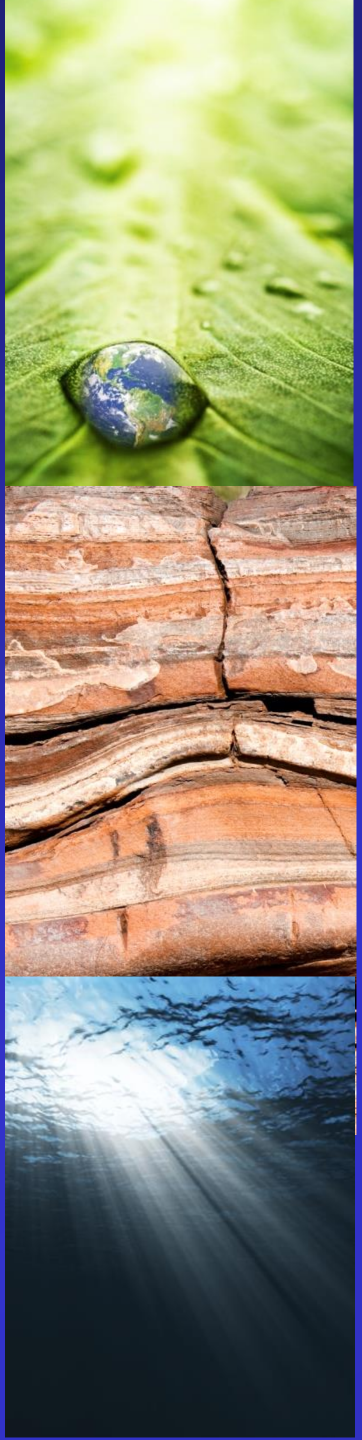

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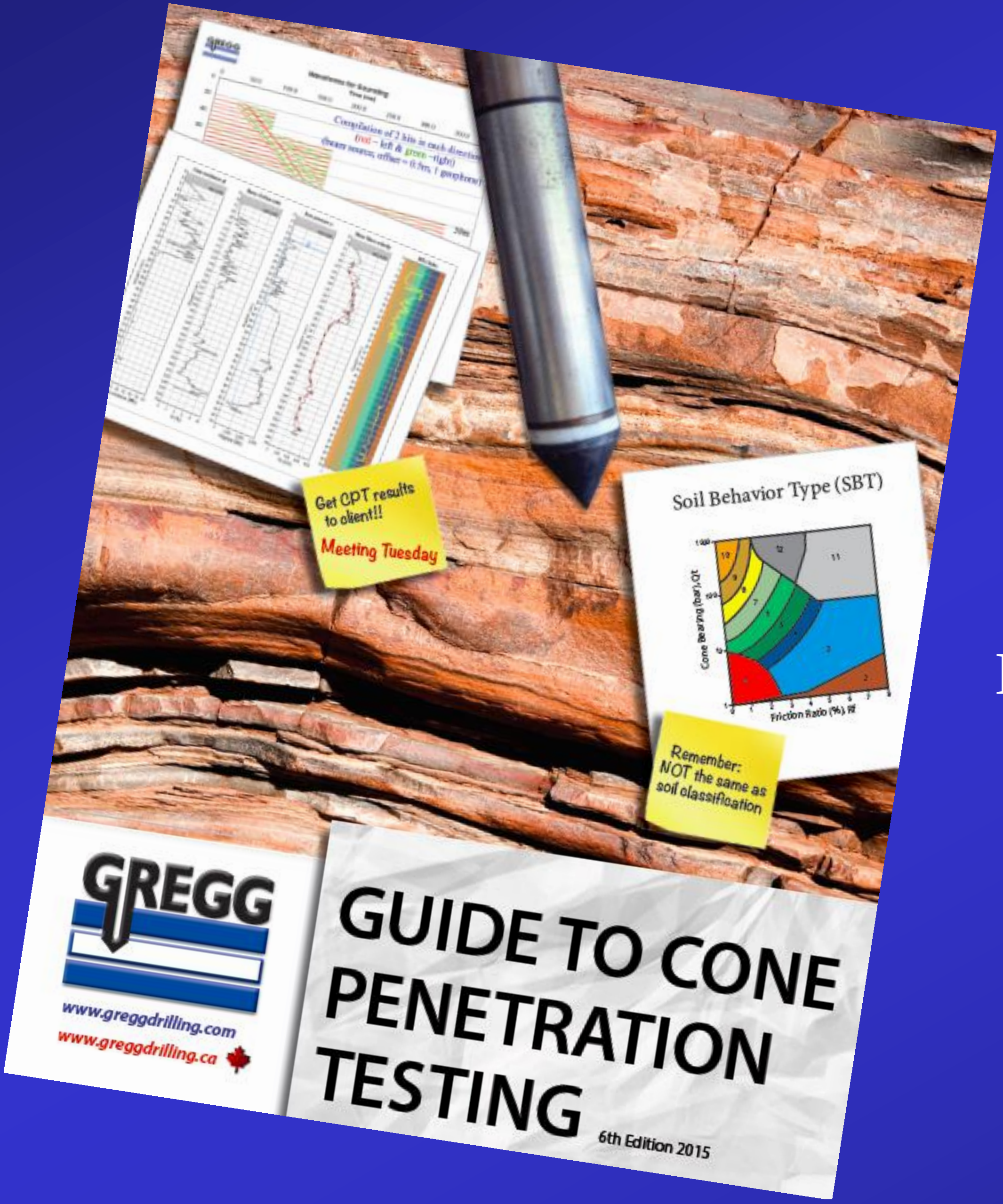
DIPARTIMENTO DI INGEGNERIA CIVILE E INDUSTRIALE
DICI

CPT for Quality Control (QC) of Ground Improvement (Deep Compaction)

Peter K. Robertson

14 June 2019

Recenti Sviluppi nelle Indagini in Sito



Robertson & Cabal

CPT Guide

6th Edition

2015

Download ***FREE*** copy from:

www.greggdrilling.com

www.cpt-robertson.com

www.geologismiki.gr

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Robertson, 2015

CPT-based Software

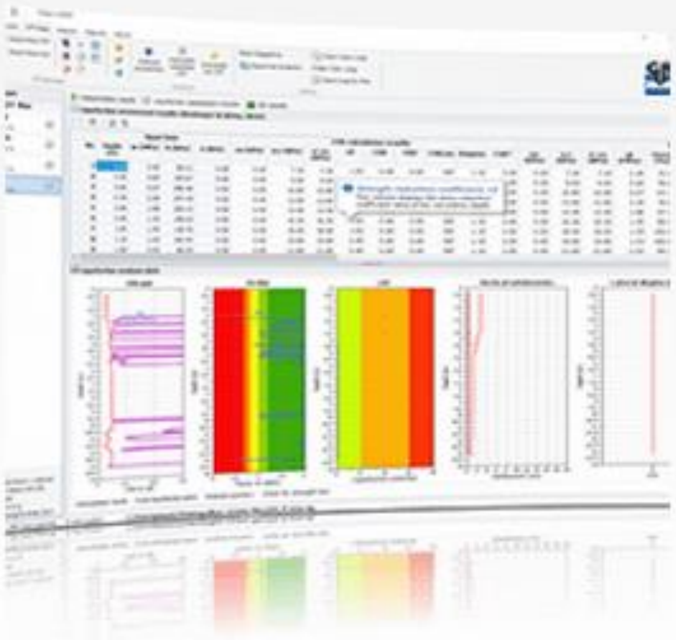
CPeT-IT

POPULAR

Interpretation and presentation of Cone Penetration Test data using the latest Dr. Robertson methodology. Analytical tabular results and reports quickly and easy.

CLiq

POPULAR



Assessment of soil liquefaction from data acquired with Cone Penetration Test, using the latest and most widely used methodologies.

GEOLOGISMIKI

WE DO THE NUMBERS, YOU DO THE JOB!

Ground Improvement

- Objective of ground improvement is typically for:
  - Increased bearing capacity (strength)
  - Reduced settlements (stiffness)
  - Increased resistance to liquefaction (cyclic resistance)
- Many techniques available for ground improvement
- Vibratory techniques are common in sandy soil, e.g.
  - Vibro-compaction (VC)
  - Vibro-replacement (stone columns - VR/VD)
  - Dynamic compaction (DC)
  - Rapid Impact (RI)

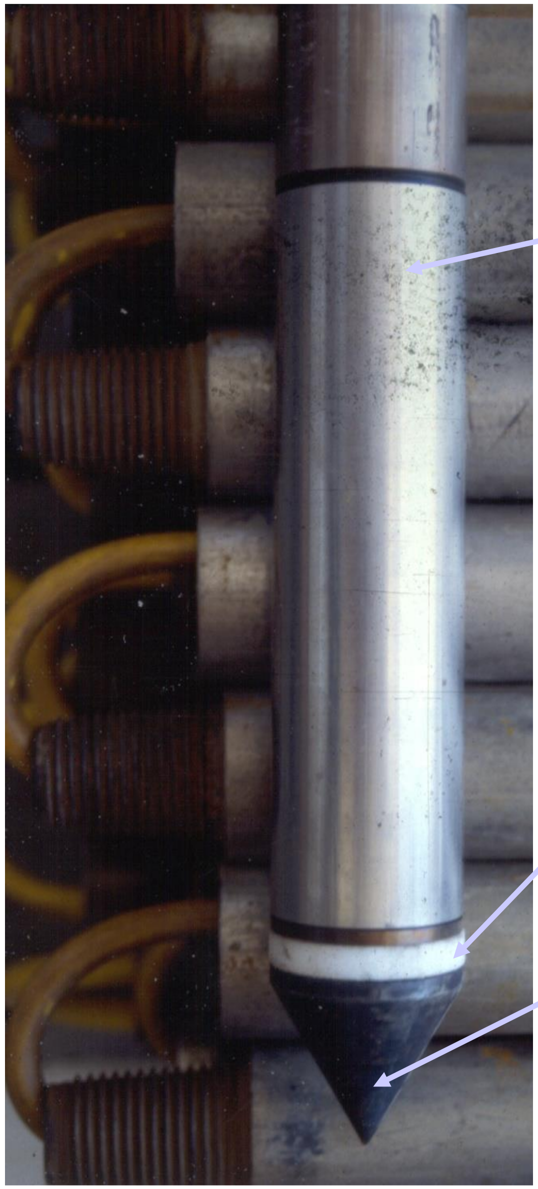
Principle behind vibratory methods

- Disrupt sand structure to form denser packing
- Vibration (drained cyclic loading) the most effective means to densify granular soils (i.e. sand)
- Most vibratory methods also:
  - Increase lateral stress (i.e. change K_o and OCR)
  - Destroy any existing microstructure (age, cementation, etc.)

QC for ground improvement

- CPT often used for quality control (QC)
  - Fast & cost effective
  - Continuous profile
  - Reliable/repeatable measurements
  - More than one measurement (q_c f_s u & V_s)
- CPT in granular (sand-like) soils is influenced by:
  - Density (state)
  - In-situ stresses (K_o)
  - Stress history (OCR)
  - Grain characteristics (e.g. compressibility, fines content)
  - Microstructure (e.g. age, cementation)

Basic CPT Parameters



Sleeve Friction

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

Pore Pressure

u_2

Tip Resistance

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

CPT – Normalization

CPT (Wroth, 1984):

$$Q_{t1} = (q_t - \sigma_v) / \sigma'_{vo} \quad \text{(clay)}$$

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

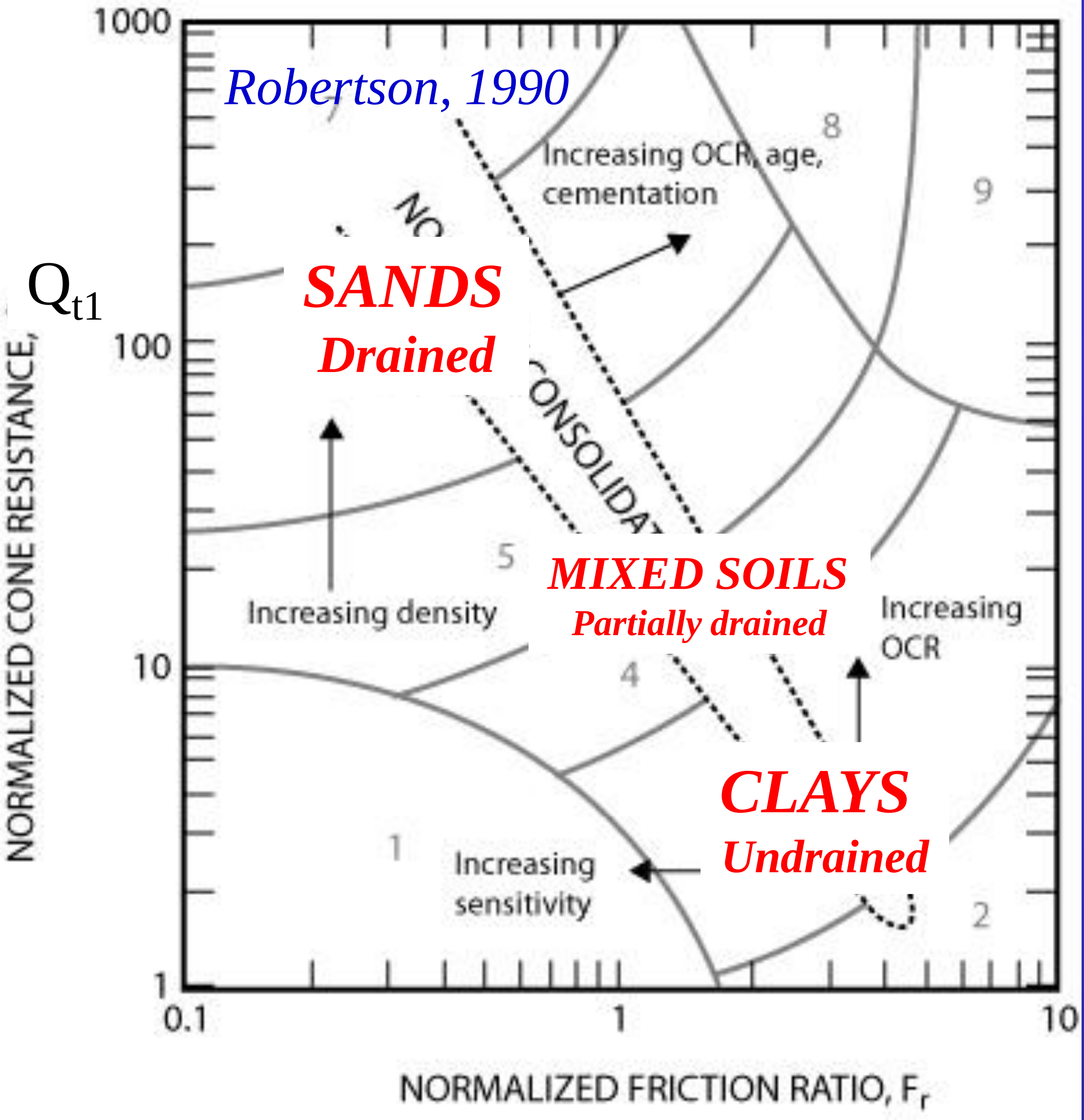
$$F_r = f_s / (q_t - \sigma_v)100 \ (\%)$$

CPTu:

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

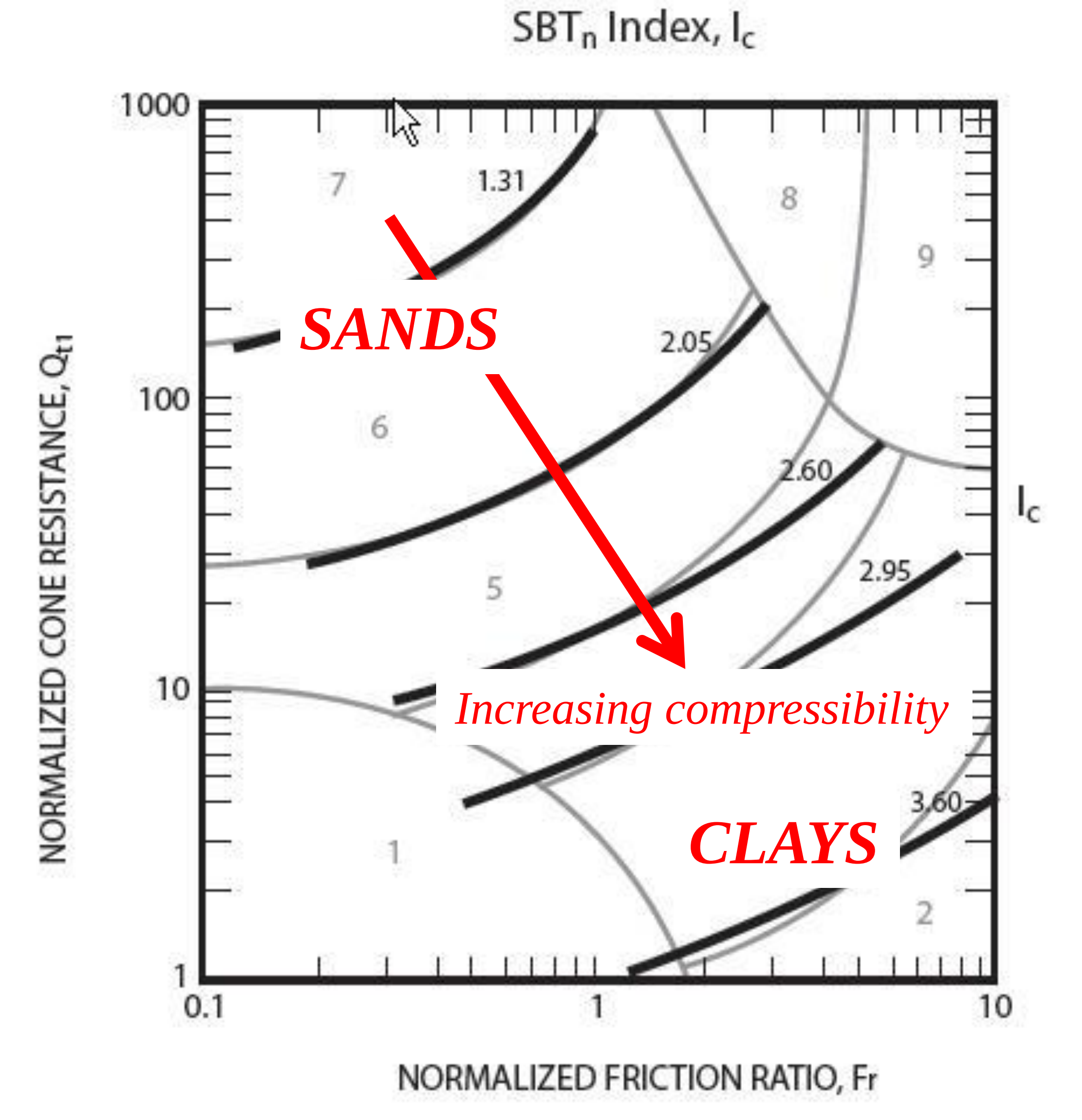
$$U_2 = (u_2 - u_0) / \sigma'_{vo}$$

CPT Soil Behavior Type SBT



CPT SBT based on
in-situ soil behavior
(*strength, stiffness, compressibility*)
not the same as traditional 'classification' based
physical characteristics
(*Atterberg limits, grain size*) on disturbed samples

