CTICS-ABMS *Singeo 2013*

24 April 2013 *Rio de Janeiro*

The seismic dilatometer. Stress History, liquefaction, settlements.

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FROM LAB TO INSITU TESTING

In the last decades : massive migration from lab testing to insitu testing. Often today in situ testing is the major part of an investigation.

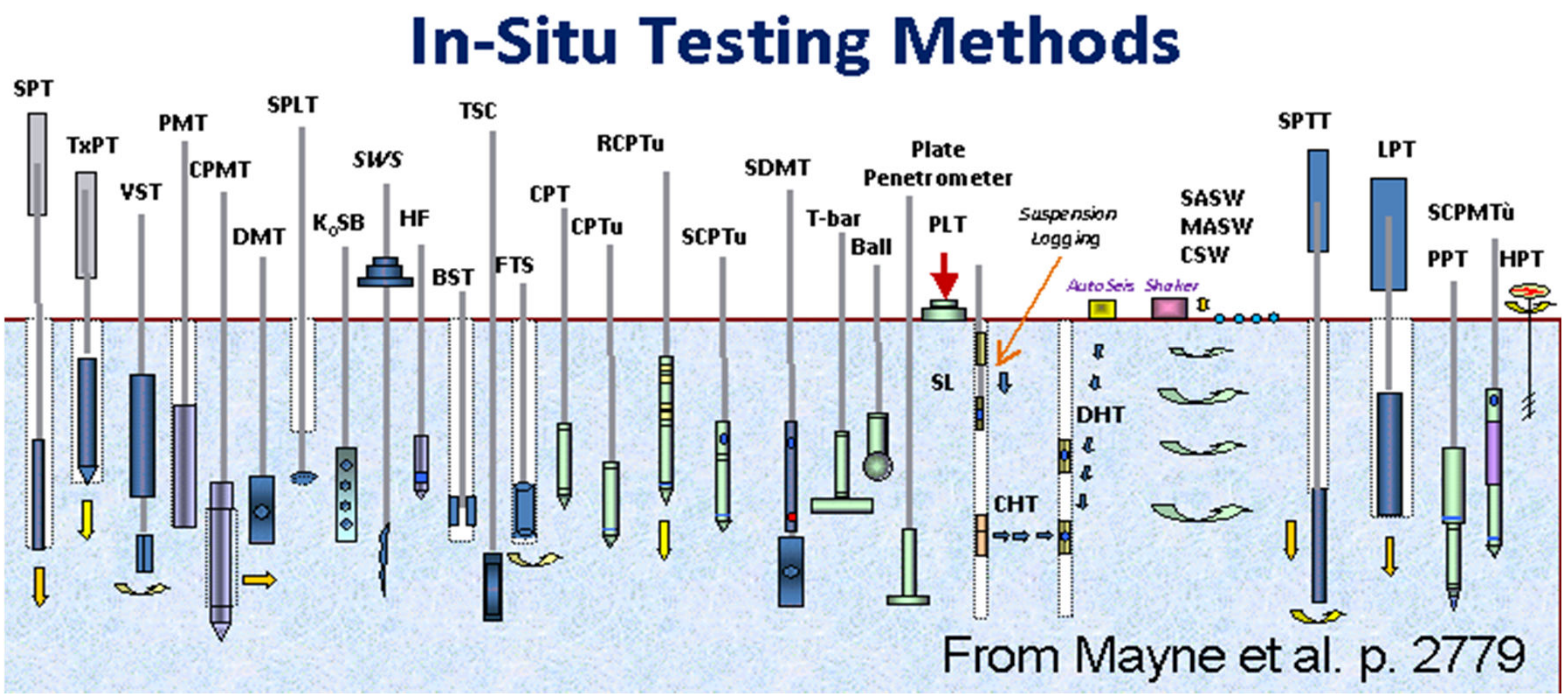
In situ : Fast, economical, reproducible, informative, many data, reduced scatter, cost much less than sampling & testing….

<u>True</u> in Sand : Recovering samples is difficult. Field tests method of choice - state-of-practice.

<u>Caution</u> : lab remains fundamental for research

2009 Mayne et al. : many in situ tests

Some are too slow, some expensive or difficult to run etc.. Which ones to use ?



Mayne et al. SOA 17th ICSMGE Egypt 2009

Mayne P.W.	Georgia Institute of Technology, Atlanta, USA
Coop M.R.	Imperial College, London, UK
Springman S.M.	Swiss Federal Inst. of Technology, Zurich, CH
Huang A.B.	National Chiao Tung Univ., Taiwan, China
Zornberg J.G.	University of Texas, Austin, USA

"in this fast-paced world, direct-push… SCPT and SDMT should serve as the basis … in *routine daily* site investigations…"

Robertson (ISC4 2012) "use direct-push multi-measurement in-situ devices, such as SCPT and SDMT" *abandon SPT crude, unreliable*

Mlynarek (ISC 2012) : ***in many countries CPTU and SDMT/ DMT are becoming basic methods for evaluating subsoil properties. Howie 2012…***

Direct push ***CPT/DMT increasingly*** **recommended everyday practice**

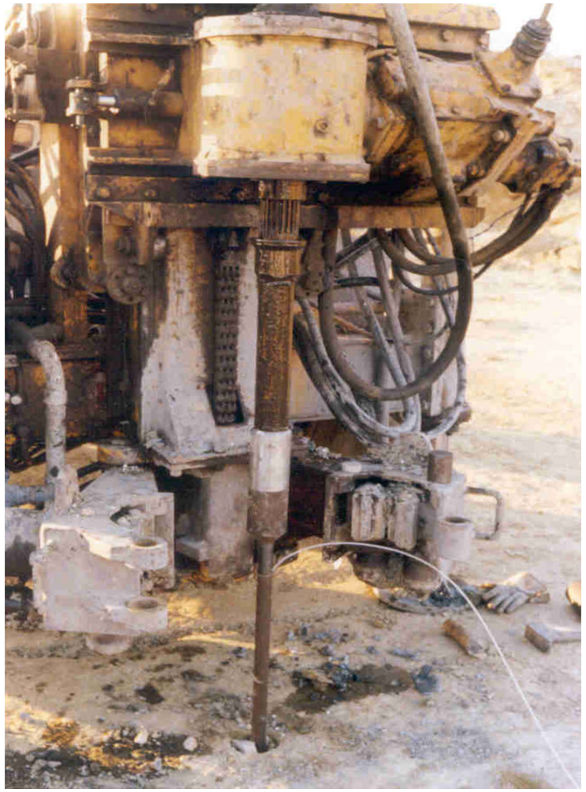
This presentation : describes DMT, results, eng. applications

DMT components

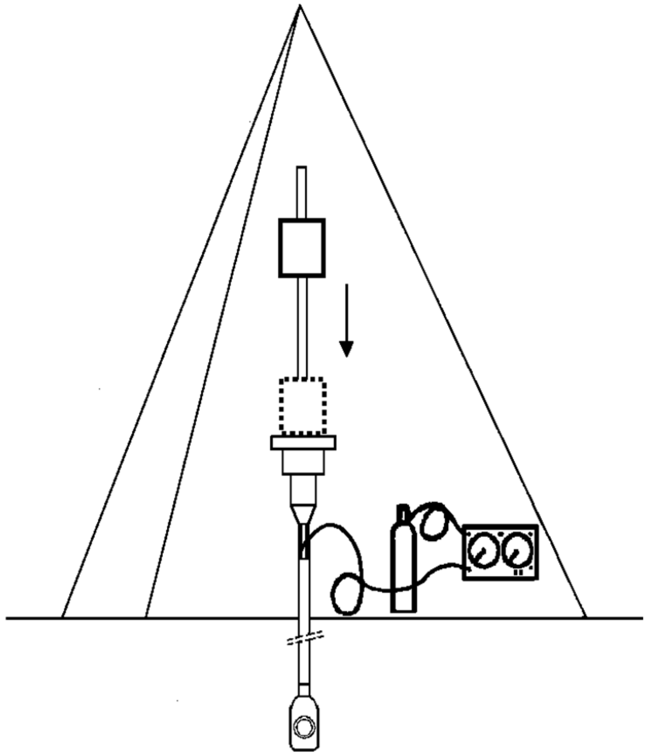
DMT pushed by a truck mounted penetrometer

Use same rigs used for pushing CPT. But many more insertion methods : no need of 2 cm/sec

Blade can also be inserted by a drill rig, used as a penetrometer for pushing

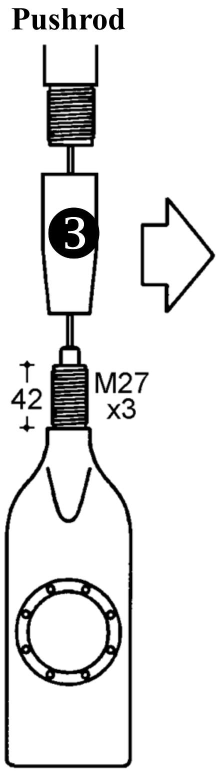


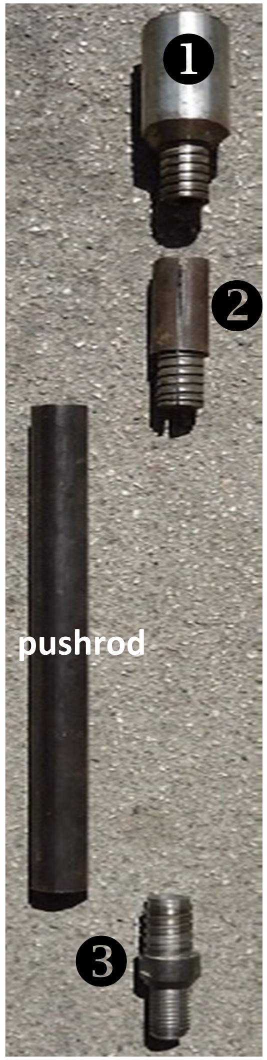
Blade can also be driven by SPT hammer (though quasi static preferable)



Drill rig :“SCIACCA” METHOD

DMT pushed by a drill rig, using it as a penetrometer. Lateral exit of cable is above ground (all needed : 3 adaptors)





Suitable for penetrable soils (sand, silt, clay)

Nearly liquid soils : highly accurate due to the “balance of zero” method

Hard soils (e.g. Cu 800 kPa), weak rock: OK but need strong push - heavy truck

LIMITS

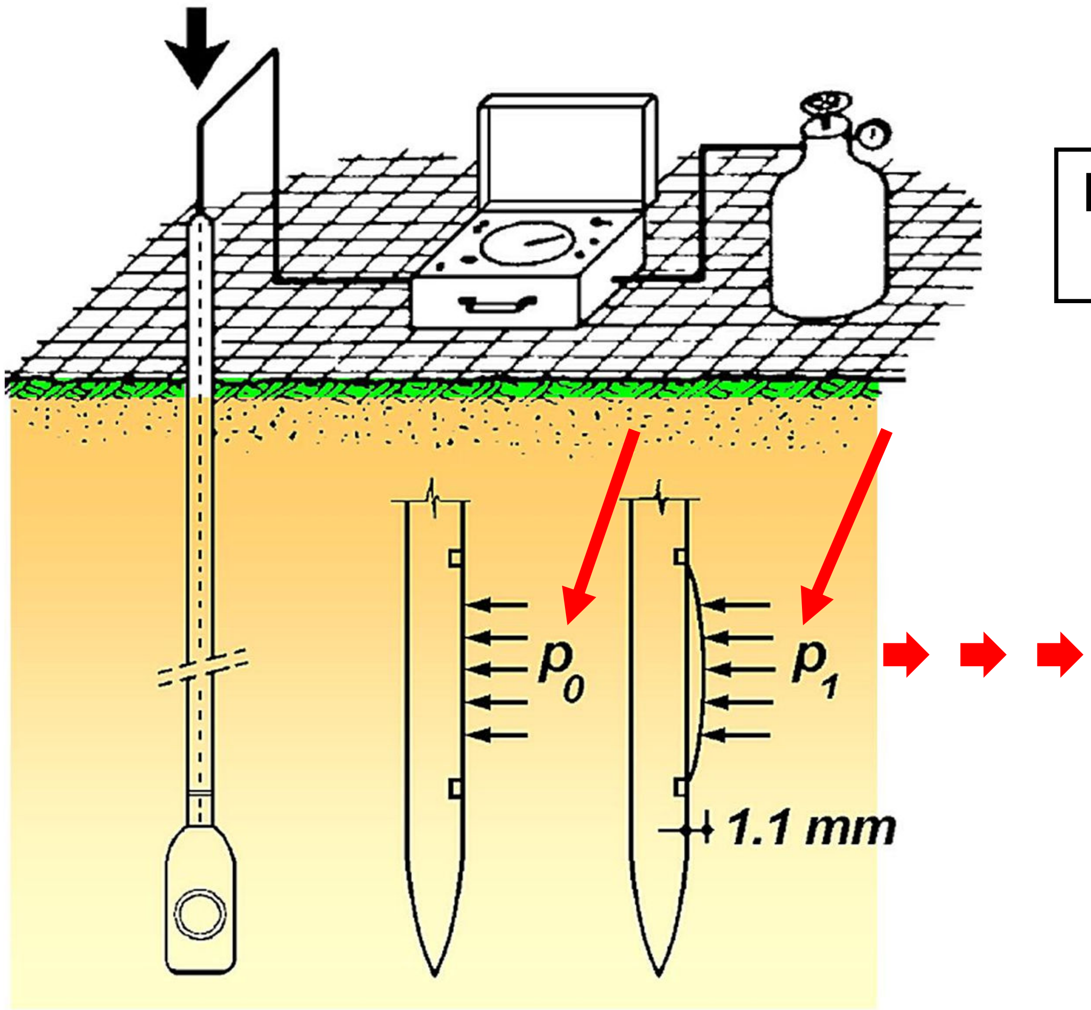
Clays   Cu=2-4 kPa up to 1 MPa (marl)

