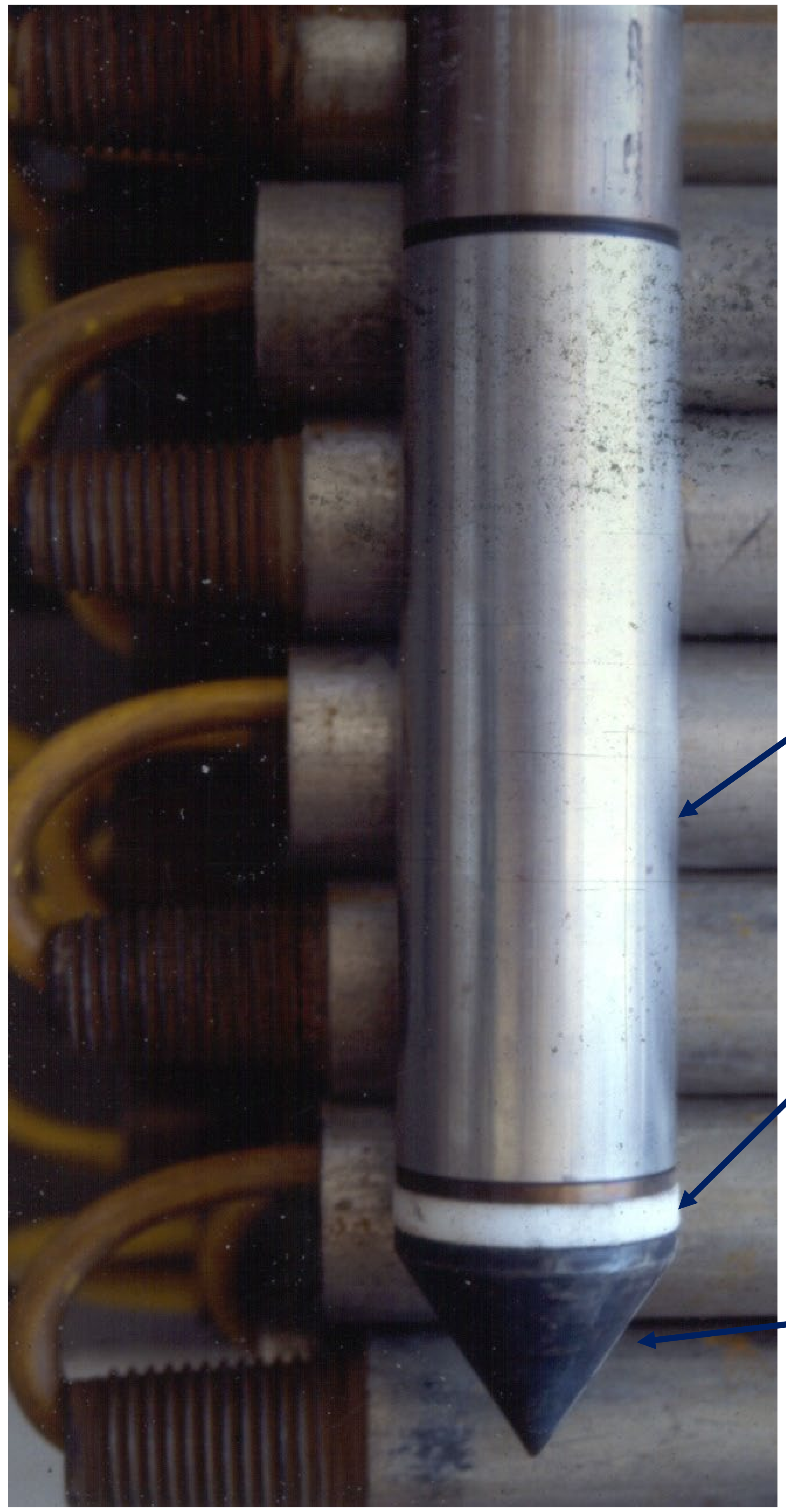


1970s
Primary device Offshore

2000s
Digital cones and advanced software



BASIC CONE PENETROMETR



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

Pore Pressure, u_2

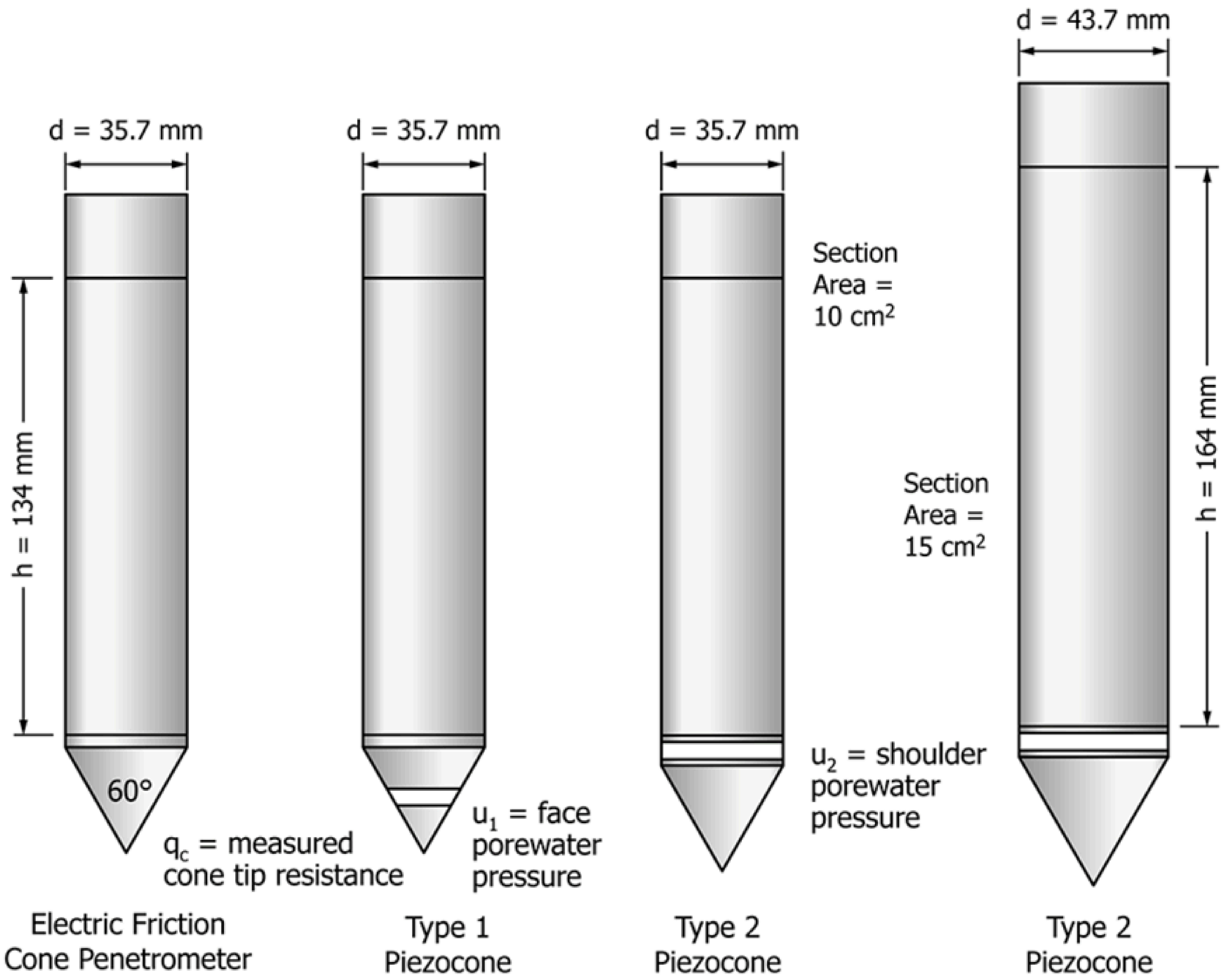
Tip Resistance
$q_c = {}^{load}/_{\pi r}$

Friction Ratio
$R_f = (f_s/q_c)\,100$

CPT SENSORS

- Early cones measured only q_c & f_s
- 1970's – *pore pressure* sensors added (u_1, u_2)
- u_2 most common – ideal for q_t correction
  - *–CPTu now very common*
- 1980's geophone added (V_s)
  - *–SCPTu becoming common*

MOST COMMON



CONES

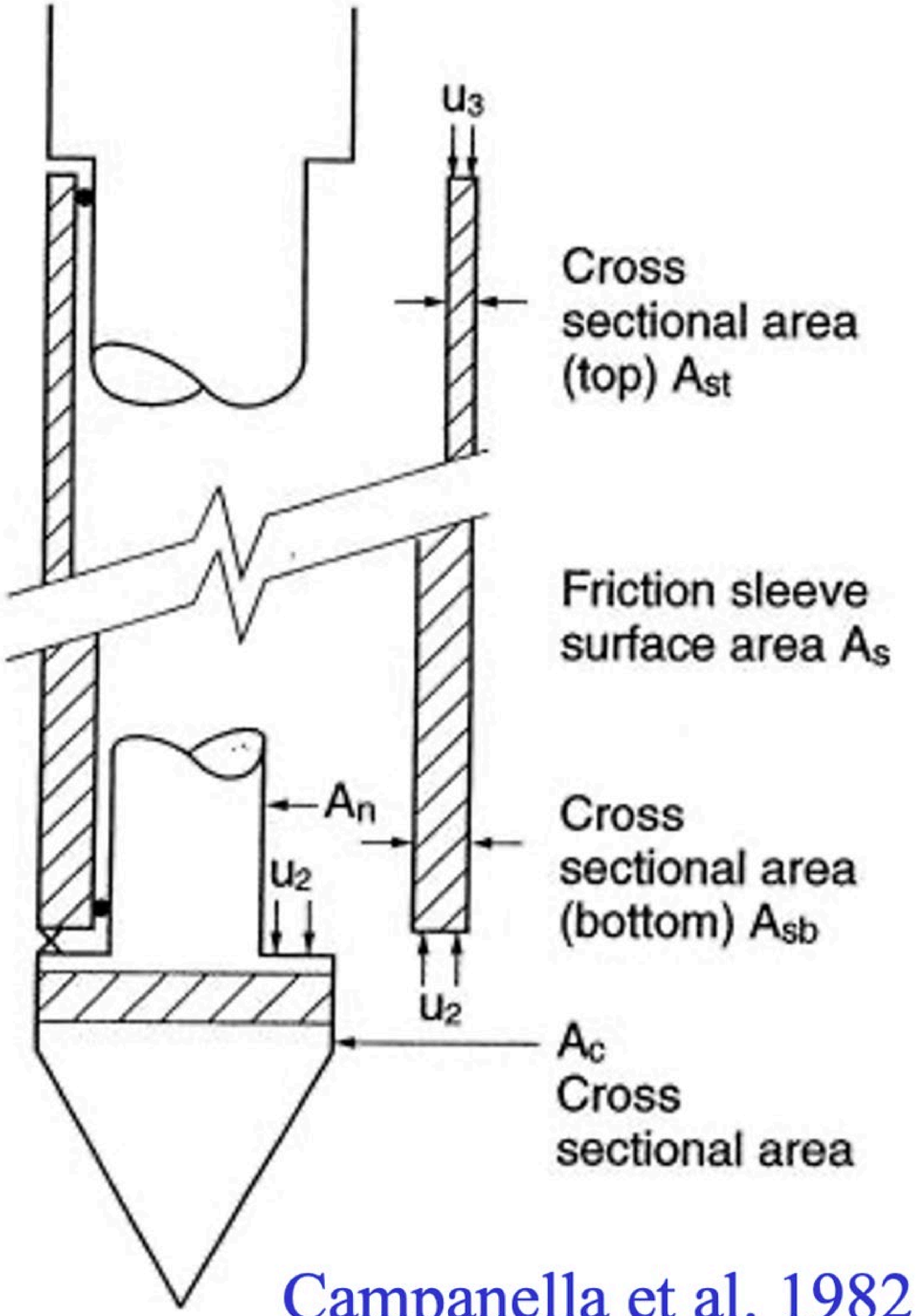
Equal end area sleeves and
small tip net area (a > 0.8)

$$q_t = q_c + u_2(1\text{-}a)$$

$$a > 0.80$$

$$A_{sb} = A_{st}$$

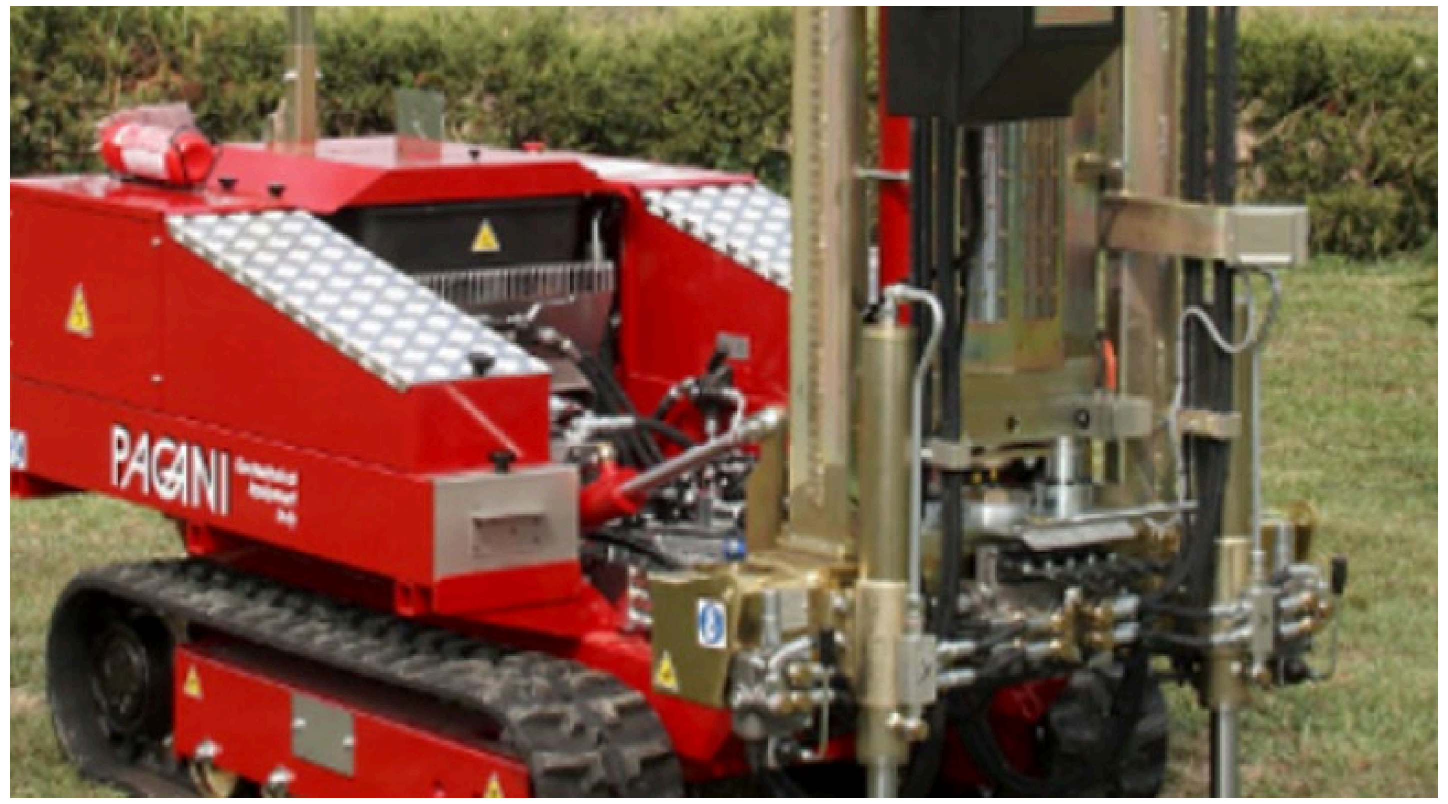
Required in most Standards



Campanella et al. 1982

CPT PUSHING EQUIPMENT

Portable: Small (10kN) to Large (200kN)



CPT PUSHING EQUIPMENT

Mostly ~ 200 to 250kN

Truck Systems

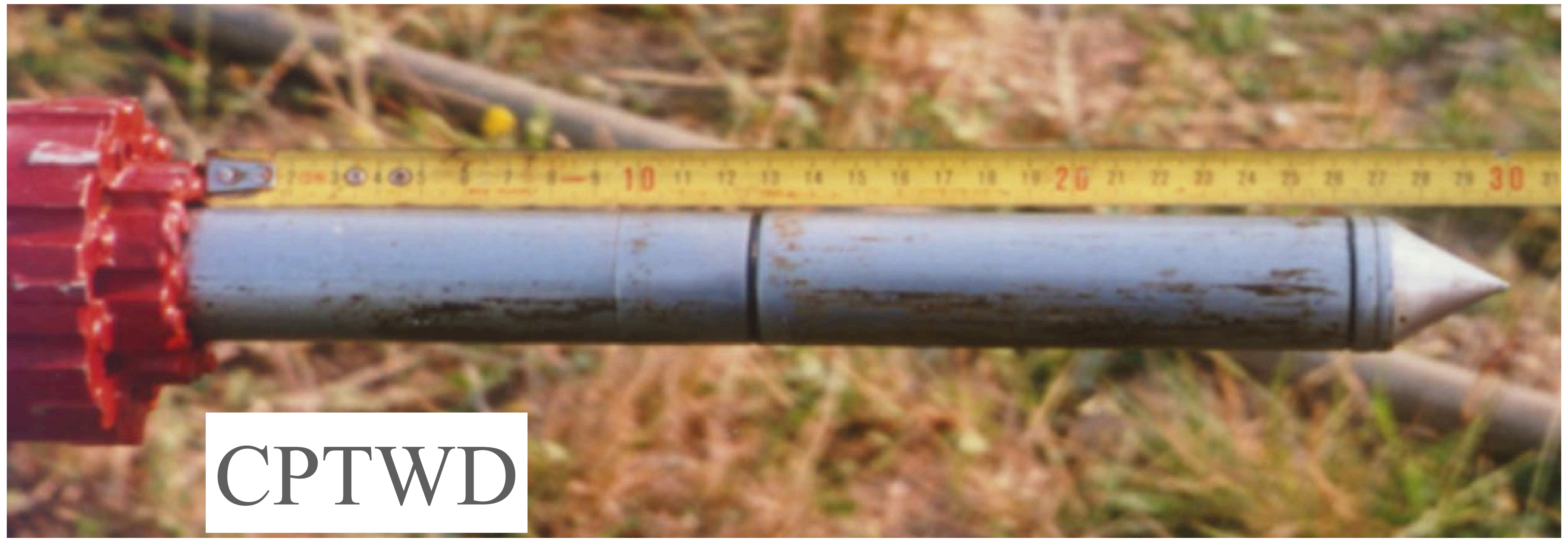
Tracked Systems

Combination

CPT PUSHING EQUIPMENT

DRILL RIG UNITS

CPT PUSHING EQUIPMENT



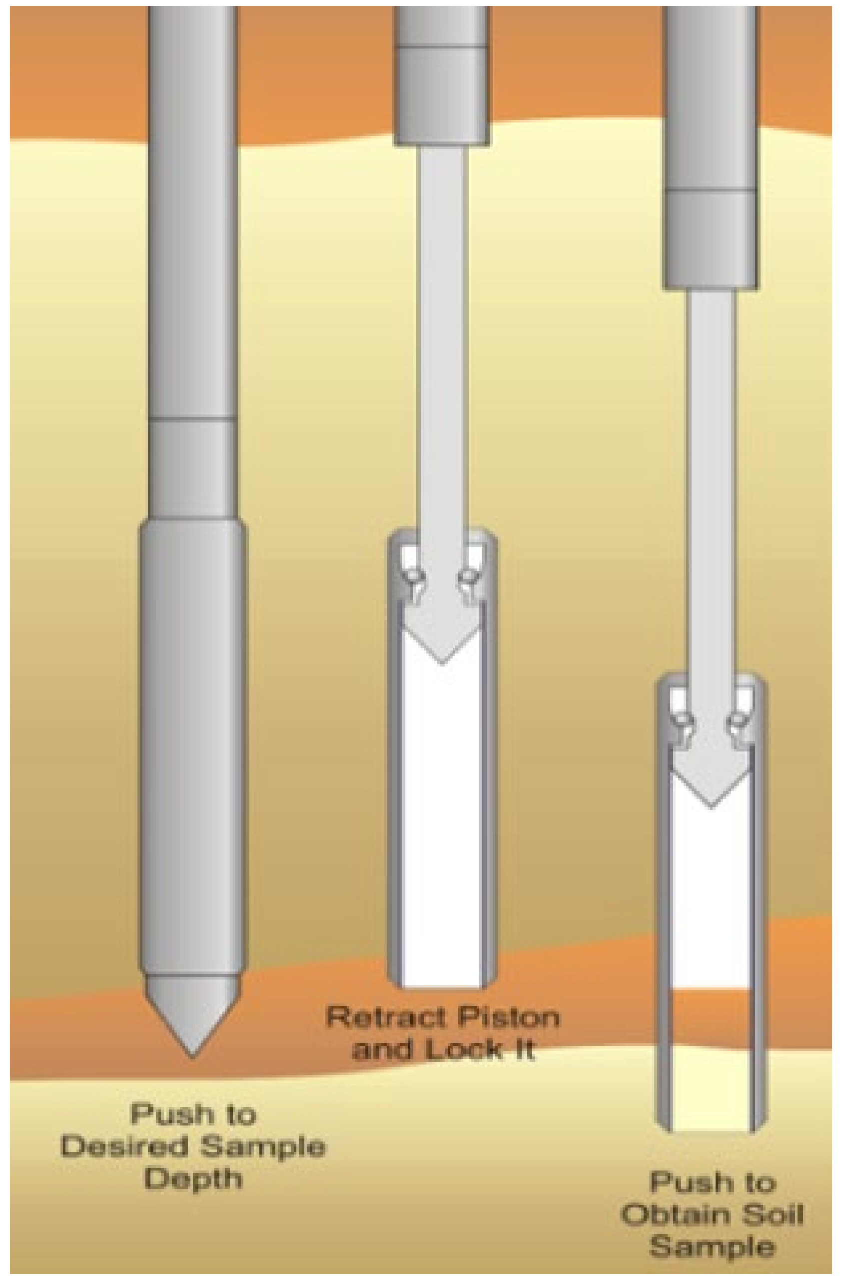
Wireline capabilities
to allow deeper CPT
Improved efficiency at depth

