

How reliable is CPT to estimate settlement of foundations?

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2026

Calculating Settlement of Foundations

- Requires:
 - Magnitude of settlement, S
 - Rate of settlement,
 - Compatibility with acceptable behavior of structure
- For well-designed foundations, strains are generally small ($\epsilon < 10^{-1} \%$)
- Total settlement (S) is combined immediate (distortion), S_i + consolidation, S_c + creep, S_t

$$S = S_i + S_c + S_t$$

Calculating Settlement of Foundations

- Coarse-grained soils:
 - High permeability
 - Immediate and consolidation settlements occur together (primarily controlled by G & E')
 - Creep settlements are generally small
- Fine-grained soils:
 - Low permeability
 - If $OCR < 4$: approx. 80% to 90% of settlements are from consolidation (controlled by M, Cc, Cr)
 - If $OCR > 4$: approx. 50% from consolidation
- Most immediate settlements occur during construction (unless rapid loading on soft soils)
- Hence, consolidation settlements tend to dominate, in most cases

Bearing Capacity of Foundations - CPT

- Settlement criteria generally controls design, but estimates of suitable applied loads often guided by bearing capacity (q_{ult}) estimates
- Bearing capacity, q_{ult} can be estimated directly from CPT:

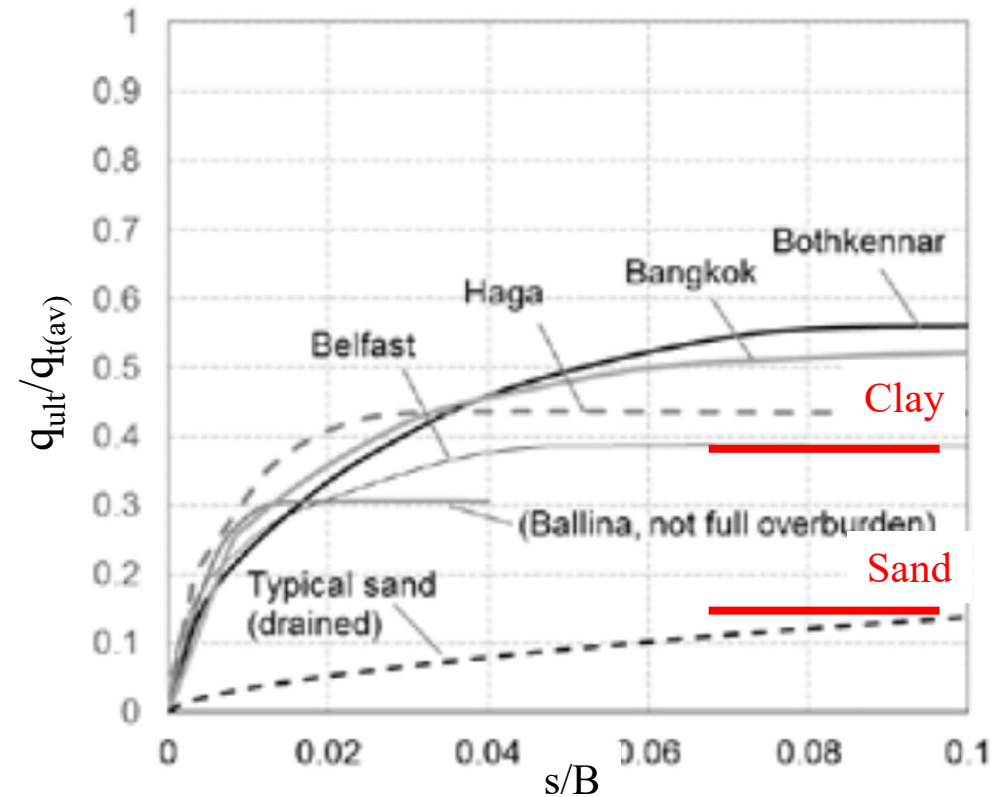
$$q_{ult} = \alpha q_{t(av)}$$

$q_{t(av)}$ = average cone resistance below footing, $z = B$

$0.15 < \alpha < 0.50$ depending on shape of footing and soil type

$\alpha \sim 0.15$ sands and $\alpha \sim 0.40$ clays

- Allowable bearing pressure, $q_{all} = q_{ult}/\text{FoS}$ (with $2 < \text{FoS} < 5$)



CPT based Settlement

Traditional Approach - SAND

Schmertmann (1970) – Young's Modulus E'

$$s = C_1 C_2 \Delta p \sum \left(\frac{I_z}{C_3 E'} \right) \Delta z$$

C_1 = correction for depth of footing
 = $1 - 0.5(\sigma'_1/\Delta p)$

C_2 = correction for creep and cyclic loading
 = $1 + 0.2 \log(10 t_{yr})$

C_3 = correction for shape of footing
 = 1.0 for circular footings
 = 1.2 for square footings
 = 1.75 for strip footings

σ'_1 = effective overburden pressure at footing depth

Δp = net footing pressure

t_{yr} = time in years since load application

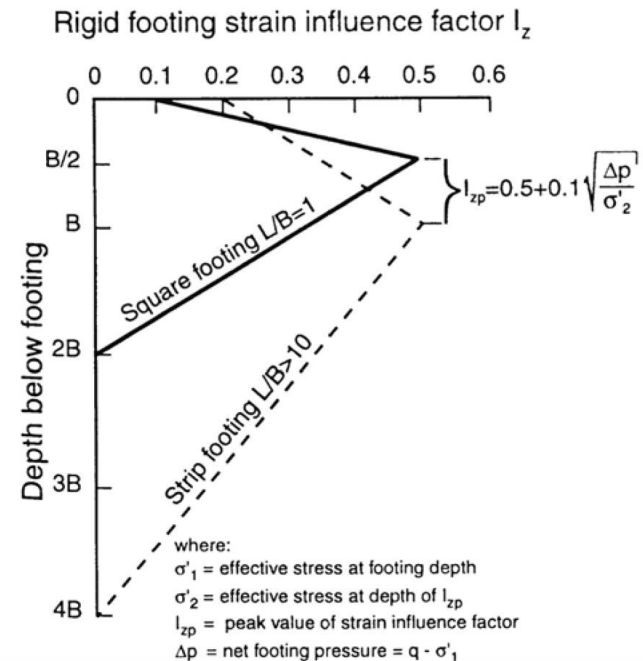
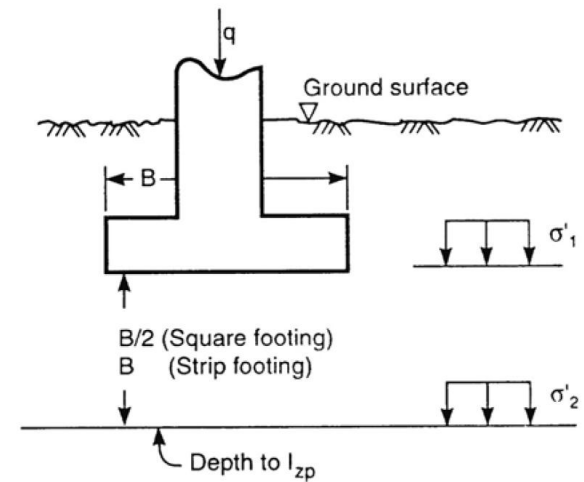
I_z = strain influence factor (see Figure 39)

Δz = thickness of sublayer

E' = Equivalent Young's modulus = $\alpha_E q_c$

$$E' = \alpha_E q_c$$

$$\alpha_E \sim 2$$



CPT based Settlement Traditional Approach - CLAY

Normally Consolidated, $\sigma'_0 + \Delta\sigma'_0 > \sigma'_p$

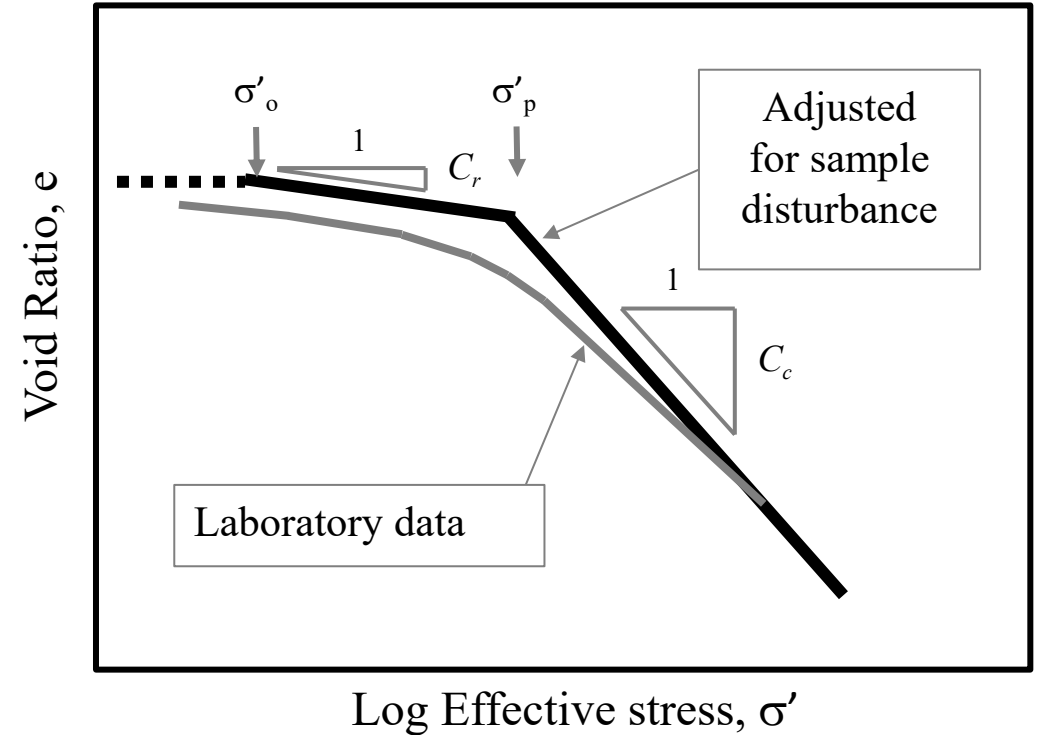
$$S_c = \left(\frac{C_c}{1 + e_0} \right) \cdot H \cdot \log \left(\frac{\sigma'_0 + \Delta\sigma'_0}{\sigma'_0} \right)$$

Over Consolidated, $\sigma'_0 + \Delta\sigma'_0 < \sigma'_p$

$$S_c = \left(\frac{C_r}{1 + e_0} \right) \cdot H \cdot \log \left(\frac{\sigma'_0 + \Delta\sigma'_0}{\sigma'_0} \right)$$

1. **Layer Division:** Divide the compressible clay layer into sub-layers.
2. **Parameter Determination:** From consolidometer (oedometer) tests:
 1. Find initial void ratio (e_0) and effective overburden stress (σ'_0).
 2. Determine Compression Index (C_c) for normally consolidated clay
 3. Determine Swell Index (C_s) for overconsolidated clay (C_s)
 4. Find pre-consolidation pressure (σ'_c).
3. **Stress Increment:** Calculate the applied stress increase ($\Delta\sigma'$) at the middle of each layer.

1D Consolidation Test



Complex & difficult to apply in practice
Needs: C_r , C_c , e_0 , σ'_p

Traditional Methods using CPT

- Traditional CPT methods to estimate either E (sands) or $C_{c/r}$ (clays) have been poor
- Typically, CPT over-estimates settlement (i.e., very conservative)
- Traditional approach difficult to apply for interbedded soil
- DMT has been shown to have better estimates settlements based on 1D Constrained Modulus, M

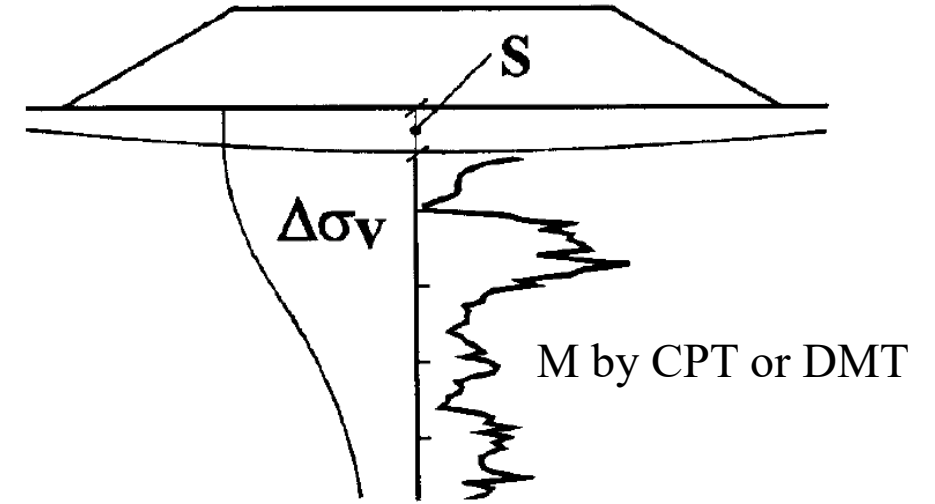
Interbedded soils?

