1950 - 2020
Swedish Geotechnical Society
Svenska Geotekniska Föreningen

Dilatometer (DMT) and Seismic Dilatometer (SDMT) for site characterization

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Stoccolm, 11 March 2020

MARCHETTI DILATOMETER

www.marchetti-dmt.it

Course Description:

The course consists in two parts:

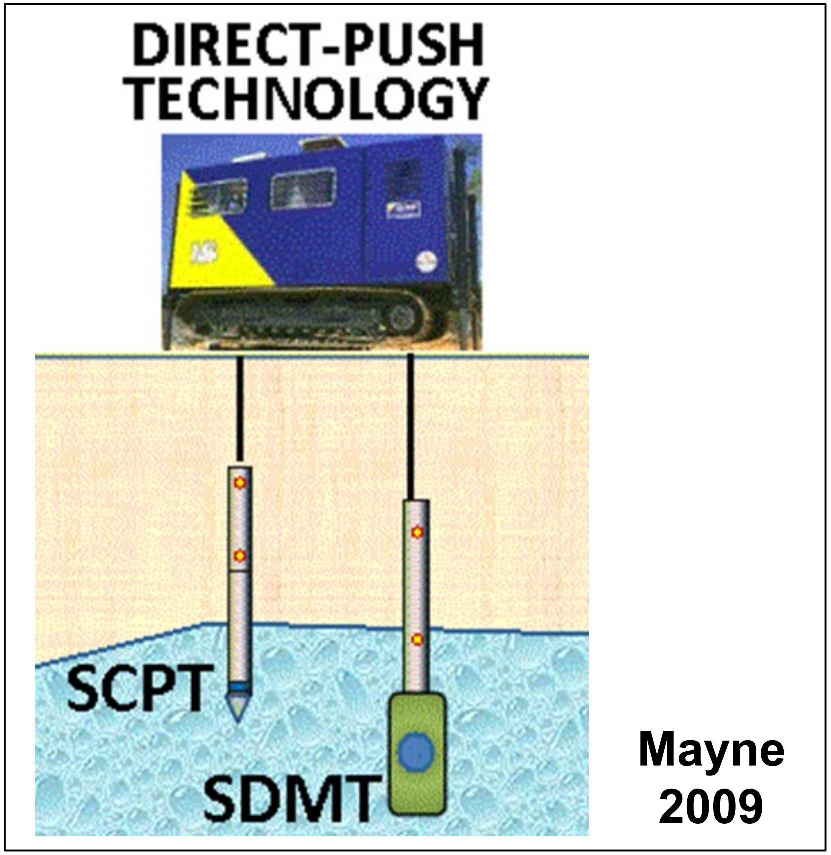
- DMT/SDMT for in situ-testing - Diego Marchetti
- DMT/SDMT testing in Sweden - Dr. Tara Wood

At the end of the course, participants will have a clear picture of the DMT and SDMT technology and the geotechnical parameters it may provide for soil characterization. In future projects, they will be able to consider the possible benefits of employing this cost-effective equipment to improve soil investigations and optimize their geotechnical design.

In penetrable soils: Lab Testing → Direct Push: SCPT & SDMT

Direct Push Technology:

- ✓ simple
- ✓ fast
- ✓ repeatable
- ✓ continuous soil profile
- ✓ results real time



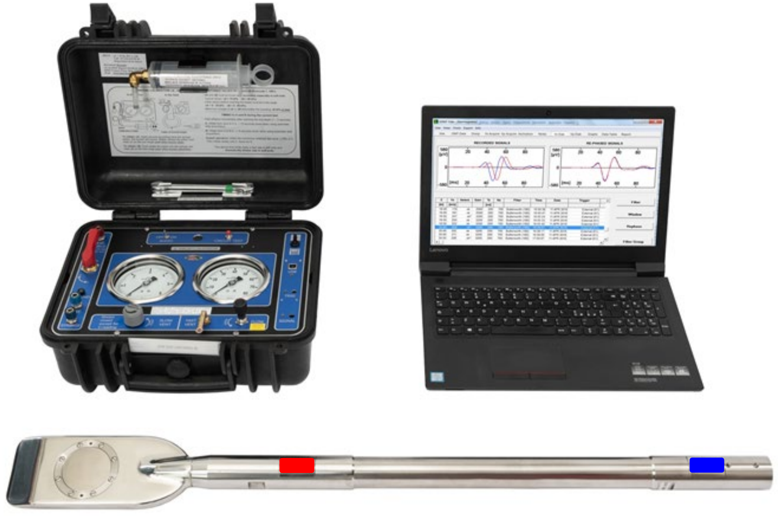
Sands:

recovering undisturbed samples very difficult

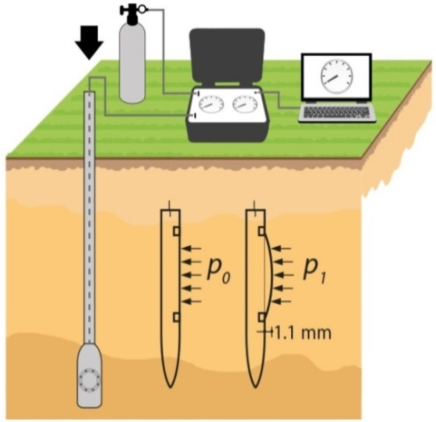
→ Direct Push Technology is the state-of-practice

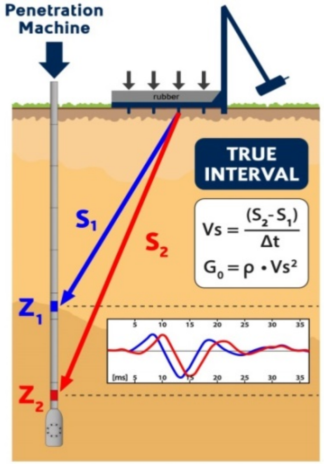
Seismic Dilatometer (S + DMT)

Seismic Dilatometer (SDMT)



Flat Dilatometer 1980

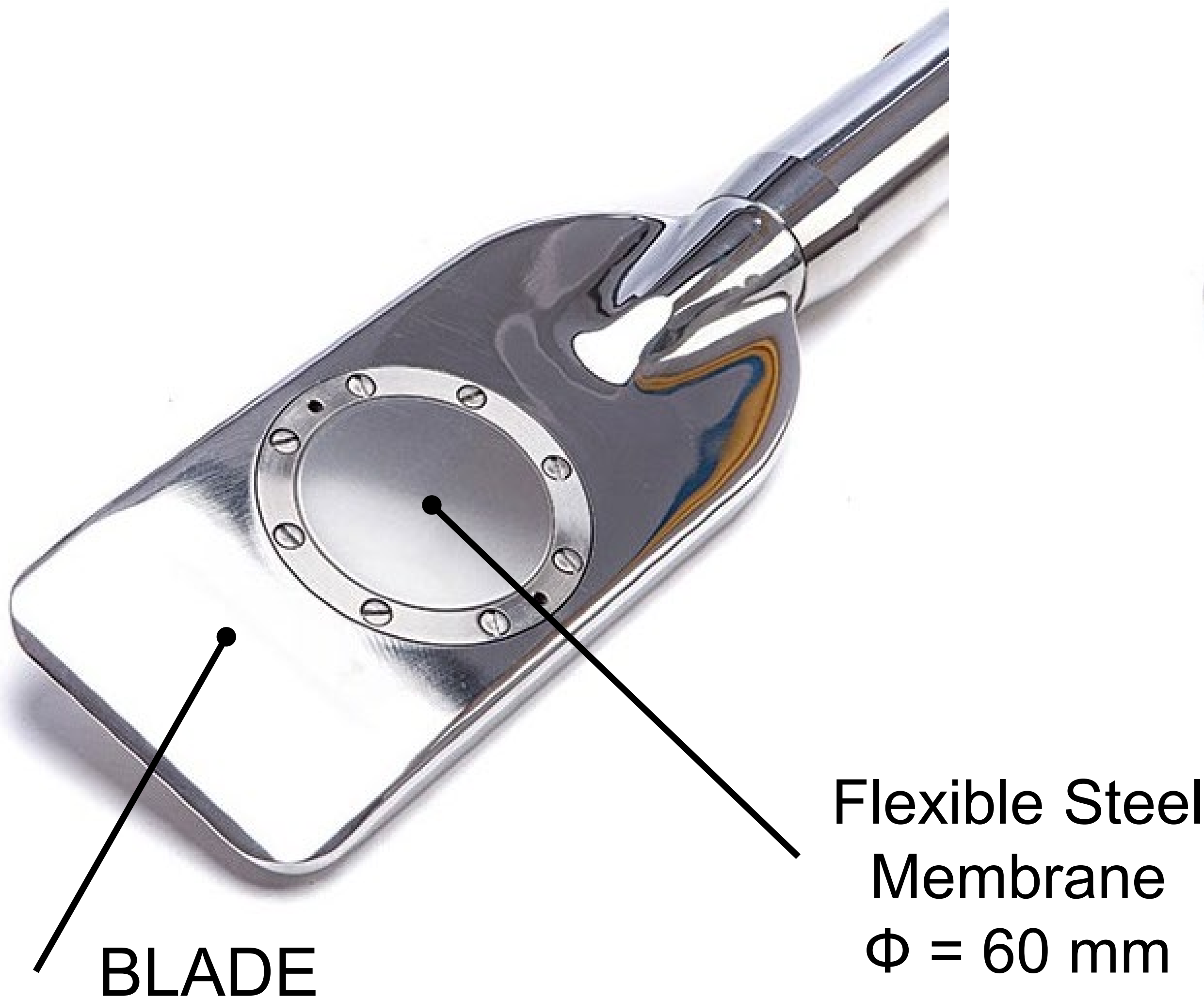




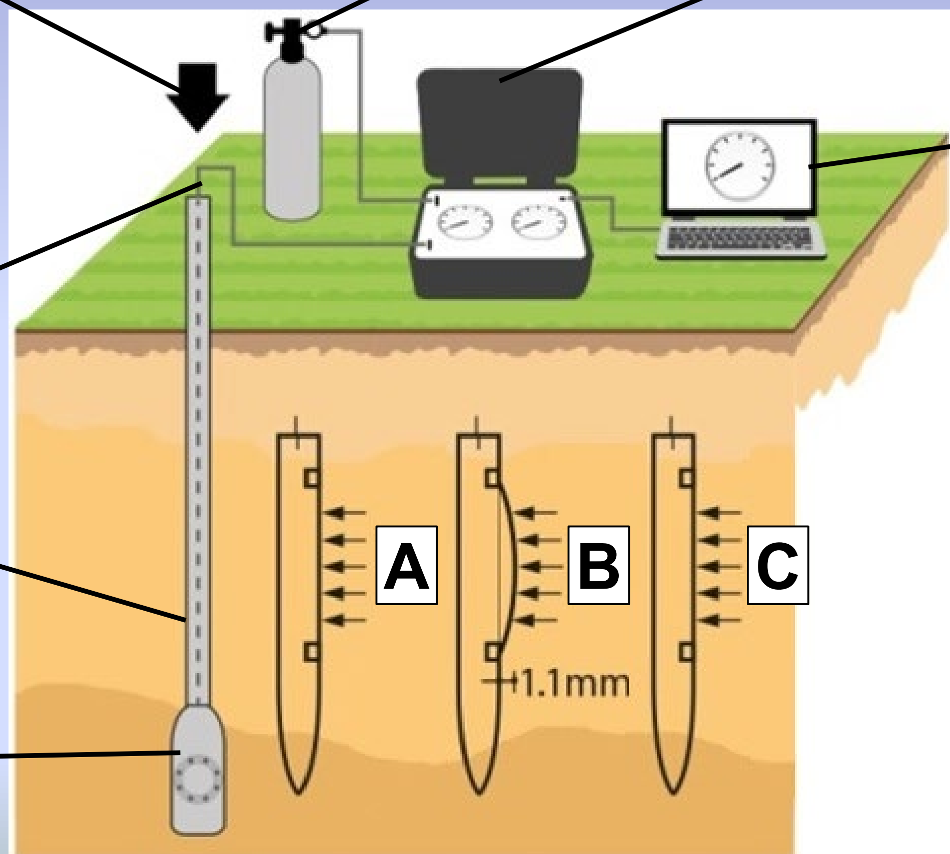
Seismic Module 2004

Equipment and Test Procedures

DMT blade



DMT Test Layout



Test Procedure

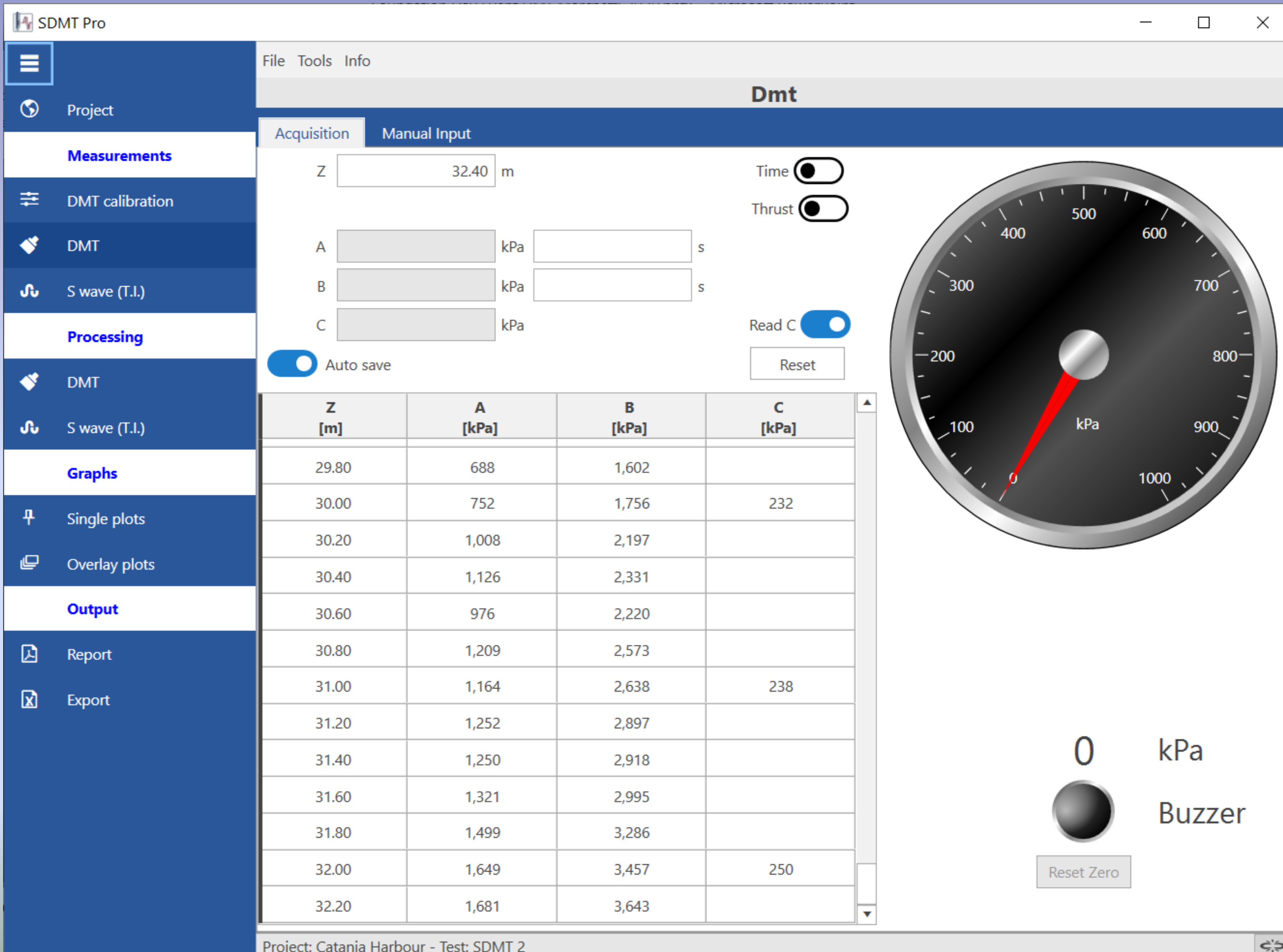
stop every 20 cm

A : Lift-off pressure

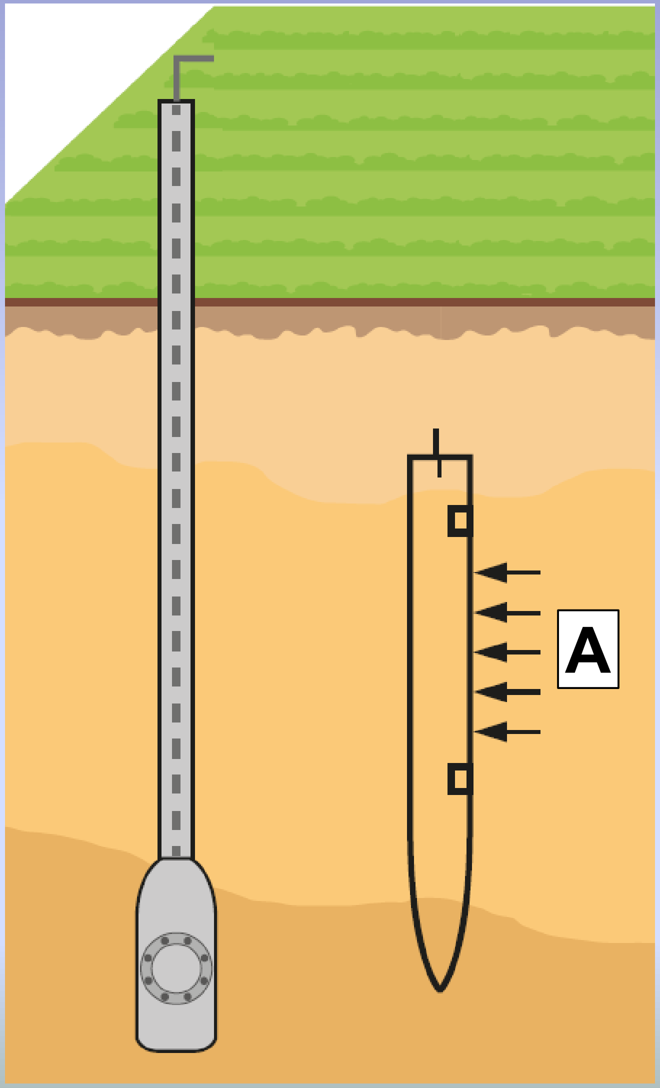
B : Pressure for 1.1 mm expansion

C : Closing pressure

DMT Data: A, B and C with depth (Z)



DMT Dissipation Test



Test procedure:

- *Stop penetration (origin T = 0 s)*
- *Repeat only A readings*

NO MEMBRANE EXPANSION

T [min]	A [kPa]
0.280	1,040
0.600	966
0.870	921
1.350	868
2.430	776
4.600	674

Dissipation Test

SDMT Pro

File Tools Info

Dissipation

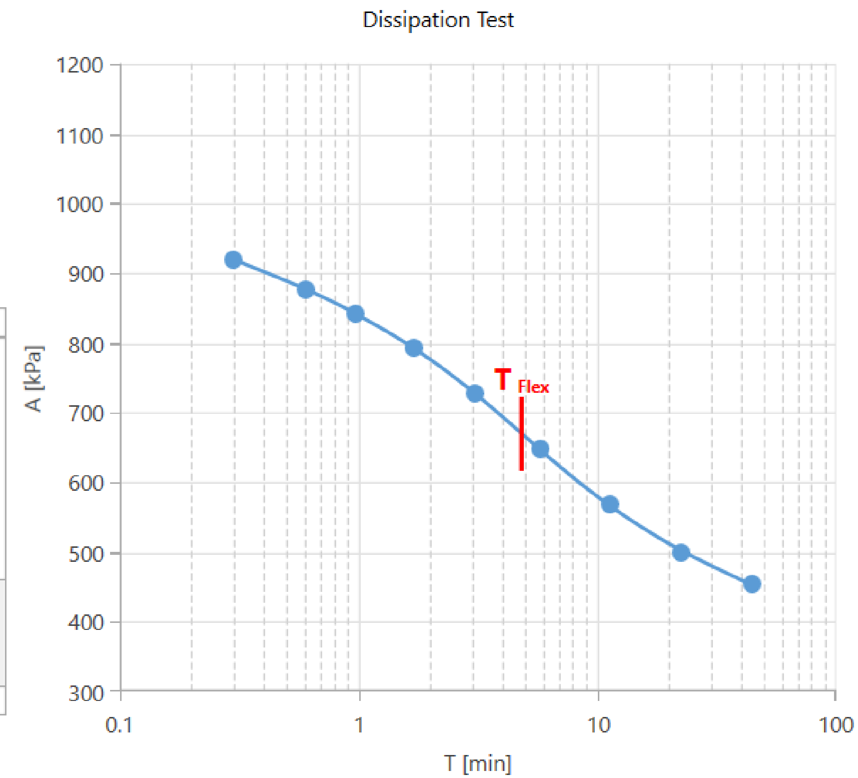
Data Acquisition

Depth 27.40 m

Start time 10/1/2015 10:52:23 AM

New Delete

N	T [min]	A [bar]	Time
1	0.300	9.19	10:52:41 AM
2	0.600	8.77	10:52:59 AM
3	0.970	8.41	10:53:21 AM
4	1.700	7.92	10:54:05 AM
5	3.070	7.27	10:55:27 AM
6	5.750	6.48	10:58:08 AM