CPT SAMPLERS

25mm up to 75mm diameter

MOSTAP Sampler

Thick-walled
disturbed



Piston Sampler

Thick-walled
disturbed

PPI Sampler

Thin-walled
undisturbed

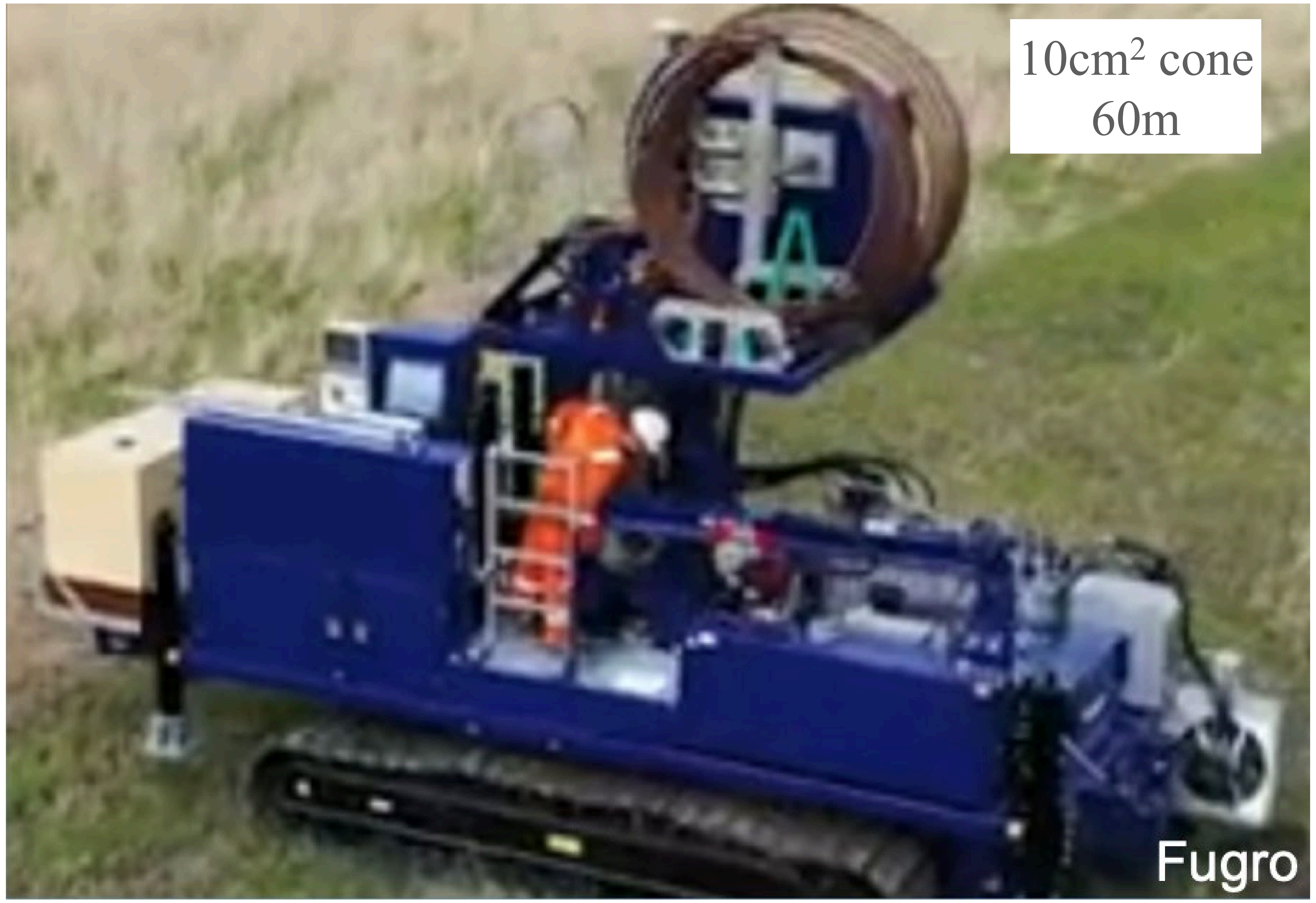
CONTINUOUS & AUTOMATION

Single-twist

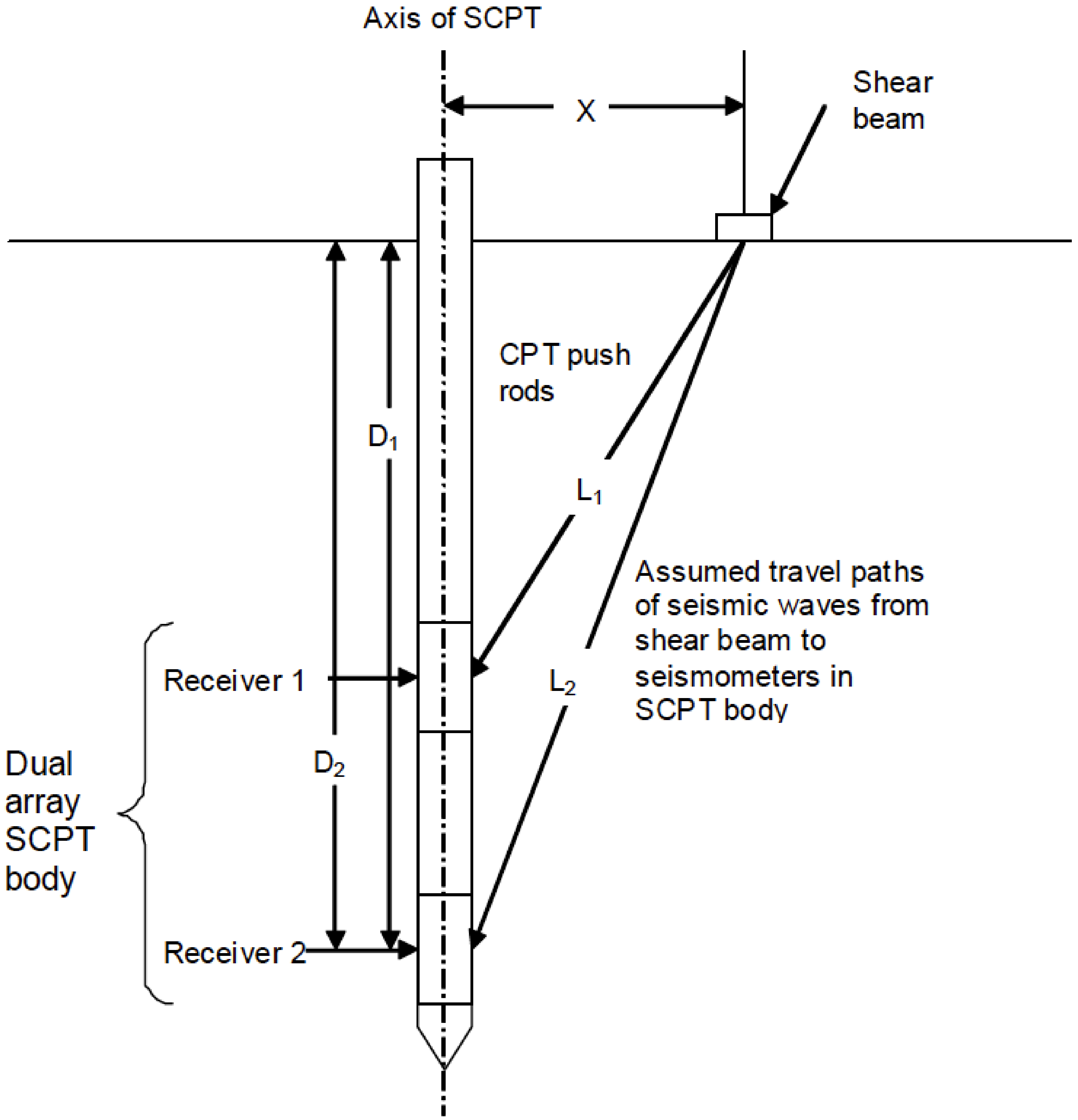
Coiled Tubing

CONTINUOUS & AUTOMATION

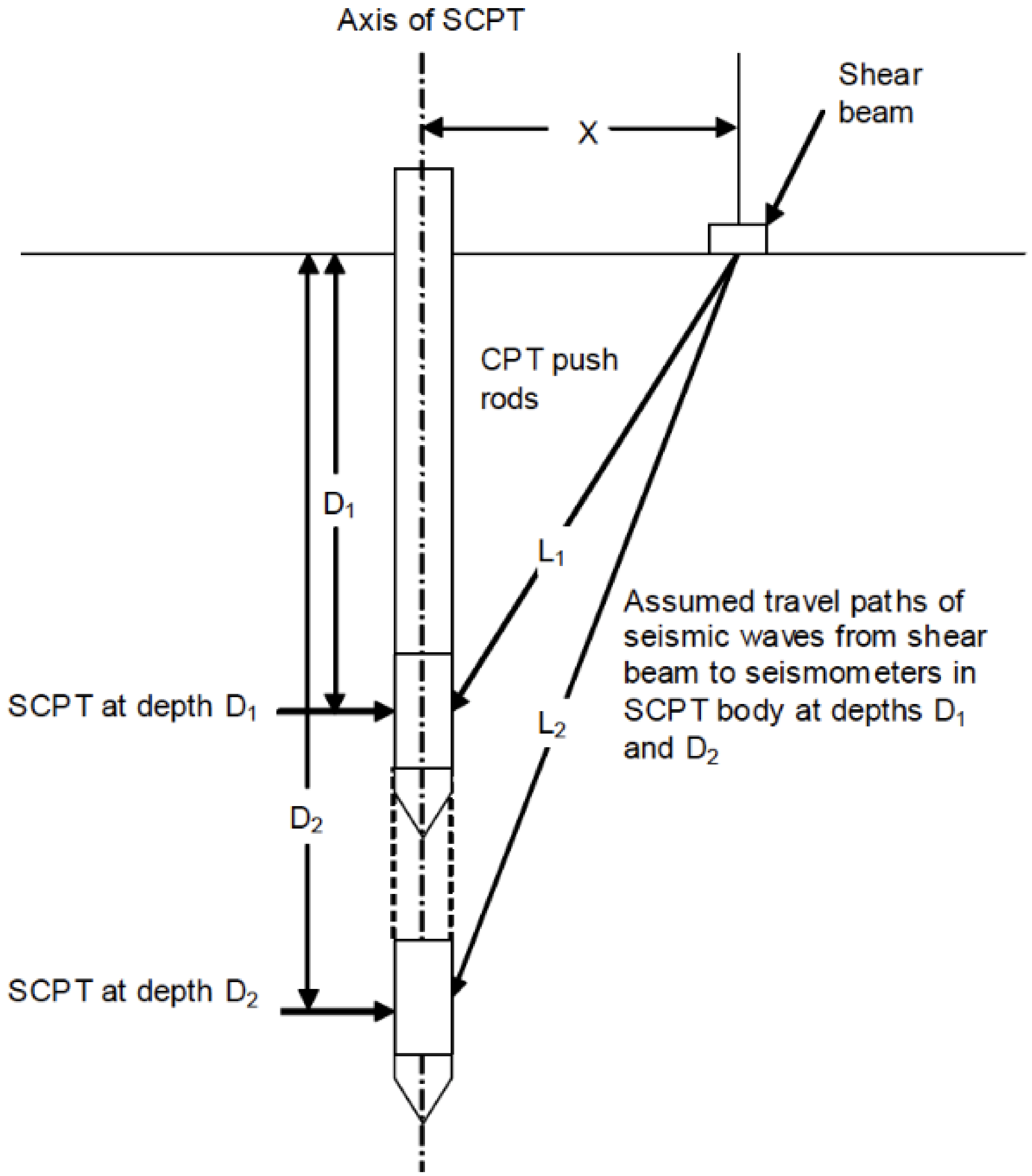
Remotely Operated – Coiled tubing



Seismic CPT PROCEDURE

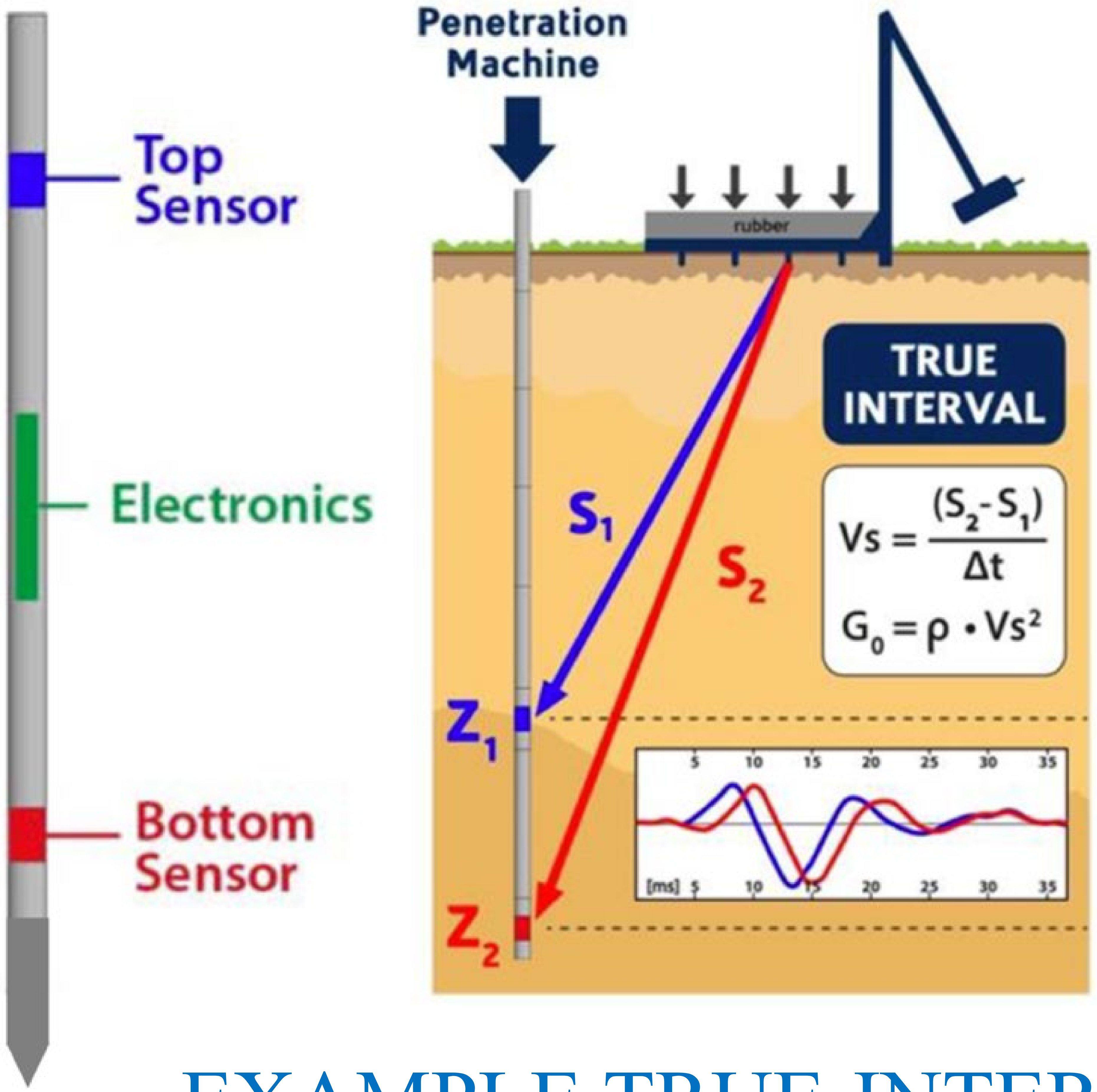


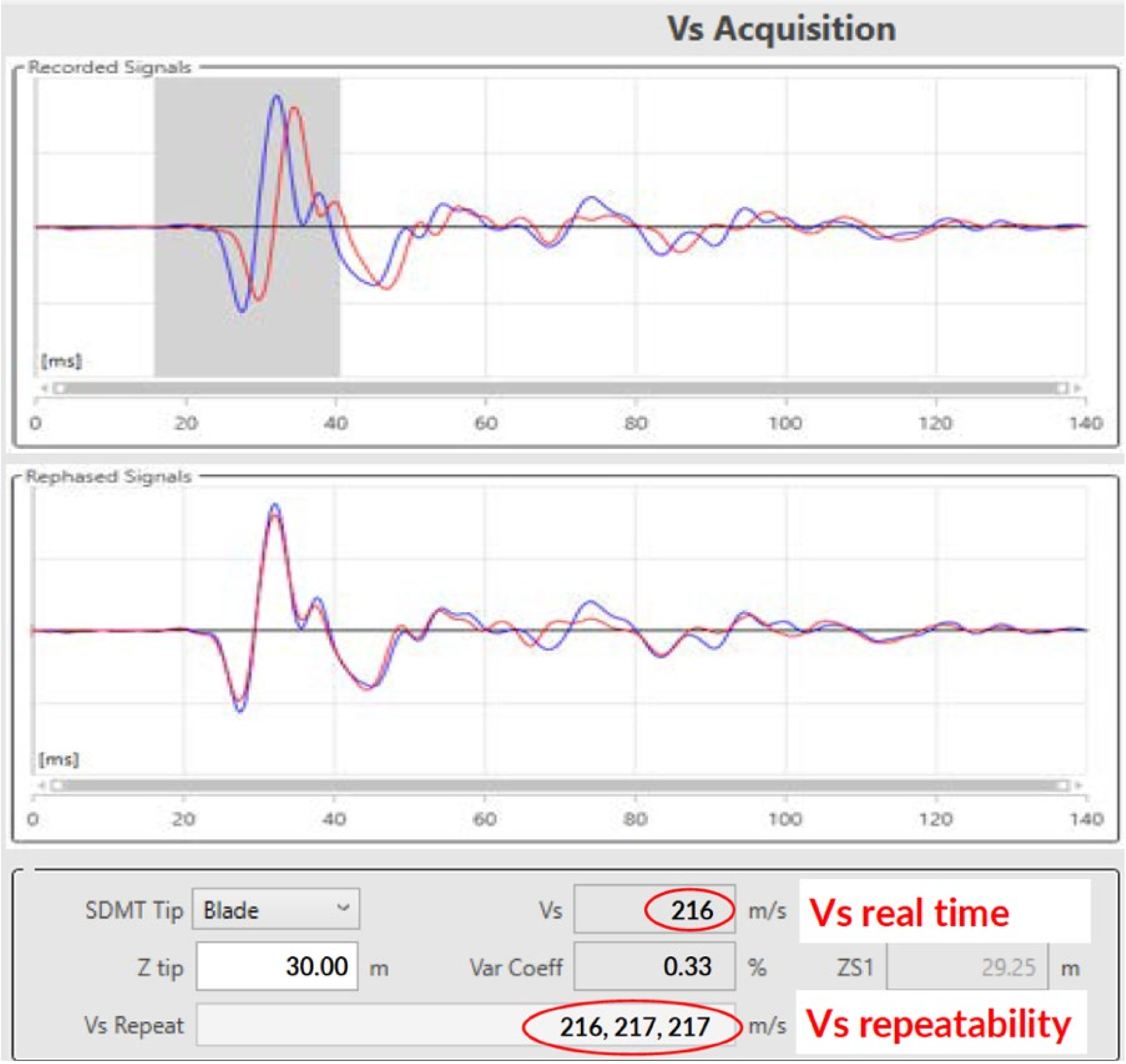
TRUE-INTERVAL



PSEUDO-INTERVAL

SCPT PROCEDURE





EXAMPLE TRUE-INTERVAL

SCPT METHODS

True-interval Method

Advantages:

- Only requires single shear wave source
- Independent of seismic source trigger characteristics
- Obtains V_s directly in the field

Limitations:

- Probe longer and harder to push to required depths
- Seismometers must have identical response characteristics
- If signals are stacked, trigger must be repeatable

Pseudo-interval Method

Advantages:

- Probe can be shorter and easier to push to required depths

Limitations:

- Requires two seismic waves for depth D_1 & D_2
- Requires fast and repeatable trigger
- Challenging to determine V_s in the field and requires post-processing

SEISMIC CPTu

SCPTu Advantage

7 measurements!

q_t

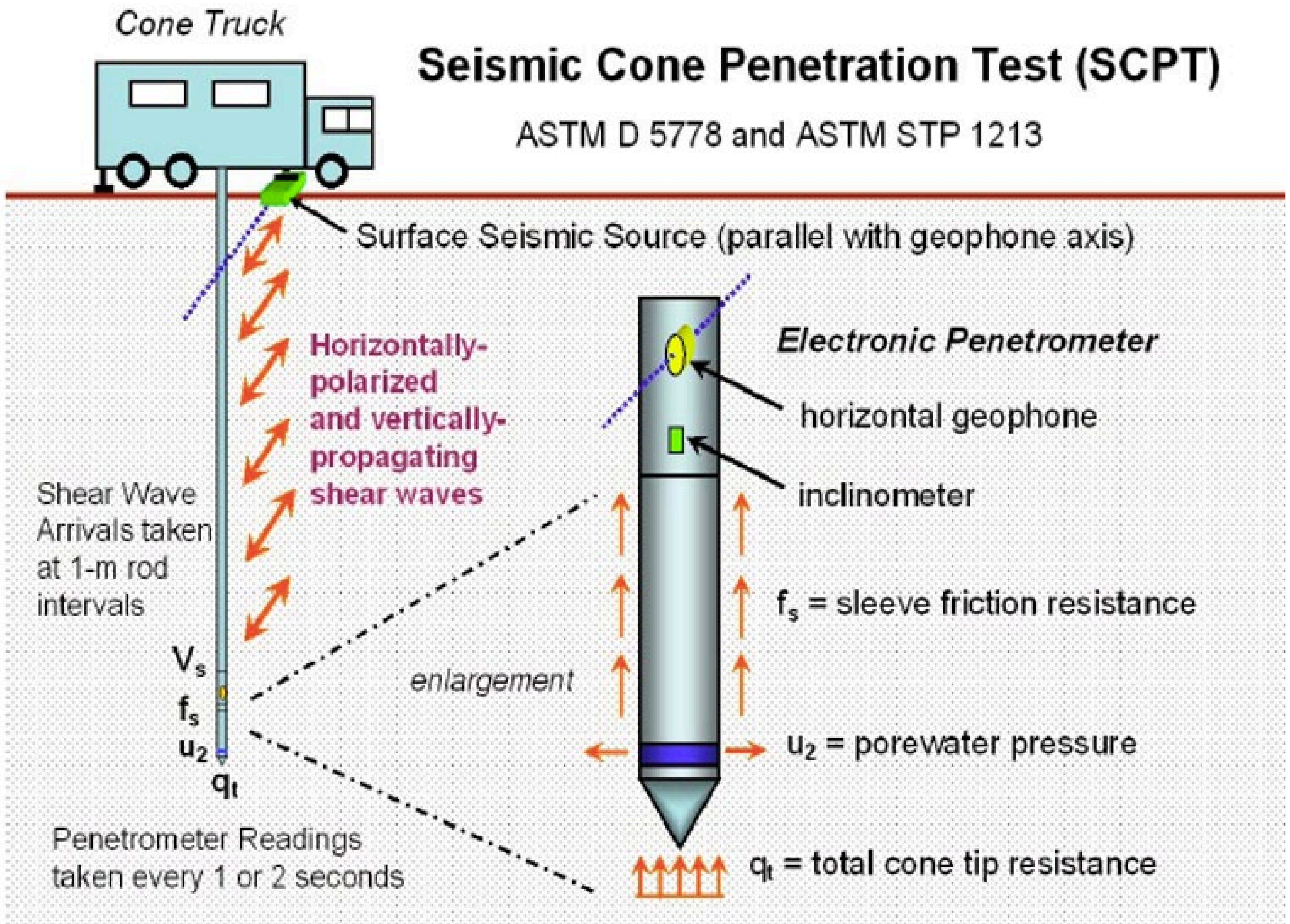
f_s

u_2

V_s ($\&$ V_p)

Dissipation { t_{50}, u_o }

i



Mayne, 2014

SEISMIC CPTu

SCPTu Advantage

7 measurements!

q_t

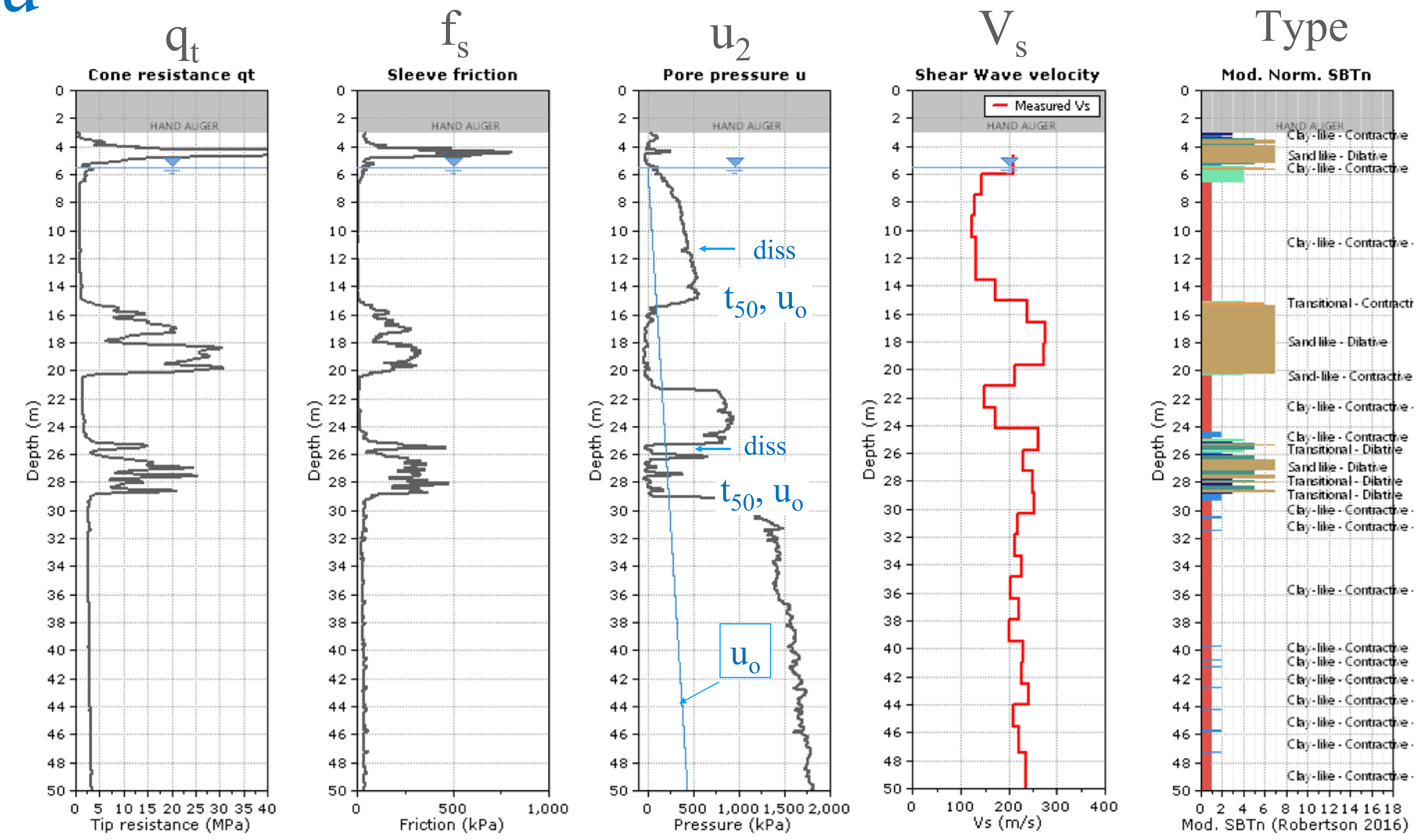
f_s

u_2

V_s (& V_p)

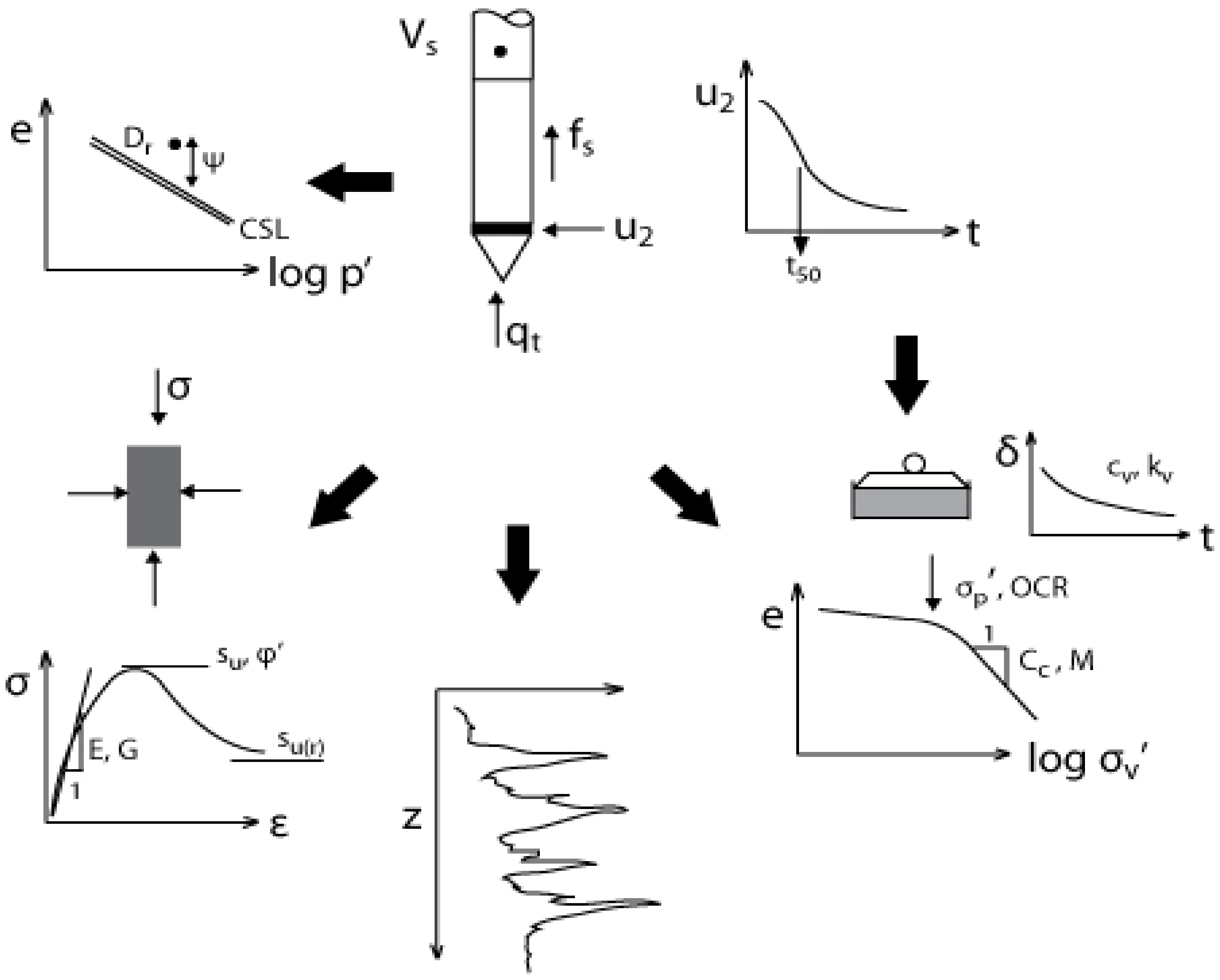
Dissipation { t_{50}, u_o }

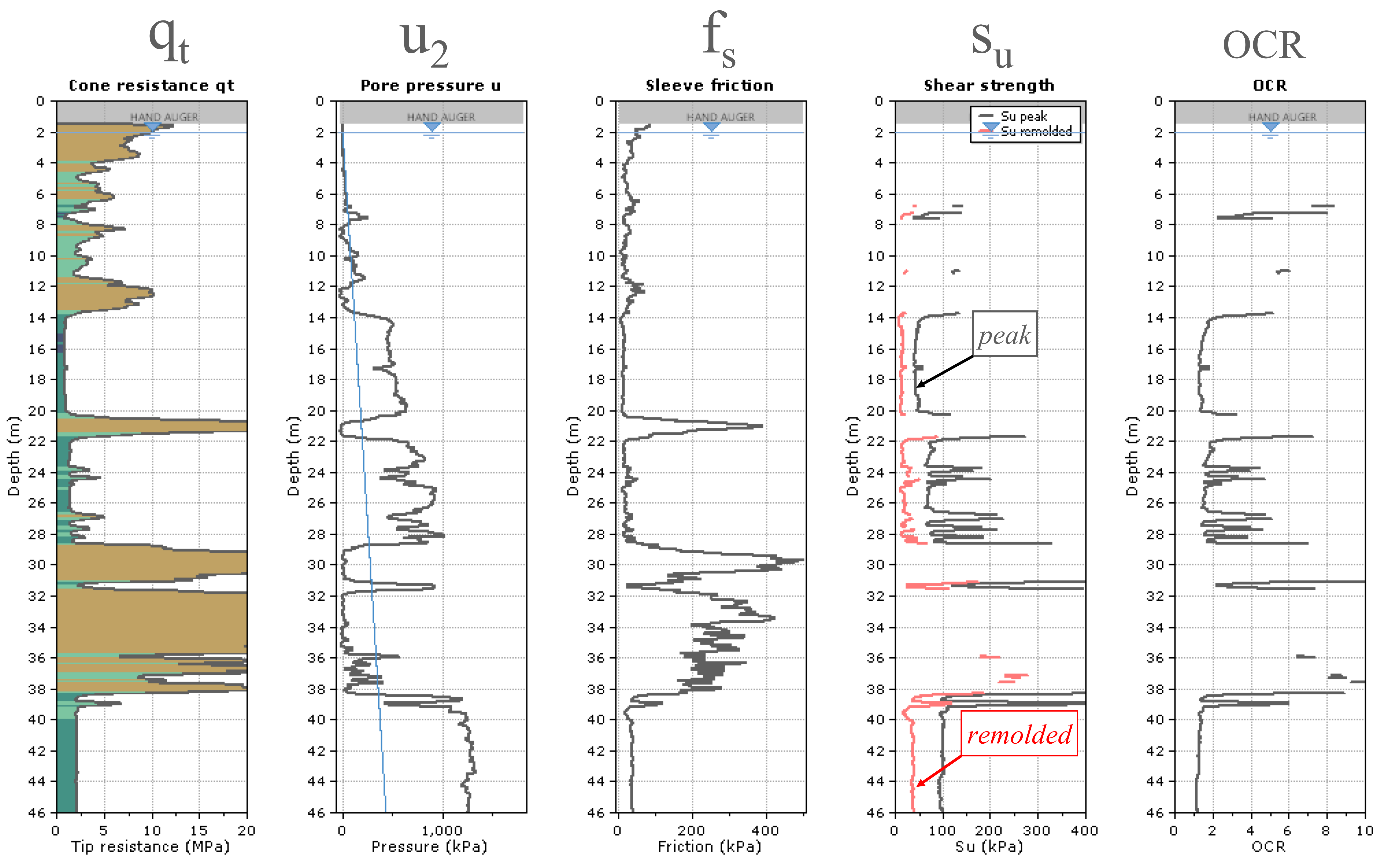
i



SCPTu INTERPRTATION

Full range of interpretation of soil behavior





CPT NORMALIZED PARAMETERS

- Early normalization (Wroth, 1984)

$$Q_t = (q_t - \sigma_v) / \sigma'_v$$

- Normalization based on soil type, density and stress level (Robertson, 2009)

$$Q_{tn} = [(q_t - \sigma_v)/p_a] (p_a/\sigma'_v)^n$$

Where:

$(q_t - \sigma_v)/p_a$ = dimensionless net cone resistance,
$(p_a/\sigma'_v)^n$ = stress normalization factor
n = stress exponent that varies with soil type, density & stress level
p_a = atmospheric reference pressure in same units as q_t and σ_v

$$n = 0.381 (I_c) + 0.05 (\sigma'_{vo}/p_a) - 0.15 \qquad \text{where } n \leq 1.0$$

