UNIVERSITÀ DI PISA
DIPARTIMENTO DI INGEGNERIA CIVILE E INDUSTRIALE
DICI

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SIGEA TOSCANA — Società Italiana di Geologia Ambientale
Ordine dei Geologi della Toscana
Politecnico di Torino
Università di Pavia
AGI Associazione Geotecnica Italiana
Regione Toscana
PAGANI Geotechnical Equipment
PerlAmbiente

WORKSHOP

Recenti Sviluppi nelle Indagini in Sito

Scuola di Ingegneria - Polo Etruria - Aula F6 - Pisa

14 giugno 2019

USE OF CPT IN PARTIALLY SATURATED SOILS

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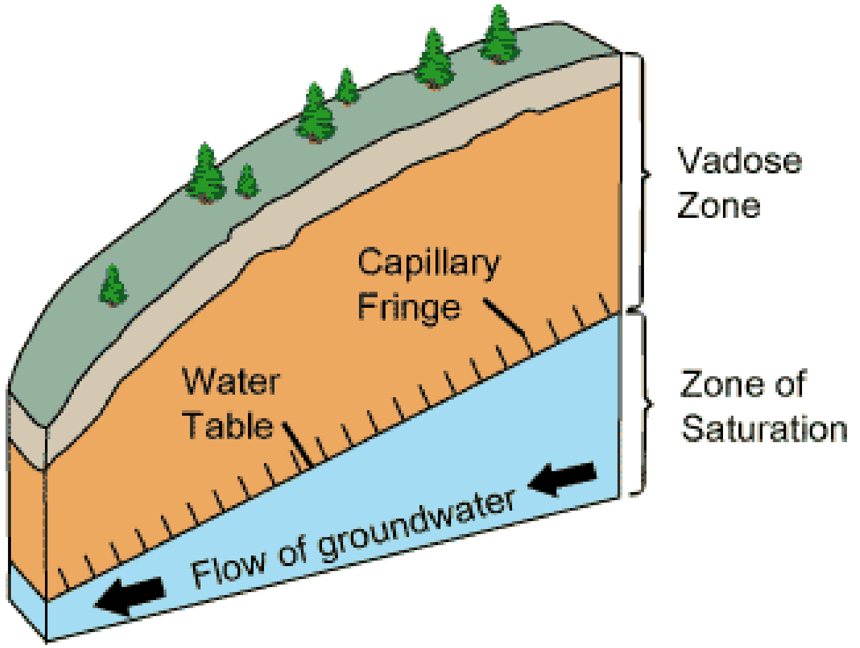
Soil strength in partially saturated soils



Soil Strength = f (*effective stress* σ')

Fully saturated soil – *Terzaghi's Theory (1936)*

$$\sigma' = \sigma - u_w$$

Partially saturated soil – *Bishop's Theory (1959)*

$$\sigma' = (\sigma - u_a) + \chi(u_a - u_w) \longrightarrow \boldsymbol{\psi} = (u_a - u_w) \text{ matric suction} \longrightarrow \boldsymbol{\psi} = \frac{\sigma' - \sigma + u_a}{\chi}$$

$\boldsymbol{\sigma}$ = total overburden (geostatic) stress

$\boldsymbol{\sigma'}$ = effective overburden (geostatic) stress

$\boldsymbol{u_a}$ = air pressure

$\boldsymbol{u_w}$ = water pressure

χ = effective stress parameter

$$\tau = c' + \sigma_n' \tan\phi'$$

$$\tau = c' + [(\sigma_n - u_a) + \chi(u_a - u_w)] \tan\phi'$$

Fredlund & Rahardjo (1993)

$$\tau = c' + (\sigma_n - u_a)\tan\phi' + (u_a - u_w)\tan\phi^b$$

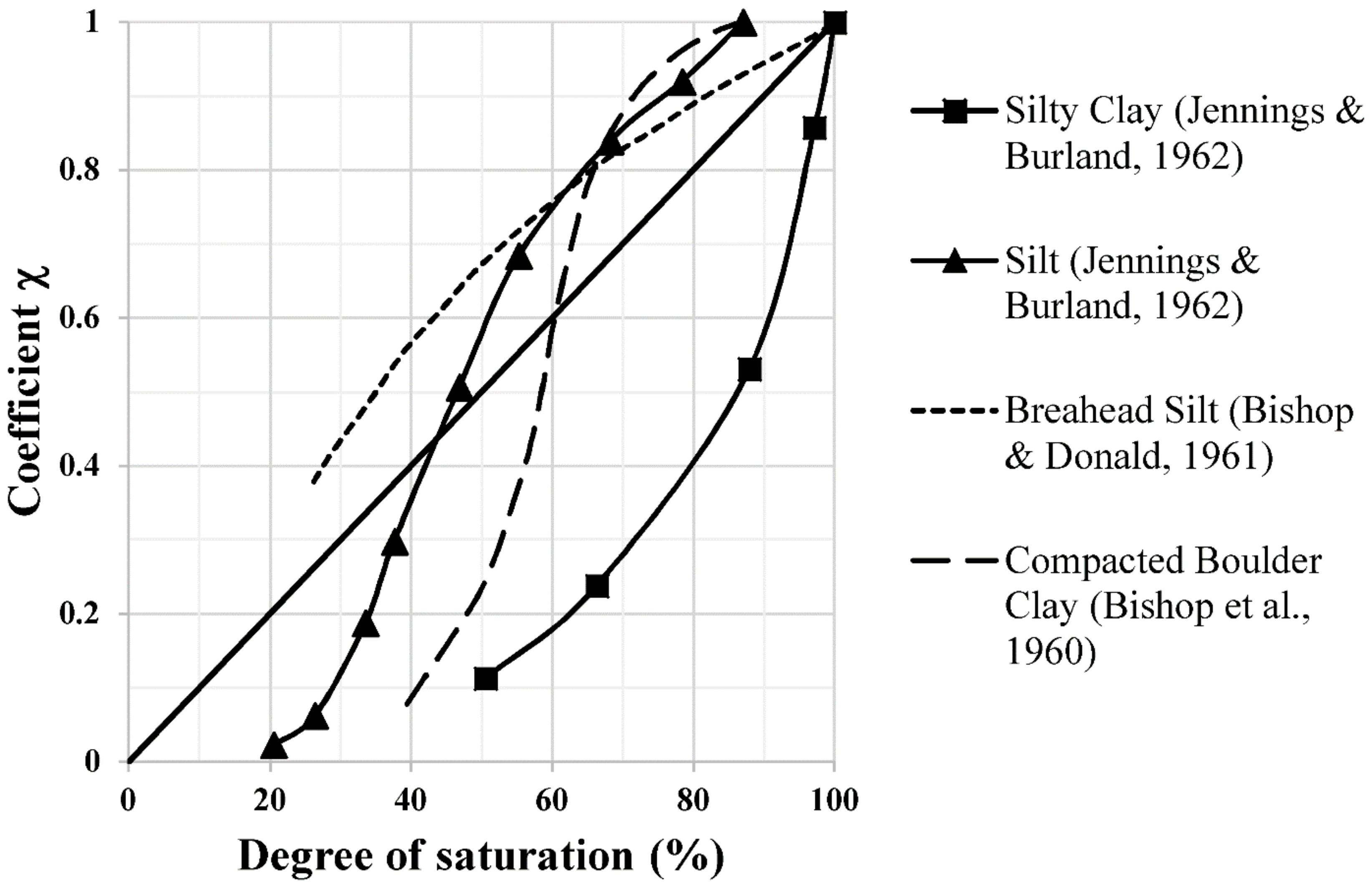
$$\tan\phi^b = \tan\phi' \left({\theta - \theta_r}/{\theta_s - \theta_r} \right)$$ *Vanapalli et al (1996)*

Effective stress parameter

χ = effective stress parameter

$$\boldsymbol{\psi} = \frac{\sigma' - \sigma + u_a}{\chi}$$

Are function of the soil type and the degree of saturation



Water Retention Curve (non cohesive soil)

S_r total degree of saturation

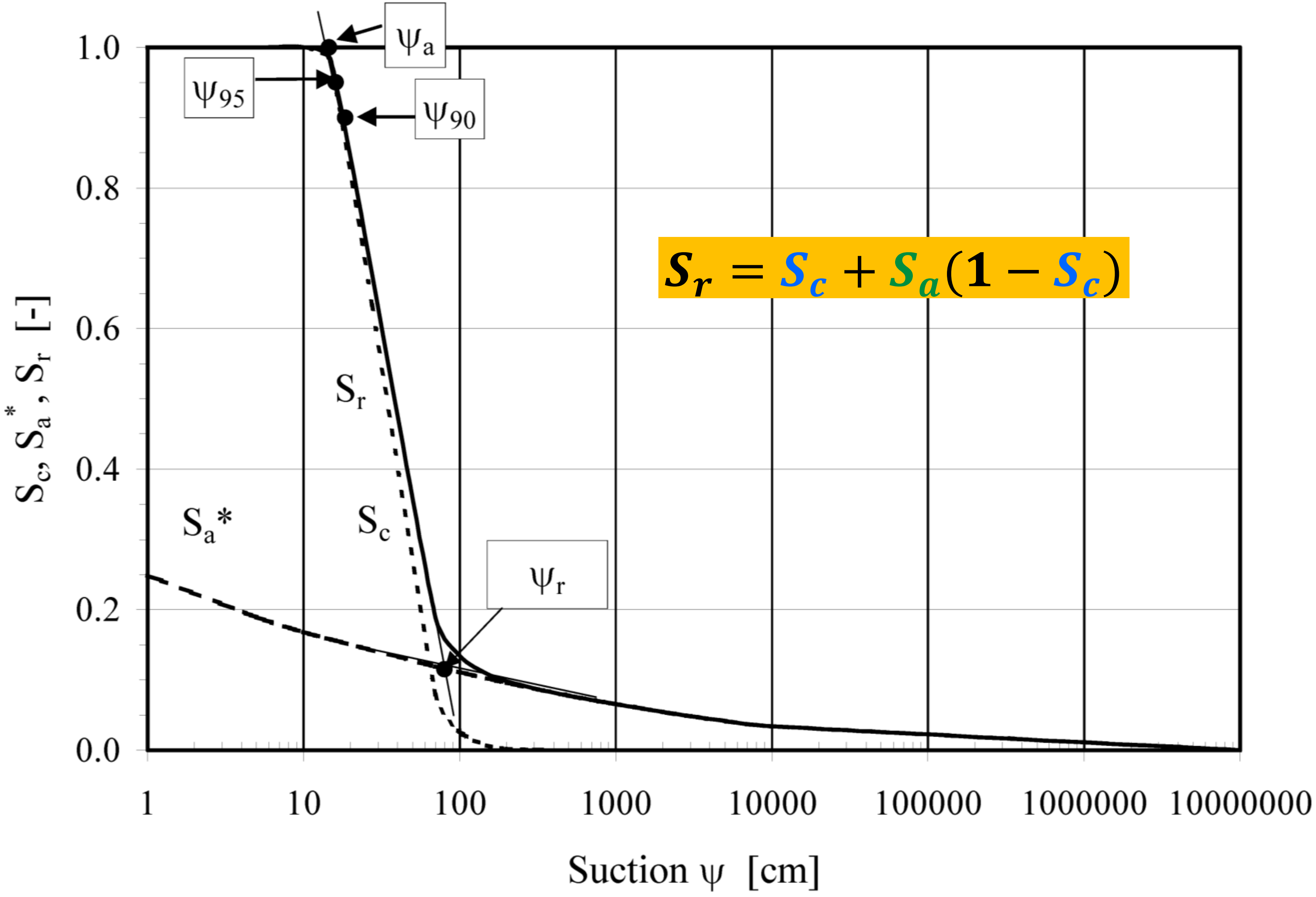
S_c capillary saturation contribution to total S_r

S_a adhesion saturation contribution to total S_r

ψ matric suction

ψ_a Suction corresponding to the air entry value (AEV)

ψ_r Suction corresponding to the residual water content (WEV - water entry value)



$$S_r = S_c + S_a(1 - S_c)$$

Modified Kovacs Model (MK model) - Aubertin et al (2003)

Water Retention Curve (cohesive soil)

S_r total degree of saturation

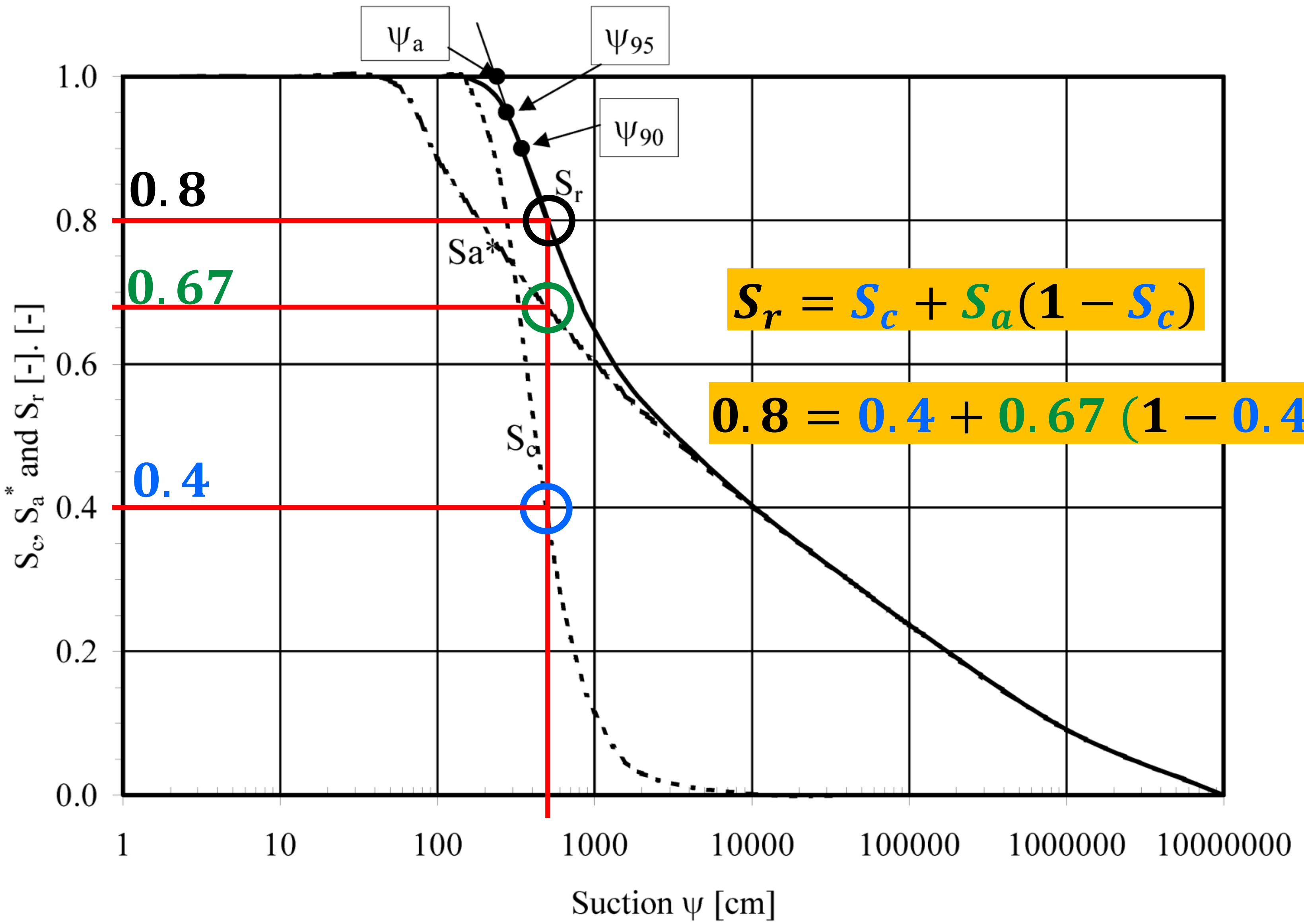
S_c capillary saturation contribution to total S_r

S_a adhesion saturation contribution to total S_r

ψ matric suction

ψ_a Suction corresponding to the air entry value (AEV)

ψ_r Suction corresponding to the residual water content (WEV - water entry value)



$$S_r = S_c + S_a(1 - S_c)$$

$$0.8 = 0.4 + 0.67\,(1 - 0.4)$$

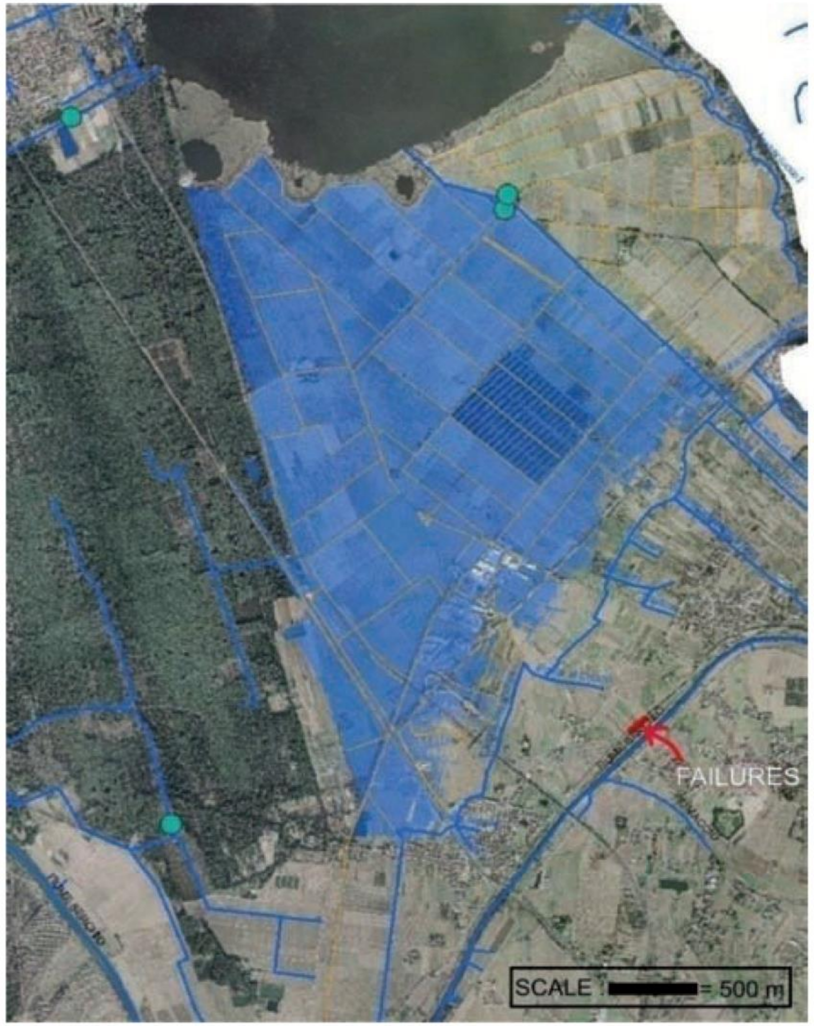
Modified Kovacs Model (MK model) - Aubertin et al (2003)

Why is useful to evaluate the soil effective stress state?

Shallow Landslides and Failure of levee systems

Cosanti et al (2014)

Nozzano - Santa Maria a Colle (LU)



Nodica – Migliarino (PI)

Fig. 1 – Failures and flooded areas in the District of Lucca (left) and in the District of Pisa (right).

District of Pisa: piping phenomenon through the embankment (landside over the river bank). From "La voce del Serchio".

Why is useful to evaluate the soil effective stress state?

Shallow Landslides and Failure of levee systems

<u>River embankments</u>

The **instability occurs after very prolonged rain periods** and following the repetition of flood events (1 week) even with **water levels less than the maximum** (Cosanti et al. 2014, Basin Authority of Serchio River 2010a,b).

Maximum discharge of the Serchio River for various past flood event.