Moduli M=0.5 to 400 Mpa

Robust, can safely withstand **25 ton**

DMT BLADE

HOW DMT WORKS (mechanical)



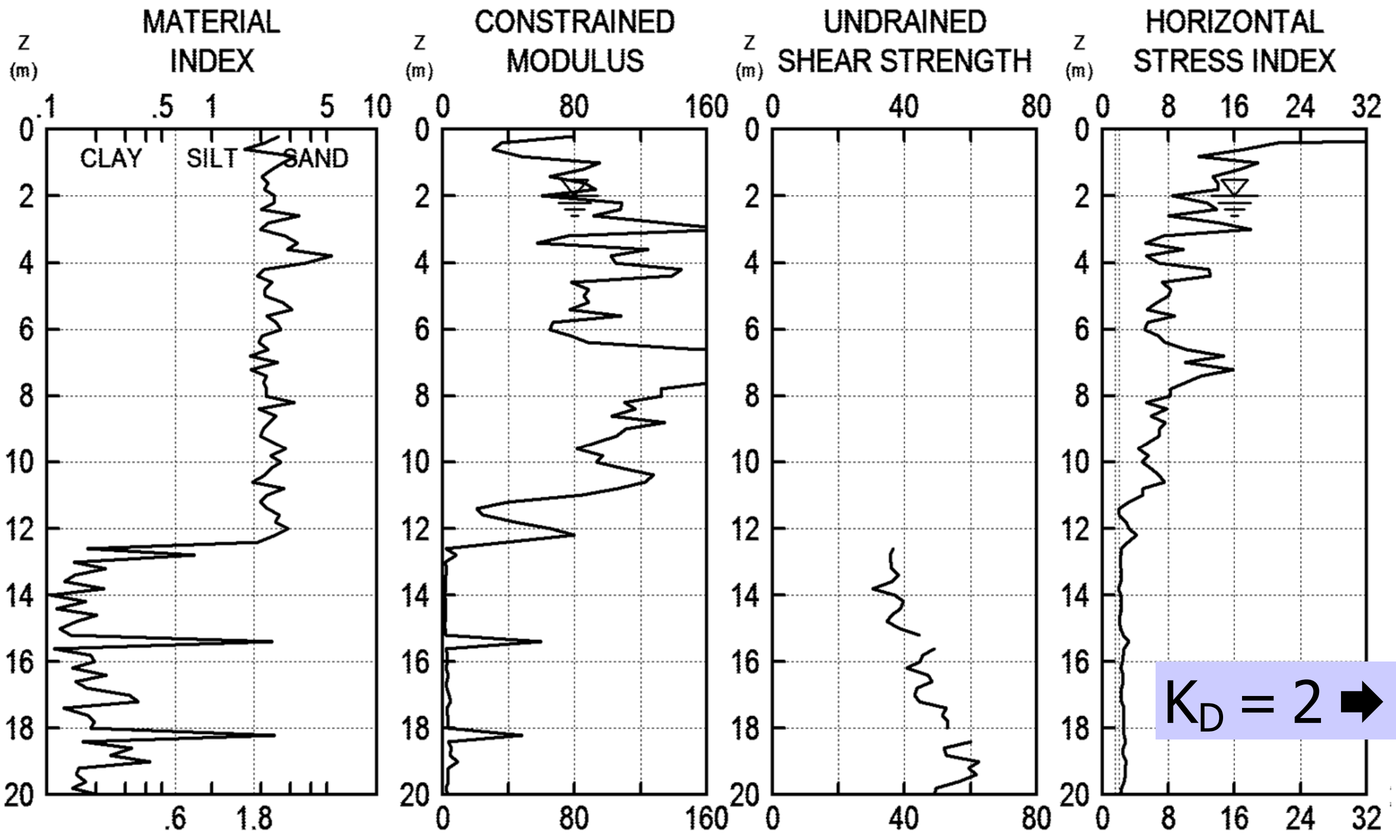
REDUCTION FORMULAE in → TC16 (2001) issmge

p_o, p_1 → Id, Kd, Ed
→ Soil parameters
(M, Cu …)

DMT FORMULAE

SYMB	DESCRIPTION	BASIC DMT REDUCTION FORMULAE	
P_0	Corrected First Reading	$p_0 = 1.05\,(A - Z_M + \Delta A) - 0.05\,(B - Z_M - \Delta B)$	Z_M = Gage reading when vented to atm.
P_1	Corrected Second Reading	$p_1 = B - Z_M - \Delta B$	However, if ΔA & ΔB are measured with the same gage used for current readings A & B, set Z_M=0 (Z_M is compensated)
I_D	Material Index	$I_D = (p_1 - p_0) / (p_0 - u_0)$	u_0 = pre-insertion pore pressure
K_D	Horizontal Stress Index	$K_D = (p_0 - u_0) / \sigma'_{v0}$	σ'_{v0} = pre-insertion overburden stress
E_D	Dilatometer Modulus	$E_D = 34.7\,(p_1 - p_0)$	E_D is NOT a Young's modulus E. E_D should be used only AFTER combining it with Kd (Stress History). First obtain $M_{DMT} = R_M E_D$, then e.g. $E \approx 0.8\,M_{DMT}$
K_0	Coeff. Earth Pressure in Situ	$K_{0,DMT} = (K_D / 1.5)^{0.47} - 0.6$	for $I_D < 1.2$
OCR	Overconsolidation Ratio	$OCR_{DMT} = (0.5\,K_D)^{1.56}$	for $I_D < 1.2$
c_u	Undrained Shear Strength	$c_{u,DMT} = 0.22\,\sigma'_{v0}\,(0.5\,K_D)^{1.25}$	for $I_D < 1.2$
φ	Friction Angle	$\varphi_{safe,DMT} = 28 + 14.6 \log K_D - 2.1 \log^2 K_D$	for $I_D > 1.8$
c_h	Coefficient of Consolidation	$c_{h,DMTA} \approx 7\,cm^2 / T_{flex}$	T_{flex} from A-log t DMTA-decay curve
k_h	Coefficient of permeability	$k_h = c_h\,\gamma_w / M_h$ $(M_h \approx K_0\,M_{DMT})$	
γ	Unit Weight and Description	(see chart)	
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 $0.6 < I_D < 3$ $R_M = R_{M,0} + (2.5 - R_{M,0}) \log K_D$ where $R_{M,0} = 0.14 + 0.15(I_D - 0.6)$ If $K_D > 10$ $R_M = 0.32 + 2.18 \log K_D$ If $R_M < 0.85$ set $R_M = 0.85$	
U_0	Equilibrium pore pressure	$U_0 = p_2 \approx C - Z_M + \Delta A$	

DMT results



or Stress History Index

Kd=(Po-Uo)/σ'v0
"amplified Ko"

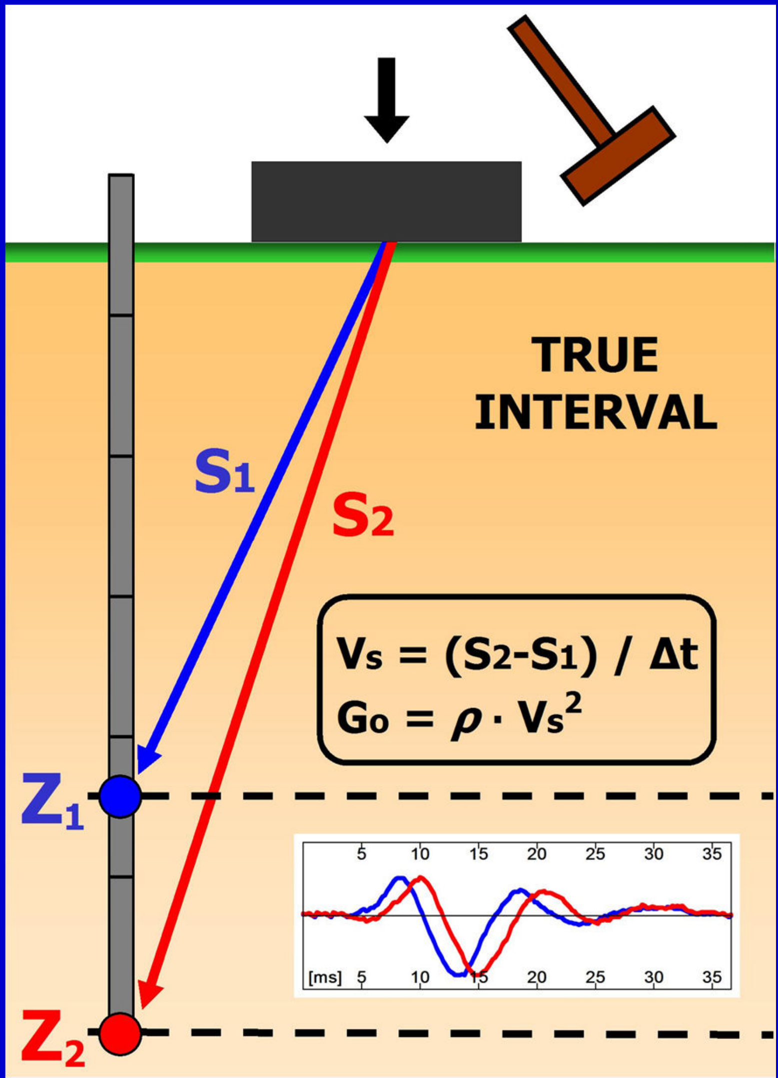
K_D = 2 ➡ NC clay

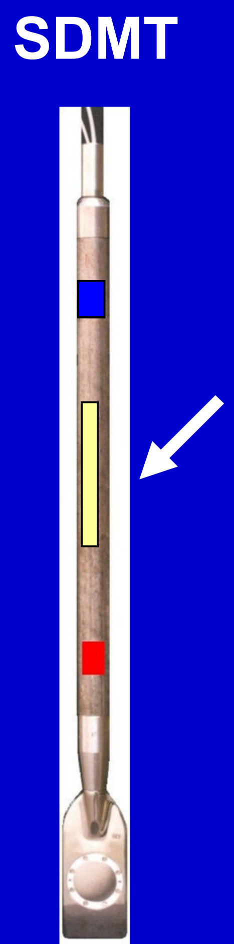
I_D ⬇ soil type (clay, silt, sand)

M ⬇ Cu ⬇ common use

K_D ⬇ shape similar to OCR helps understand *history* of deposit

SEISMIC DILATOMER : DMT with the addition of a seismic module (tube) →Vs





Vs from delay of pulse

2 receivers vs 1 receiver:

- Same blow
- Trigger not critical
- No mitical 1st arrival
- Delay well conditioned

