Flat Dilatometer (DMT) and Seismic Dilatometer (SDMT): Applications and Recent Developments

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In cooperation with:

Global Geotech
Explorational Drilling & Sampling Equipment
In penetrable soils: 
Lab Testing → In situ: CPT & DMT

Reason: simple, fast, economical, repeatable, provides continuous soil profile, results real time, ..

In Sand: recovering undisturbed samples very difficult and in situ testing is the state-of-practice.
“Soil borings ... laboratory testing ... SPT ... pressuremeter (PMT) ... vane (VST) ... crosshole (CHT) ... Taken together, all of these are suitable ... yet at considerable cost in time and money ...”

17th Int. Conference on Soil Mechanics and Geotechnical Engineering

SCPT & SDMT → fast and convenient tools for everyday investigations
SDMT = DMT + Seismic Equipment

DMT (static) 1980

Seismic (dynamic) 2004
DMT blade

FLEXIBLE MEMBRANE
(D = 60mm)

BLADE
DMT Test Layout

Test Procedure
advance 20 cm
stop penetration

$P_0$: Lift-off pressure
$P_1$: Pressure for 1.1 mm expansion
SDMT – Test Layout

- Top Sensor
- Acquisition Board
- Bottom Sensor
Truck Penetrometer (most efficient)

cable exits from rods
Light Penetrometer (less expensive)
DMT using TORPEDO + DRILL-RIG

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

≈ 40 m / day
ability to overcome obstacles
GLOBAL GEO RIG

THE GLOBAL GEO RIG

The Complete Solution for Environmental Soil Sampling and In-Situ Testing

The GEO is a highly mobile drive-sampling rig ideal for working inside and around the edges of buildings, low-headroom situations, slopes and embankments and sites where access is restricted.

It is easy to set up and drilling can begin within minutes of arrival on site. The light weight of each unit ensures that site disturbance is minimized, especially important on environmentally sensitive sites.

Applications:
- Environmental Sampling
- Small-scale geotechnical works
- Determination of piling depths
- Location of voids and buried obstructions
- Archaeological Surveys
- Continuous (Windowless) Soil Sampling
- Undisturbed Soil Sampling
- SPT and DP Testing
- Installation of Monitoring Wells

Global Geotech
Explorational Drilling & Sampling Equipment
Role of penetration for the DMT

DMT readings taken when blade is not moving → Penetration is only to advance the blade to next test depth – no strict constraint on penetration speed.

High flexibility to advance DMT in the soil

Difference with CPT: measurements taken during penetration at a fix speed of 2 cm / sec
SDMT used in over 70 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, Korea, Kosovo, Kuwait, Lithuania, Malaysia, Netherland, New Zealand, Norway, Oman, Pakistan, 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.
Soils testable by DMT/SDMT

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

**SDMT**
- All penetrable soils
- Non penetrable soils (gravel, rock, ..): inside a backfilled borehole
  
  Max depth: 135 m in L’Aquila (2009)
SDMT main results and repeatability (≈ 1-2%)
### Field Data

<table>
<thead>
<tr>
<th>Z (m)</th>
<th>( P_0 ) (kPa)</th>
<th>( P_1 ) (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.20</td>
<td>220</td>
<td>300</td>
</tr>
<tr>
<td>0.40</td>
<td>210</td>
<td>310</td>
</tr>
<tr>
<td>0.60</td>
<td>305</td>
<td>420</td>
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<tr>
<td>0.80</td>
<td>310</td>
<td>450</td>
</tr>
<tr>
<td>1.00</td>
<td>285</td>
<td>380</td>
</tr>
<tr>
<td>1.20</td>
<td>290</td>
<td>390</td>
</tr>
<tr>
<td>…</td>
<td>…</td>
<td>…</td>
</tr>
</tbody>
</table>
DMT Intermediate parameters

DMT Field Readings

- $P_0$
- $P_1$

Intermediate Parameters

- $I_d$: Material Index
- $K_d$: Horizontal Stress Index
- $E_d$: Dilatometer Modulus
DMT Formulae – Interpreted parameters