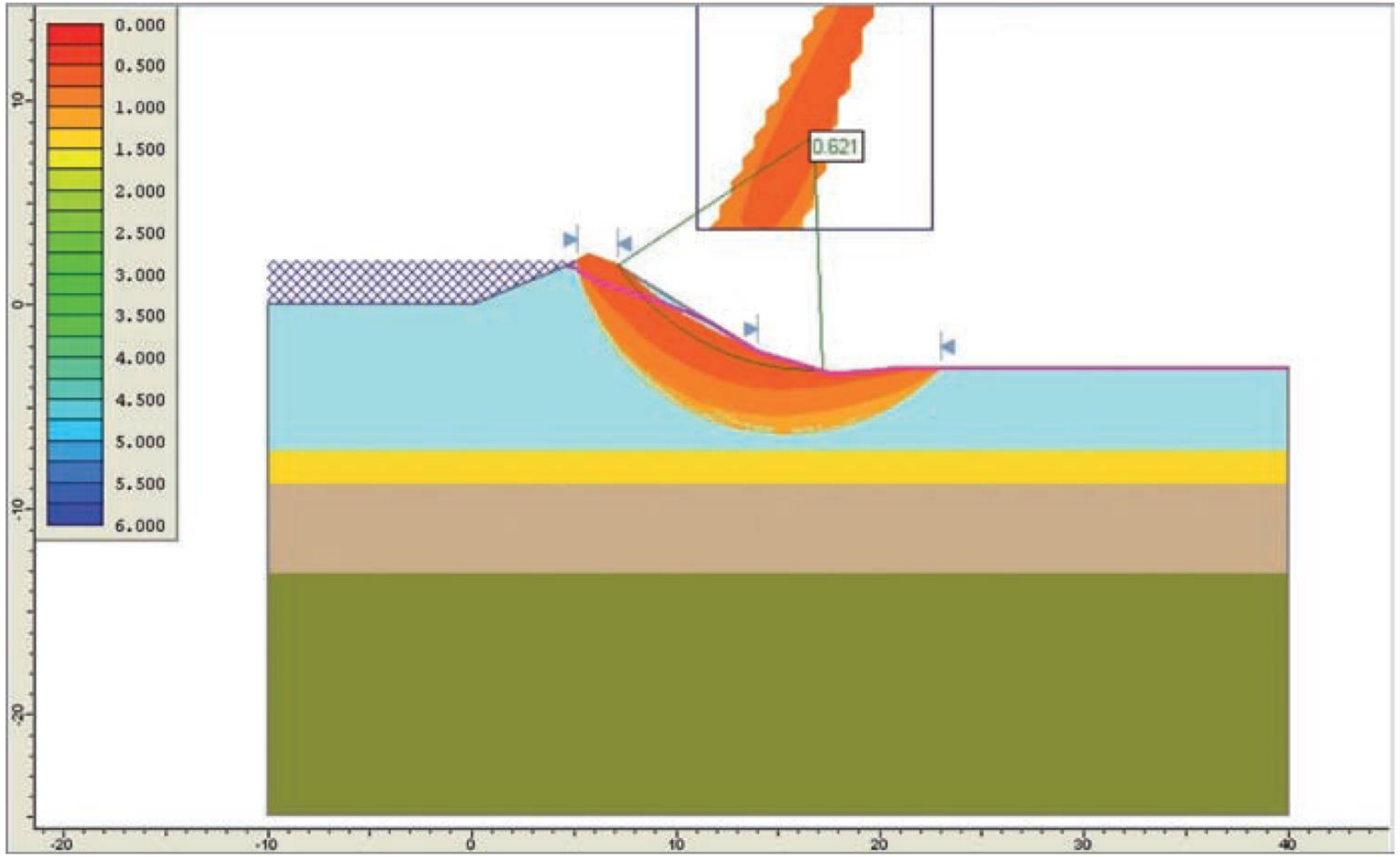
Flood - event	Maximum River Discharge m^3/s	Embankment failure
November 9th 1982	2000	NOT
November 1st 2000	1580	NOT
November 9th 2000	1580	YES (*)
December 5th 2008	1025	NOT
December 10th 2009	1200	NOT
December 25th 2009	1900	YES (*)

(*) Repeated floods in 10 – 15 days during 2000 and 2009 events produced embankment failures in the same areas.

Cosanti et al. et al (2014)

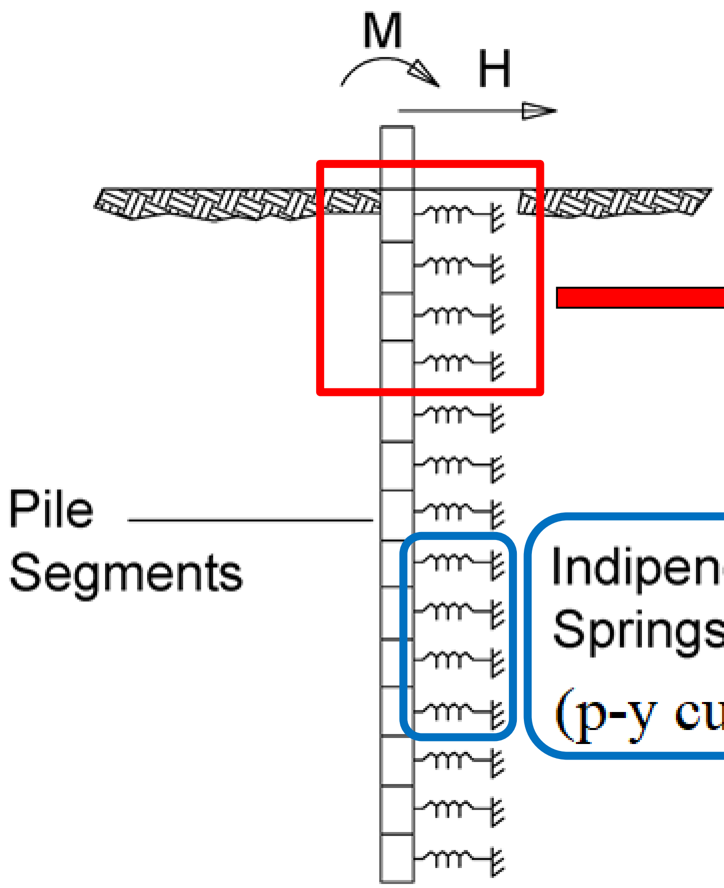
The **increase** of the **degree of saturation**
The **decrease** of soil **suction**

responsible for the instability phenomena of the bank



Why is useful to evaluate the soil effective stress state?

Laterally loaded piles

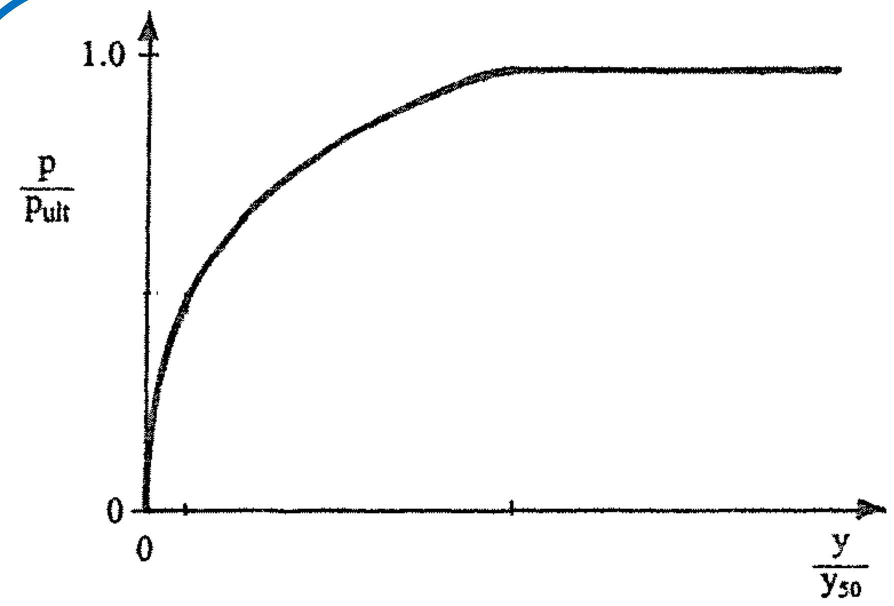


Lateral response is mostly influenced by the soil strength in the upper soil layers. (up to 5-10 Pile Diameters)

Indipendent Springs
(p-y curves)

Beam on Nonlinear Winkler Foundation

(*p-y* curves)



p_u (soil resistance)

How to evaluate soil suction and degree of saturation in-situ?

Estimate of Suction

- Tensiometers
- Dielectric sensors

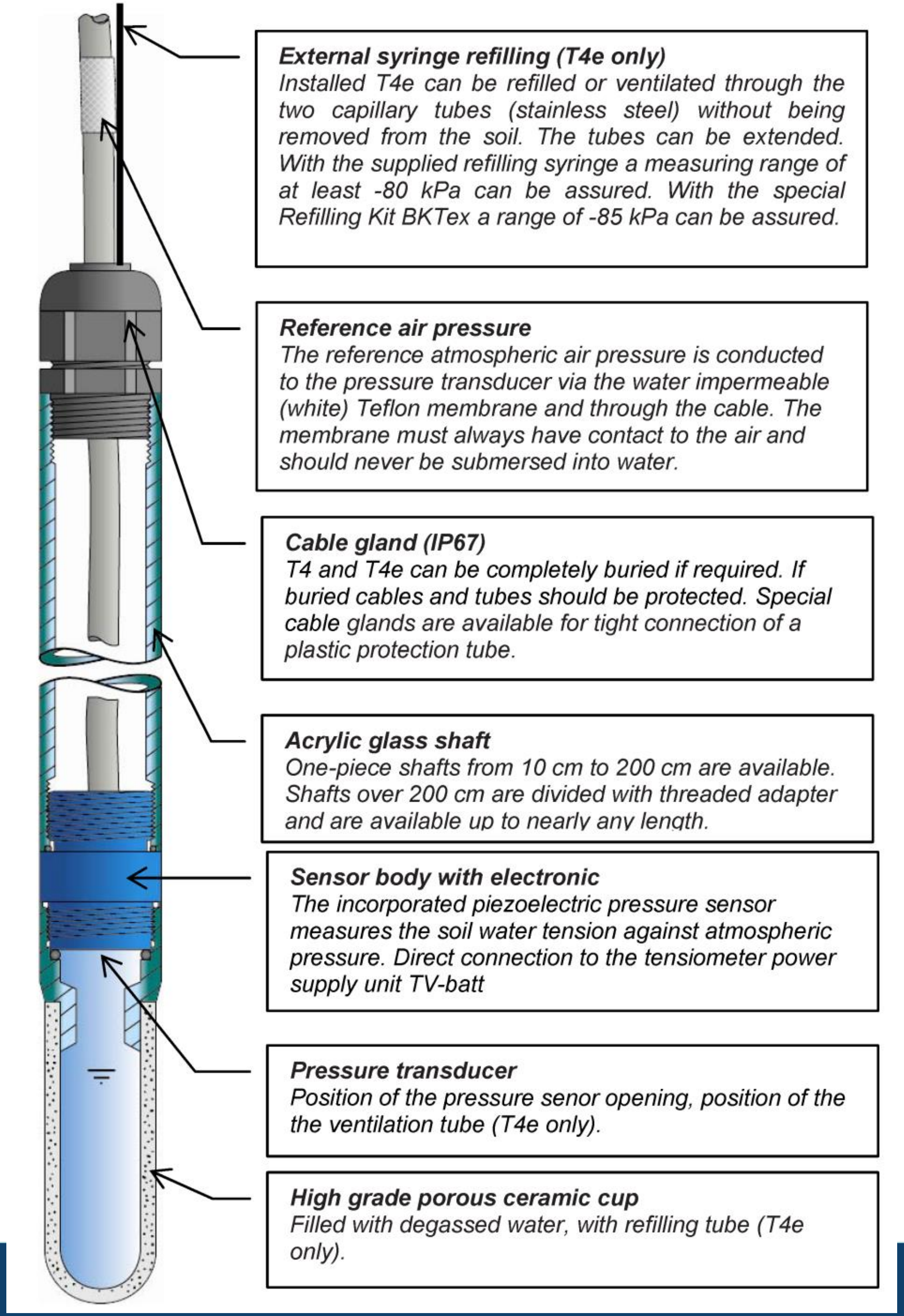
Estimate of volumetric water content and saturation degree

- Water content probes
- Geoelectric methods (electrical resistivity)
- Seismic methods (P-waves -> V_p)

How to evaluate soil suction and degree of saturation in-situ?

Tensiometers

Model T4e- UMS GmbH



A **tensiometer** is used to determine the **matric water potential**.

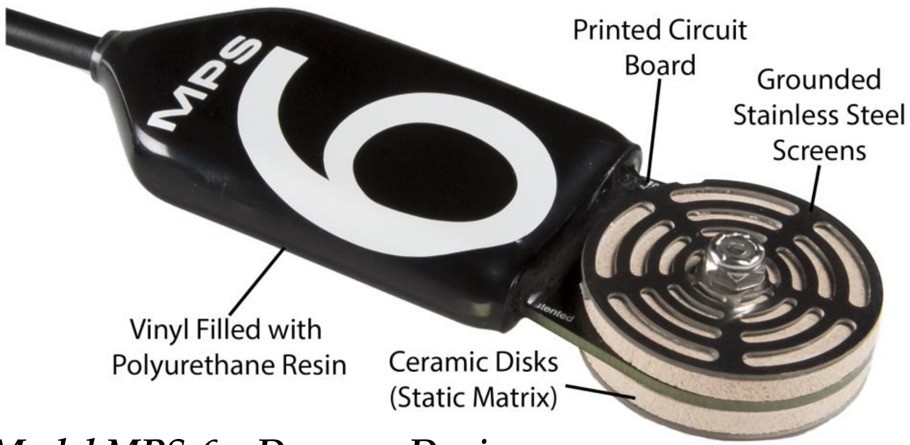
This device **consists of a glass or plastic tube with a porous ceramic cup and is filled with water**.

The tensiometer is buried in the soil, and a hand pump is used to pull a partial vacuum.

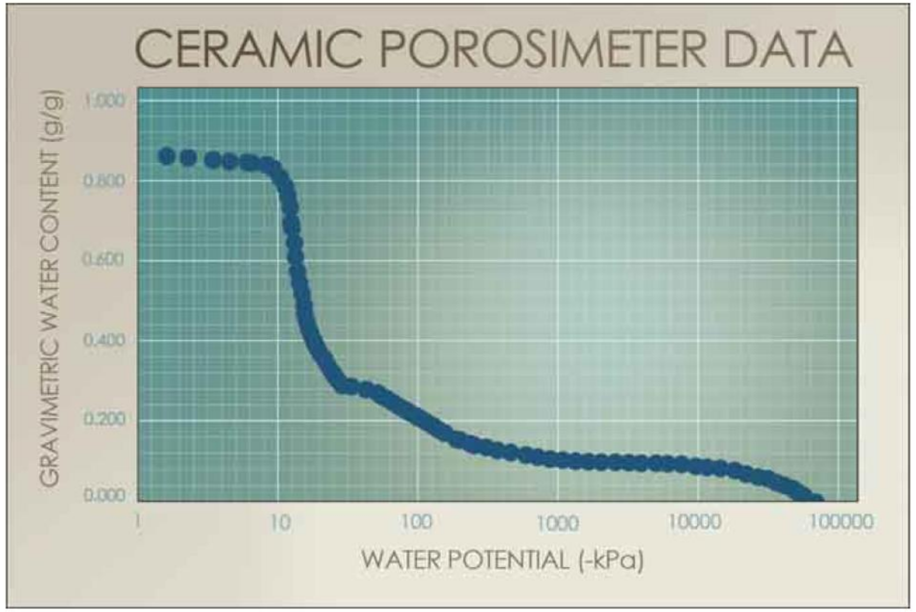
As the water in tensiometer is considered to be equilibrium with the soil water, the gauge reading of the tensiometer represents the matric potential of the soil.

How to evaluate soil suction and degree of saturation in-situ?

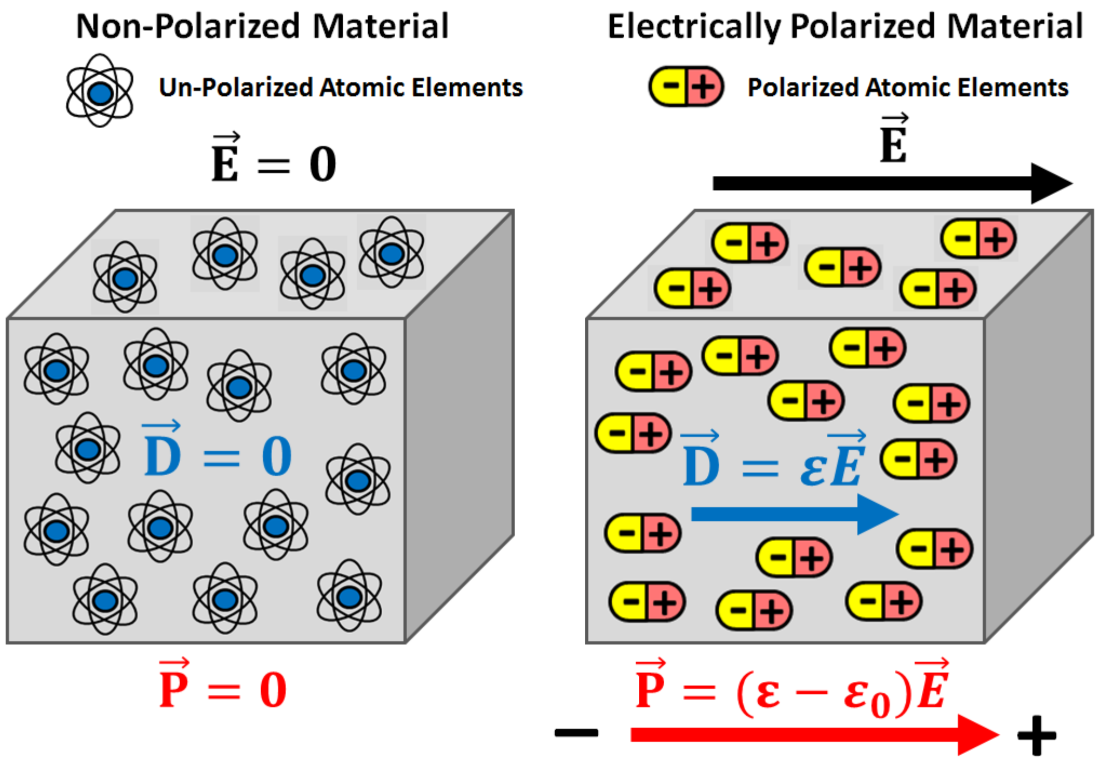
Dielectric sensors



Model MPS-6 – Decagon Devices



Moisture characteristic curve for ceramic



Measure

Dielectric permittivity of the porous ceramic disks

relative permittivity of the air = 1

relative permittivity of the solid ceramic = 5

relative permittivity of the water = 80

The relative permittivity of the ceramic disks depends on the amount of water present in the disc pore spaces

How to evaluate soil suction and degree of saturation in-situ?

Water content probes

Model GS3 – Decagon Devices

Volumetric Water Content Estimate

The sensor uses an electromagnetic field to measure the dielectric permittivity of the surrounding medium.

The sensor supplies a 70 MHz oscillating wave to the sensor prongs that charges according to the dielectric of the material. The stored charge is proportional to substrate dielectric and substrate volumetric water content.

The microprocessor of the instrument measures the charge and outputs a value of dielectric permittivity from the sensor.

The dielectric value is then converted to substrate water content by a calibration equation specific to the media you are working in.