T_{Flex} 4.85 [min] Info T_{flex}

B_{Final} bar Delete

Save Cancel Verify

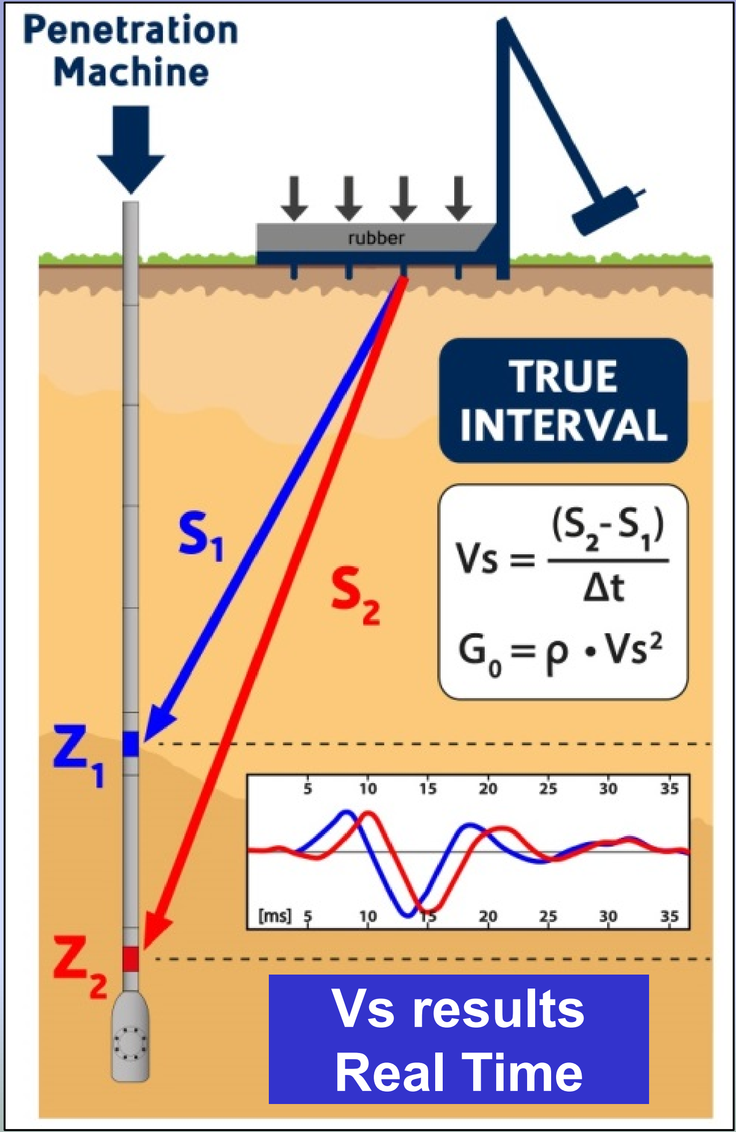
Project: Paracelsusbad - Test: SDMT 2/15

SDMT – Test Layout

– Top Sensor

– Acquisition Board

– Bottom Sensor

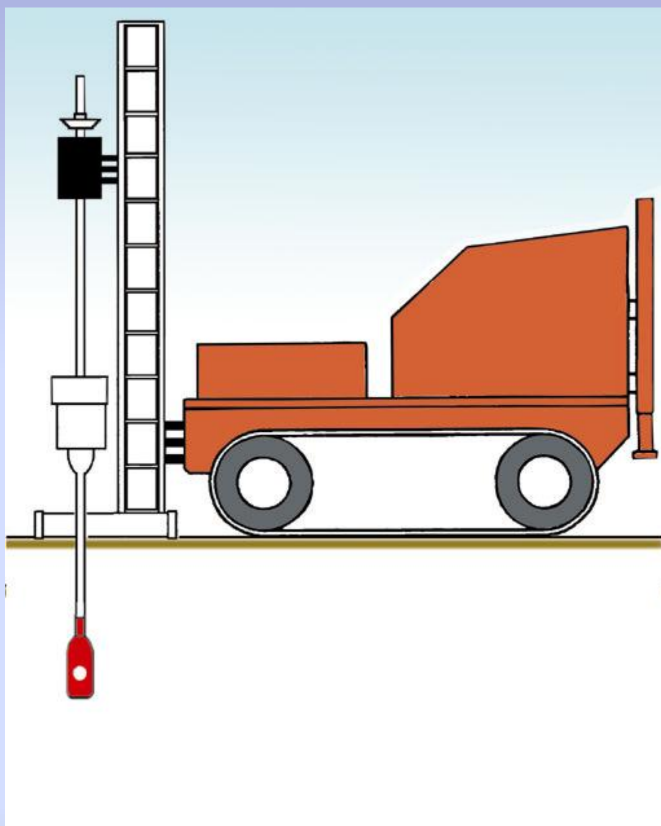


Truck Penetrometer (most productive)

Zelazny Most Tailings Dam (Poland)
November 2019

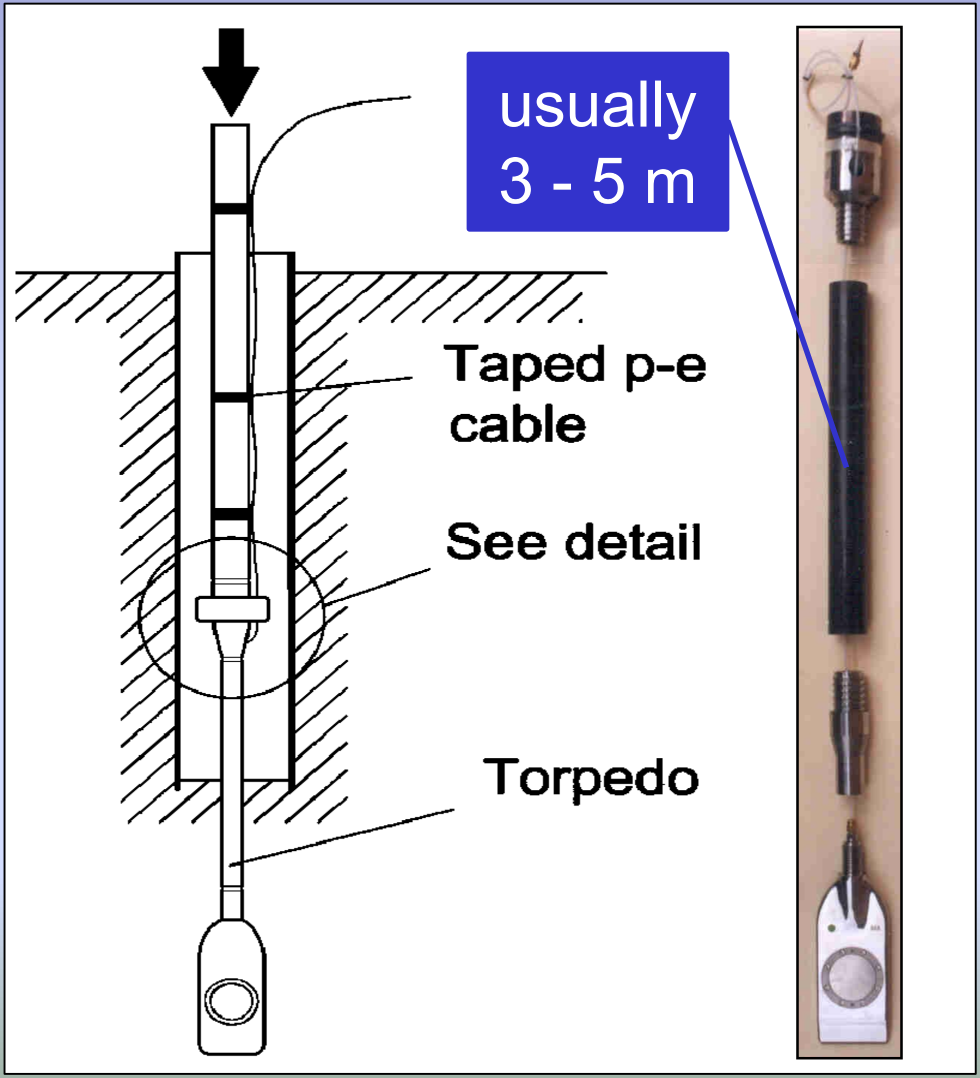
Blade penetration (~ 25 ton)

Light Penetrometer (less expensive)



DRILL-RIG (overcome obstacles)

Test starts from bottom of a borehole (like SPT, but 3-5m long)



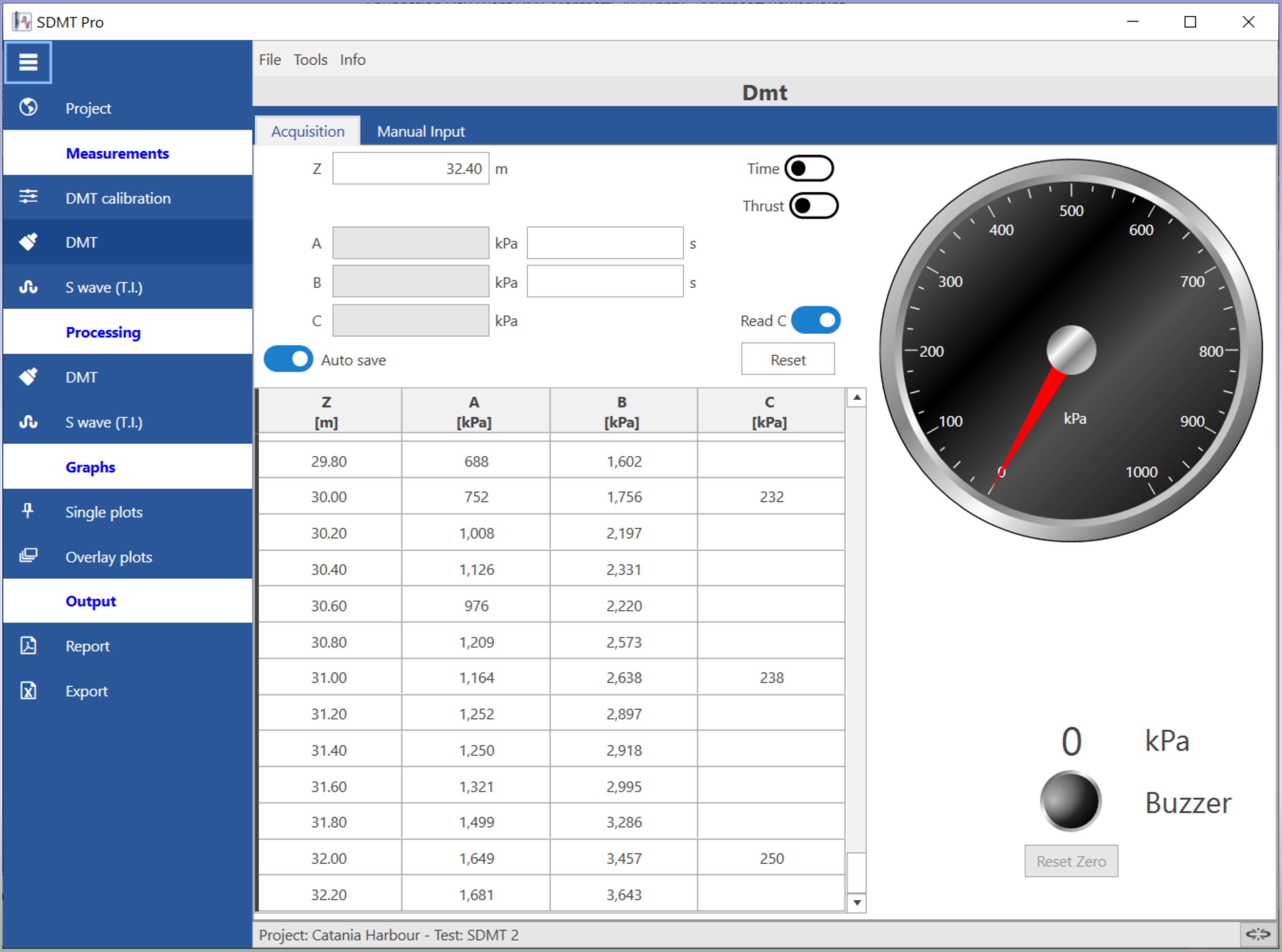
≈ 40 m / day
ability to overcome obstacles

DMT testable Soils (same blade)

- ALL SANDS, SILTS, CLAYS
- **Very soft soils (Su = 2-4 kPa, M=0.5 MPa)**
- **Hard soils/Soft Rock (Su = 1 MPa, M=400 MPa)**
- **Blade robust (safe push 25 ton)**

Interpretation of the Results

Field Data: Depth A, B, C

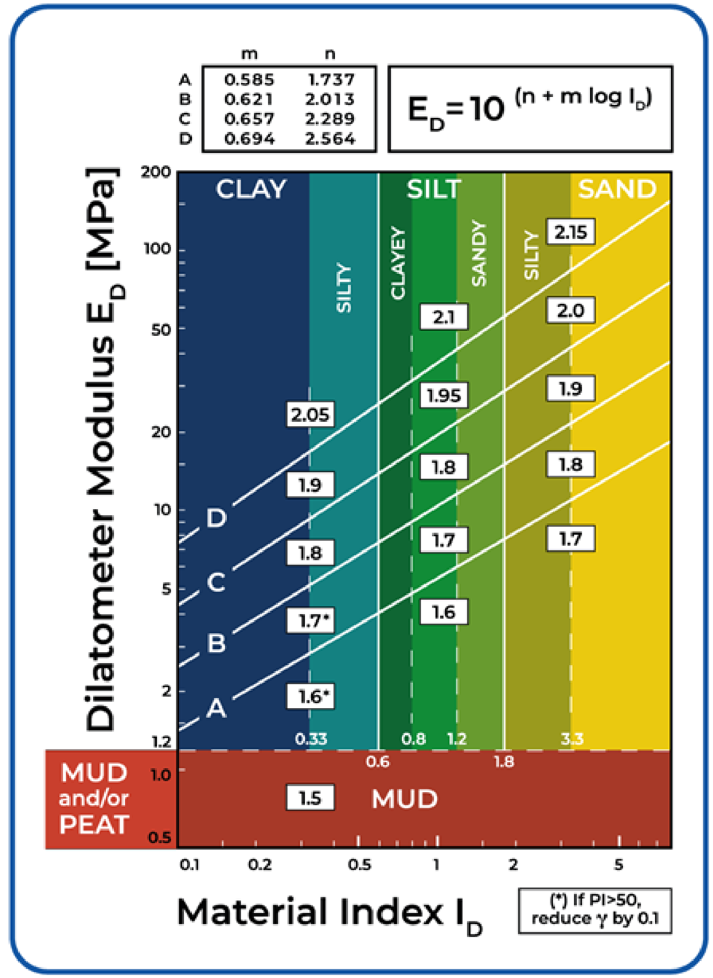


Z [m]	A [kPa]	B [kPa]	C [kPa]
29.80	688	1,602	
30.00	752	1,756	232
30.20	1,008	2,197	
30.40	1,126	2,331	
30.60	976	2,220	
30.80	1,209	2,573	
31.00	1,164	2,638	238
31.20	1,252	2,897	
31.40	1,250	2,918	
31.60	1,321	2,995	
31.80	1,499	3,286	
32.00	1,649	3,457	250
32.20	1,681	3,643	

DMT Formulae (1980 - today)

	SYMBOL	PARAMETER NAME	FORMULA /DESCRIPTION	
Field Readings	A	First Reading	Membrane lift-off pressure	
	B	Second Reading	Pressure for 1.1 mm membrane expansion	
	C	Third Reading	Membrane closing pressure	
	ΔA	Membrane Calibration (A in free air)	Suction as positive pressure	
	ΔB	Membrane Calibration (B in free air)	Inflation as positive pressure	
	[T, A]	Dissipation Test Readings	A-readings with time (at specific depth)	
Corrected Readings	P_0	Corrected First Reading	$P_0 = 1.05 (A + \Delta A) - 0.05 (B - \Delta B)$	
	P_1	Corrected Second Reading	$P_1 = B - \Delta B$	
	P_2	Corrected Third Reading	$P_2 = C + \Delta A$	
Intermediate Parameters	I_D	Material Index	$I_D = (P_1 - P_0) / (P_0 - U_0)$	
	K_D	Horizontal Stress Index	$K_D = (P_0 - U_0) / \sigma'_{v0}$	
	E_D	Dilatometer Modulus	$E_D = 34.7 (P_1 - P_0)$	
	U_D	Pore Pressure Index	$U_D = (P_2 - U_0) / (P_0 - U_0)$	
	T_{Flex}	Dissipation Flex Point		
Interpreted Geotechnical Parameters	γ	Unit weight	see unit weight chart	
	K_0	Earth Pressure Coefficient	$K_{0\ DMT} = (K_D / 1.5)^{0.47} - 0.6$	$I_D \le 1.2$
	OCR	Overconsolidation Ratio	$OCR_{DMT} = (0.5\ K_D)^{1.56}$	$I_D \le 1.2$
	Su	Undrained Shear Strength	$Su_{DMT} = 0.22\ \sigma'_{v0} (0.5\ K_D)^{1.25}$	$I_D \le 1.2$
	Φ	Friction Angle	$\Phi_{safe\ DMT} = 28 + 14.6 \log K_D - 2.1 \log^2 K_D$	$I_D > 1.8$
	M	Vertical Drained Constrained Modulus	$M_{DMT} = R_M E_D$	
			If $(I_D \le 0.6)$ $R_M = 0.14 + 2.36 \log K_D$	
			If $(I_D \ge 3)$ $R_M = 0.5 + 2 \log K_D$	
			If $(0.6 < I_D < 3)$ $R_M = R_{M0} + (2.5 - R_{M0}) \log K_D$	
			$R_{M0} = 0.14 + 0.15 (I_D + 0.6)$	
			If $(K_D > 10)$ $R_M = 0.32 + 2.18 \log K_D$	
			If $(R_M < 0.85)$ set $R_M = 0.85$	
	C_h	Coefficient of Consolidation	$C_{h\ DMT} = 7\ cm^2 / T_{Flex}$	
	K_h	Coefficient of Permeability	$K_{h\ DMT} = C_{h\ DMT}\ \gamma_w / M_h$ $(M_h \approx K_{0\ DMT} M_{DMT})$	
	U_0	Equilibrium Pore Pressure	$U_0 \approx P_2$ for drained layers only	

DMT soil behaviour type chart



Corrected readings:

to account for membrane rigidity (calibration)

DMT Field Readings	Corrected Readings
A	**P_0**: Corrected A reading
B	**P_1**: Corrected B reading
C	*P_2: Corrected C reading*

DMT Intermediate parameters

DMT Field Readings		Intermediate Parameters
P_0	→	I_D: Material Index
P_1		K_D: Horizontal Stress Index
P_2		E_D: Dilatometer Modulus
		U_D: Pore Pressure Index

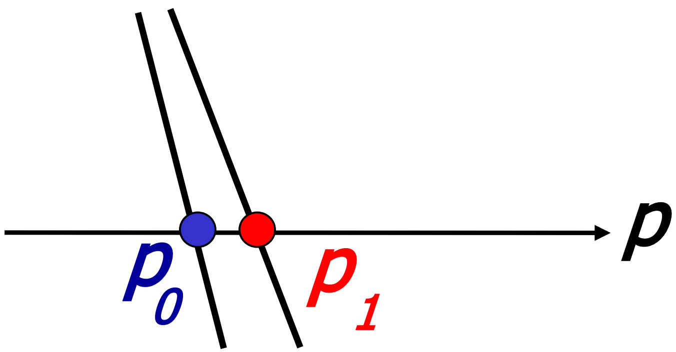
I_D, K_D, E_D, U_D are definitions, not correlations !!!