CPT SBT Index, I_c



Soil Behavior Type Index, I_c

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

Function primarily of Soil Compressibility

Compressibility linked to soil plasticity & amount/type of fines

Generalized CPT Normalization

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

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

$$Q_{tn}\ (= q_{c1N}) = [(q_t - \sigma_v)/p_a]\ C_N$$

Where:

$(q_t - \sigma_v)/p_a$ = dimensionless net cone resistance,

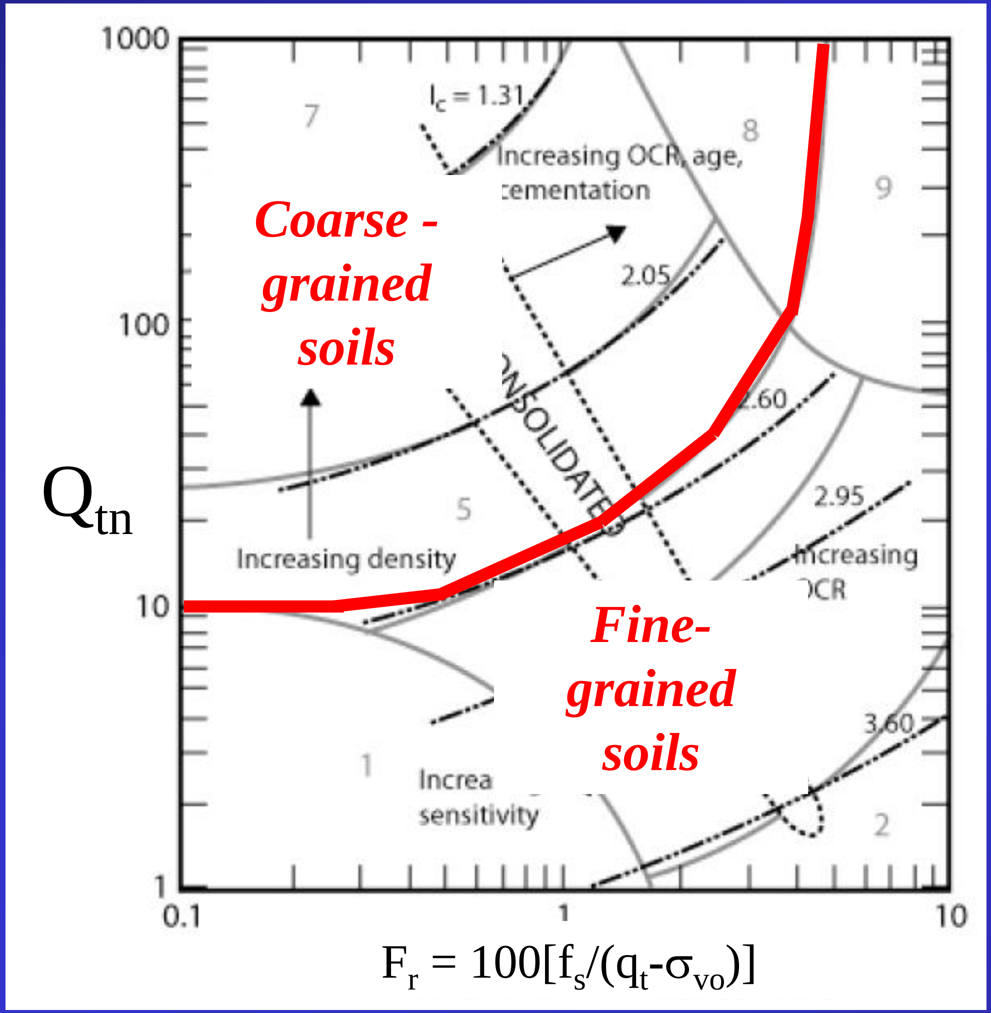
$(p_a/\sigma'_v)^n$ = stress normalization factor = C_N

n = stress exponent that varies with soil type & density (*Ic*) + stress level

- typically n ~ 1 clay ($Q_{t1} = Q_{tn}$) and n ~ 0.5 clean sand

p_a = atmospheric pressure in same units as q_t and σ_v

Soil Behaviour Type (SBTn)

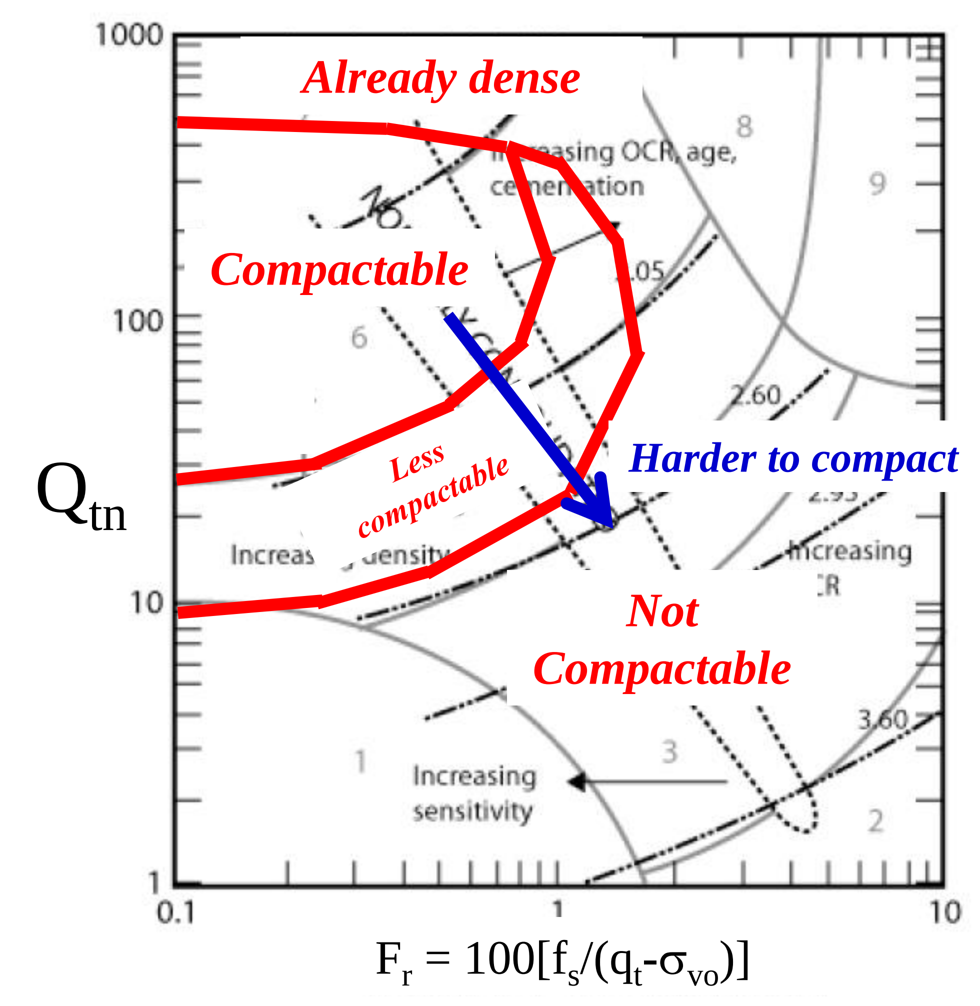


Robertson (2009)

Coarse-grained soils essentially plot in SBT zones 5, 6, 7 and 8 on the normalized SBTn chart by Robertson (2009)

Approx. $I_c < 2.60$

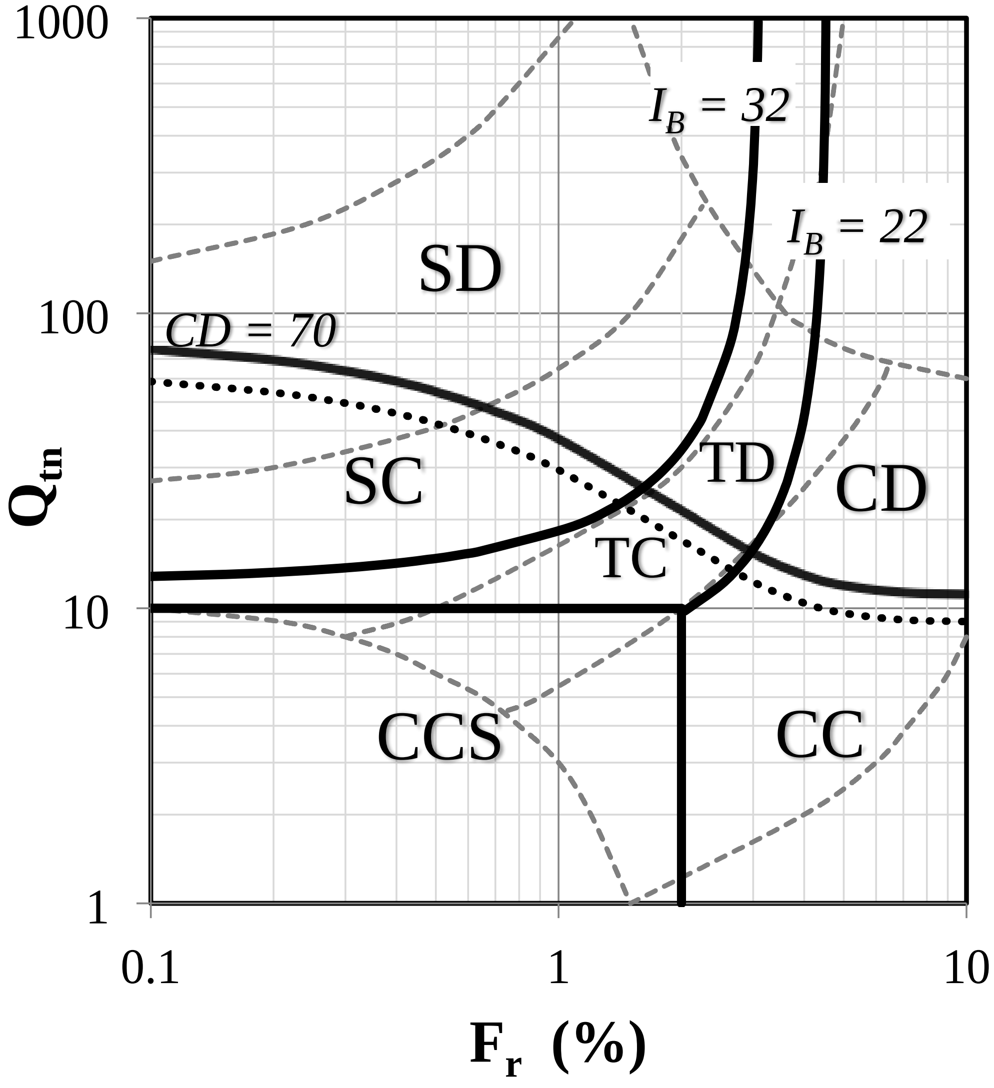
Compactability based on CPT



Modified from Massarsch, (1991)

Soils suitable for vibro-compaction essentially plot in SBT zones 5, 6 and 7 on the normalized SBTn chart by Robertson (2009)

Updated SBTn Charts



Behavior Descriptions

Soil Behaviour Type

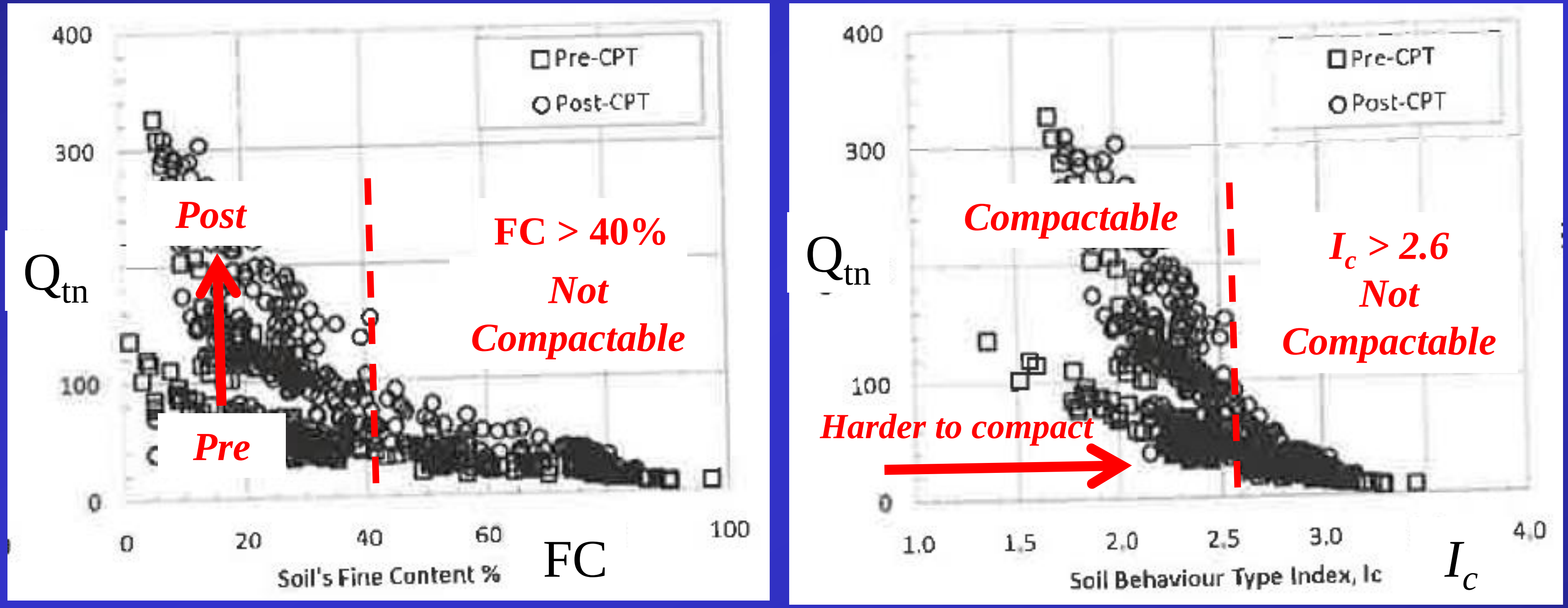
1: CCS Clay-like - Contractive - Sensitive
2: CC Clay-like - Contractive
3: CD Clay-like - Dilative
4: TC Transitional - Contractive
5: TD Transitional - Dilative
6: SC Sand-like - Contractive
7: SD Sand-like - Dilative

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

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

Compactability?

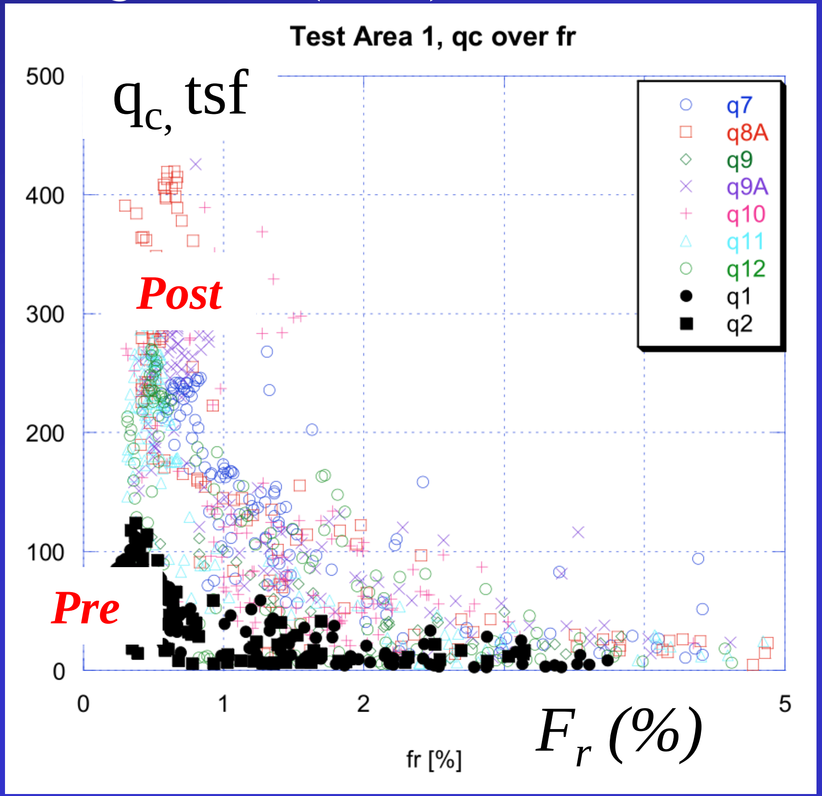
Kirsch & Kirsch (2010) – data courtesy Hayward Baker

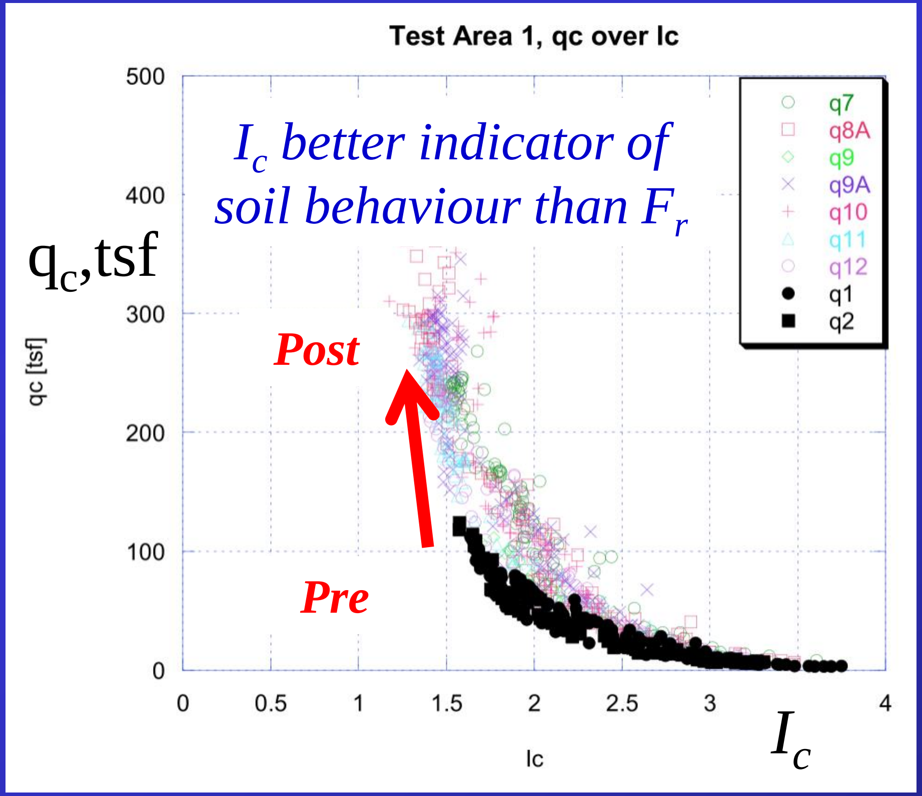


Sandy soils with high fines content (> ~40%) and high CPT I_c (I_c > 2.6) are *generally* *<u>less compactable</u>*