Measure: Dielectric permittivity of the surrounding medium (soil)

relative permittivity of the air = 1

relative permittivity of the water = 80

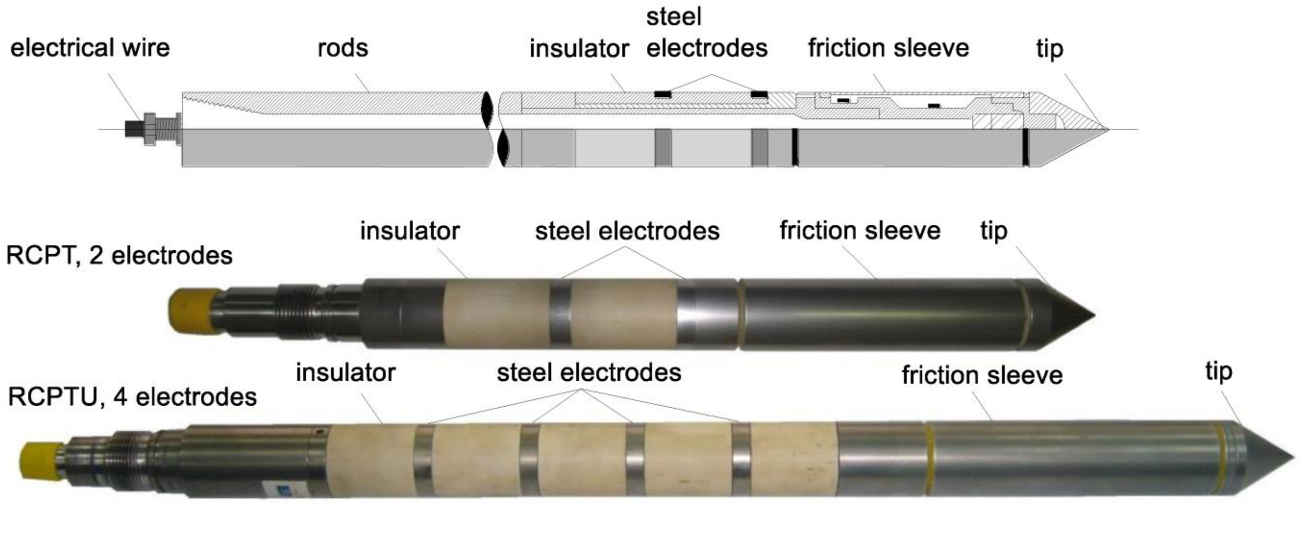
How to evaluate soil suction and degree of saturation in-situ?

Geoelectric Methods

$$R = \frac{V}{I} \qquad R = \frac{\rho}{2\pi K} \qquad \rho = 2\pi K \frac{V}{I}$$

V = voltage (V)
I = electric current (amp)
R = resistance (Ω)

ρ = resistivity (Ωm)
K = geometric factor (m)



A cross-section and a photo of RCPT and RCPTU cones

Campanella and Weemees (1990)

Water Content and Degree of Saturation Estimate

Archie (1942)

$$S_r = \left(\frac{\rho_{s,sat}}{\rho_{s,part}}\right)^{\frac{1}{g}}$$

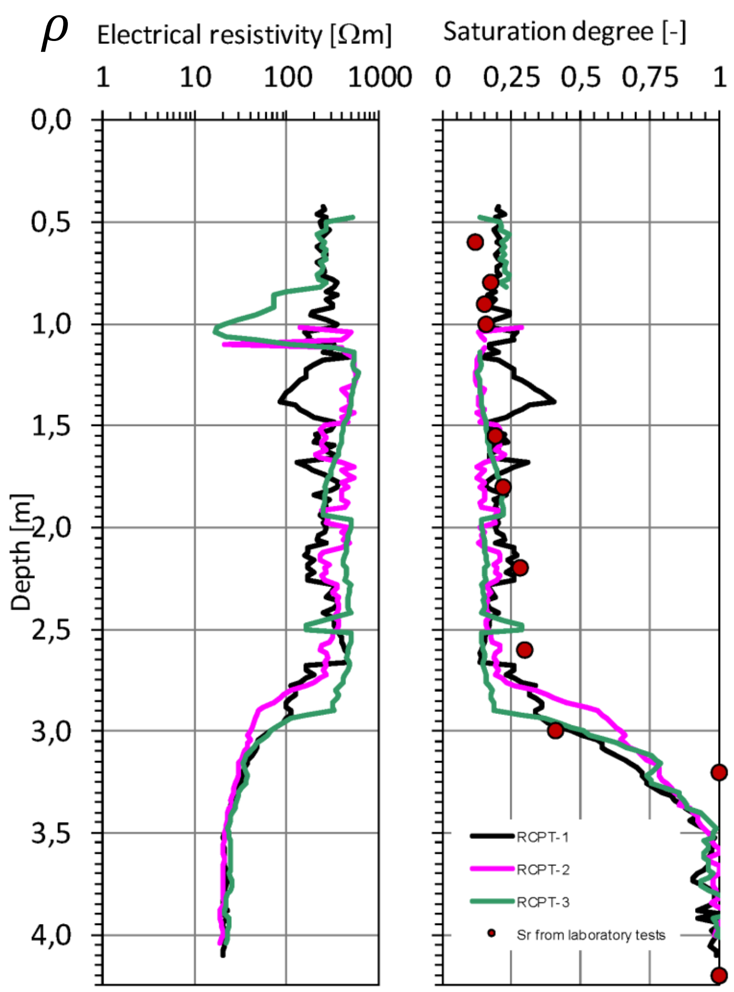
Formation Factor (F)

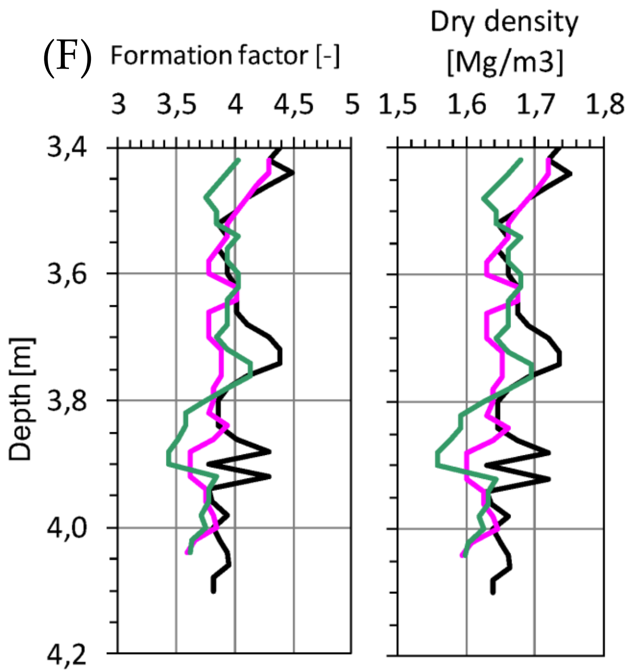
$$F = \frac{\rho_{s,sat}}{\rho_w}$$

$$F = n^{-m} = \left(1 - \frac{\gamma_d}{\gamma_s}\right)^{-m}$$

n = porosity
m and g are coefficients

$$\gamma_d = \gamma_s\left(1 - F^{-\frac{1}{m}}\right)$$



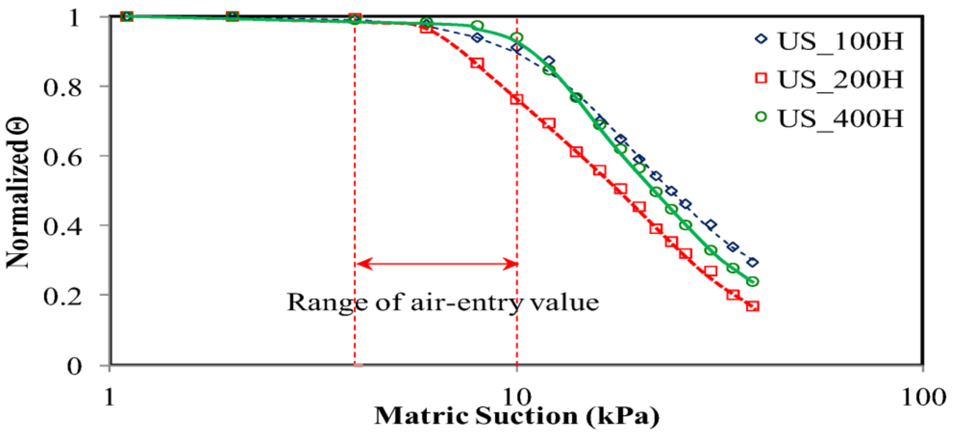


How to evaluate soil suction and degree of saturation in-situ?

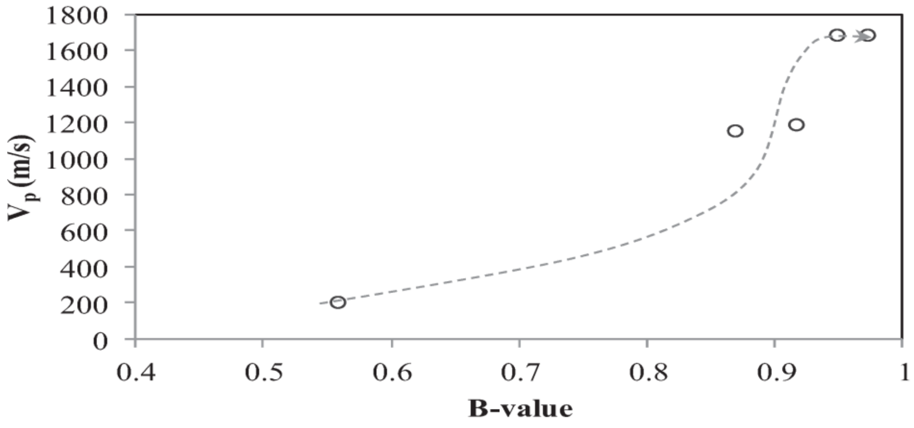
Seismic Methods (P-wave velocity)

Early evidences shown in *Mitchell et al (1994)*

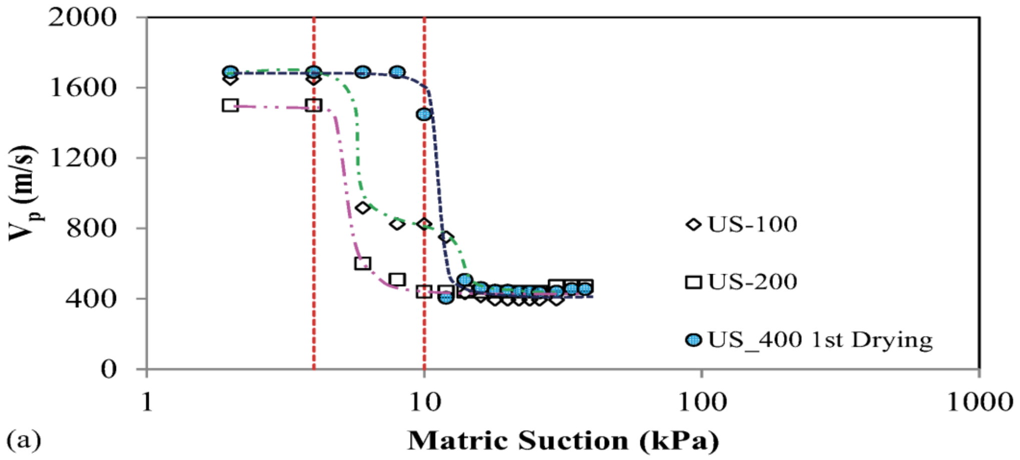
Water Content and Degree of Saturation Estimate

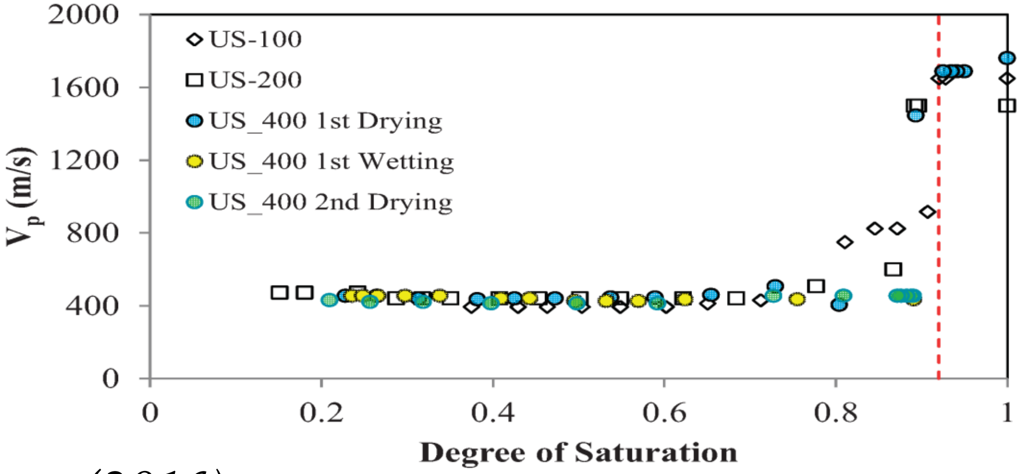


SWCC of the soil specimens tested



Variation of Skempton B with V_p during the saturation phase





Leong and Cheng (2016)

- Measure of suction is technically difficult
- Measuring sensors are expensive
- Installation and monitoring activities are time-consuming

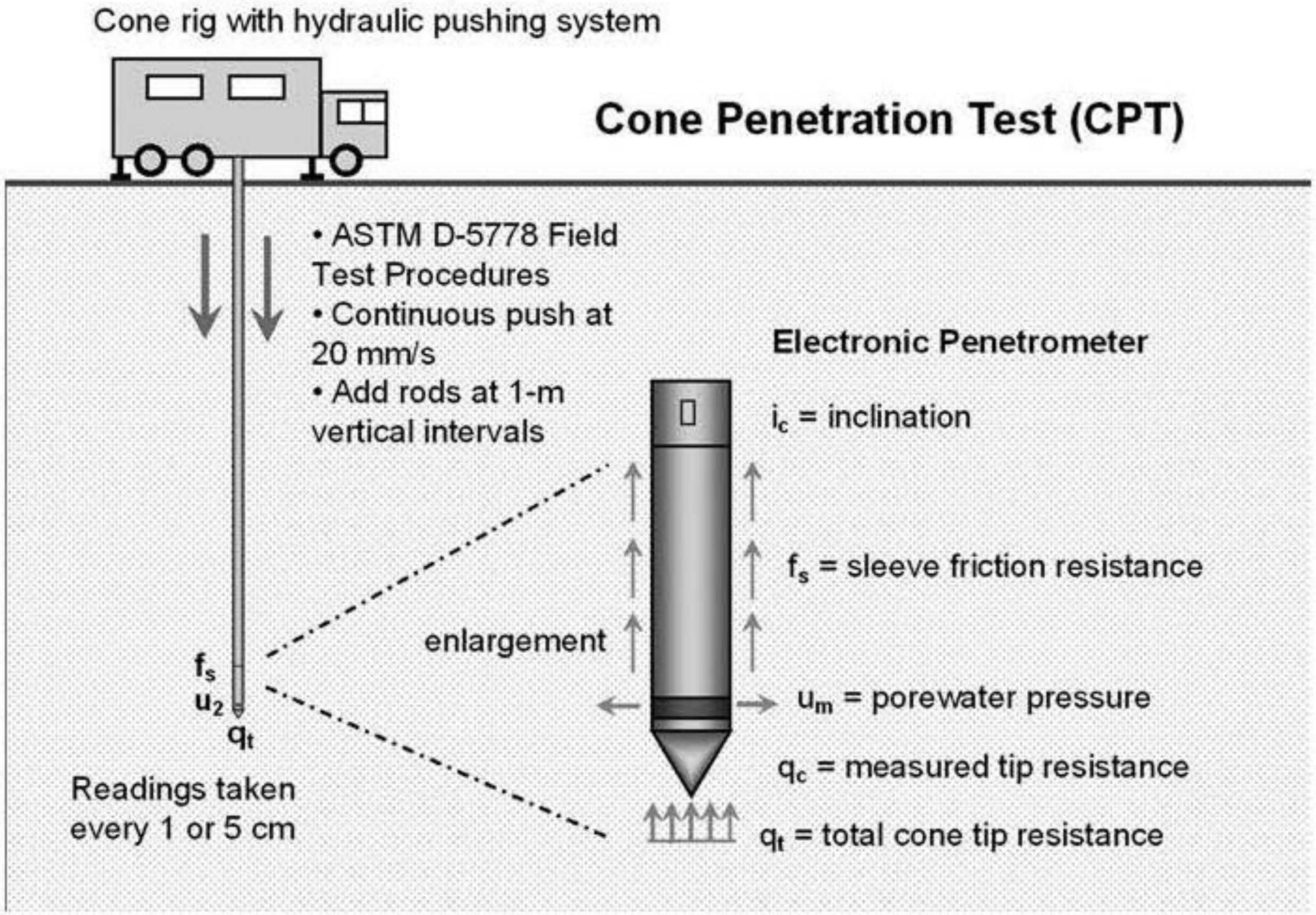
USE OF IN SITU TESTS (CPT) FOR PORE PRESSURE AND EFFECTIVE STRESS MEASURE

CPT Testing Method – Measurements

1. Pushing the cone into the soil at a rate of 20 mm/s
   - Clay (Undrained)
   - Sand (Drained)

2. CPT ($q_c - f_s - i$ - u) – Every 2 cm (ASTM D5778)

3. SCPT ($q_c - f_s - i - u - t_s - t_p$)



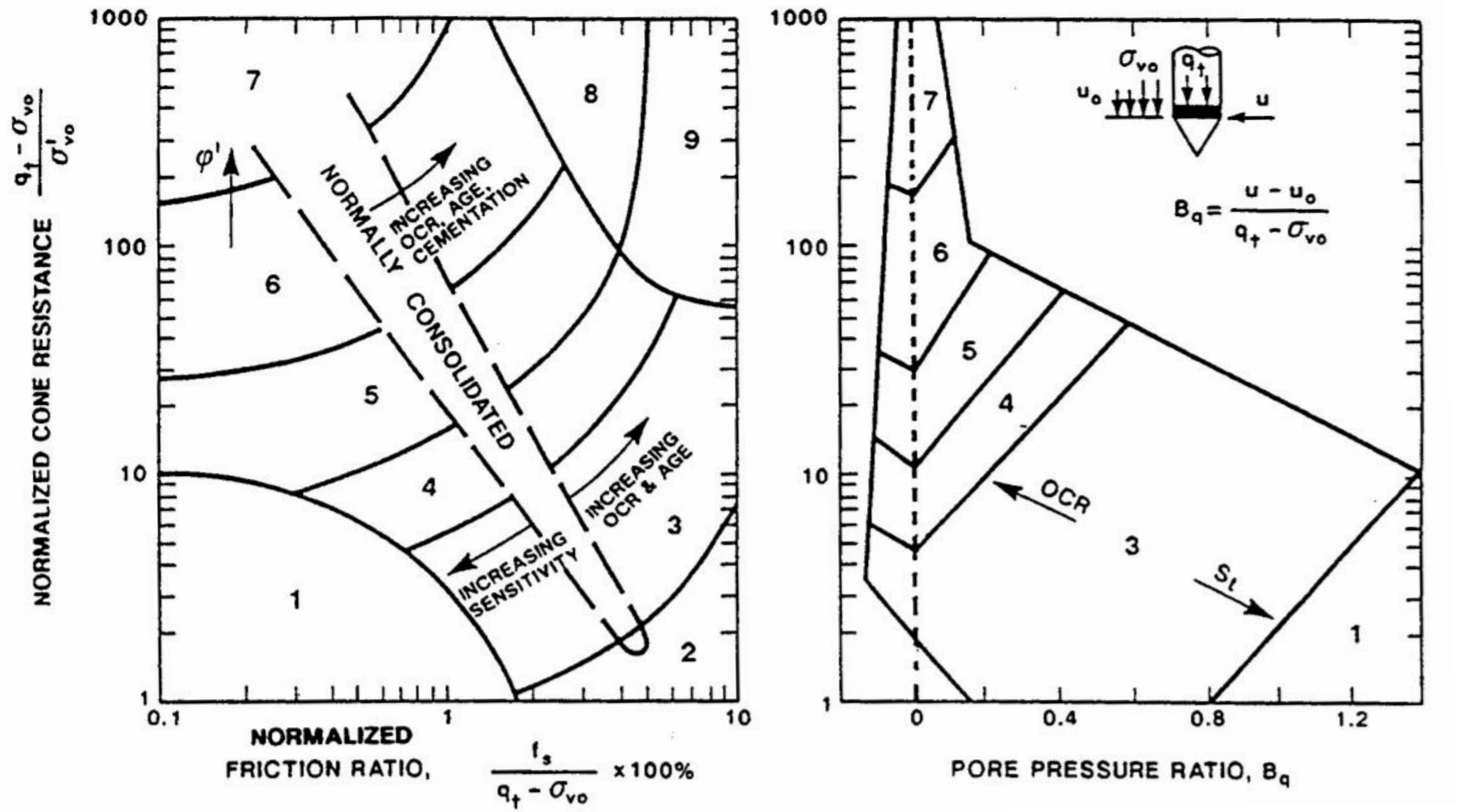
Overview of the cone penetration test per ASTM D 5778 procedures.