Traditional methods are difficult to apply in interbedded soils

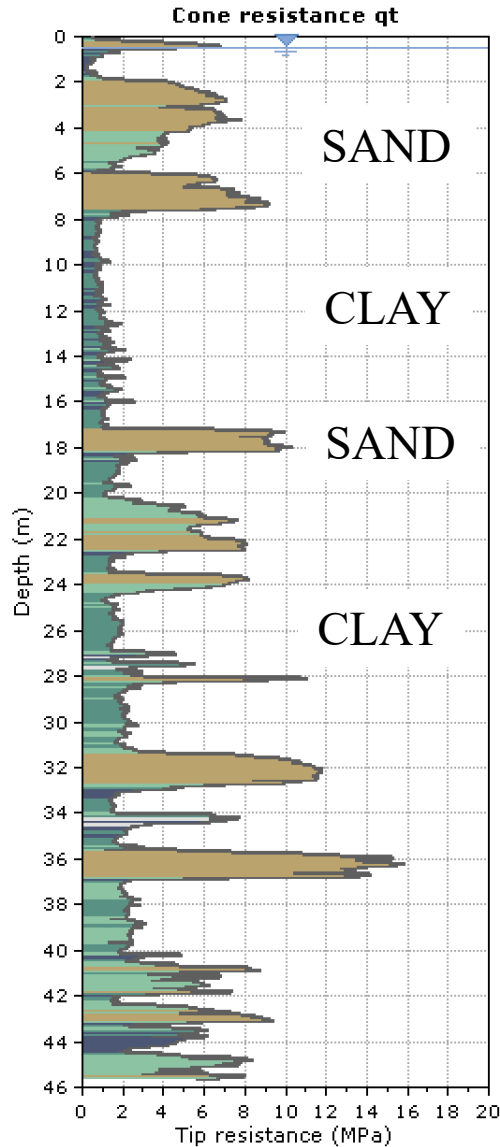
Alternate approach:

1D Constrained Modulus, M
Continuous profile for all soils

$$M = 2.3(1+e_o) \sigma'_{vo} / C_{c/r}$$



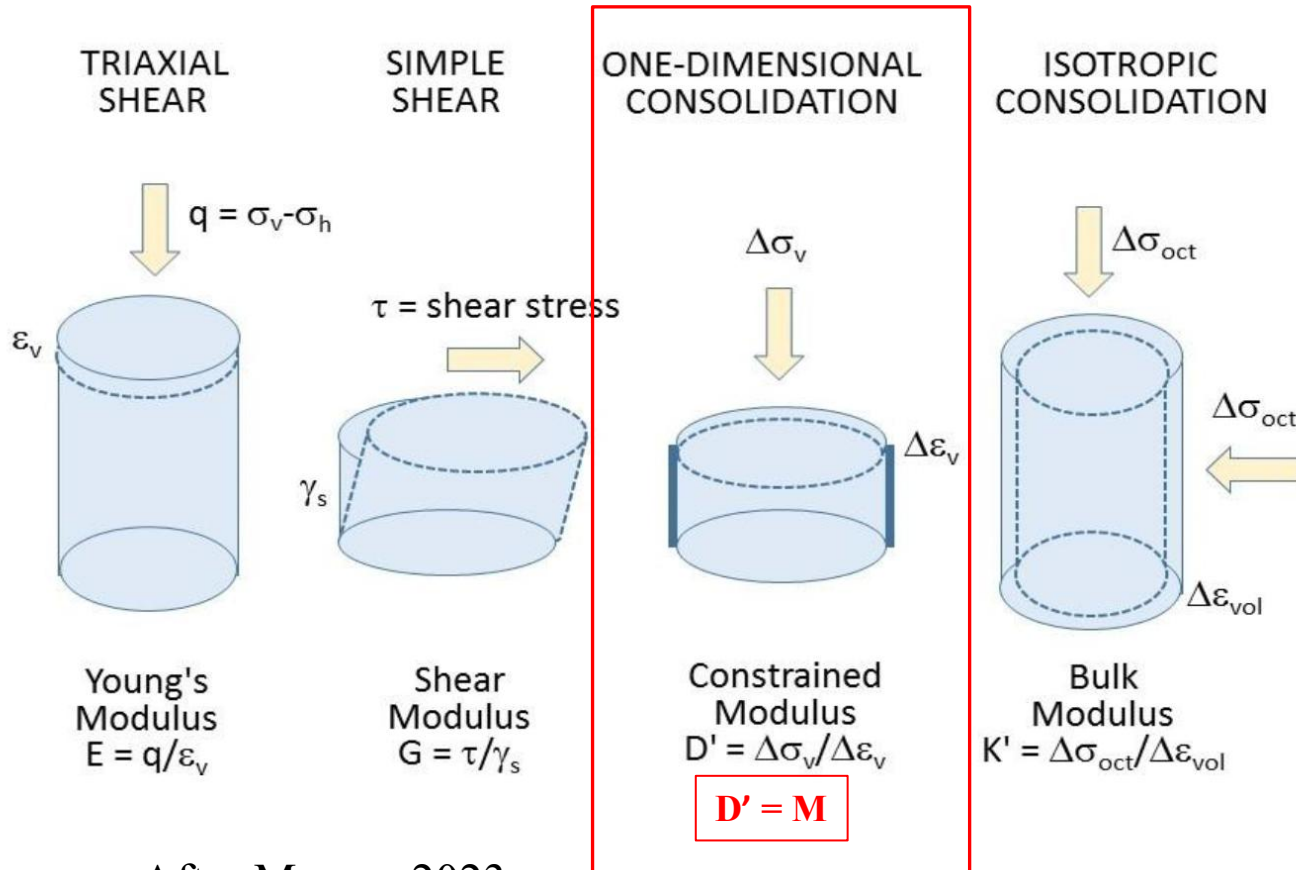
$$S = \sum \frac{\Delta\sigma_v}{M} \cdot \Delta Z$$



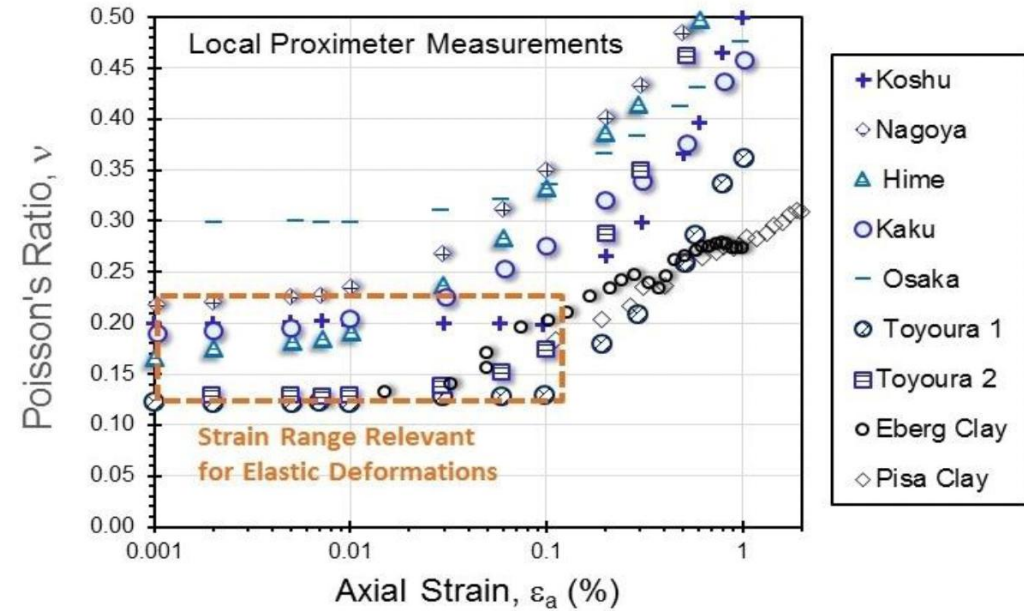
Elastic Moduli of Soils

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

$$M = E \frac{(1-\nu)}{(1+\nu)(1-2\nu)}$$



After Mayne, 2023



for $\nu = 0.2$
 $E' \sim 2.4 G$
 $M \sim 1.1 E'$ (for Sand)

1D Constrained Modulus

Janbu (1963)

$$M = K_m p_a (\sigma'_{vo}/p_a)^a$$

Where K_m is a dimensionless modulus number

For normally consolidated soils ($a = 1$)

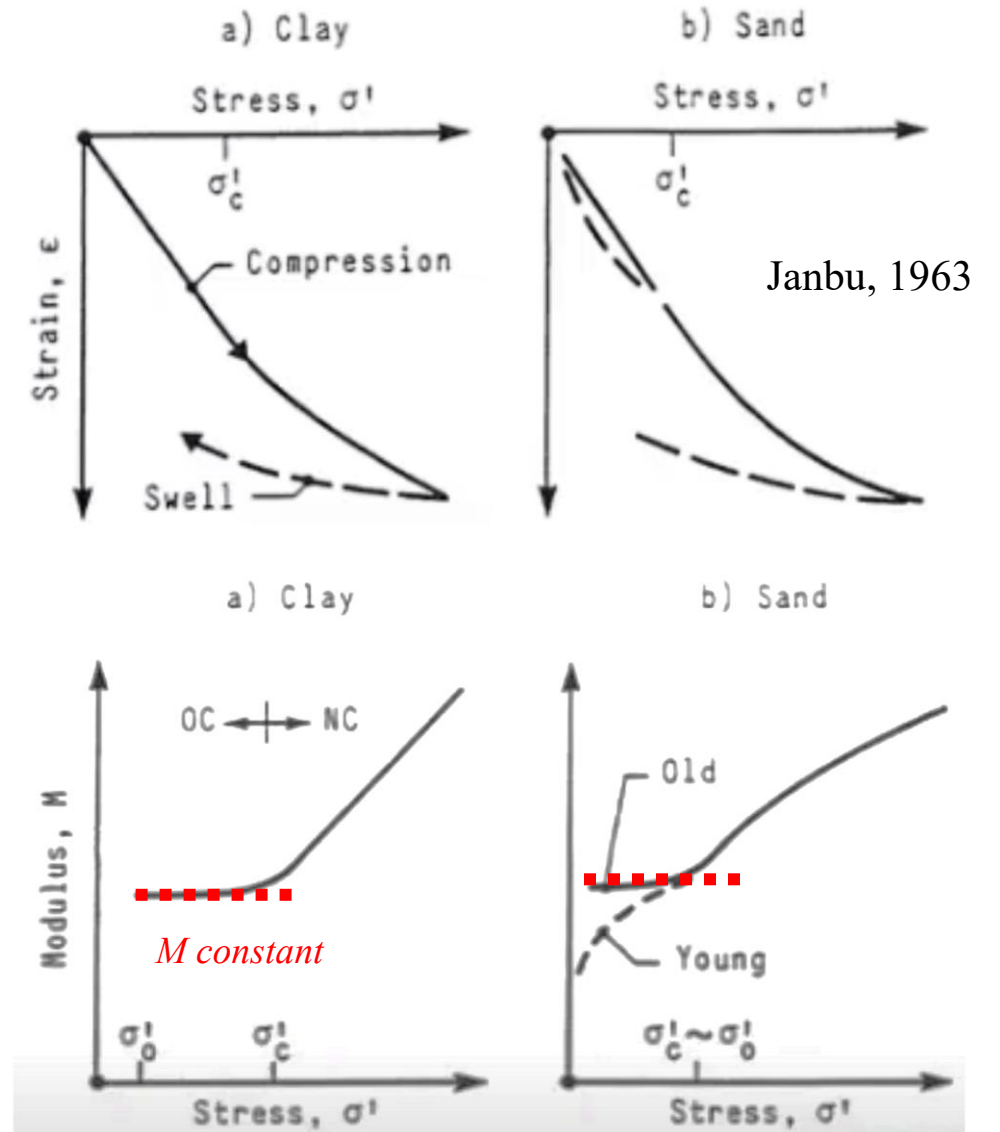
$$M = K_m \sigma'_{vo}$$

For Over consolidated soil ($a = 0$)

$$M = K_m p_a$$

K_M controlled by:

OCR in Clay and D_r in Sand



1D Constrained Modulus

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For Over consolidated soil ($a = 0$)

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K_M controlled by:

OCR in Clay and D_r in Sand

Soil Type	Modulus Number, K_M
Very Soft Clay/Silt	5 – 20
Soft Clay/Silt	20 – 40
Medium Clay/Silt	40 – 80
Stiff Clay/Silt	80 – 150
Loose Sand	50 – 150
Medium Dense Sand	150 – 300
Dense Sand/Gravel	300 – 500+
Overconsolidated Clays	100 – 300+ (high)

Janbu, 1963

Typical values

1D M of soils from CPT

After Mayne, 2023

$$M = \alpha_m (q_t - \sigma_{vo})$$

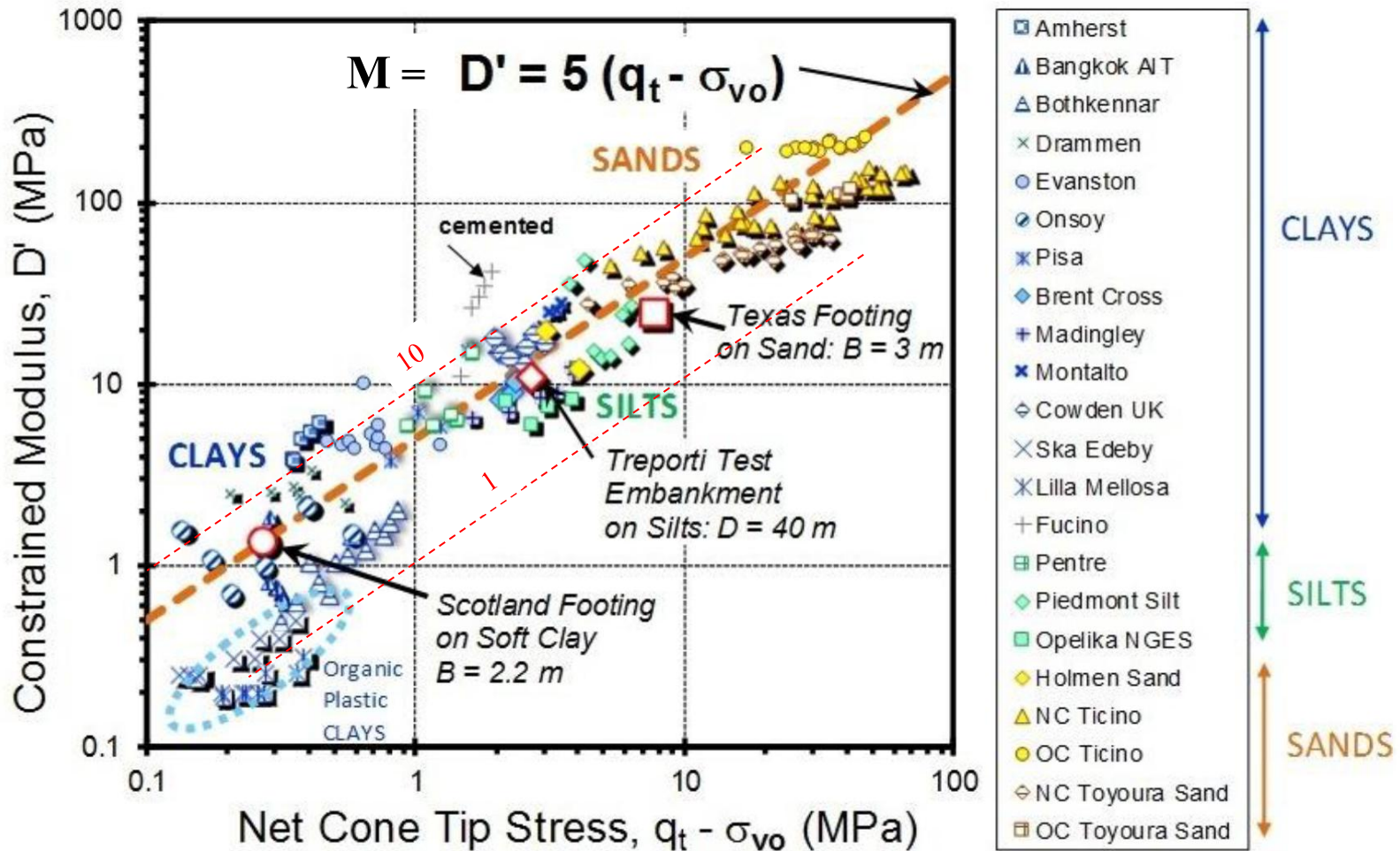
$$M = \alpha_m q_{net}$$

Mayne (2023)

$$1 < \alpha_m < 10$$

Mayne, suggested:

$$\alpha_m \sim 5 \text{ (average value)}$$



Flat-Plate Dilatometer Test (DMT)