Compactability and I_c-value

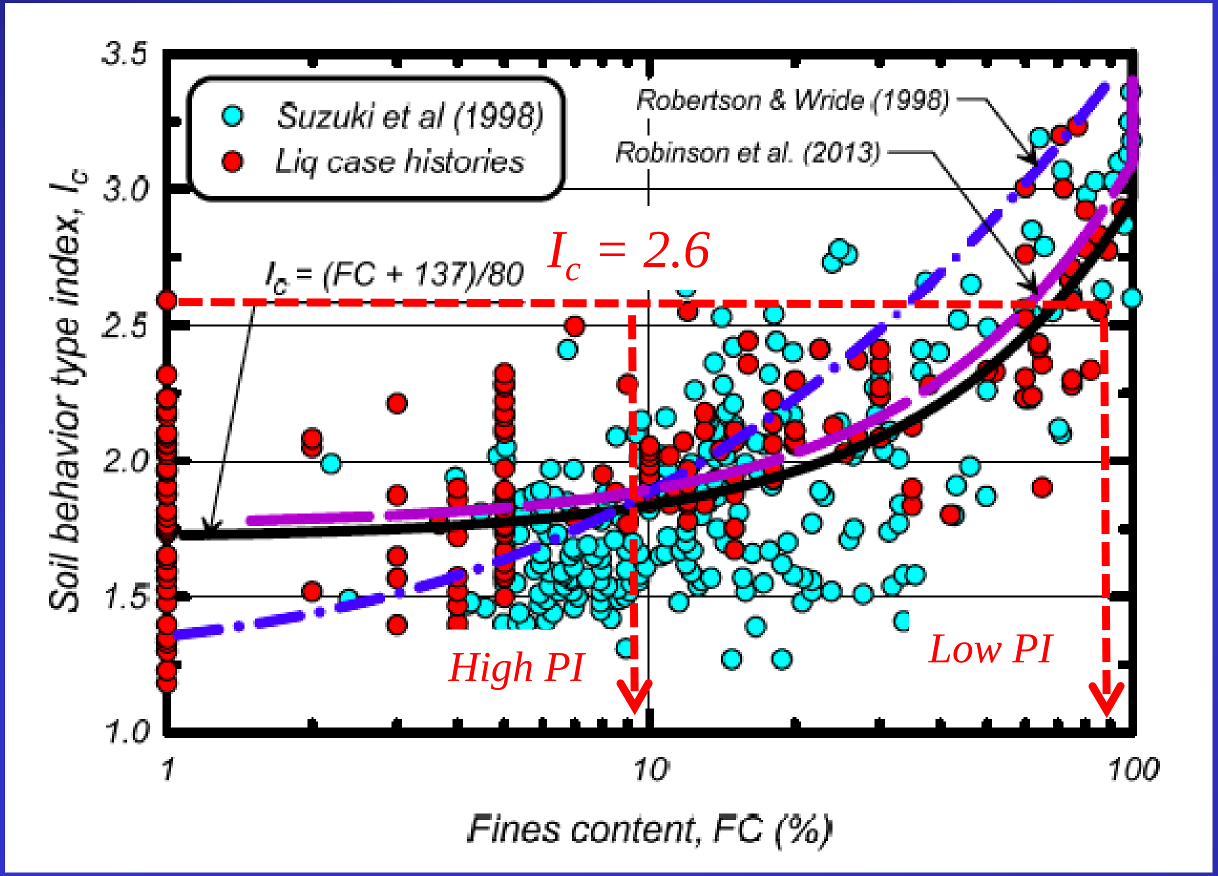
Degen et al (2005)





Sandy soils with high fines content and high CPT I_c ($I_c > 2.6$) are *generally* *not compactable*

Compactability and fines content



(Modified from Boulanger & Idriss, 2015)

Plastic fines prevent compaction.

Fines content does not distinguish between plastic and non-plastic fines.

I_c value captures the presence of plastic fines in one value

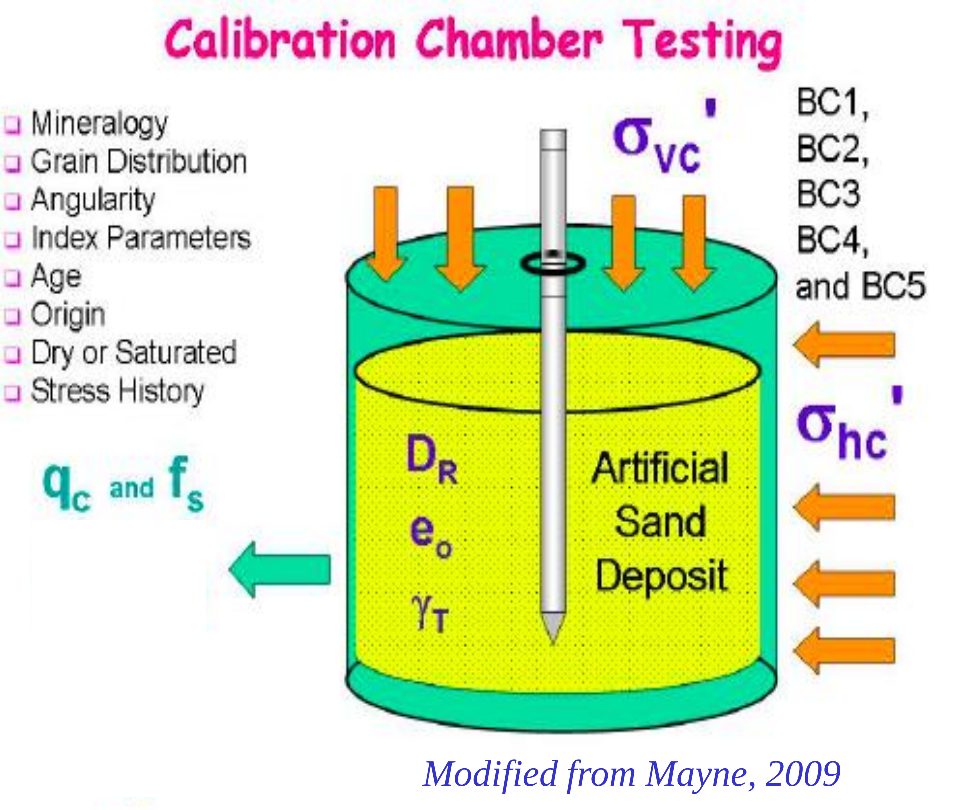
QC based on Relative Density, D_r

- In the past – QC criteria often based on Relative Density (D_r) as an intermediate parameter

$$D_r = (e_{max} - e)/(e_{max} - e_{min})$$

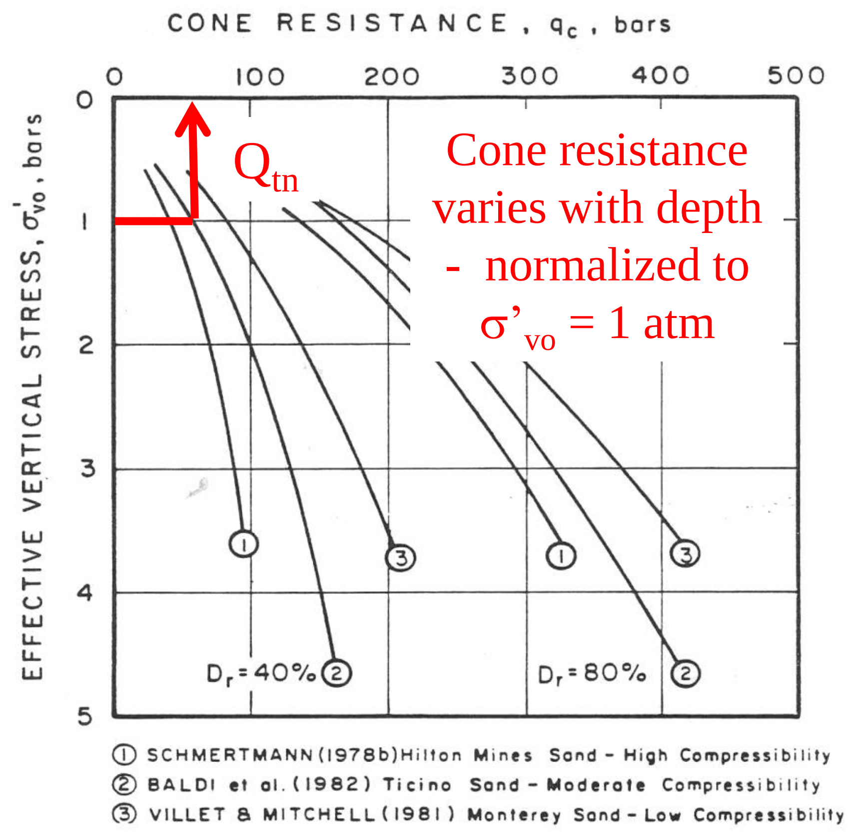
- Strength and stiffness not always well represented by D_r
- Most relationships between D_r and CPT based on large calibration chamber (CC) testing using clean sand

Calibration Chamber Testing

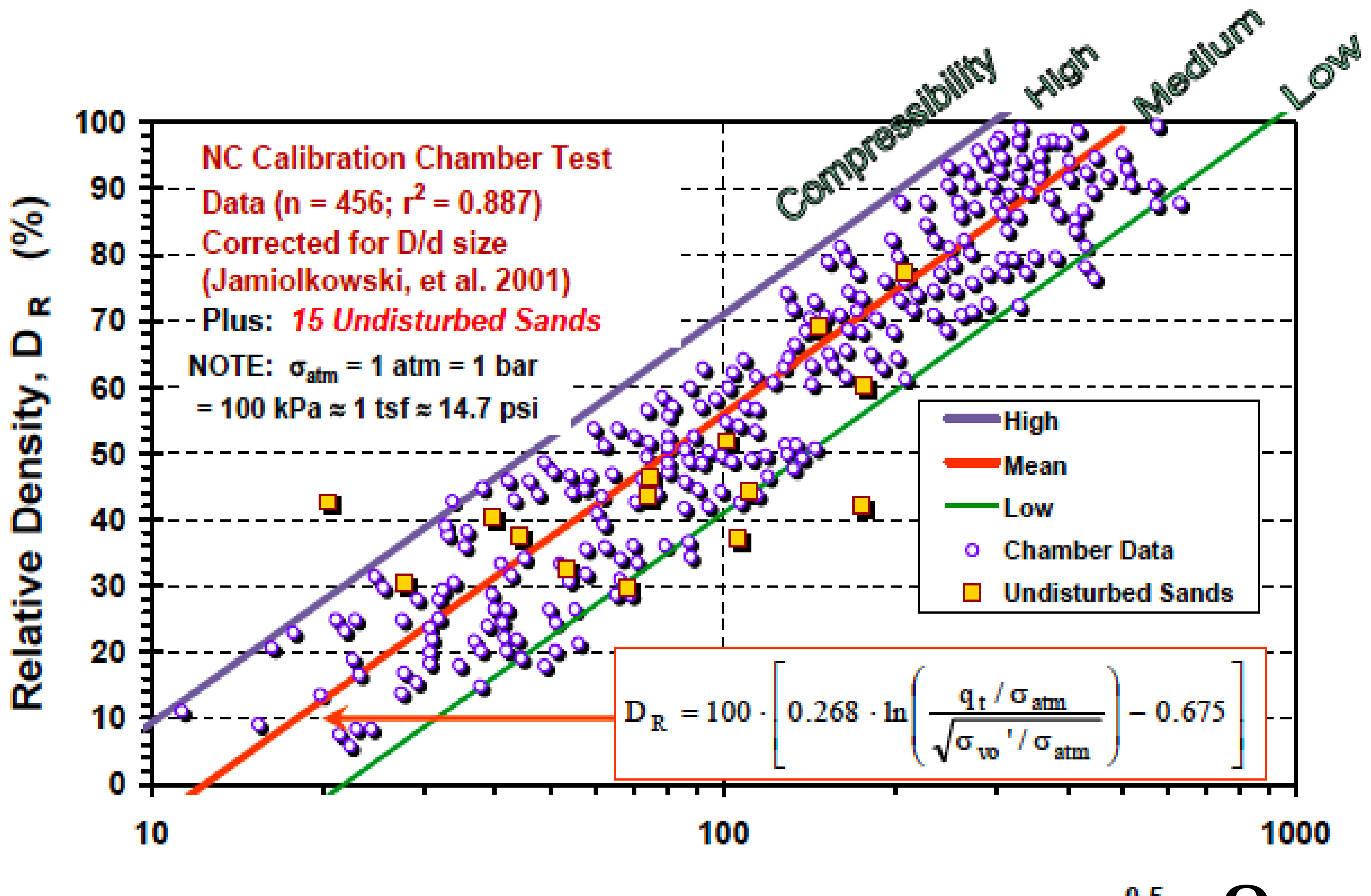


Controlled test environment to study link between CPT q_c and relative density D_r in clean sands

Since cone resistance varies with overburden stress – it requires 'normalization' to account for depth



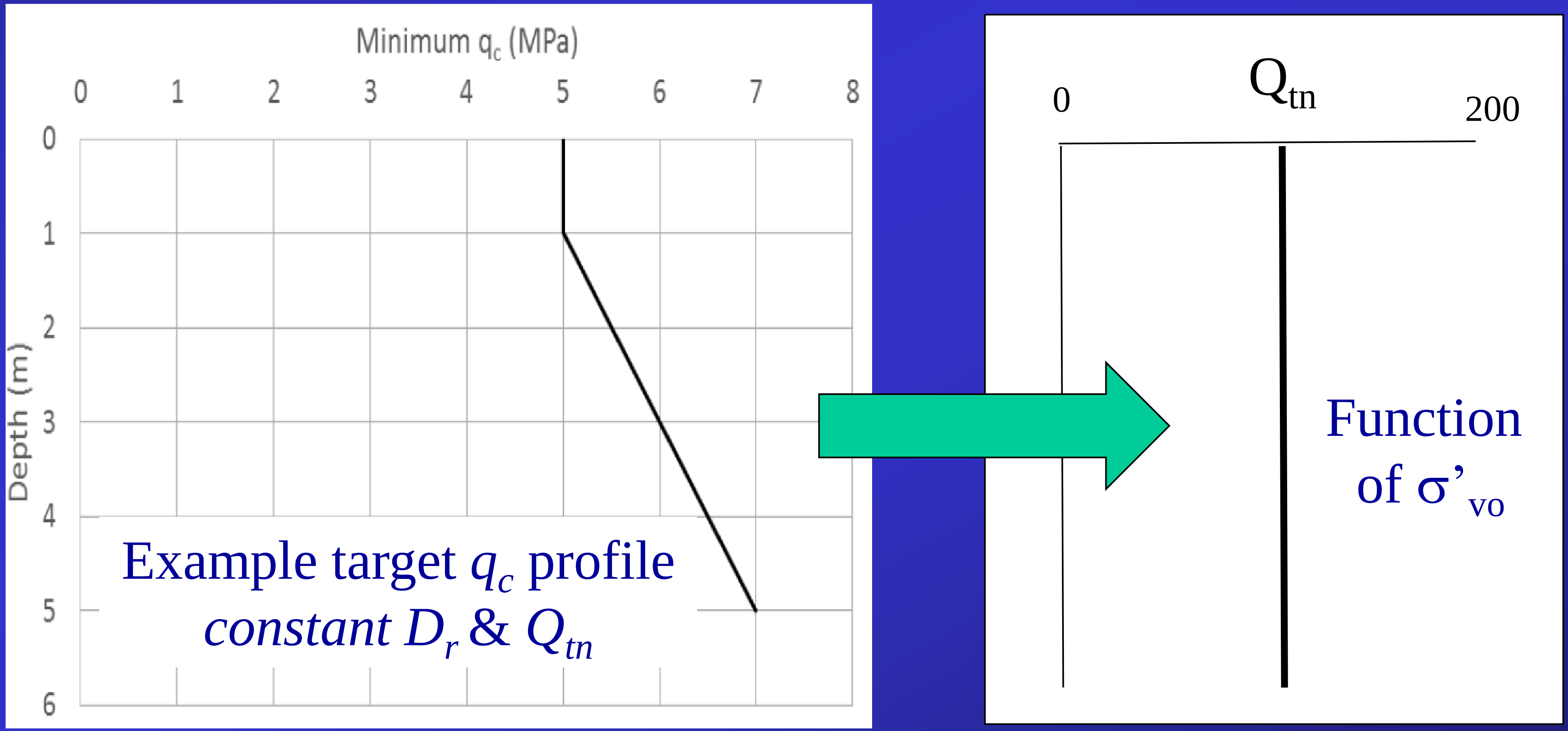
Summary of D_r CC - sand



Mayne, 2009

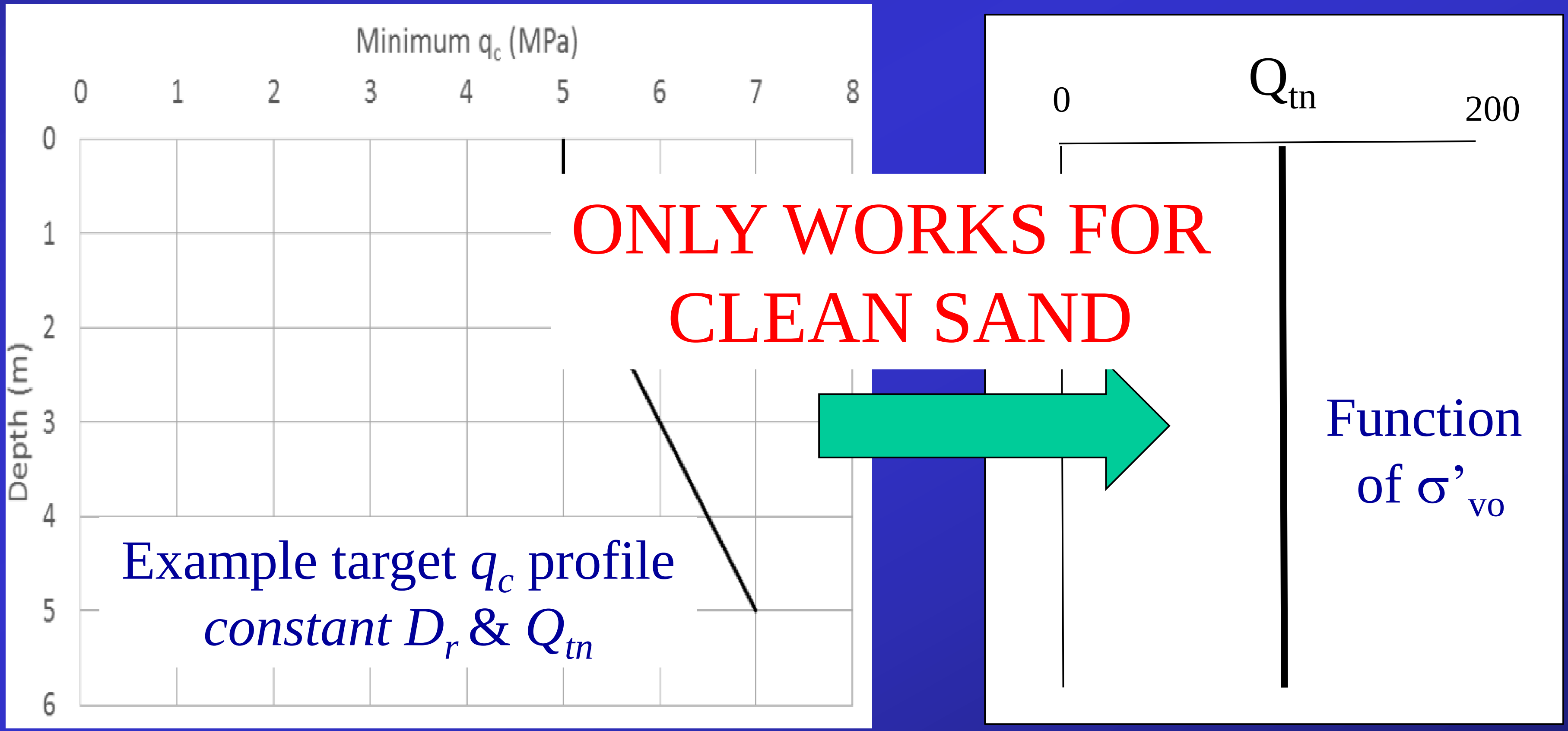
QC Criteria

In the past, typical to define target CPT q_c in terms of either relative density or defined q_c profile (i.e. Q_{tn} = constant)



NOT recommended

Will NOT apply to sands with some fines (e.g. silty sands and sandy silts)



Soils with fines content?