CPT Test Interpretation – Soil Profiling

1. Begemann (1965)
2. Schmertmann (1978)
3. Searle (1979)
4. Douglas and Olsen (1981)
5. Robertson and Campanella (1986)
6. Robertson (1990, 2009)
7. Eslami and Fellenius (1997)

Normalized Classification Chart - *Robertson (1990), Robertson and Wride (1998)*

$$Q_{t1} = \frac{q_t - \sigma_{v0}}{\sigma'_{v0}}\ ; \qquad F = \frac{f_s}{q_t - \sigma_{v0}} \cdot 100; \qquad B_q = \frac{u_2 - u_0}{q_t - \sigma_{v0}}$$



SBTn Soil Classes:

-1: sensitive, fine grained
-2: organic soil-peat
-3: clays-clays to silty clay
-4: silt mixtures-clayey silt to silty clay
-5: sand mixtures-silty sand to sandy silt
-6: sands- clean sand to silty sand
-7: gravelly sand to sand
-8: very stiff sand to clayey sand (heavily OC or cemented)
-9: very stiff, fine grained (heavily OC or cemented)

Normalized Classification Chart - *Robertson (1990), Robertson and Wride (1998)*

Soil Classification Index (I_c) -> I_c assessment requires an iterative procedure

$$I_c = \sqrt{(3.47 - \log Q_{tn})^2 + (\log F + 1.22)^2}$$

$$Q_{tn} = \left(\frac{q_t - \sigma_{v0}}{\sigma_{atm}}\right)\left(\frac{\sigma_{atm}}{\sigma'_{v0}}\right)^n \qquad F = \frac{f_s}{q_t - \sigma_{v0}} \cdot 100$$

$$n = 0.381 \cdot I_c + 0.05 \cdot \left(\frac{\sigma'_{v0}}{\sigma_{atm}}\right) - 0.15$$

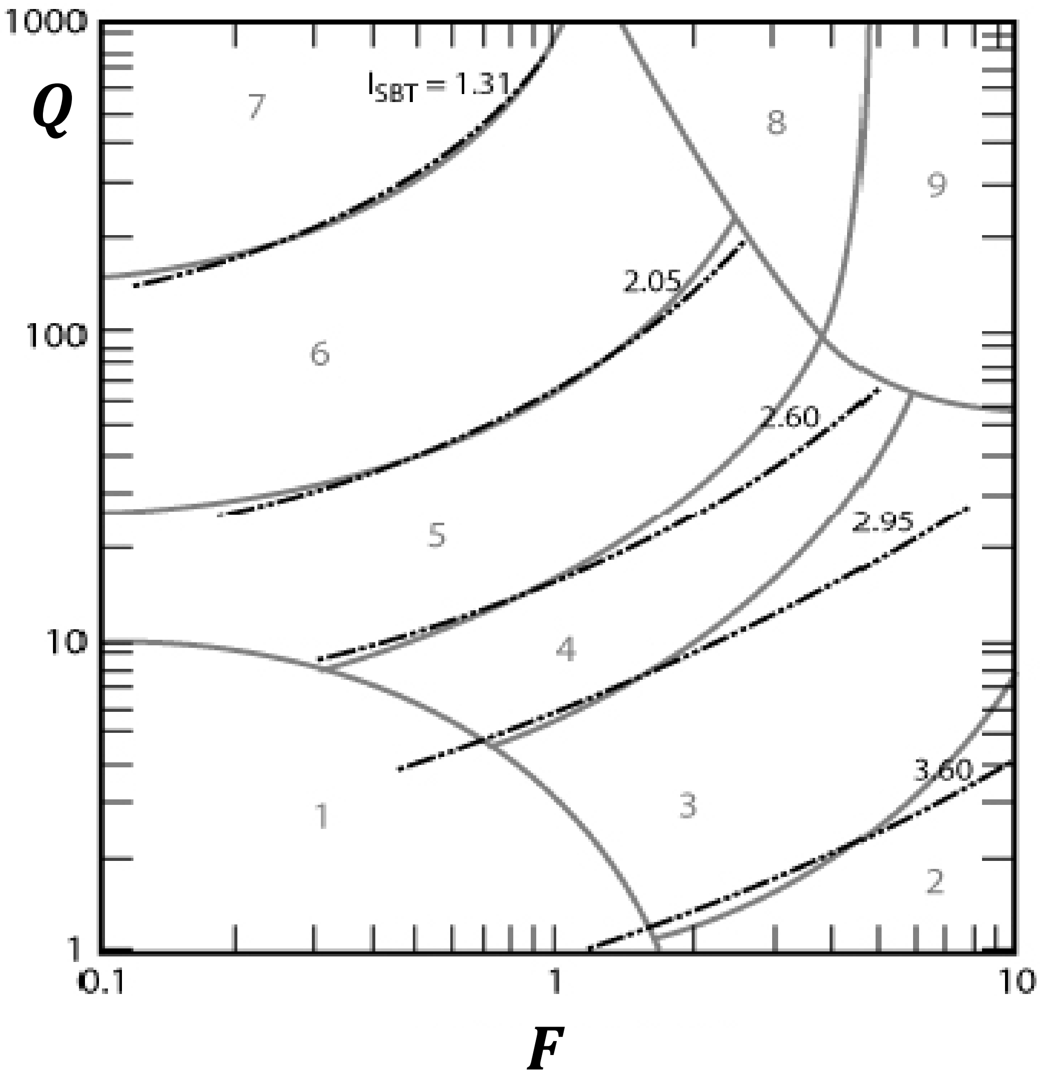
Q_{tn} = normalized tip resistance
q_t = total tip resistance

σ_{atm} = 1 atm (= 98 kPa)

n = stress exponent = 1 in fine grained soils

F = normalized friction ratio
fs = sleeve friction

Soil classification (SBTn)	Zone number (Robertson SBTn 1990)	Ic Index Values
Organic soils: peats	2	$I_c > 3.60$
Clays: silty clay to clay	3	$2.95 < I_c < 3.60$
Silt Mixtures: clayey silt to silty clay	4	$2.60 < I_c < 2.95$
Sand Mixtures: silty sand to sandy silt	5	$2.05 < I_c < 2.60$
Sands: clean sand to silty sand	6	$1.31 < I_c < 2.05$
Gravelly sand to dense sand	7	$I_c < 1.31$

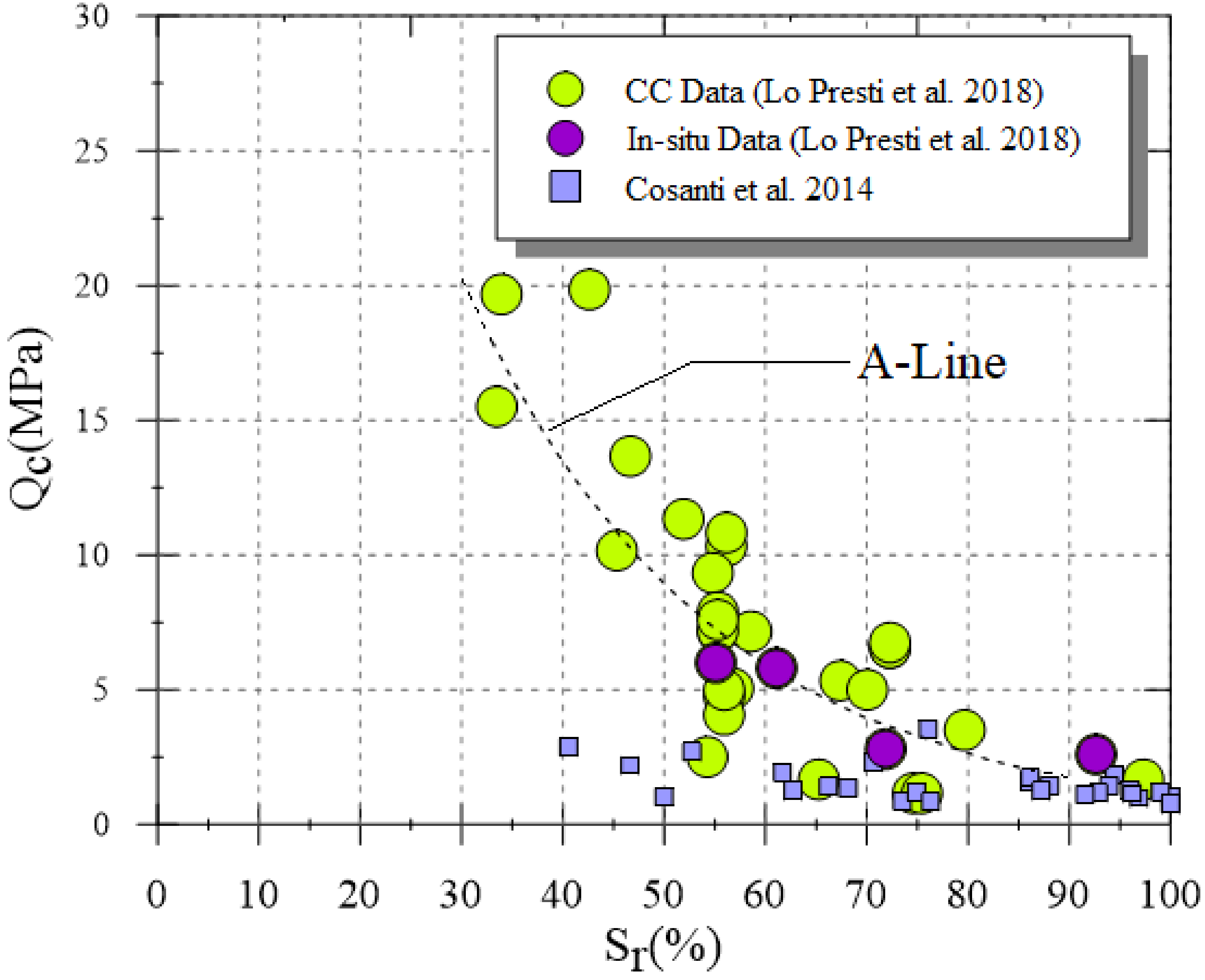


Influence of partial saturation on tip resistance

- Cone tip resistance (q_c) strongly depends on the water content in the case of fine-grained soils

- Suction effect has a significant influence on the cone penetration resistance through suction hardening and its contribution to the effective stress state *(Yang and Russell, 2016)*

Influence of partial saturation on tip resistance



Lo Presti et al. (2019)

Montuolo (LU, Italy)
Serchio River side-bank
Ringrosso Arginale Fiume Serchio.
2 punti con maggior S_r (post irrigazione biostuoie)

Existing levees of the Serchio River

Calibration Chamber: 4 soils A4-A6 (AASHTO)

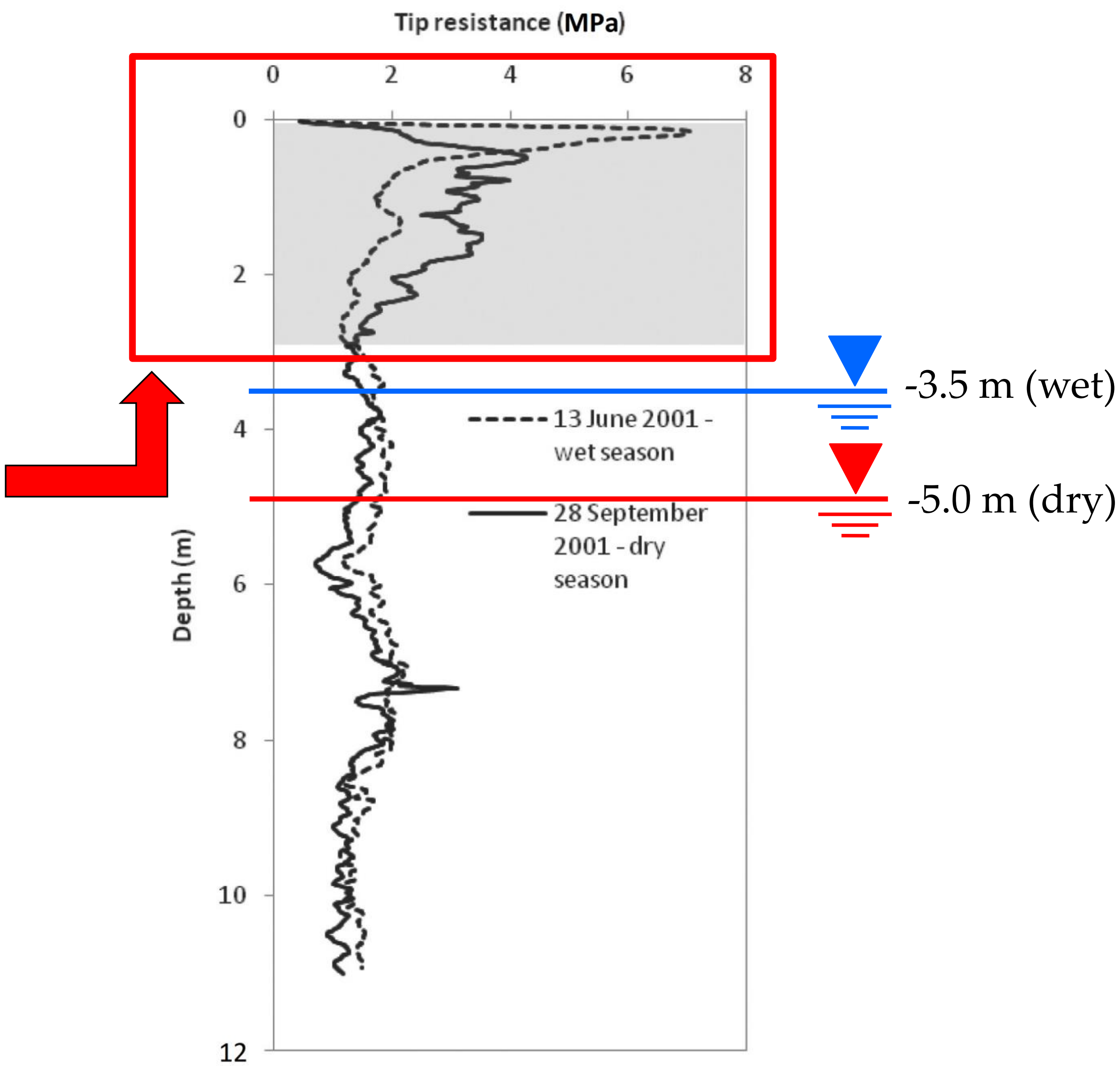
Montuolo and Calibration Chamber
Compacted Soils (90-95%γ_d - Modified Proctor)

Influence of partial saturation on tip resistance

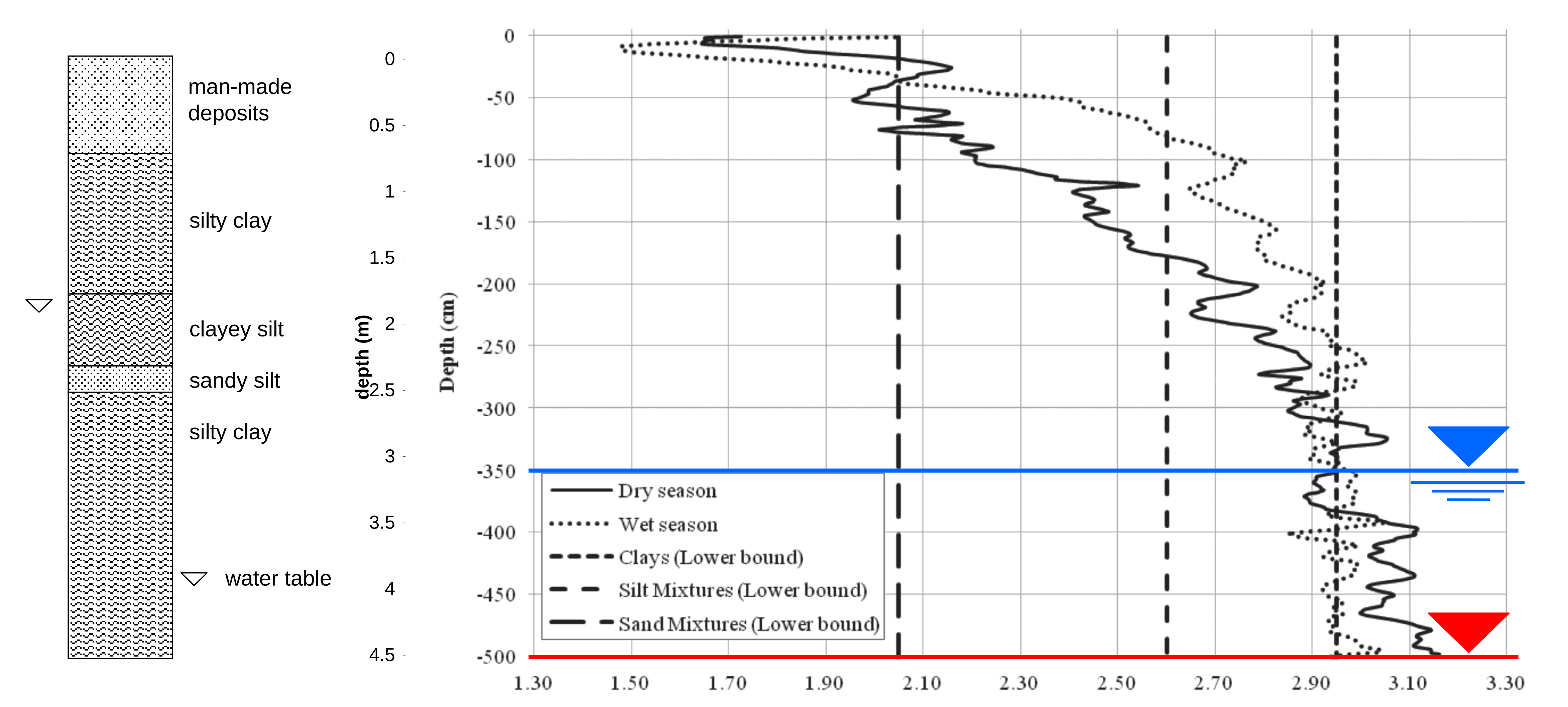
Test site Broni (PV - Italy)

In dry season σ'_{vo} increase due to soil partial saturation q_c increases from 1–2 MPa to 3–4 MPa in the vadose zone above the water table

Typical trend of the tip resistance within a partially saturated clayey soil



Lo Presti et al (2016) – Test site Broni (PV - Italy)



Lo Presti et al (2016) – Test site Broni (PV - Italy)

The effect of suction is evident in terms of soil classification index (I_c) values.

The I_c values decrease from about 3.0 at the water table depth to about 2.0 at a depth of 50 cm.
In terms of SBTn classes, silts and sand mixtures become predominant instead of OC stiff clay

CPT Method to Assess the Soil Effective Stress

- Applying a new method *(Lo Presti et al, 2018)* for assessing the effective stress state and suction for partially saturated clayey soils by using the I_c (Soil Behaviour type Index) calculated from CPT tests.

