Charles-Augustin COULOMB - A geotechnical tribute

Paris, September 25 & 26, 2023

Developments in Seismic CPT and links to the Ménard Pressuremeter Test

P.K. Robertson
Gregg Drilling & Testing, Inc.
HISTORY OF CPT

1930s
First Mechanical Cones

1960s
Electric Cones Developed

1970s
Primary device Offshore

2000s
Digital cones and advanced software
BASIC CONE PENETROMETER

Sleeve Friction
\[ f_s = \frac{\text{load}}{2} \]

Pore Pressure, \( u_2 \)

Tip Resistance
\[ q_c = \frac{\text{load}}{\pi r} \]

Friction Ratio
\[ R_f = \left( \frac{f_s}{q_c} \right) 100 \]
CPT SENSORS

- Early cones measured only $q_c$ & $f_s$
- 1970’s – pore pressure sensors added ($u_1$, $u_2$)
  - $u_2$ most common – ideal for $q_t$ correction
  - CPTu now very common
- 1980’s geophone added ($V_s$)
  - SCPTu becoming common
CONES

Equal end area sleeves and small tip net area \((a > 0.8)\)

\[ q_t = q_c + u_2(1-a) \]

\[ a > 0.80 \]

\[ A_{sb} = A_{st} \]

*Required in most Standards*

Campanella et al. 1982
CPT PUSHING EQUIPMENT

Portable: Small (10kN) to Large (200kN)
CPT PUSHING EQUIPMENT

Mostly ~ 200 to 250kN
CPT PUSHING EQUIPMENT

DRILL RIG UNITS
CPT PUSHING EQUIPMENT

Wireline capabilities to allow deeper CPT
Improved efficiency at depth
CPT SAMPLERS

MOSTAP Sampler
Thick-walled disturbed

Piston Sampler
Thick-walled disturbed

PPI Sampler
Thin-walled undisturbed

25mm up to 75mm diameter
CONTINUOUS & AUTOMATION

Single-twist

Coiled Tubing
CONTINUOUS & AUTOMATION

Remotely Operated – Coiled tubing

5cm² cone
30m

10cm² cone
60m
Seismic CPT PROCEDURE

TRUE-INTERVAL

PSEUDO-INTERVAL
SCPT PROCEDURE

EXAMPLE TRUE-INTERVAL

\[ Vs = \frac{(S_2 - S_1)}{\Delta t} \]

\[ G_0 = \rho \cdot Vs^2 \]
SCPT METHODS

True-interval Method

Advantages:
- Only requires single shear wave source
- Independent of seismic source trigger characteristics
- Obtains $V_s$ directly in the field

Limitations:
- Probe longer and harder to push to required depths
- Seismometers must have identical response characteristics
- If signals are stacked, trigger must be repeatable

Pseudo-interval Method

Advantages:
- Probe can be shorter and easier to push to required depths

Limitations:
- Requires two seismic waves for depth $D_1$ & $D_2$
- Requires fast and repeatable trigger
- Challenging to determine $V_s$ in the field and requires post-processing
SEISMIC CPTu

SCPTu Advantage

7 measurements!

\[
\begin{align*}
q_t \\
f_s \\
u_2 \\
V_s (\& \ V_p) \\
t_{50} \\
u_0 \\
i
\end{align*}
\]

Dissipation

Mayne, 2014
SEISMIC CPTu

SCPTu Advantage

7 measurements!

$q_t$
$f_s$
$u_2$
$V_s$ ($& V_p$)
$\text{Dissipation}$

$\text{Soil Type}$
SCPTu INTERPRETATION

Full range of interpretation of soil behavior
CPT NORMALIZED PARAMETERS

• Early normalization (Wroth, 1984)
  \[ Q_t = \frac{(q_t - \sigma_v)}{\sigma'_v} \]

• Normalization based on soil type, density and stress level (Robertson, 2009)
  \[ Q_{tn} = \left[ \frac{(q_t - \sigma_v)}{p_a} \right] \left( \frac{p_a}{\sigma'_v} \right)^n \]

Where:
- \( (q_t - \sigma_v)/p_a \) = dimensionless net cone resistance,
- \( (p_a/\sigma'_v)^n \) = stress normalization factor
- \( n \) = stress exponent that varies with soil type, density & stress level
- \( p_a \) = atmospheric reference pressure in same units as \( q_t \) and \( \sigma_v \)

\[ n = 0.381 \left( I_c \right) + 0.05 \left( \sigma'_{vo}/p_a \right) - 0.15 \quad \text{where } n \leq 1.0 \]
CPT NORMALIZED PARAMETERS