Interpreted Geotechnical Parameters

Intermediate Parameters	Interpreted Geotechnical Parameters
I_D	M: Constrained Modulus
E_D	Cu: Undrained Shear Strength (clay)
K_D	K_0: Earth Pressure Coeff (clay)
U_D	OCR: Overconsolidation Ratio (clay)
	Φ: Safe floor friction angle (sand)
	γ : Unit weight and description
	U : Pore pressure (sand)
	Drained vs Undrained behaviour

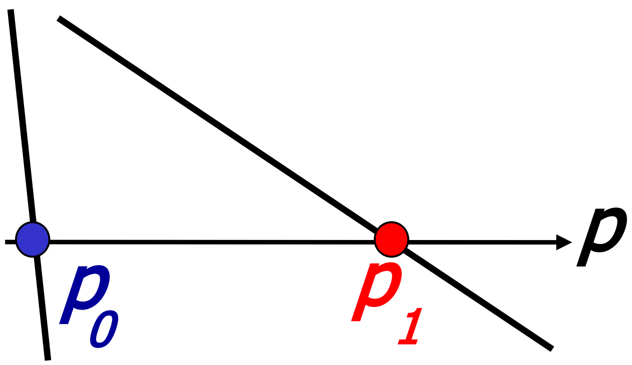
I_D contains information on soil type

CLAY



$$\frac{P_1}{P_0} \approx 1.1\text{-}1.3$$

SAND



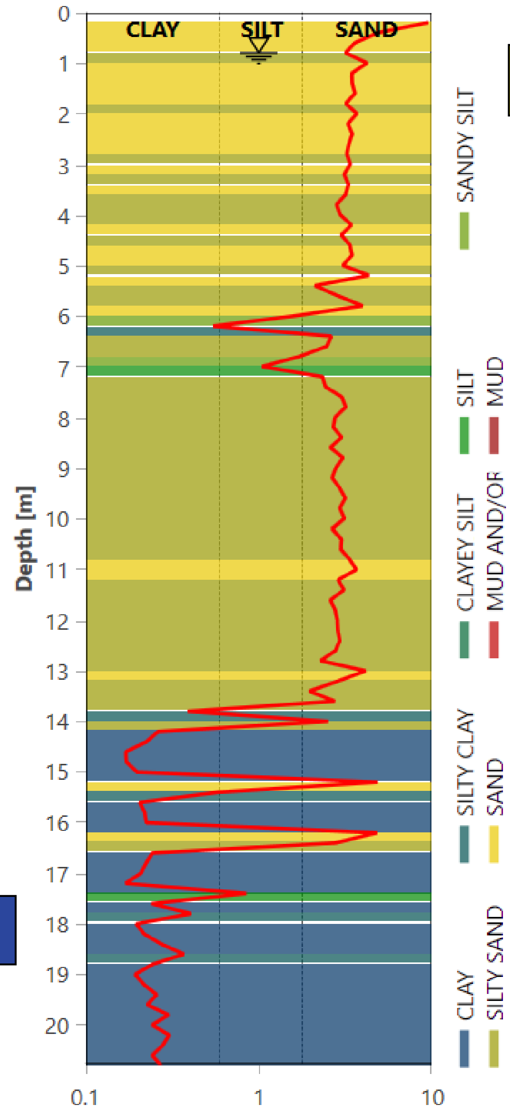
$$\frac{P_1}{P_0} \geq 2.5$$

SILT falls in between

Definition: $I_D = \frac{(P_1 - P_0)}{(P_0 - U_0)}$

I_D contains information on soil type

Material Index



SAND

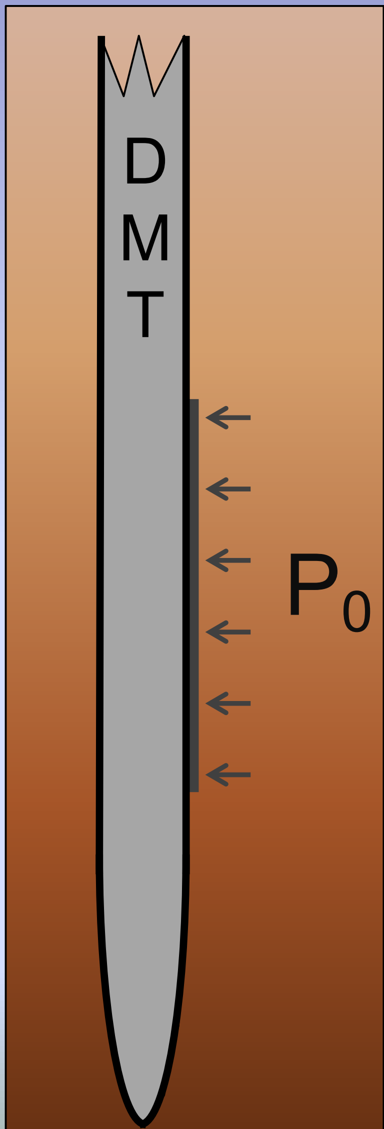
Z [m]	P_0 [bar]	P_1 [bar]
…	…	…
2.0	2.61	11.90
2.2	2.78	11.55
2.4	2.68	11.53
2.6	2.64	10.90
2.8	3.06	12.40
3.0	3.08	12.90
…	…	…

CLAY

Z [m]	P_0 [bar]	P_1 [bar]
…	…	…
19.0	5.86	6.65
19.2	5.91	6.80
19.4	5.90	6.95
19.6	6.01	6.95
19.8	6.04	7.30
20.0	6.00	7.02
…	…	…

Fiumicino 2005

K_D contains information on stress history



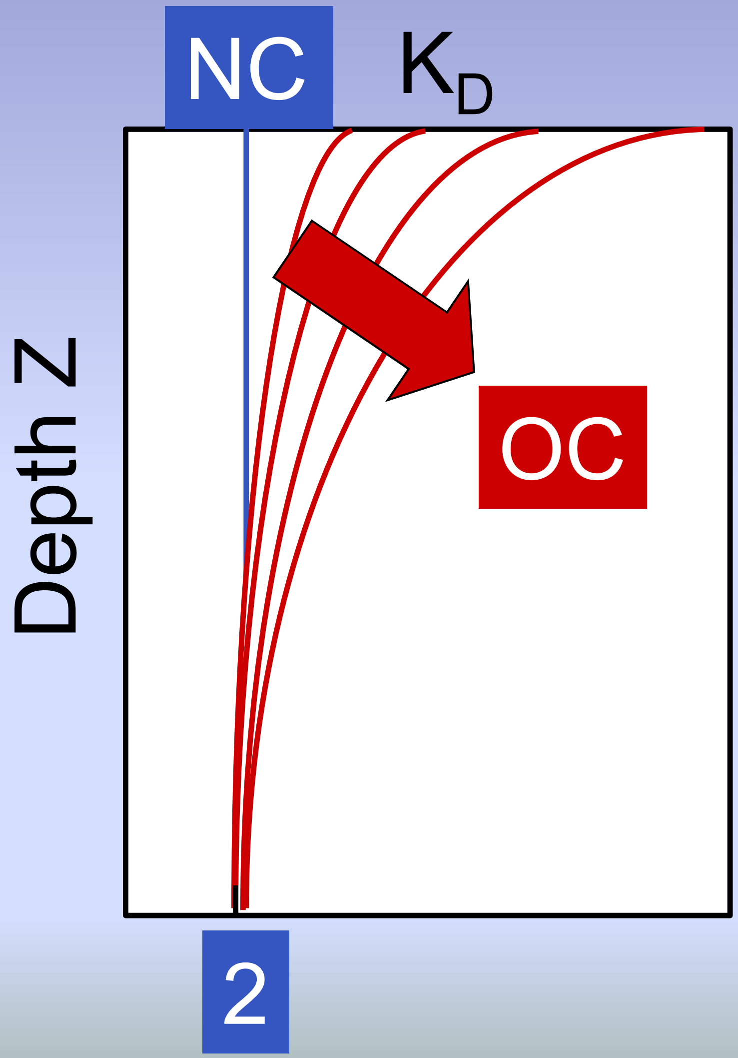
$$K_D = \frac{(P_0 - U_0)}{\sigma'_v}$$

same formula as K_0: $(P_0 - U_0) \rightarrow \sigma'_h$

K_D is an '*amplified*' K_0, because $(P_0 - U_0)$ is an '*amplified*' σ'_h, due to penetration

K_D well correlated to K_0 & OCR (clay)

K_D contains information on stress history

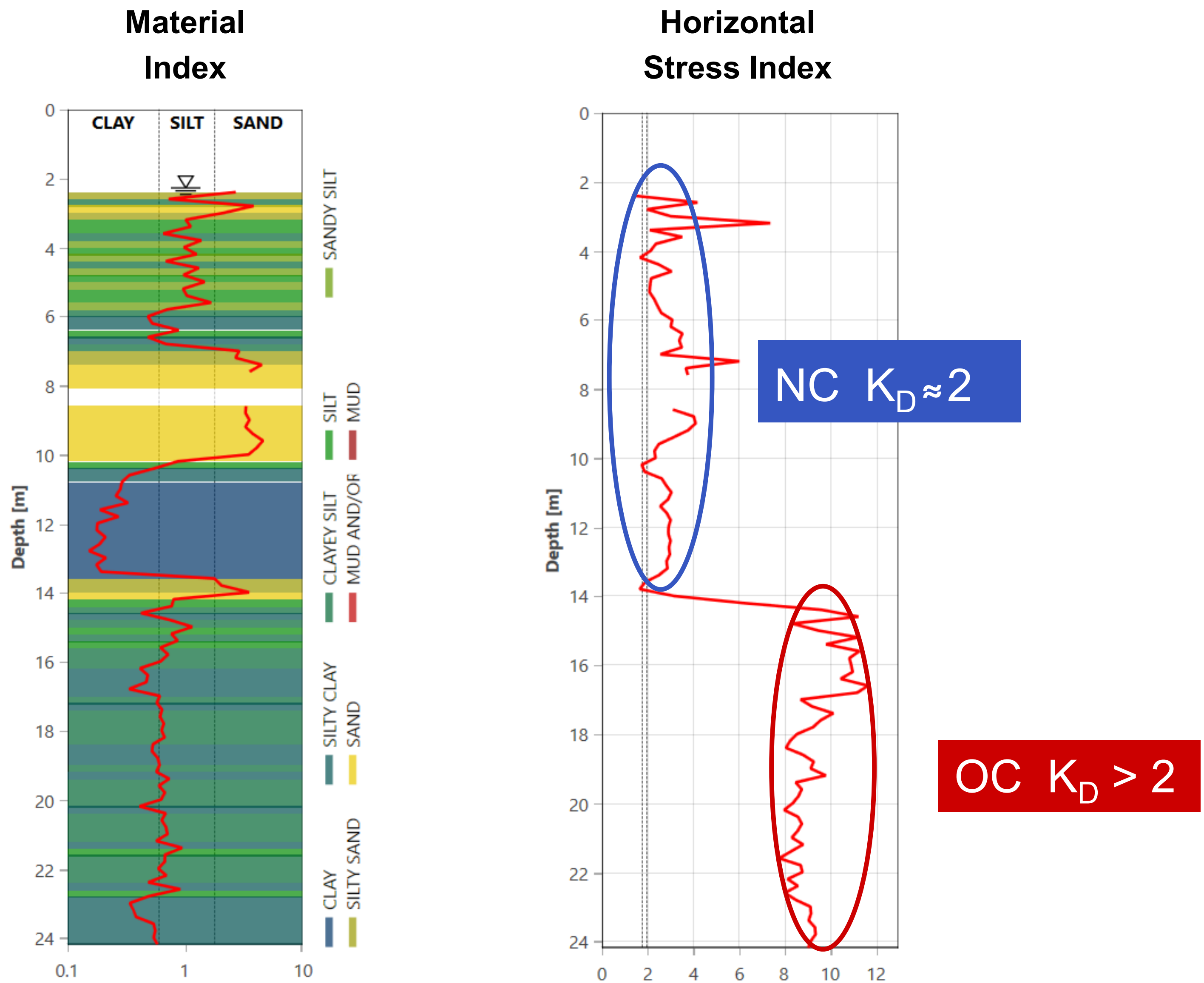


K_D = 2 in NC clay (OCR = 1)

KD > 2 in OC clay (OCR > 1)

K_D stress history index

K_D contains information on stress history



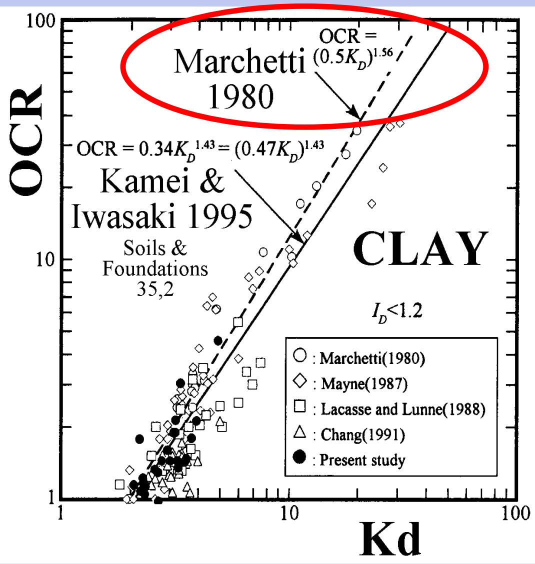
Taranto 1987

CLAY: K_D correlated to OCR

$$OCR = (0.5 \cdot K_D)^{1.56}$$ **Marchetti 1980 (experimental)**

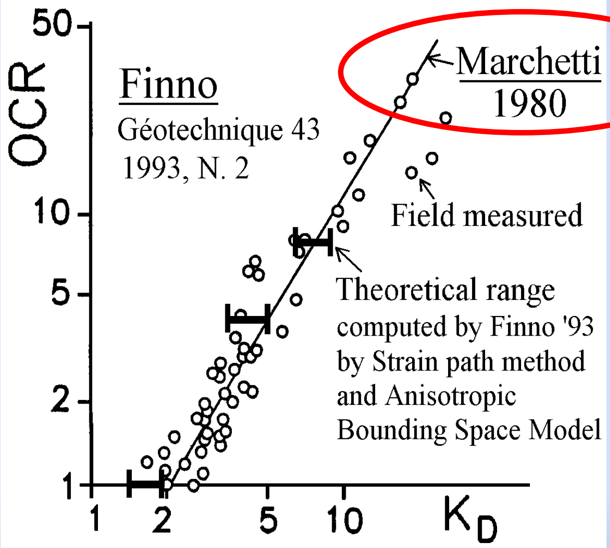
Experimental

Kamei & Iwasaki 1995



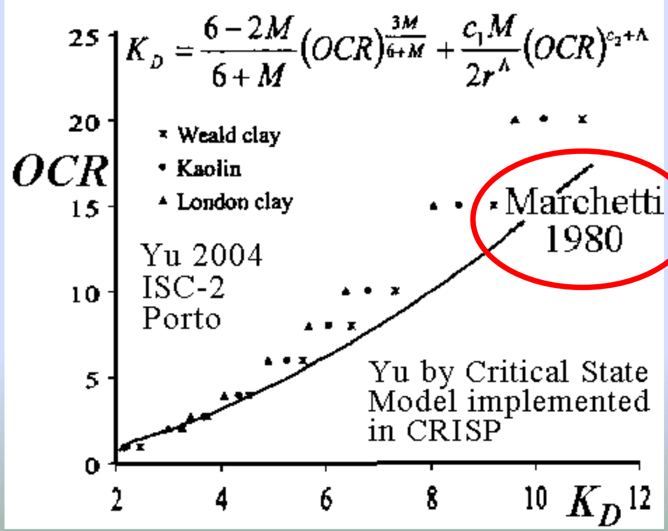
Theoretical

Finno 1993



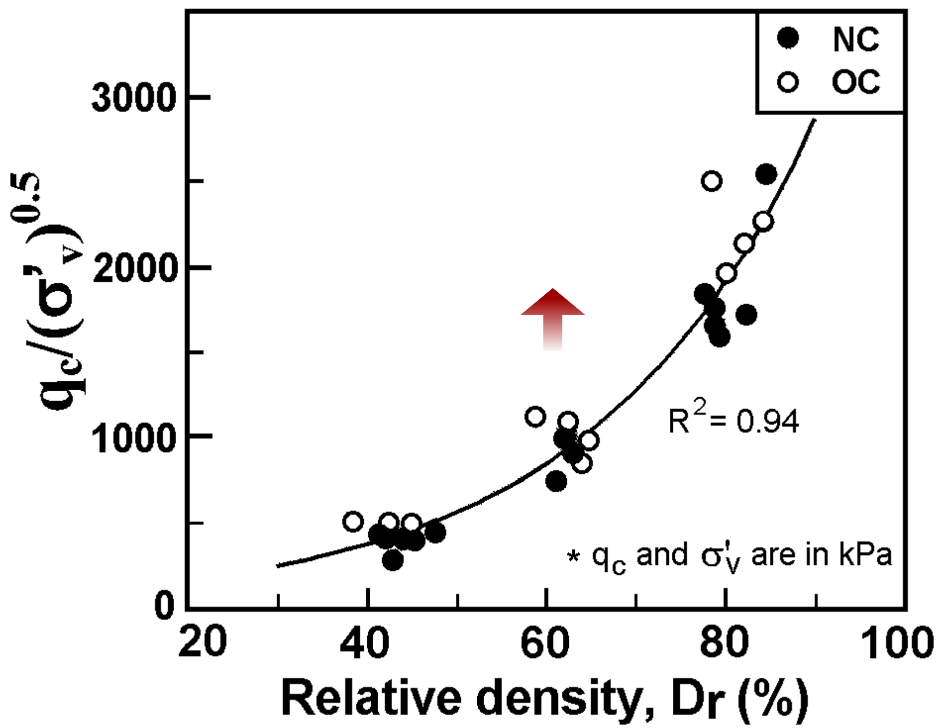
Theoretical

Yu 2004

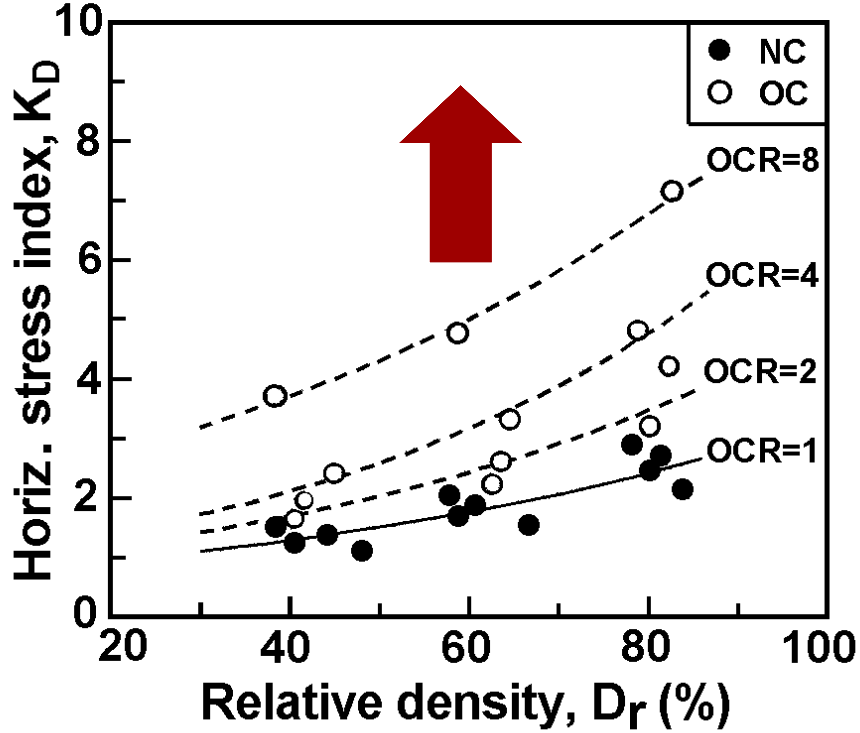


SANDS: Stress History effects on CPT & DMT

OCR sensitivity of Q_c (CPT)



OCR sensitivity of K_D (DMT)



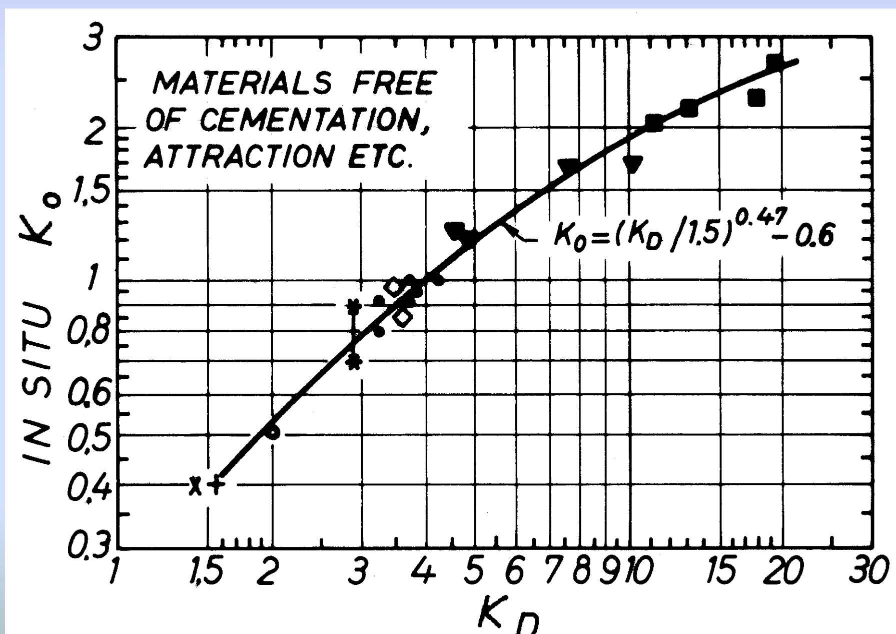
Lee 2011, Eng. Geology – CC in sand

→ K_D more sensitive to OCR than Q_C

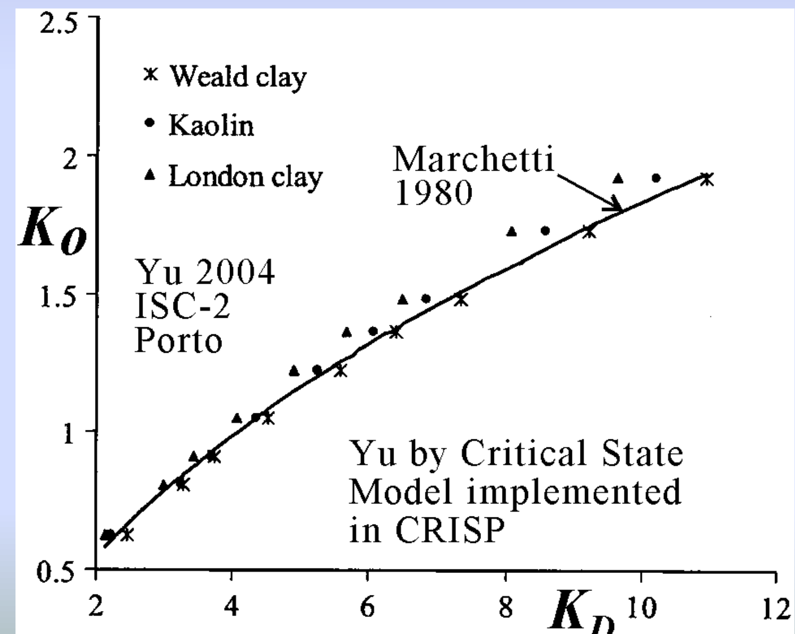
CLAY: K_D correlated to K_0

$$K_0 = \left(\frac{K_D}{1.5}\right)^{0.47} - 0.6$$ Marchetti 1980 (experimental)

Experimental
Marchetti (1980)