- Validating the method comparing the CPT predicted values of suction against the measured ones in a well-documented and monitored sites

CPT Method to Assess the Soil Effective Stress

$$Q_{tn} = \left(\frac{q_t - \sigma_{v0}}{\sigma_{atm}}\right)\left(\frac{\sigma_{atm}}{\sigma'_{v0}}\right)^n$$

I_c correction in the vadose zone → DEFINITION OF I_c target $I_{c,t}$: $I_{c,t} = I_c$ below the water table → Effective vertical stress σ'_{v0}

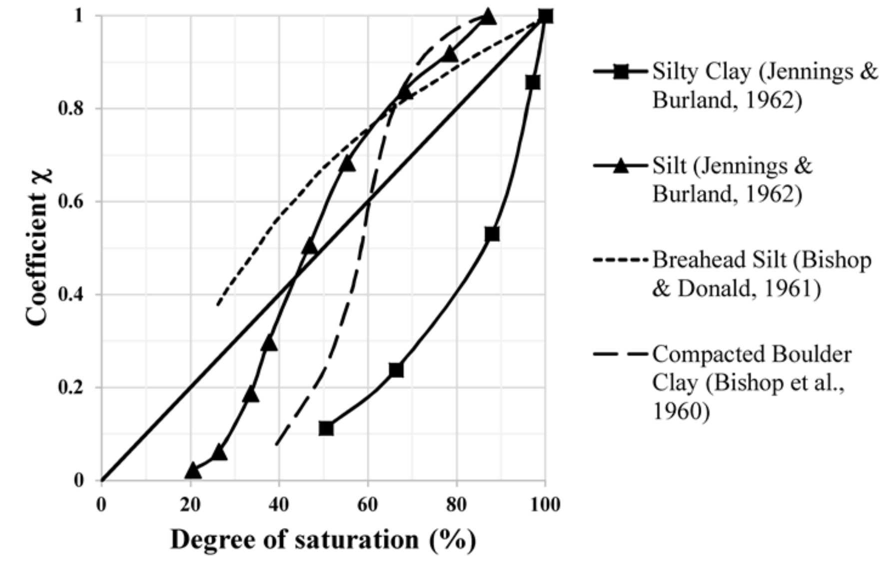
$$I_c = \sqrt{(3.47 - \log Q_{tn})^2 + (\log F + 1.22)^2}$$

$$\sigma'_{v0} = \frac{q_t - \sigma_{v0}}{10^{\,3.47 - \sqrt{I_{c,t}^2 - (\log F + 1.22)^2}}}$$

Bishop, 1959 $\sigma'_{v0} = (\sigma_{v0} - u_a) + \chi \cdot (u_a - u_w)$ → Ψ

$$\psi = \frac{\sigma'_{v0} - \sigma_{v0} + u_a}{\chi}$$

u_a = air pressure;
u_w = water pressure;
χ = effective stress parameter that is expressed as a function of the degree of saturation (S_r)



VALIDATION
- In situ values
- MK model (Aubertin et al, 1998)

Lo Presti, D., Stacul, S., Meisina, C., Bordoni, M., Bittelli, M. (2018). Preliminary validation of a novel method for the assessment of effective stress state in partially saturated soils by cone penetration tests. *Geosciences*, *8*(1), 30.

CPT Method to Assess the Soil Effective Stress

Modified-Kovacs Method *(Aubertin et al, 2003)*

1. equivalent capillary rise (hc0)

$$h_{c0}(cm) = \frac{0.15\rho_s}{e} w_L^{1.45}$$

ρ_s = soil grain density (kg/m³);
e = void ratio (-);
w_L = liquid limit (%).

2. compute Sc and Sa assuming a trial value for the unknown suction

$$S_c = 1 - \left[\left(h_{c0}/\psi\right)^2 + 1\right]^m \exp\left[-m \cdot \left(h_{c0}/\psi\right)^2\right]$$

$$S_a = a_c \cdot \left[1 - \frac{\ln\left(1 + \psi/\psi_r\right)}{\ln\left(1 + \psi_0/\psi_r\right)}\right] \cdot \frac{\left(h_{c0}/\psi_n\right)^{2/3}}{e^{1/3} \cdot \left(\psi/\psi_n\right)^{1/6}}$$

The model considers that water is held by

- capillary forces, responsible for capillary saturation (S_c),
- adhesive forces, causing saturation by adhesion (S_a).

3. compute Sr

$$S_r = S_c + S_a\left(1 - S_c\right)$$

4. repeat steps 2 and 3 assuming different values for the suction Ψ in order to obtain a degree of saturation (Sr) approximately equal to that measured in the test site

ψ_n = normalization parameter = 0.1 kPa (1 cm)

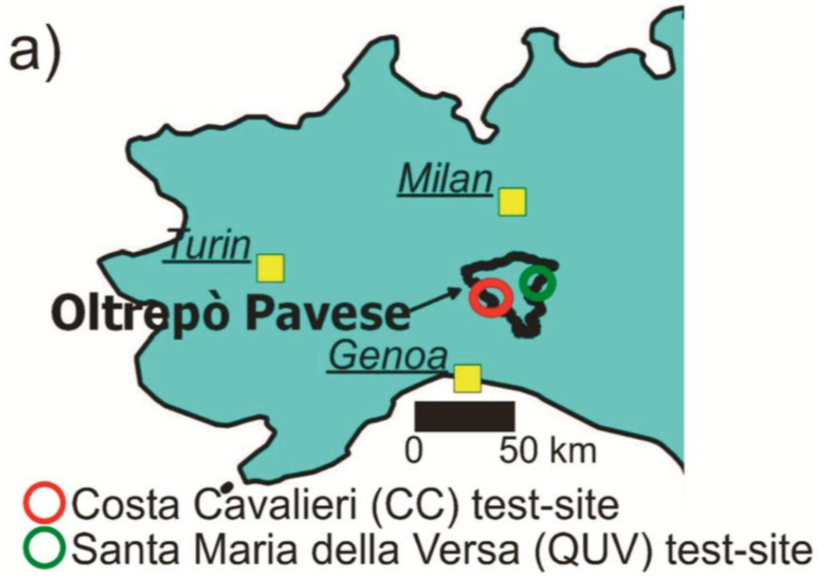
ψ_0 = suction value at complete dryness = 10^6 kPa (10^7 cm)

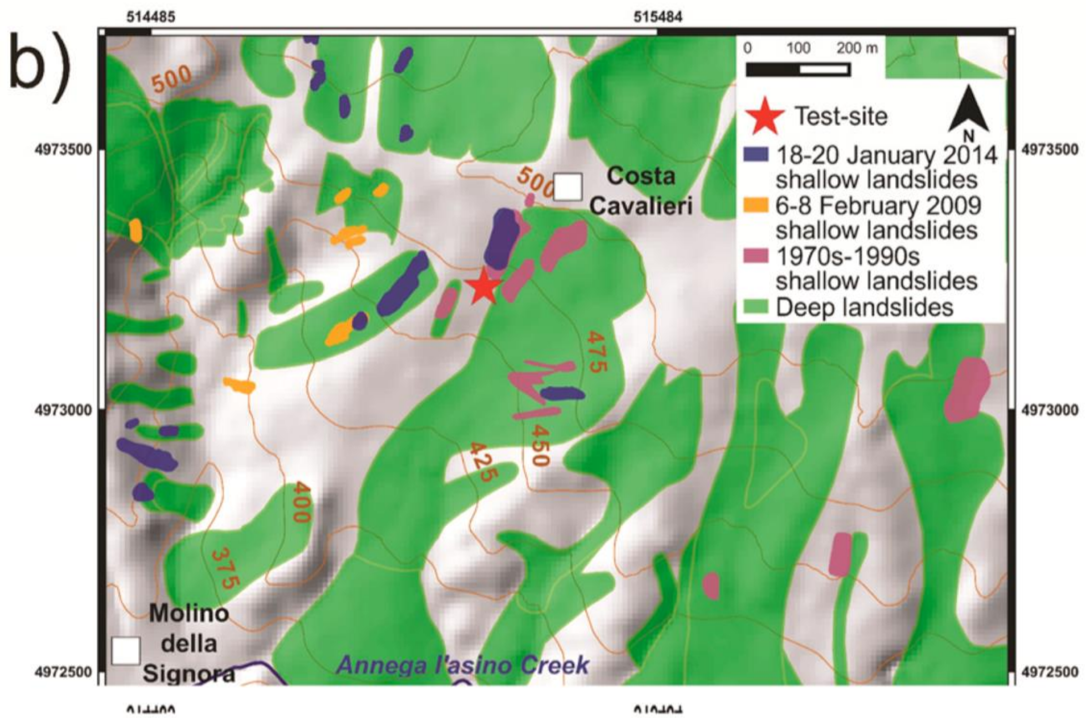
ψ_r = suction at residual water content. In cohesive soils:

$$\psi_r = 0.86\left(\frac{0.15\rho_s}{e}\right)^{1.2} w_L^{1.74}$$

***m** and **a_c** are model constants:*
***m** = 3×10^{-5} **a_c** = 7×10^{-4}*

Test Site – Costa Cavalieri





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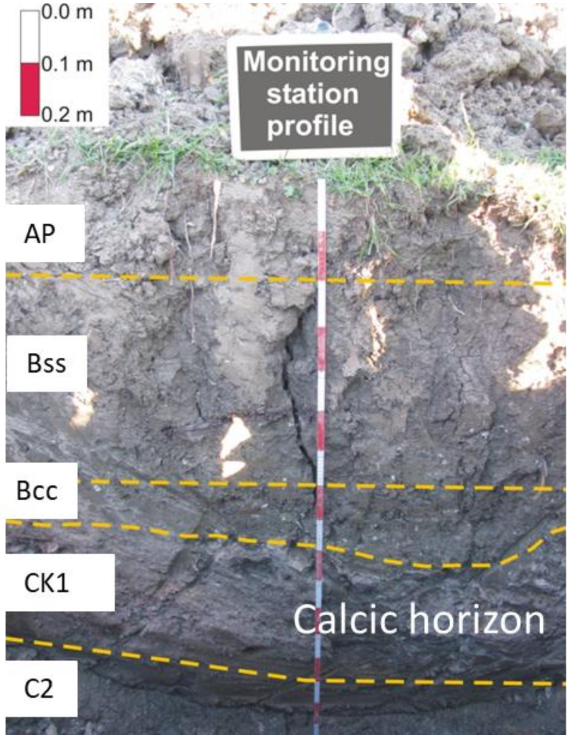


1) Past shallow landslides
(6-8 february 2009, 18-20 January 2014)

2) Geological setting: clayey and clayey-marly deposits covered by silty clay (1.7 m)

3) Geomorphological features: Low gradient slopes (10-15°), large creek valleys

Table 1. Selected geotechnical and physical properties of Costa Cavalieri test-site soil and weathered bedrock [1].

Type	D (m)	Sa (%)	S (%)	C (%)	$CaCO_3$ (%)	w_L (%)	PI (%)
A-cc	0.2	2.3	42.2	54.5	9.8	69.2	49.3
B-cc	0.4	2.2	39.7	57.5	9.8	71.3	53.1
C-cc	0.9	2.3	45.7	51.5	13.7	73.9	53.6
D-cc	1.2	3.2	46.8	47.5	26.7	65.5	45.6
E-cc	1.7	0.7	42.2	57.0	0.0	73.4	51.1

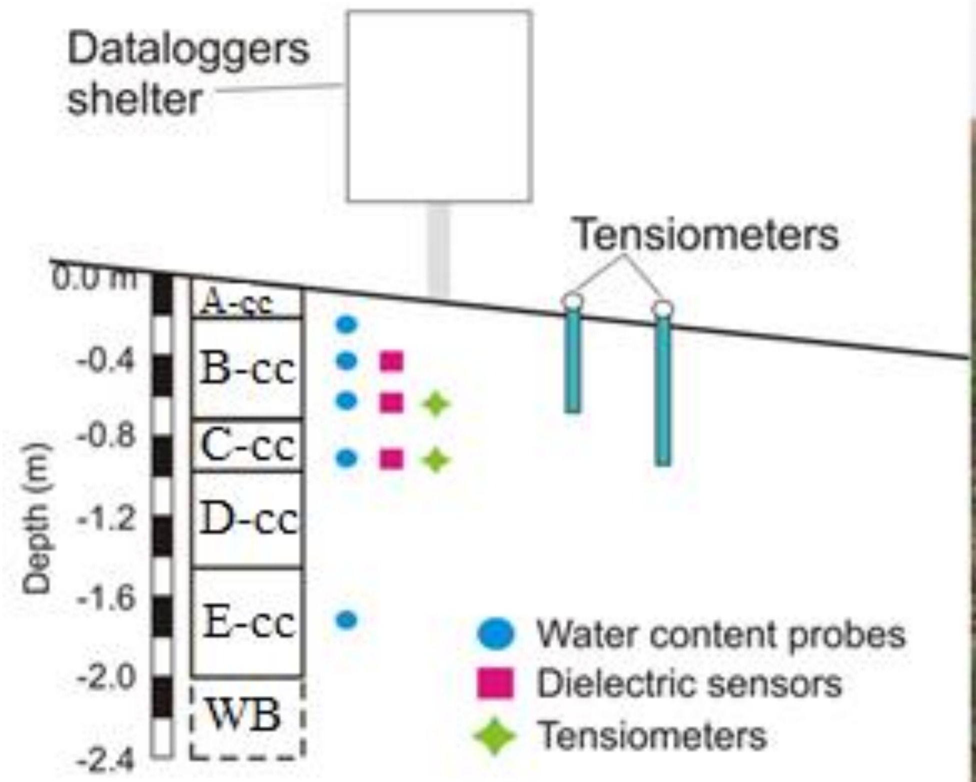
[1] D: depth; Sa: sand; S: silt; C: clay; $CaCO_3$ carbonate content; w_L: liquid limit; PI: plasticity index.

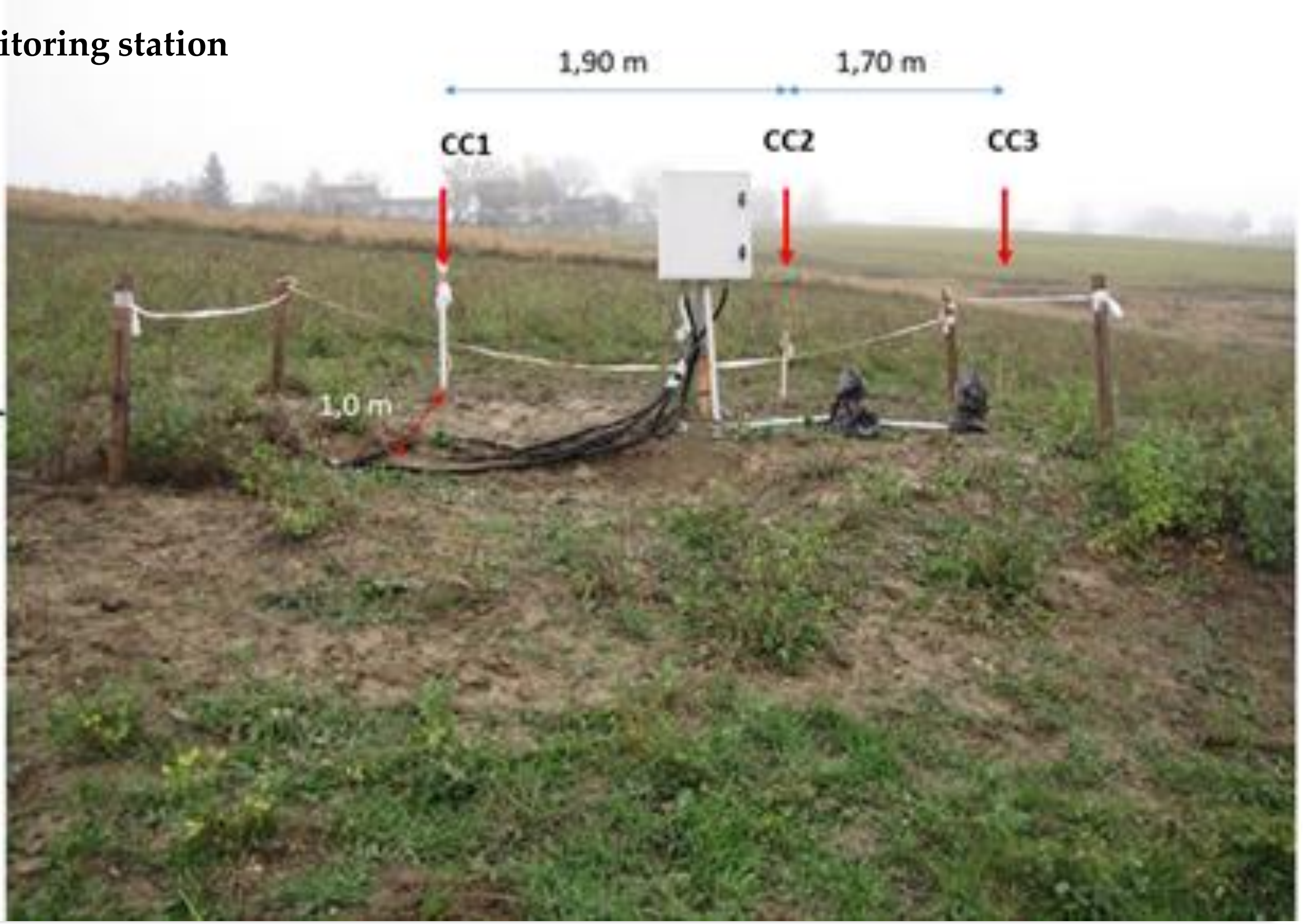
Test Site – Costa Cavalieri

Device	Model	Range of measure	Accuracy
Dielectric sensors	Model MPS-6 – Decagon Devices	-100000 / -9 kPa	3 kPa
Tensiometers	Model T4e- UMS GmbH	-85 / 10 kPa	0.5 kPa
Water content probes	Model GS3 – Decagon Devices	0.05 / 1.0 $m^3 \cdot m^{-3}$	0.01 – 0.02 $m^3 \cdot m^{-3}$

- Soil devices installed in a trench pit
- Data collection since 27/11/2015
- Temporal resolution: 10 minutes
- Datalogger (DL-6te, EM-50) powered by batteries

Soil profile and sketch of the Costa Cavalieri (CC) monitoring station





Test Site – Costa Cavalieri

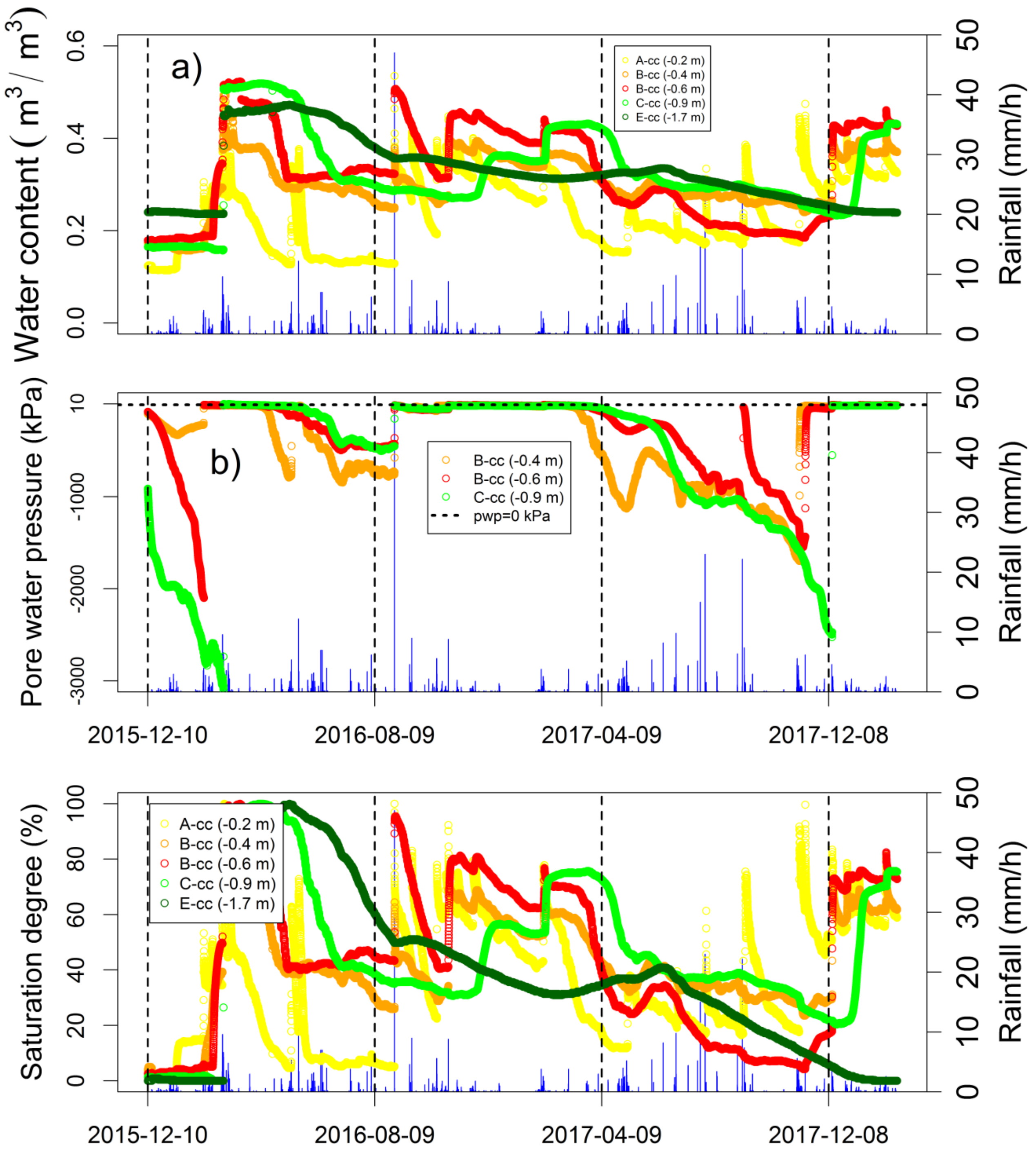


Table 3. In situ characteristics of Costa Cavalieri test-site (9 November 2017) [1]

Depth (m)	W (m^3/m^3)	S_r (%)	u_w (kPa)
0.2	0.402	80	-
0.4	0.251	55	−21.0
0.6	0.187	41	−1520.6
0.9	0.255	56	−1653.2
1.7	0.265	61	−1250

[1] w: water content; S_r: saturation degree; u_w: pore water pressure.