- Developed in 1980 by Marchetti
- Simple and repeatable
- Slower than CPT (by factor of 3 to 4)
- Test every 20cm
- Provides parameters: I_D , K_D and E_D
- Excellent track record for estimating $1D M$ in wide range of soils



Flat-Plate Dilatometer Test (DMT)

Measurements:

- Liftoff pressure, p_o
- Pressure to expand 1.1mm, p_1

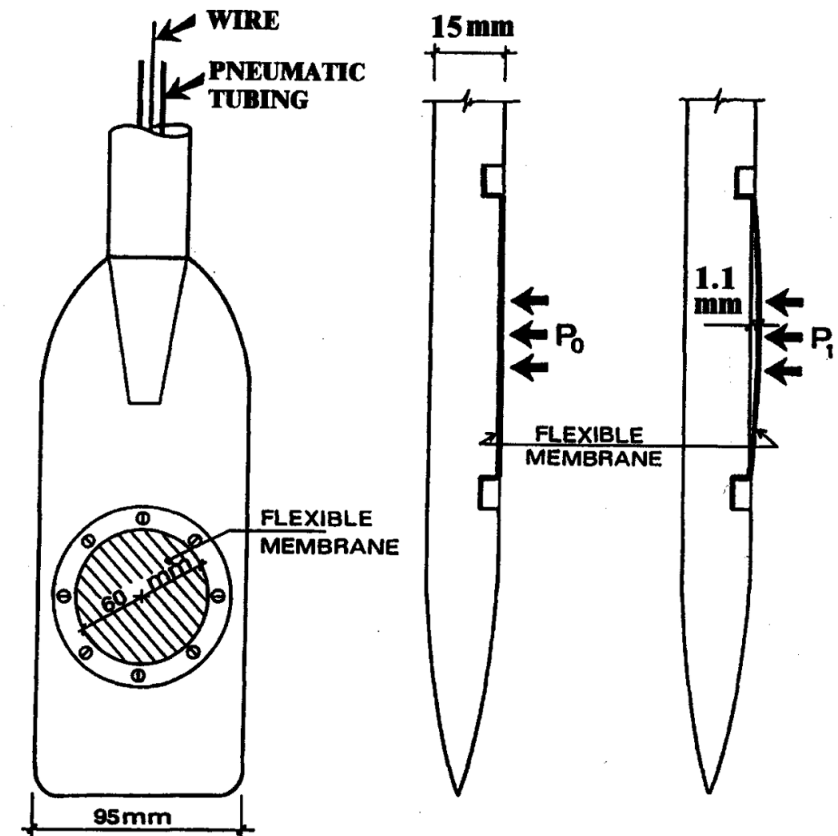
Calculated parameters:

Material Index, $I_D = (p_1 - p_o) / (p_o - u_o)$

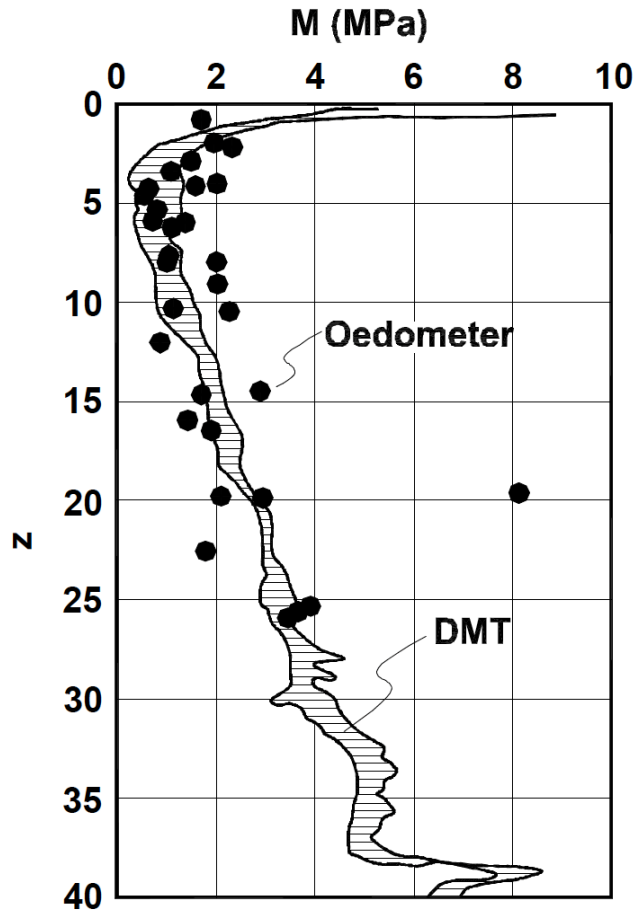
Horizontal Stress Index, $K_D = (p_o - u_o) / \sigma'_{vo}$

Dilatometer Modulus, $E_D = 34.7 (p_1 - p_o)$

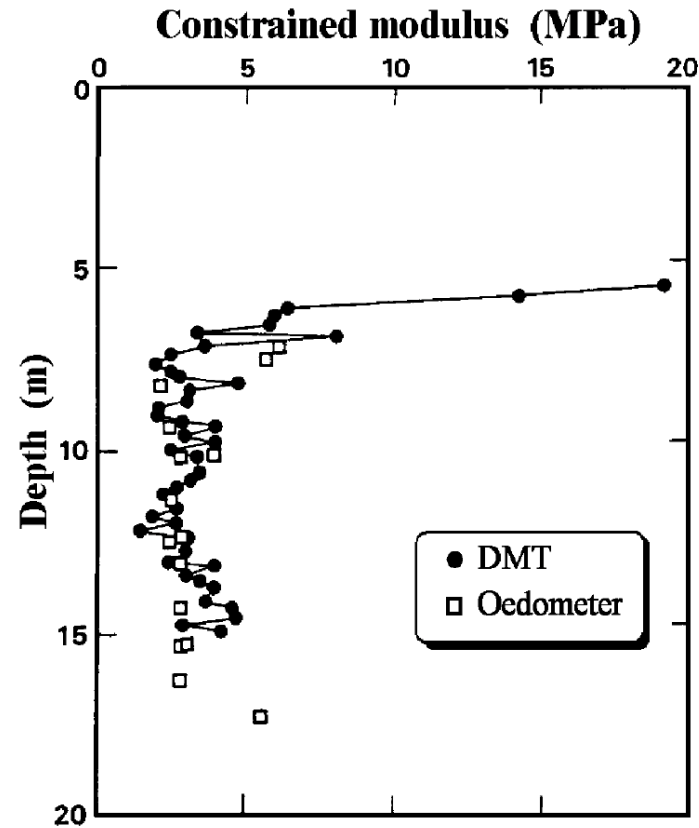
Note: $E_D = 34.7 I_D K_D \sigma'_{vo}$



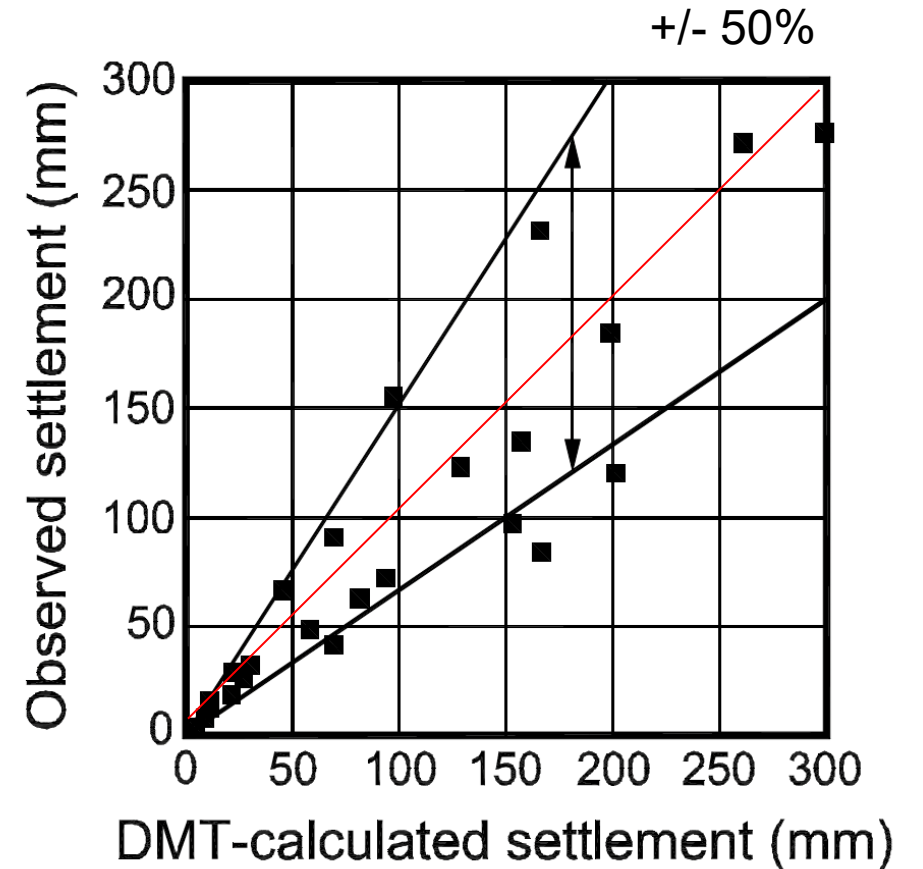
Flat-Plate Dilatometer Test (DMT)



Norway Lacasse, 1986



Japan, Iwasaki et al, 1991



Hayes, 1990

Flat-Plate Dilatometer Test (DMT)

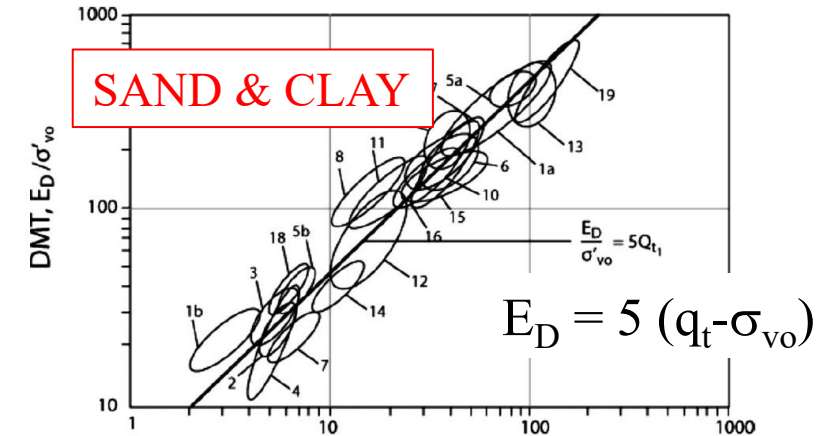
CPT-DMT

- Empirical correlation for 1D M (Marchetti, 1980)

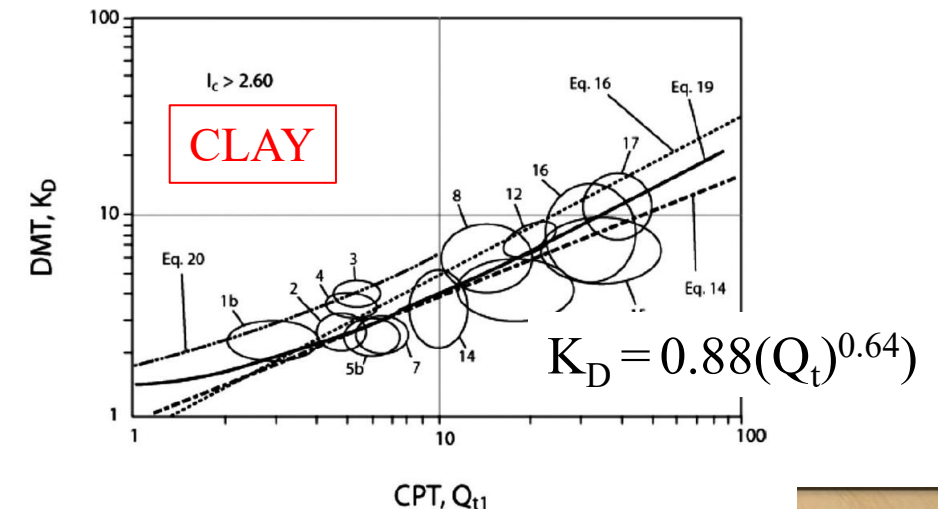
SAND: $M = E_D (0.5 + 2 \log K_D)$

CLAY: $M = E_D (0.14 + 2.36 \log K_D)$

- Empirical correlation links M to E_D with K_D as a multiplier (K_D is a measure of in-situ state)
- Robertson (2009) showed strong link between DMT and CPT (i.e., can predict K_D and E_D from CPT)



Robertson, 2009



CPT - DMT

DMT-CPT Correlations (Robertson 2009) plus Marchetti (1980)

SAND: $E_D \sim 5 (q_t - \sigma_{vo})$ and $K_D \sim Q_{tn,cs}/25$ (Robertson, 2009)

$M = E_D (0.5 + 2 \log K_D)$ (Marchetti, 1980)

Hence, $M = 5 [0.5 + 2 \log(0.04Q_{tn,cs})] (q_t - \sigma_{vo}) = \alpha_m (q_t - \sigma_{vo})$

$$\alpha_m = 5 [0.5 + 2 \log(0.04Q_{tn,cs})] \quad \alpha_m = 5 +/-$$

CLAY: $E_D = 5 (q_t - \sigma_{vo})$ and $K_D = 0.88(Q_t)^{0.64}$ (Robertson, 2009)