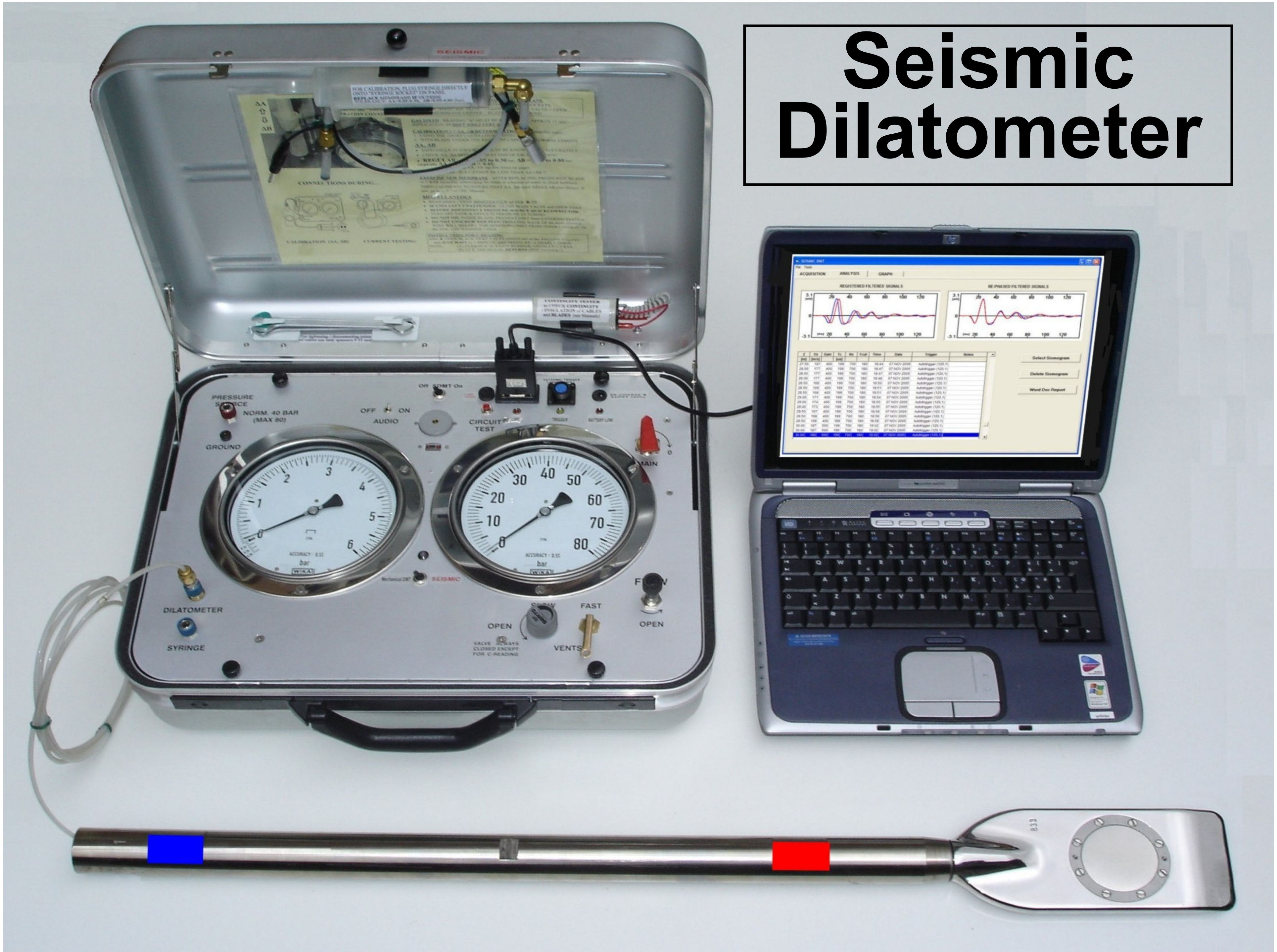
Amplified + digitiz at depth

Operator independent
Interpreter independent

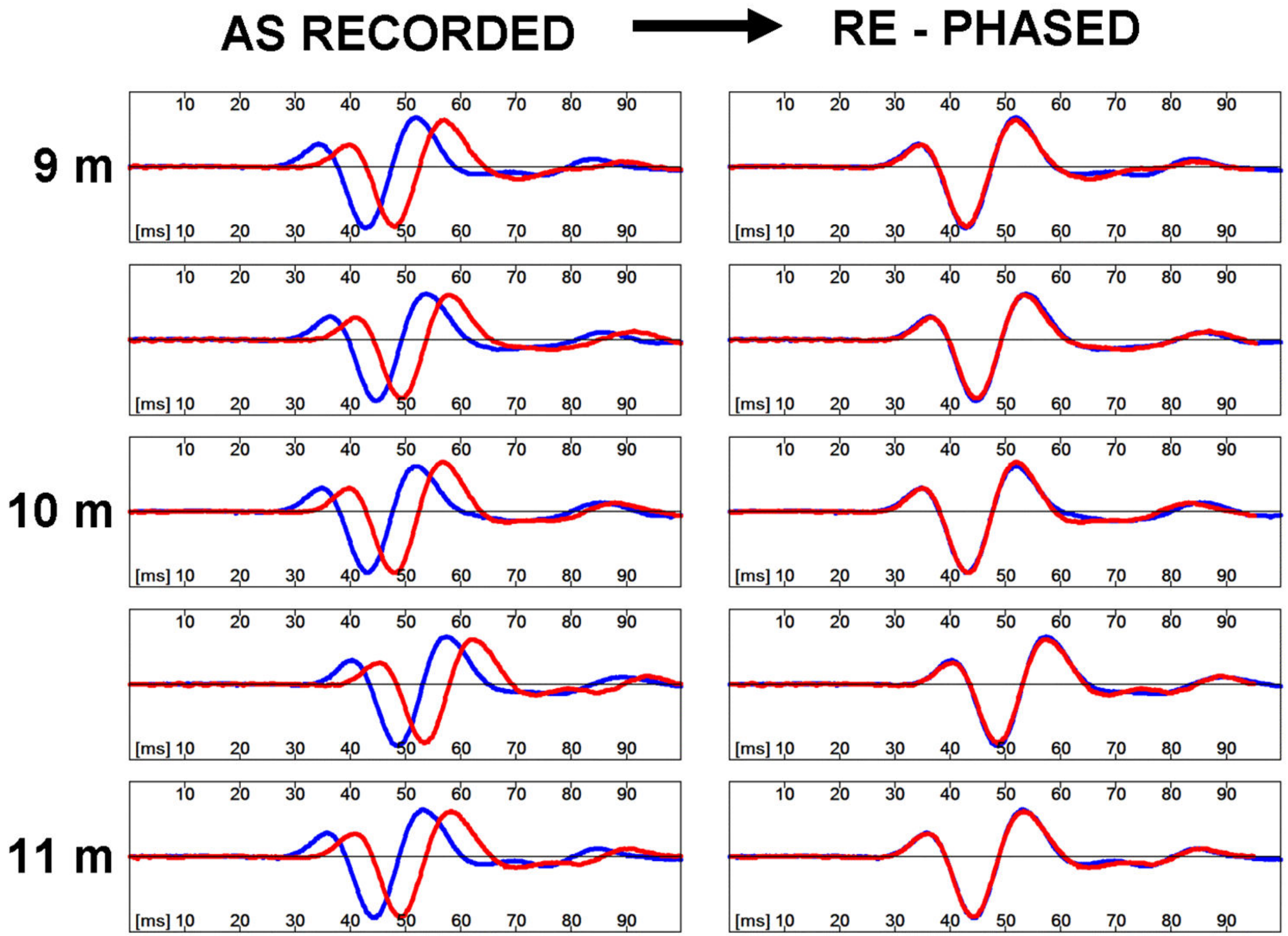
Much faster & economical than Down hole – X hole

No hole/ no samples, no grouting pipes (supervision for voids? Stop for cement..)
Same day

Seismic Dilatometer



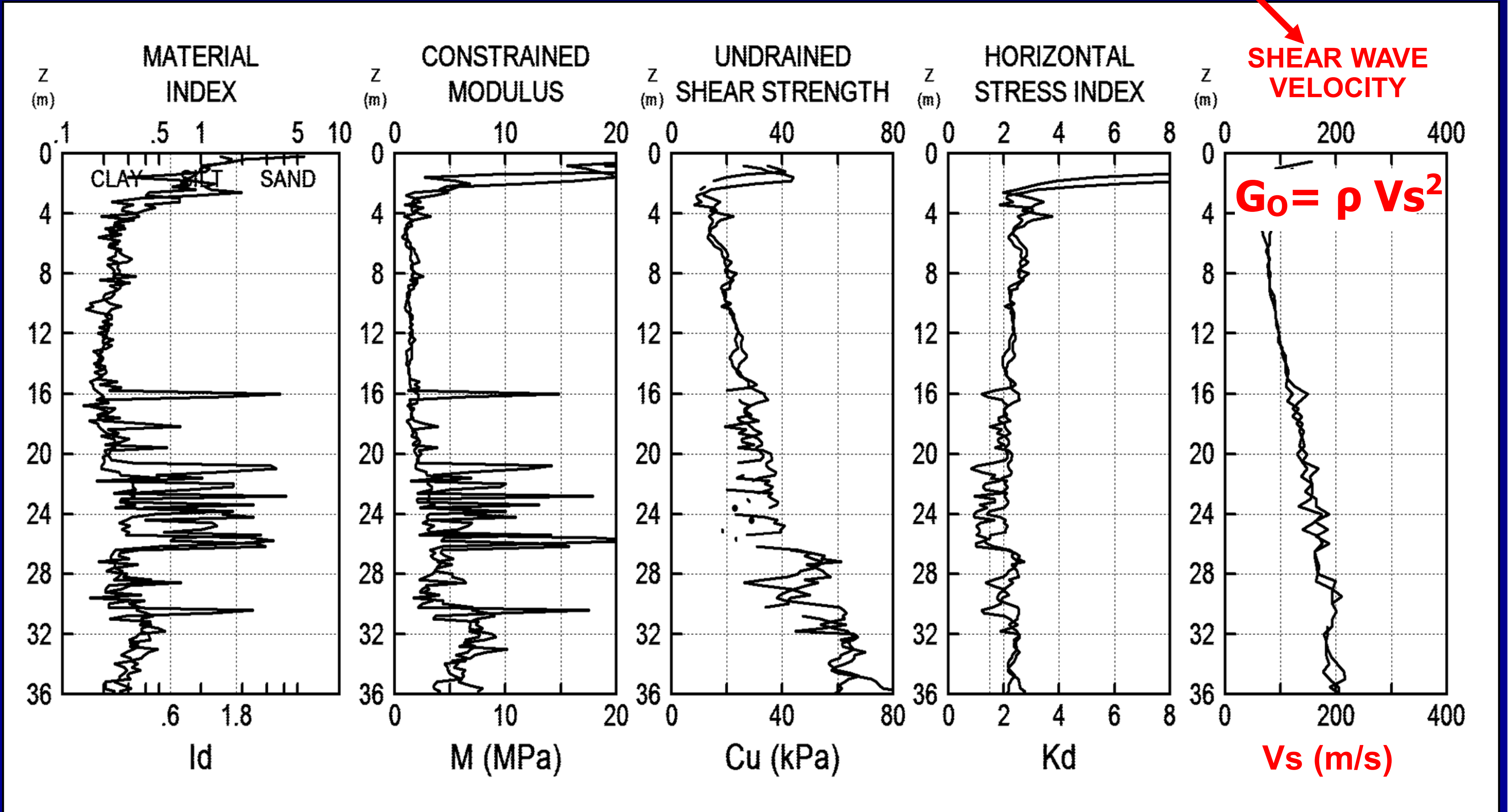
Seismograms SDMT at Fucino



Delay well conditioned → Cross correlation

(no first arrival) Repeatability of Vs 1-2 %

SDMT results *repeatability ≈ 1-2%*



mechanical DMT ***Seismic DMT***

When designing : helpful such clear vision of the site

STANDARDS

***EUROCODE 7* (1997).** Standard Test Method, European Committee for Standardization, Part 3: Design Assisted by Field Testing, Section 9: Flat Dilatometer Test (DMT), 9 pp.

***ASTM (2002)*.** Standard Test Method D6635-01, American Society for Testing and Materials. The standard test method for performing the Flat Dilatometer Test (DMT), 14 pp.

***TC16 (2001)*.** “The DMT in soil Investigations”, a report by the ISSMGE Technical Committee tc16 on Ground Property, Characterization from in-situ testing, 41 pp.

ASTM (2011) – Standard Test Method D7400 – 08, “Standard Test Methods for Downhole Seismic Testing“, 11 pp.