CPT NORMALIZED PARAMETERS

Difference normalized CPT parameters:

$$\mathbf{Q_{tn} = [(q_t - \sigma_v)/p_a]\,(p_a/\sigma'_v)^n}$$

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

$$\mathbf{F_r = [f_s\,/\,(q_t - \sigma_{vo})]100\ \%}$$

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

$$B_q = \Delta u/(q_t - \sigma_{vo})$$

CPT NORMALIZED PARAMETERS

Difference normalized CPT parameters:

$$\mathbf{Q_{tn} = [(q_t - \sigma_v)/p_a]\,(p_a/\sigma'_v)^n}$$

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

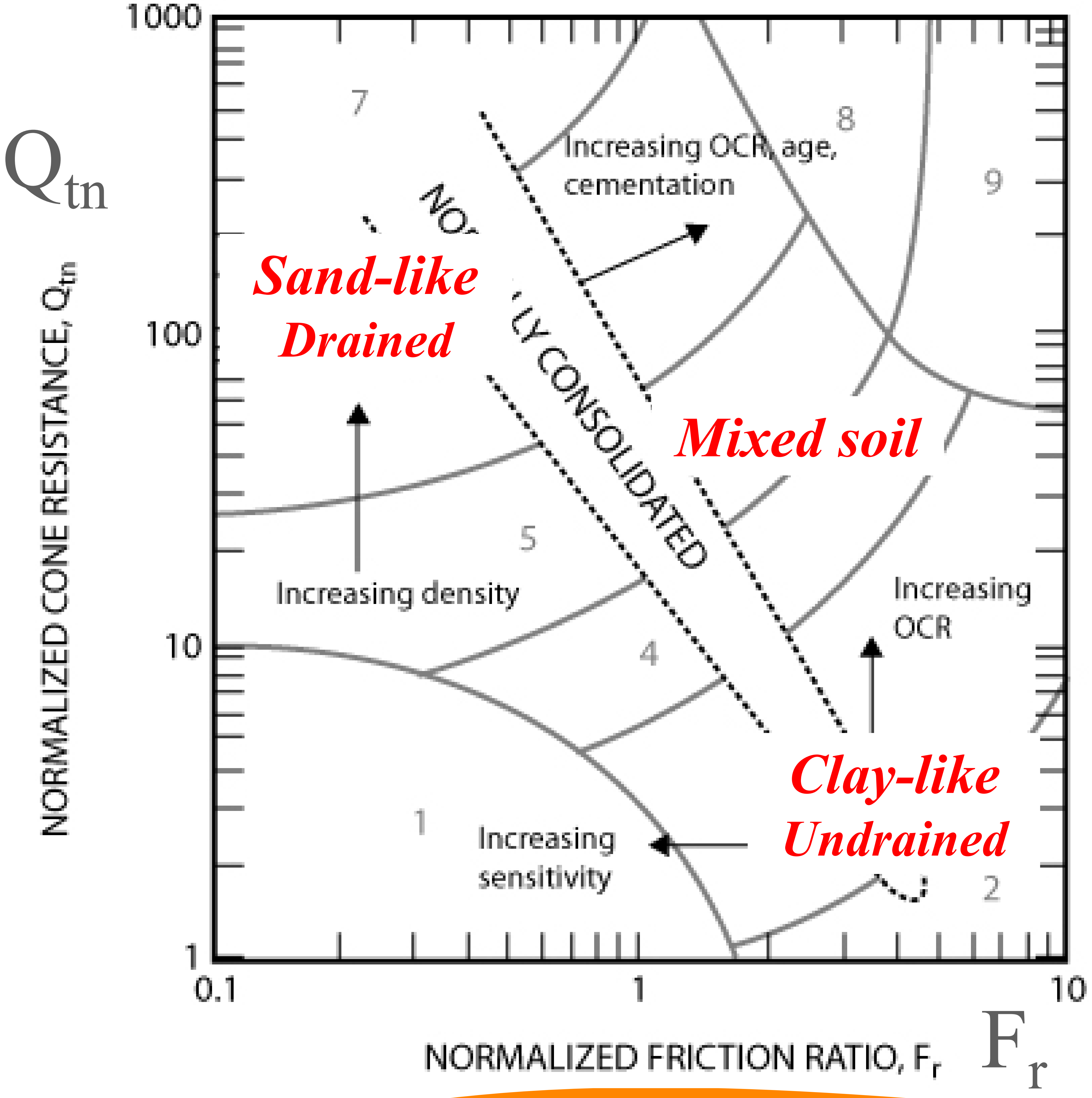
$$\mathbf{F_r = [f_s\,/\,(q_t - \sigma_{vo})]100\ \%}$$

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

$$B_q = \Delta u/(q_t - \sigma_{vo})$$

Main parameters

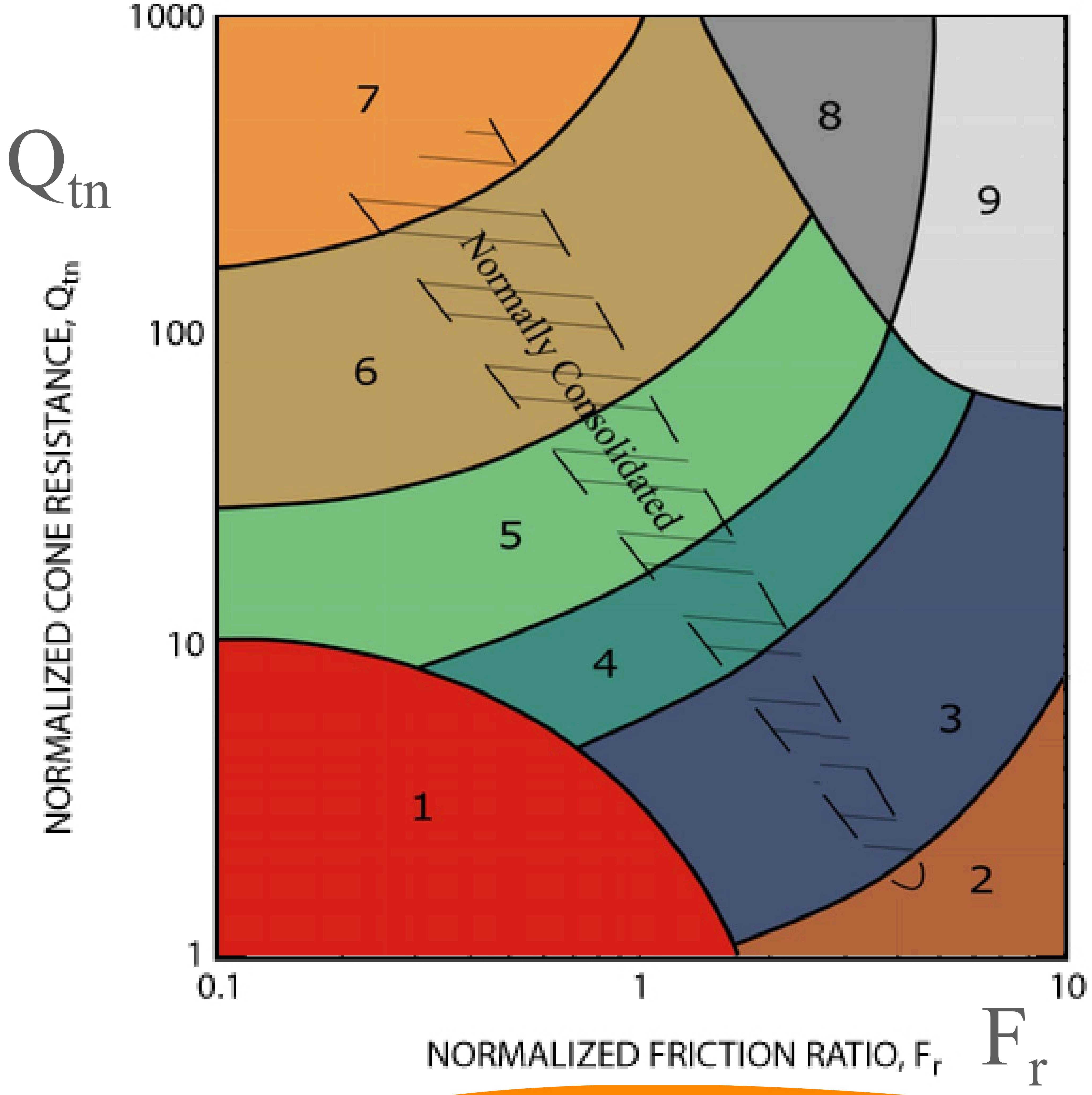
CPT SOIL BEHAVIOR TYPE (SBT)



CPT SBT based on in-situ soil *behavior* - not the same as traditional classification based on *physical* characteristics using Atterberg Limits and grain size carried out on disturbed samples

Robertson (2009)

CPT SOIL BEHAVIOR TYPE (SBT)

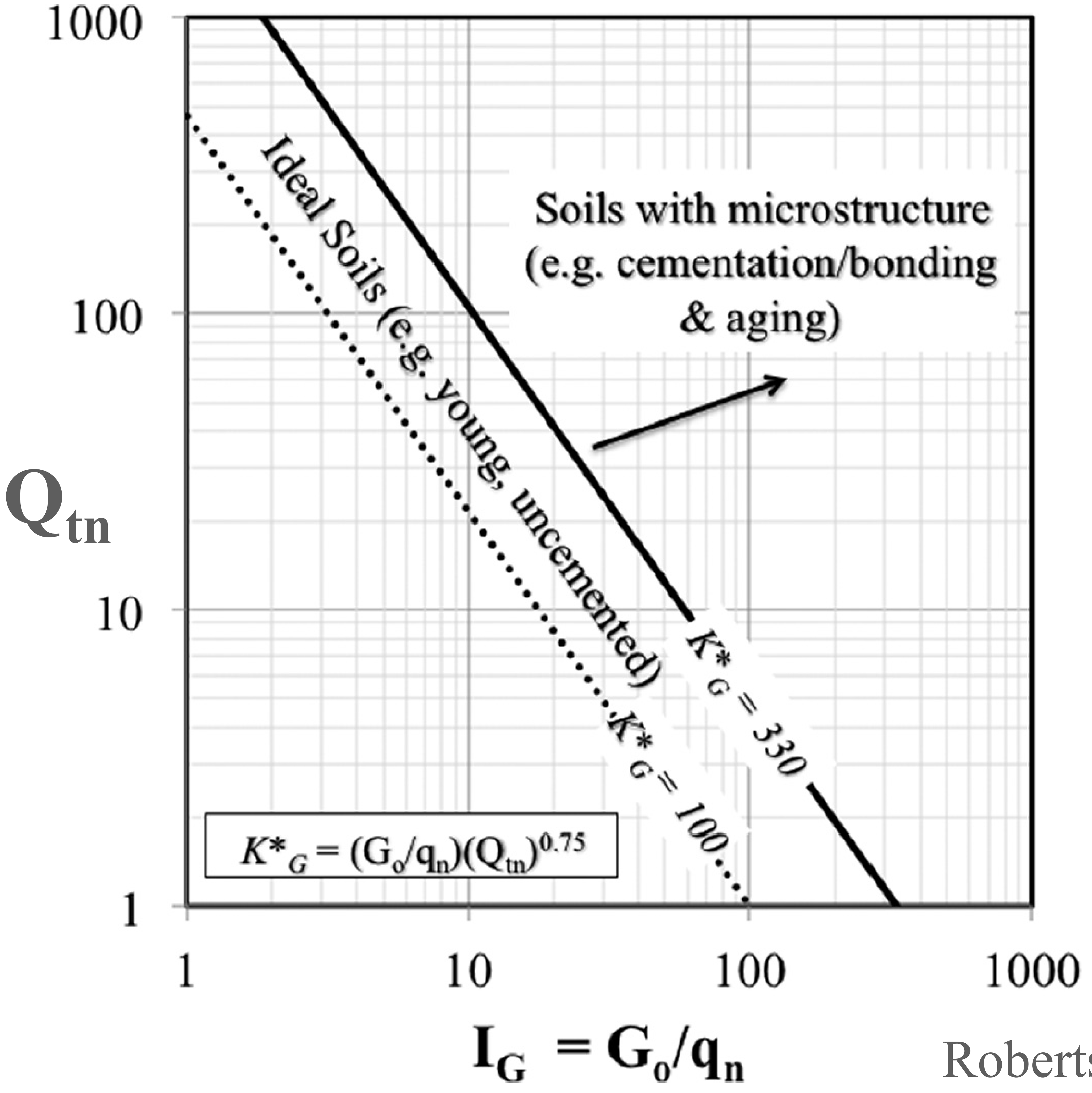


CPeT-IT software

CPT SBT based on in-situ soil *behavior* - not the same as traditional classification based on *physical* characteristics using Atterberg Limits and grain size carried out on disturbed samples

Robertson (2009)

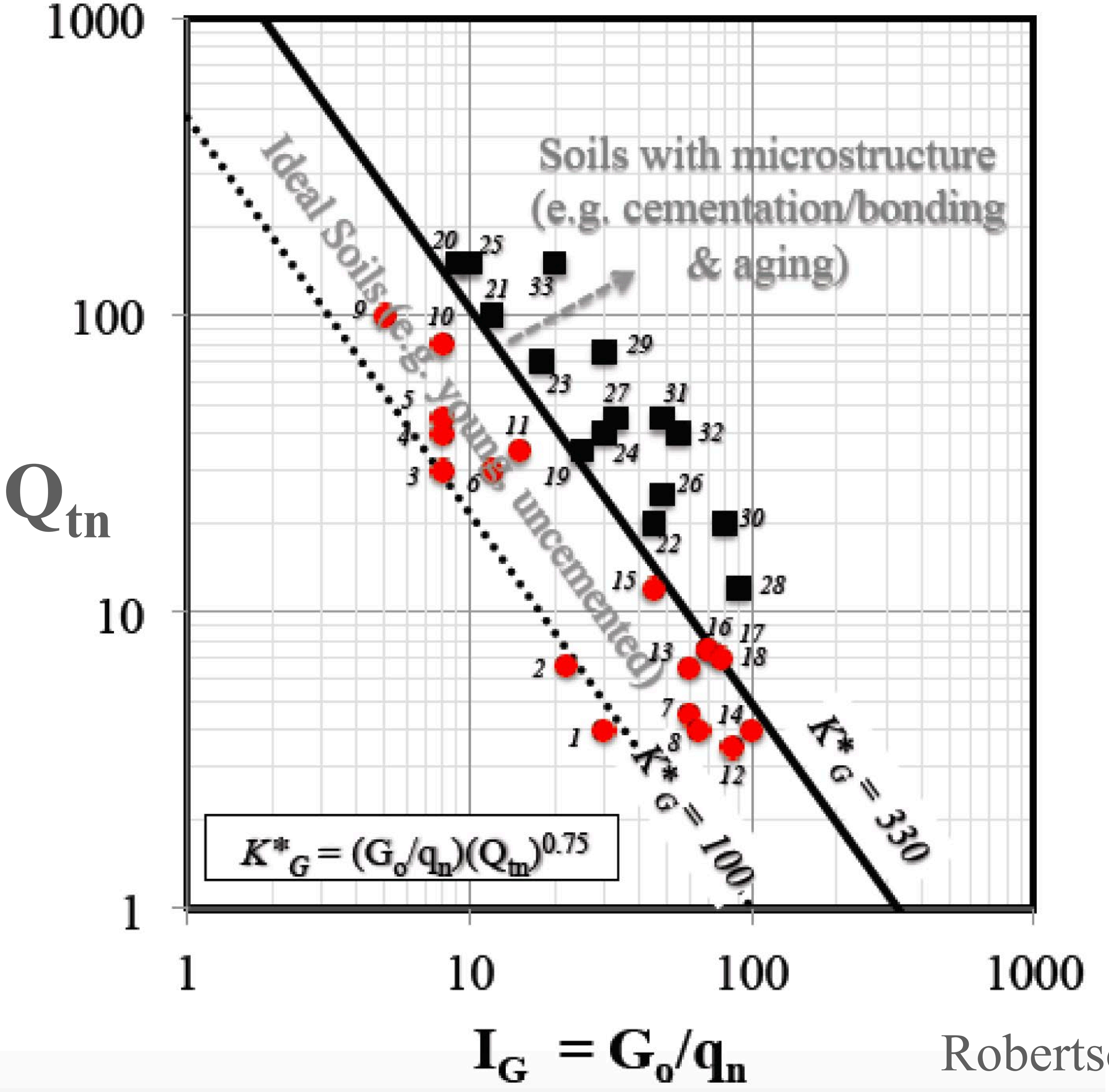
SOIL MICROSTRUCTURE



Robertson (2016)

- Identification of soil microstructure
  - Q_{tn} (at large strains)
  - $G_o = \rho\ V_s^2$ (at very small strains)
  - $I_G = G_o/q_{n.}$ (stiffness to strength ratio)
  - $K_G = I_G\ (Q_{tn})^{0.75}$
- Soils with microstructure (K_G>200) have higher resistance at small strains

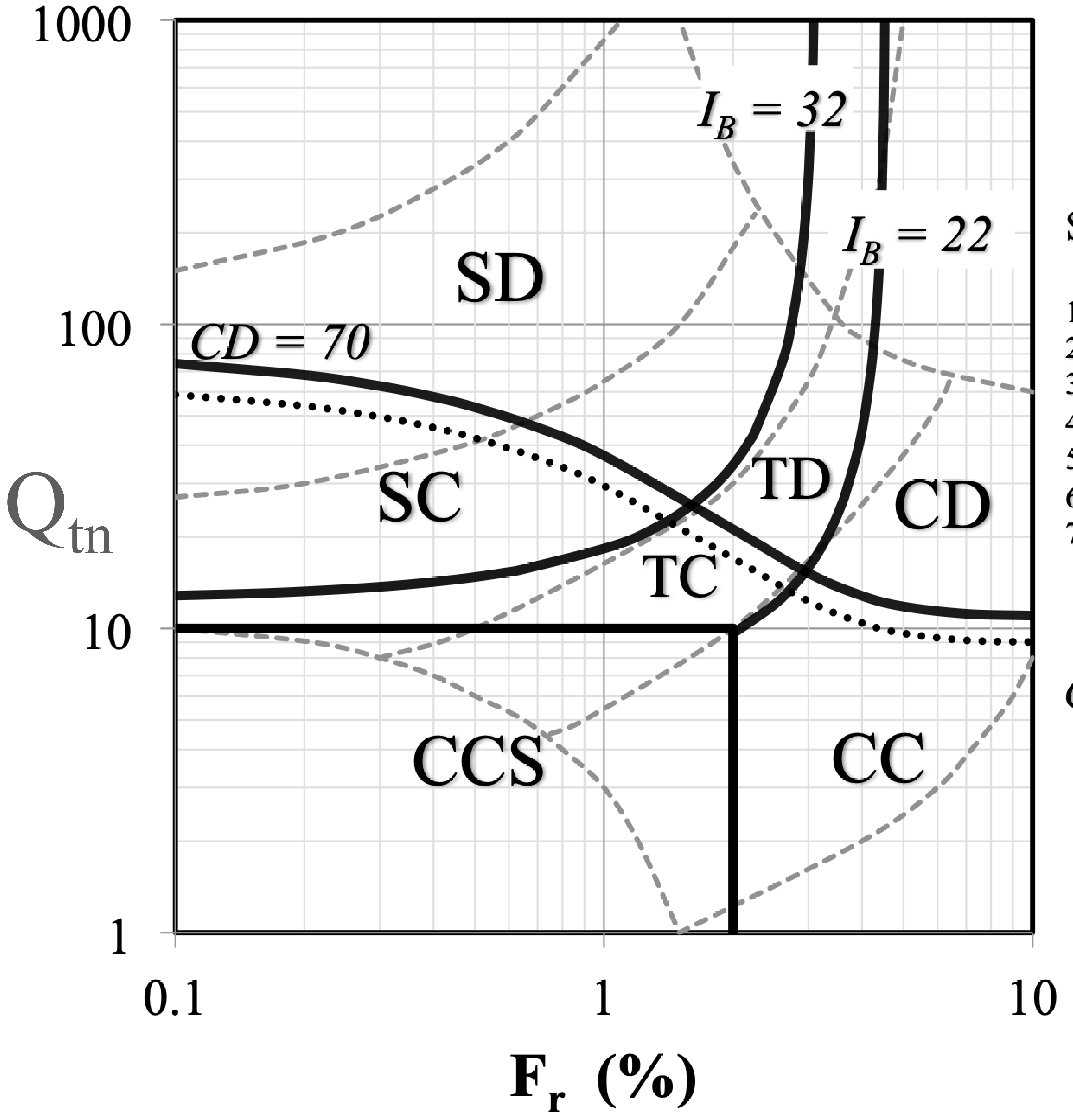
SOIL MICROSTRUCTURE



Robertson (2016)

- Identification of soil microstructure
  - Q_{tn} (at large strains)
  - $G_o = \rho V_s^2$ (at very small strains)
  - $I_G = G_o/q_n$ (stiffness to strength ratio)
  - $K_G = I_G (Q_{tn})^{0.75}$
- Soils with microstructure (K_G>200) have higher resistance at small strains