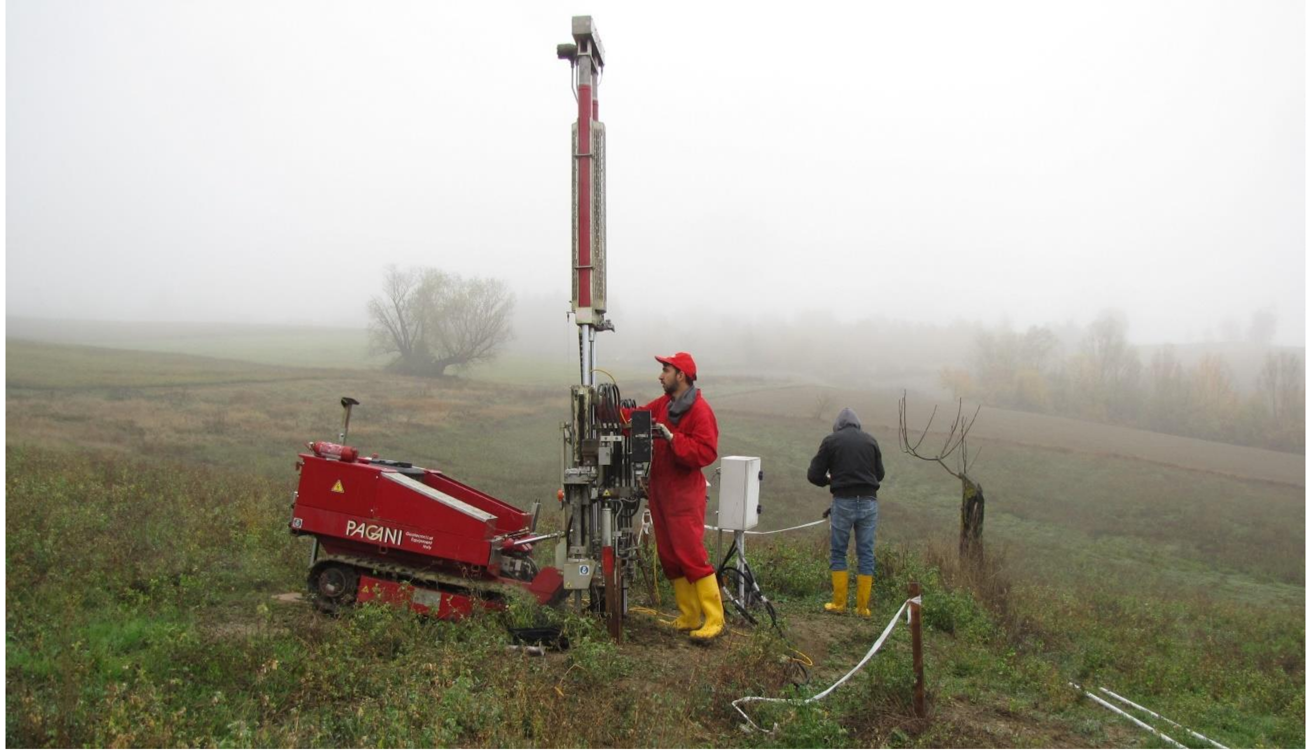
Test Site – Costa Cavalieri

- CPTu tests were carried out by using a Pagani Penetrometer TG63-150kN (ASTM D5778), in a dry period in November 2017

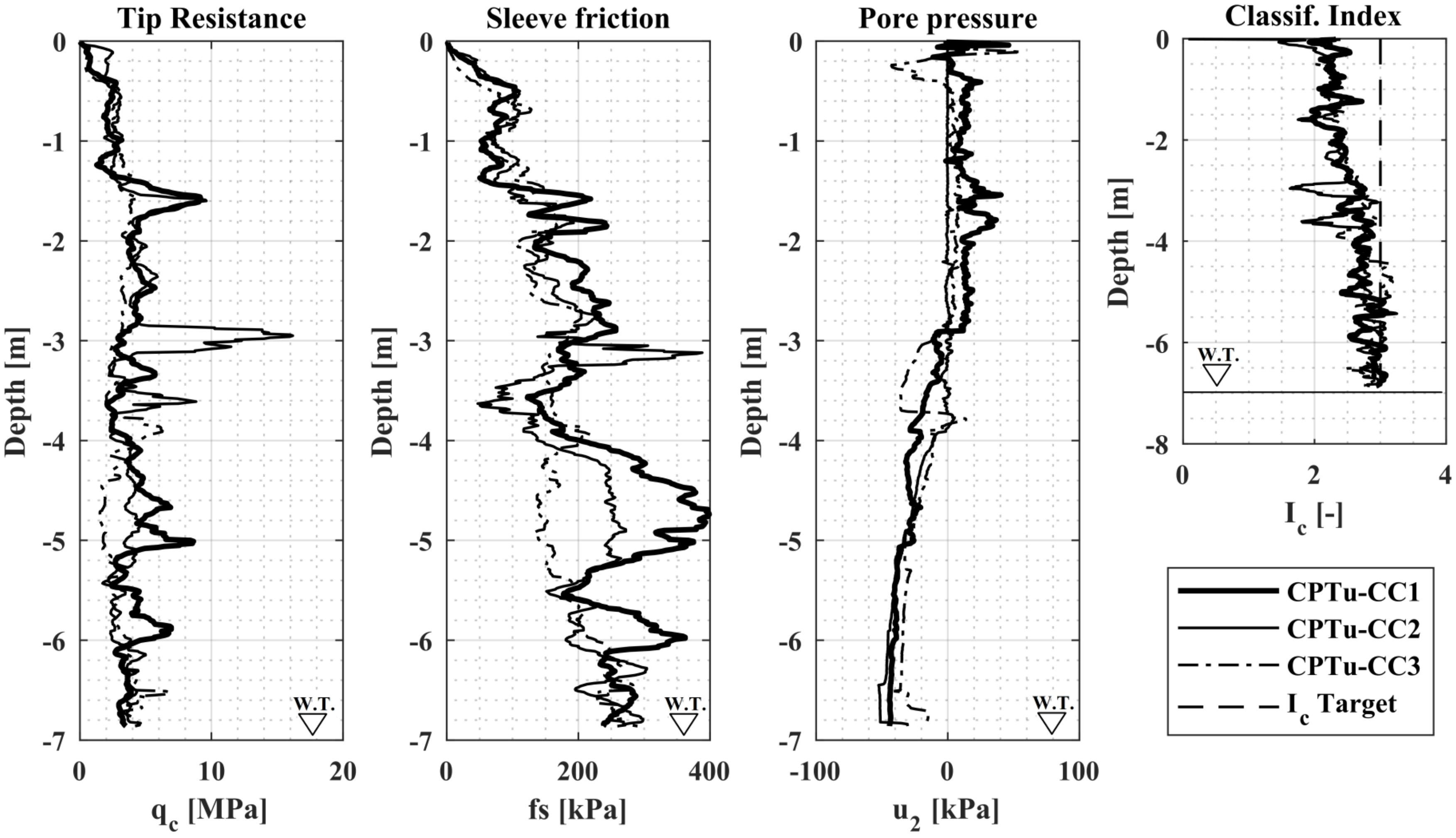
- Acquisition system/data logger TGAS-08.

- Silicone oil was used for the saturation of the filter.

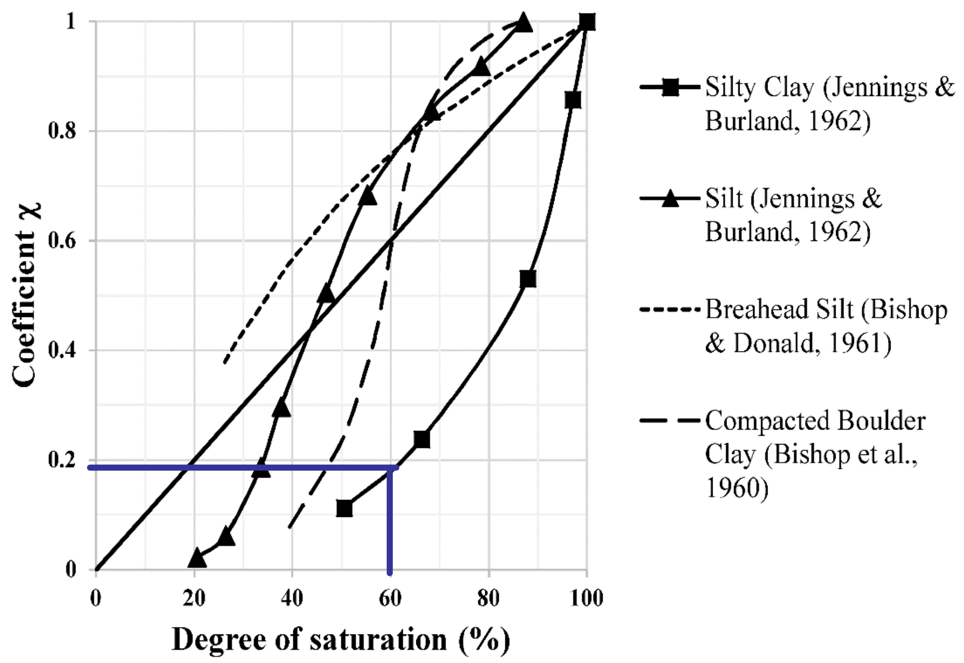
- Saturation of the Bronze Filter was done using a professional vacuum pump for 24 hours at Pagani Company.



Test Site – Costa Cavalieri – Results



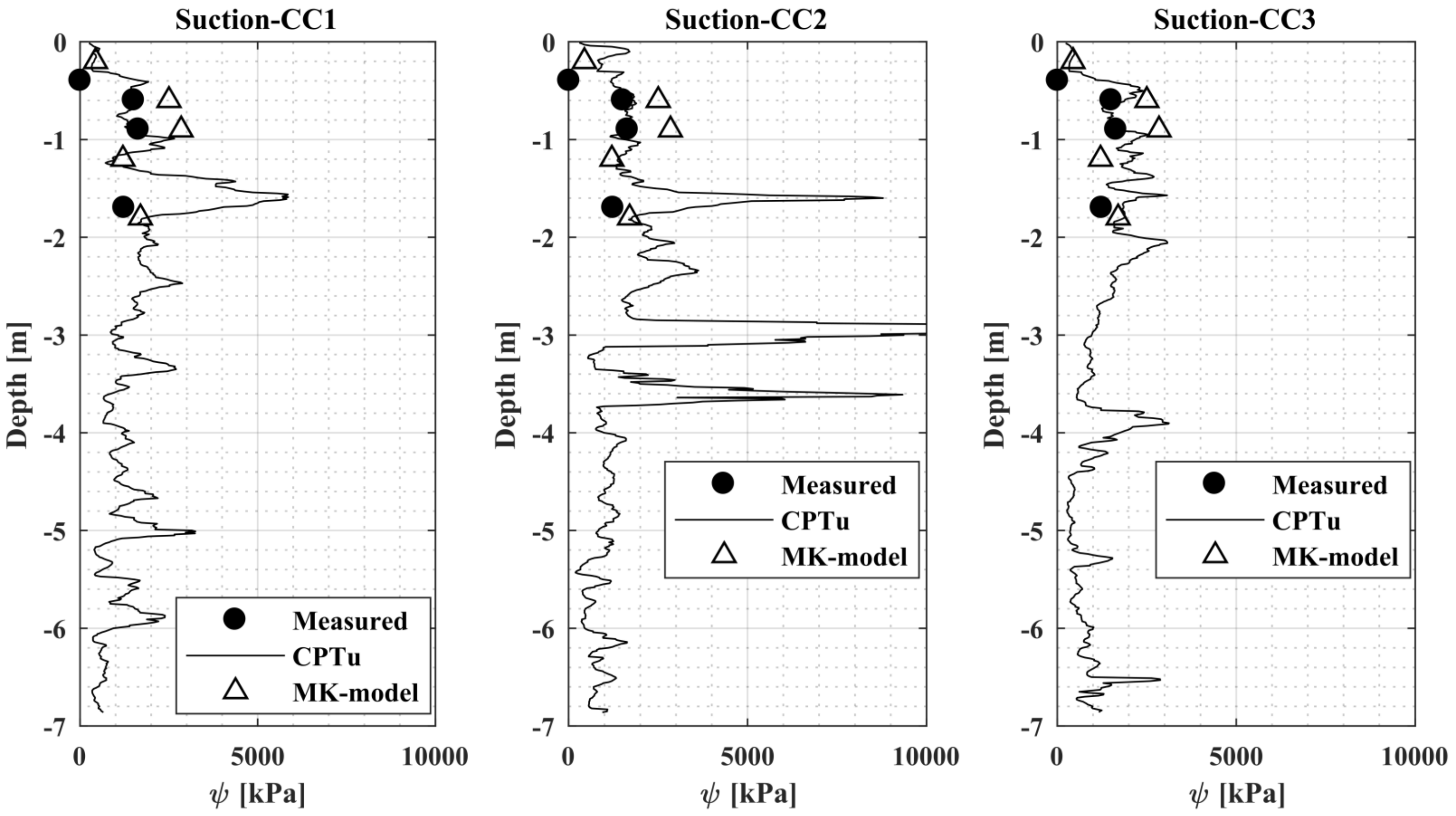
CPTu test results at Costa Cavalieri (CC) site



Test Site – Costa Cavalieri – Results

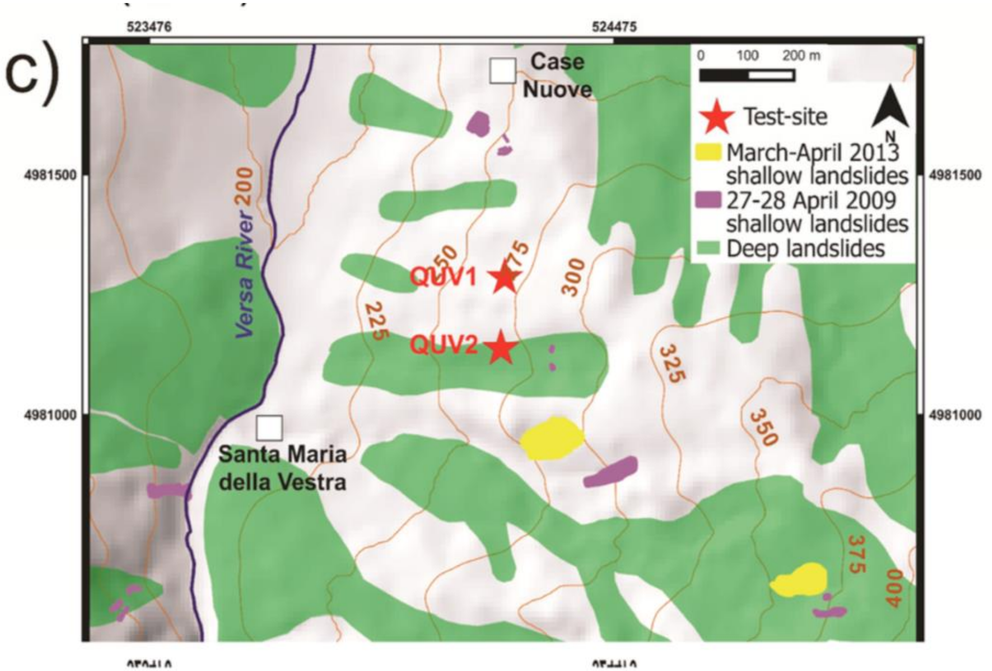
- The measured values of suction and those inferred by means of the MK method and from re-interpretation of CPTu are in very good agreement.

- Both the considered methods are capable of perfectly miming the trend of suction with an important reduction in the shallower part because of the raining during few days before CPTu testing.