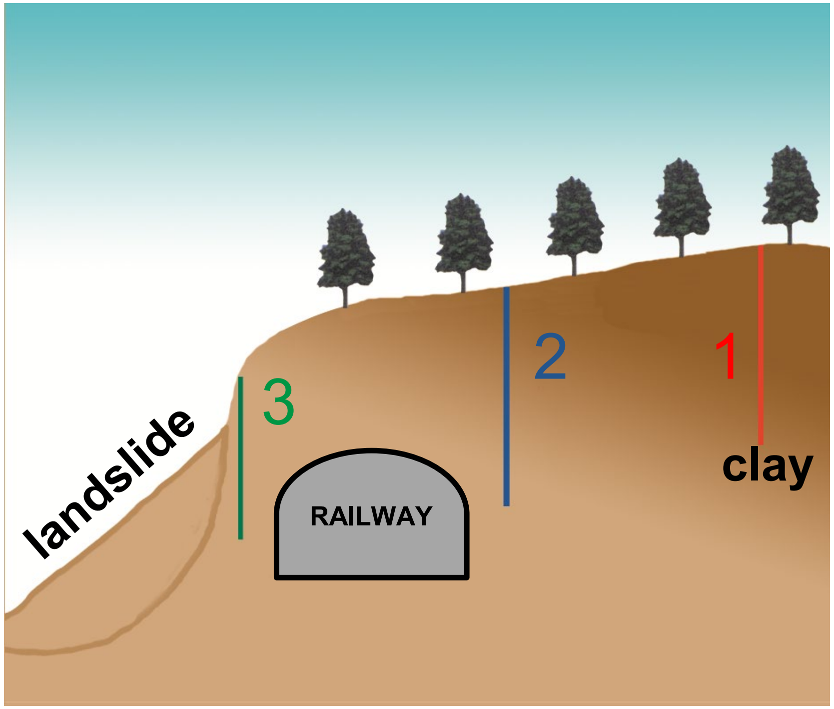


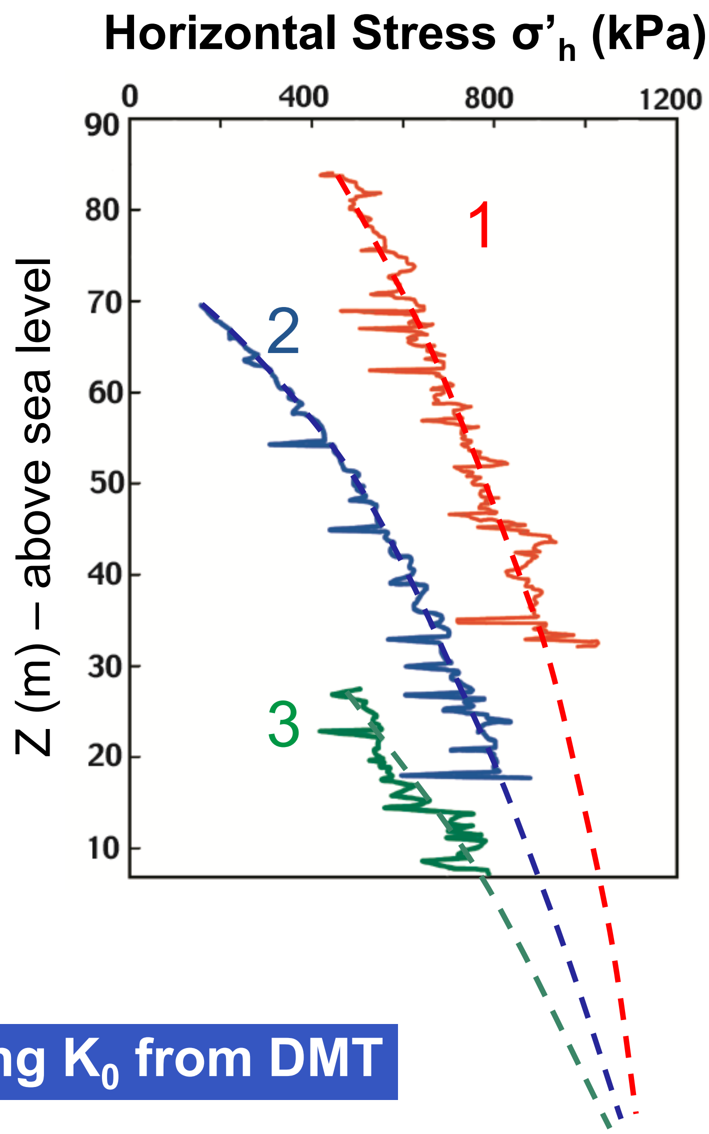
Theoretical
2004 Yu



Example: σ'$_h$ relaxation behind a landslide (K_0)

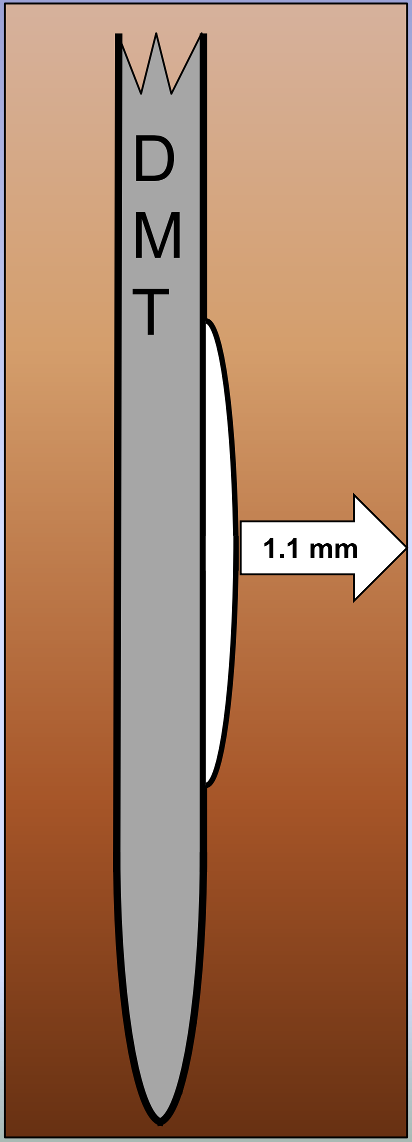
Case History (2002):
Landslide in Milazzo, Sicily





σ'$_h$ obtained using K_0 from DMT

E_D contains information on deformation



Theory of elasticity:

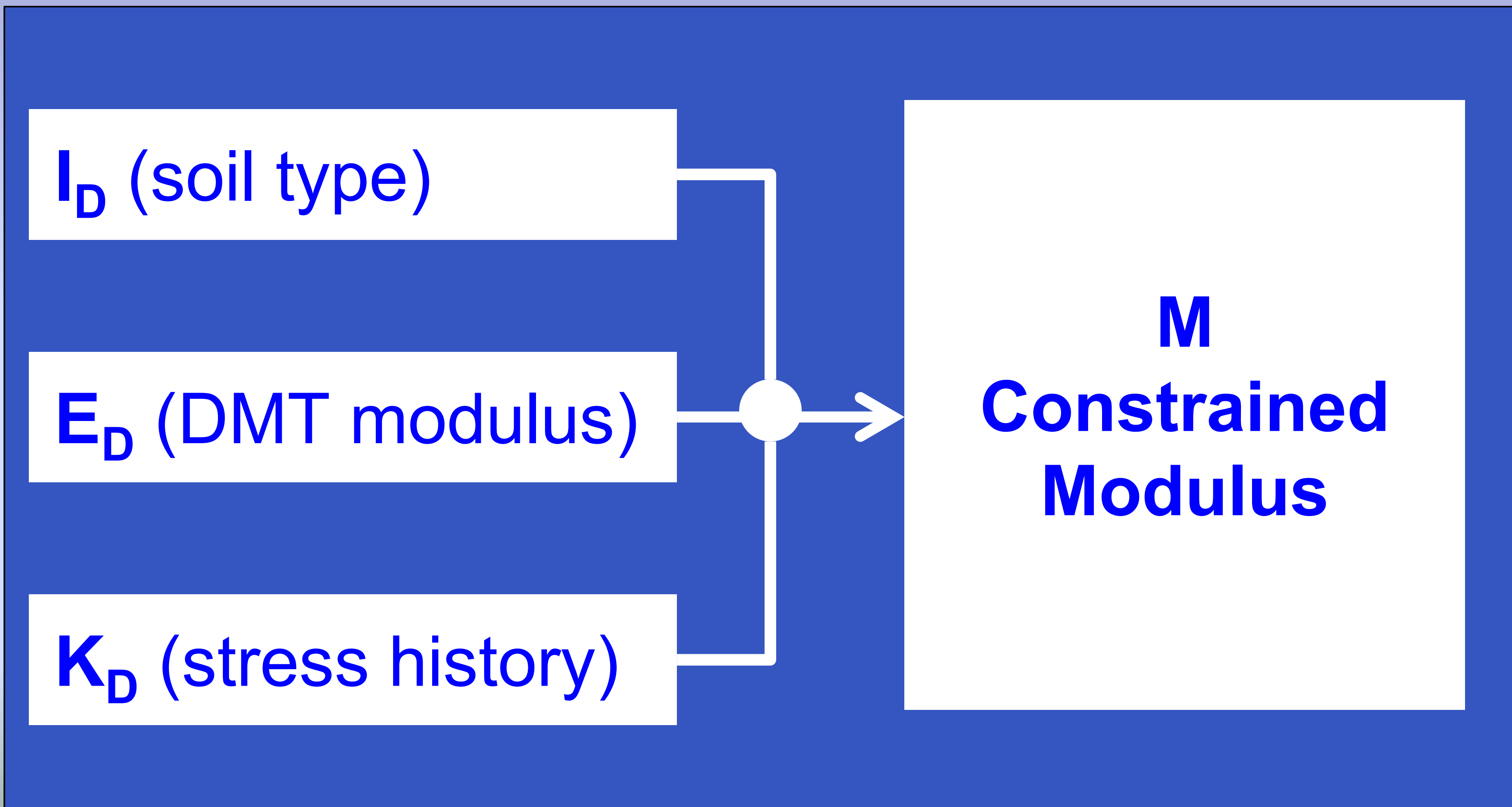
E_D = elastic modulus of the horizontal load test performed by the DMT membrane (D = 60mm, 1.1 mm expansion)

$$E_D = 34.7 \cdot (P_1 - P_0)$$

Gravesen S. "Elastic Semi-Infinite Medium bounded by a Rigid Wall with a Circular Hole", Danmarks Tekniske Højskole, No. 11, Copenhagen, 1960, p. 110.

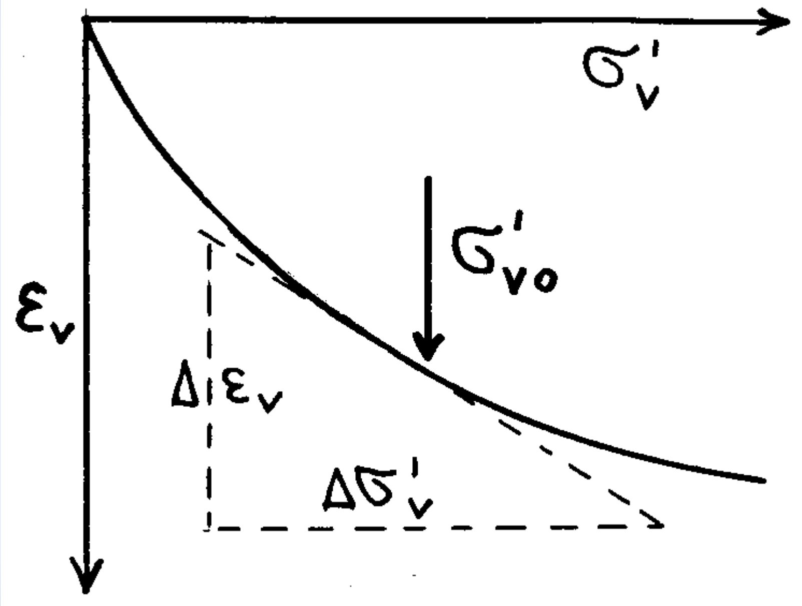
E_D not directly usable → corrections (penetration,etc)

M obtained from E_D using information on soil type I_D and stress history K_D



Definition of M from DMT

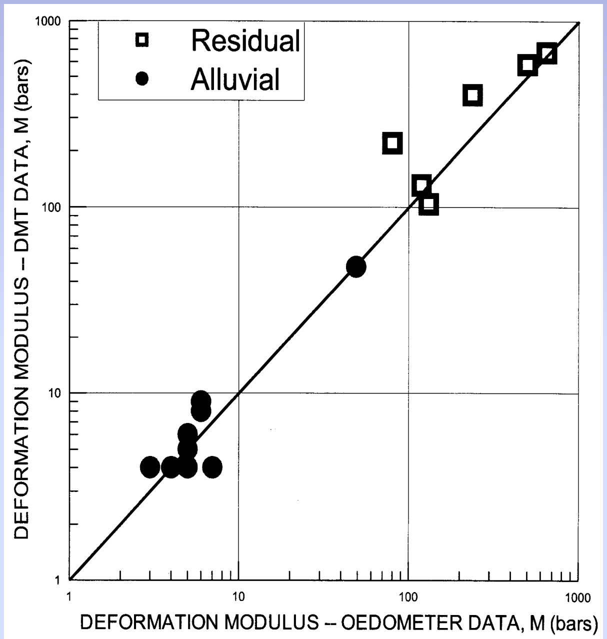
$$M = E_{oed} = 1/mv = \Delta\sigma'_v / \Delta\varepsilon_v \quad (\text{at } \sigma'_{vo})$$



Vertical drained confined tangent modulus (at σ'_{vo})

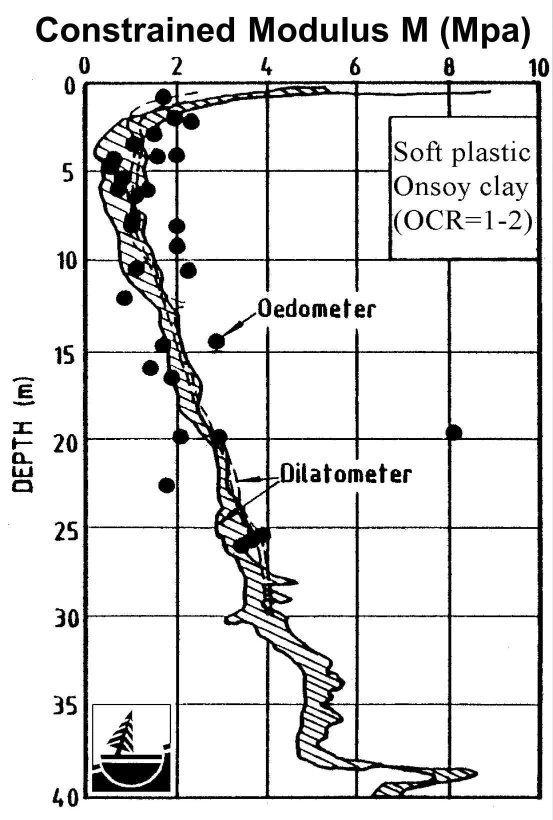
M Comparison from DMT and from Oedometer

Virginia - U.S.A.



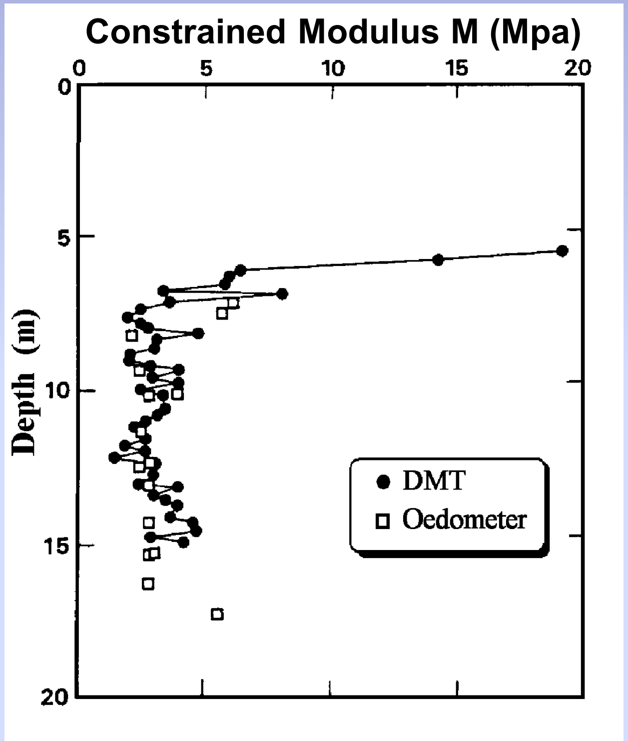
Failmezger, 1999

ONSOY Clay - NORWAY



Norwegian Geotechnical Institute (1986). "In Situ Site Investigation Techniques and interpretation for offshore practice". Report 40019-28 by S. Lacasse, Fig. 16a, 8 Sept 86

Tokyo Bay Clay - JAPAN



Iwasaki K, Tsuchiya H., Sakai Y., Yamamoto Y. (1991) "Applicability of the Marchetti Dilatometer Test to Soft Ground in Japan", GEOCOAST '91, Sept. 1991, Yokohama 1/6

Su in clay (Ladd 1977 Tokyo)

Ladd: *best Su measurement not from TRX UU !!*

best Su: oedometer → OCR → SHANSEP

$$\left(\frac{Su}{\sigma'_v}\right)_{OC} = \left(\frac{Su}{\sigma'_v}\right)_{NC} \cdot OCR^{m}$$

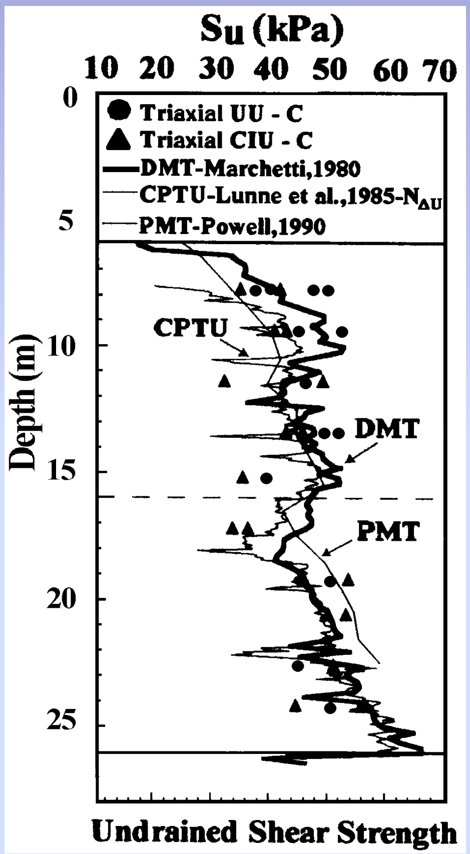
$$OCR = \left(0.5 \cdot K_D\right)^{1.56}$$

Using m ≈ 0.8 (Ladd 1977) and $(Su/\sigma'_v)_{NC} \approx 0.22$ (Mesri 1975)

$$Su = 0.22\, \sigma'_v \left(0.5 \cdot K_D\right)^{1.25}$$

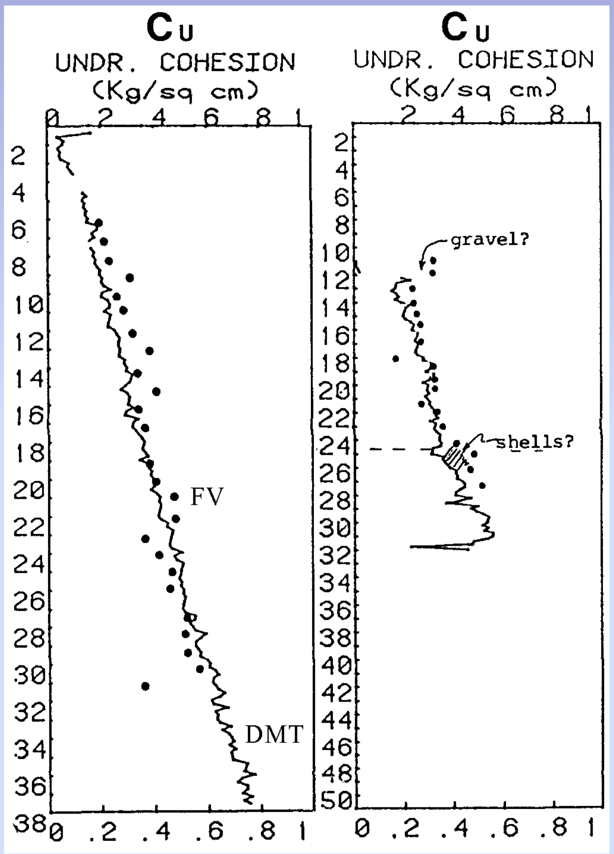
Su comparisons from DMT and from other tests