Diffusion : DMT used in 50 countries (200 DMT in US)

Main SDMT applications

Kd indicator of Stress History (prelim. capability)

Settlements of shallow foundations

Compaction control

Slip surface detection in OC clay

Quantify σ'_h relaxation behind a landslide (or diaphragm wall upon excavation)

Laterally loaded piles

Diaphragm walls “springs” for design

FEM input parameters

Liquefability evaluation

Seismic design (NTC08, Eurocode 8)

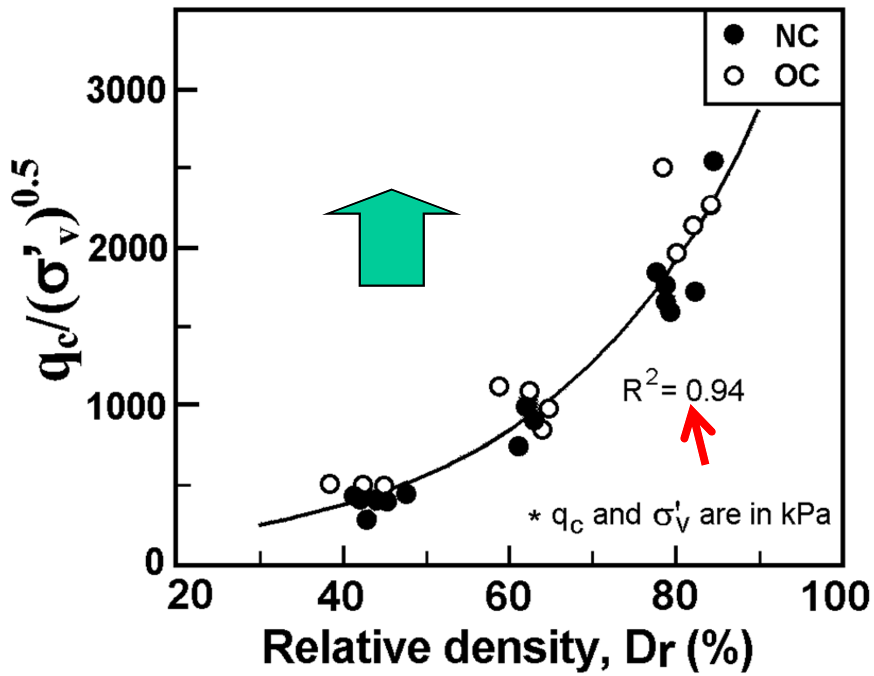
In situ G-γ decay curves

A key parameter by DMT is Kd.
Kd a powerful indicator of Stress History

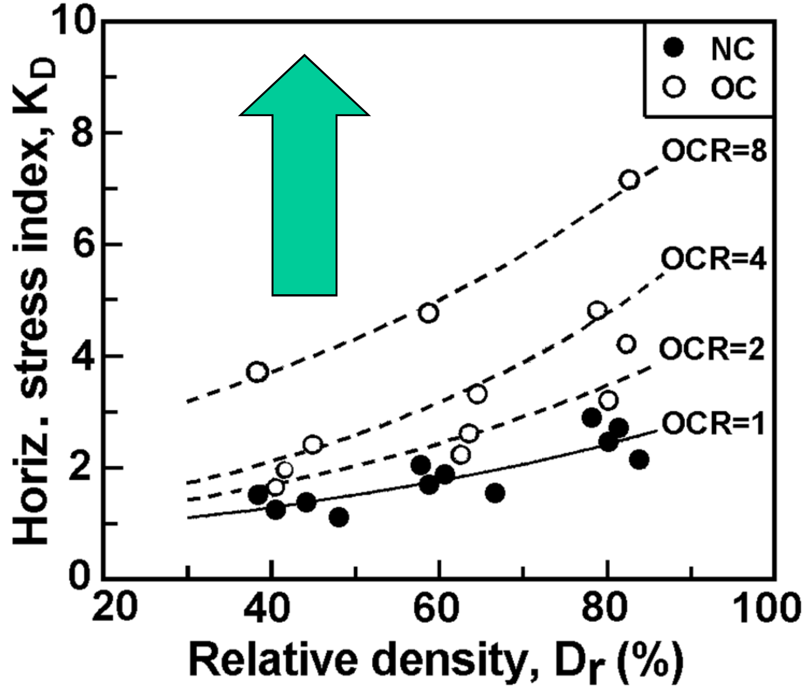
Effects of Stress History on CPT and DMT

Lee 2011, Eng. Geology – ≈ 30 CC in sand

Effect of stress history on normalized Qc (x 1.10-1.15)



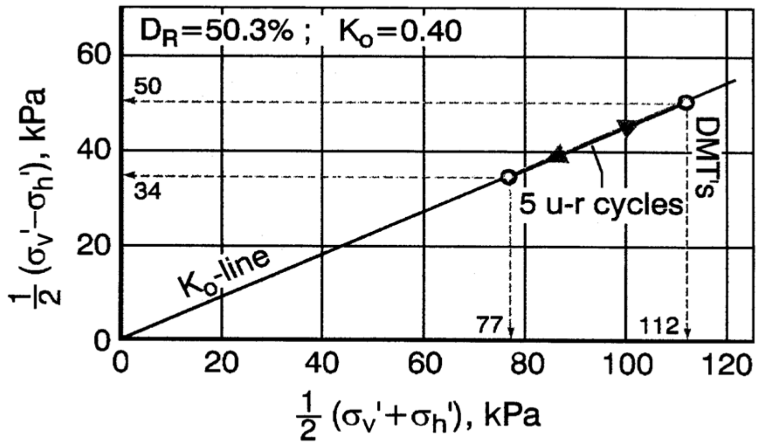
Effect of stress history on Kd (x 1.30-2.50)



DMT far more sensitive to SH & aging

Jamiolkowski *(ISC'98 Atlanta)* ***applied prestraining cycles in calibration chamber. Found :*** **K_D** (DMT) 3 to 7 times more sensitive to **AGING** than **penetration resistance**

CC TEST N. 216 IN TICINO SAND



	I_D (-)	K_D (-)	E_D (MPa)	M_D (MPa)	q_D (MPa)
Before	2.62	1.98	29.0	30.3	16.0
After	2.41	2.38	31.8	37.8	16.4

PRESTRAINING CYCLES
simulate AGING (grain slippage)

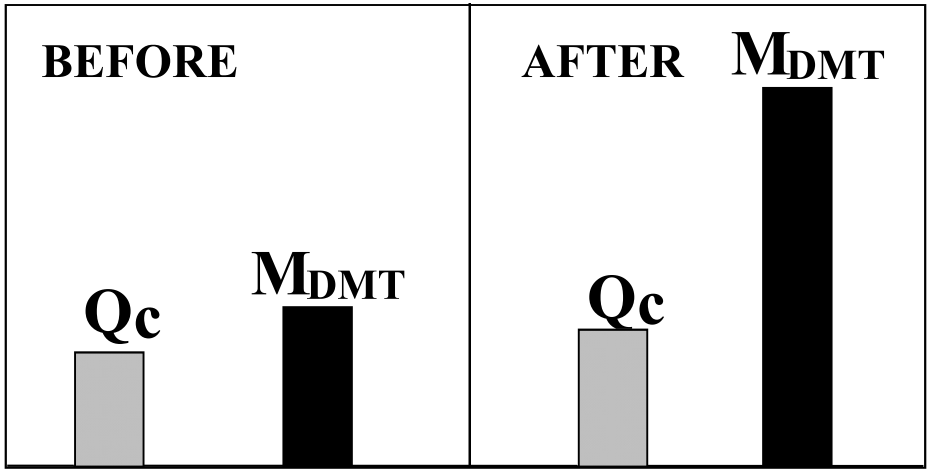
K_D + 20 %
q_D + 3 %

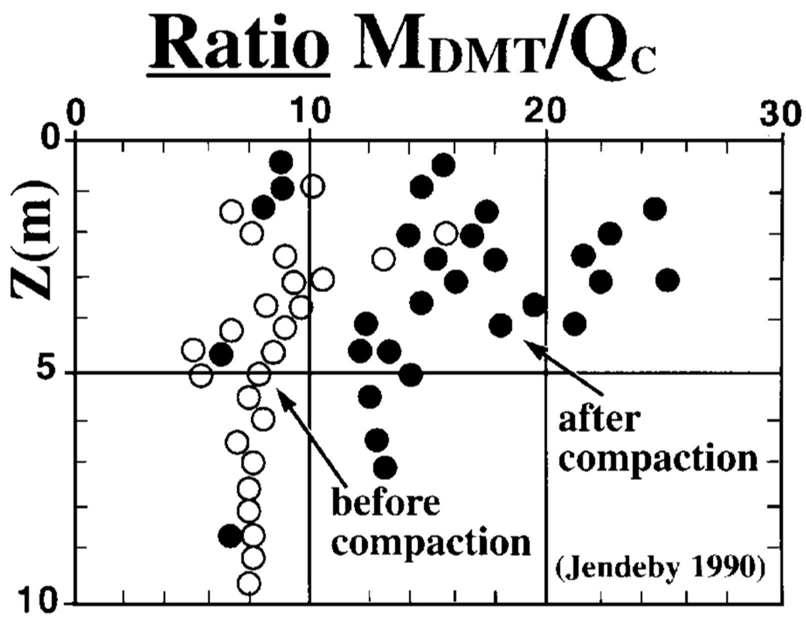
DMT MORE REACTIVE TO STRESS HISTORY

Confirmed in the field …

Jendeby 92
Measured in a loose sandfill Qc & Mdmt before-after compaction

→ OCR in sand
NC : M/Qc ≈ 5-12
OC : M/Qc ≈ 12-24





COMPACTION (impose SH) produces a M_{DMT}% increase ≈ ***twice*** the Qc% increase

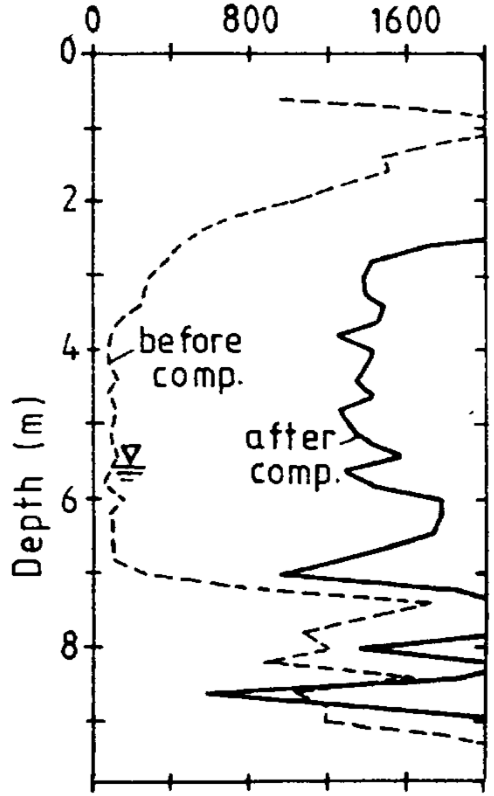
Schmertmann (1986) **DYNAMIC COMPACTION of sand site. M_{DMT} % increase ≈ *twice* % increase in Qc.**

Jendeby (1992) **monitored DEEP COMPACTION in a sand fill by *VIBROWING*. M_{DMT} increase ≈ *twice* increase in qc.**

Pasqualini & Rosi (1993) **VIBROFLOTATION job : *"DMT clearly detected improvement even in layers where benefits were undetected by CPT"*.**

Ghent group (1993) **before-after CPTs DMTs to evaluate effects (±Δσh , Dr) by PILE (Atlas) INSTALLATION *"DMTs before-after installation demonstrate more clearly [than CPT] beneficial effects of Atlas installation"*.**

M_{DMT} before-after compaction



Resonant vibro-compaction technique
Van Impe, De Cock, Massarsch, Mengé, New Delhi (1994)

Settlement predictions by DMT

Data shown indicate Kd as an effective Stress History indicator (interesting : not many SH tools – sand)

Jamiolkowski (Isopt-1,'88,1) **: "*without Stress History, impossible to select reliable E (or M) from Qc" (also Terzaghi, Leonards, Schmertmann…)***

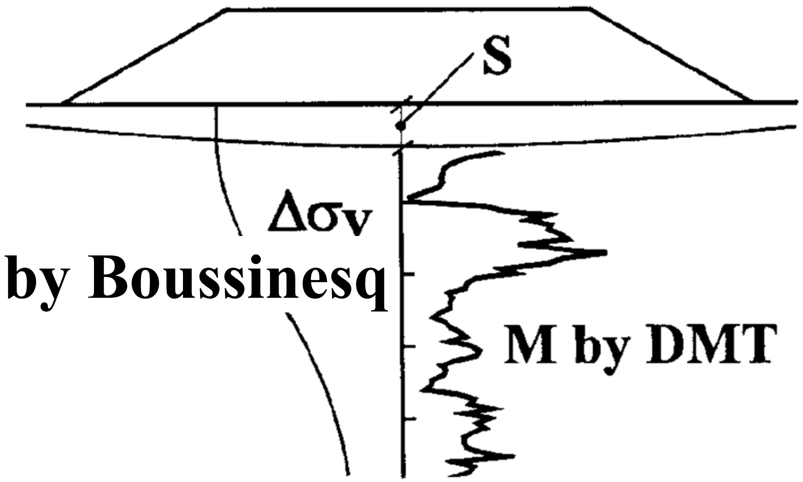
Yoshimi (1975) "… upon initial loading the NC sand specimens were >six times more compressible than the prestressed sand" hence imperative SH to characterize compressibility of sand

Application #1 DMT : predict settlements (operative modulus)

Mdmt= Ed x Rm(Kd, Id) (combines Ed with Stress History)

Settlement predictions by DMT

$$S_{1-DMT} = \sum \frac{\Delta\sigma_v}{M_{DMT}} \Delta z$$

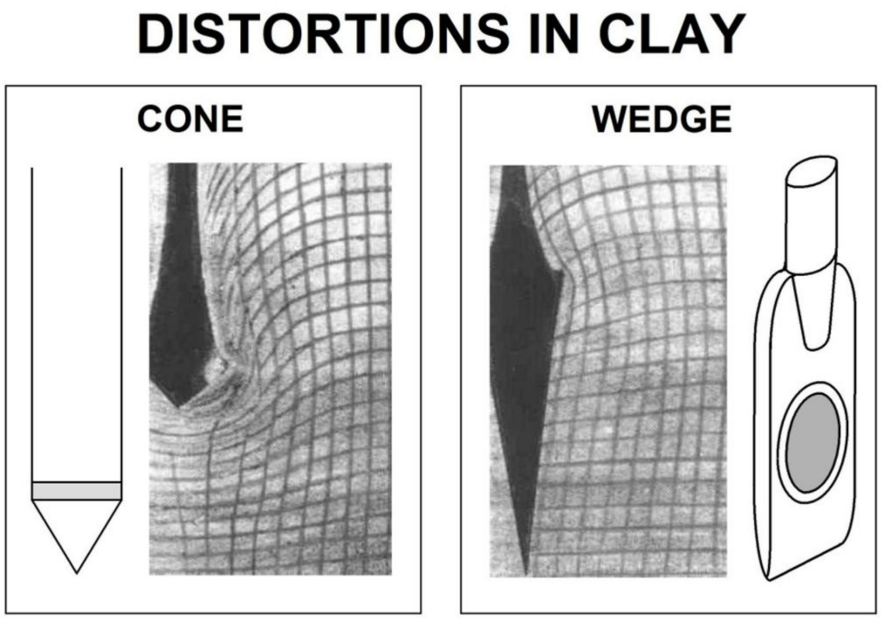


Reliability confirmed by a large number case histories favourable comparisons <u>measured</u> vs <u>DMT-predicted</u> settlements - or moduli

Cruz (2010), 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 (1986)……………

(**see > 40 papers at ISC4-2012**).