UPDATED CPT SOIL BEHAVIOR TYPE (SBT)



Behavior Descriptions

Soil Behaviour Type

1: CCS Clay-like - Contractive - Sensitive
2: CC Clay-like - Contractive
3: CD Clay-like - Dilative
4: TC Transitional - Contractive
5: TD Transitional - Dilative
6: SC Sand-like - Contractive
7: SD Sand-like - Dilative

$CD = (Q_{tn} - 11)(1 + 0.06F_r)^{17}$

$I_B = 100(Q_{tn} + 10)/(70 + Q_{tn}F_r)$

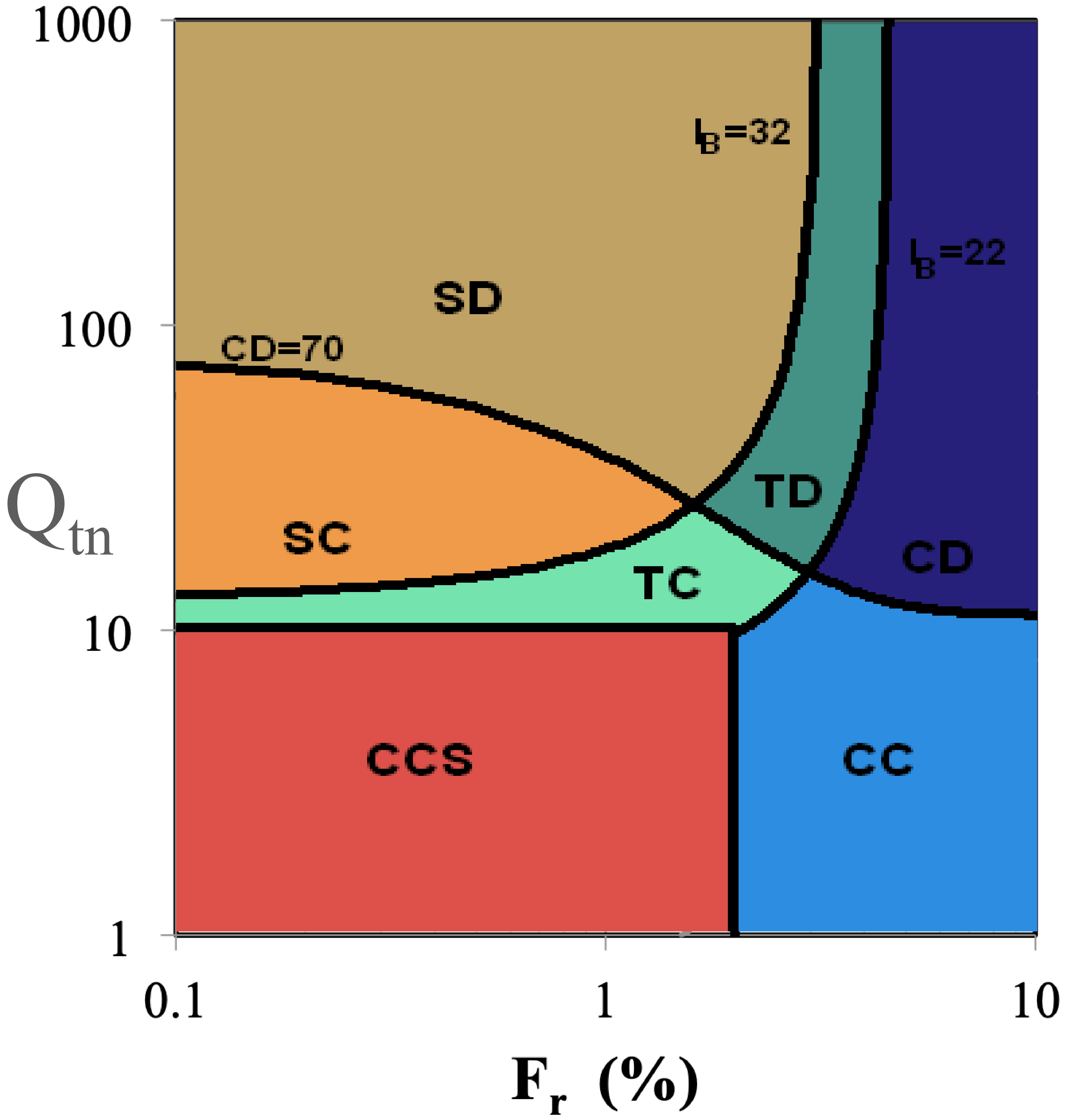
Robertson, 2016

Behavior descriptions

- Sand- and Clay-like
- Dilative-Contractive boundary
- Transition materials

Based on soils with little or no microstructure

UPDATED CPT SOIL BEHAVIOR TYPE (SBT)



Behavior Descriptions

Soil Behaviour Type

1: CCS Clay-like - Contractive - Sensitive
2: CC Clay-like - Contractive
3: CD Clay-like - Dilative
4: TC Transitional - Contractive
5: TD Transitional - Dilative
6: SC Sand-like - Contractive
7: SD Sand-like - Dilative

$$CD = (Q_{tn} - 11)(1 + 0.06F_r)^{17}$$

$$I_B = 100(Q_{tn} + 10)/(70 + Q_{tn}F_r)$$

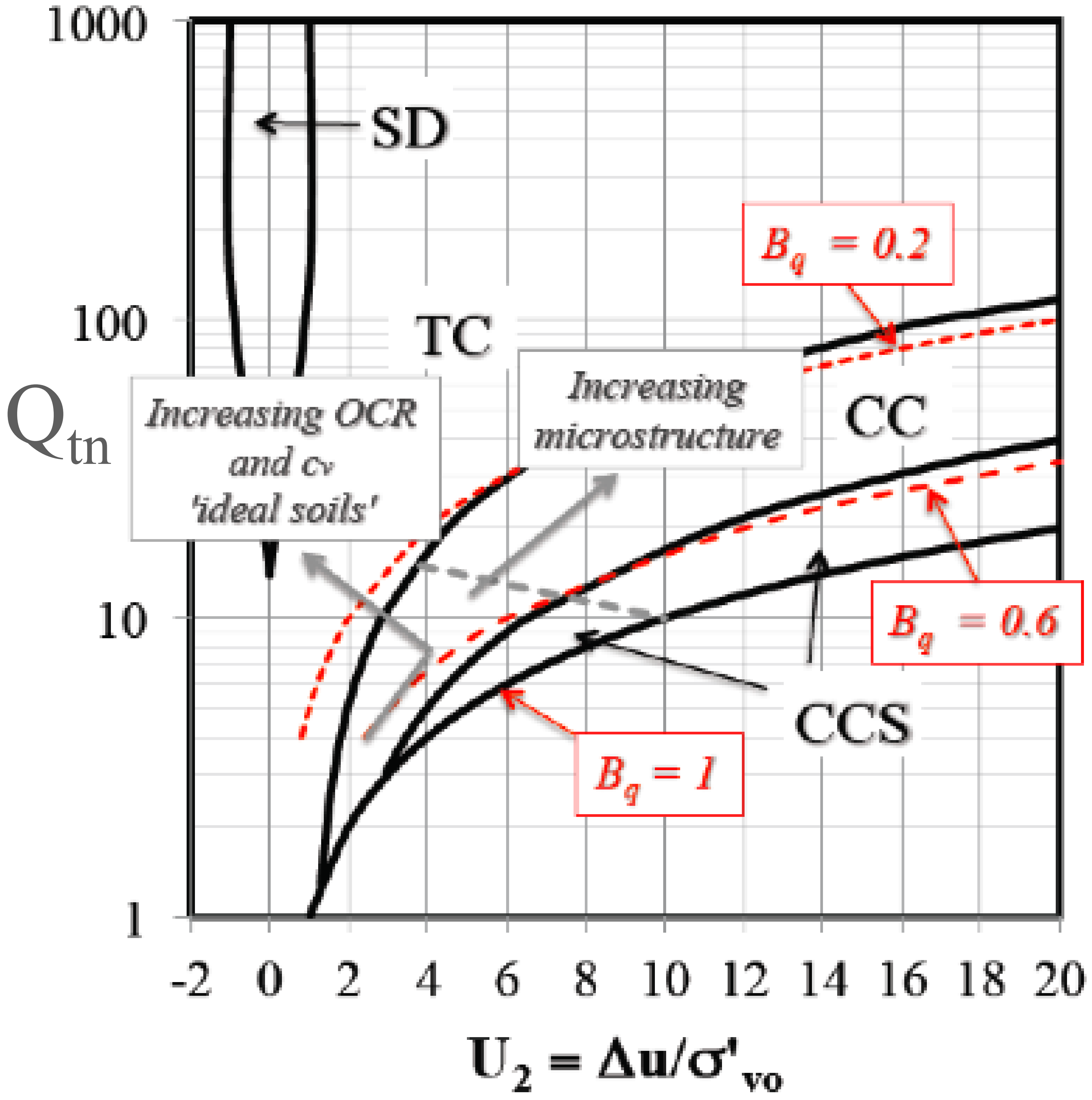
Robertson, 2016

Behavior descriptions

- Sand- and Clay-like
- Dilative-Contractive boundary
- Transition materials

Based on soils with little or no microstructure

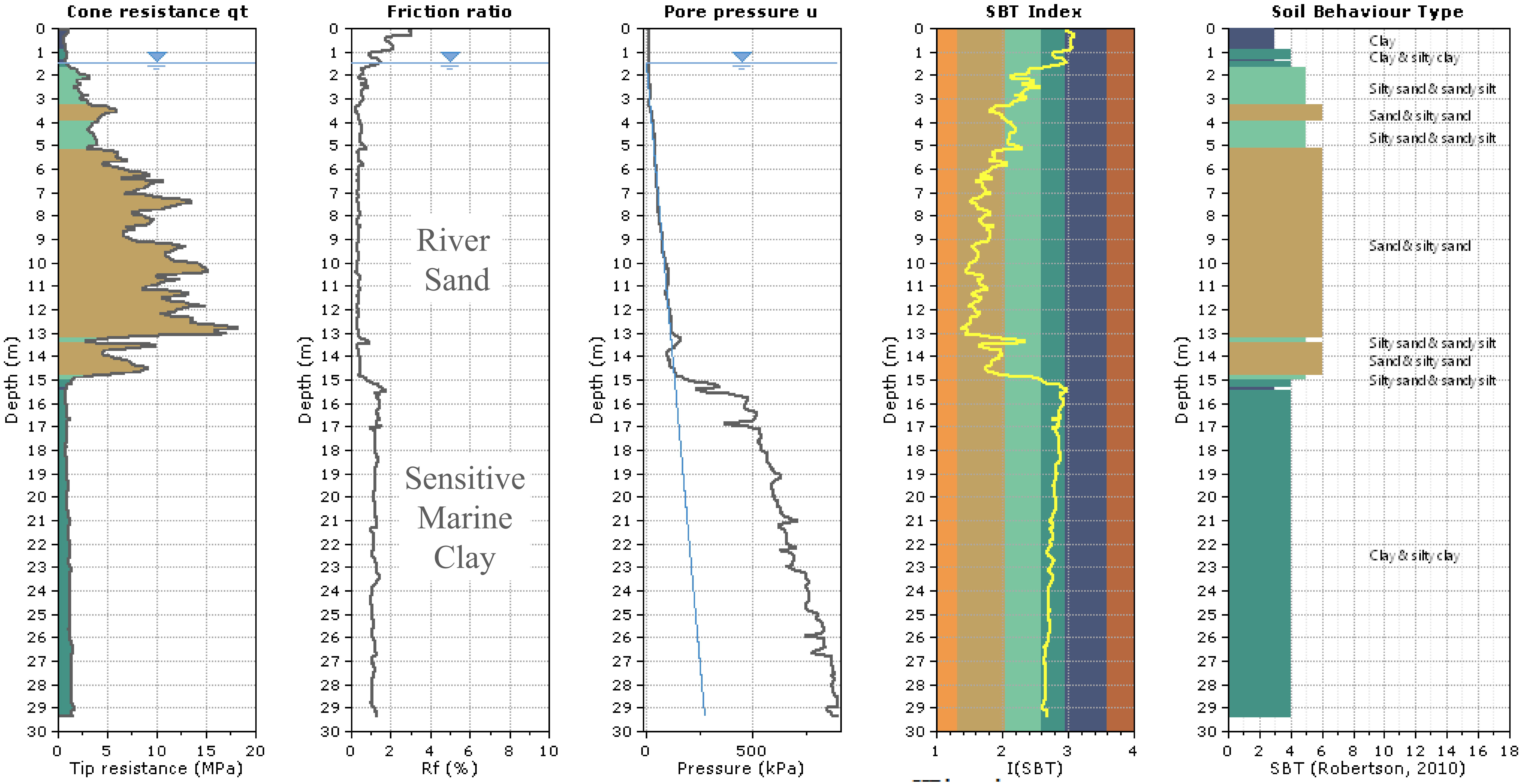
UPDATED CPT SOIL BEHAVIOR TYPE (SBT)



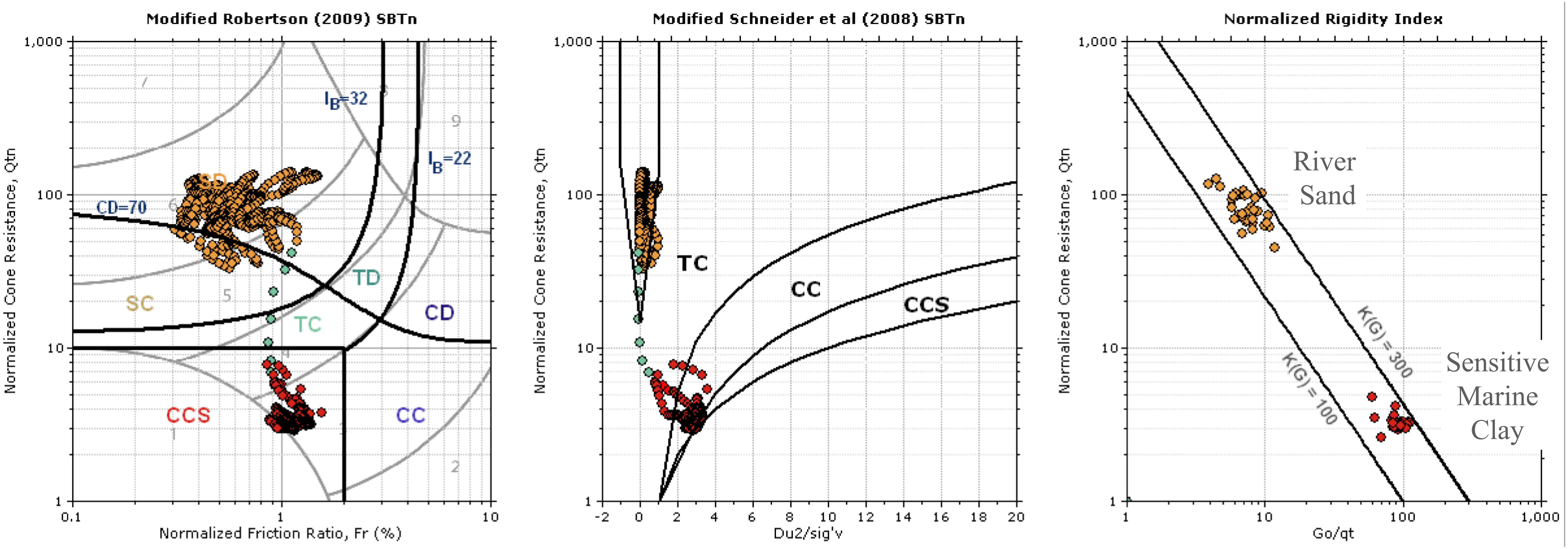
Updated Schneider et al (2008) chart based on $Q_{tn} - U_2$ with proposed new soil behavior type boundaries (B_q lines in red)