Recife - Brazil



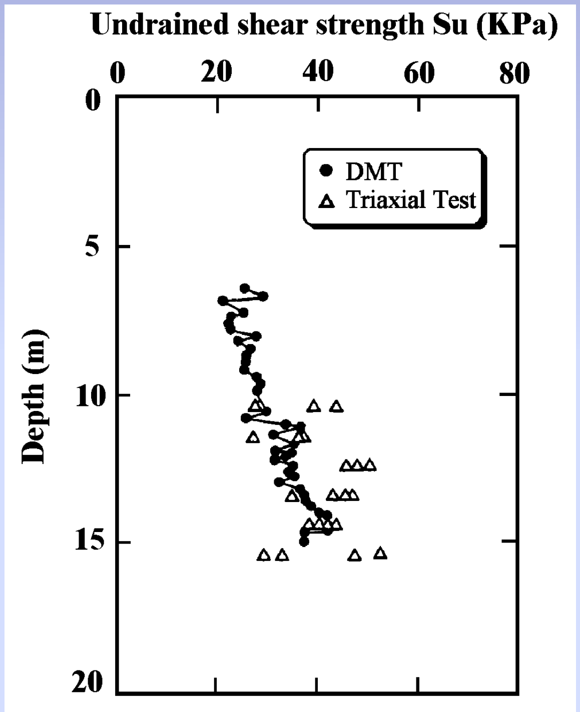
Coutinho et al., Atlanta ISC'98

Skeena Ontario – Canada



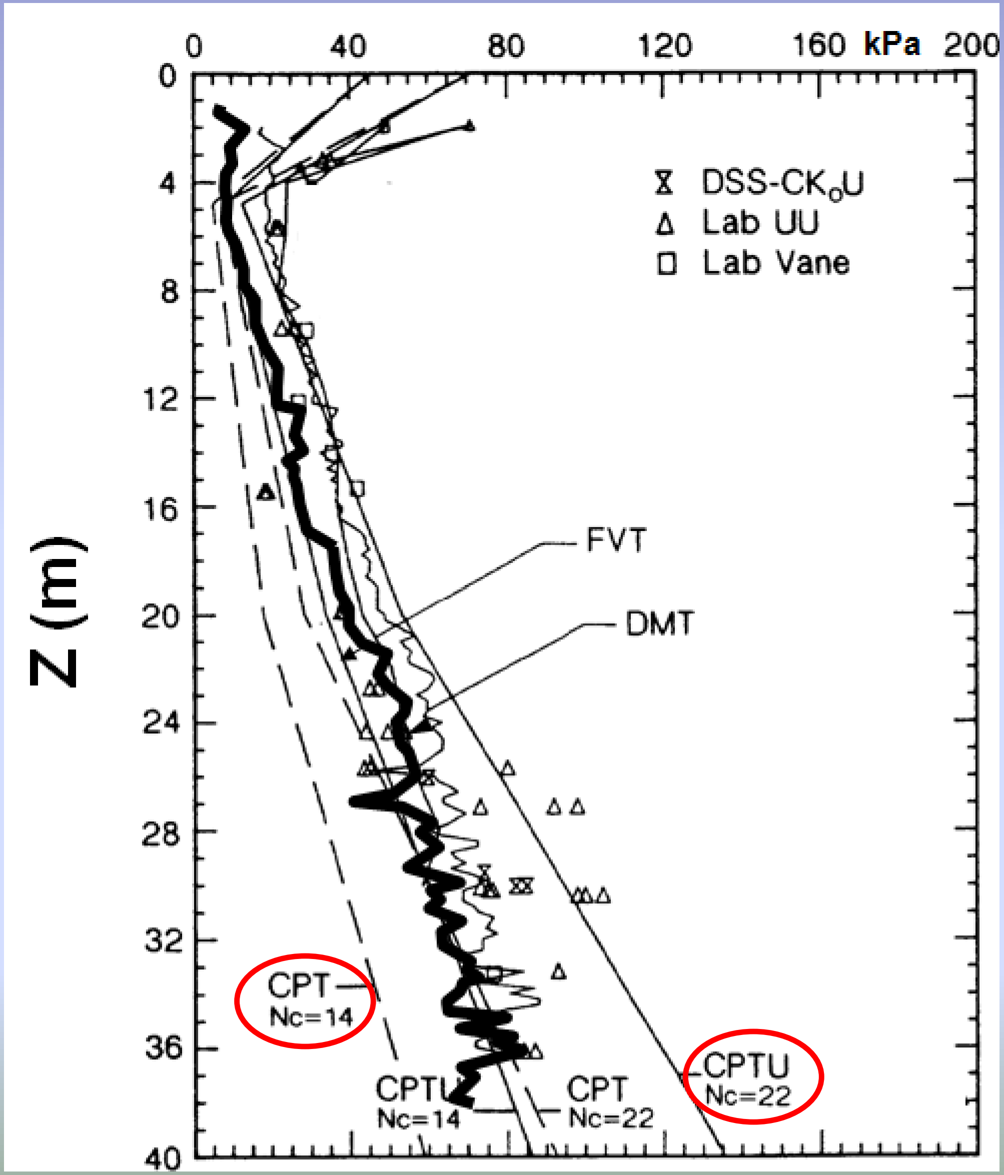
Mekechuk J. (1983). "DMT Use on C.N. Rail Line British Columbia",
First Int.Conf. on the Flat Dilatometer,
Edmonton, Canada, Feb 83, 50

Tokyo Bay Clay - Japan



Iwasaki K, Tsuchiya H., Sakai Y., Yamamoto Y. (1991) "Applicability of the Marchetti Dilatometer Test to Soft Ground in Japan", GEOCOAST '91, Sept. 1991, Yokohama 1/6

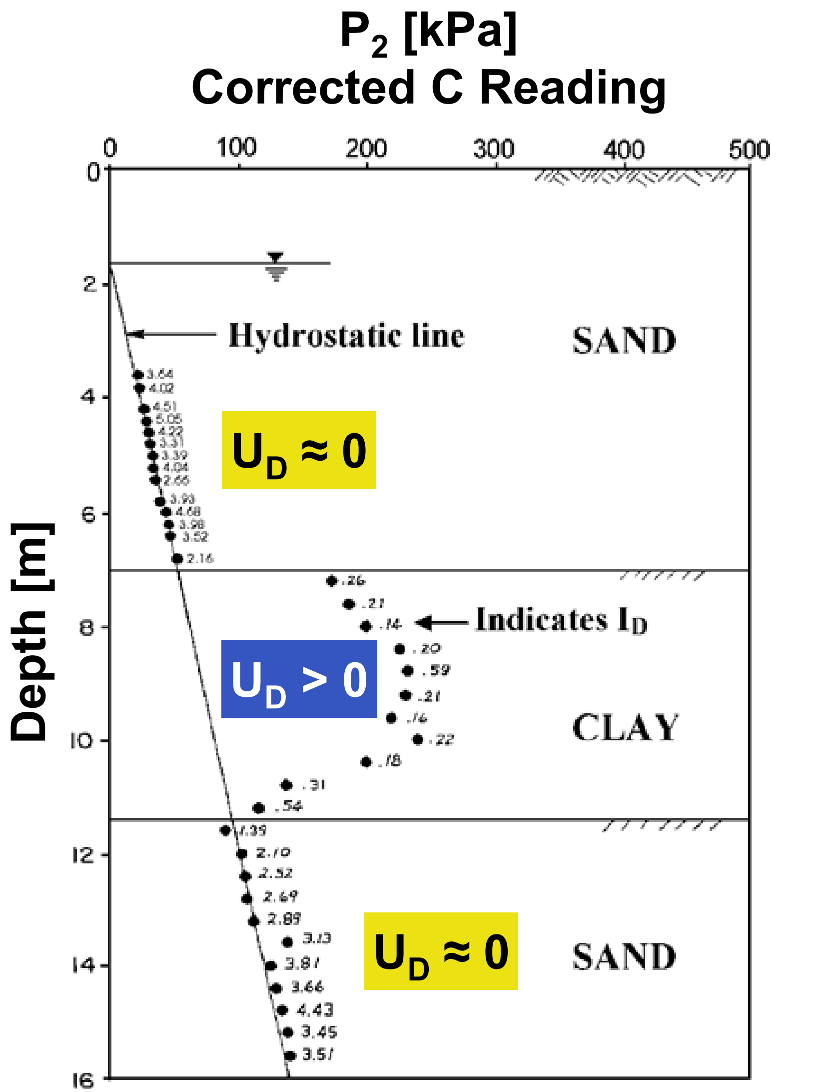
Su at National Site FUCINO – ITALY



CPT: different profiles according to Nc (=14-22)

A.G.I., 10th ECSMFE Firenze 1991
Vol. 1, p. 37

Pore water pressure: C Readings (P_2)



Schmertmann 1988 (DMT Digest No. 10, May 1988, Fig. 3)

SAND: $P_2 \approx U_0$
drainage (≈ piezometer)

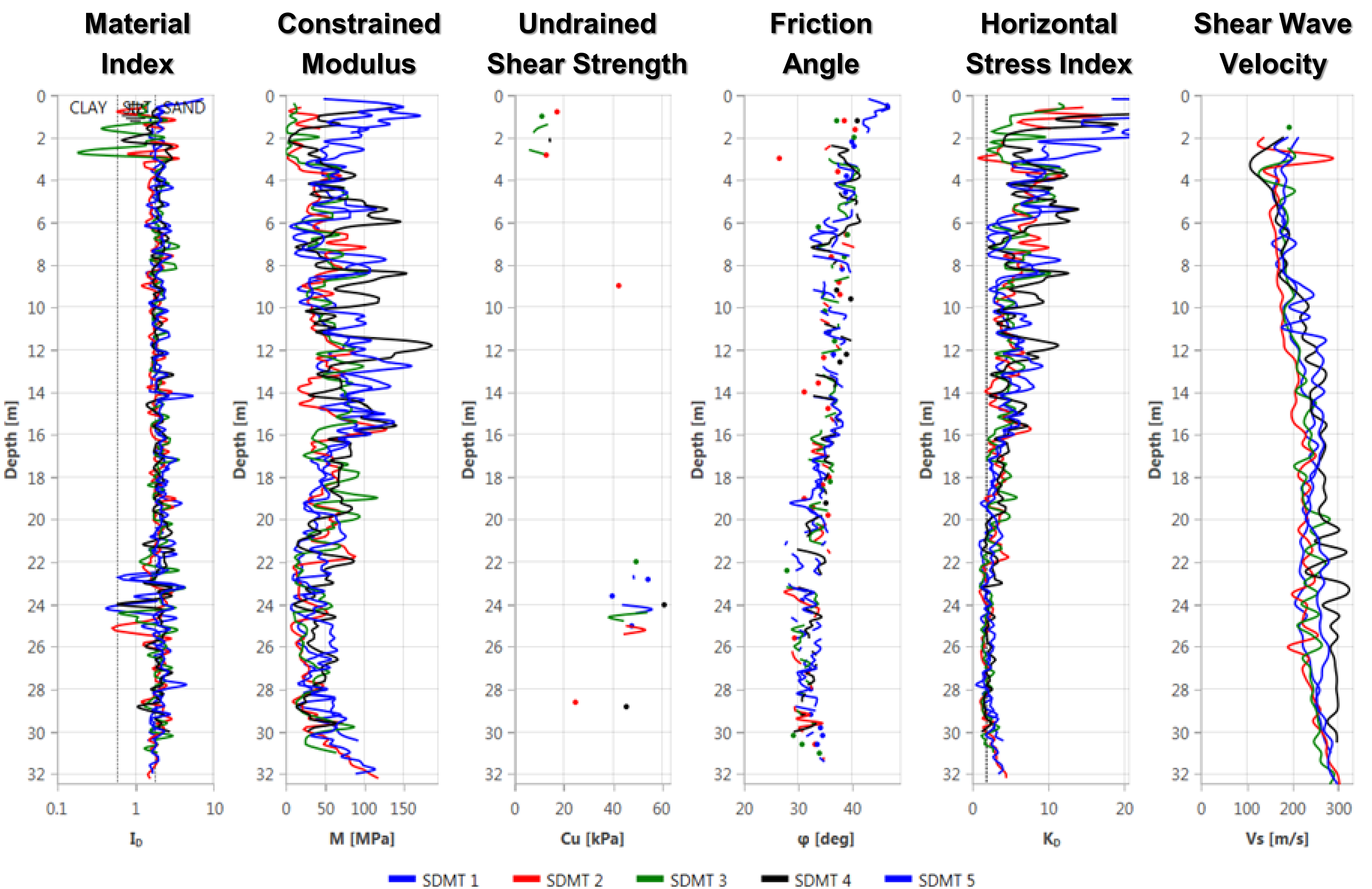
CLAY: $P_2 > U_0$
no drainage (≈ highlights Δu)

Definition: $U_D = \dfrac{(P_2 - U_0)}{(P_0 - U_0)}$

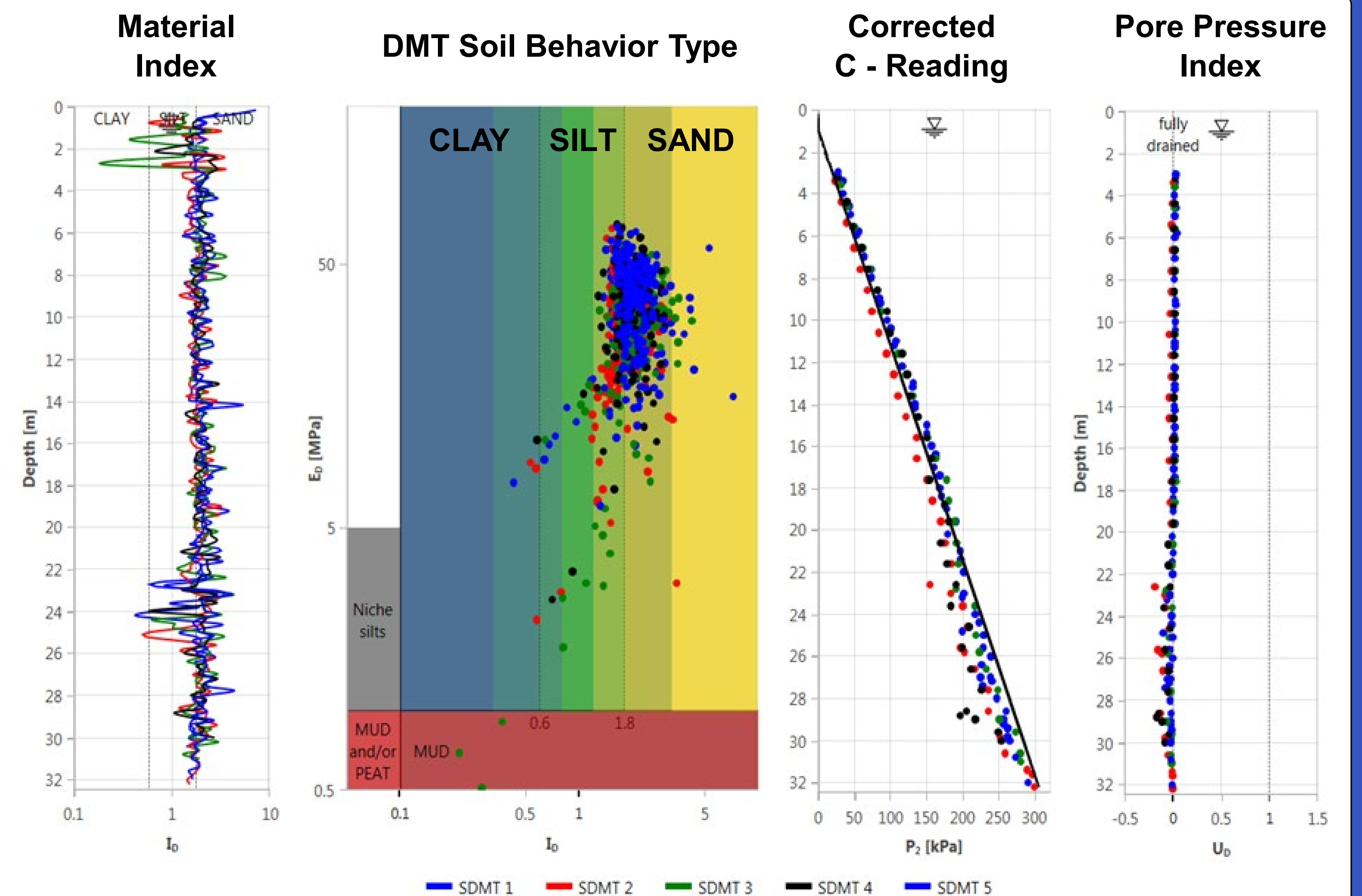
EXAMPLE OF SDMT TESTS IN SAND

Catania Harbour - 2012

SDMT TESTS IN SAND (Catania 2012)



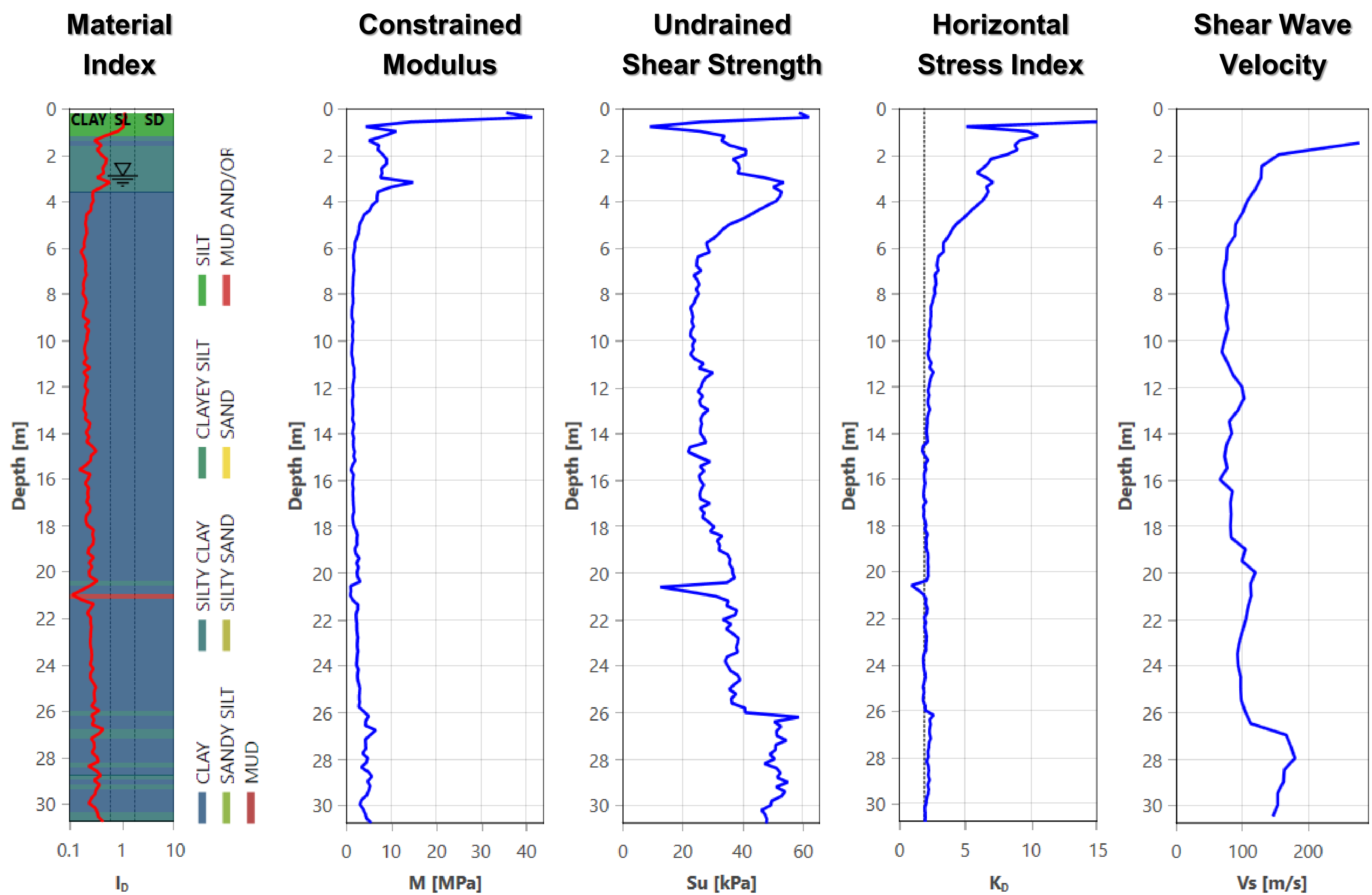
SDMT TESTS IN SAND (Catania 2012)