$M = E_D (0.14 + 2.26 \log K_D)$ (Marchetti, 1980)

Hence, $M = 5[0.14 + 2.26 \log(0.88(Q_t)^{0.64})](q_t - \sigma_{vo}) = \alpha_m (q_t - \sigma_{vo})$

$$\alpha_m = 5[0.14 + 2.26 \log(0.88(Q_t)^{0.64})] \quad \alpha_m = 5 +/-$$

CPT - DMT

DMT-CPT Correlations (Robertson 2009) plus Marchetti (1980)

Summary:

SAND: $M = 5 [0.5 + 2 \log(0.04Q_{tn,cs})] (q_t - \sigma_{vo})$

where $2 < \alpha_M < 11$ (for $20 < Q_{tn,cs} < 200$)

CLAY: $M = 5[0.14 + 2.26 \log(0.88(Q_t)^{0.64})](q_t - \sigma_{vo})$

where $2 < \alpha_M < 8$ (for $2 < Q_t < 8$)

Consistent with Mayne lab. data

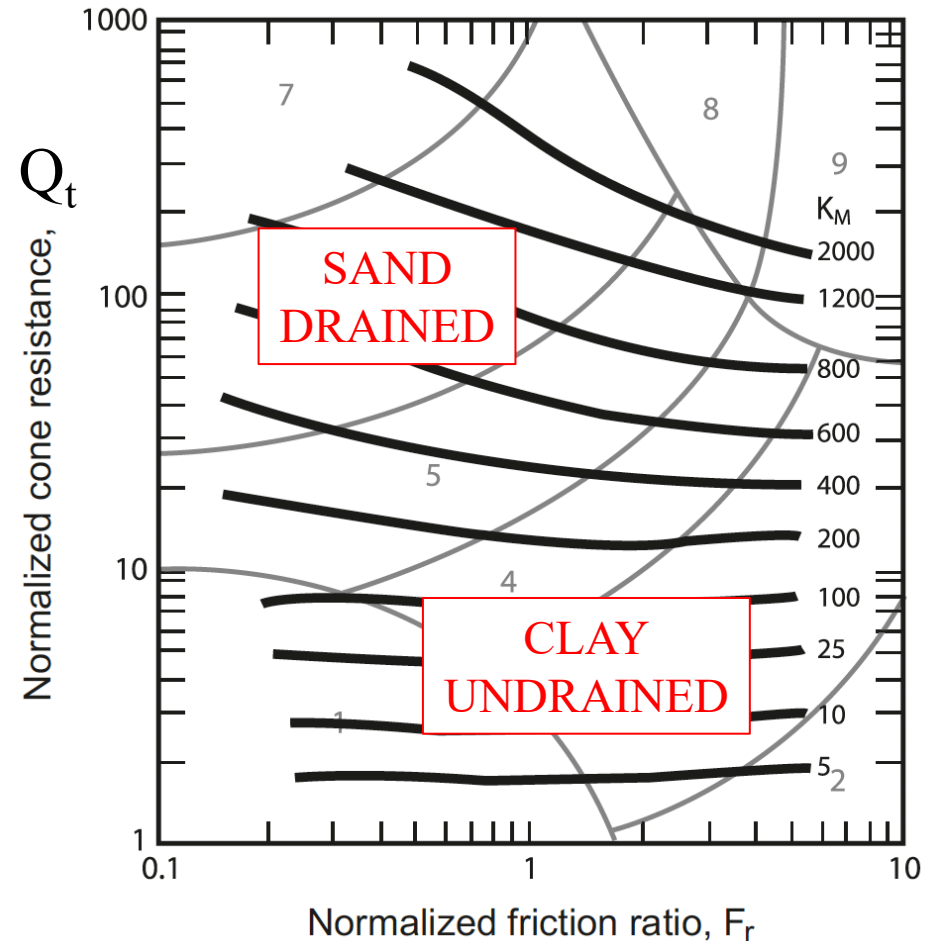
1D Constrained Modulus (M) from CPT

Robertson (2009) – Simplified Method

- Contours of K_M guided by CPT-DMT links, case history data and lab data
- Controlled by:
 - $Q_{tn,cs}$ in Sands
 - Q_t in Clays

$$Q_{tn,cs} = K_c Q_{tn} \text{ where } K_c = \text{fn}(I_c)$$

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

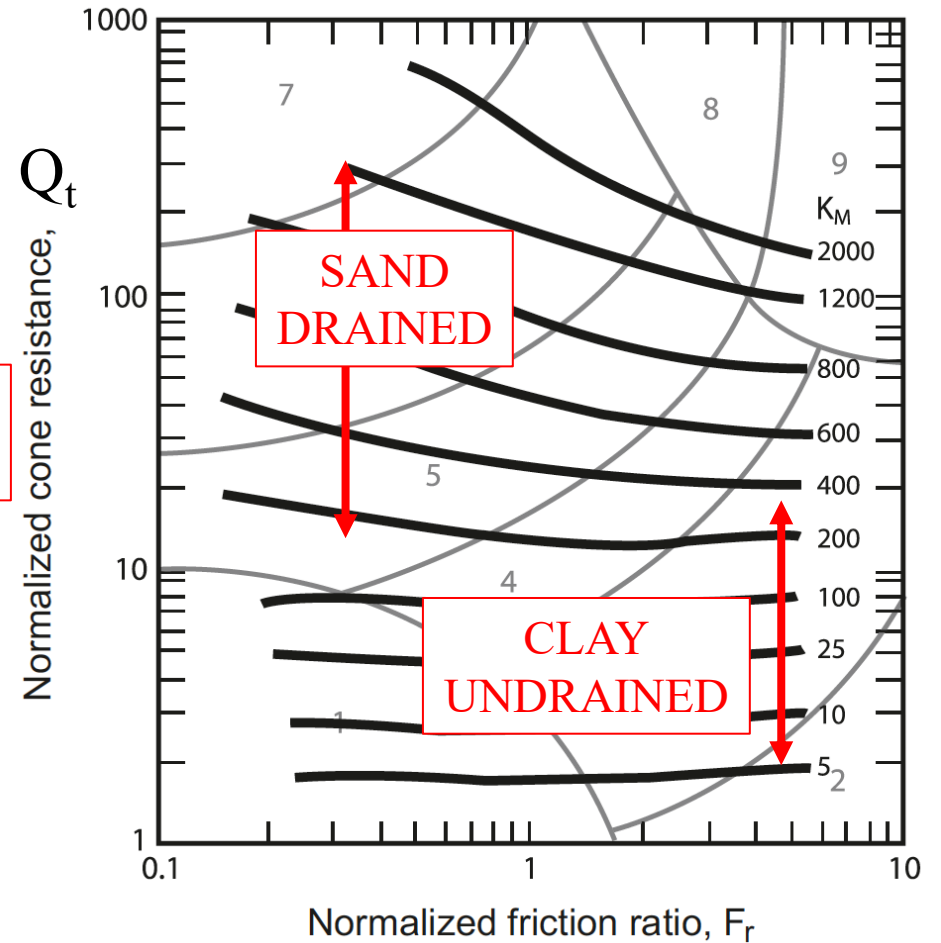


1D Constrained Modulus (M) from CPT

Soil Type	Modulus Number, K_M
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Dense Sand/Gravel	300 – 500+
Overconsolidated Clays	100 – 300+ (high)

Consistent with Janbu typical values

Janbu, 1963



1D Constrained Modulus (M) from CPT

Robertson & Cabal (2023)

For NC soils ($a = 1$)

$$M = K_m \sigma'_{vo} = \alpha_m (q_t - \sigma_{vo})$$

$$\alpha_m = K_M / Q_t$$

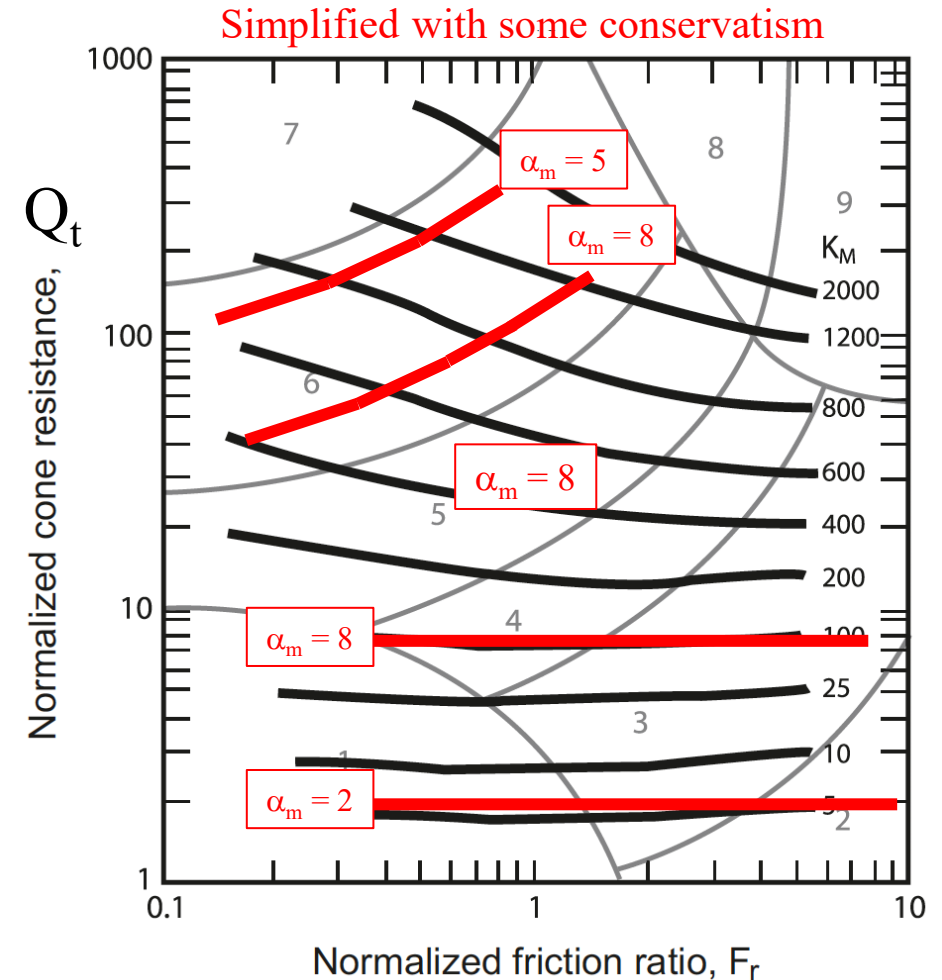
- When $I_c < 2.2$ (coarse-grained soils)

$$\alpha_m = 0.0188 [10^{(0.55I_c + 1.68)}] < 8$$

- When $I_c > 2.2$ (fine-grained soils)

$$\alpha_m = Q_t \quad \text{when } Q_t < 8$$

$$\alpha_m = 8 \quad \text{when } Q_t > 8$$



1D Constrained Modulus (M) from CPT

Robertson & Cabal (2023)

$$M = \alpha_m q_{(net)}$$

When $I_c < 2.2$ (SAND)

$$\alpha_m = 0.0188[10^{(0.55I_c + 1.68)}] < 8$$

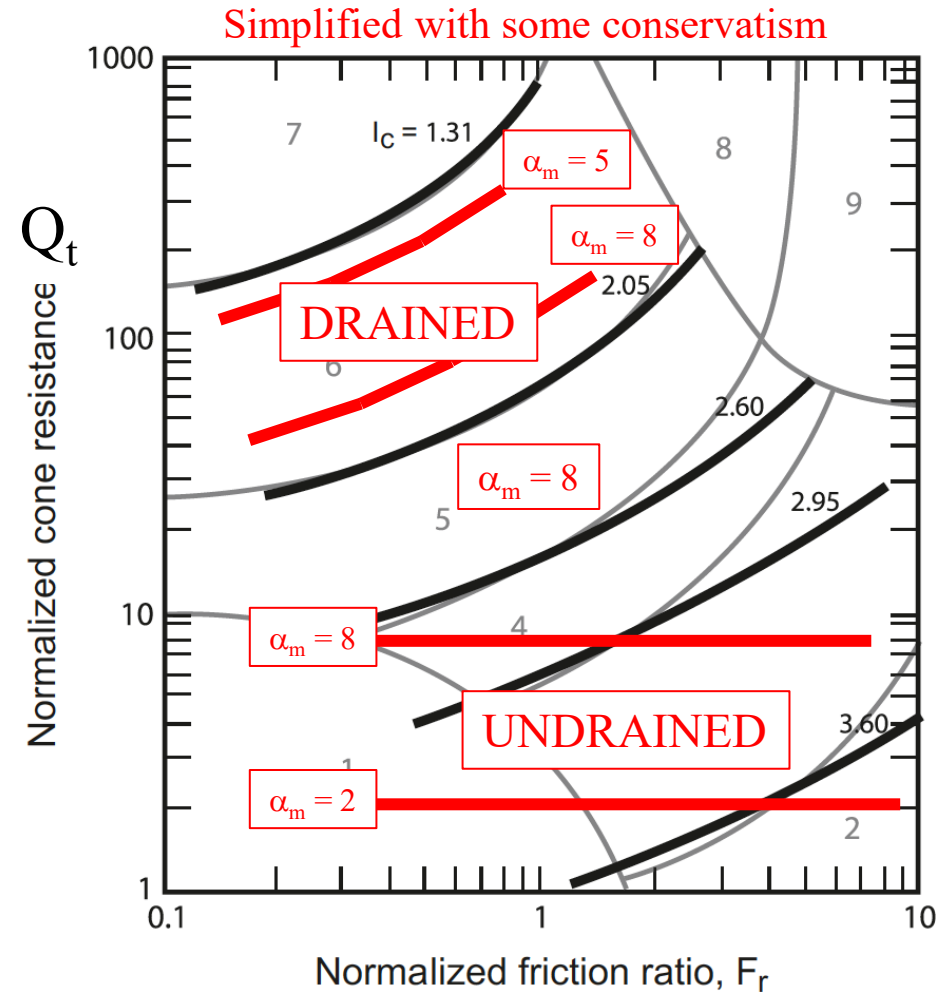
$$2 < \alpha_m < 8$$

When $I_c > 2.2$ (CLAY)