Suitable for fine-grained soil with excess CPT pore pressures

EXAMPLE: McDONALD FARM, VANCOUVER

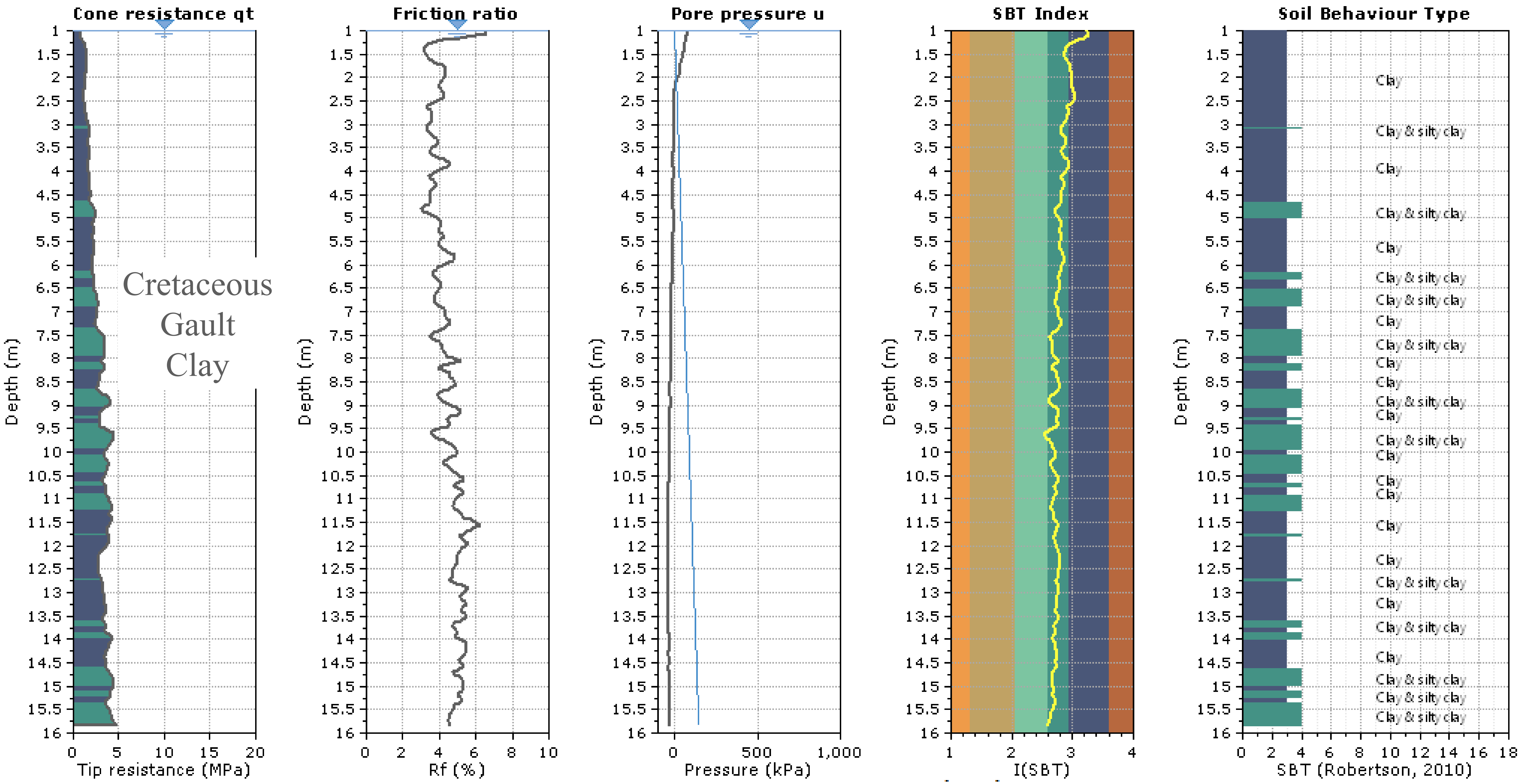


EXAMPLE: McDONALD FARM, VANCOUVER

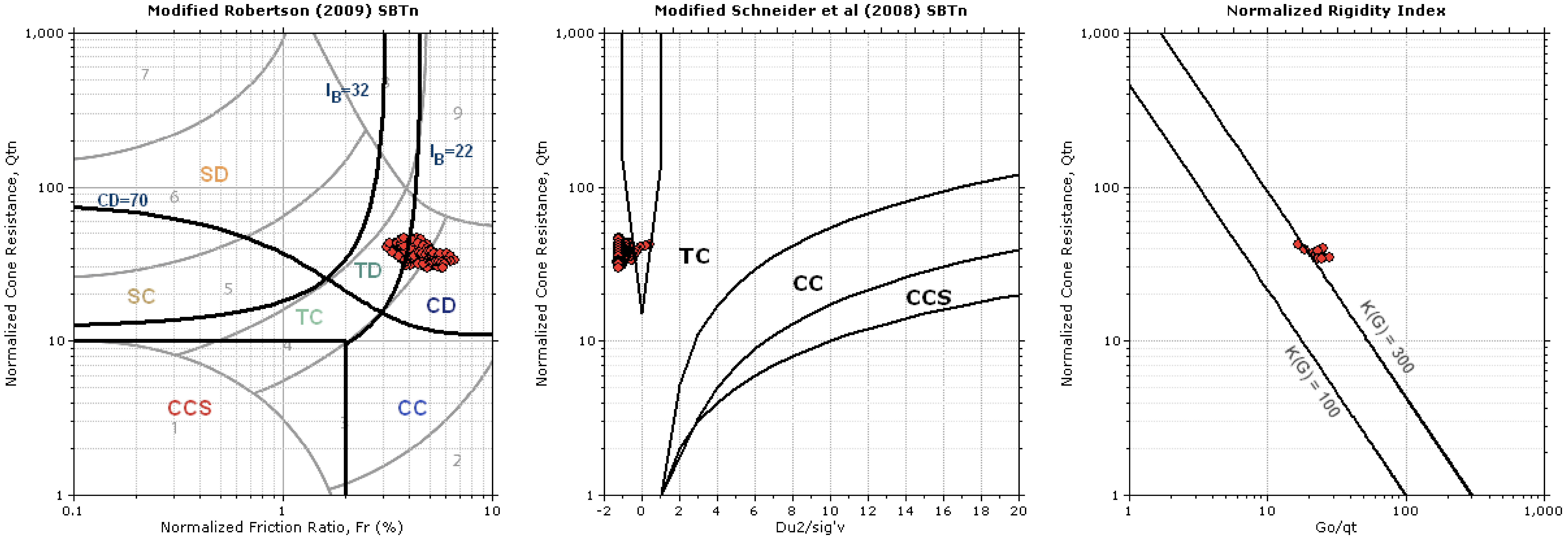


Holocene-age alluvial Fraser River deposit

EXAMPLE: MADDINGLY, UK

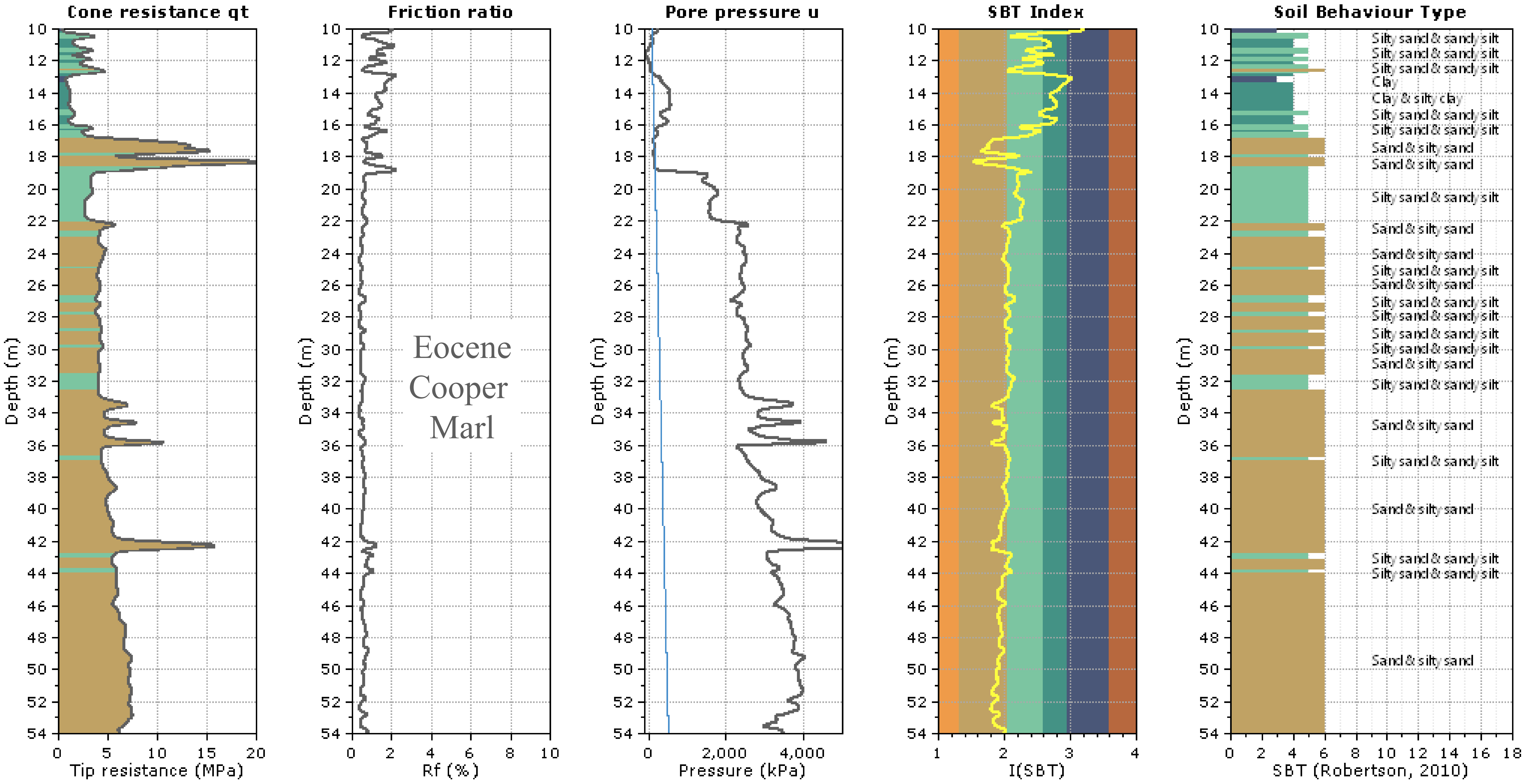


EXAMPLE: MADDINGLY, UK

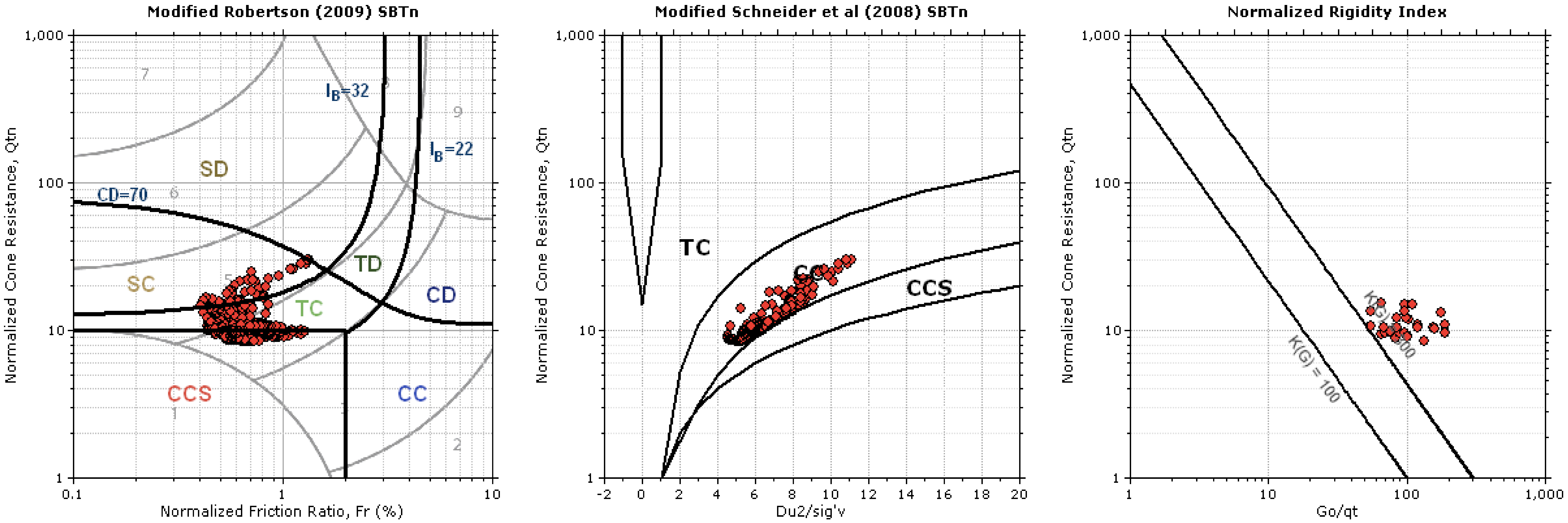


Very stiff overconsolidated fissured Gault clay of Cretaceous period (~110 million years ago) with OCR > 10

EXAMPLE: COOPER MARL, USA

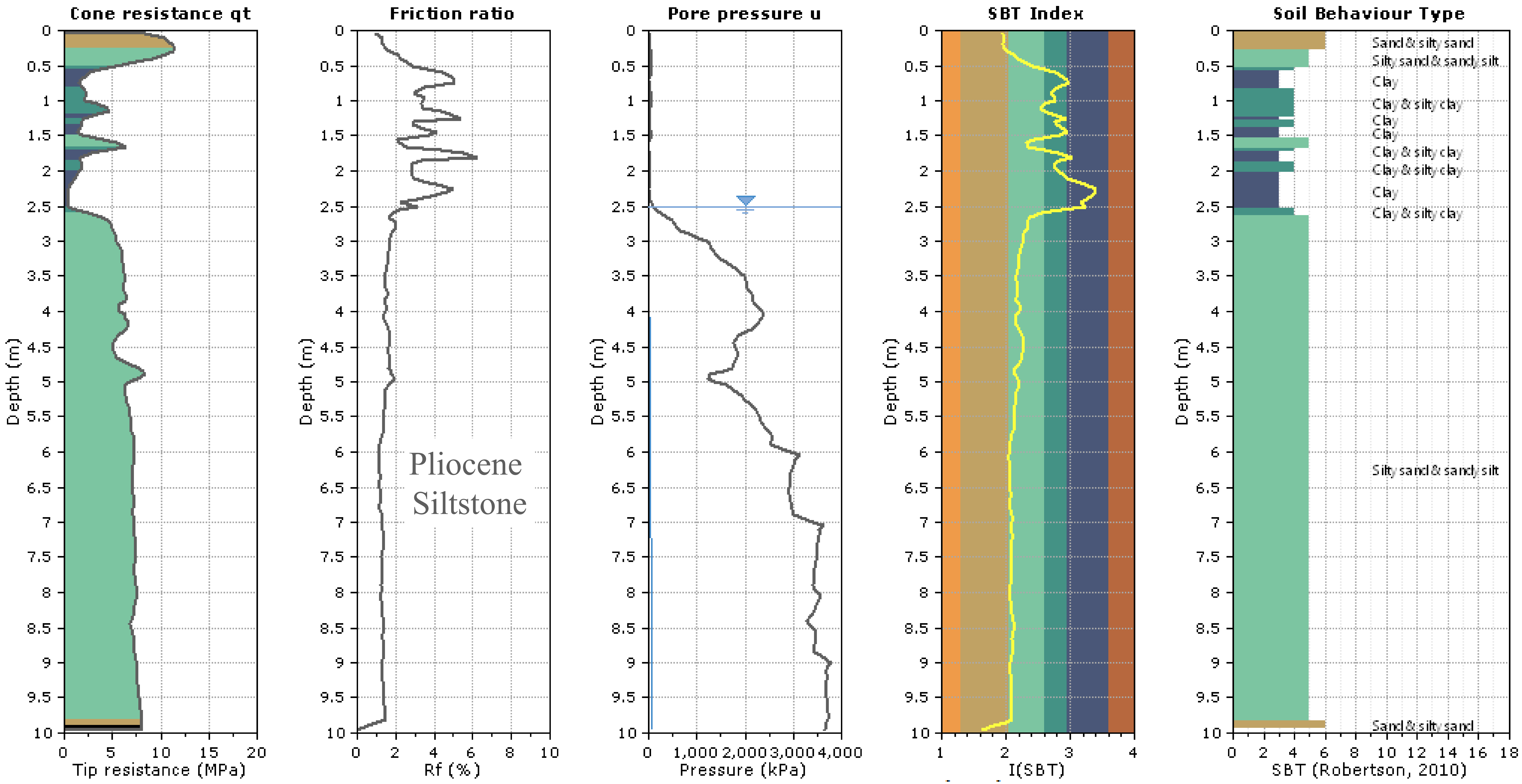


EXAMPLE: COOPER MARL, USA

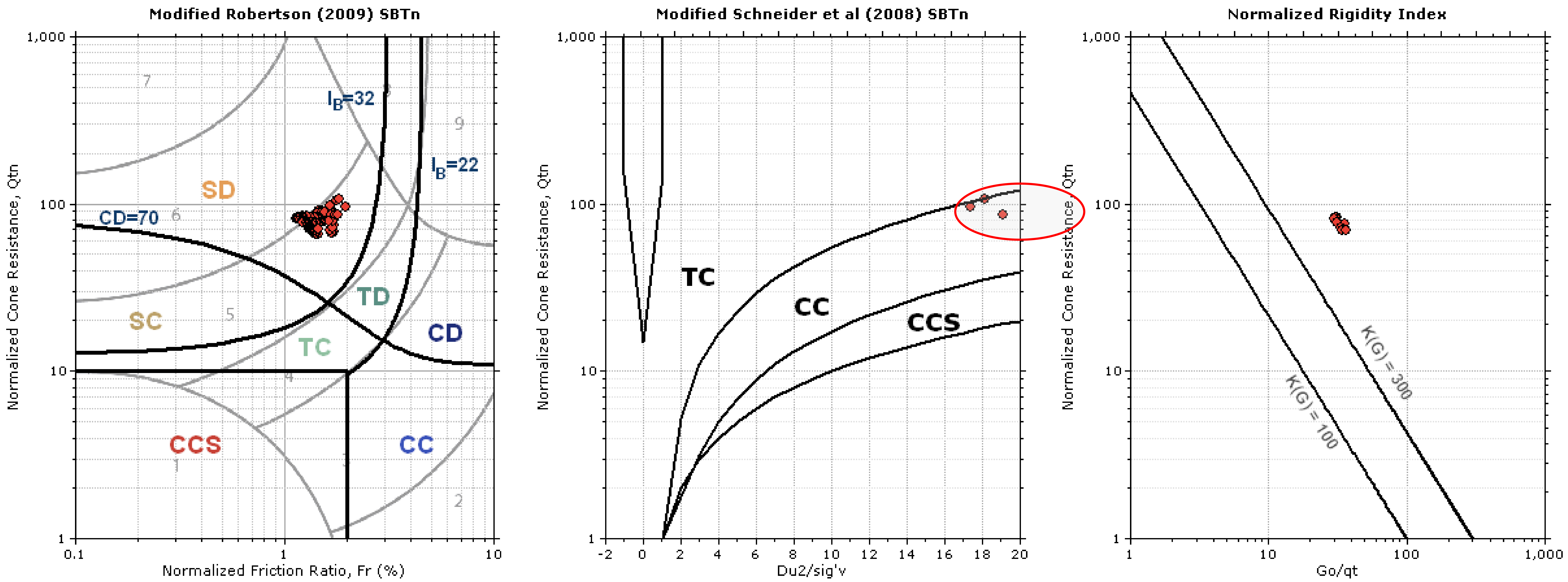


SCPTu data from 20 to 50m in Cooper Marl (calcareous cemented clay/silt), Eocene to Oligocene-age (~30 to 40 million years ago)

EXAMPLE: SILTSTONE, LOS ANGELES, USA



EXAMPLE: SILTSTONE, LOS ANGELES, USA



SCPTu data from 3 to 10m in siltstone Fernando formation of Pliocene age (~3 to 5 million years ago).

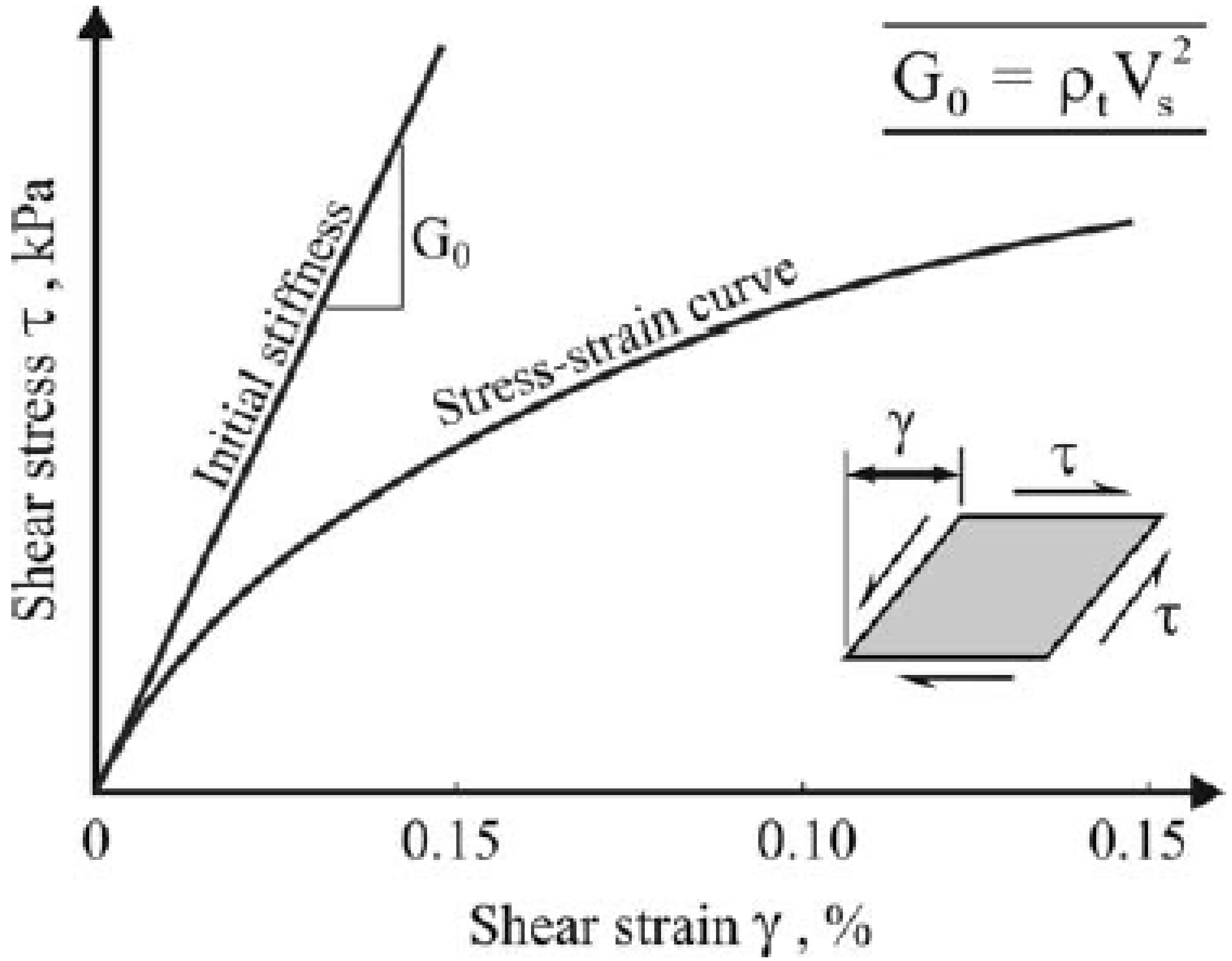
Seismic methods measure soil stiffness at small strains