Measured and estimated values of suction at Costa Cavalieri (CC) site

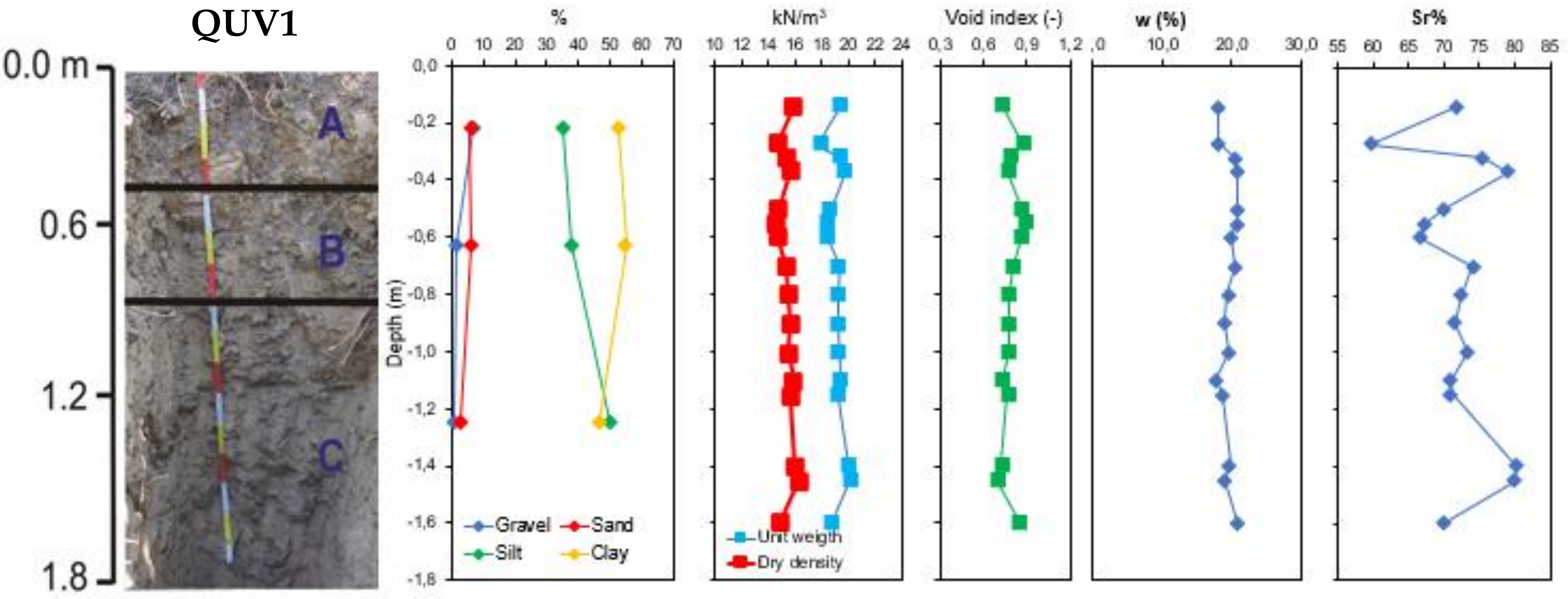
Test Site – Santa Maria della Versa



1) Past shallow landslides
2) Geological setting: flysch covered by silty clay
3) Geomorphological features: Low gradient slopes (8°), large creek valleys

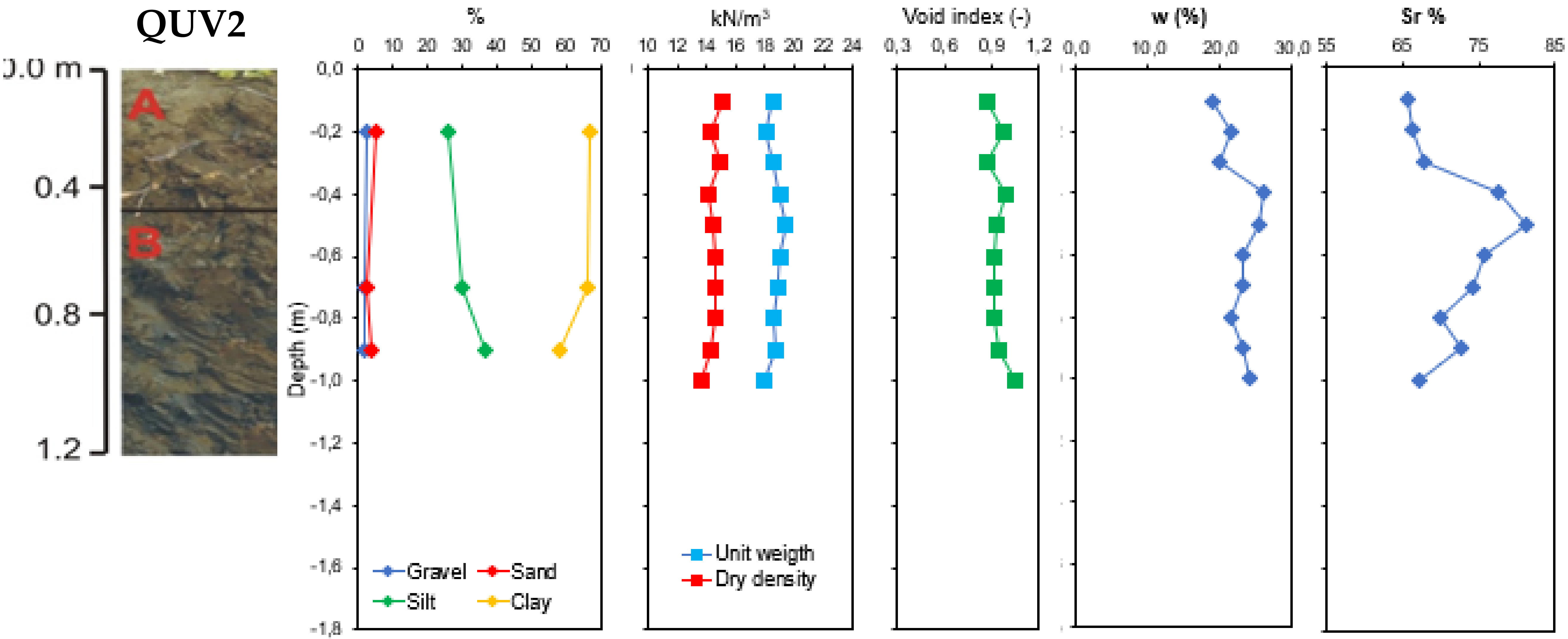
Trench pit with measures of the water content with GS3 sensors

Test Site – Santa Maria della Versa



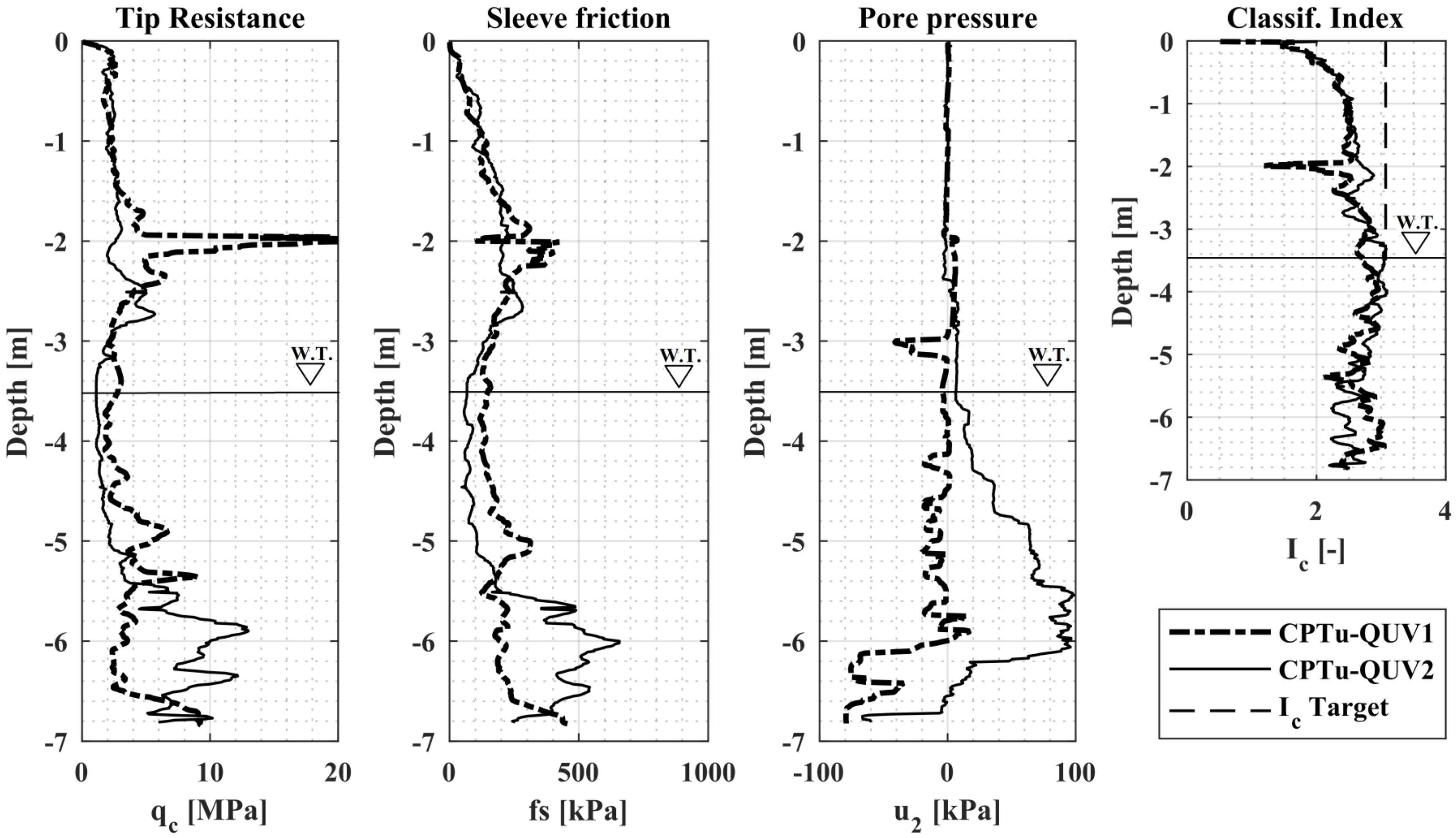
In situ characteristics (25 August 2017)

Test Site – Santa Maria della Versa

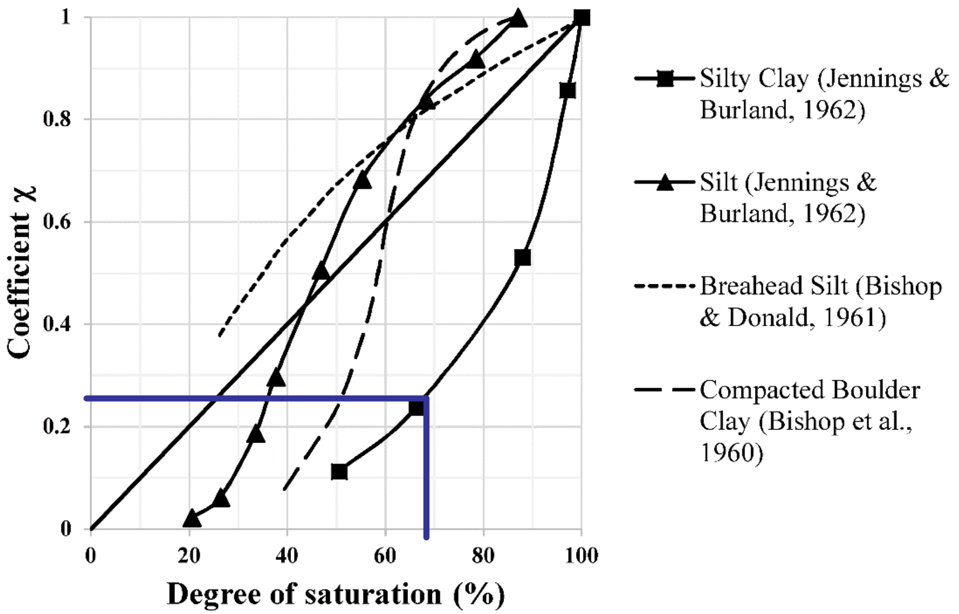


In situ characteristics (25 August 2017)

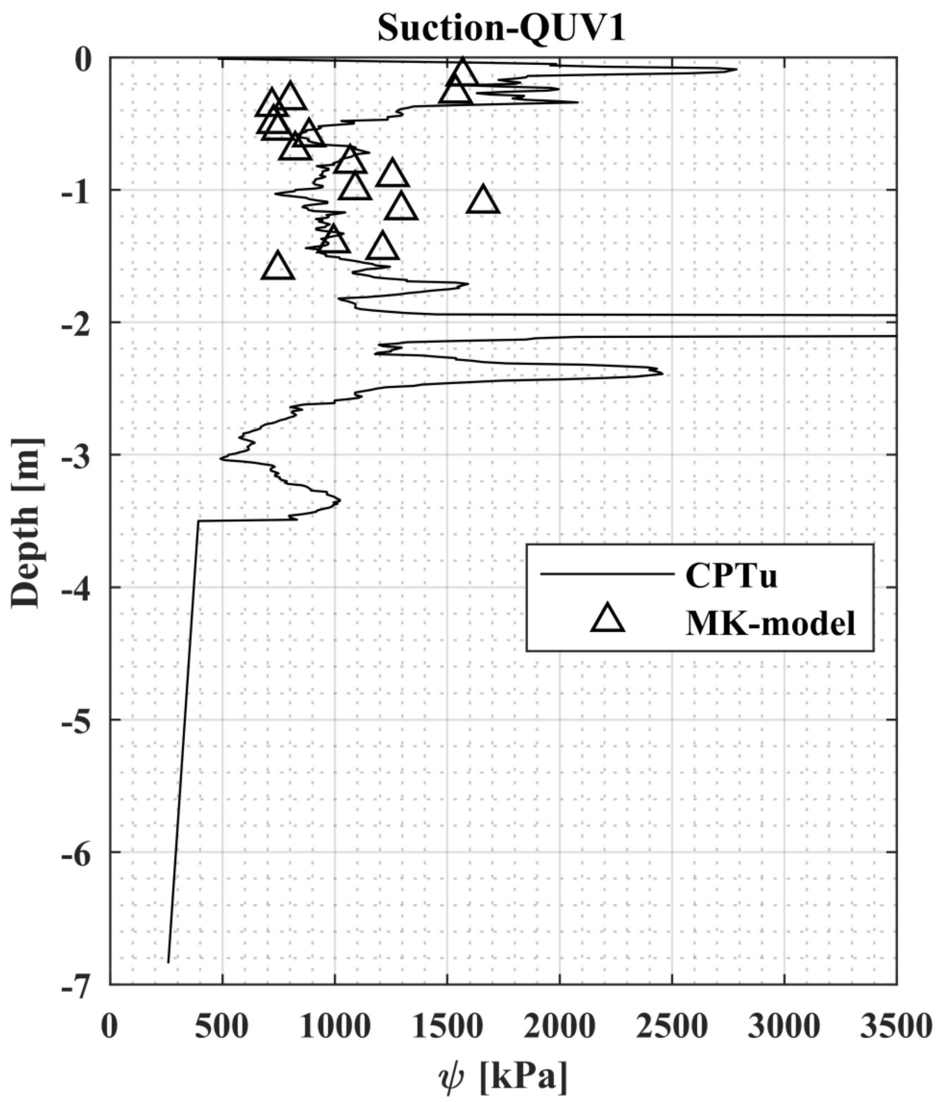
Test Site – Santa Maria della Versa – Results