Possible reasons DMT predicts well settlement

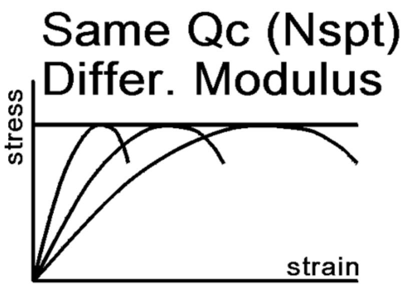


1.Wedges deform soil << cones

2.Modulus by *mini load test* relates better to modulus than penetr. resistance

3.Availability of <u>Stress History parameter Kd.</u>
(DMT is a 2-parameter test.
Fundamental to have both: Ed and Kd)

Stiffnes
≠
Strength



For the same strength : various moduli ⇒ must measure moduli, not strength !

Stress history/aging <u>also</u> necessary for <u>liquefiability</u>

- Jamiolkowski et al. (S. Francisco 1985) "Reliable predictions of sand liquefiability...require…some new in situ device [other than CPT or SPT], more sensitive to effects of past **STRESS-STRAIN HISTORIES**"
- Leon et al. (ASCE GGE 2006) South Carolina sands. "Ignoring **AGING** and evaluating CRR from in situ tests insensitive to aging (SPT, CPT, VS) underestimated CRR by a large 60 %"
- Monaco & Schmertmann (ASCE GGE 2007) Disregarding **AGING** ≈ omitting a primary parameter in the correlation predicting CRR

Lack of Stress History ≈ omission of a primary parameter ⇒ scatter

Is probably the reason of high scatter in the CPT-liquefaction correlations

Scatter is reason why v. cautious recommendations on CRR by CPT

Robertson & Wride (1998) ➡ CRR by CPT adequate for low-risk projects. For high-risk : estimate CRR by more than one method

Youd & Idriss 2001 (NCEER Workshops) ➡ use 2 or more tests for a more reliable evaluation of CRR

Idriss & Boulanger (2004) ➡ the allure of relying on a single approach (e.g. CPT-only) should be avoided

WHY EXPECT A "GOOD" Kd-CRR

•Liquefiability needs SH-aging
Kd is sensitive to SH-aging → **expect "good" Kd-CRR**

•Yu (2004), Robertson (2012) found correlations Kd-ψ
(ψ State Parameter, close proxy of liquefiability)
→ reinforce expectation good Kd-CRR.

Note : ***ψ*** **alone is incomplete indicator of resistance to liquefaction (lacks structure, stress history, aging).**

Two identical sites of same "*e*" (hence same *ψ*) - but the second prestressed : same *ψ*, but the second higher CRR (and higher Kd)

Kd **, being related to *ψ*, but at the same time incorporating Stress History and aging, possibly uniquely well correlated with CRR**

Have seen various reasons for expecting good Kd-CRR.
But how to translate the large experimental base behind Qc1-CRR? (e.g. Youd & Idriss 2001).

Translation done by Tsai (2009).

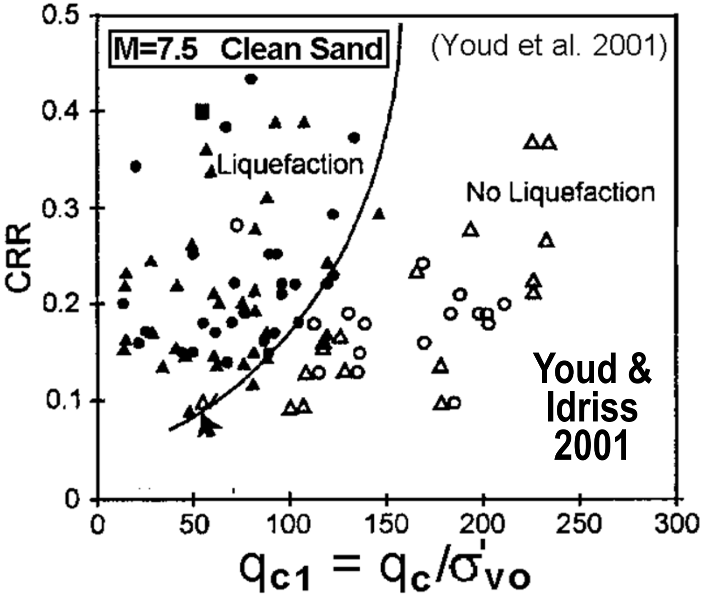
He first determined a Kd-Qc1 correlation by running side-by-side CPT-DMT in loose saturated clean sand.

Then used said Kd-Qc1 correlation to replace Qc1 with Kd in Youd & Idriss, thereby obtaining a correlation CRR-Kd.

Innovations : Tsai cut out elusive Dr, a parasitic parameter, difficult to estimate in situ (Qc1, Kd easily measured).

Tsai translated the CRR-Qc database into CRR-Kd

CONSENSUS q_{c1}- CRR for CPT



↑

$\boxed{q_{c1} = f(Kd)}$

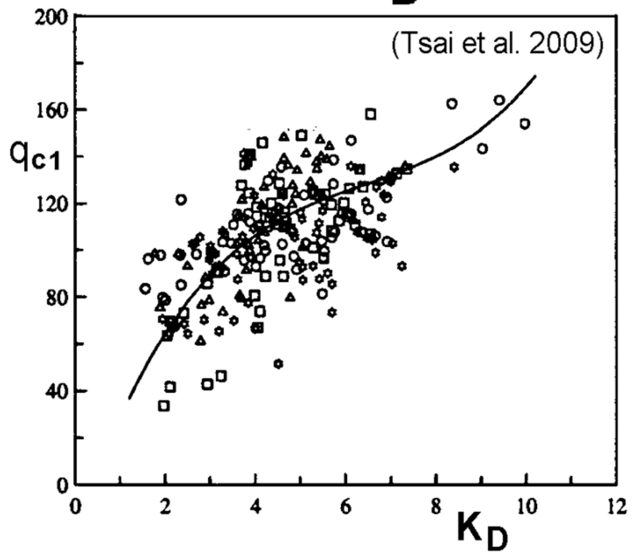
Replace q_{c1} with Kd
Thus : obtain CRR-Kd

Tsai ran side-by-side CPT-DMT obtain parallel profiles of Qc1-Kd

⇓

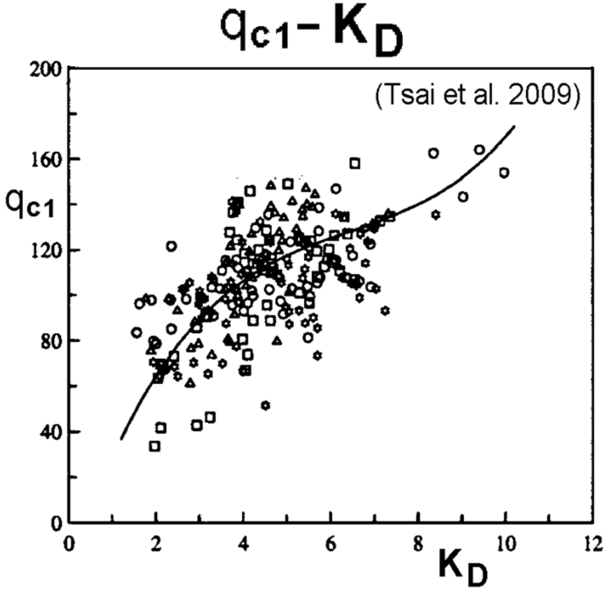
Qc1=f(Kd)

q_{c1} – K_D



(but <u>scatter</u>)

Scatter of the Qc1-Kd relation

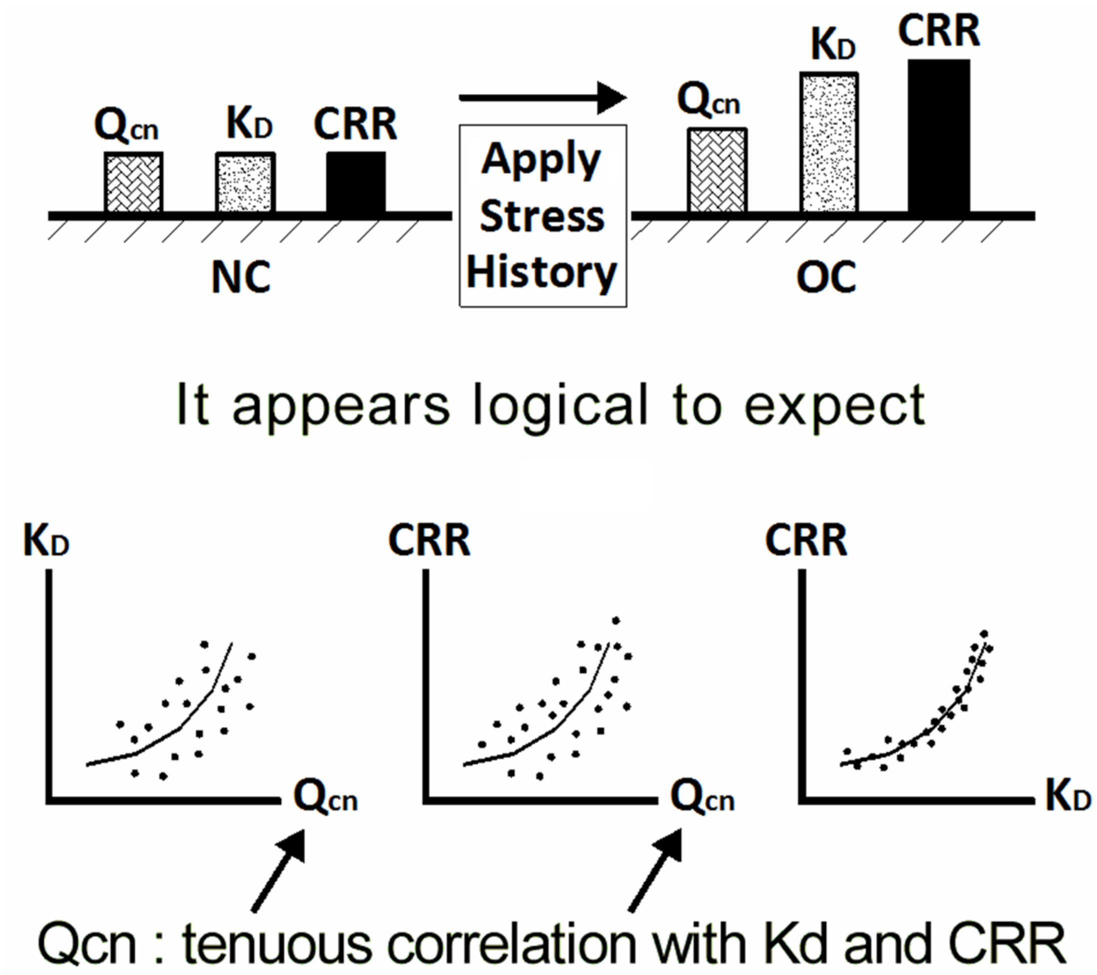


At first sight one might consider doubtful the resulting Kd-CRR correlation, being based on the highly dispersed Qc1-Kd correlation.

Not so. The scatter is just natural, is the consequence of Kd reacting to factors unfelt by Qc1. E.g. for a same Qc1, there can be many Kd - depending if the site has had Stress History.

Scatter is healthy. If there was no scatter : Qc1 and Kd contain the same information, i.e. Qc1 reactive to SH as Kd. Not so.

Explain dispersions of intercorrelations Qcn Kd CRR



High scatter in Kd-Qcn is good news

The more the scatter, the higher is the possible accuracy gain in predicting CRR by moving from predicting CRR based on parameters scarcely sensitive to Stress History to predicting CRR based on K_D >>sensitive to Stress History.