V_s is direct measure of small strain shear modulus, G_o

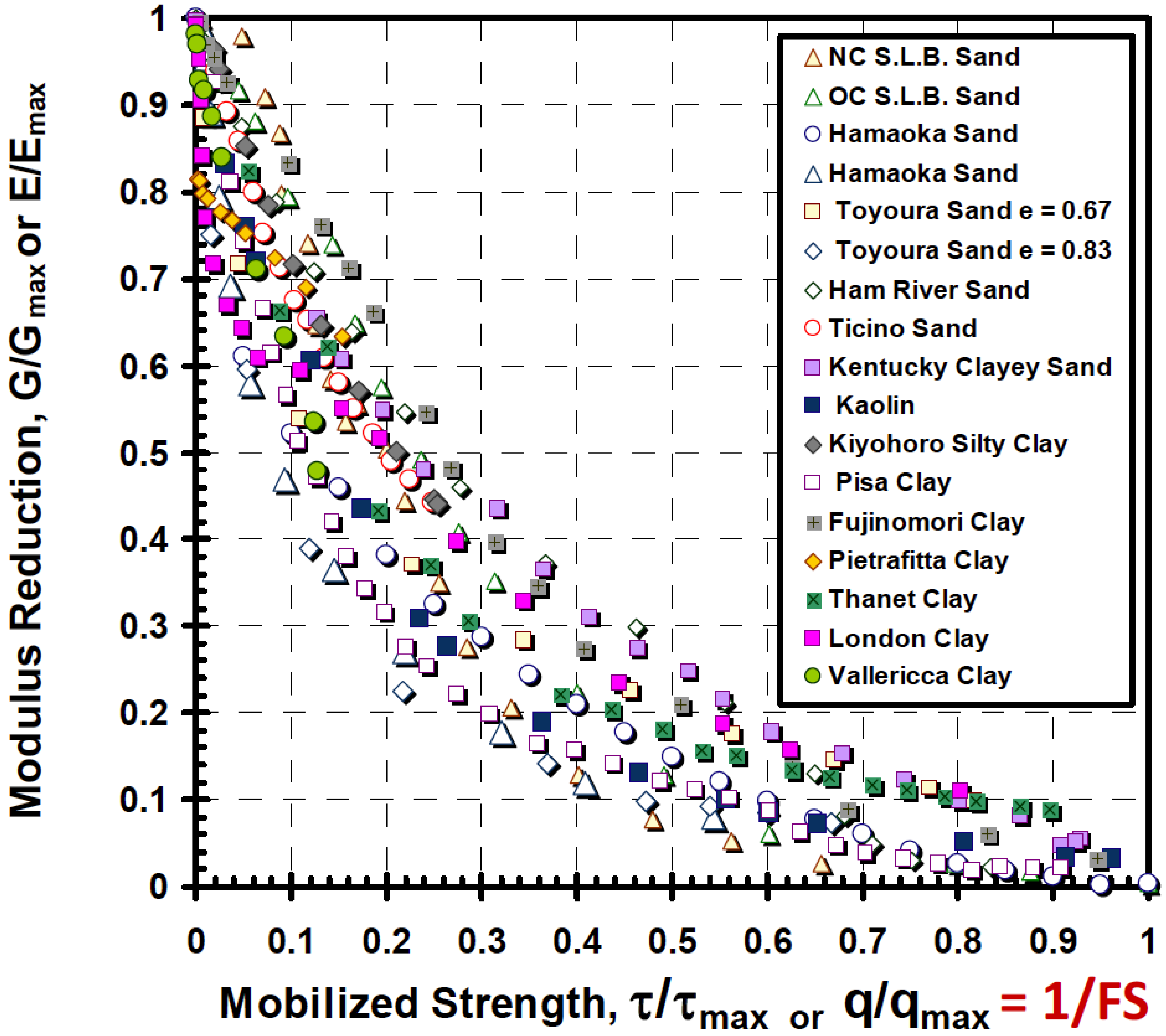
$$G_o = \rho_t (V_s)^2$$

$$\rho_t = \gamma / g$$

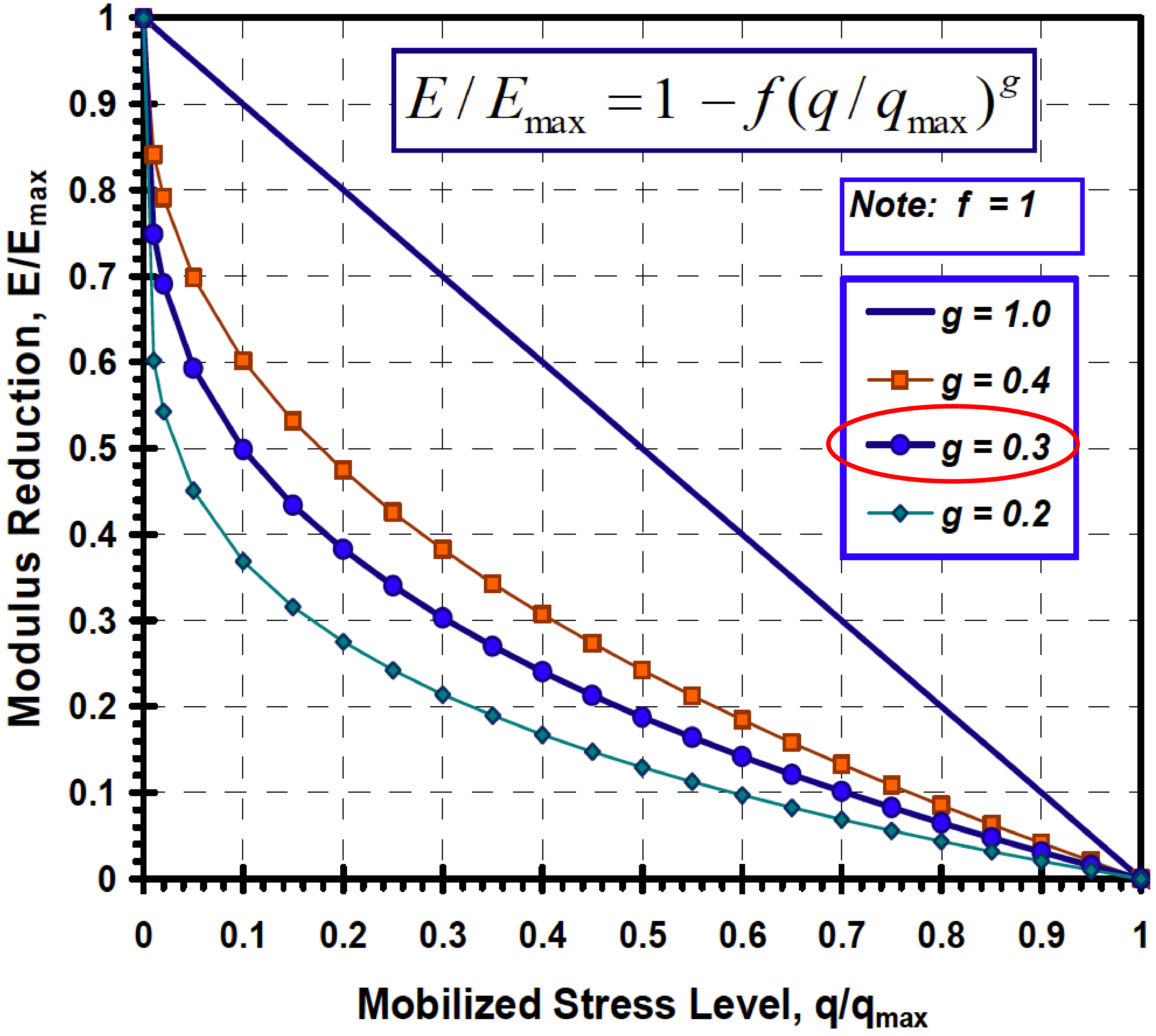
Small strain (elastic) shear modulus,
G_o is a fundamental soil parameter
($\gamma < 10^{-4}$ %)



SCPT Method to Estimate Soil Modulus

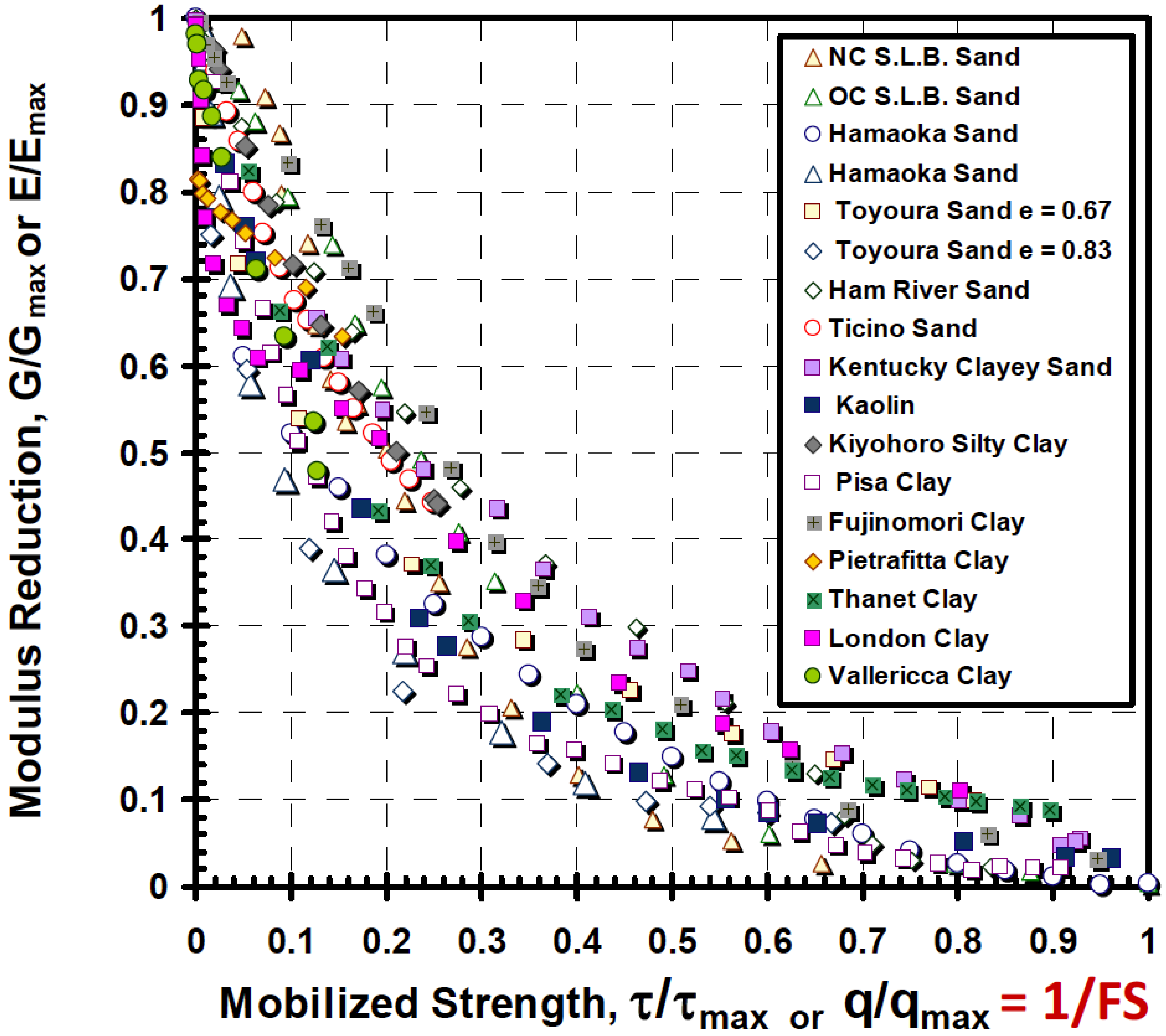


Modulus Reduction Scheme (Fahey & Carter 1993)

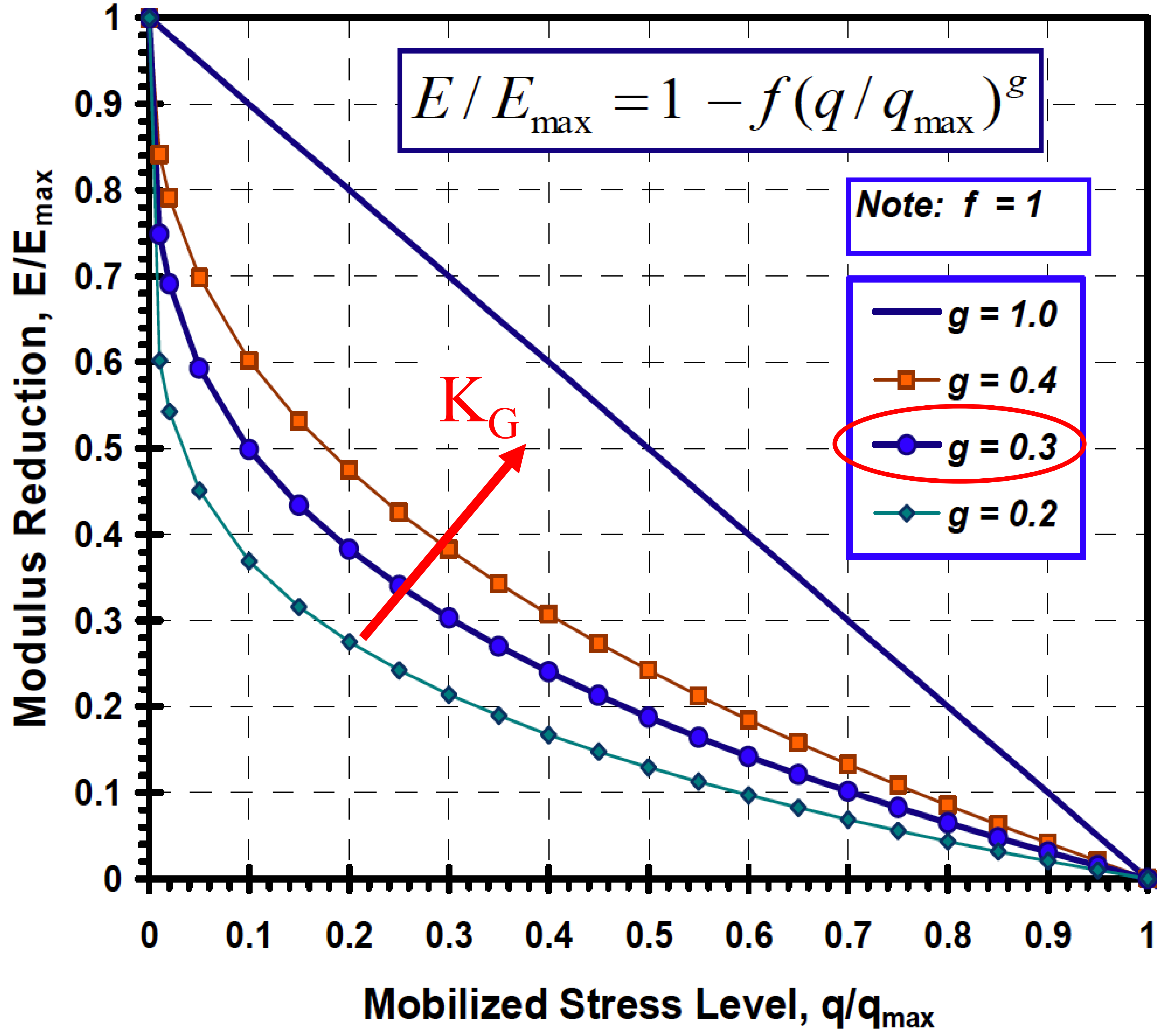


After Mayne, 2018

SCPT Method to Estimate Soil Modulus



Modulus Reduction Scheme (Fahey & Carter 1993)



After Mayne, 2018

SCPT for Foundation Load-Settlement

Equivalent Modulus for Foundation Response

- **Initial stiffness from small-strain shear modulus**
  - $G_{max} = \rho V_s^2$
  - $E_{max} = 2G_{max}(1+\nu)$
- **Modulus reduction factor (Fahey & Carter 1993):**
  - $E/E_{max} = 1 - f(q/q_{ult})^g = 1 - (FS)^{-g}$
  - where $FS = q_{ult}/q$
  - Operational $E = (E/E_{max}) \cdot E_{max}$
  - for "well-behaved" soils: $f = 1$ and $g \approx 0.3$

Likely that "g" varies with K^*_G

Nonlinear Foundation Displacement Analyses

$$s_{center} = \frac{q \cdot d \cdot I_G \cdot I_F \cdot I_E (1-\upsilon^2)}{E_{MAX}[1-(q/q_{ult})^{0.3}]}$$

where

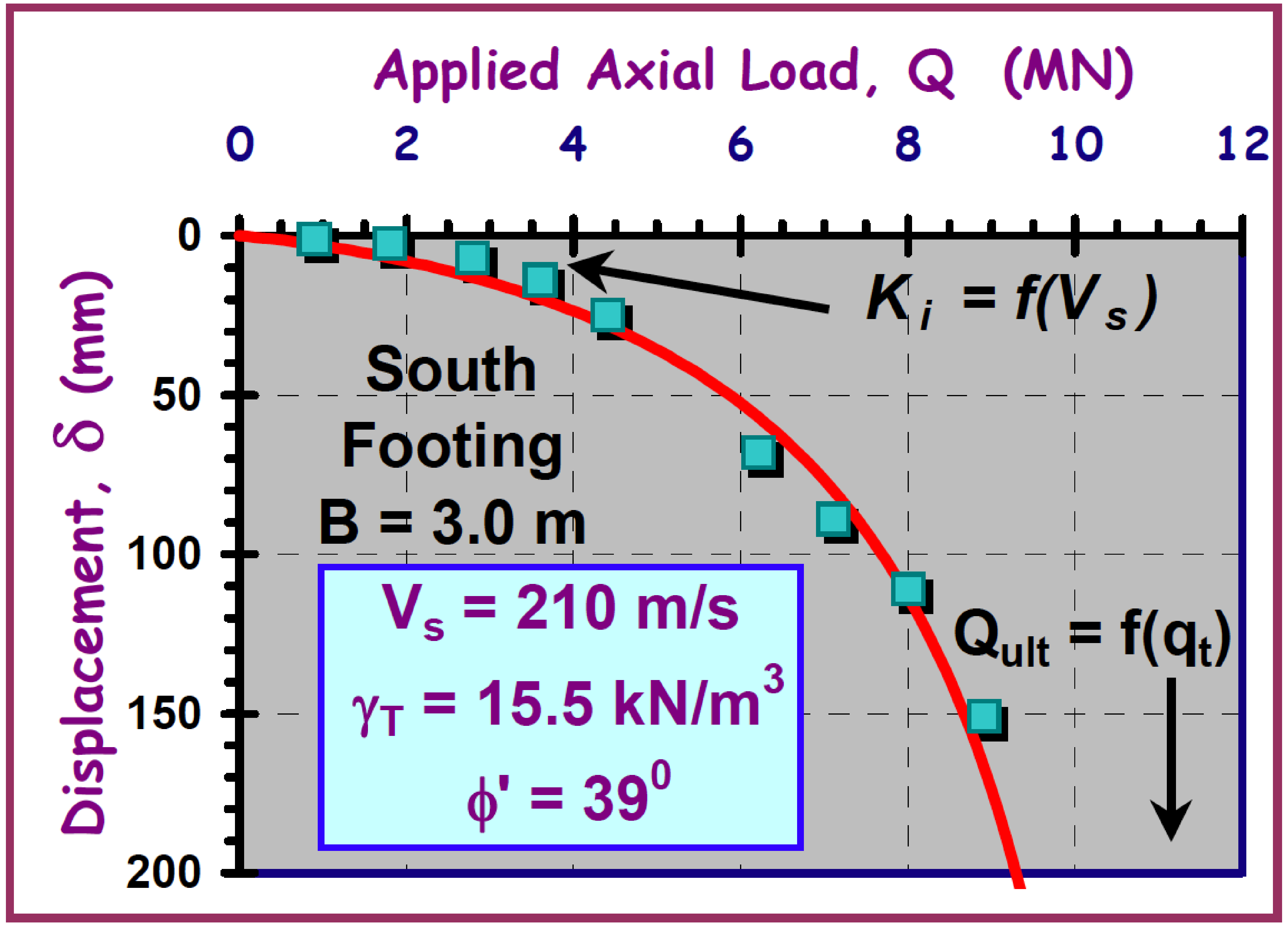
- **q = applied surface stress;**
- **q_{ult} = ultimate bearing stress;** *from CPT*
- **d = equivalent footing diameter**
- **I_G, I_F, I_E = elastic factors for modulus variation, rigidity, and embedment, respectively.**
- **ν = Poisson's ratio**
- **E_{max} = initial elastic modulus = $2G_{max}(1+\nu)$** *from SCPT*
- **See Mayne & Poulos (ASCE J. Geot. Engrg. - Jan 2001)**