- Ground improvement methods based on densification are generally less effective in sandy soils with high fines content and depends on plasticity of fines
- Penetration resistance (CPT) less sensitive in soils with high fines content
- Application of *'clean sand equivalent cone resistance'* ($Q_{tn,cs}$)

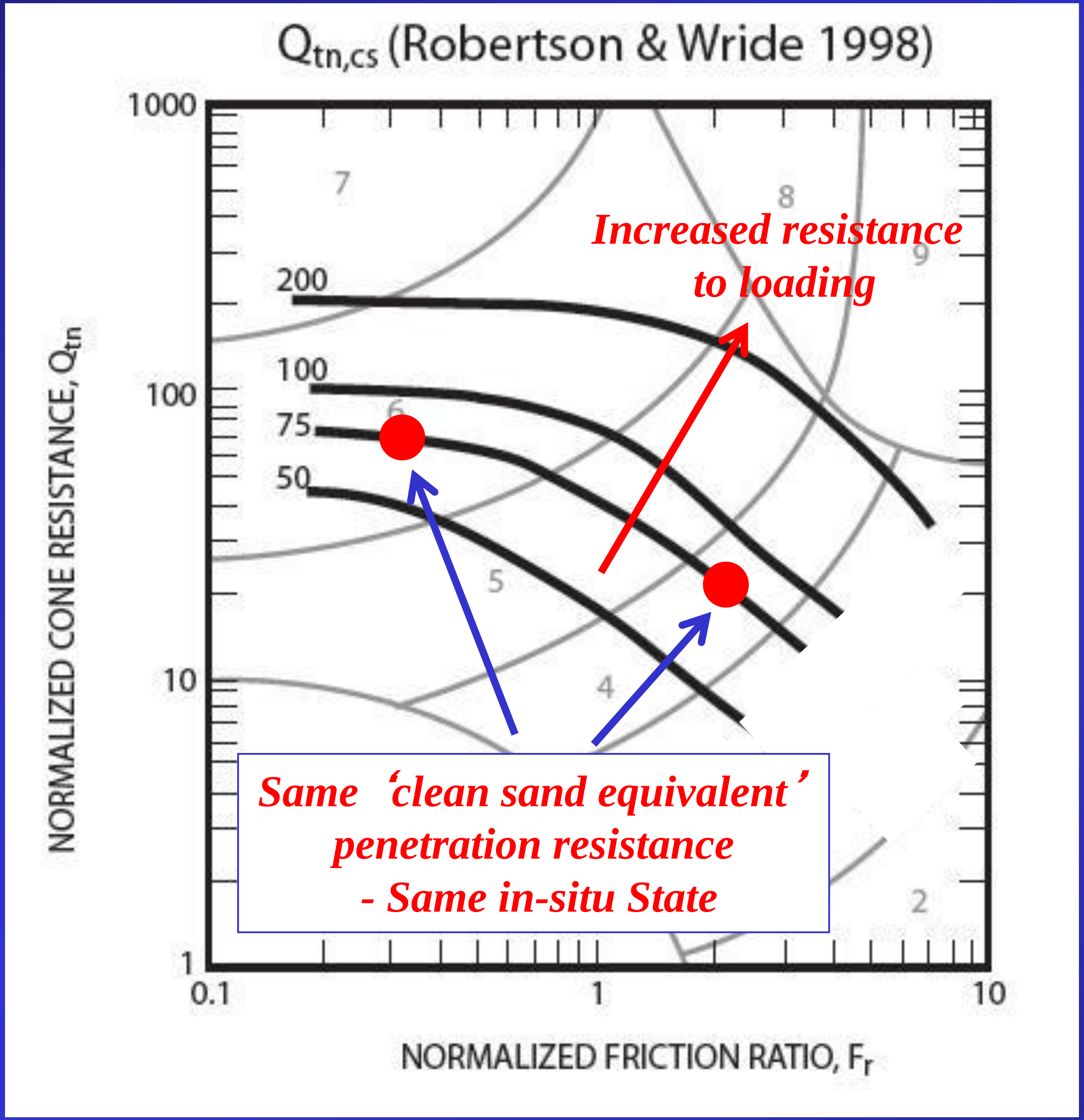
Clean Sand Equivalent

Evolved from early work of Seed et al (1985) based on liquefaction case histories - observed that soils with same resistance (CRR) have different penetration resistance (q_t) with different fines content (FC).

Based on concept that soils with same '*clean sand equivalent*' penetration resistance have same soil response to cyclic loading (CRR), i.e. soils have same *in-situ state*.

(works well in young, uncemented silica based soils – i.e. soils with little or no microstrcuture)

Clean sand equivalent, $Q_{tn,cs}$



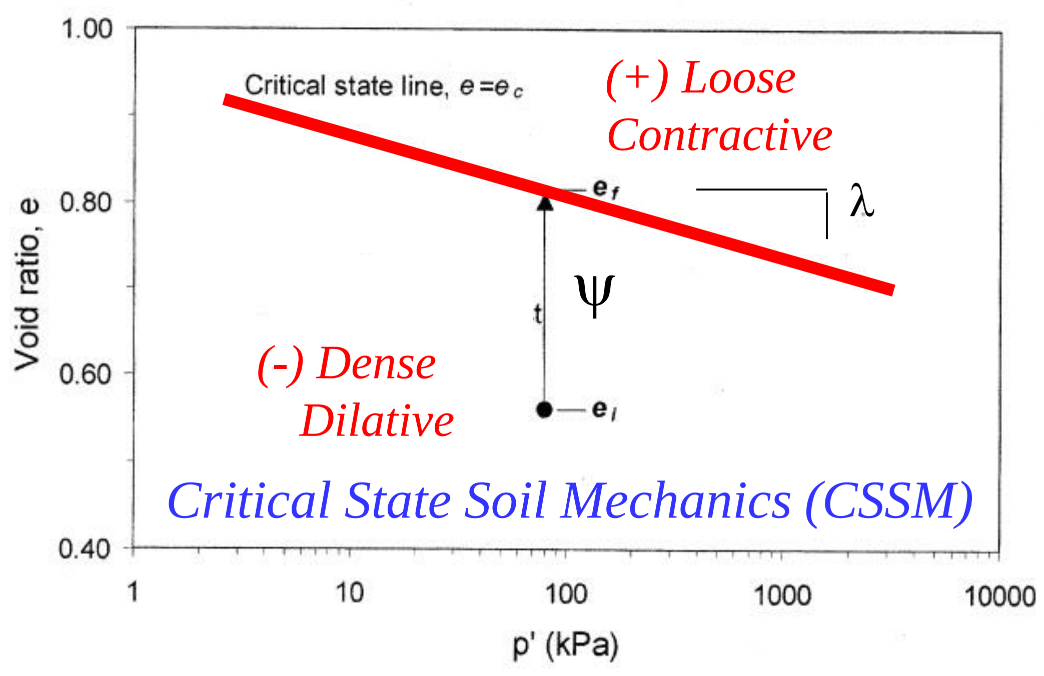
Soils with same 'clean sand equivalent' $Q_{tn,cs}$ have similar behavior

Based on case histories of young, uncemented silica-based sandy soils

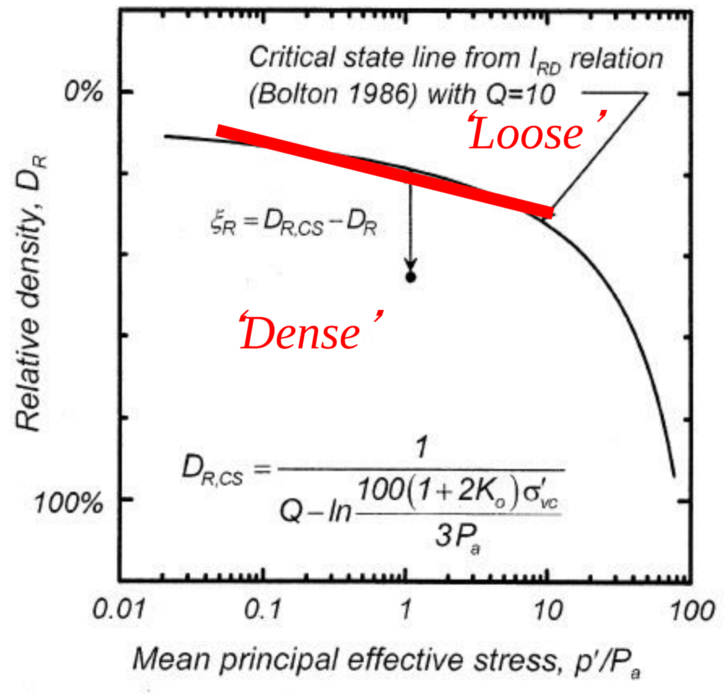
$$Q_{tn,cs} = K_c\, Q_{tn}$$

Simple correction based on soil behavior type index, I_c

Theoretical (CSSM) framework State Parameter, Ψ

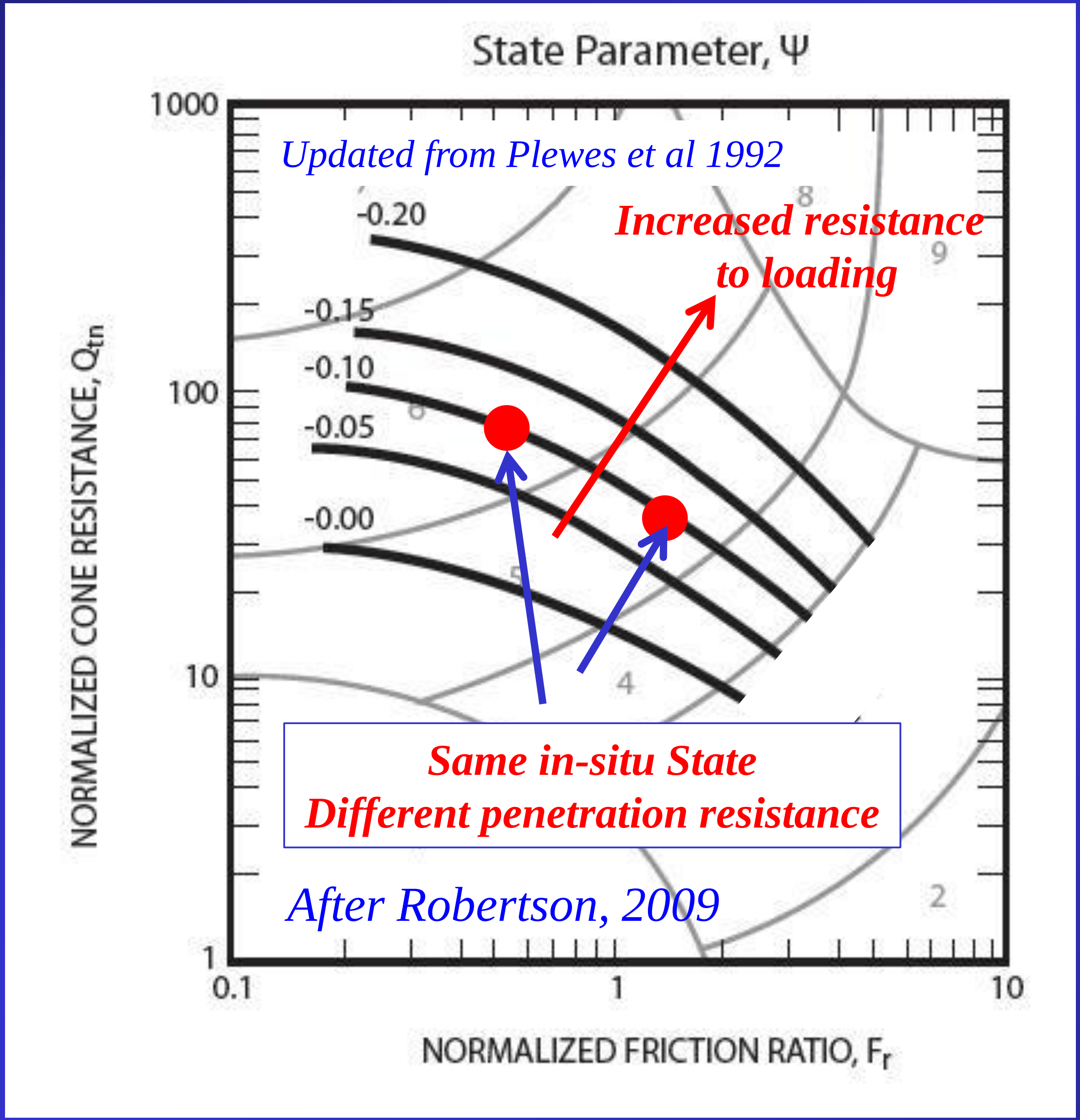


After Jefferies and Been, 1985



Relative State Parameter index
After Boulanger, 2003

State Parameter from CPT (screening)

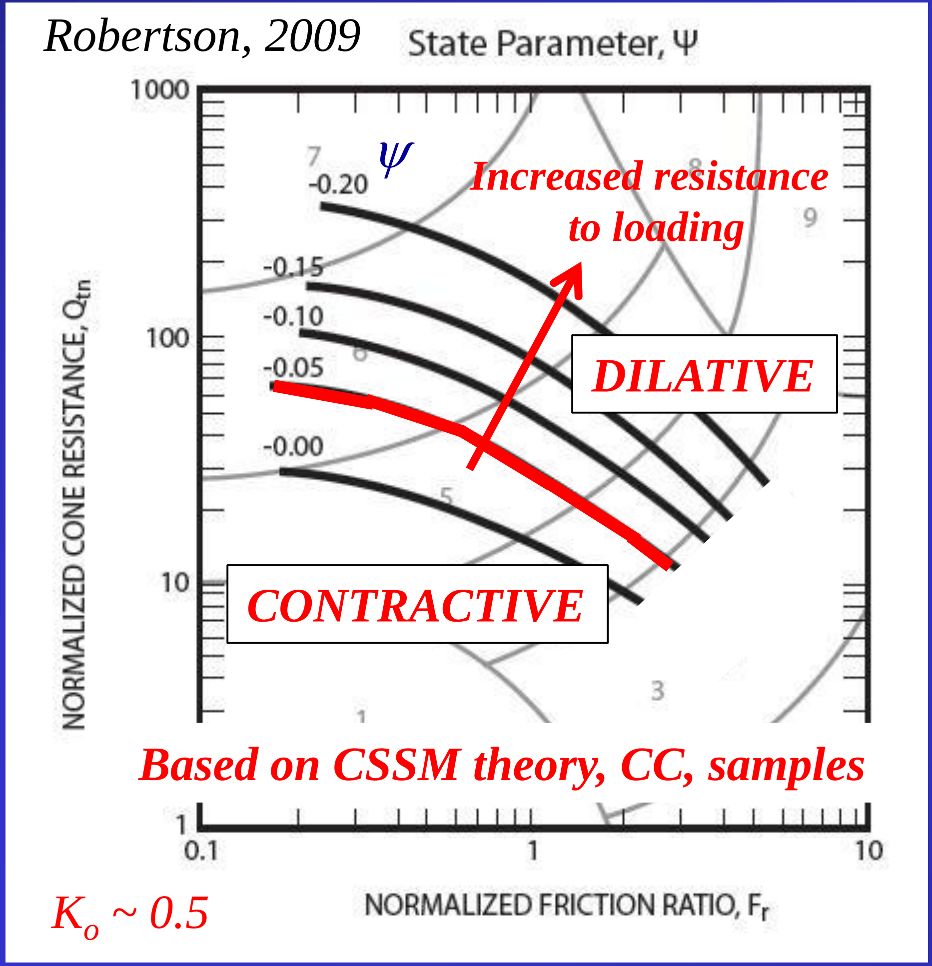


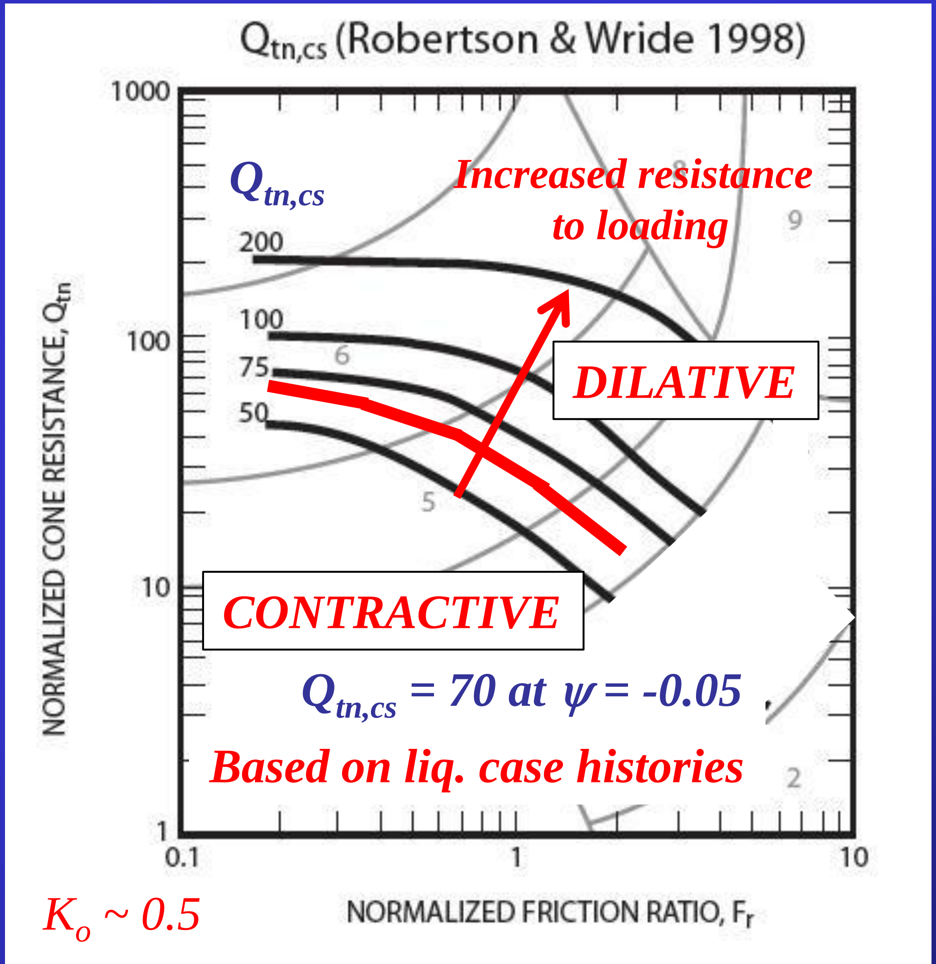
Soils with same *state* have similar behavior