Translation occurs via the <u>average</u> : eliminates that part of scatter due to the insensitivity of Qc1 to Stress History.

A legitimate question

Is it possible to translate the consensus Q_{cn} - CRR into a K_D - CRR correlation better than its source?

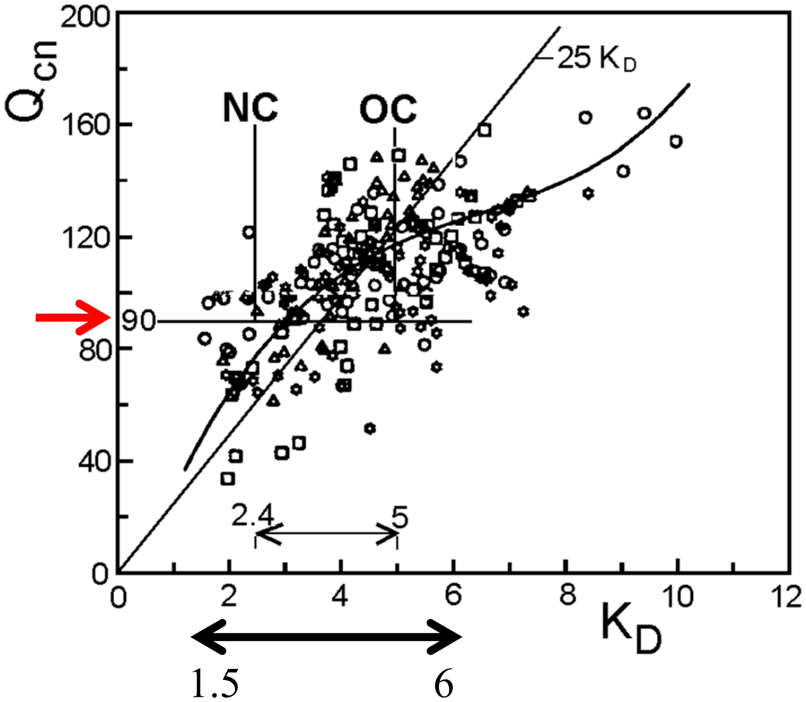
To answer this question, a clarifying similitude may be the following.

If two telescopes of different sharpness look at the Milky Way, the average curve is the same.

Then, once the sharper telescope has been calibrated, so as it sees the same AVERAGE, the sharper telescope may be used to obtain a sharper vision.

A numerical example

In Tsai's sites one finds the same Qcn= 90 in a Kd= 2.4 sand and in a Kd = 5 sand



For Qcn= 90 : Youd CRR = 0.15

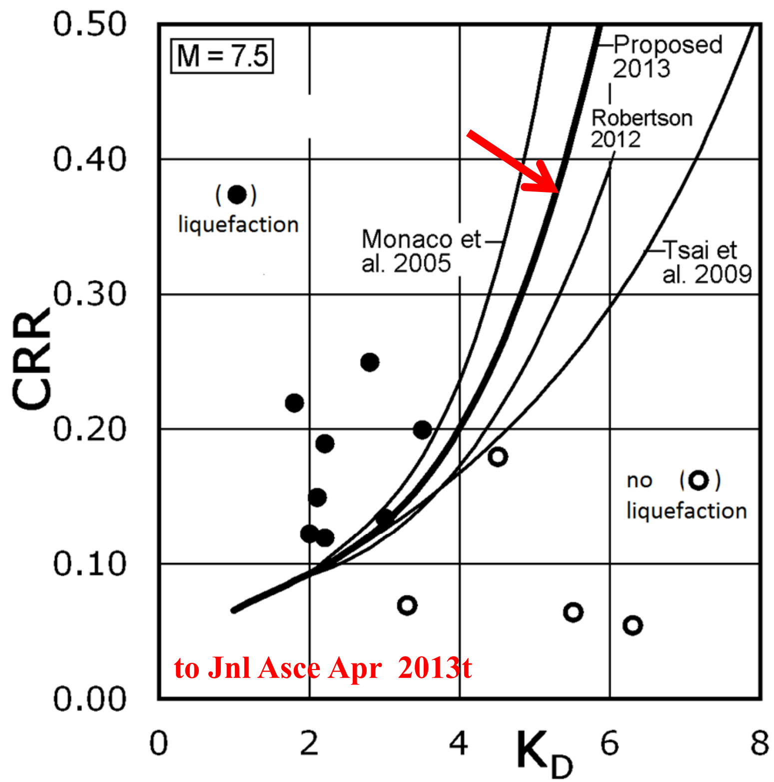
For Kd= 2.4 CRR = 0.10

For Kd= 5 CRR = 0.22

$\Rightarrow$ 0.15 (youd) -33% +47%

∴ CRR predicted by Qcn varies considerably depending on Stress History - unknown to the designer

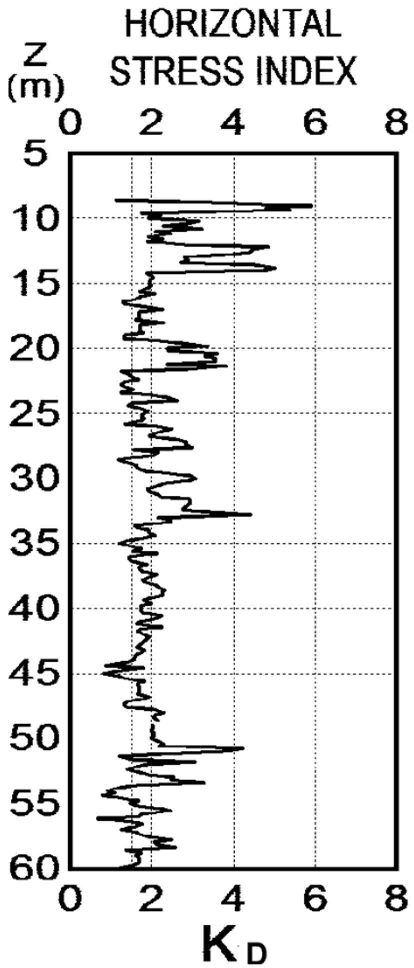
Recent correlations (clean sand)



Monaco et al 2005	$0.0107\ K_D^3 - 0.0741\ K_D^2 + 0.2169\ K_D - 0.1306$
Tsai et al. 2009	$\exp\left[\left(\frac{K_D}{8.8}\right)^3 - \left(\frac{K_D}{6.5}\right)^2 + \left(\frac{K_D}{2.5}\right) - 3.1\right]$
Robertson 2012	$93\ (0.025\ K_D)^3 + 0.08$
Proposed 2013	$0.0038\ K_D^3 - 0.0176\ K_D^2 + 0.0532\ K_D + 0.0264$

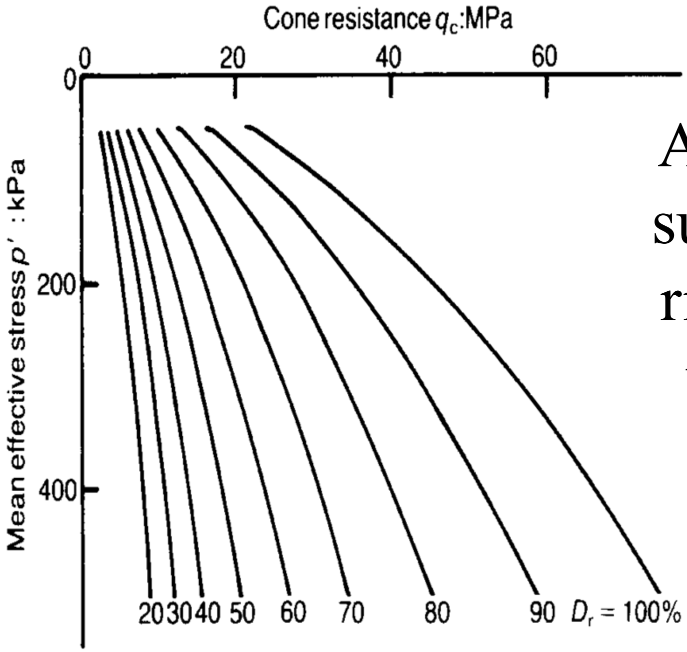
- •Converge to a central narrow band
- •There is a limit to the usefulness of small refinements
- •All recent curves predict CRR in a relatively narrow range, with a fraction dispersion of the Qcn predictions in numerical example
- •Obtaining +datapoints faster, due to better resolution expected for CRR=f(Kd)
- •Qcn : controversy. Sand with same Qcn could liquefy/ not. Depends on unknown Stress History

DMT : Normaliz. exponent n = 1



No arching : side ratio ≈6

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



Arching : laterally suspended floating ring reduces σ'_v at tip level ⇒, less than linear $q_c(z)$

n = 1 a welcome simplification - cuts out iterative procedure to determine Q_{cn} and *n*, an additional soil unknown

Liquefaction : SDMT 2 <u>independent</u> estimates of CRR

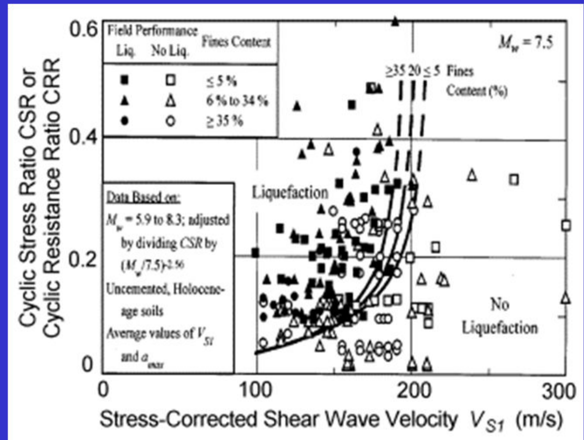
CRR Cyclic Resistance Ratio for Seed & Idriss (1971) simplified procedure

CRR from Vs_{SDMT}

$$CRR = \left[0.022\left(\frac{K_{a1}V_{S1}}{100}\right)^2 + 2.8\left(\frac{1}{V_{S1}^{*} - K_{a1}V_{S1}} - \frac{1}{V_{S1}^{*}}\right)\right]K_{a2}$$

Andrus and Stokoe 2000

Light earthquakes

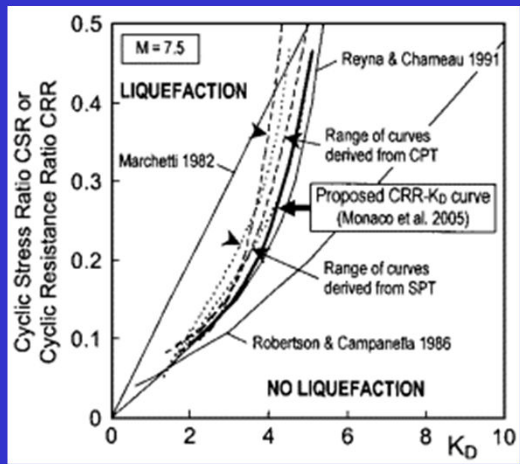


CRR from Kd_{DMT}

$$CRR = 0.0107\,K_D^3 - 0.0741\,K_D^2 + 0.2169\,K_D - 0.1306$$

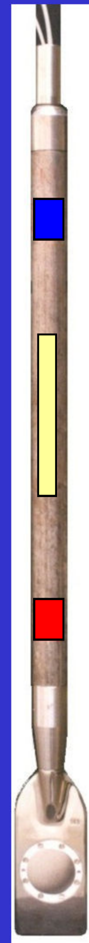
Monaco 2005

Strong earthquakes



V_S

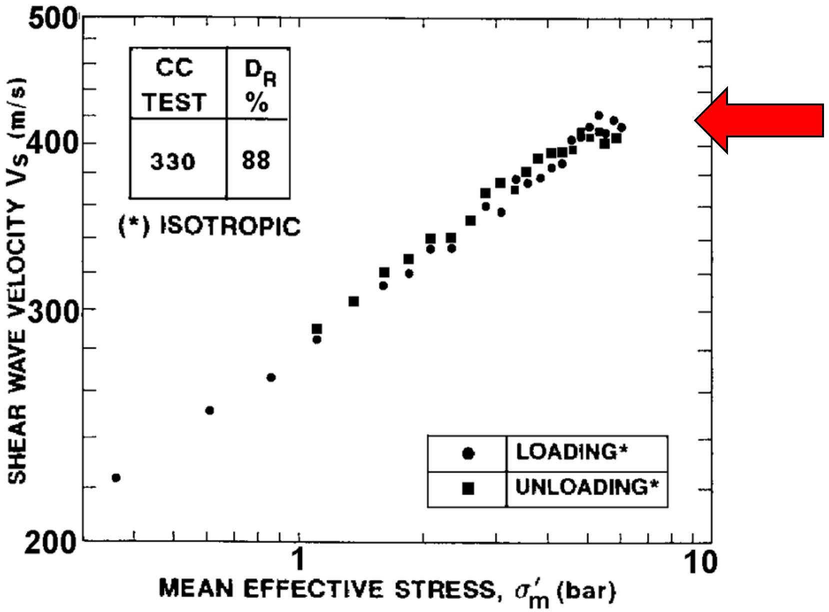
K_D



Monaco (2007) "Evaluating Liquefaction Potential by Seismic Dilatometer (SDMT) accounting for Aging/Stress History" 4th Int. Conf. Earthquake Geotechn. Eng. - Thessaloniki