$$\alpha_m = Q_t \quad \text{when } Q_t < 8$$

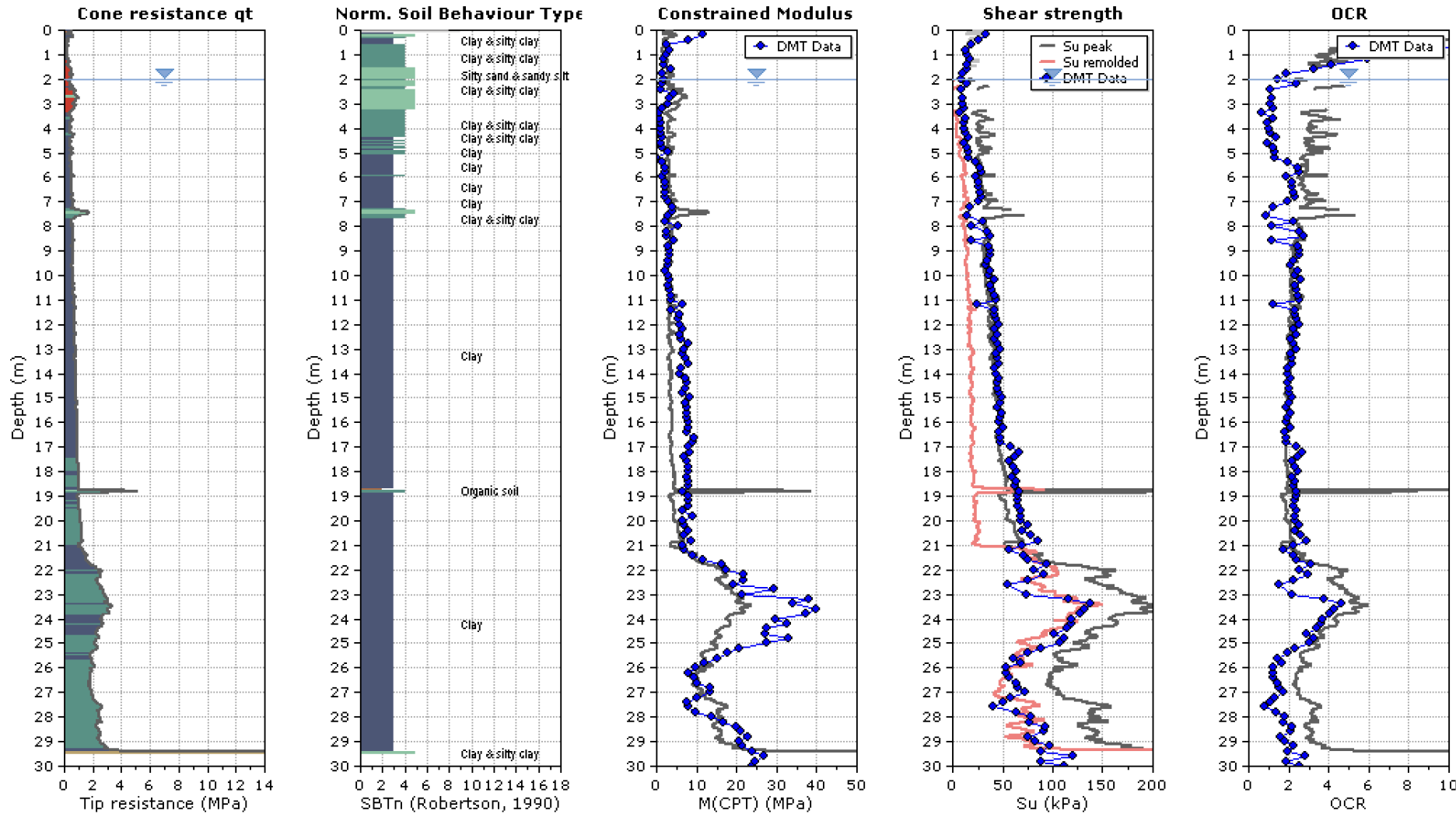
$$\alpha_m = 8 \quad \text{when } Q_t > 8$$

$$1 < \alpha_m < 8$$



CPT-DMT Comparison

Brisbane Airport



CPeT-IT

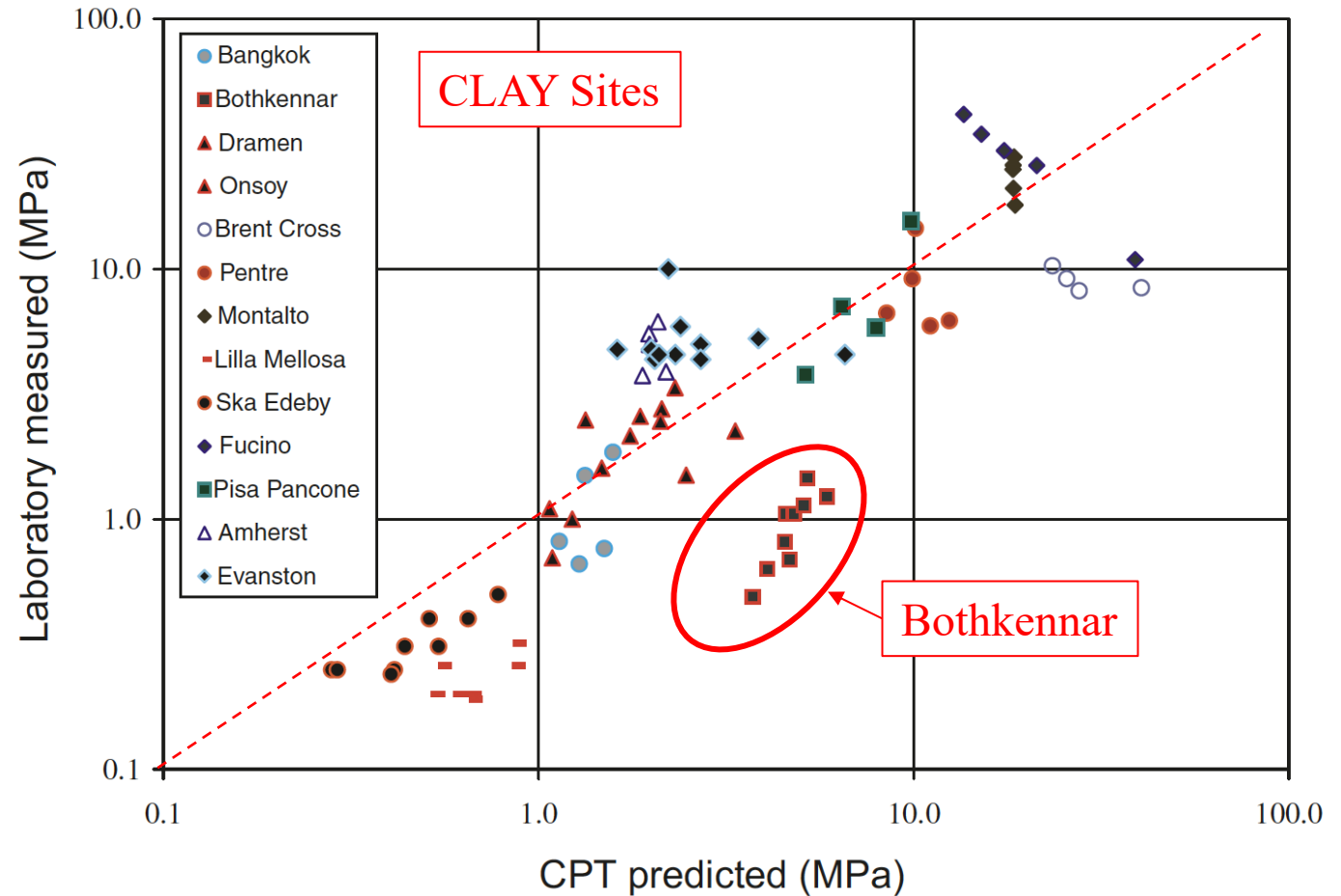
Laboratory comparison

Laboratory data from clay sites
(courtesy P. Mayne, 2008)

$$Q_t < 8$$

$$\alpha_m \sim Q_t$$

Sample disturbance considered to be
an issue for structured clay
(Bothkennar)



Young's Moduli of SAND (E') – Alternate Approach

$$E' = 2G(1+\nu)$$

for $\nu = 0.2$

$$E' = 2.4G$$

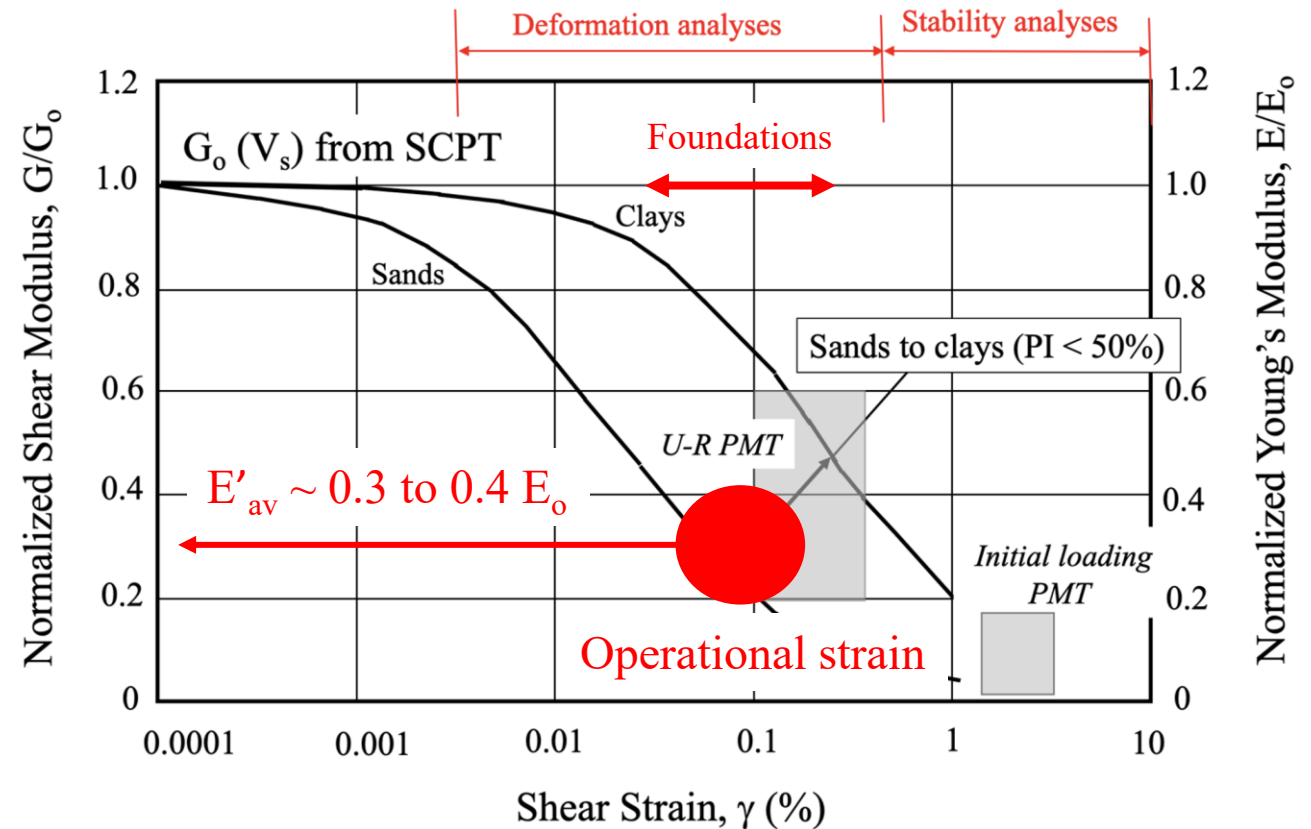
G_0 at very small strains $< 10^{-4} \%$