Essentially contours of *'dilation' angle'* – a fundamental mechanical behavior

Approx. contours of state parameter for *young, uncemented silica-based soils*

State parameter (ψ) and $Q_{tn,cs}$





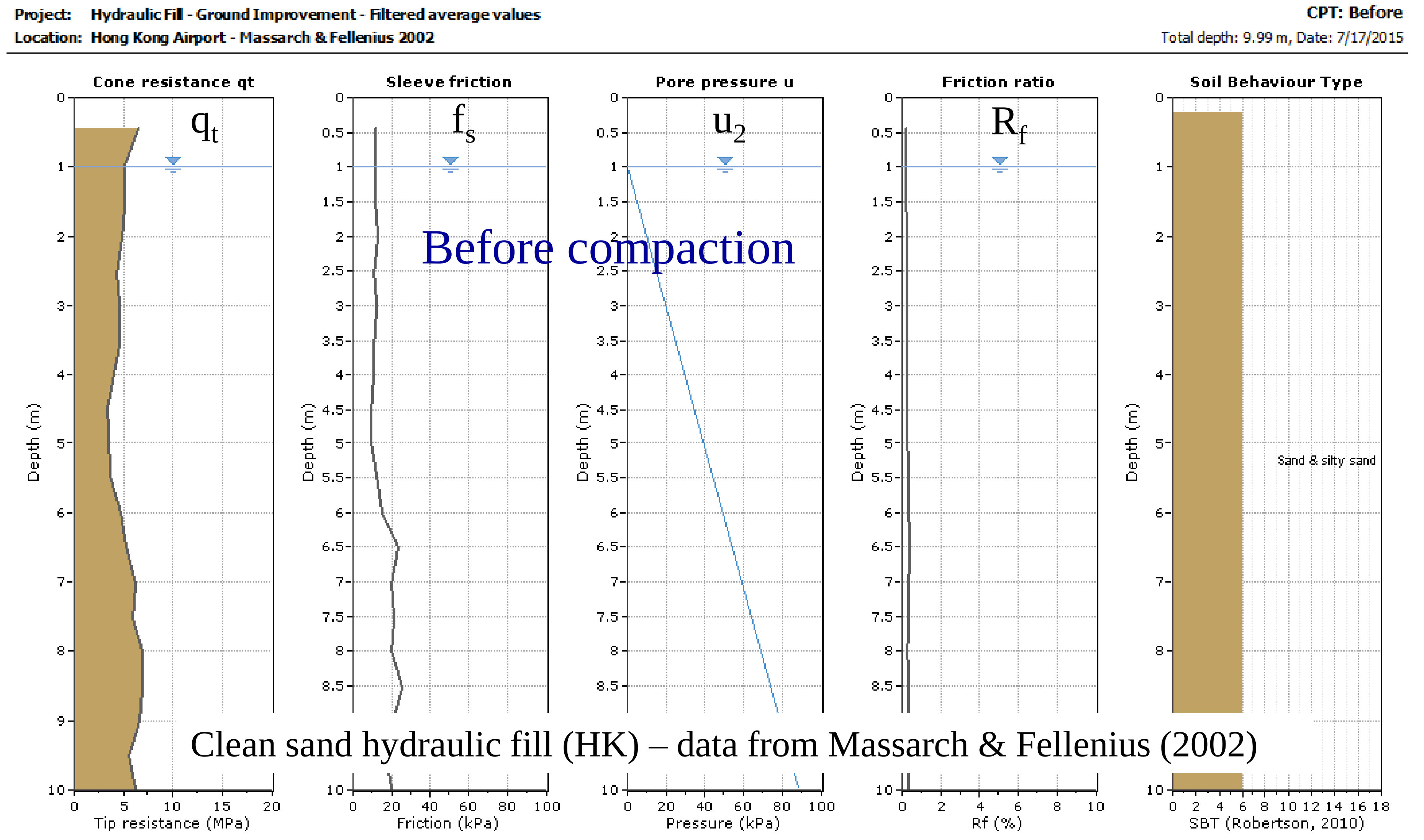
Young, uncemented, silica-based soils

$\psi \sim 0.56 - 0.33 \log Q_{tn,cs}$

Recommended QC Criteria

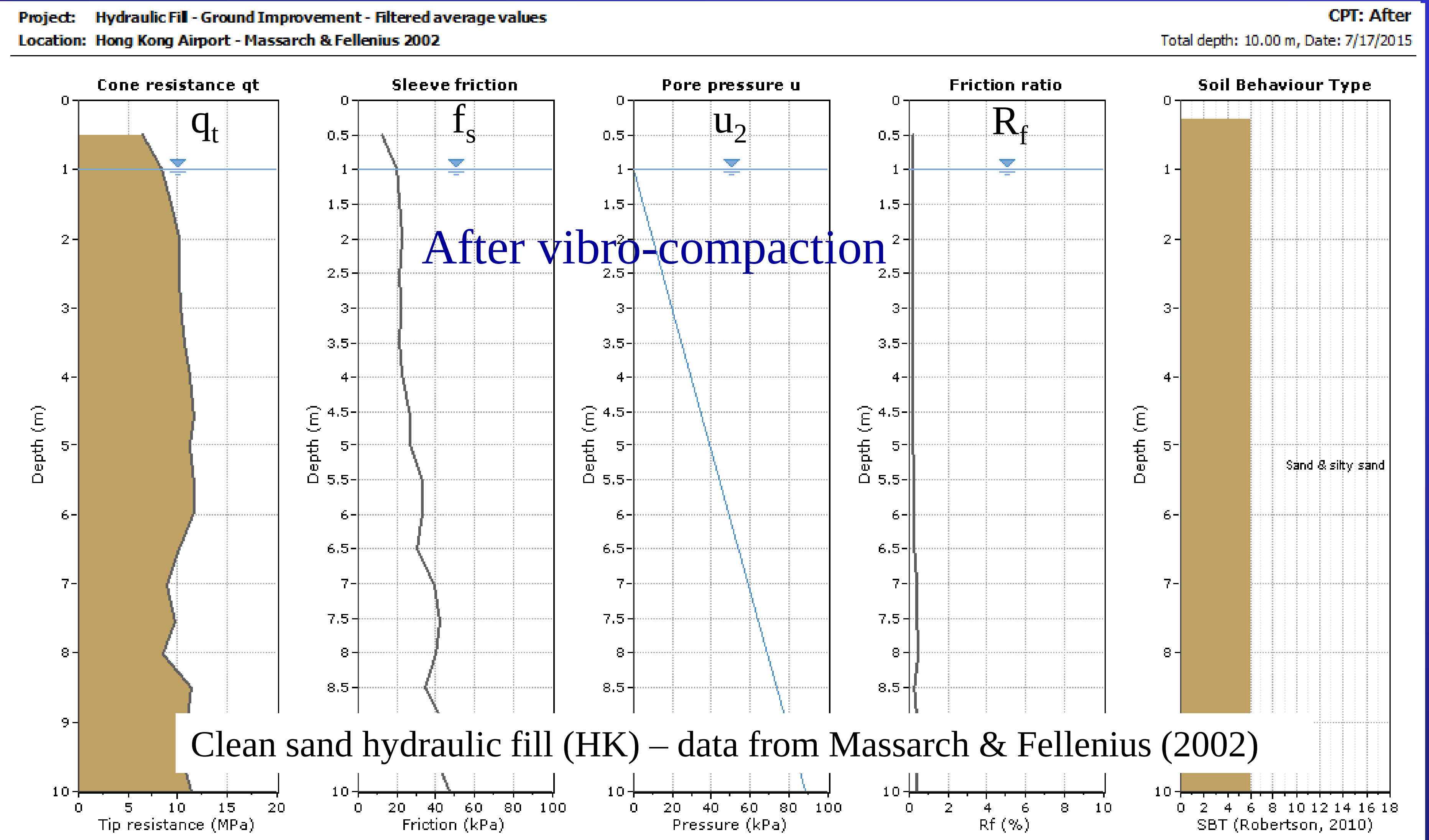
- Recommend using CPT criteria based on *'clean sand equivalent'* $Q_{tn,cs}$
- Applies to wide range of soils (not just clean sand)
- Requires a pre-agreed method to calculate $Q_{tn,cs}$
  - Robertson & Wride (1998) - based on I_c
  - Boulanger and Idriss (2014) - based on fines content (but generally converted to I_c)
- Can not be presented as a single line (depends on soil type, i.e. I_c)
- Software can process data

Example – clean sand



Clean sand hydraulic fill (HK) – data from Massarch & Fellenius (2002)

Example – clean sand



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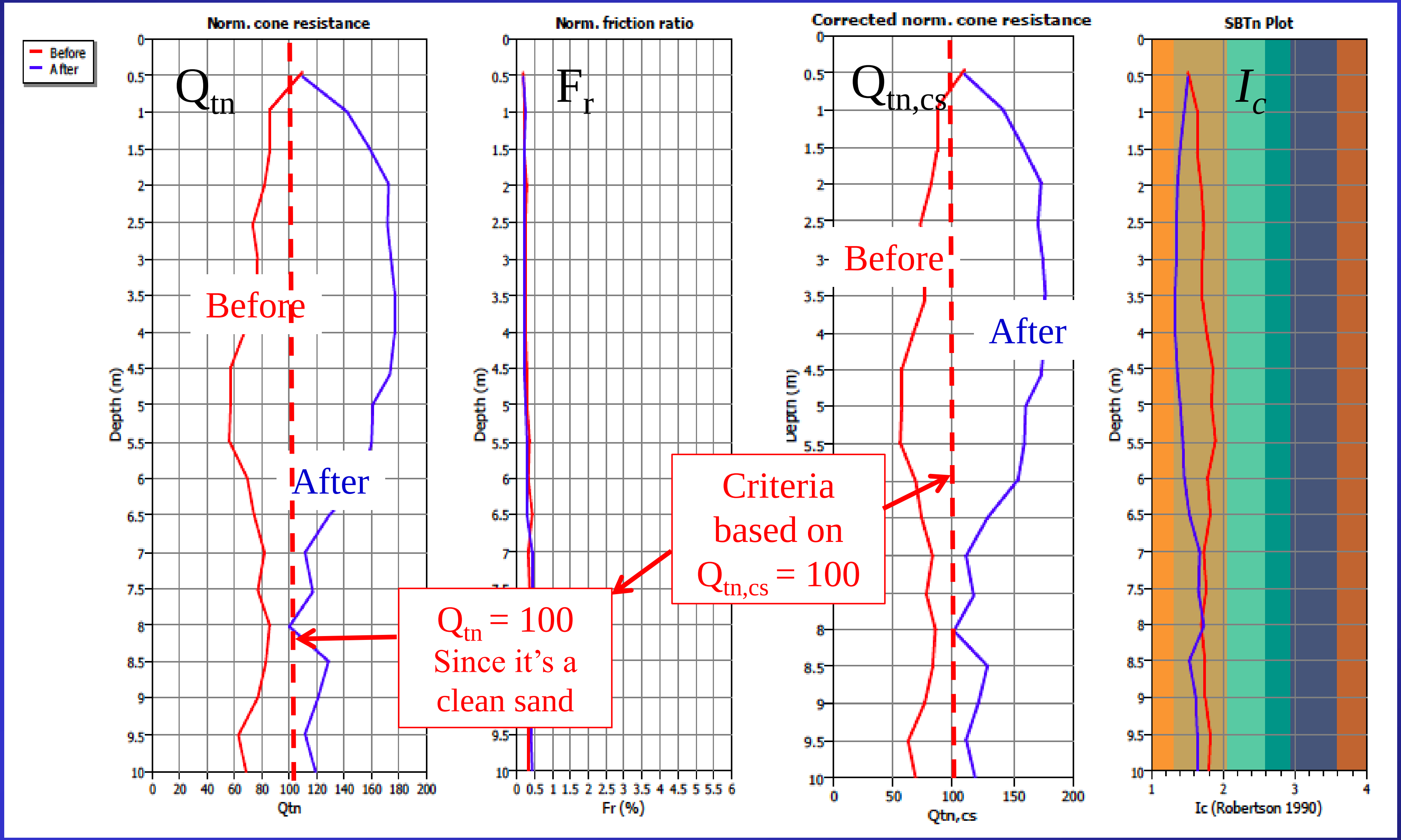