Intermediate Parameters

Id
Ed
Kd

Interpreted Geotechnical Parameters

M: Constrained Modulus
Cu: Undrained Shear Strength (clay)
Ko: Earth Pressure Coeff (clay)
OCR: Overconsolidation ratio (clay)
Φ: Safe floor friction angle (sand)
γ: Unit weight and description
Performing DMT, immediately notice that:

$$I_D = \frac{(p_1 - p_0)}{(p_0 - u_0)}$$

SILT falls in between
$I_D$ contains information on soil type

CLAY

SAND
Definition of $K_D$ (Horizontal stress index)

$$K_D = \frac{(p_0 - u_0)}{\sigma'_v}$$

same formula as $K_0$: $(p_0 - u_0) \rightarrow \sigma'_h$

$K_D$ is an ‘amplified’ $K_0$, because $p_0$ is an ‘amplified’ $\sigma_h$, due to penetration
$K_D$ information on stress history

$K_D = 2$ in NC clay (OCR = 1)

$K_D > 2$ in OC clay (OCR > 1)
$K_D$ contains information on stress history
$K_D$ is the key intermediate parameter for the interpretation of the geotechnical parameters
CLAY: $K_D$ correlated to OCR

\[
OCR = \left(0.5 \cdot K_d\right)^{1.56}
\]  
Marchetti 1980 (experimental)

**Experimental**
Kamei & Iwasaki 1995

**Theoretical**
Finno 1993

**Theoretical**
Yu 2004

\[
K_D = \frac{6 - 2M}{5 + M} \left(\frac{OCR}{6 + M}\right)^{3M} + \frac{c_1 M}{2p_{\text{eff}}} (OCR)^{2 + \lambda}
\]
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

- Weald clay
- Kaolin
- London clay
- Marchetti 1980
- Yu 2004
- ISC-2
- Porto

Yu by Critical State Model implemented in CRISP
SAND: $K_D$ sensitive to prestressing

Calibration chamber tests with prestressing cycles

CC TEST N. 216 IN TICINO SAND

$D_R = 50.3\%$; $K_o = 0.40$

$\frac{1}{2} (\sigma_V - \sigma_h)$, kPa

$\frac{1}{2} (\sigma_V' + \sigma_h')$, kPa

Kd increased 7 times the increase of penetration resistance

$Jamiolkowski \ & Lo\ Presti\ ISC'98\ Atlanta$
Sensitivity to prestressing is valuable!

Normally Consolidated

Prestressed

SAME FINAL STATE OF STRESS, but after prestress soil is stiffer and stronger → Important impact on design (settlements, liquefaction, compaction, ..)
Stress History: effects on CPT and DMT

Effect of SH on normalized $Q_c$ (CPT)

$\frac{q_c}{(\sigma'_v)^{0.5}}$

Effect of SH on $K_D$ (DMT)

Horiz. stress index, $K_D$

Lee 2011, Eng. Geology – CC in sand

Kd sensitive to Stress History
Theory of elasticity:

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

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


$E_D$ not directly usable $\rightarrow$ corrections (penetration, etc)
M obtained from $E_D$ using information on soil type $I_D$ and stress history $K_D$. 

- $I_D$ (soil type)
- $E_D$ (DMT modulus)
- $K_D$ (stress history)

M Constrained Modulus
Definition of $M$ (no ambiguity)

$$M = E_{oed} = \frac{1}{mv} = \frac{\Delta \sigma'_v}{\Delta \varepsilon_v} \quad (at \ \sigma'_v)$$

Vertical drained confined tangent modulus (at $\sigma'_v$)
M Comparison from DMT and from Oedometer

Virginia - U.S.A.