SDMT provides two independent CRR estimates
From Kd   From Vs

Sometimes different CRR. We consider more reliable CRR(Kd)

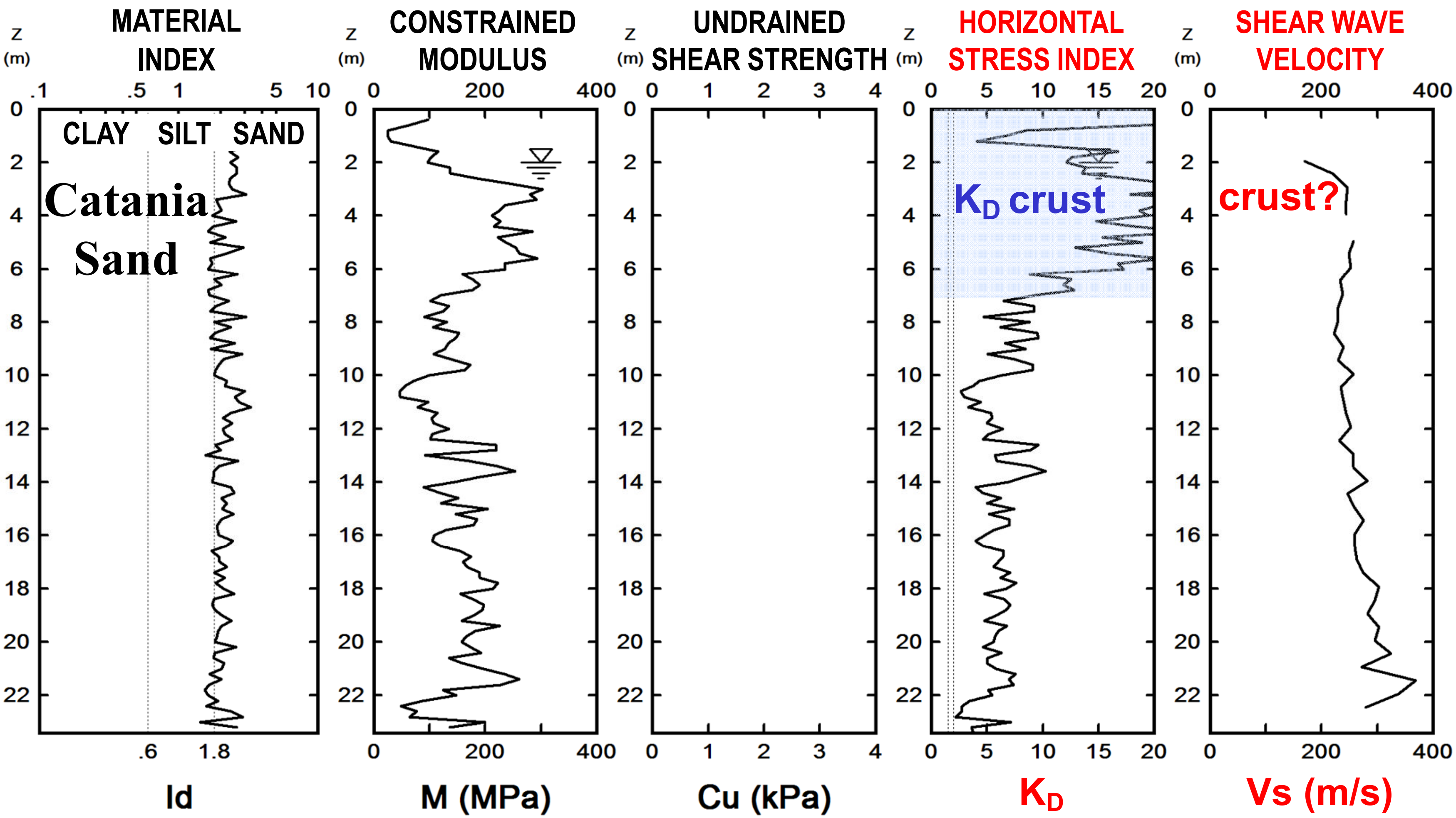


Vs insensitive to Stress History: ***Vs*** **measured on sand specimens in the calibration chamber during loading and unloading**

Waves produce strains too small to initiate trend to dilate/ contract (essence of liquefaction)

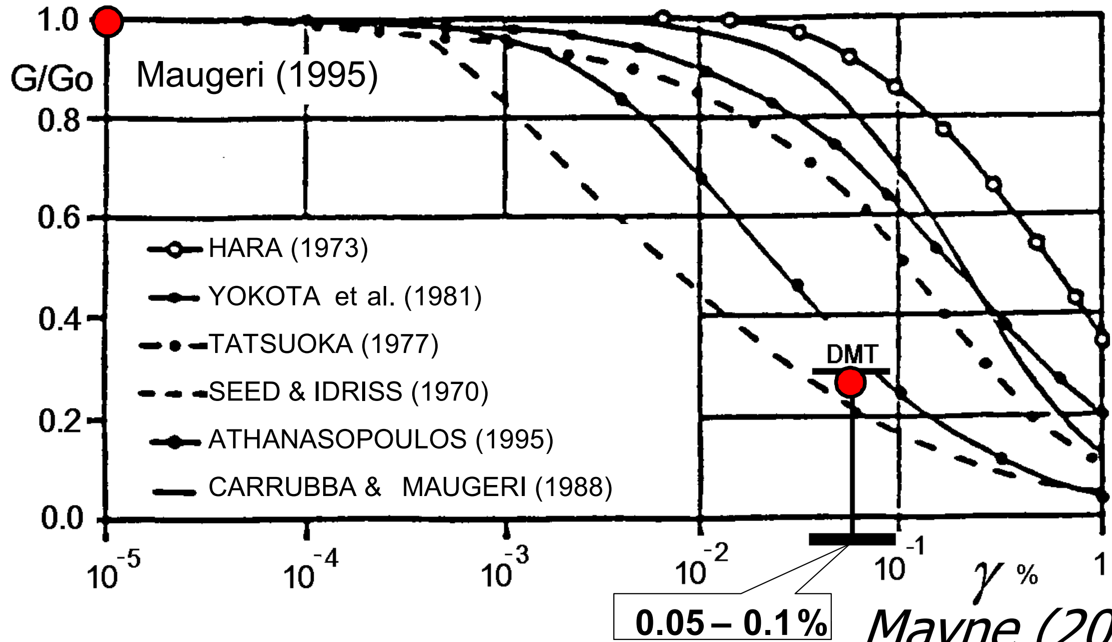
In cemented sands CRR(Vs) usually higher (optimistic) …(cementation increases Vs) . But strong earthquakes may destroy weak bonding.
CRR from *Vs* possibly ok in cemented sands if light earthquakes expected – (bonding preserved).

K_D reflects Stress History



Stress History crusts –clearly evidenced by K_D but "unfelt" by V_S ➡ suggests lesser ability of V_S to profile SH hence liquefiability

SDMT provides Go (small strain modulus) & Mdmt (working strain modulus). Two points of the G-γ curve. May help select the design G-γ curve. (Mayne & Martin 1999)



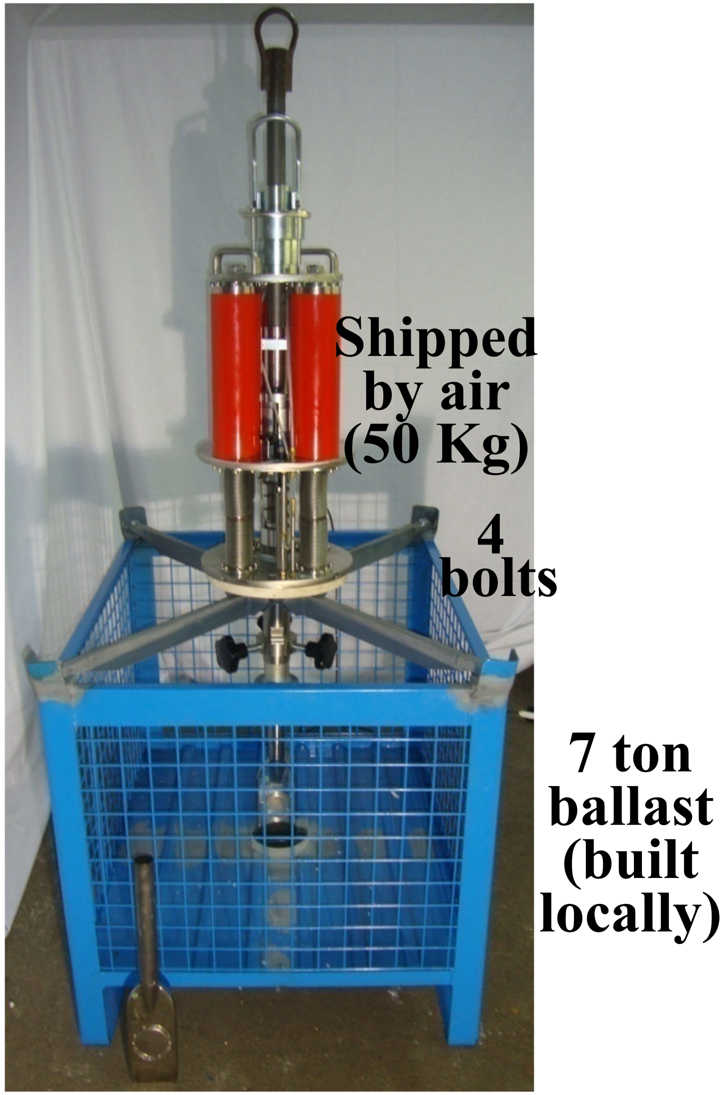
Mayne (2001)
Ishihara (2001)

More info

- Marchetti et al (2008) in Schmertmann Volume

- Lehane & Fahey (2004) Porto ISC-2 – non linear settlement analysis from in situ tests