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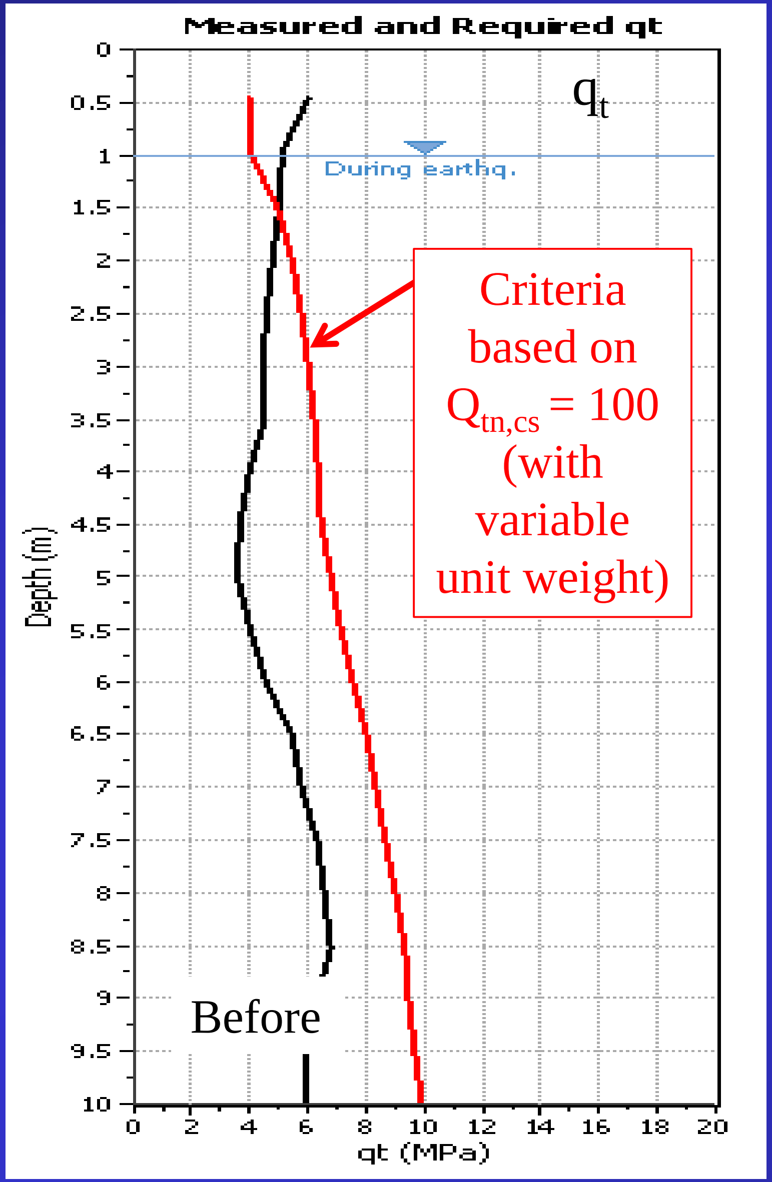
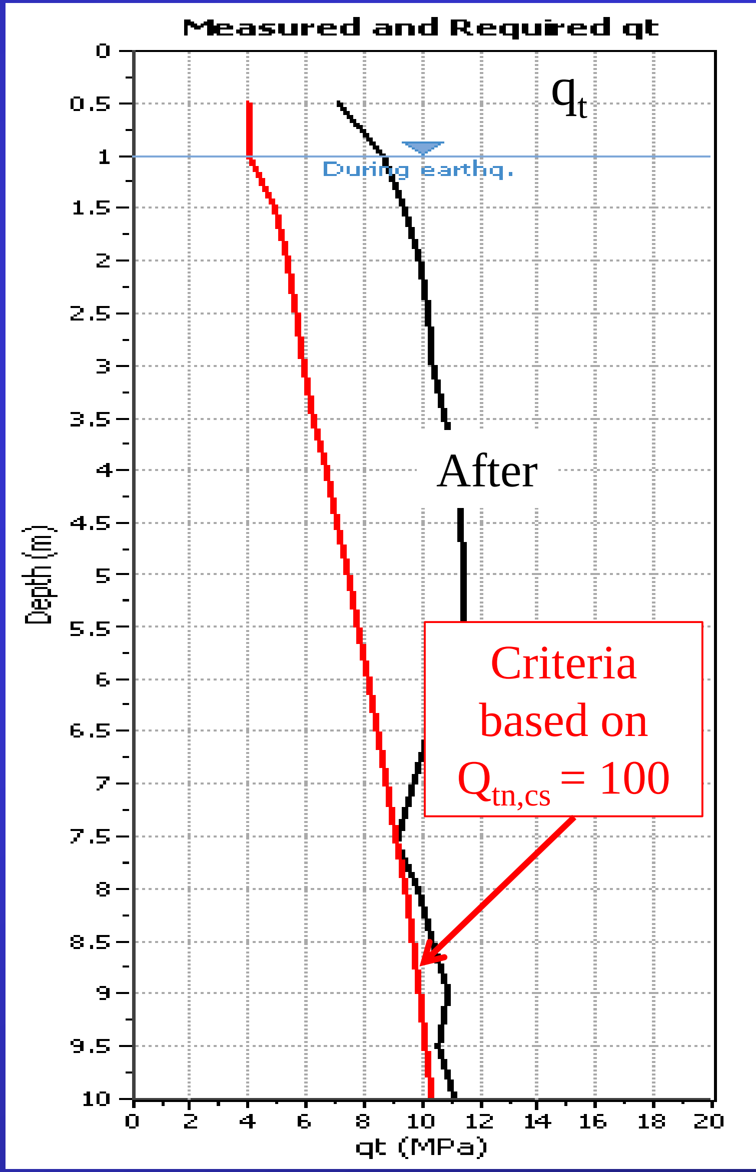
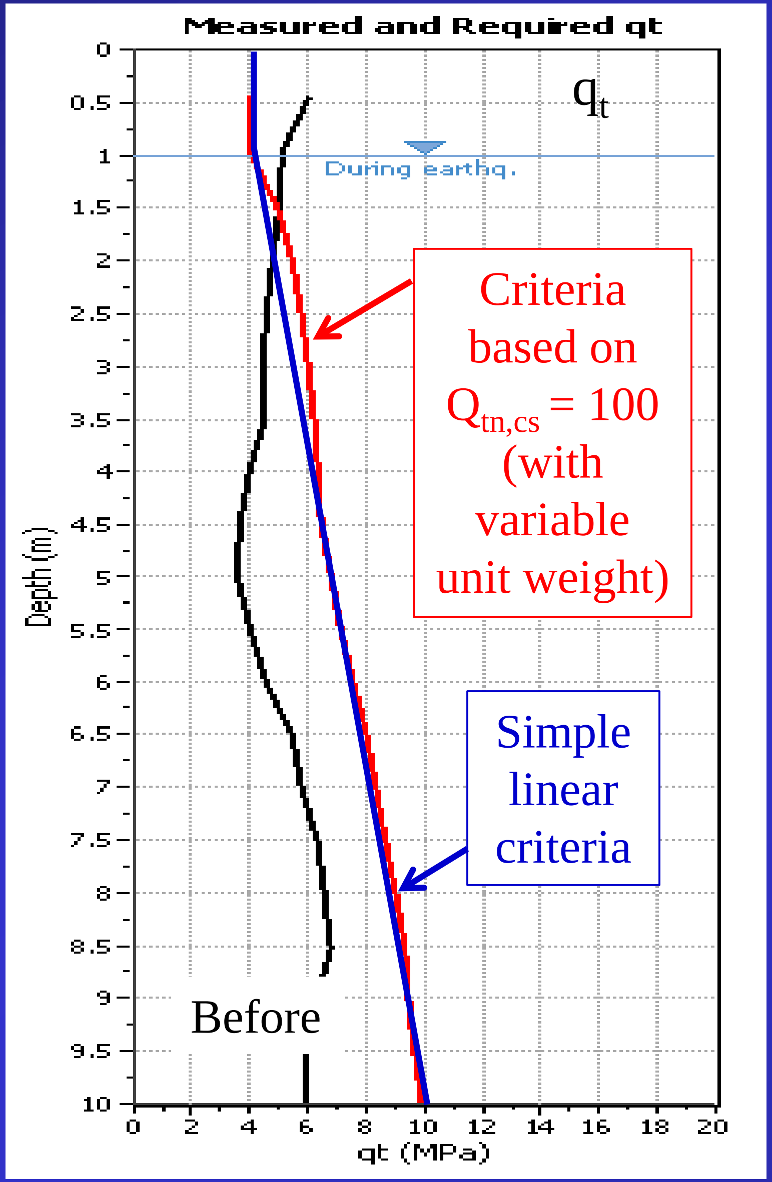
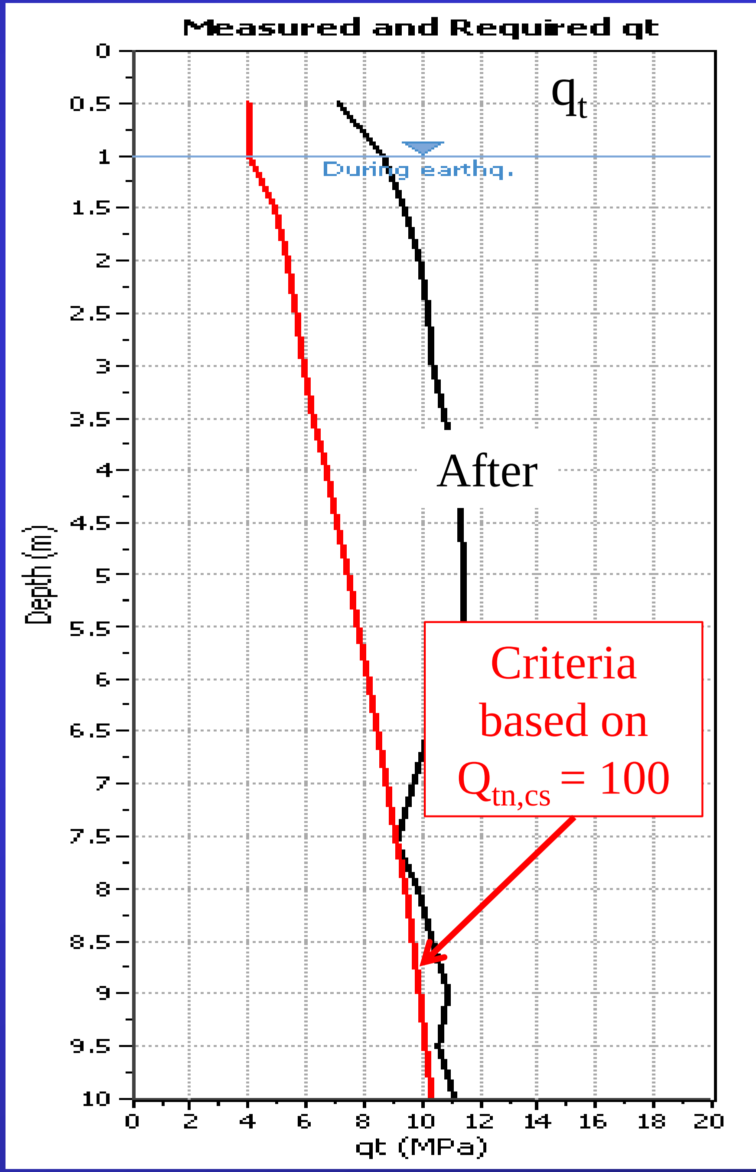


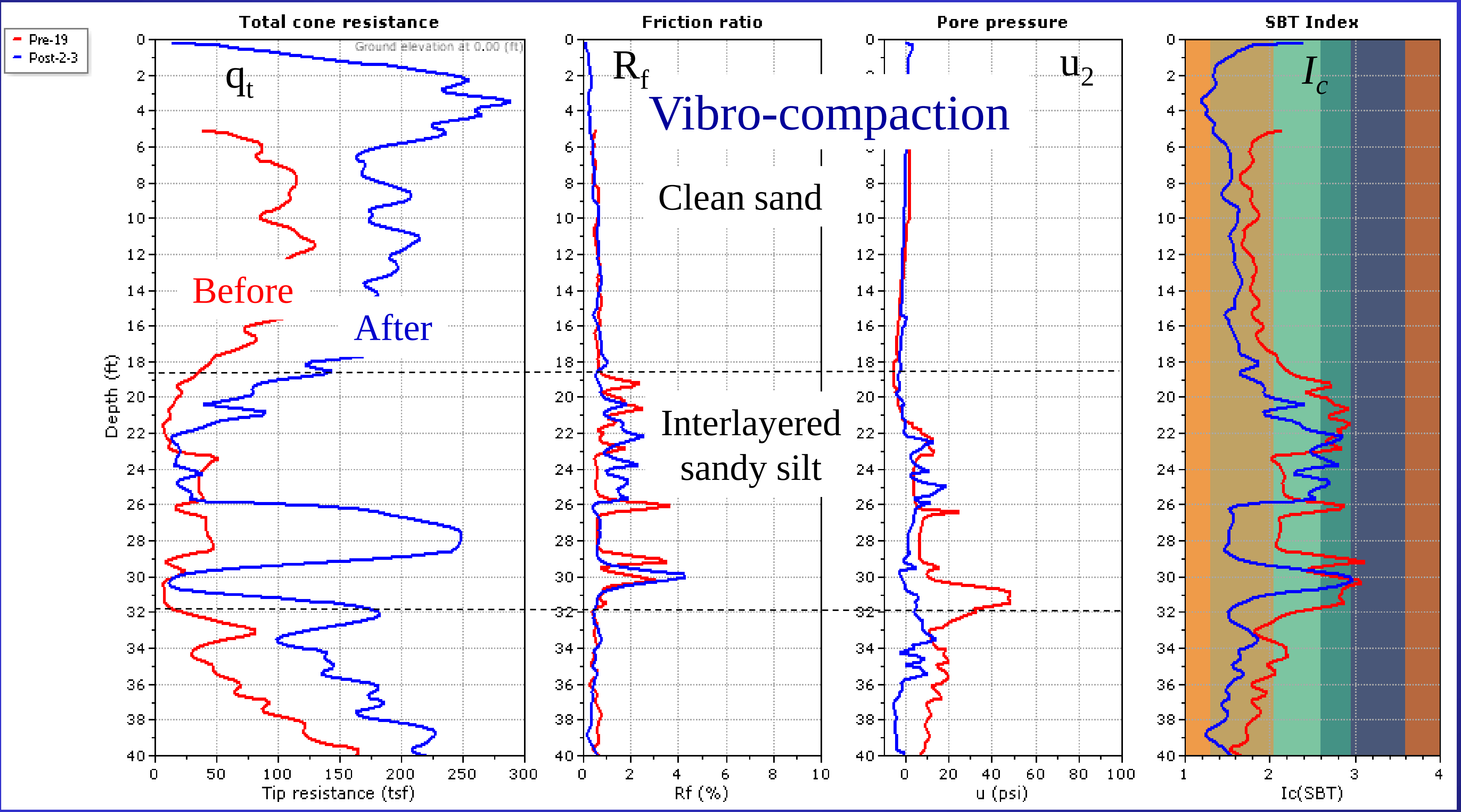


Example – clean sand

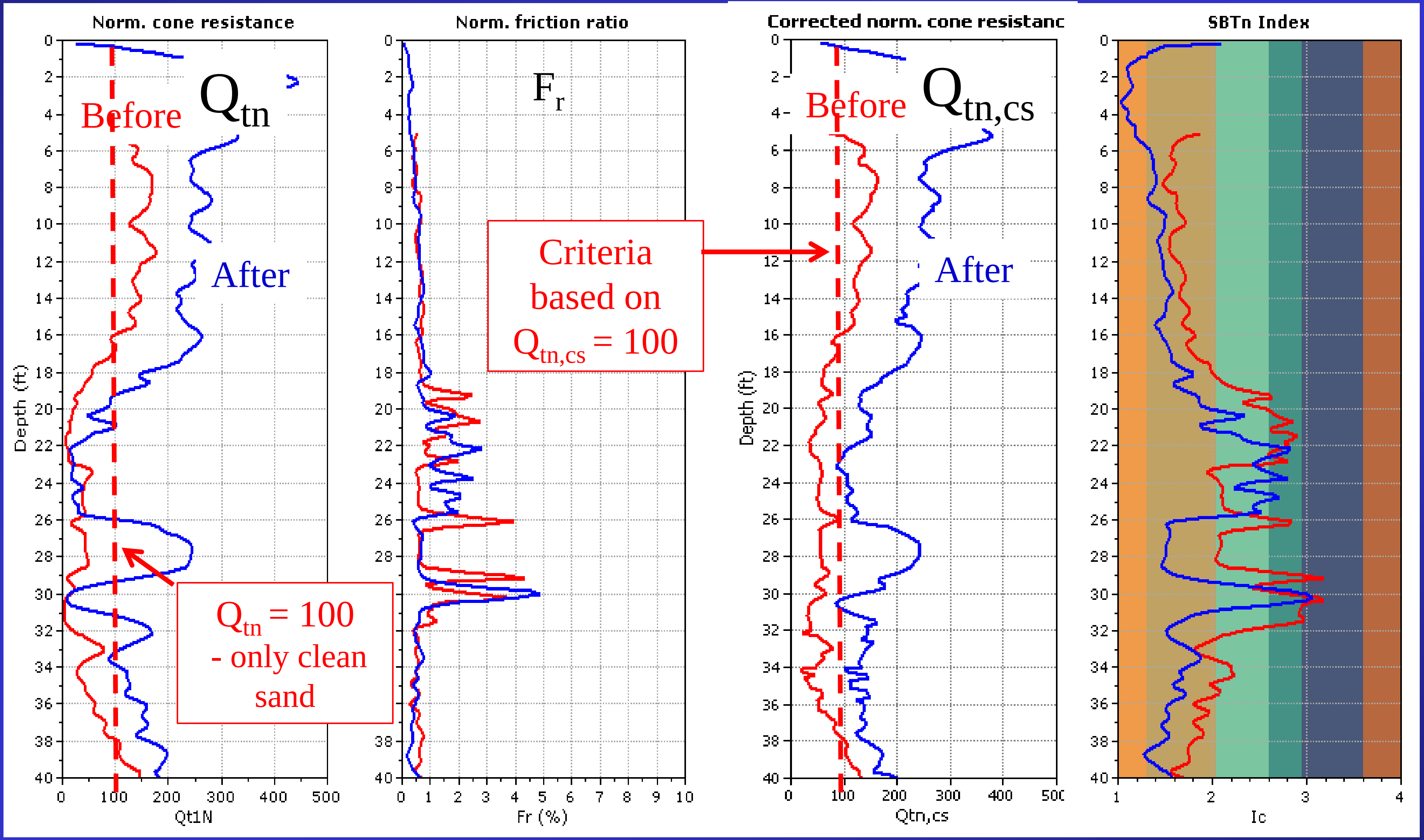




Example – complex profile



Example – complex profile



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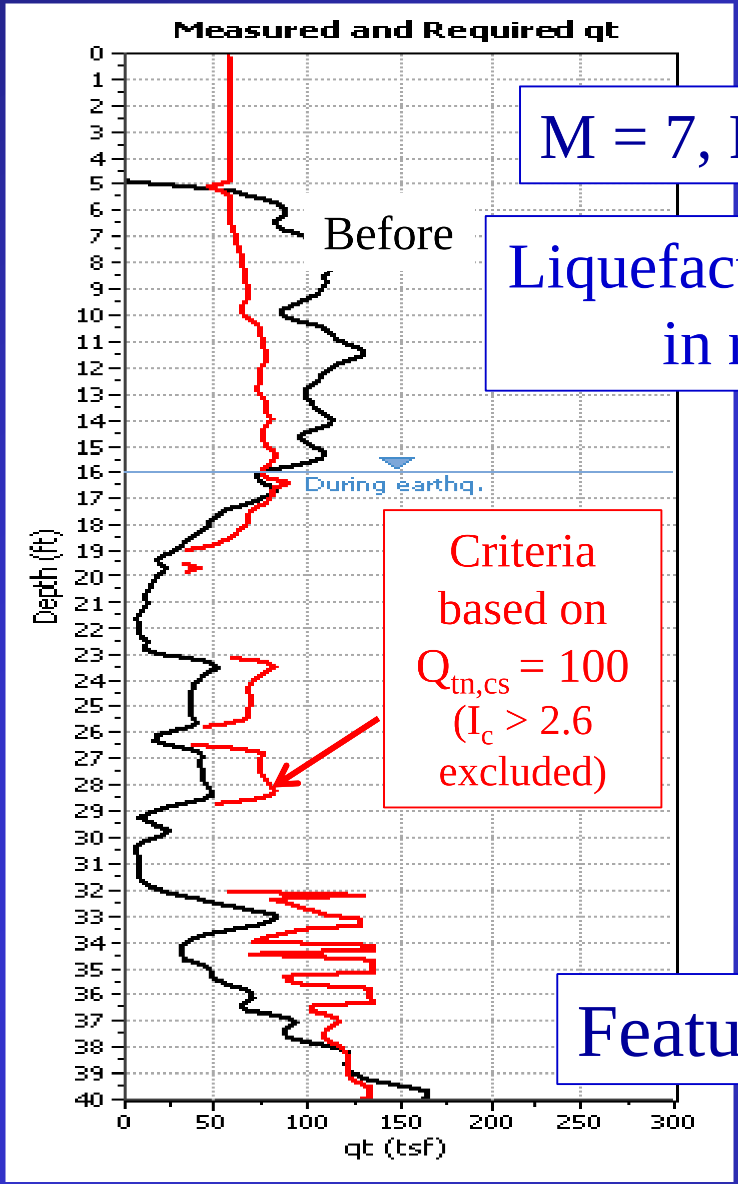
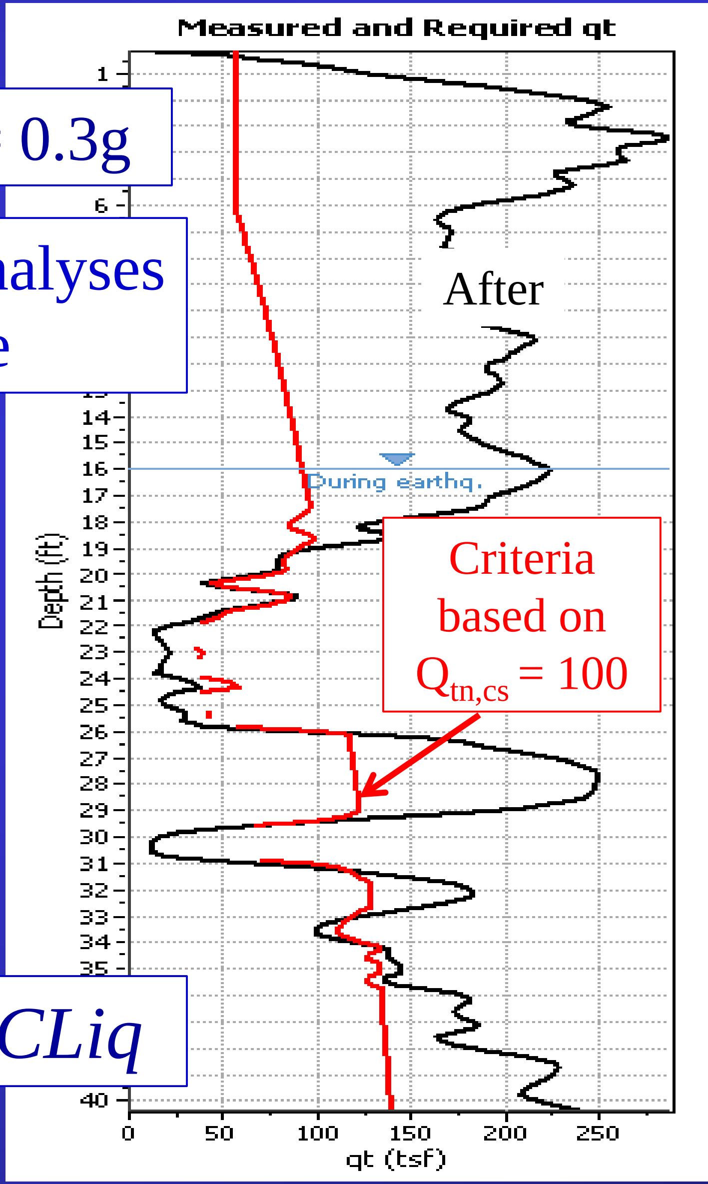