Onsoy Clay – Norway

Tokyo Bay Clay - Japan

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


Failmezger, 1999
Many publications & case histories of good agreement between measured and DMT-predicted settlements / moduli:

- **McNulty & Harney** (2014)
- **Berisavijevic** (2013)
- **Vargas** (2009)
- **Bullock** (2008)
- **Monaco** (2006)
- **Lehane & Fahey** (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 by DMT
Silos on Danube Bank (Belgrade)

Silo founded on mat 100 m x 23 m, with $q_{net} = 160$ kPa
DMT Settlement prediction: 77 cm
Measured Settlement: 63 cm
DMT +22%

D. Berisavijevic, 2013
M from DMT $\approx 200$ MPa ($\approx 1000$ DMT data points)
M from laboratory: $M \approx 50$ MPa
M from observed settlements: $M \approx 240$ MPa
→ DMT good estimate of $M$
Observed vs. predicted by DMT
Dormitory Building 13 storeys (Atlanta - USA)

Settlements profile: Measured vs DMT predicted
(Piedmont residual soil)

SPT Settlement prediction: 46 mm
DMT Settlement prediction: 250 mm
Observed Settlement: 250 mm

SPT ➔ large error !!!
Possible reasons DMT good settlement predictions

1. Wedge minimizes soil disturbance

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

Baligh & Scott (1975)

Stiffness ≠ Strength
Possible reasons DMT predicts well settlement

Soil is loaded at strain level for deformation analysis

Range for Deformation Analyses

Region for Bearing Capacity and Stability Calculations

Mayne (2001)
Ladd: *best Cu measurement not from TRX UU!!*

*best Cu from oed → OCR → Shansep*

\[
\left( \frac{Cu}{\sigma'_v} \right)_{OC} = \left( \frac{Cu}{\sigma'_v} \right)_{NC} \cdot OCR^m
\]

\[
OCR = \left( 0.5 \cdot K_d \right)^{1.56}
\]

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

\[
Cu = 0.22 \sigma'_v \left( 0.5 \cdot K_d \right)^{1.25}
\]
Cu comparisons from DMT and from other tests

**Recife - Brazil**

- **Su (kPa)**
  - 10 20 30 40 50 60 70
  - **Symbols:**
    - Triaxial UU - C
    - Triaxial CIU - C
    - DMT-Marchetti, 1980
    - CPTU-Lunne et al., 1985 - $N_{cu}$
    - PMT-Powell, 1990
  - **Depth (m):**
    - 0 5 10 15 20 25
  - **Undrained shear strength Su (kPa)**

**Skeena Ontario – Canada**

- **C_u**
  - UNDR. COHESION (Kg/sq cm)
  - 2 4 6 8 1
  - **Symbols:**
    - Triaxial Test
  - **Depth (m):**
    - 0 20 40 60 80
  - **Gravel?**
  - **Shells?**

**Tokyo Bay Clay - JAPAN**


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**References:**

- Coutinho et al., Atlanta ISC’98
- Mekechuk J. (1983). "DMT Use on C.N. Rail Line British Columbia", First Int.Conf. on the Flat Dilatometer, Edmonton, Canada, Feb 83, 50
Cu at National Site FUCINO – ITALY

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

- Settlements of shallow foundations
- Compaction control
- Liquefaction risk analysis
- Slip surface detection in OC clay
- Seismic design (Eurocode 8)
- In situ $G-\gamma$ decay curves
- Laterally loaded piles ($P-y$ curves)
- Diaphragm walls (springs model)
- FEM input parameters (es. Plaxis)
DMT tests are increasingly used in compaction jobs to quantify soil improvement.
DMT for Compaction Control

*Van Impe, De Cock, Massarsch, Mengé - New Delhi (1994)*

**Compaction of a loose sandfill**

*Resonant vibrocompaction technique*
Many publications show that DMT is \( \approx \textit{twice} \) more sensitive than CPT to detect benefits of compaction

(Schmertmann 1986, Jendeby 1992, Pasqualini & Rosi 1993, Balachowsky 2015, …).
Jendeby (1992) measured in a loose sandfill $Q_C$ and $M_{DMT}$ before & after compaction.