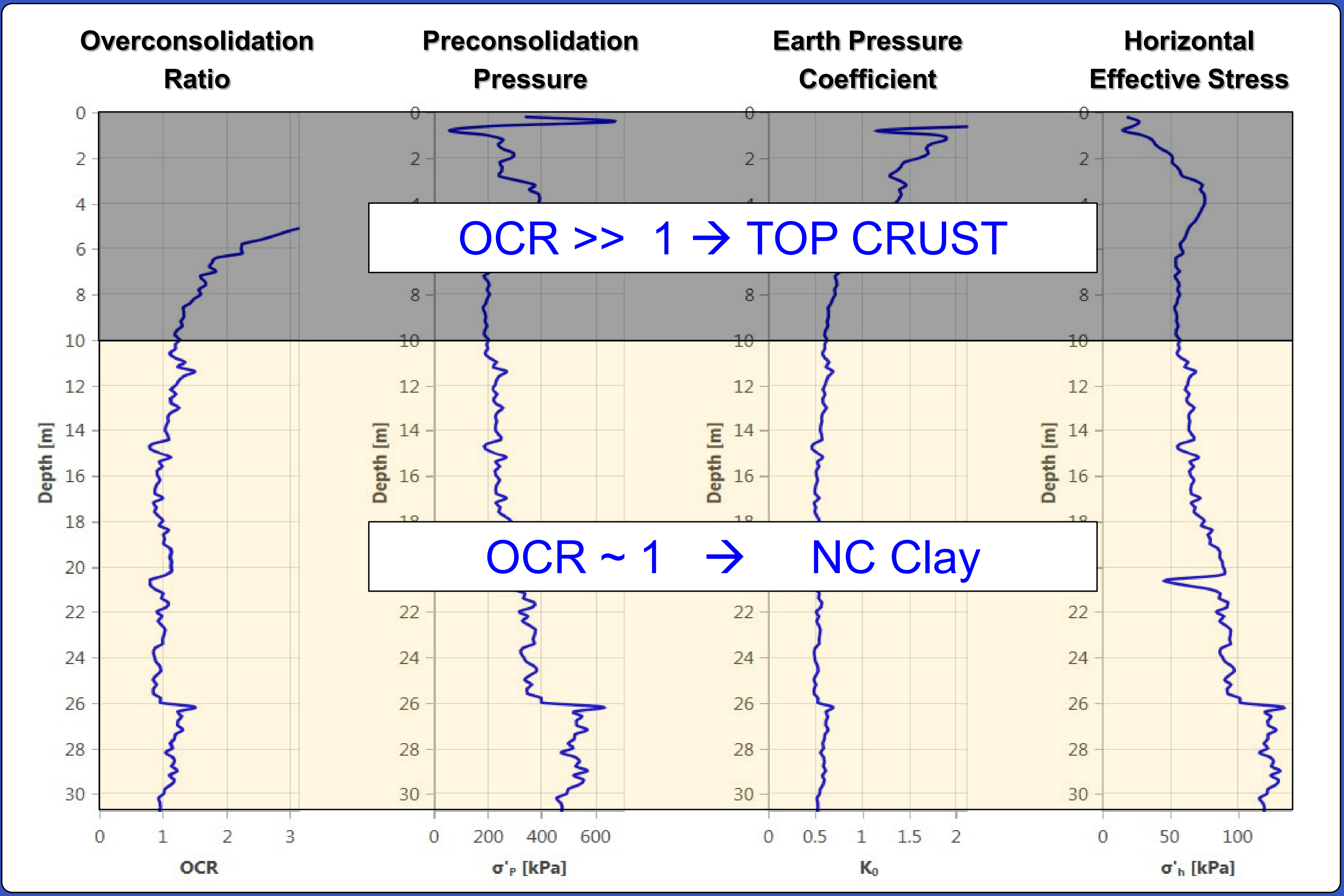
Example of SDMT tests in Clay

SDMT Workshop in Colombia (May 2015, Bogotà)

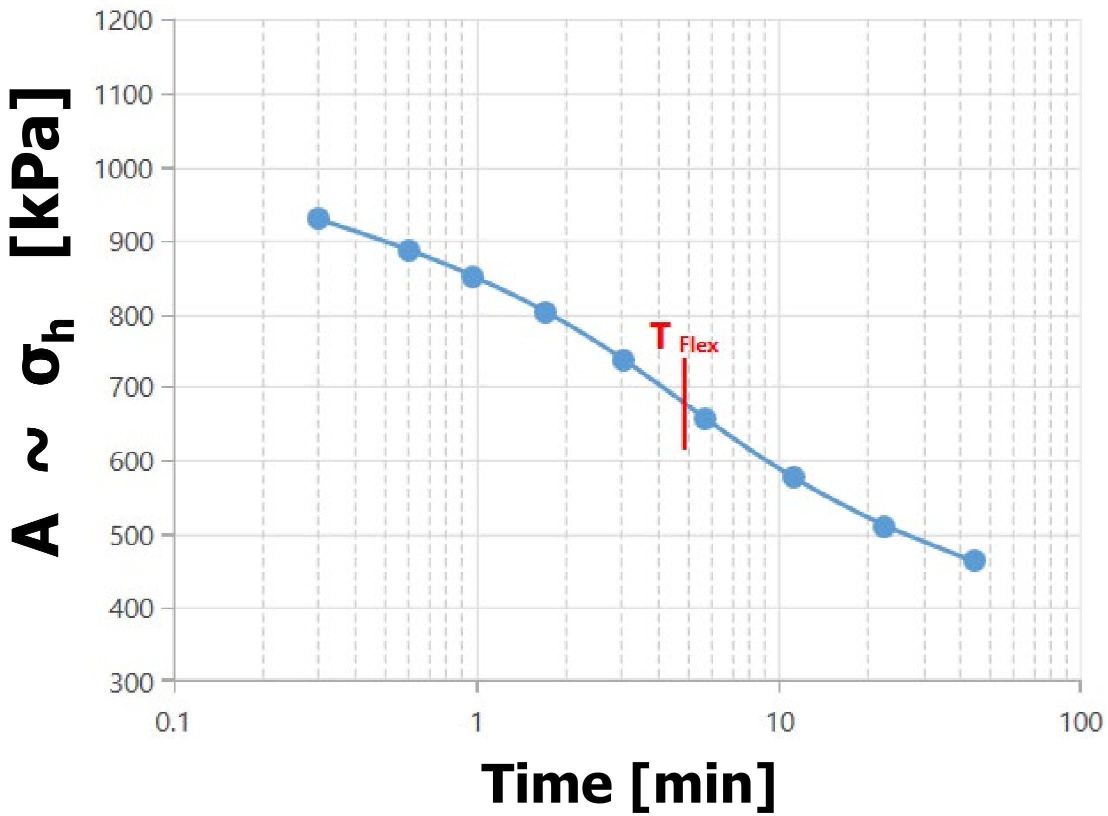
SDMT Escuela Colombiana 9 May 2015



SDMT Escuela Colombiana 9 May 2015



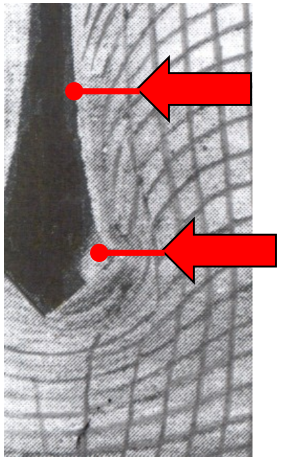
Dissipation test in cohesive soils for coefficients of consolidation & permeability



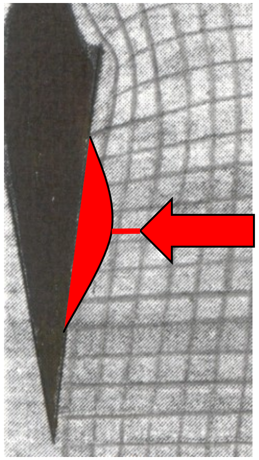
$$C_h \cong \frac{7\ cm^2}{T_{flex}} \qquad k_h = \frac{C \times \gamma_w}{M}$$

Totani et al. (1998)

wedge vs cone (dissipation)

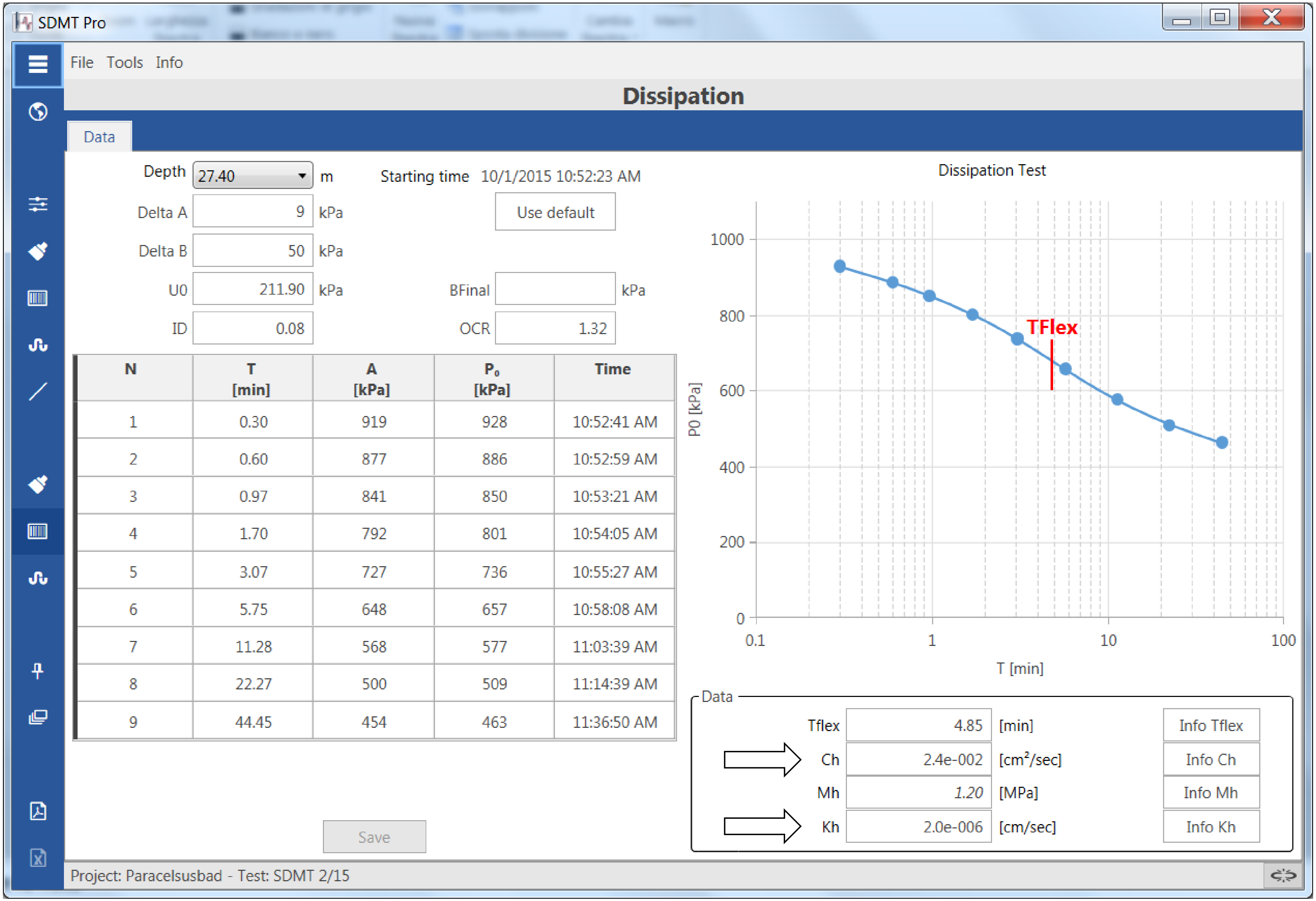


cone
From u(t) in a singular highly disturbed point



wedge
From a ≈ mini embankment
Larger volume in a less disturbed zone

Consolidation (c_h) and Permeability (k_h) from DMT



N	T [min]	A [kPa]	P_0 [kPa]	Time
1	0.30	919	928	10:52:41 AM
2	0.60	877	886	10:52:59 AM
3	0.97	841	850	10:53:21 AM
4	1.70	792	801	10:54:05 AM
5	3.07	727	736	10:55:27 AM
6	5.75	648	657	10:58:08 AM
7	11.28	568	577	11:03:39 AM
8	22.27	500	509	11:14:39 AM
9	44.45	454	463	11:36:50 AM

First validation of c_h and k_h from DMT (1998)

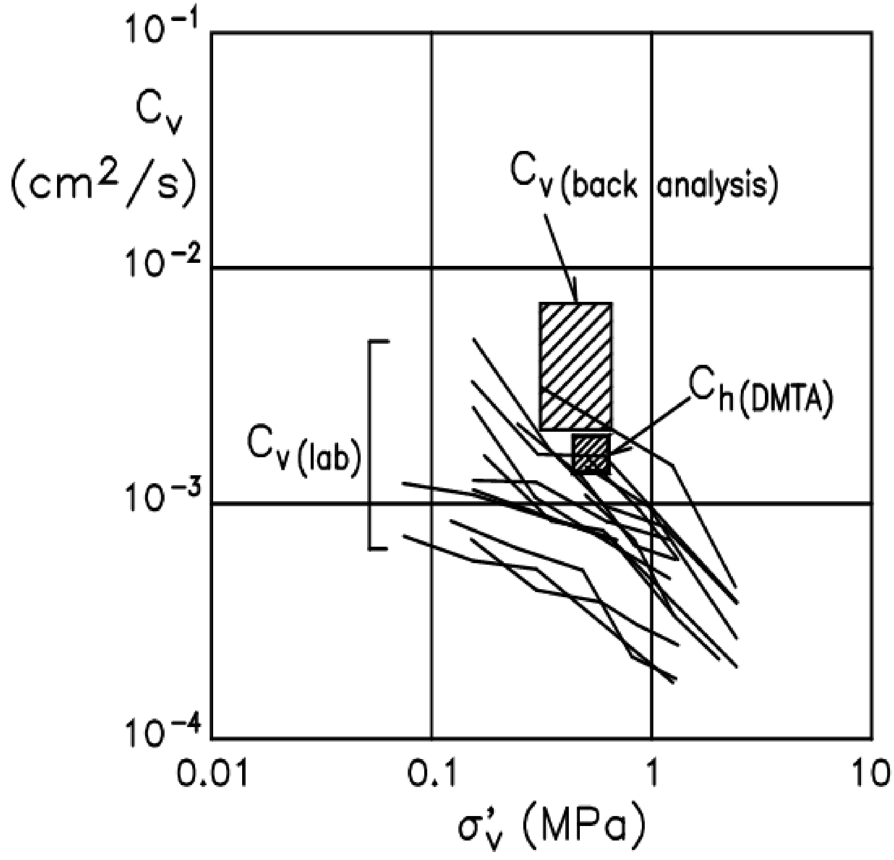


Figure 9. Santa Barbara - Comparison between c_v from laboratory tests, in situ c_v from back analysis (D'Elia et al. 1994) and in situ $c_{h,OC}$ from DMTA

Totani et al. ISC 1998 - Atlanta, Georgia (USA)

International Standards

***EUROCODE 7* (2007).** Standard Test Method, European Committee for Standardization, Part 3: Design Assisted by Field Testing, Section 9: Flat Dilatometer Test (DMT), 9 pp.

***ISO* (2017).** ISO/TS 22476-11, Geotechnical investigation and testing - Field testing Part 11: The Flat Dilatometer Test, 9 pp

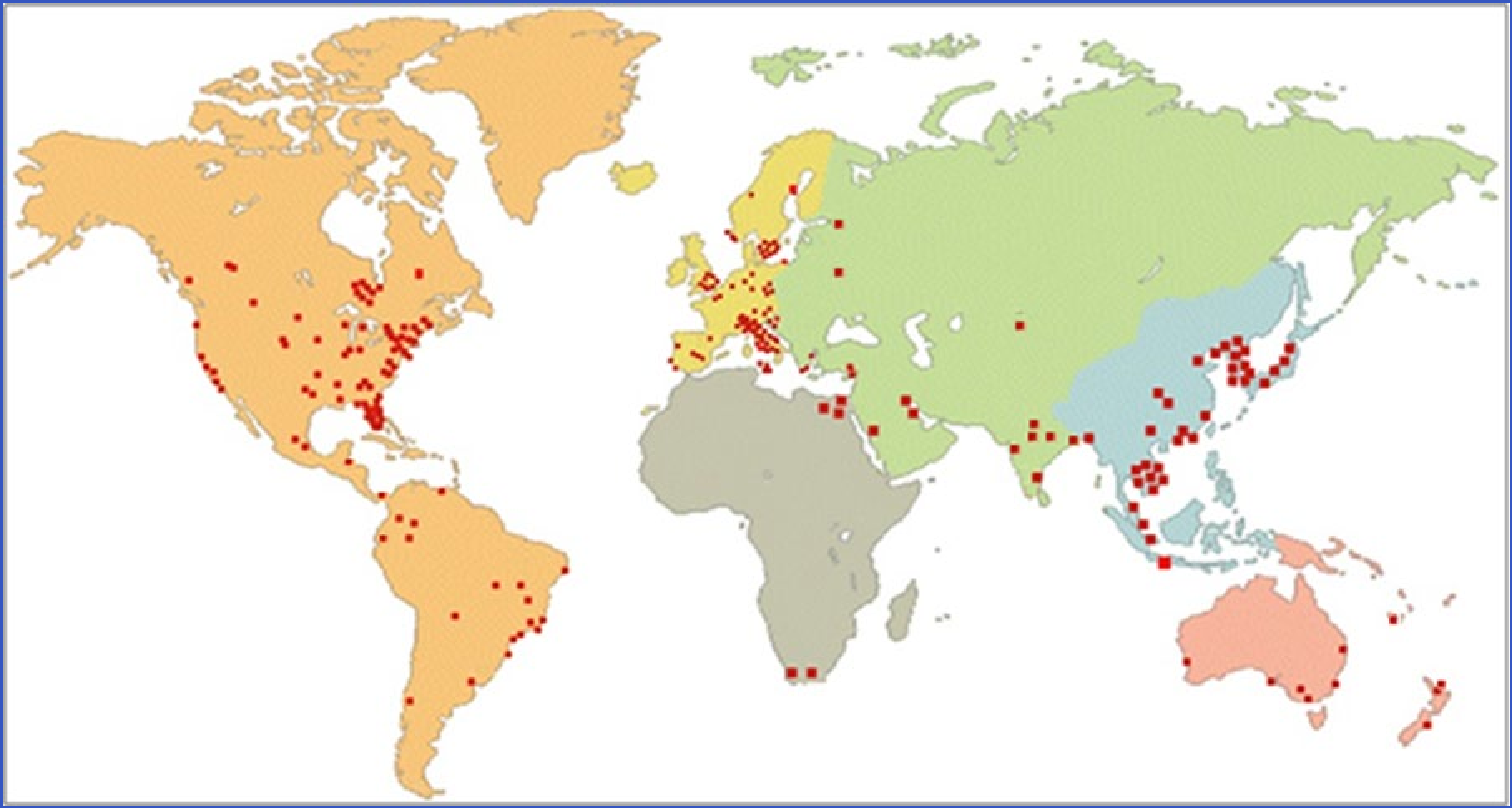
***ASTM (2016)*.** Standard Test Method D6635-15, American Society for Testing and Materials. Standard test method for performing the Flat Dilatometer Test (DMT), 14 pp.

***TC16 / TC102 (2001)*.** “The DMT in soil Investigations”, ISSMGE Technical Committee on Ground Property, Characterization from in-situ testing, 41 pp.

NATIONAL STANDARDS:

- **Italy: Consiglio Superiore Lavori Pubblici (2009), Protezione Civile (2008)**
- **Sweden: Swedish Geotechnical Society SGF report (1994)**
- **France: ISO/TS 22476-11:2005(F)**
- **China: TB10018 (2003), GB50021 (2003), DGJ08-37 (2012)**
- **..**

SDMT used in over 80 countries (°) (200 DMT in US)



(°) Algeria, Angola, Argentina, Australia, Austria, Bahrain, Bangladesh, Belgium, Bolivia, Bosnia, Brazil, Bulgaria, Canada, Czech Republic, China, Chile, Cyprus, Colombia, Costa Rica, Croatia, Denmark, Ecuador, Egypt, United Arab Emirates, Estonia, Finland, France, Germany, Greece, Guadalupe, Guatemala, Honduras, Hong Kong, Hungary, India, Indonesia, Iran, Ireland, Israel, Italy, Japan, Kazhakstan, Korea, Kosovo, Kuwait, Lithuania, Malaysia, Mexico, Myanmar, Netherland, New Zealand, Norway, Oman, Panama, Peru, Paraguay, Philippines, Poland, Portugal, Romania, Russia, Saudi Arabia, Serbia, Singapore, Slovenia, South Africa, Spain, Sri Lanka, Sweden, Switzerland, Taiwan, Thailand, Tunisia, Turkey, United Kingdom, United States of America, Venezuela, Vietnam.

Main DMT applications

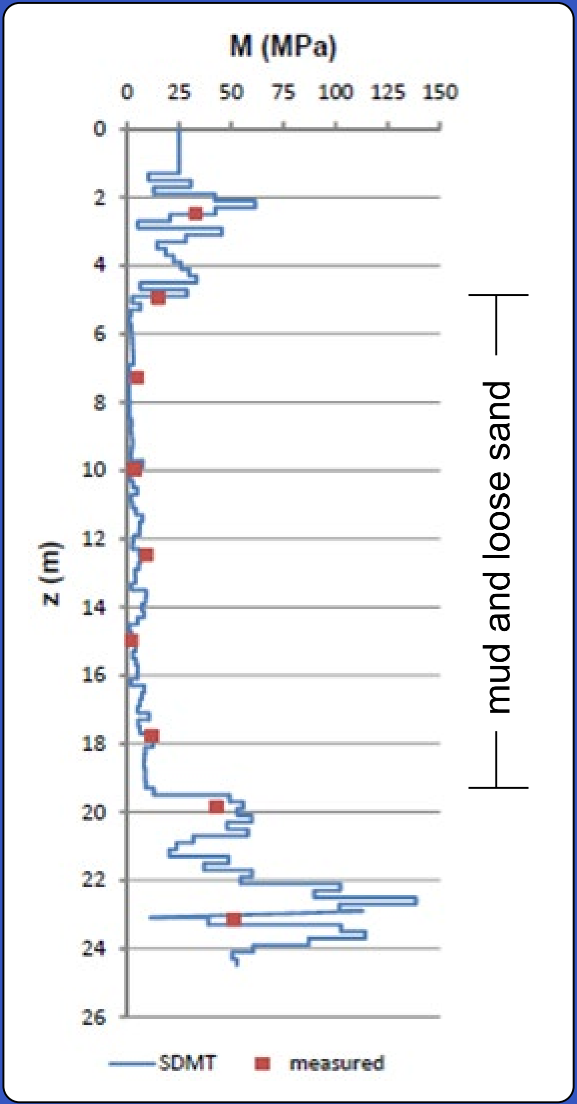
- Settlements of shallow foundations
- Compaction control
- Liquefaction resistance (CRR)
- Slip surface detection in OC clay
- Laterally loaded piles (P-y curves)
- In situ G-γ decay curves
- Diaphragm walls (springs model)
- FEM input parameters (es. Plaxis)
- Vs for soil sample quality assessment

Many publications & case histories of good agreement between measured and DMT-predicted settlements / moduli:

- ***Failmezger*** *(2020)*
- ***Godlewski*** *(2018)*
- ***McNulty & Harney*** *(2014)*
- ***Berisavijevic*** *(2013)*
- ***Vargas*** *(2009)*
- ***Bullock*** *(2008)*
- ***Monaco*** *(2006)*
- ***Lehane & Fahey*** *(2004)*
- ***Mayne*** *(2001, 2004)*
- ***Failmezger*** *(1999, 2000, 2001)*
- ***Crapps & Law Engineering*** *(2001)*
- ***Tice & Knott*** *(2000)*
- ***Woodward*** *(1993)*
- ***Iwasaki et al.*** *(1991)*
- ***Hayes*** *(1990)*
- ***Mayne & Frost*** *(1988)*
- ***Schmertmann*** *1986,1988)*
- ***Steiner*** *(1994)*
- ***Leonards*** *(1988)*
- ***Lacasse*** *and* ***Lunne*** *(1986)*
- ..
- ..