$$G_0 = \rho (V_s)^2$$

At strains of $\sim 10^{-1} \%$,

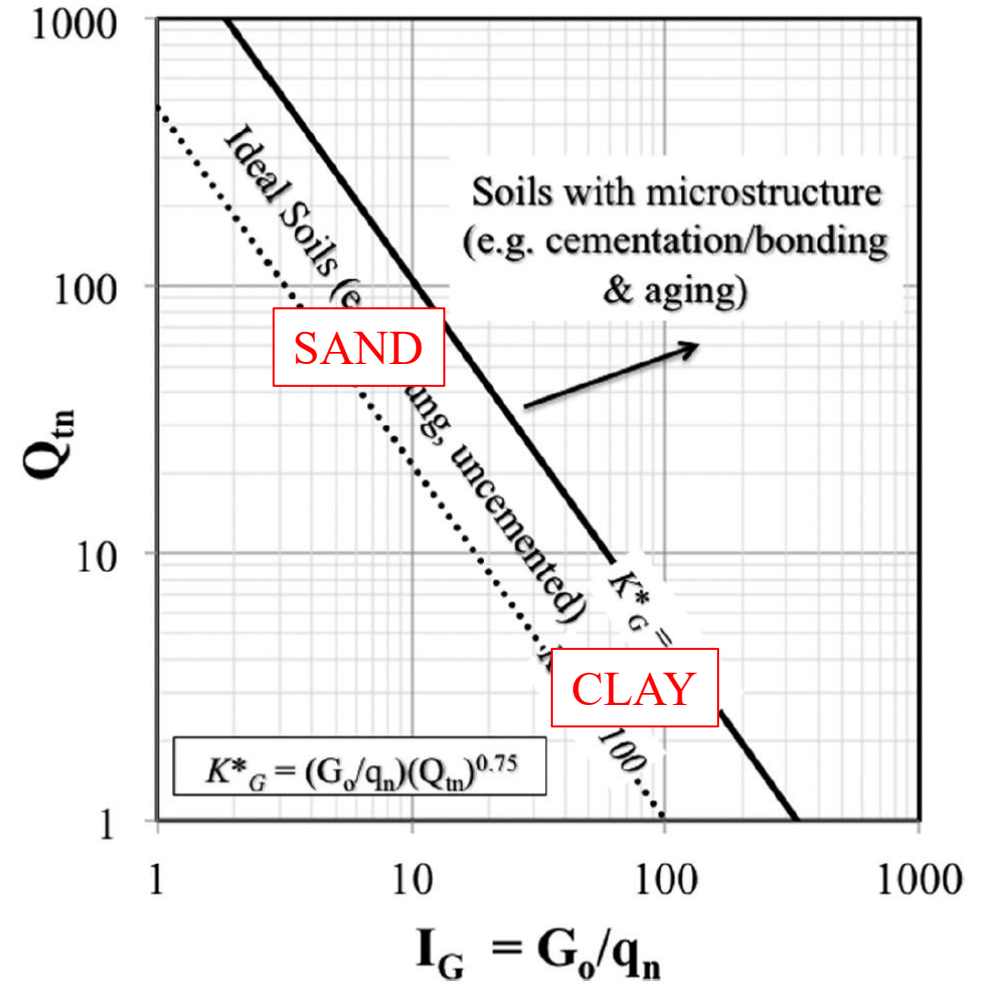
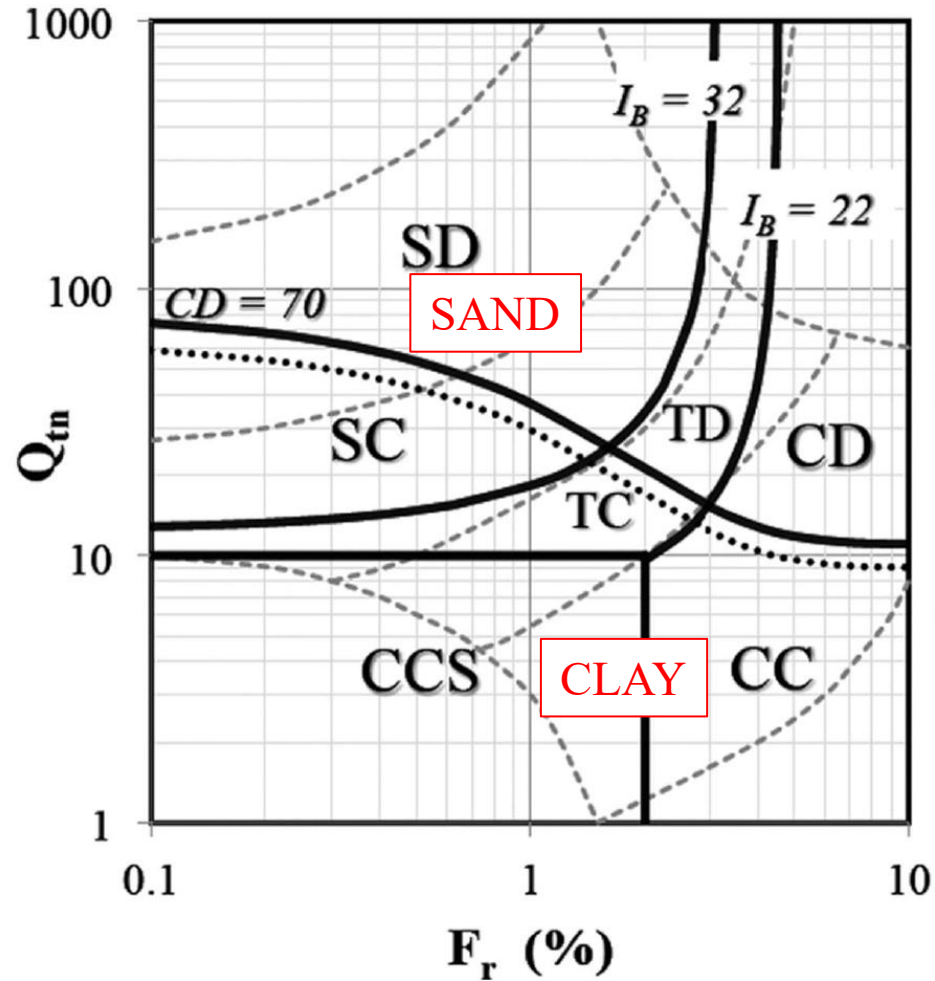
$$E'_{av} \sim 2.4G_0 (0.3 \text{ to } 0.4)$$

Hence, $E'_{av} \sim G_0$



CPT Soil Behavior Type (SBT)

Robertson, 2016



Elastic Moduli of SAND

$$E'_{av} \sim G_o$$

CPT correlations: $E'_{av} = \alpha_E (q_t - \sigma_{vo}) = \alpha_E q_n$

$$\alpha_E = E'_{av}/q_n = (G_o/q_n)$$

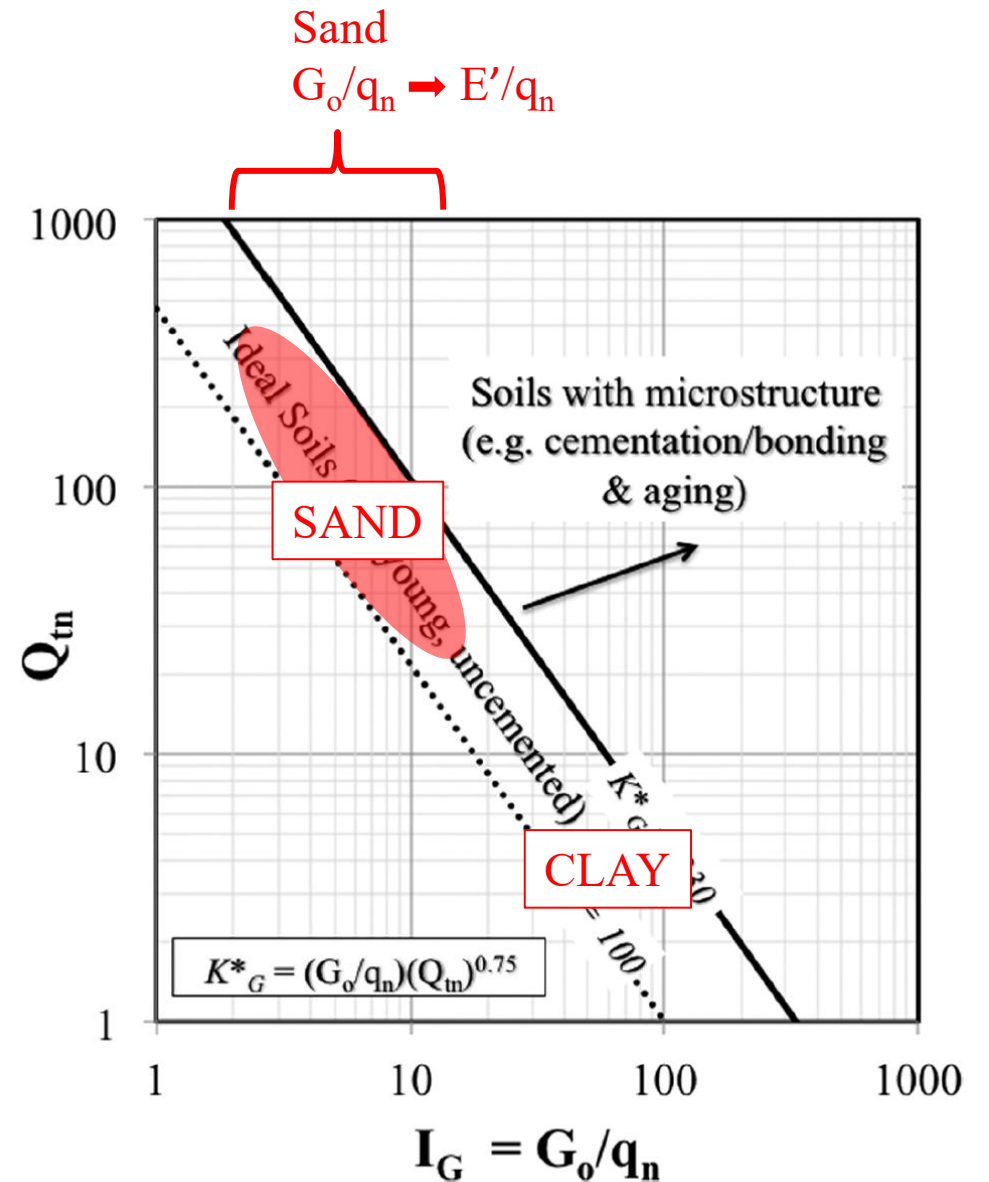
For sands with little/no microstructure
(young, uncemented):

$$1.5 < \alpha_E < 10$$

Microstructure increases stiffness

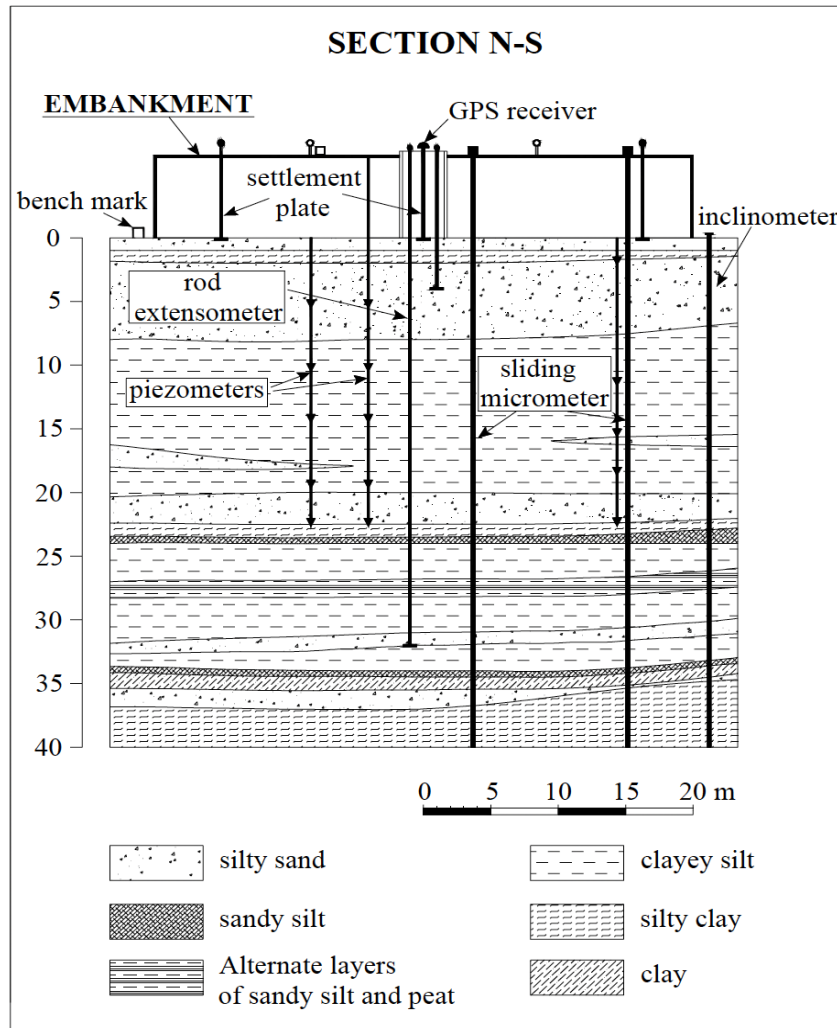
Measure V_s to get G_o

Improved estimate of E'



Case History - Venice

(Simonini et al, 2004)