$M_{DMT}$ increases about twice the increase of $Q_C$.
Sensitivity to $\sigma_h$ of DMT and CPT/SPT

Hughes & Robertson (Canadian Journal August 1985)

Arching effect
M_{DMT} / Q_C before and after compaction

In many soil improvement jobs:

M_{DMT} / Q_C before compaction ≈ 5-10
M_{DMT} / Q_C after compaction ≈ 12-24

Tentative correlation
OCR = f \left( \frac{M_{DMT}}{q_t} \right)

Ratio M/Qc appears solid and site-independent, but further validation required
OCR in SANDS: requires both CPT and DMT

\[ Q_c \sim D_R \]

\[ K_D \sim (D_R, OCR) \]

\[ \frac{q_c}{(\sigma'_v)^{0.5}} \]

\[ q_c \text{ and } \sigma'_v \text{ are in kPa} \]

Lee 2011, Eng. Geology – CC in sand

\[ Q_c \sim D_R \text{ and } K_D \sim (D_R, OCR) \implies OCR \sim f (Q_c, K_D) \]
Aim of DMT tests: to confirm OC of vibrocompaction, detected also by very high $V_s$ (400-500 m/s)

“..hydraulically filled silty fine calcareous sand dredged from sea bed, underlain by sedimentary rock of very weak sandstone and siltstone..”
DMT for Compaction Control - Palma Jumeirah Dubai

E. Sharif (2015)
DMT and SDMT offshore
DMT from Jack-up with Drill Rig + Torpedo

MO.SE. Project
Venice, Italy
2003
SDMT from Jack-up with penetrometer

Vado Ligure, Italy
2006
SDMT in Lago Maggiore – Italy (2015)
SDMT in Lago Maggiore – Italy (2015)

Drill Rig with SDMT

Hammer for Vs
SDMT in Lago Maggiore – Italy (2015)
SDMT from a floating barge: Genova (Italy)

New Terminal Container – Calata Bettolo (Genova Harbour)
Floating barge configuration is adequate only nearshore (harbour, bay, ..)

Offshore impracticable:

- horizontal anchoring difficult and time consuming
- waves $\geq 0.5$ m
Seafloor DMT
Seafloor Dilatometer version 1

WATERDEPTH 0 to 100 m - PUSH CAPACITY 5 ton
Max test depth is the depth penetrable with 5 ton push.

Shipped by air (50 Kg)

4 bolts

ballast (built locally)
Seafloor Dilatometer version 2 (2015)

Seafloor

Support anchored to ballast

Seismic Dilatometer

ballast built locally
Seafloor DMT version 2 (2015)

2015 April 30th
6.5 ton ballast (steel plate)
5 ton push max (measured)
Seafloor DMT - USA (January 2016)
Seafloor DMT - USA (January 2016)

Material Index:
- Clay
- Silt
- Sand

Constrained Modulus (M):
- Depth (Z) vs. Modulus (M)

Undrained Shear Strength (Cu):
- Depth (Z) vs. Shear Strength (Cu)

Horizontal Stress Index (Kd):
- Depth (Z) vs. Stress Index (Kd)
Seafloor DMT - USA (January 2016)

- **Material Index**: Clay, Silt, Sand
- **SEAFOOT - 15.40 m**
- **Gravel**

**Graphs:**
- **Constrained Modulus**
- **Undrained Shear Strength**
- **Horizontal Stress Index**

**Axes:**
- **Zabs (m)**
- **Id**
- **M (MPa)**
- **Cu (kPa)**
- **Kd**
Seafloor DMT - USA (January 2016)
Seafloor DMT - USA (January 2016)
Medusa DMT

• Self-contained cableless DMT probe
• Pulsates indefinitely at programmable fix periods: example 1-minute:
  • DMT readings: 1/2 minute
  • Penetration to next depth → 1/2 minute
• DMT readings stored with time
• Probe depth recorded with time
• Data downloaded and synchronized at end of test
Thank you for your attention