Observed vs. Predicted Settlements by DMT

Silos on Danube Bank (Belgrade)



Silo founded on mat 100 m x 23 m, with qnet = 160 kPa

DMT Settlement prediction: 77 cm

Measured Settlement: 63 cm

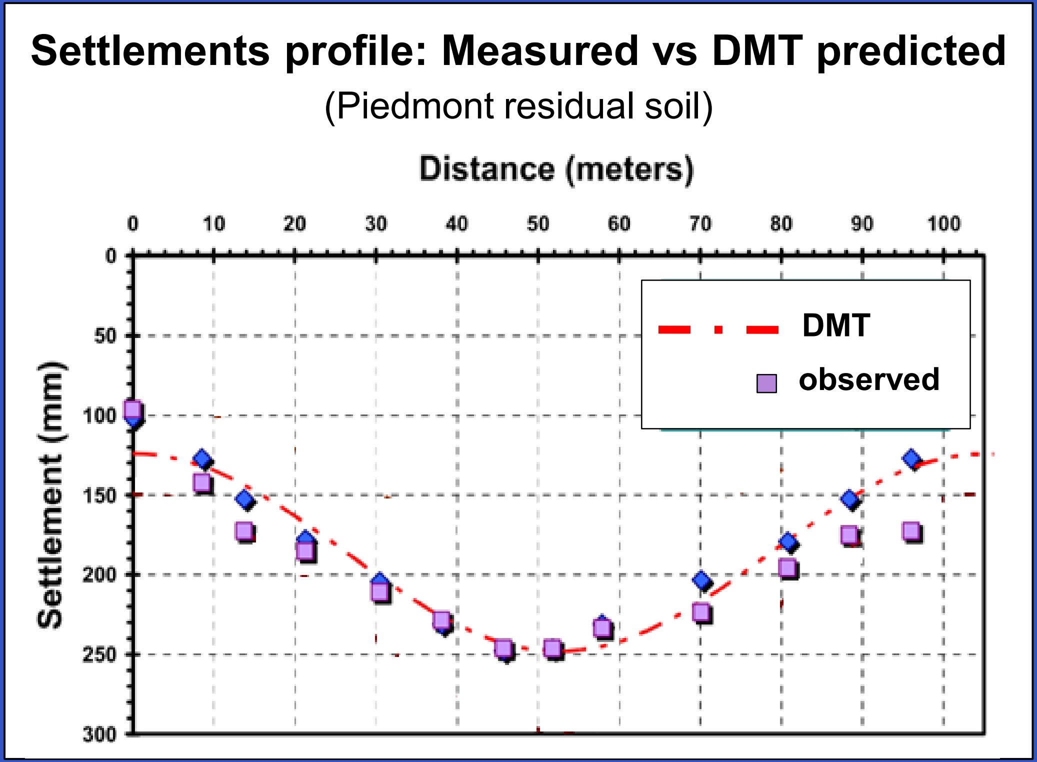
DMT +22%

D. Berisavijevic, 2013

Observed vs. Predicted Settlements by DMT

Dormitory Building 13 storeys (Atlanta - USA)

Mayne, 2005



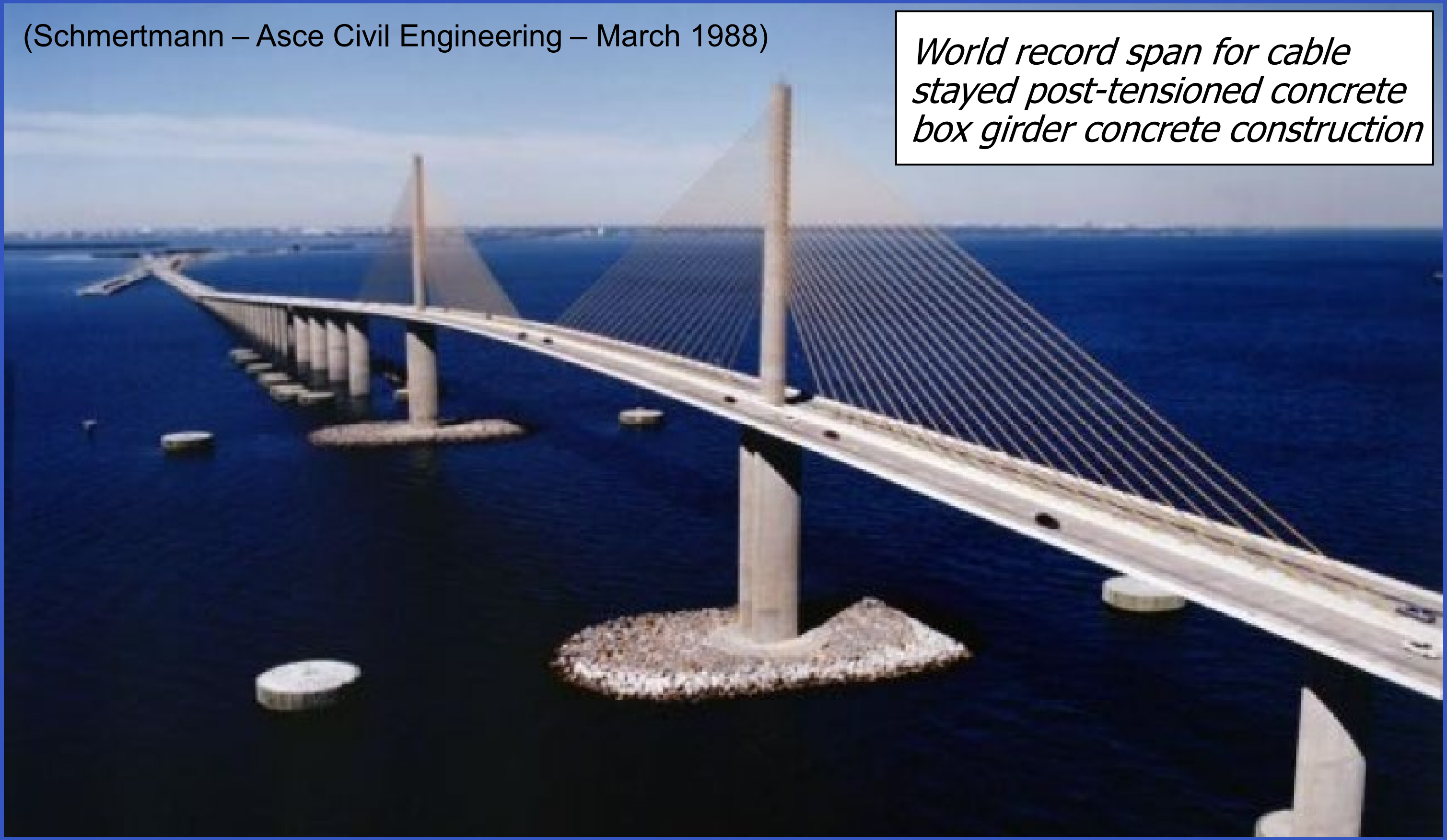
SPT Settlement prediction: 46 mm

DMT Settlement prediction: 250 mm

Observed Settlement: 250 mm

SPT → error is large and unsafe !!!

Sunshine Skyway Bridge – Tampa Bay – Florida



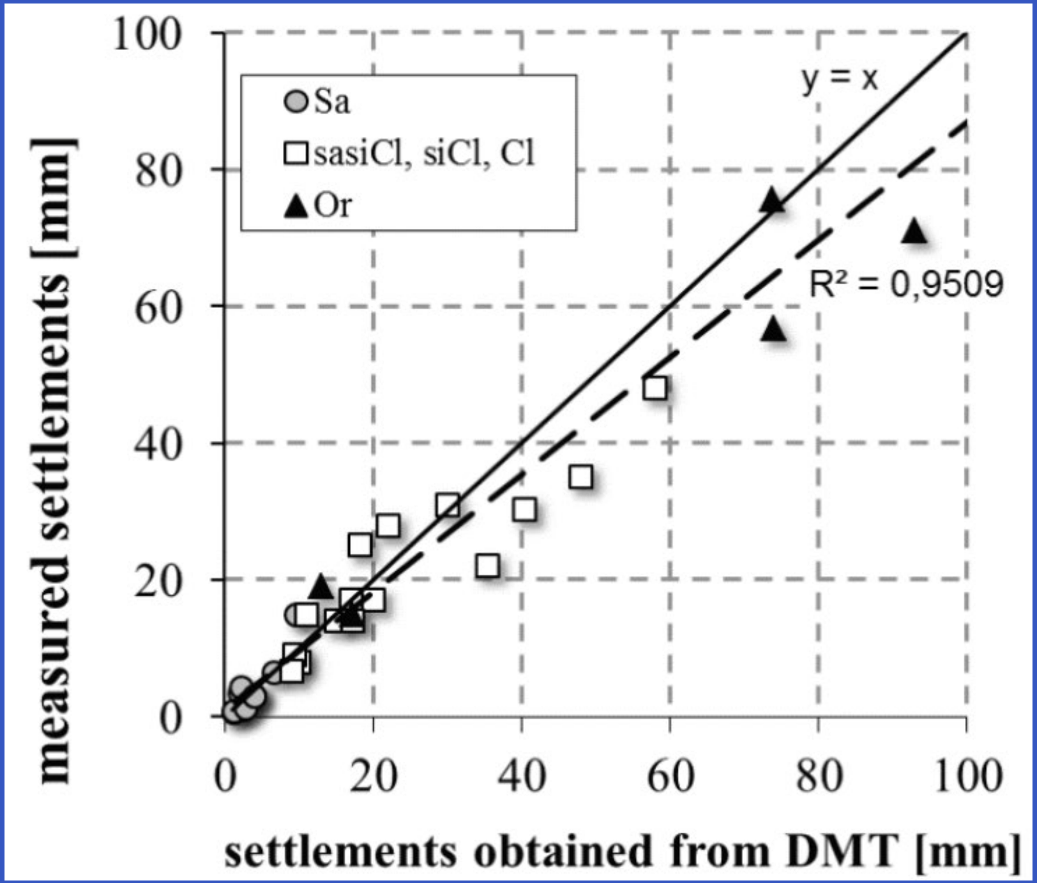
M from DMT ≈ **200** MPa (≈ 1000 DMT data points)

M from laboratory: M ≈ **50** MPa

M from observed settlements: M ≈ **240** MPa

→ DMT good estimation of M in this site

Observed vs. predicted by DMT



Different soil types

Godlewski, 2018

"..comparison of settlement values measured at the structures with respect to those obtained by dilatometer data and observations (28 structures). It should be added that the given set of buildings was limited to structures with shallow foundation.."

Main differences DMT - CPT

1. Flexibility in penetration

CPT – measurements performed at fix penetration rate of 2 cm / sec

→ penetrometer *required*

→ penetration rate may influence results

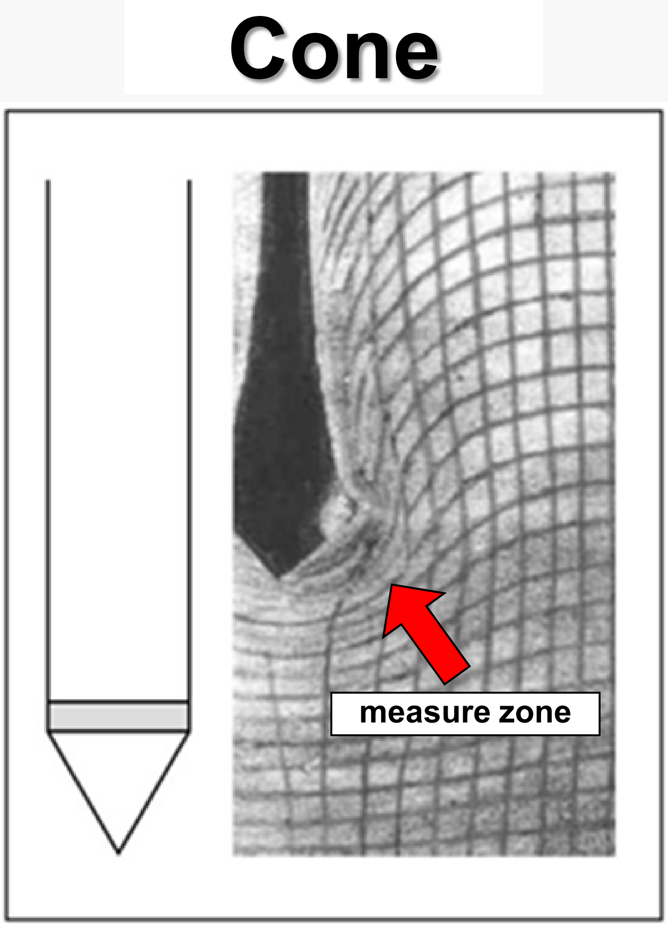
DMT – no requirement on penetration rate.

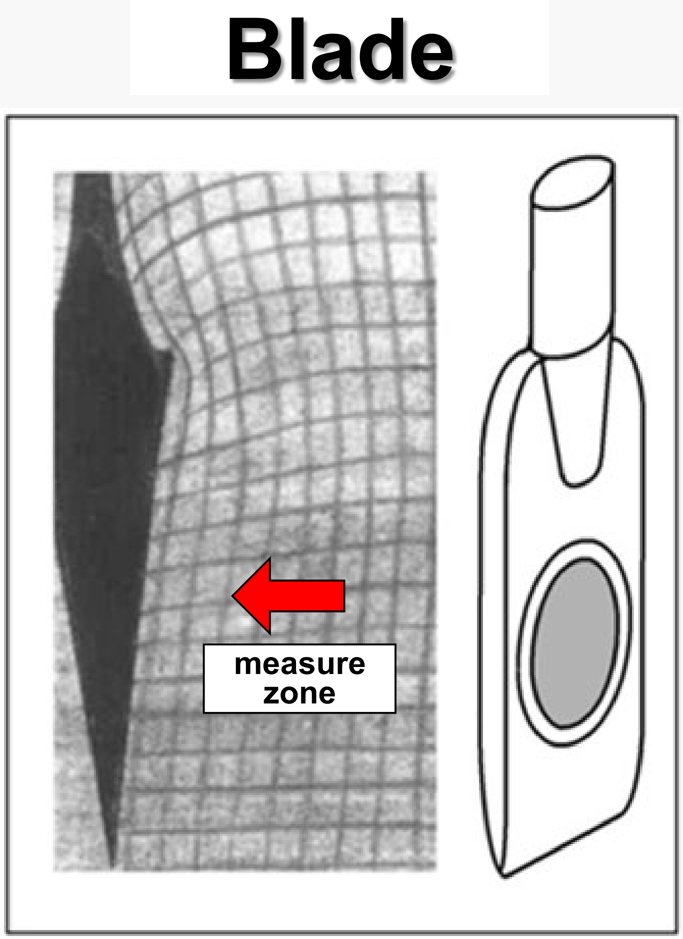
Measurements when blade is not moving.

→ penetrometer, drill rig, floating barge, etc

→ measurements independent of penetration rate

2. Blade shape minimizes soil disturbance

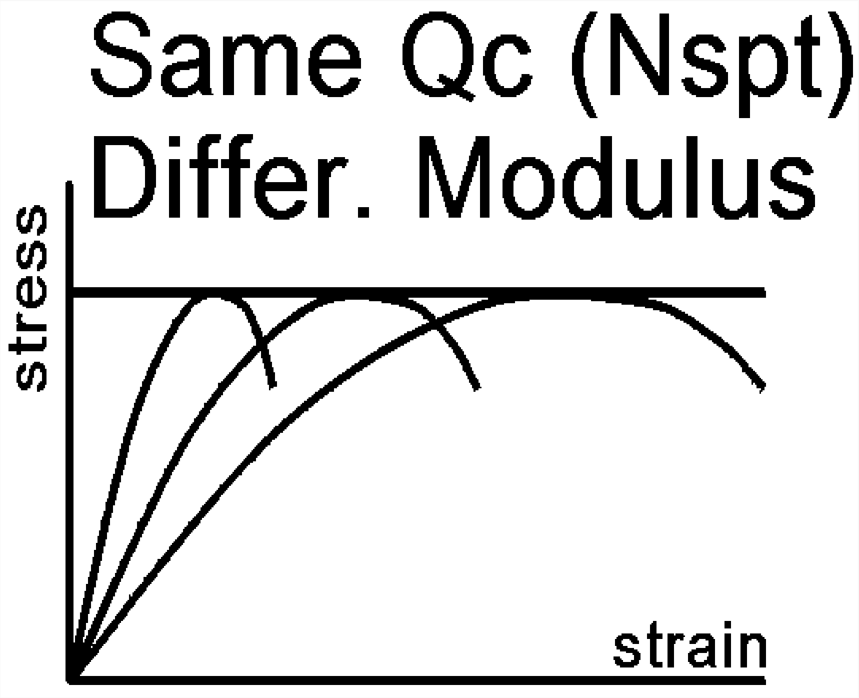




Baligh & Scott (1975)

Accurate measurements require low soil disturbance

3. DMT direct measurement of stiffness

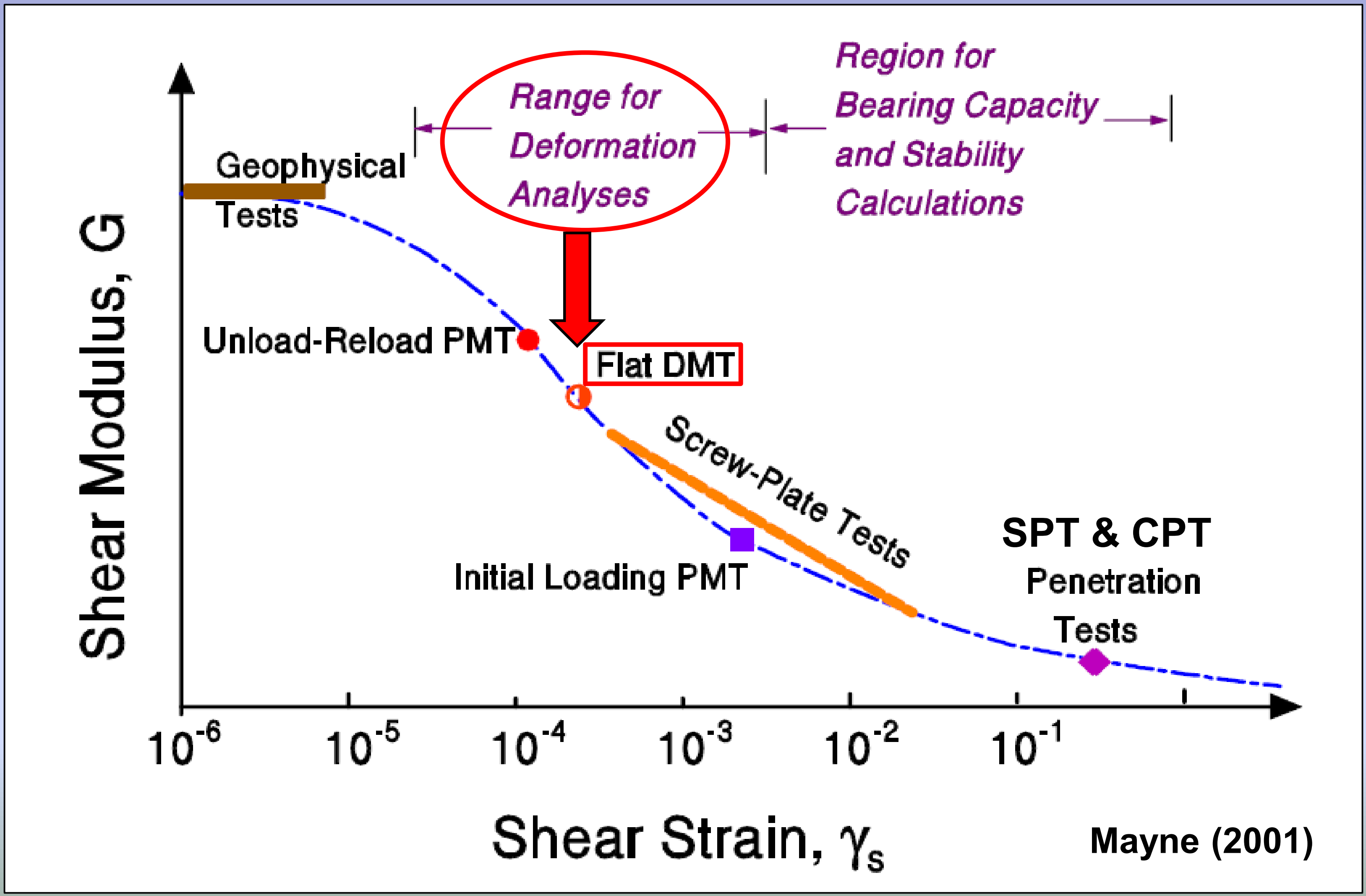


Stiffness ≠ Strength

CPT measures strength and correlates to stiffness with a factor ranging significantly: ~ (3 – 24)