Test Site Treporti, Venice, Italy

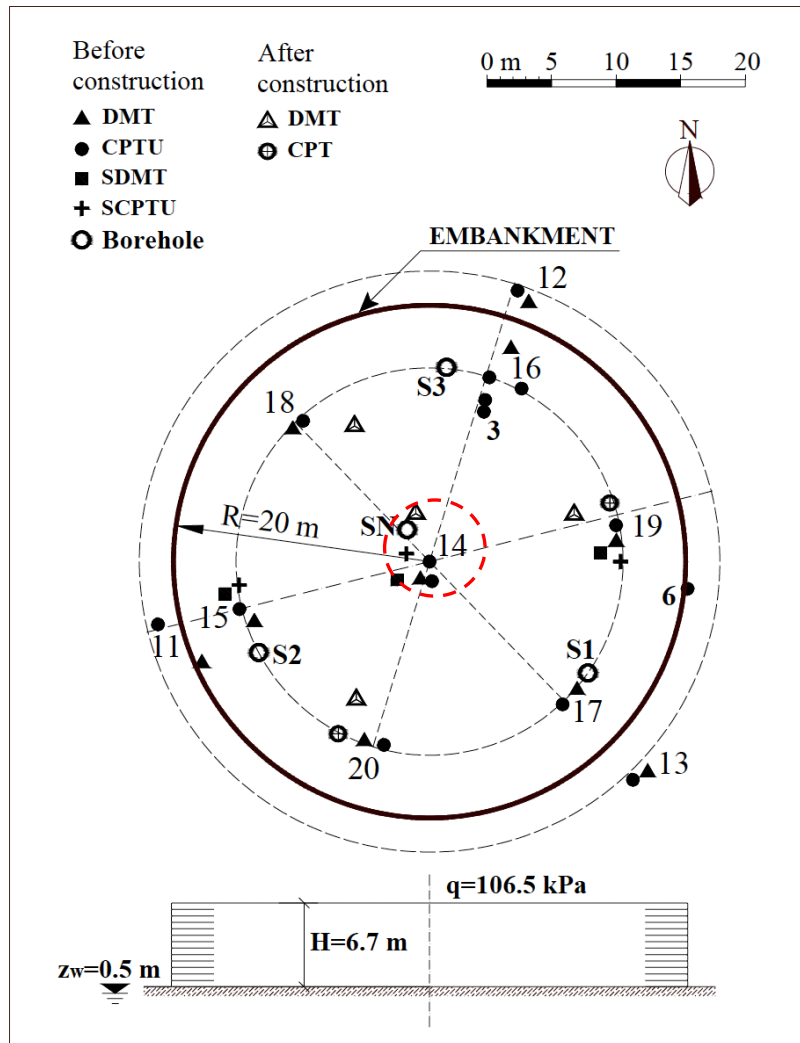
40m diameter, 6.7m high tank

Applied stress = 106.5 kPa

Variable alluvial soils

Case History - Venice

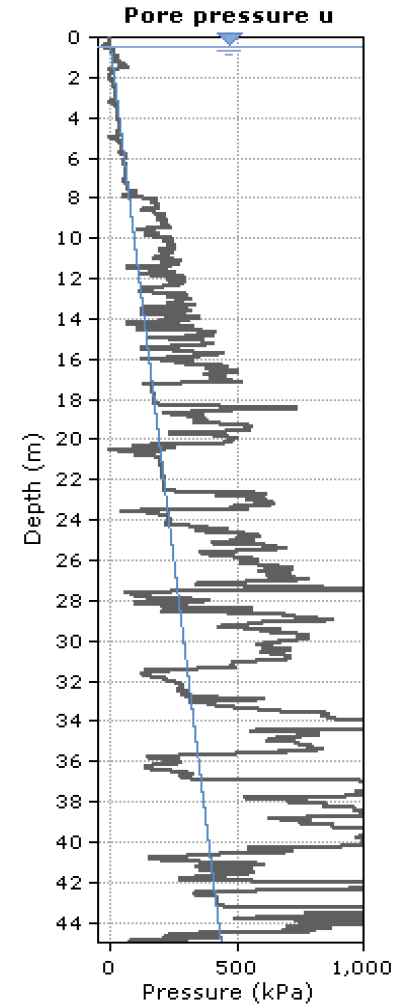
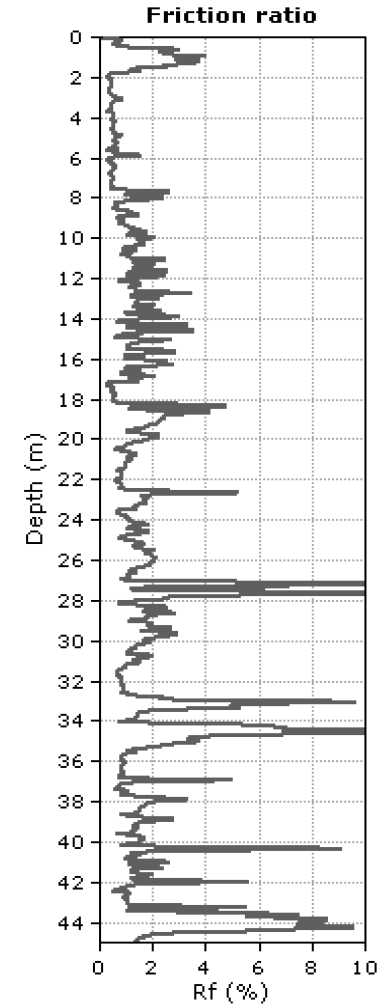
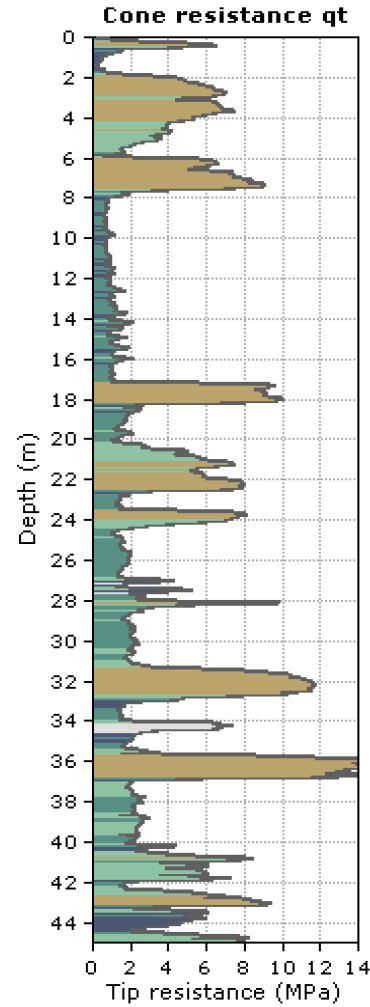
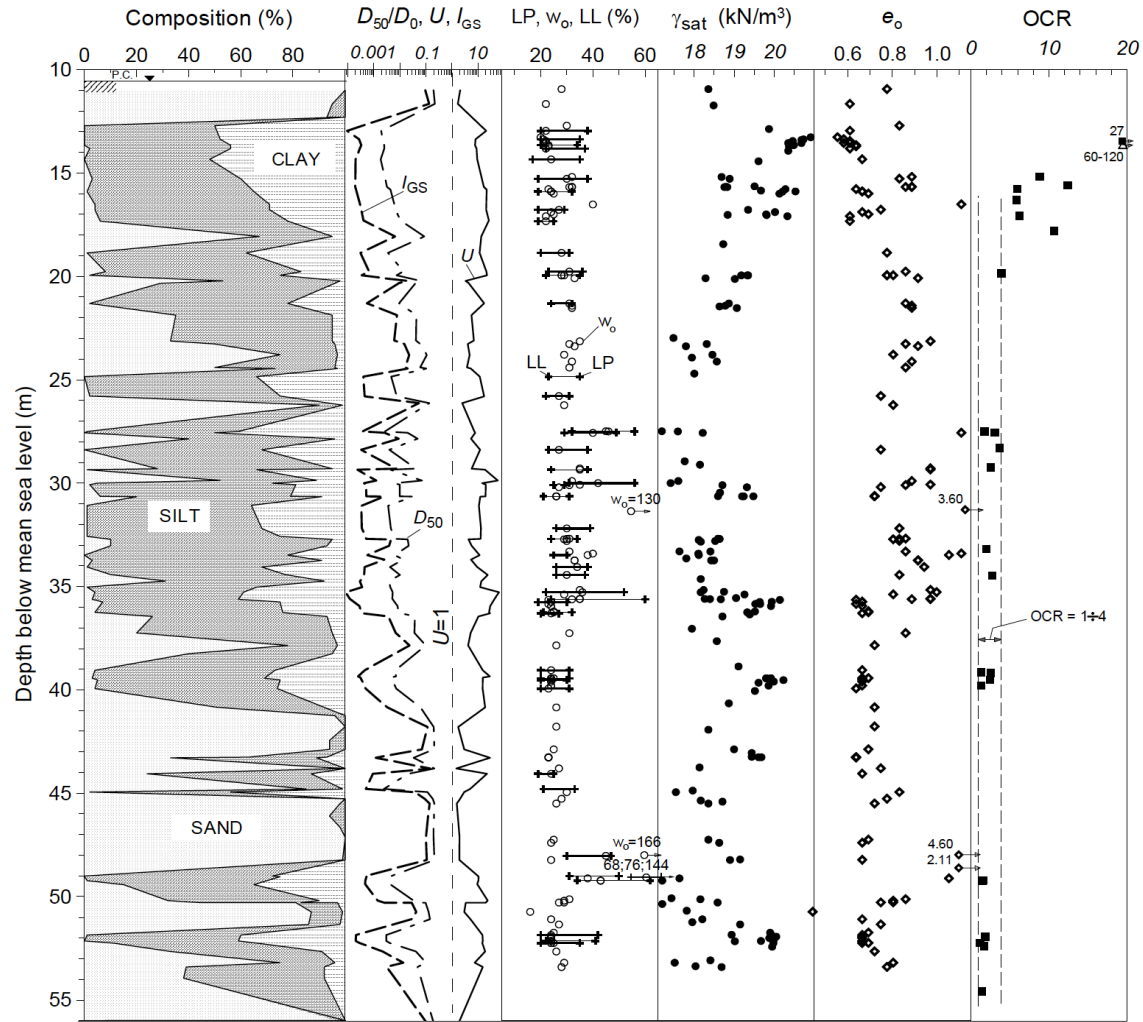
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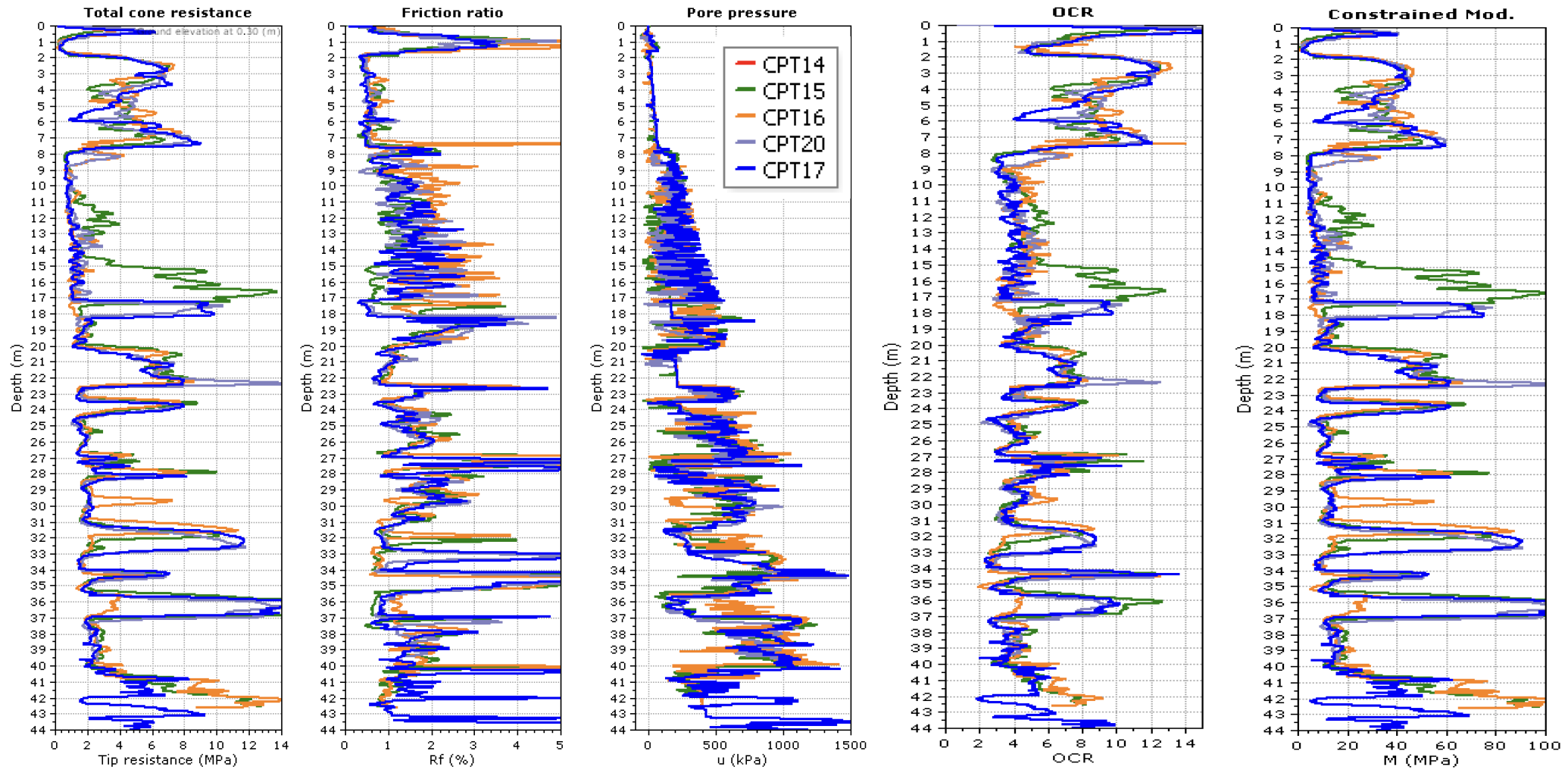
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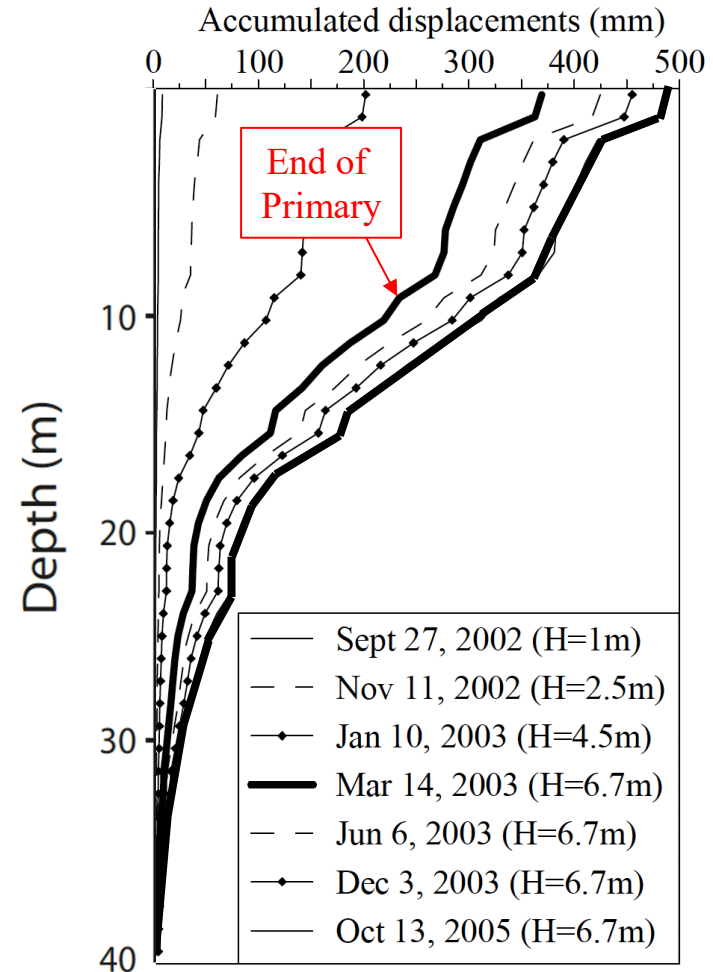
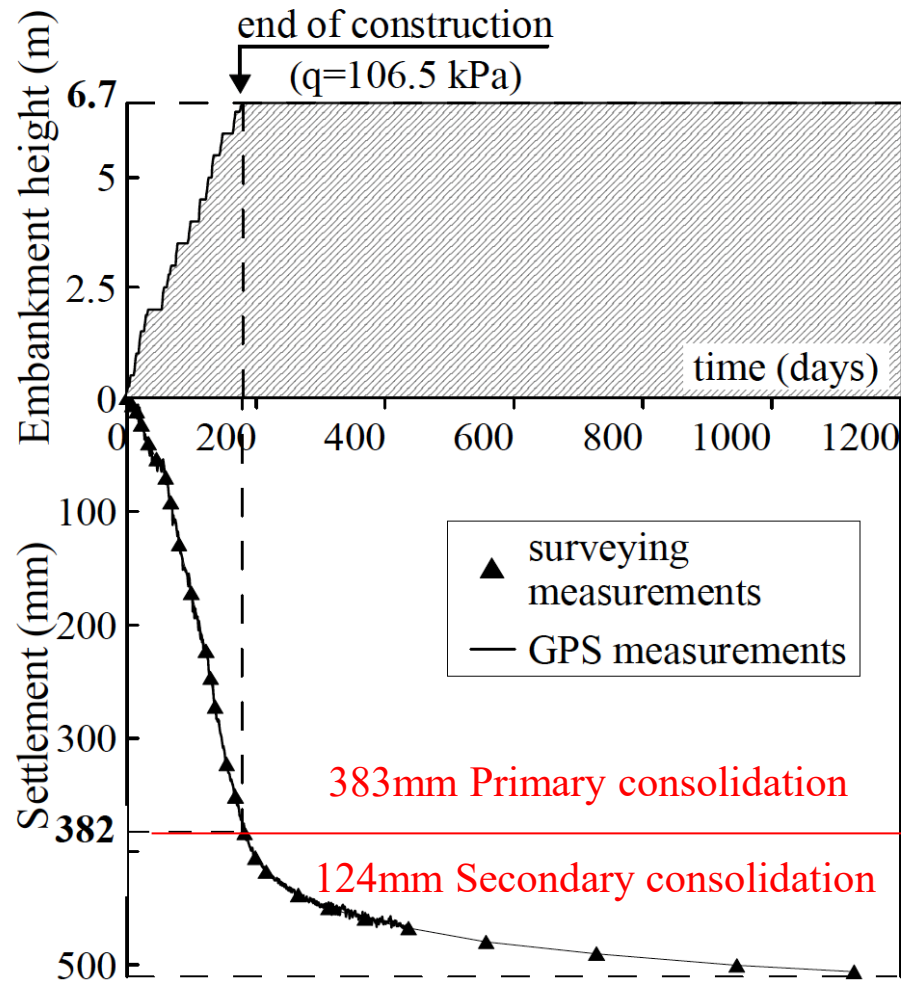
CPT-14