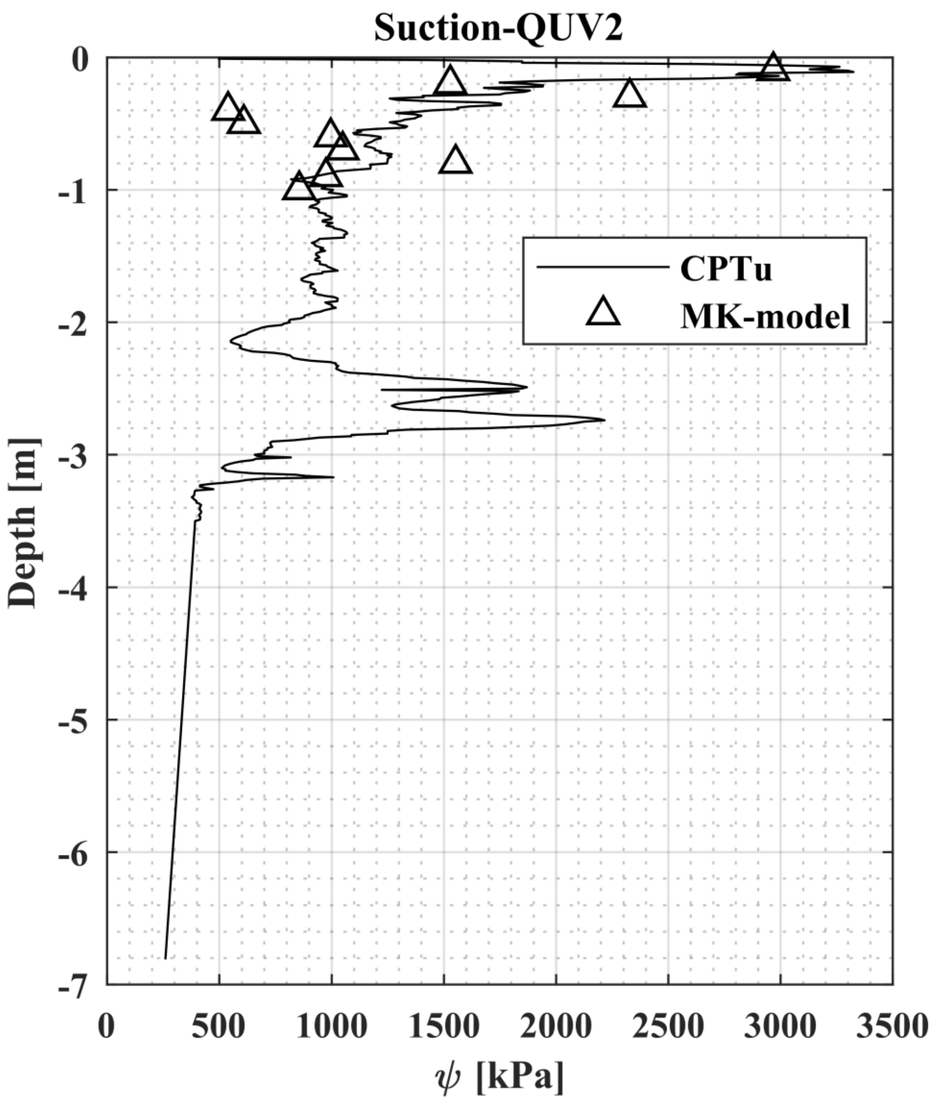


CPTu test results at Santa Maria della Versa (QUV) site



Test Site – Santa Maria della Versa – Results





Estimated values of suction at Santa Maria della Versa (QUV) site

Additional evidences in recent literature

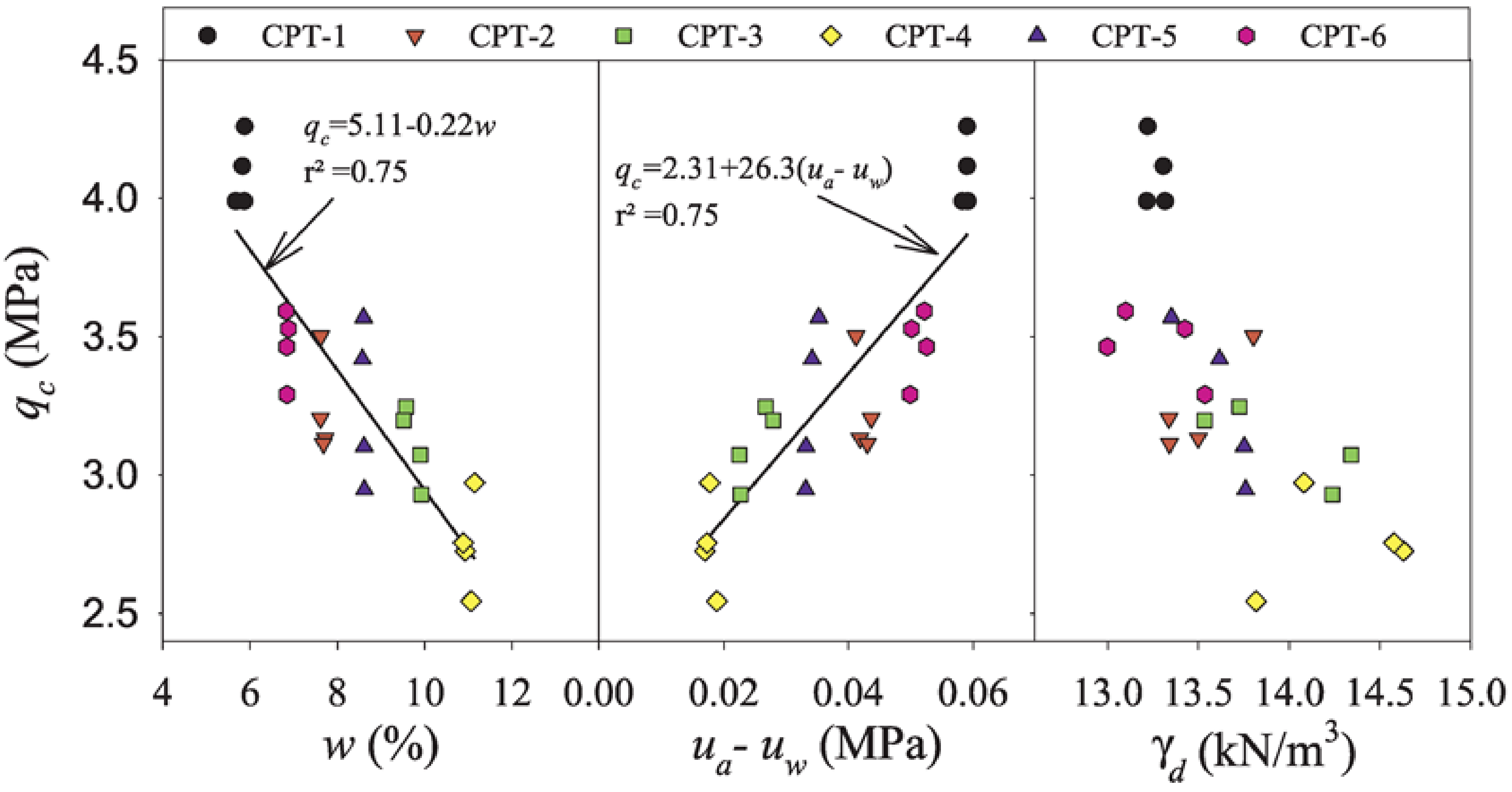
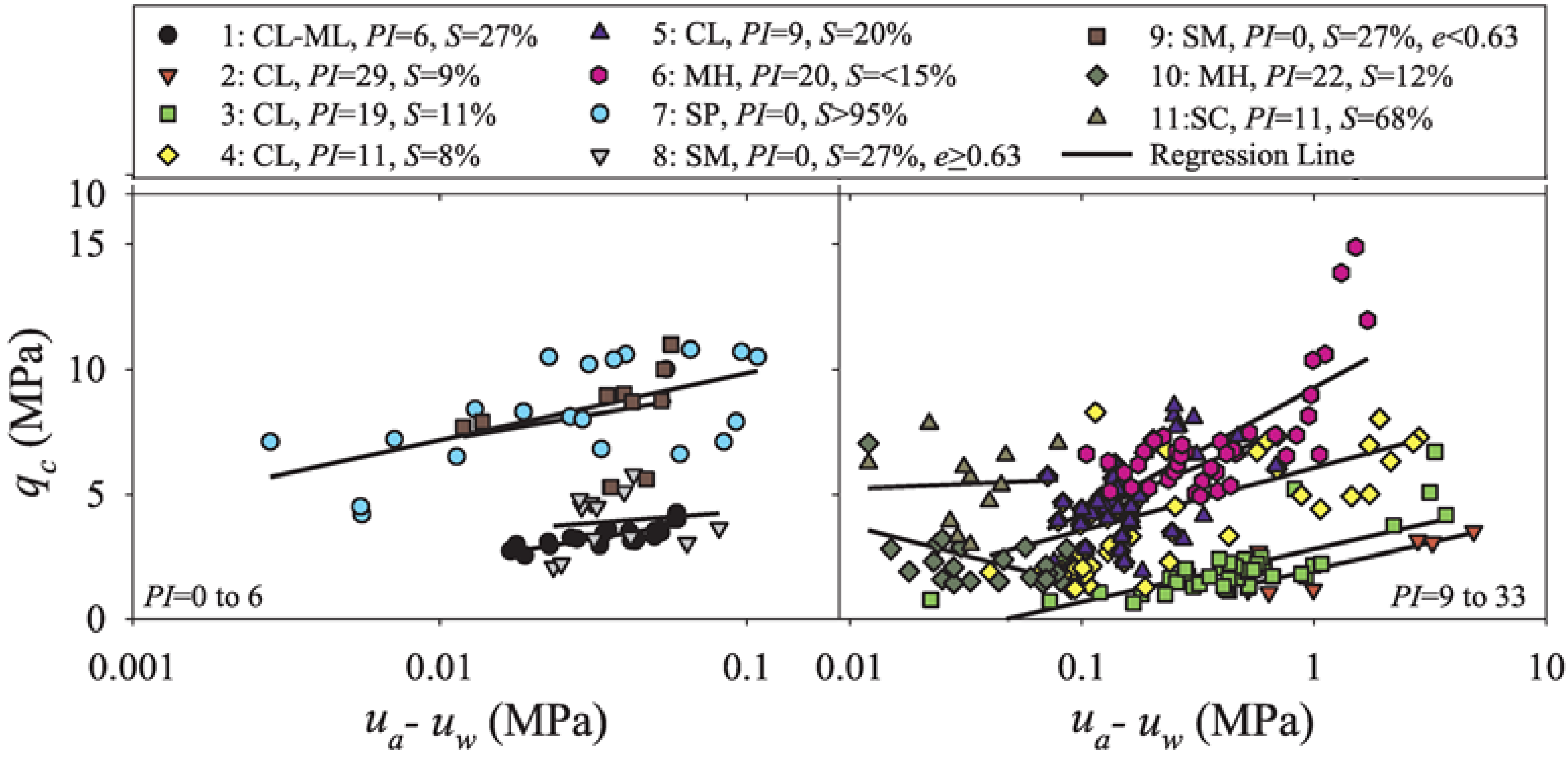


Fig. 3. Summary of CPT results in the OU calibration chamber (under isotropic confining stress of 100 kPa): average tip resistance versus water content, matric suction, and dry unit weight.

Particle unit weight $\gamma_s = \frac{P_s}{V_s}$	**Dry unit weight** $\gamma_d = \frac{P_s}{V_{tot}}$
Void index $e = \frac{V_v}{V_s}$	**Void index** $e = \frac{\gamma_s}{\gamma_d} - 1$
Water content $w = \frac{P_w}{P_s}$	**W (Sr=100%)** $w_{max} = \frac{\gamma_w}{\gamma_s} e$
Degree of Saturation $S_r(\%) = \frac{V_w}{V_v} 100$	**Degree of Saturation** $S_r(\%) = \frac{w}{w_{max}} 100$

Miller, G. A., Tan, N. K., Collins, R. W., Muraleetharan, K. K. (2018). Cone penetration testing in unsaturated soils. *Transportation Geotechnics*, 17, 85-99.



Miller, G. A., Tan, N. K., Collins, R. W., Muraleetharan, K. K. (2018). Cone penetration testing in unsaturated soils. ***Transportation Geotechnics***, 17, 85-99.

Additional evidences in recent literature

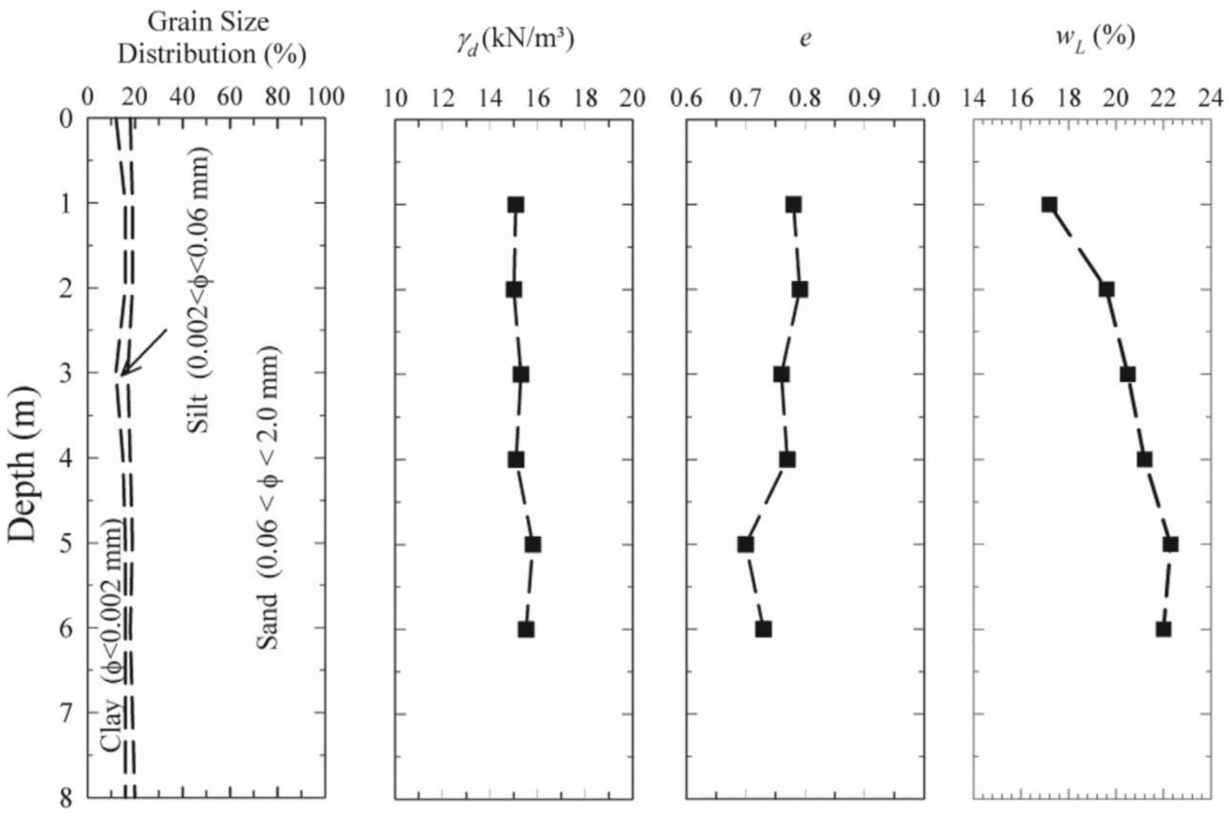
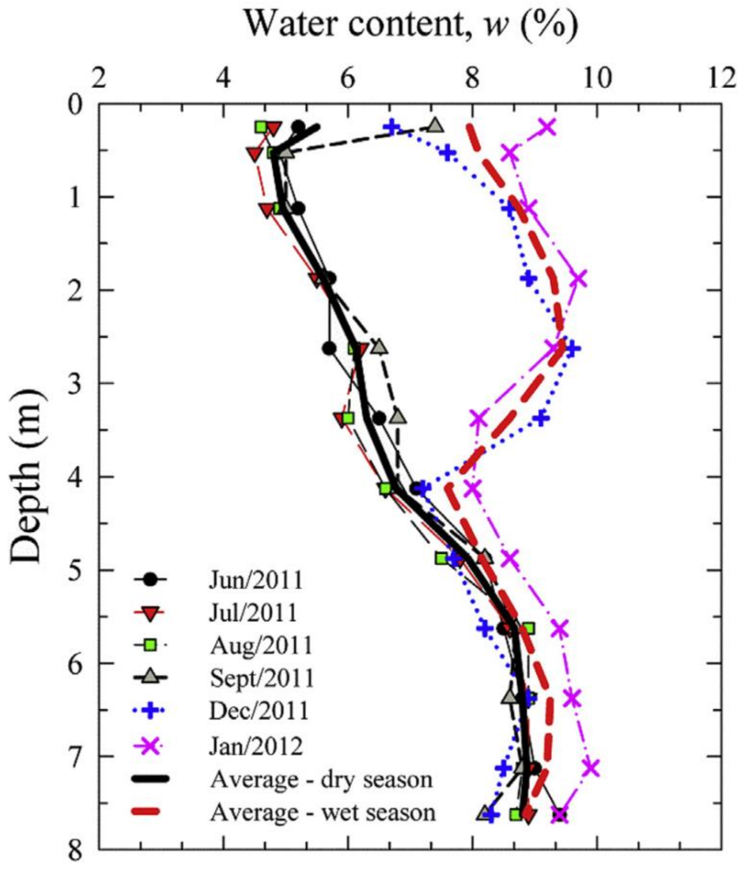


Fig. 1. Grain size distribution and index properties of the soil in the study site (adapted from Saab, 2016).



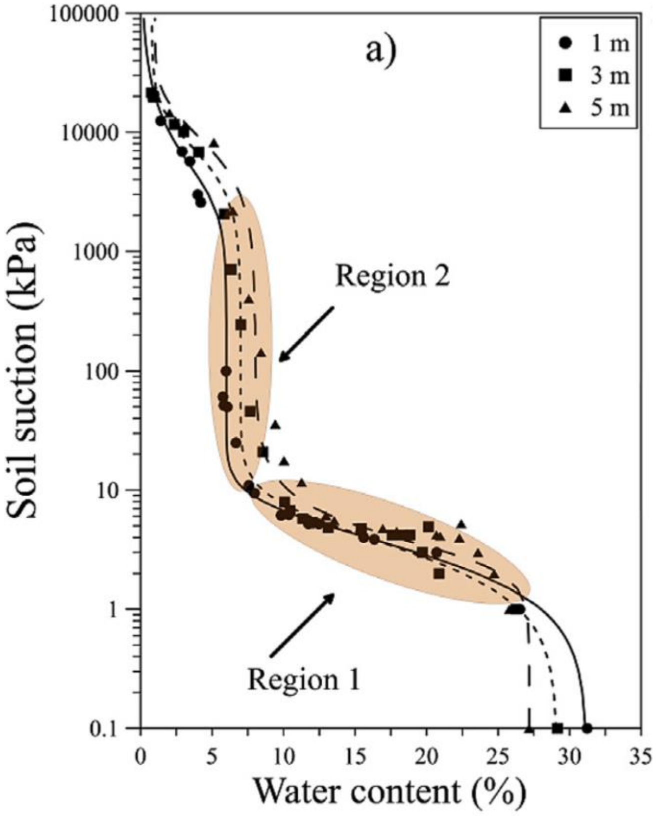


Fig. 4. Water content profiles for wet and dry seasons, highlighting the average profiles.

Clayey Sand (tropical soil)

Giacheti, H. L., Bezerra, R. C., Rocha, B. P., Rodrigues, R. A. (2019). Seasonal influence on cone penetration test: An unsaturated soil site example. *Journal of Rock Mechanics and Geotechnical Engineering*, 11, 361-368.

Additional evidences in recent literature

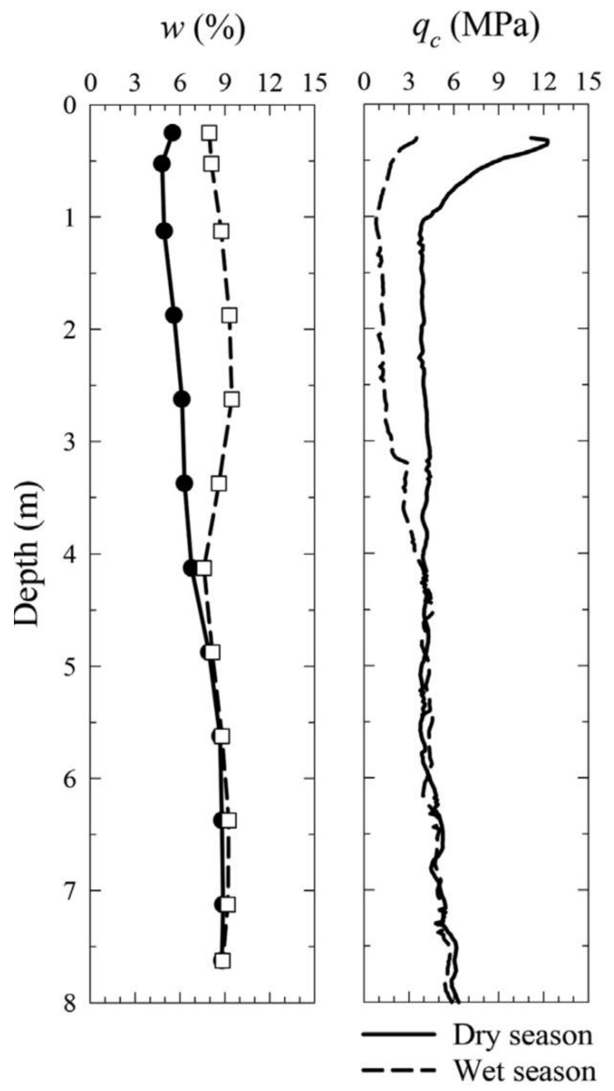


Fig. 7. Average CPTs and water content profiles in the wet and dry seasons.

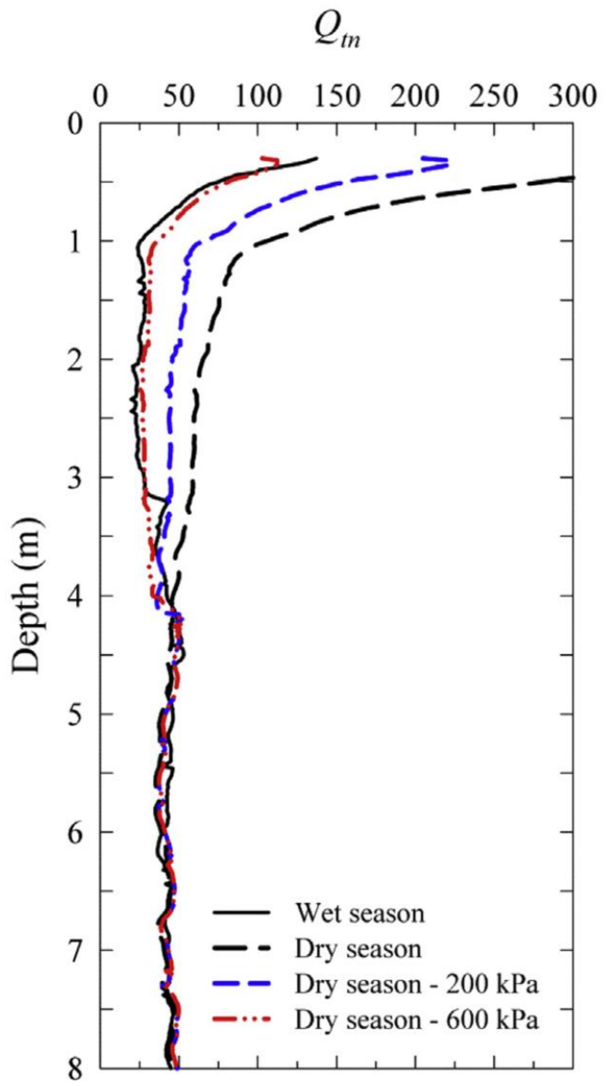


Fig. 8. Normalized cone resistance (Q_{tn}) profiles considering soil suction.

Giacheti, H. L., Bezerra, R. C., Rocha, B. P., Rodrigues, R. A. (2019). Seasonal influence on cone penetration test: An unsaturated soil site example. ***Journal of Rock Mechanics and Geotechnical Engineering***, 11, 361-368.

Conclusions

1. The obtained results are really encouraging and suggest that the proposed method based on the CPTu interpretation could be a fast and economic tool for the estimate of the in situ effective stress state in fine-grained soil deposits.

2. The method applicability requires that the soil is homogeneous, and the water table known.

3. The CPTu should be performed down to a depth below the water table.

4. If the proposed method is applied to evaluate the soil effective stress state the knowledge of the saturation degree is not required. In this case only the water table position and the results from CPTu tests are required.

5. The knowledge of the saturation degree is necessary to estimate suction by using the "effective stress parameter (χ) vs. degree of saturation" relationships available in literature for specific soil types.

Applications and Future Activities

Applications (measure of pore water pressure in different meteorological conditions)

- shallow landslides
- failure of levees
- foundation affected by swelling/shrinking soil problems

Future work

- mini-penetrometer
- special piezocone for the measure of electrical resistivity
- use of geo-electric tomography in combination with CPT

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14 giugno 2019

THANKS FOR THE ATTENTION

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