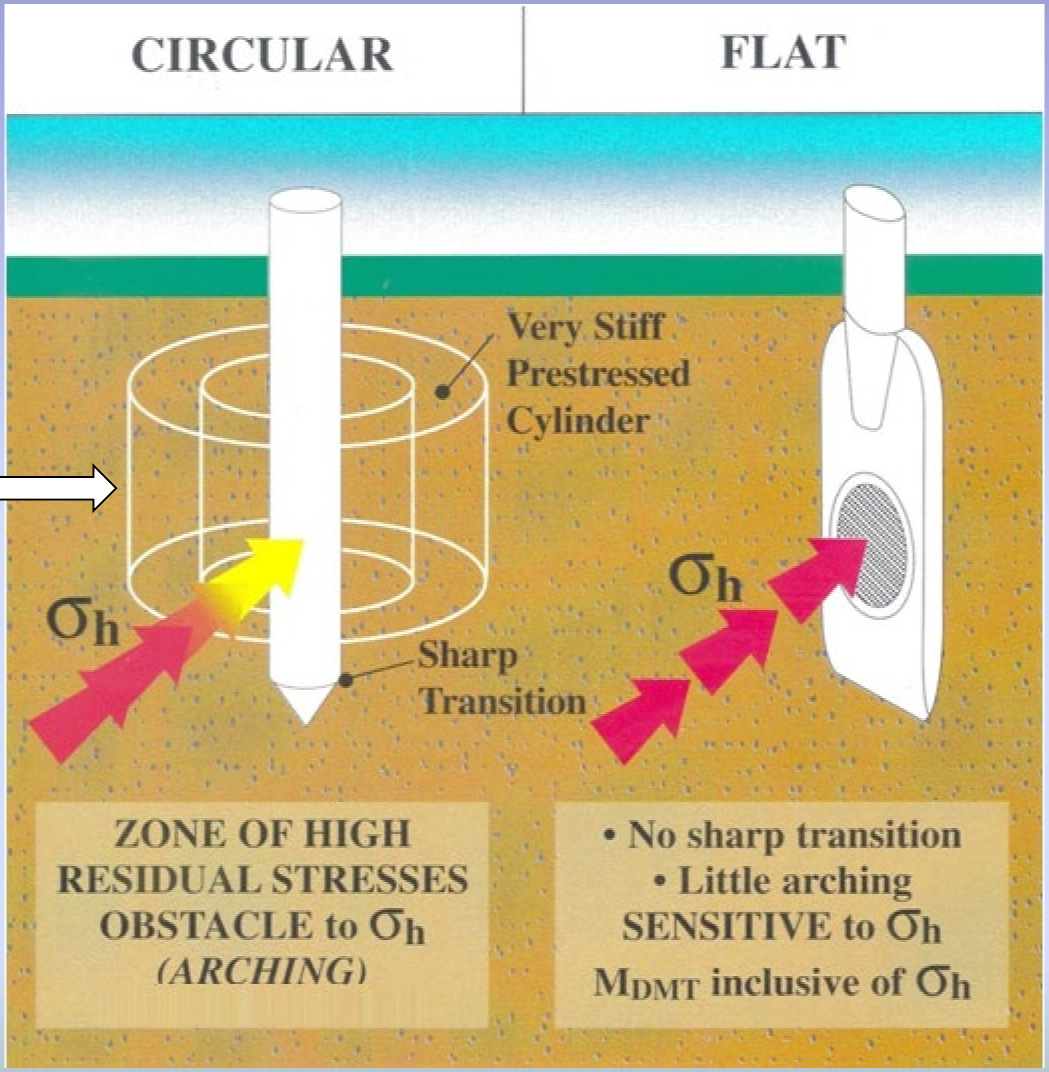
Possible reasons DMT predicts well settlement

Soil is loaded at strain level for deformation analysis



Sensitivity to σ_h of DMT and CPT/SPT

Arching effect



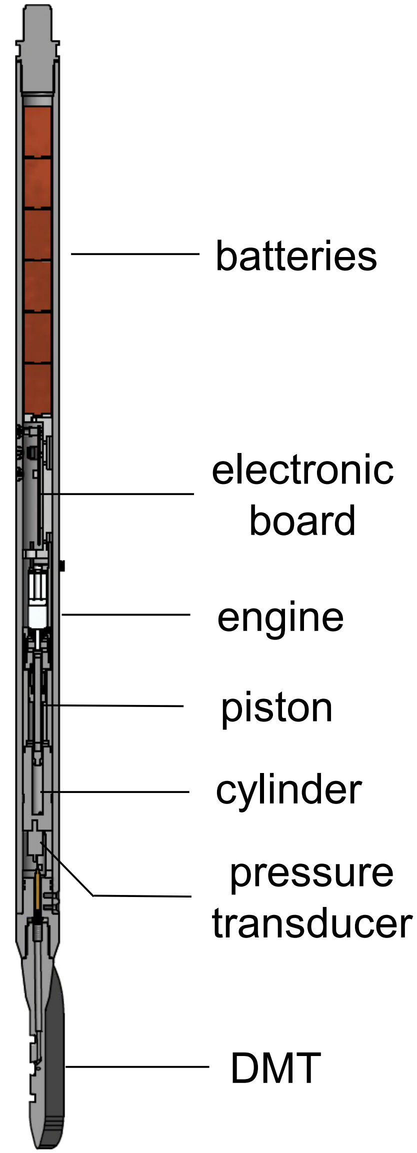
Hughes & Robertson (*Canadian Journal August 1985)*

MEDUSA DMT

ONSHORE AND OFFSHORE SOIL TESTING

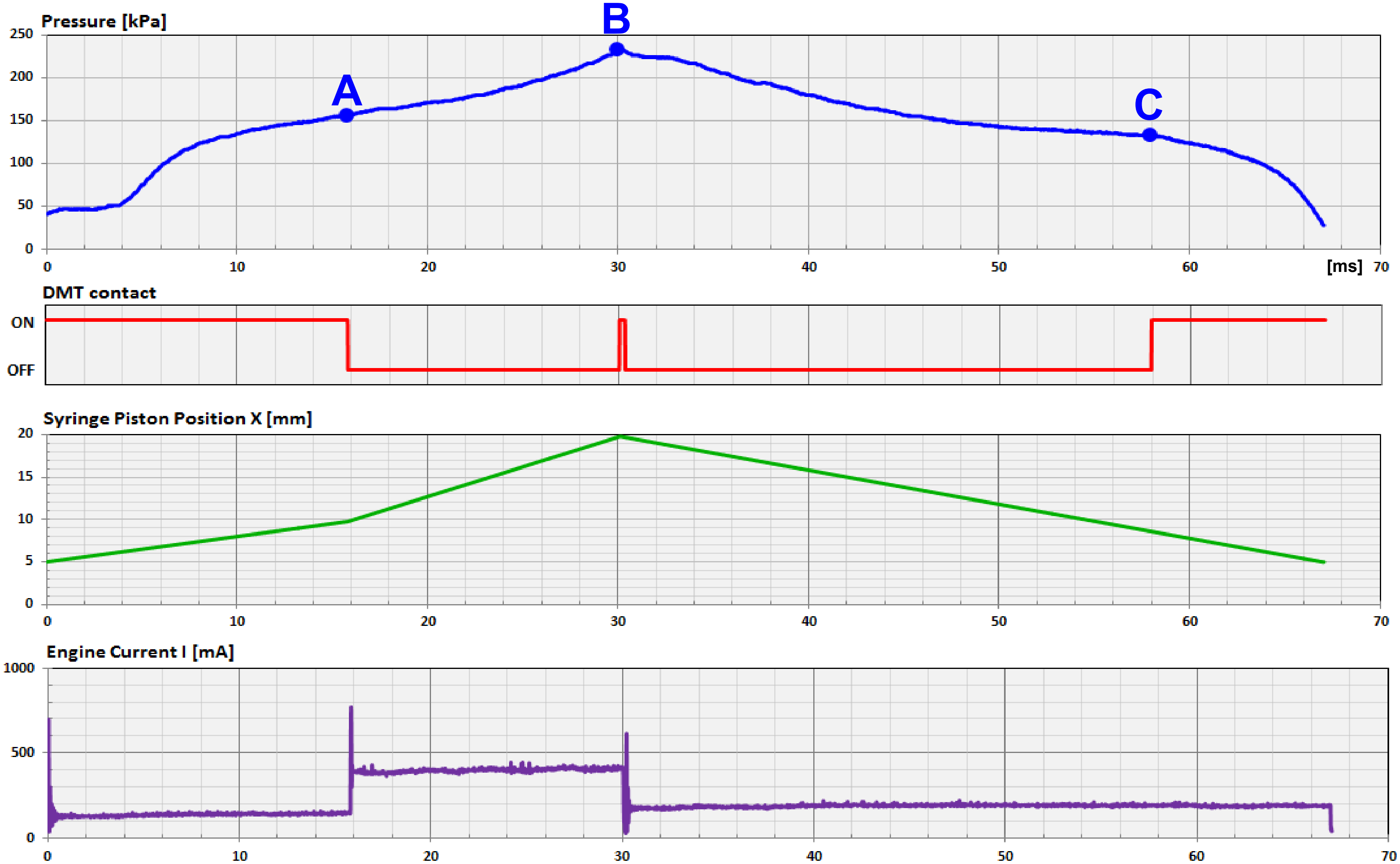
Medusa DMT: Automated Dilatometer

- **Battery Power Pack (24h operational)**
- **Electronic Board**
- **Hydraulic Motorized Syringe:**
  - **Electric Engine**
  - **Piston**
  - **Cylinder**
- **Pressure Transducer**
- **Blade with standard dimensions**



patent no. 18457.0137.US0000

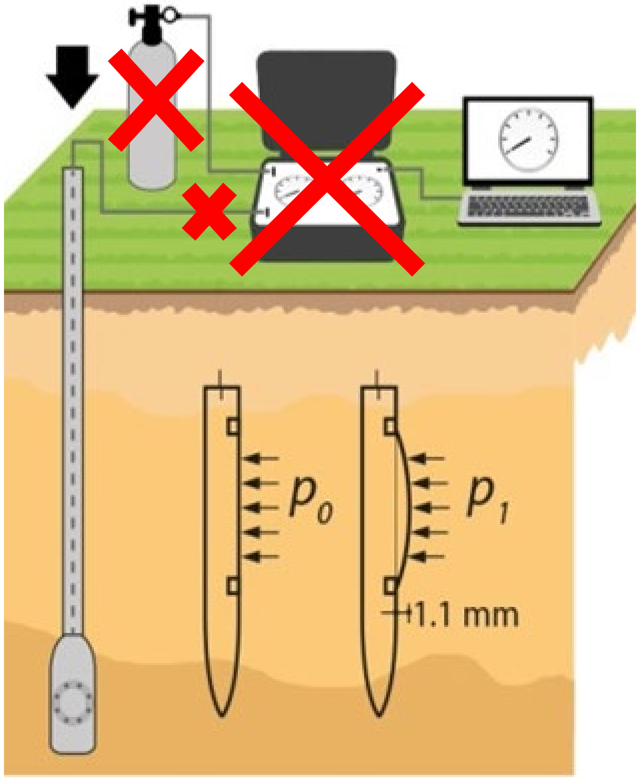
Medusa DMT: example of test cycle



T = 0 when penetration stops and test cycle begins

Medusa DMT vs. Traditonal DMT

- No gas tank
- No control unit
- No pneumatic cable
- No operator required for inflation

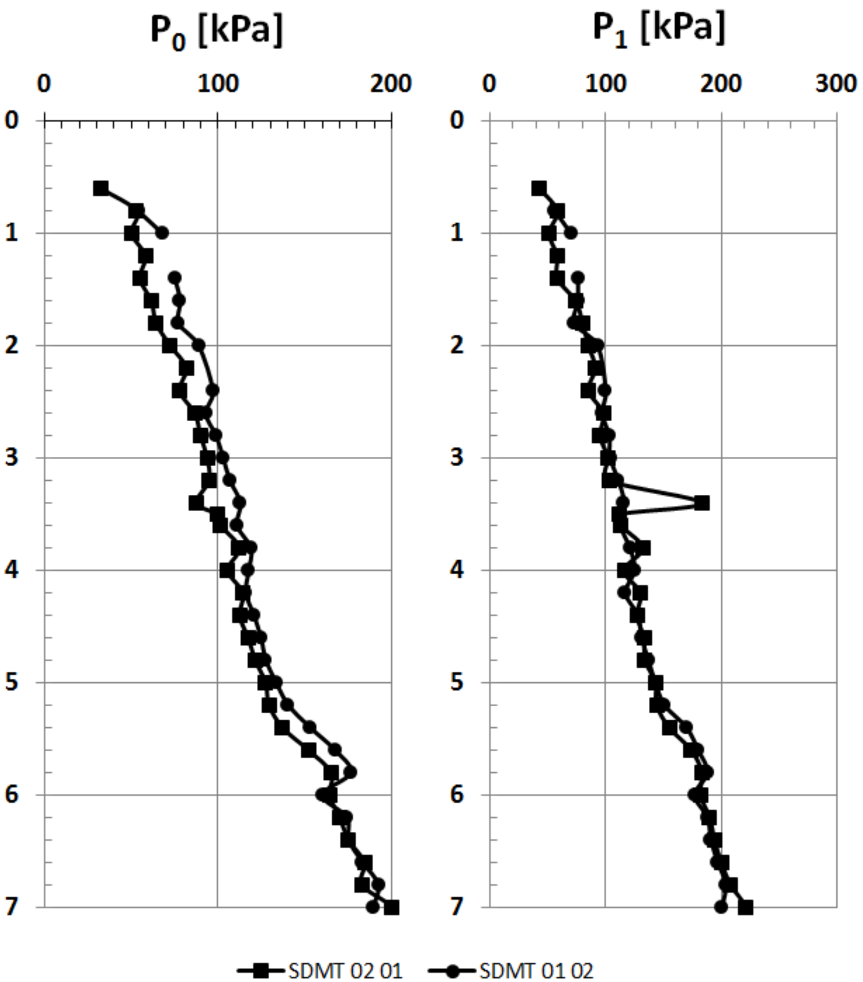


Medusa DMT in extremely soft soil

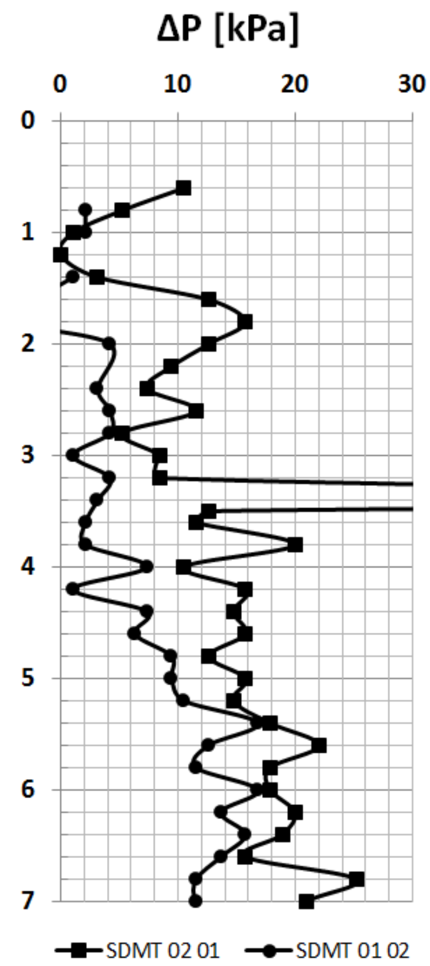
Sarapui II
Rio de Janeiro
(2018)

Traditional DMT in soft soil

Danziger et al. 2015

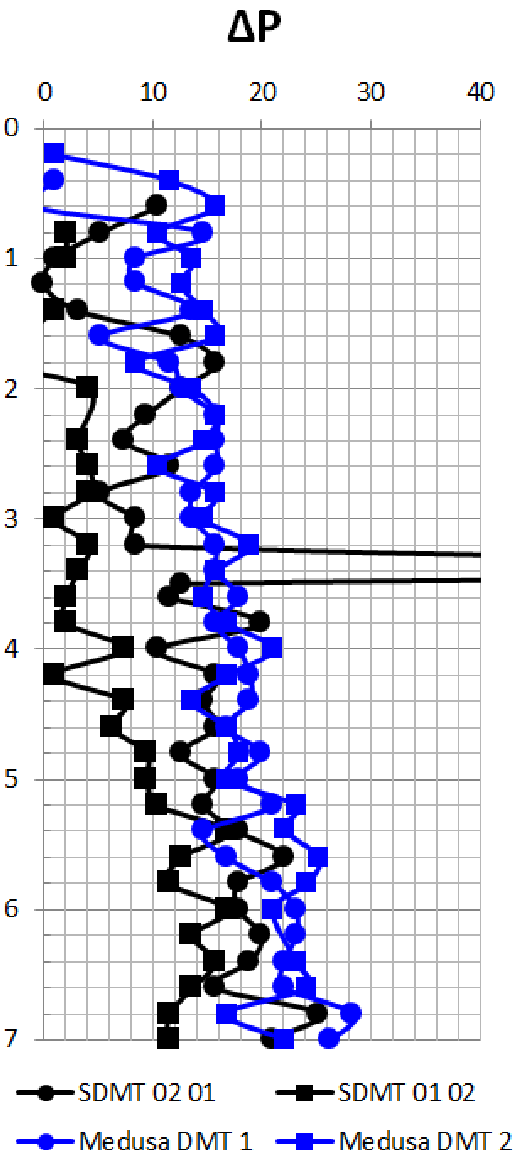


P_0 and P_1 good repeatability



ΔP (~10 kPa) → High Scatter

Medusa DMT in soft soils



Not yet published results !!

ISC'6 Budapest 2020 (Januzzi, Danziger, Marchetti)

The Medusa DMT highly reduced scatter and increased repeatability of ΔP in soft soil

I_D and E_D are both f(ΔP)

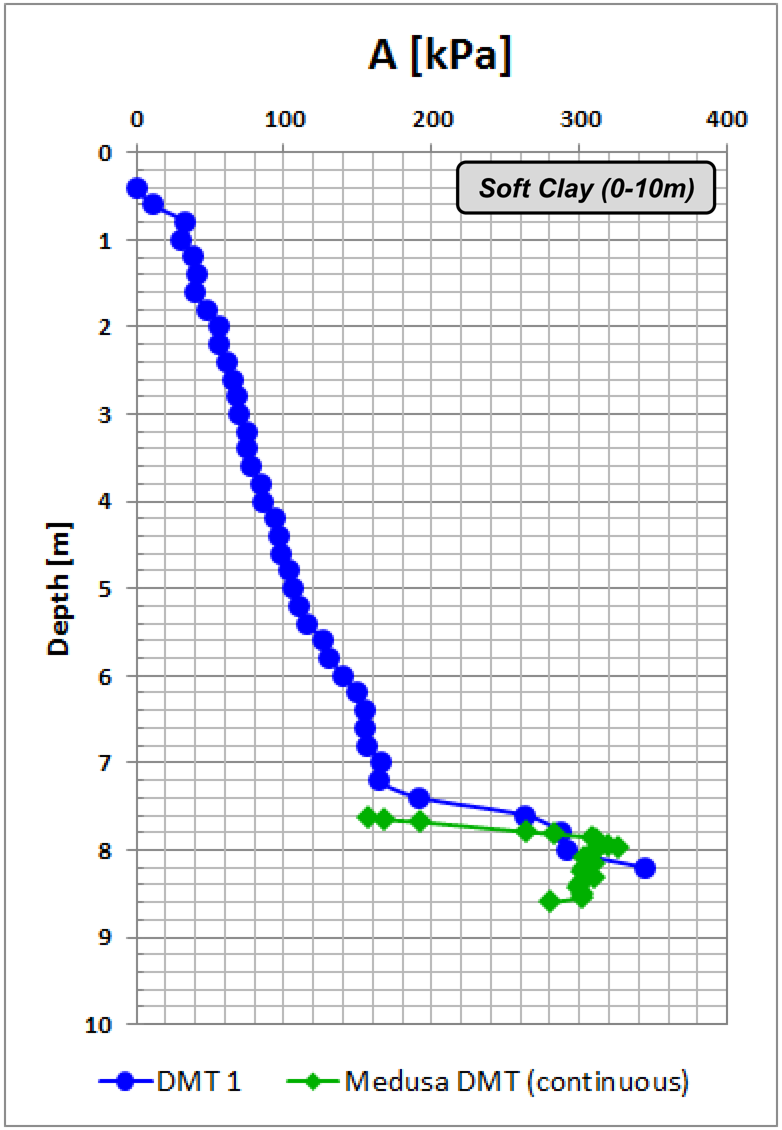
→ Important for M = f (I_D, E_D)

DMT with Continuous penetration

New Methodology :

- ***Like CPT, the Medusa DMT is advanced maintaining the membrane in the A position during penetration***
- ***Readings of A plotted with depth***

Validation of continuous penetration (A_{T0})



Preliminary results appear encouraging

Further research required to understand possible benefits of this methodology

Sarapui II, Brazil (2018)

Swedish Geotechnical Society
Svenska Geotekniska Föreningen
1950 - 2020

Thank you for your attention

Eng. Diego Marchetti (*diego@marchetti-dmt.it*)

Stoccolm, 11 March 2020

MARCHETTI DILATOMETER

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Documentation

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Commercial Information

E-shop: *www.marchettidilatometershop.com*