Case History - Venice

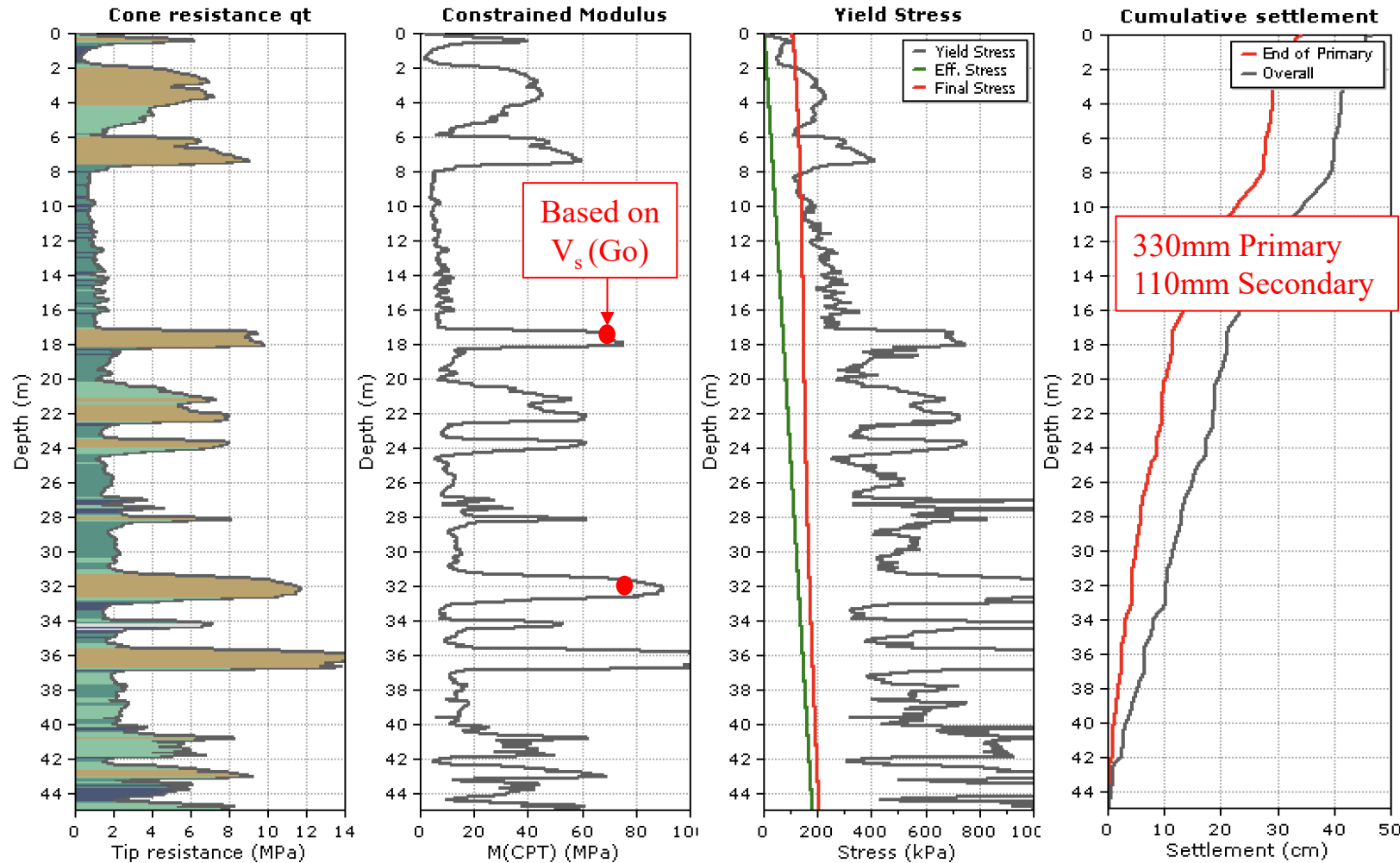


Case History - Venice



Case History - Venice

CPeT-IT Software



Calculation properties

Footing type: Circular
 Footing diameter: 40.00 (m)
 L/B: 1.0
 Footing pressure: 106.50 (kPa)
 Embedment depth: 0.01 (m)
 Footing is rigid: No
 Remove excavation load: No
 Apply 20% rule: No
 Calculate secondary settlements: Yes
 Time period for primary consolidation: 1 months
 Time period for second. settlements: 33 months

* Primary settlement calculation is performed according to the following formula:

$$S = \sum \frac{\Delta \sigma_v}{M_{CPT}} \Delta z$$

* Secondary (creep) settlement calculation is performed according to the following formula:

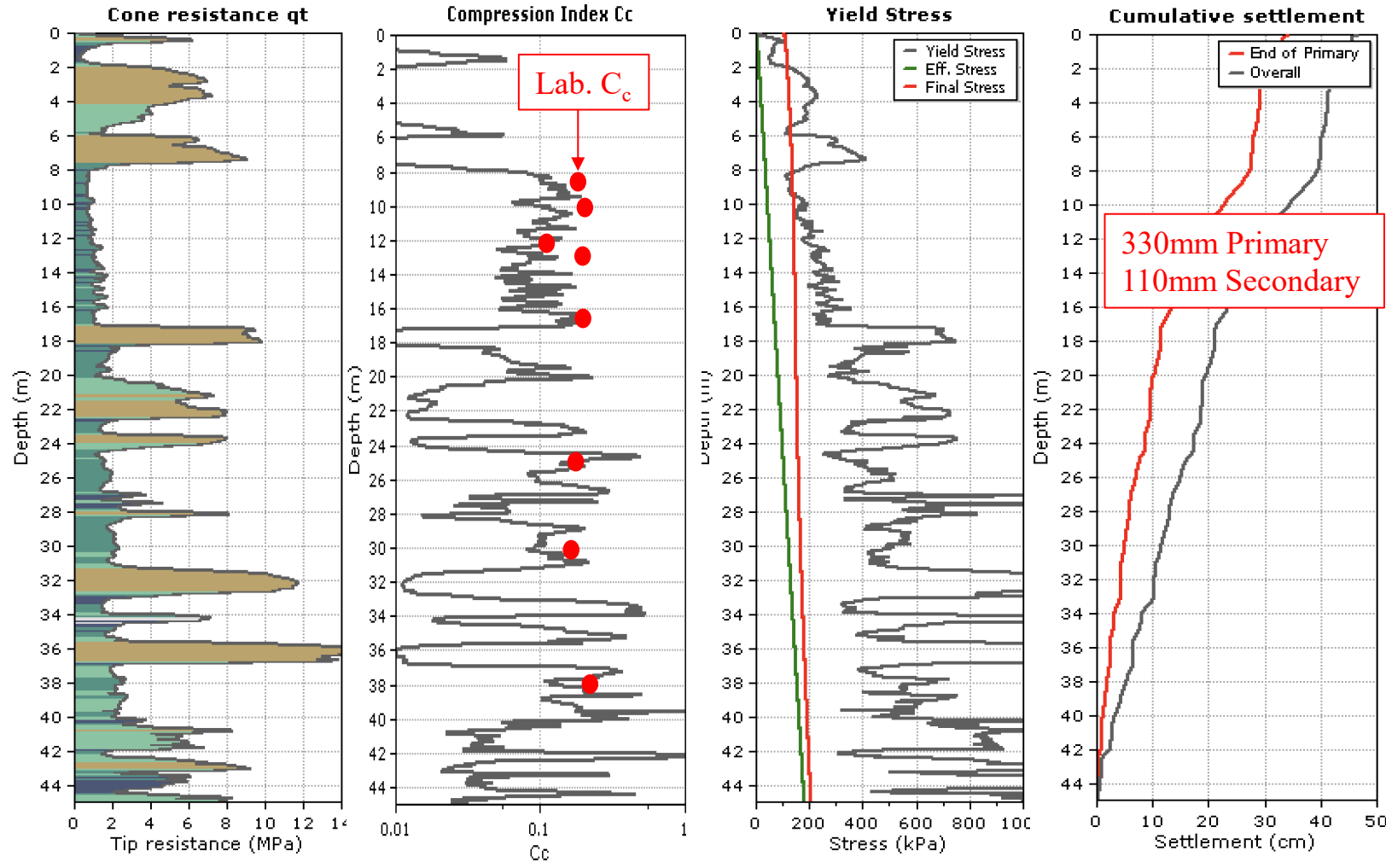
$$S = C_\alpha \cdot \Delta z \cdot \log(t/t_p)$$

where t_p is the duration of primary consolidation

$$C_\alpha = 0.04 \left(\frac{C_c}{1+e_0} \right) \sim 0.1 (\sigma'_v/M)$$

Case History - Venice

CPeT-IT Software



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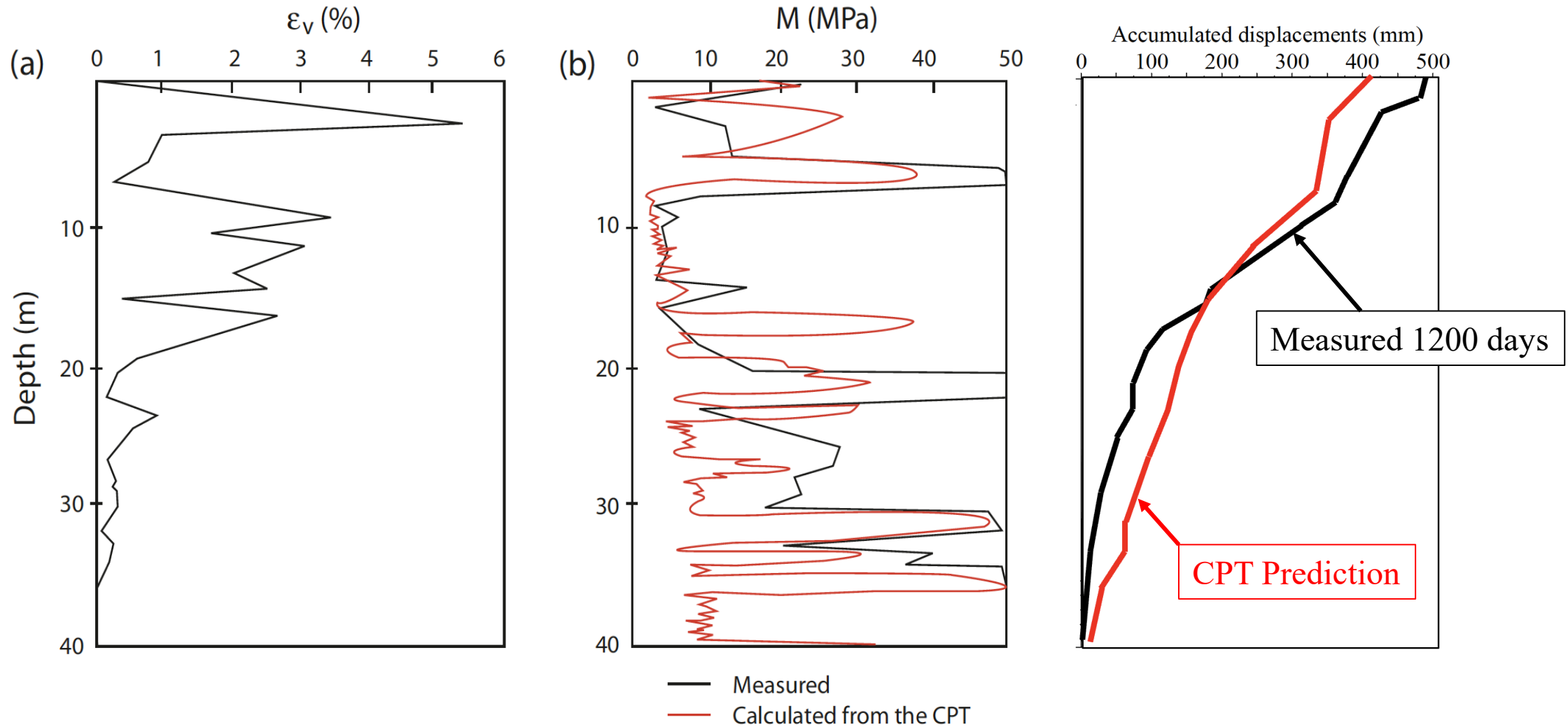
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$$S = C_\alpha \cdot \Delta z \cdot \log(t/t_p)$$

where t_p is the duration of primary consolidation

$$C_\alpha = 0.04 \left(\frac{C_c}{1 + e_o} \right) \sim 0.1 (\sigma'_v / M)$$

Case History - Venice



Advantages and Limitations

Advantages of 1D Constrained Modulus (M)

- Simple to apply
- M can be estimated from CPT & DMT for all soils
- Method accounts for soil type and in-situ state
- Experience shows improved estimates of settlement

Limitations:

- Not all conditions are 1D (however, 1D often reasonable assumption)
- Simplified approach ignores benefit of increasing M with confining stress for NC soils (most soils have some stress history)
- Focused on immediate and consolidation settlements, S_i & S_c

Summary

- Significant improvement in estimating settlements from CPT (since 2009)
- Supported by well documented case histories
- Supported by links with DMT with additional case histories
- Microstructure can play a role:
 - Stiffer response in Sands
 - Higher apparent OCR in Clays
- Helpful to include Vs measurements with CPT to identify microstructure and improve interpretation and estimates of settlement (esp. in sands)

Questions?

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www.cpt-robertson.com