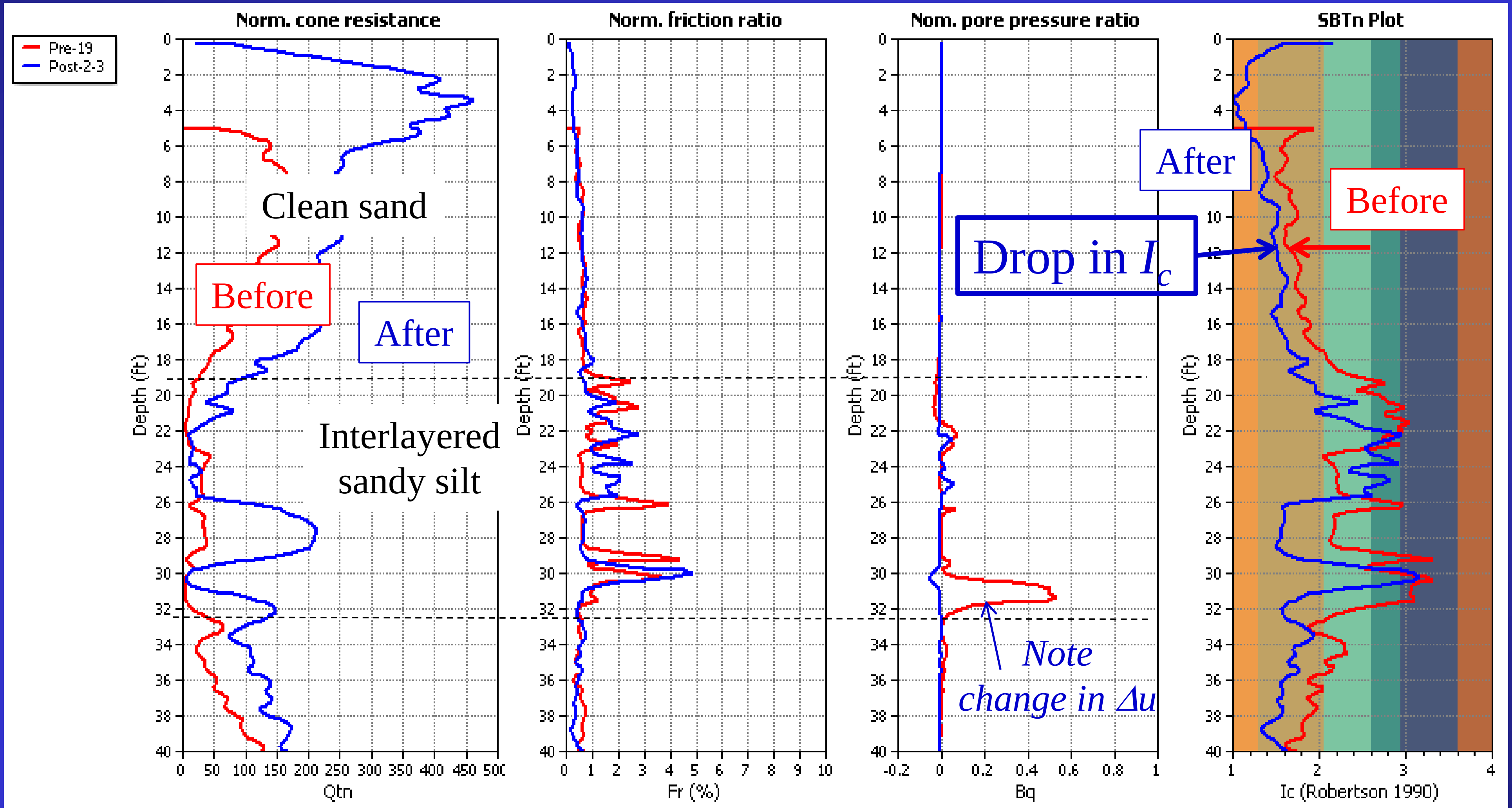
M = 7, PGA = 0.3g

Liquefaction analyses in reverse



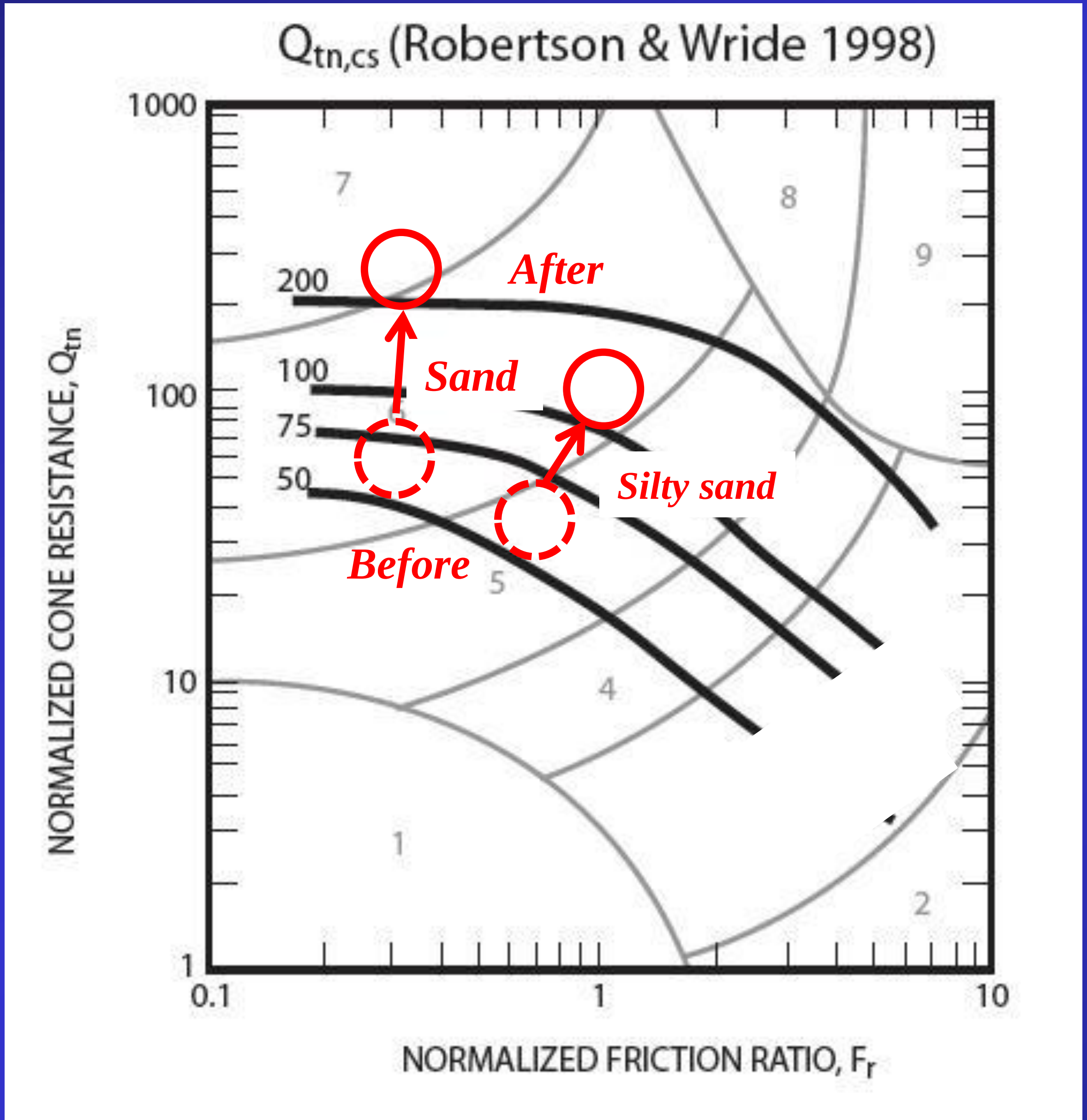
Feature in *CLiq*

Change in I_c



Pre-19
Post-2-3
Norm. cone resistance
Norm. friction ratio
Nom. pore pressure ratio
SBTn Plot
Depth (ft)
Qtn
Fr (%)
Bq
Ic (Robertson 1990)
Clean sand
Before
After
Interlayered sandy silt
Drop in I_c
After
Before
Note change in Δu

Change in I_c

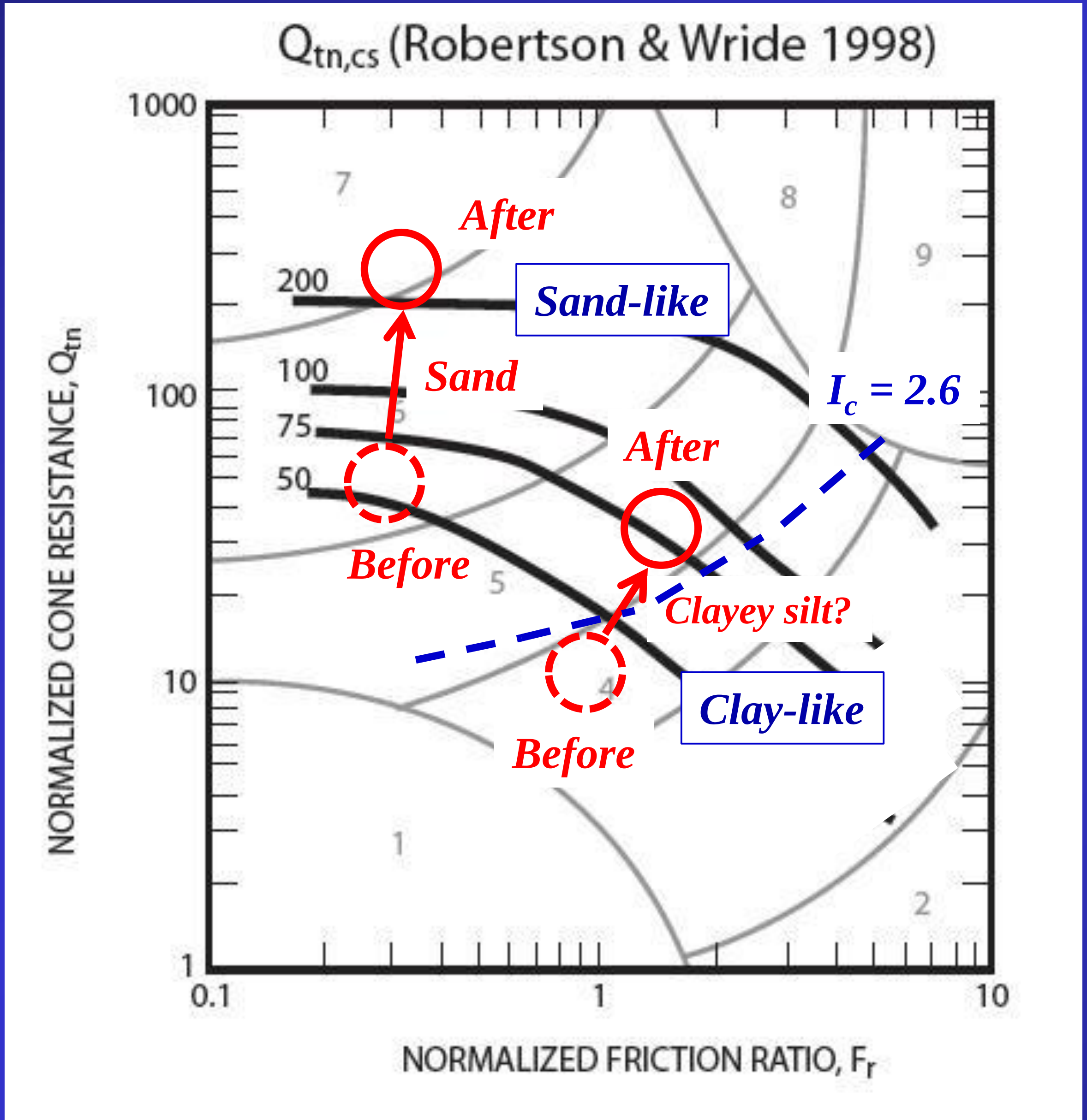


Ground improvement increases the resistance to loading.

For clean sands (F_r < 0.5%) - Q_t increases and I_c decreases.

For silt sands – Q_t increases and F_r increases and I_c will decrease less or stay constant

Change in I_c

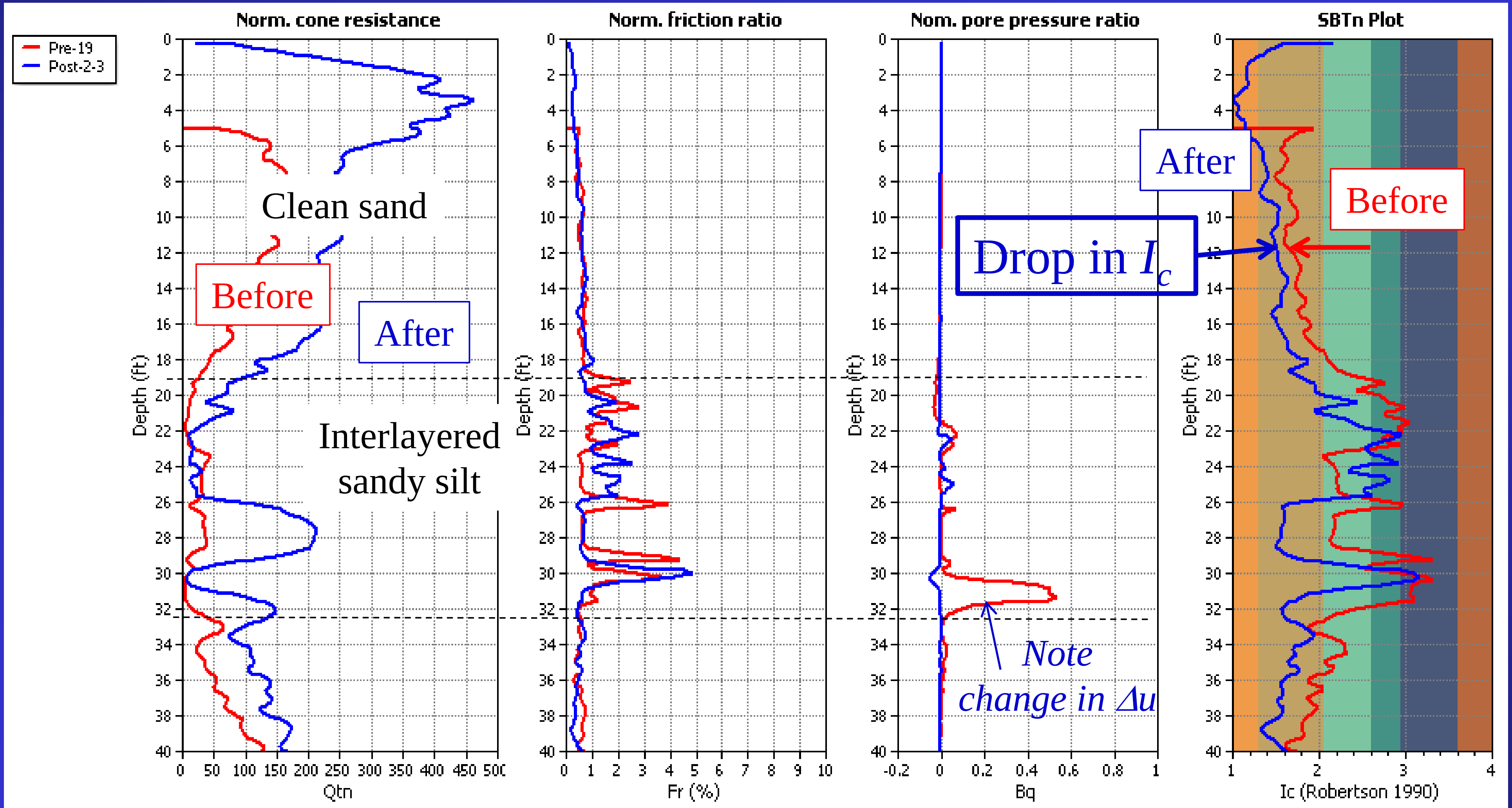


Potential problem if compaction changes I_c from
Pre - $I_c > 2.6$
to
Post - $I_c < 2.6$

Soil has NOT changed from *clay-like* to *sand-like* due to compaction?