After Mayne, 2018

SCPT for Foundation Load-Settlement

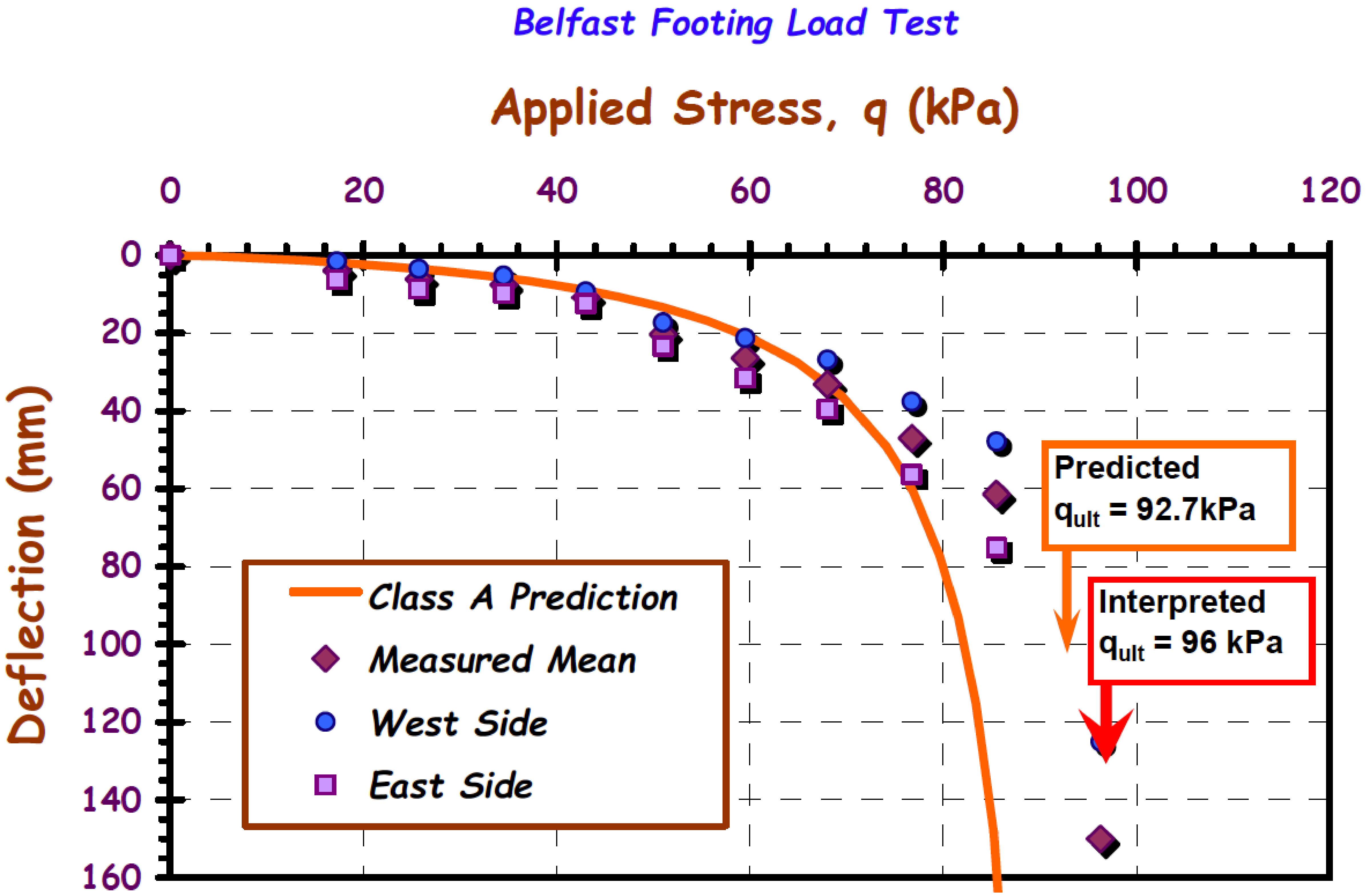
Class "A" Prediction – Texas A&M

ASCE and FHWA Symposium (1994)



European Foundation Prediction Symposium

GT Class "A" Prediction (July, 2001)



After Mayne, 2018

Links to Pre-bored Pressuremeter Test (PMT)

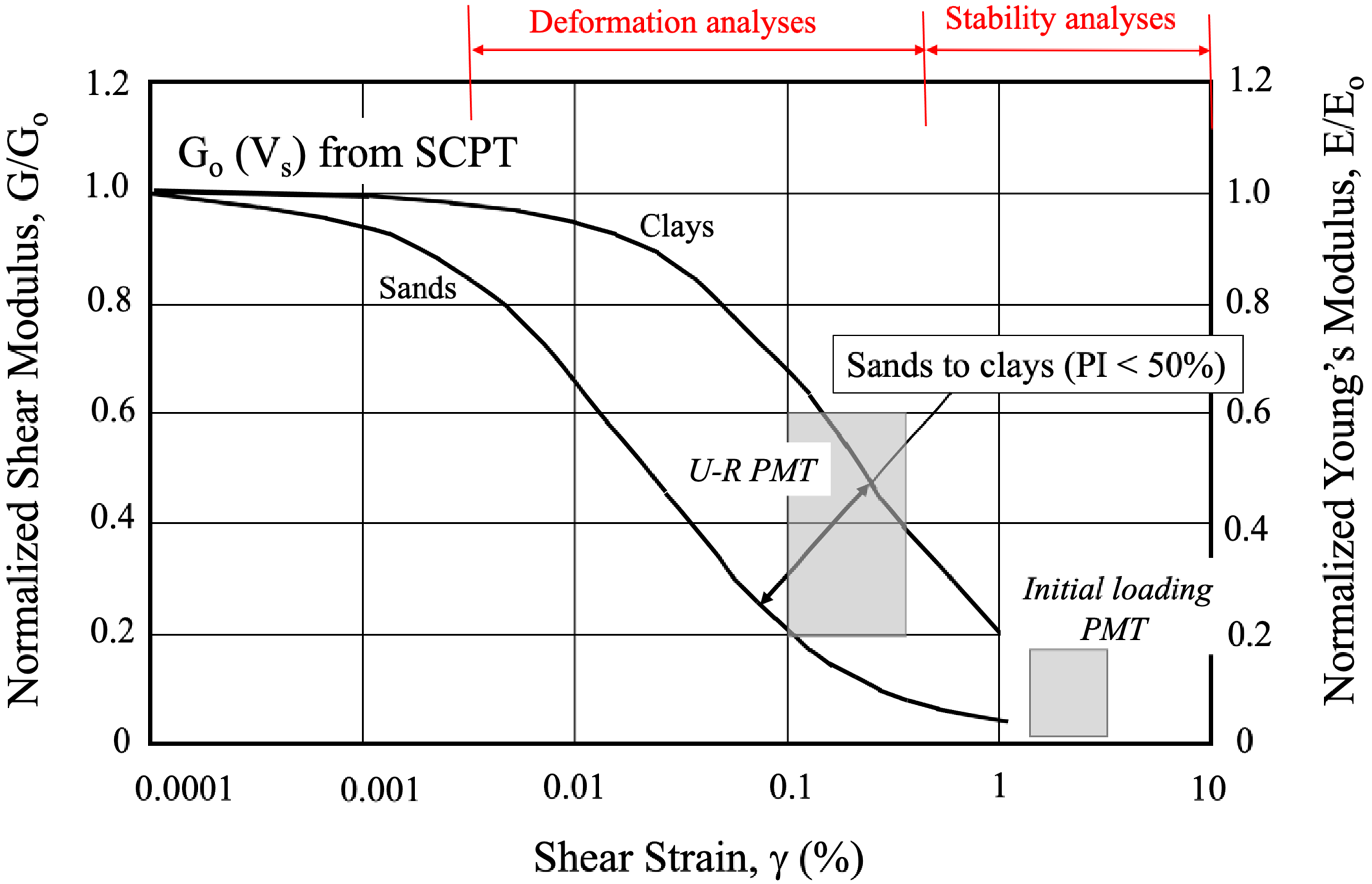
Pre-bored pressuremeter Test (Menard) - stiffness:

Initial Modulus, E_M – Stiffness at large strains
Unload-reload Modulus, E_{UR} - Stiffness at intermediate strains

Briaud (2013) $\gamma_{av.} \sim 0.3\ \gamma_{PMT}$

E_M at $\gamma_{av.} \sim 3$ to 5% and E_{UR} at $\gamma_{av.} \sim 0.1$ to 0.5%

MODULUS VARIES WITH STRAIN

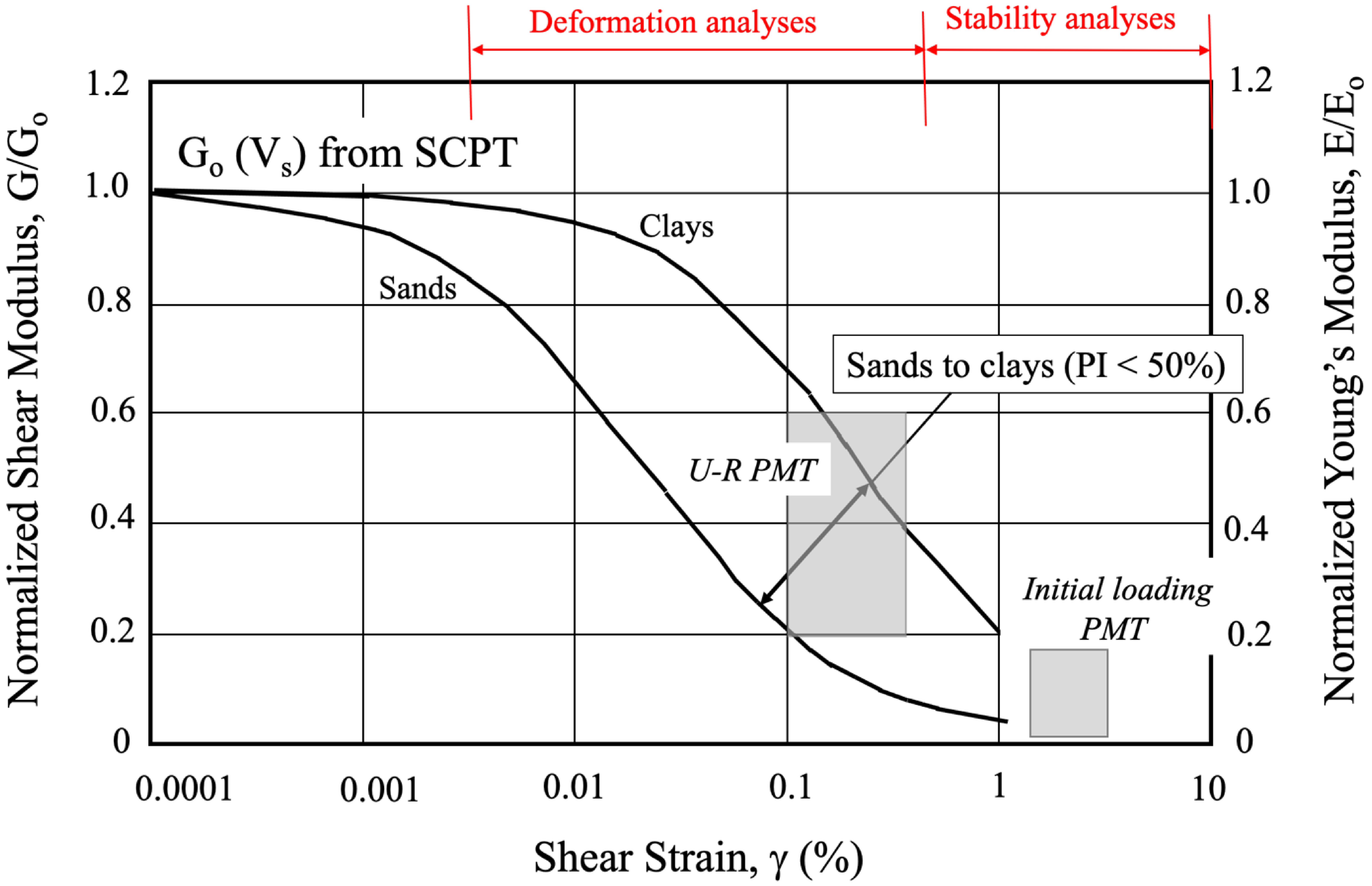


Generalized variation of Shear (G) and Youngs (E) modulus as a function of shear strain

$$E = 2(1+\upsilon)G$$

$\upsilon \sim 0.33$
$E \sim 2.66\ G$

APPLICATION TO DESIGN



Measure V_s (small strain) to get G_o (E_o) and unload-reload Modulus (E_{UR}) from PMT to evaluate modulus degradation curve with strain

Links to Pre-bored Pressuremeter Test (PMT)

Limit Pressure, P^*_{LM} – Shear strength at large strains
Net Limit Pressure, $P^*_{LM} = P_{LM} - \sigma_{ho}$
Normalized Net Limit Pressure = P^*_{LM}/σ'_{vo}

Experience in France (Bustamante & Gianeselli, 1993)

	0	1.0	2.0	3.0	4.0	5.0	**p_{LM}* [MPa]**	q_c/P^*_{LM}
Clayey and silty soils	0	3	6	9	12	15	q_c [MPa]	3
	0	15	30	45	60		N/0.3 m	
Sands and gravels	0	8	16	24	32		q_c [MPa]	8
	0	20	40	60	80		N/0.3 m	
Chalk	0	4	8	12	16		q_c [MPa]	4
	0	6-12	12-24	18-36	24-48		N/0.3 m	
Marl	0	3.5	7	10.5	15		q_c [MPa]	3.5
	0	20	40	60	80		N/0.3 m	

Links to Pre-bored Pressuremeter Test (PMT)

In clay-like soils (Gibson & Anderson, 1961):

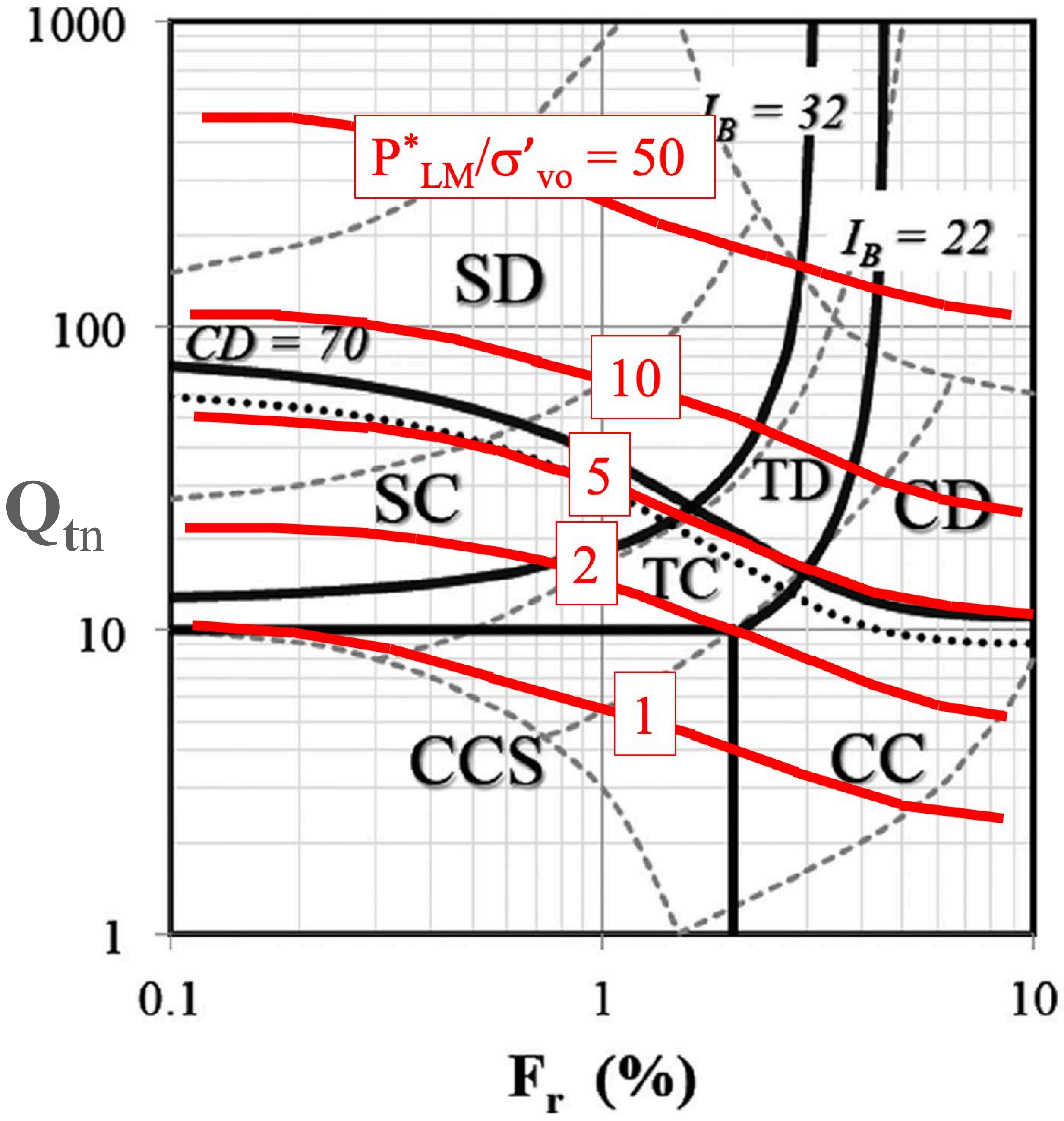
$$P^*_{LM}/\sigma'_{vo} \sim 5.5\ s_u/\sigma'_{vo} \sim 5.5\ Q_t/N_{kt} \quad (\text{for } N_{kt} \sim 14)$$

$$\mathbf{Q_t \sim 2.5\ (P^*_{LM}/\sigma'_{vo})} \qquad \textit{(France Exp. } \sim 3)$$

In sand-like soils (Yu et al, 1996):

$$P^*_{LM}/\sigma'_{vo} = 0.1 \text{ to } 0.2\ Q_t$$

$$\mathbf{Q_t \sim 5 \text{ to } 10\ (P^*_{LM}/\sigma'_{vo})} \qquad \textit{(France Exp. } \sim 8)$$



PROPOSED LINK BETWEEN CPT AND PMT

For soils with little to no microstructure

Contractive - Dilative boundary

$P^{*}_{LM}/\sigma'_{vo} \sim 5$

SUMMARY

- Significant developments made in use and application of SCPTu since first developed 40 years ago
- SCPTu can provide 7 measurements in one, cost effective in-situ test to produce near continuous profiles
- Role of soil microstructure is increasingly becoming recognized and SCPTu can identify soil microstructure
- Importance of non-linearity in soil stiffness recognized and SCPTu provides measure of the fundamental small strain stiffness G_O
- Combination of surface geophysics, such as the MASW (2D), with SCPTu and PMT has potential to provide insights into soil microstructure and non-linear soil stiffness for geotechnical design

Thank You
Questions?

probertson2005@me.com