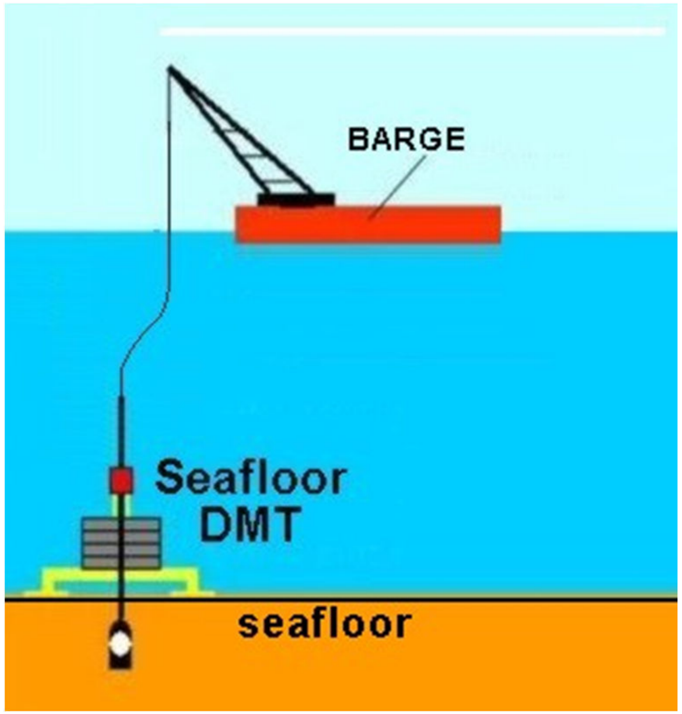
SEAFLOOR DILATOMETER



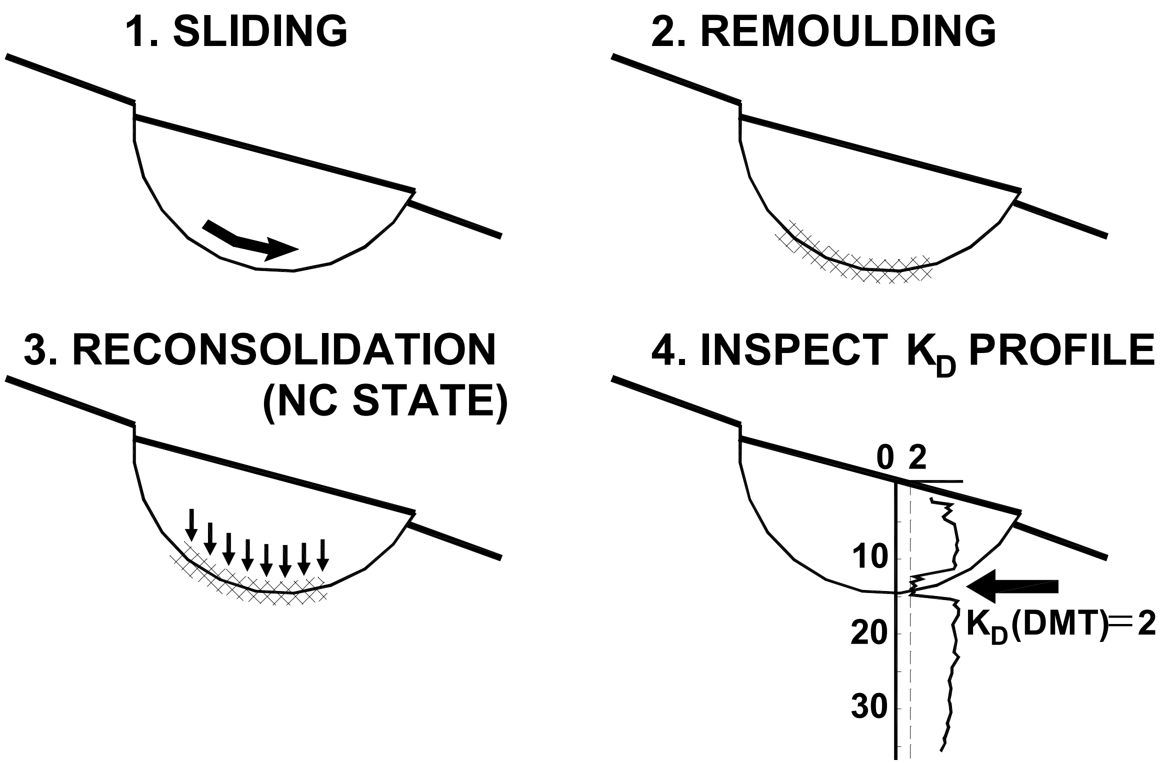
WATERDEPTH 0 to 100 m

PUSH CAPACITY 7 ton

Max test depth is the depth penetrable with 7 ton push.



Detecting slip surfaces in clay slopes

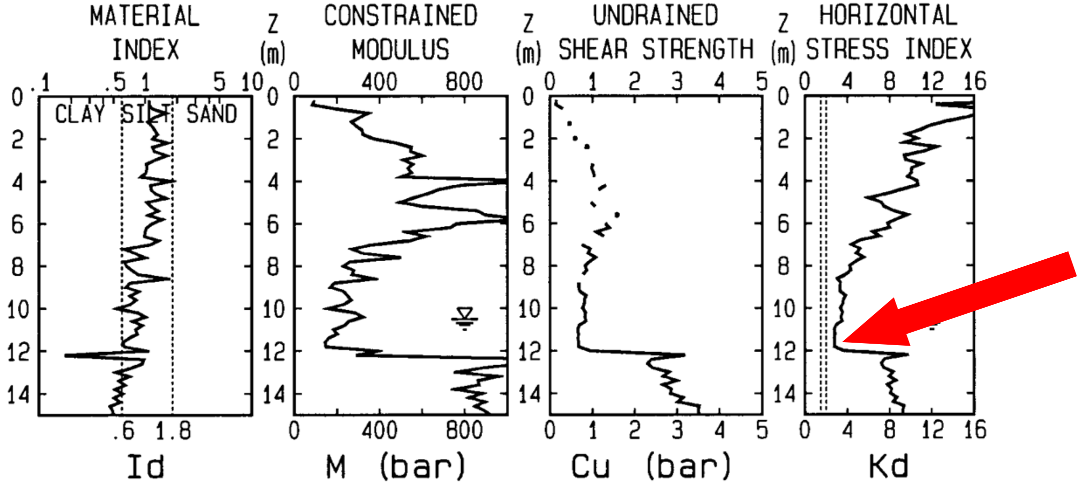


DMT-K_D method ➡ Verify if an <u>OC clay slope</u> contains ACTIVE (or old QUIESCENT) SLIP SURFACES *(Totani et al. 1997)*

Old slip surface may reactivate ! – Øresidual

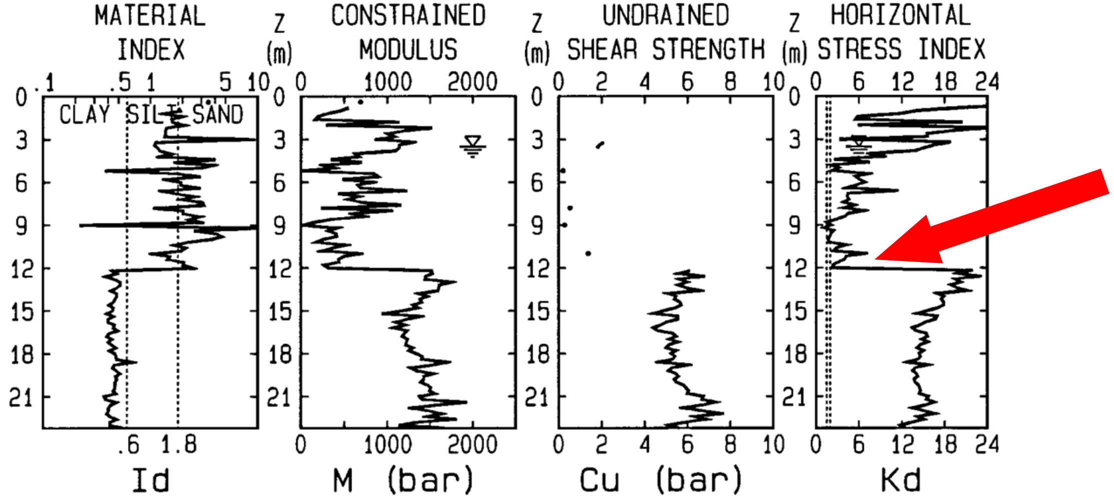
Validation of DMT-K_D method

LANDSLIDE "FILIPPONE" (Chieti)



DOCUMENTED SLIP SURFACE

LANDSLIDE "CAVE VECCHIE" (S. Barbara)



DOCUMENTED SLIP SURFACE (inclinometers)

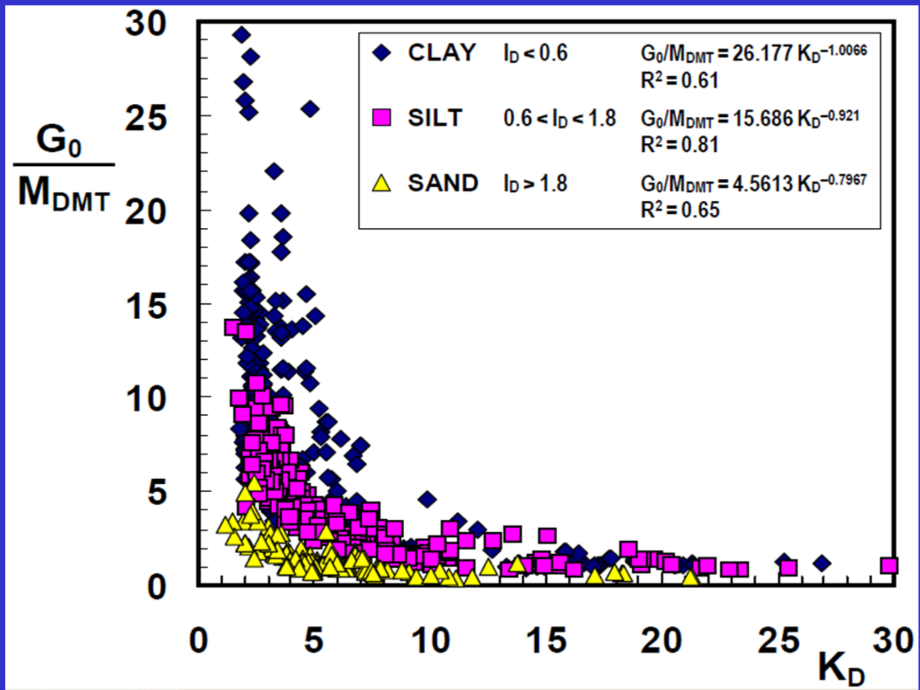
Miniera di lignite S. Barbara (San Giovanni Valdarno)

SS. N. 83 "Marsicana" Gioia dei Marsi (2006) Bloccata da dissesto

When doing SDMT : get <u>Id</u> <u>Kd</u> <u>Ed</u> (M) <u>Go</u>

Diagram : results of 34 sites various soils & geography.

Permits to estimate Vs (Go) from mechanical-DMT data



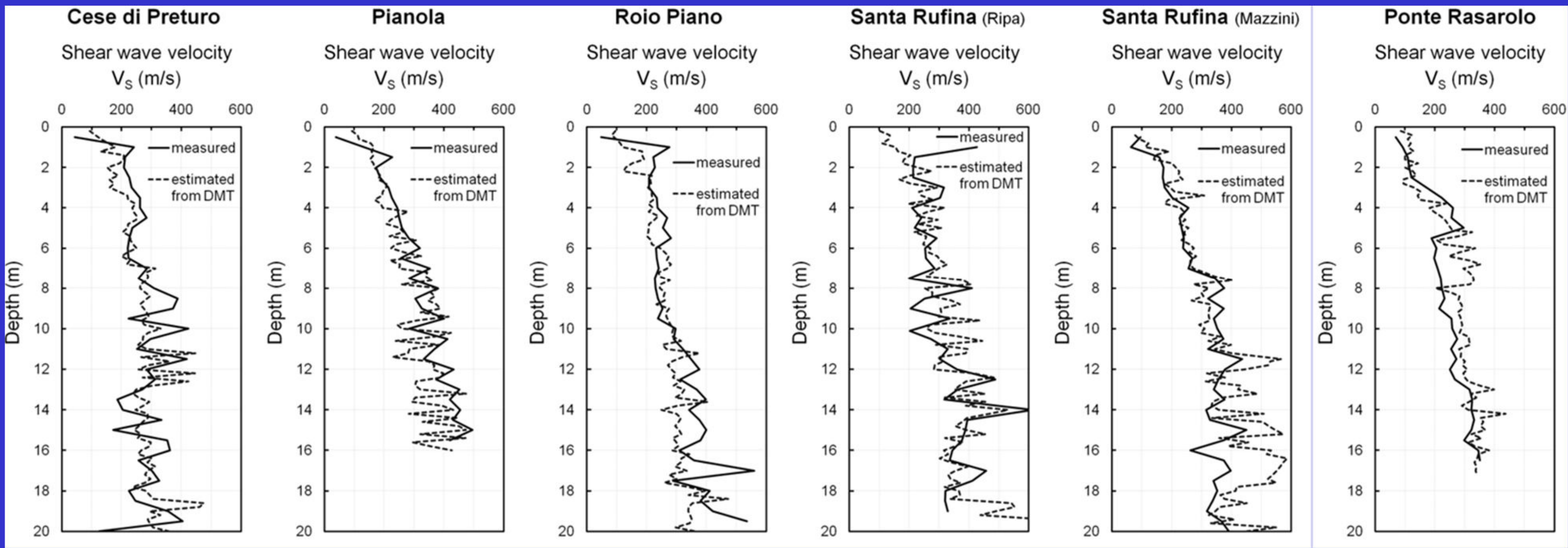
- No point today. Vs <u>direct</u>
  However :

  May provide rough Vs in previous sites DMT.

  Estimates of expected Vs.

- $\cancel{M = \frac{G_0}{\text{constant}}}$

V_S predicted by mechanical DMT (L'Aquila)



CONCLUSIONS 1

+Authors : for everyday practice use *direct push* CPT, DMT

<u>CPT</u> +fast, +economical, +widespread. Important advantages.

But Been (SOA "CPT Interpretation" at CPT 2010 Los Angeles)
"If purpose is <u>parameters</u> CPT cannot be used in isolation - must be supplemented by lab /other methods. CPT can easily mislead in terms of soil type, strength and <u>particularly modulus</u>".

Also Robertson 1986 : *"CPT predictions of settlements may be in large error"* ***(***Terzaghi and Peck 1967, Schmertmann 1970, Jamiolkowski et al. 1988, Leonards 1988, Schnaid 2009….)

⇒ CPT unable to provide SOA settlements predictions - a well known weakness of CPT (Powell etc. ..).

CONCLUSIONS 2

DMT : Slower than CPT, but still very fast

Is a genuine two-parameter test, one of which is Kd, sensitive to stress history and aging

Use of Kd :

1. **reduces scatter in estimating settlements and CRR**
2. **permits a more economical design, as Kd reflects the benefits – otherwise ignored unused - of SH on settlement and liquefaction behavior.**

Practical : Any operator gets same results. No need highly skilled workers. Short training time.

CONCLUSIONS 3

Migrating from Nspt to Q_{cn} for predicting CRR and settlements had the merit of eliminating that part of scatter due to the poor repeatability of the SPT.

Using K_D permits to reduce even that part of scatter due to the scarce ability of conical tips to distinguish between freshly deposited sands and prestressed or aged sands.

END

Thank you