Also influenced by change in K_o

Change in I_c



Pre-19
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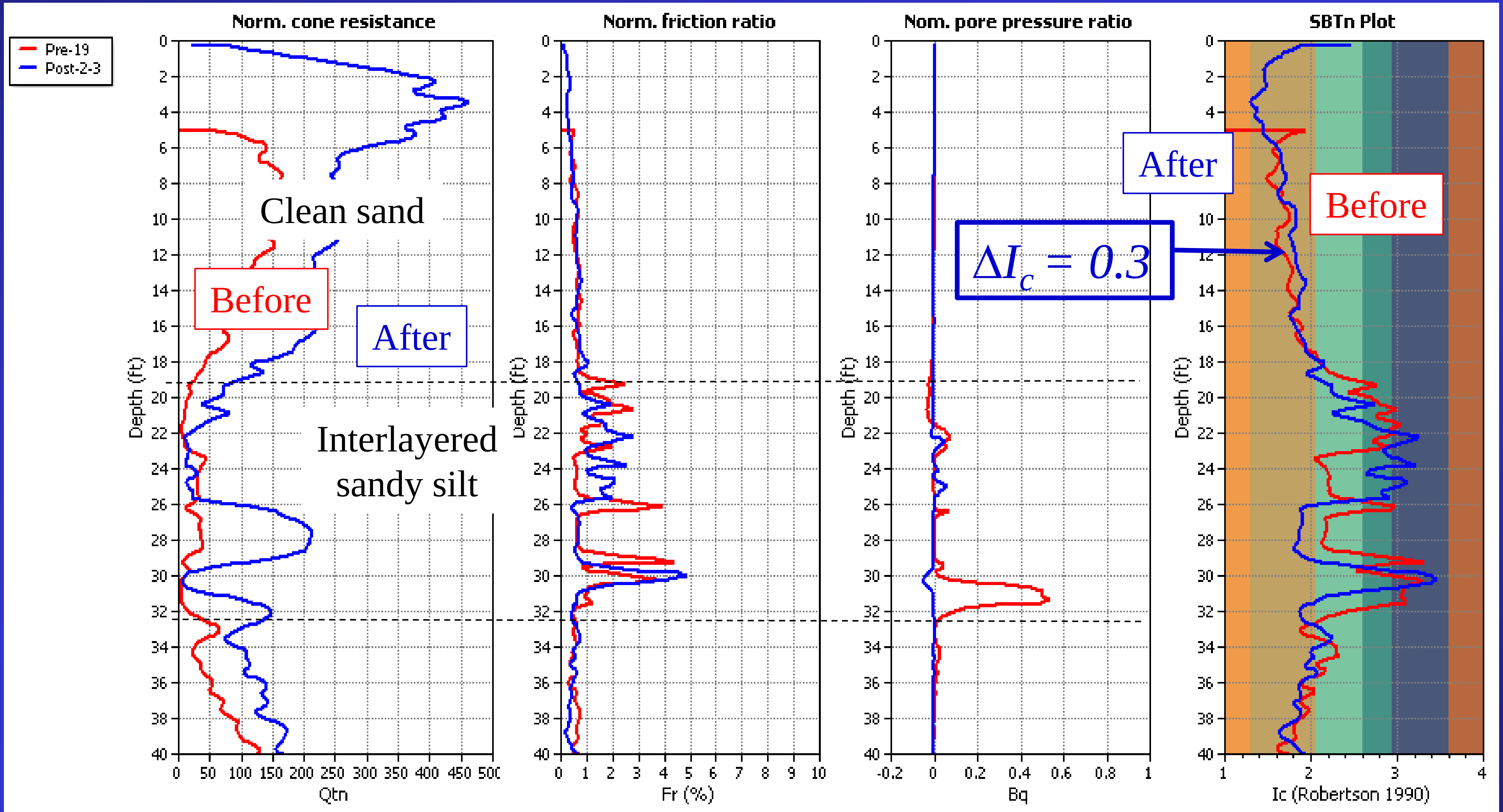
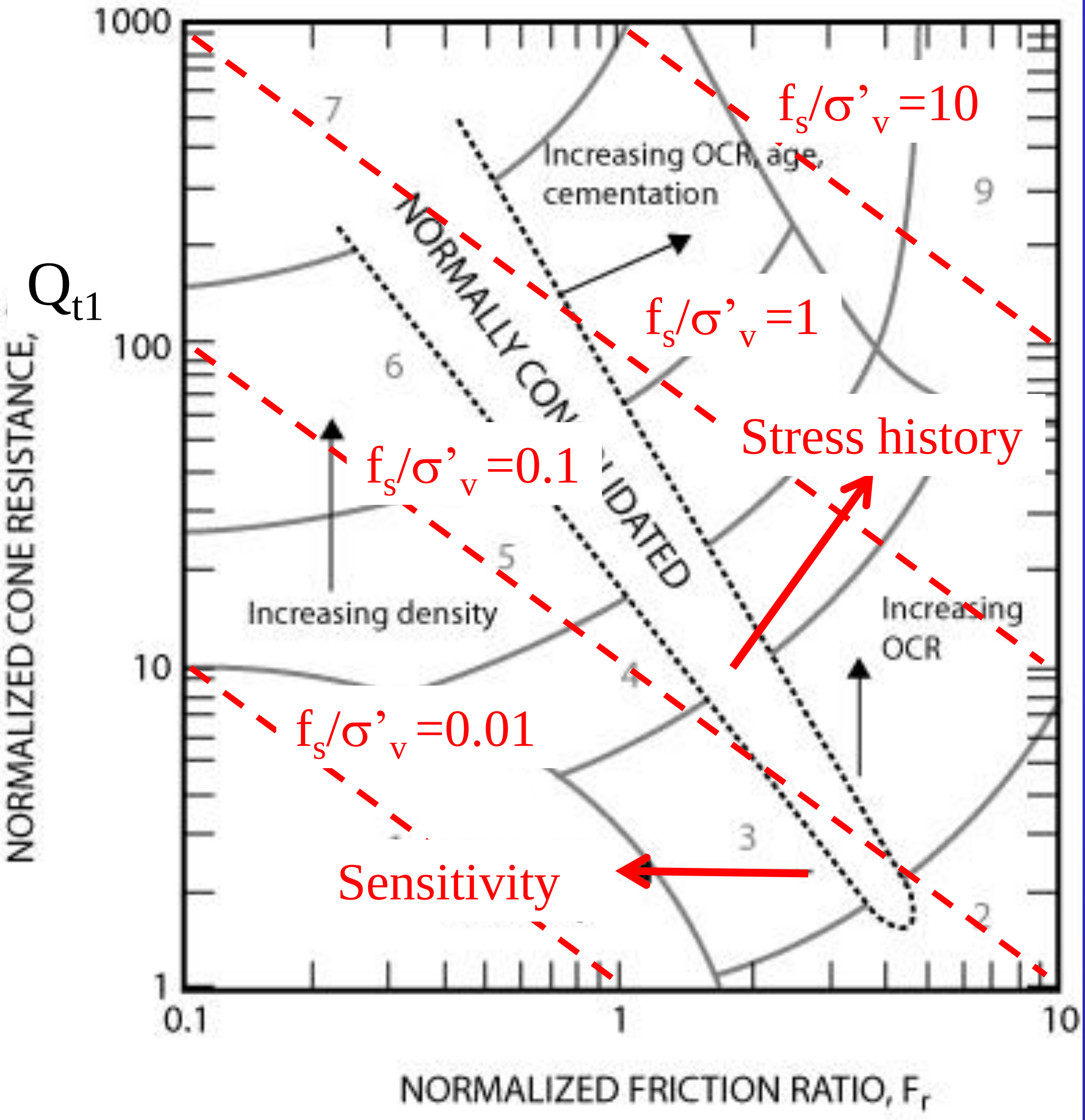
SBTn Plot
Depth (ft)
Qtn
Fr (%)
Bq
Ic (Robertson 1990)
Clean sand
Before
After
Interlayered sandy silt
Drop in I_c
After
Before
Note change in Δu

Correct for change in I_c



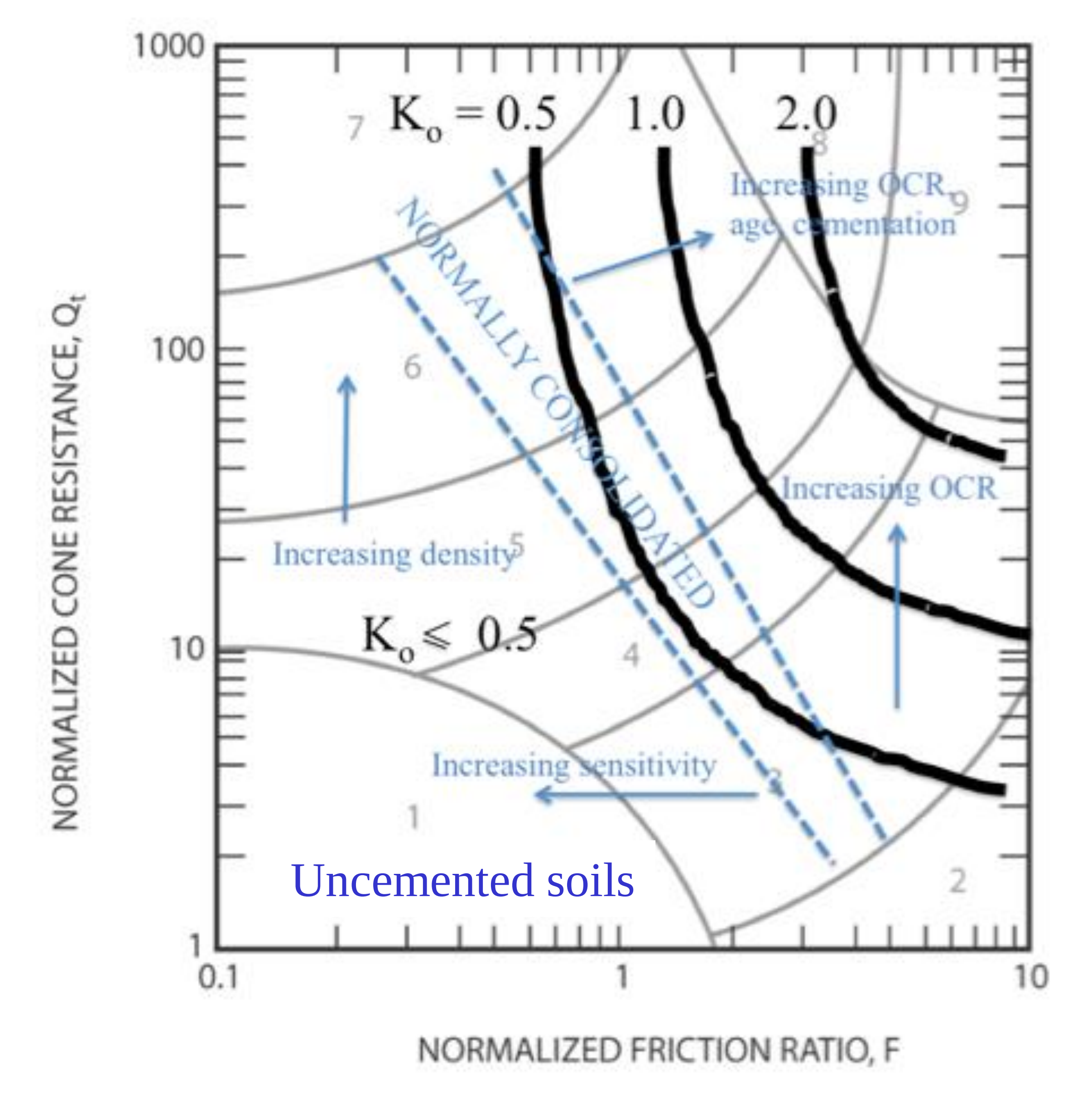
CPT Soil Behavior Type SBT



Normalized CPT sleeve resistance

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

Influenced by in-situ horizontal stress (K_o) & soil sensitivity – detects change in K_o

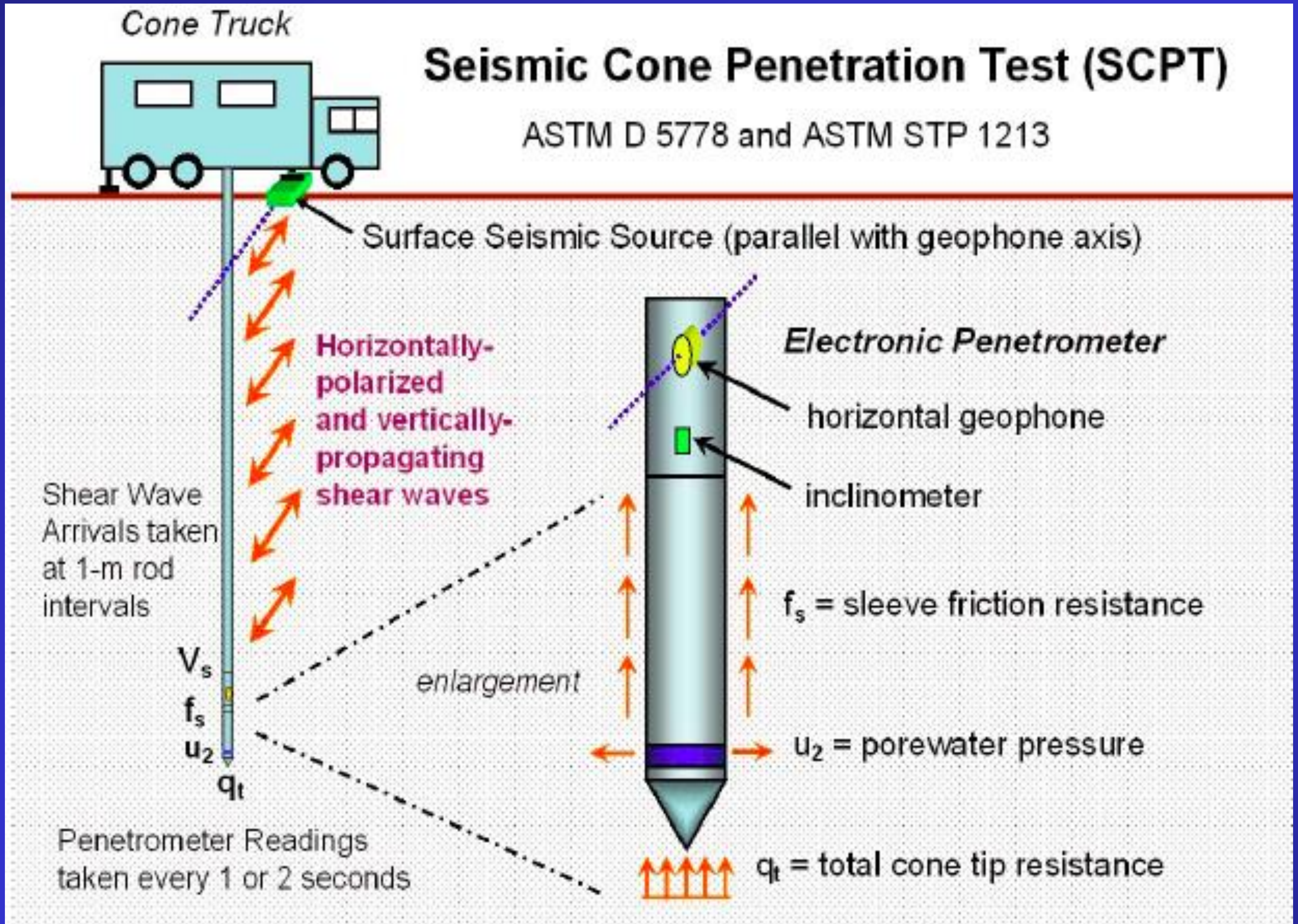


Suggested contours of in-situ K_o on the CPT-based SBTn chart

Additional measurements?

- CPTu – penetration pore pressure (u)
  - useful in fine-grained soils
  - can capture stress history
- SCPT – shear wave velocity (V_s)
  - potential to capture stress history?
  - average increase in soil stiffness
  - BUT - insensitive parameter (needs high accuracy)
- DMT – flat dilatometer test
  - Increased sensitivity to horiz. stress changes

Seismic CPT System Configuration



After Mayne, 2014

SCPTu

7 measurements!

q_t

f_s

u_2

$V_s\ (V_p)$

t_{50}

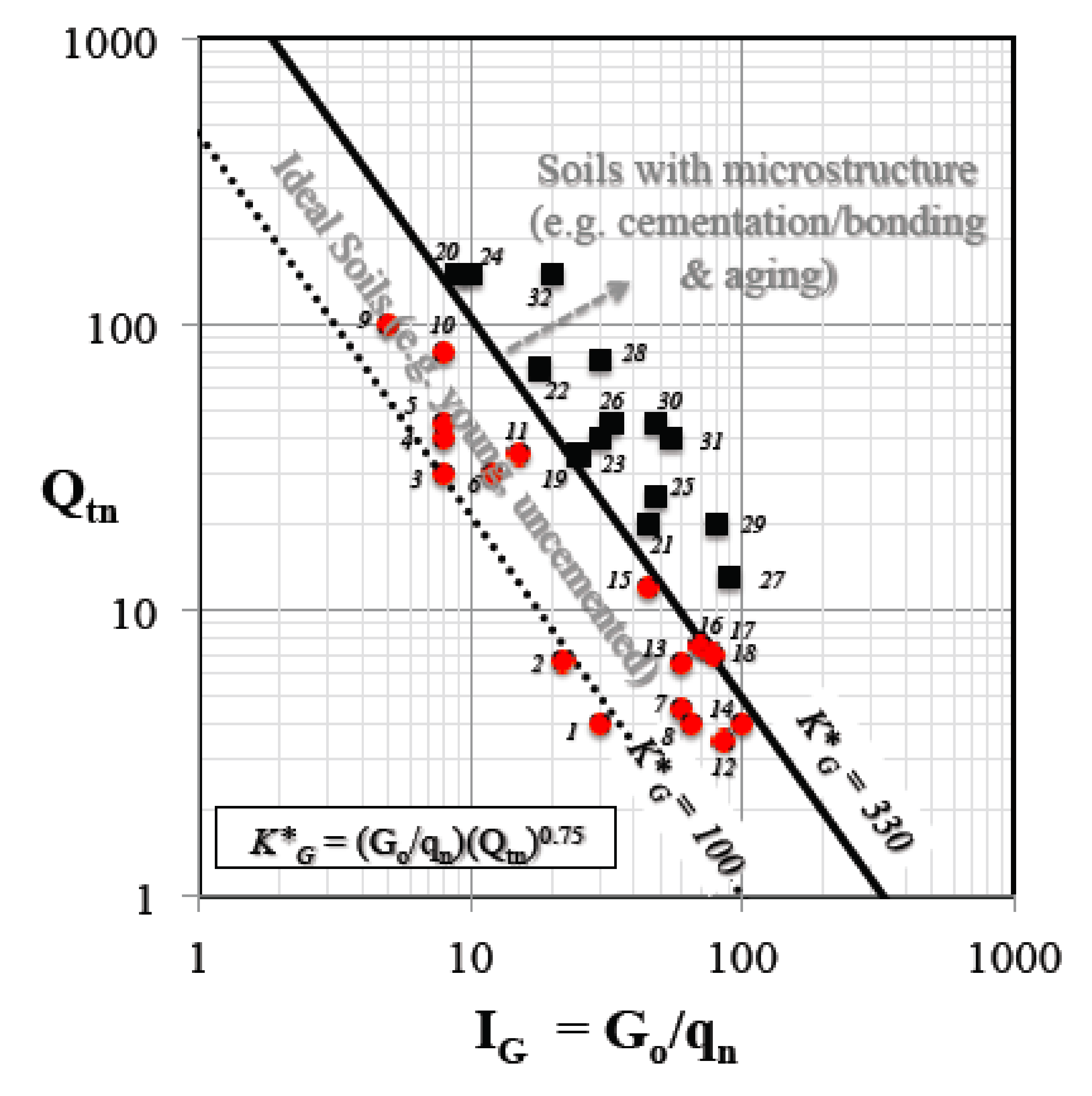
u_o

i

diss

Identification of 'unusual' soils
(soils with microstructure)

- 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



Identify 'unusual' soils - soils with microstrcuture based on SCPT

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

$$q_n = (q_t - \sigma_{vo})$$

Soil Mixing

- Soil mixing more common in either complex soil profiles and/or more fine-grained soils
- QC criteria typically based on *'unconfined compressive strength'* (q_u)
  – undrained shear strength, $s_u = q_u /2$
- CPT can be used as rapid QC based on:

$$s_u = (q_t - \sigma_{vo})/ N_k \qquad (\text{where } N_{kt} \sim 15)$$

e.g. If QC critreia q_u > 2 bar, then s_u > 1 bar

CPT q_n > 15 bar (1.5MPa)

Summary

- CPT the most common in-situ test to evaluate ground improvement (esp. deep compaction)
- Issues such as:
  - Thin layers (or transition zones - remove)
  - Soils with high fines content
    - Use *clean sand equivalent*
  - Time affects
  - Microstructure (e.g. age & cementation)

Questions?