Difference normalized CPT parameters:

\[ Q_{tn} = \left[ (q_t - \sigma_v) / p_a \right] (p_a / \sigma'_{vo})^n \]

\[ F = f_s / \sigma'_{vo} \]

\[ F_r = \left[ f_s / (q_t - \sigma_{vo}) \right] 100 \% \]

\[ U = (u_2 - u_0) / \sigma'_{vo} = \Delta u / \sigma'_{vo} \]

\[ B_q = \Delta u / (q_t - \sigma_{vo}) \]
CPT NORMALIZED PARAMETERS

Difference normalized CPT parameters:

\[ Q_{tn} = [(q_t - \sigma_v)/p_a] \left( \frac{p_a}{\sigma'_v} \right)^n \]

\[ F = \frac{f_s}{\sigma'_v} \]

\[ F_r = [f_s / (q_t - \sigma_v)] \times 100\% \]

\[ U = \left( u_2 - u_0 \right)/\sigma'_v = \Delta u/\sigma'_v \]

\[ B_q = \Delta u/(q_t - \sigma_v) \]
CPT SOIL BEHAVIOR TYPE (SBT)

CPT SBT based on in-situ soil behavior - not the same as traditional classification based on physical characteristics using Atterberg Limits and grain size carried out on disturbed samples.

Robertson (2009)
CPT SOIL BEHAVIOR TYPE (SBT)

CPT SBT based on in-situ soil behavior - not the same as traditional classification based on physical characteristics using Atterberg Limits and grain size carried out on disturbed samples

Robertson (2009)
SOIL MICROSTRUCTURE

- Identification of soil microstructure
- $Q_{tn}$ (at large strains)
- $G_o = \rho V_s^2$ (at very small strains)
- $I_G = G_o/q_n$ (stiffness to strength ratio)
- $K_G = I_G \left(Q_{tn}\right)^{0.75}$
- Soils with microstructure ($K_G > 200$) have higher resistance at small strains

Robertson (2016)
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Robertson (2016)
Behavior descriptions

- Sand- and Clay-like
- Dilative-Contractive boundary
- Transition materials

Based on soils with little or no microstructure
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Based on soils with little or no microstructure
**UPDATED CPT SOIL BEHAVIOR TYPE (SBT)**

Updated Schneider et al (2008) chart based on $Q_{tn} - U_2$ with proposed new soil behavior type boundaries ($B_q$ lines in red)

Suitable for fine-grained soil with excess CPT pore pressures
EXAMPLE: McDONALD FARM, VANCOUVER

SYMPOSIUM COULOMB
PARIS, SEPTEMBER 25 & 26, 2023
EXAMPLE: McDONALD FARM, VANCOUVER

Holocene-age alluvial Fraser River deposit
EXAMPLE: MADDINGLY, UK

Cretaceous
Gault Clay

Tip resistance (MPa)

Friction ratio

Pore pressure (kPa)

SBT Index

Soil Behaviour Type

SYMPOSIUM COULOMB
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EXAMPLE: MADDINGLY, UK

Very stiff overconsolidated fissured Gault clay of Cretaceous period (~110 million years ago) with OCR > 10
EXAMPLE: COOPER MARL, USA

Eocene Cooper Marl

Cone resistance qt
Friction ratio
Pore pressure u
SBT Index
Soil Behaviour Type

SYMPOSIUM COULOMB
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EXAMPLE: COOPER MARL, USA

SCPTu data from 20 to 50m in Cooper Marl (calcareous cemented clay/silt), Eocene to Oligocene-age (~30 to 40 million years ago)
EXAMPLE: SILTSTONE, LOS ANGELES, USA
SCPTu data from 3 to 10m in siltstone Fernando formation of Pliocene age (~3 to 5 million years ago).
Seismic methods measure soil stiffness at small strains

\( V_s \) is a direct measure of small strain shear modulus, \( G_0 \)

\[
G_0 = \rho_t (V_s)^2
\]

\[
\rho_t = \frac{\gamma}{g}
\]

Small strain (elastic) shear modulus, \( G_0 \) is a fundamental soil parameter

\( \gamma < 10^{-4} \% \)
SCPT Method to Estimate Soil Modulus

Modulus Reduction Scheme (Fahey & Carter 1993)

\[ \frac{E}{E_{\text{max}}} = 1 - f\left(\frac{q}{q_{\text{max}}}\right)^g \]

Note: \( f = 1 \)

- \( g = 1.0 \)
- \( g = 0.4 \)
- \( g = 0.3 \)
- \( g = 0.2 \)

After Mayne, 2018
SCPT Method to Estimate Soil Modulus

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\[ K_G = \frac{1}{FS} \]

After Mayne, 2018
SCPT for Foundation Load-Settlement

Equivalent Modulus for Foundation Response

- Initial stiffness from small-strain shear modulus
  \[ G_{\text{max}} = \rho V_s^2 \]
  \[ E_{\text{max}} = 2G_{\text{max}} (1+\nu) \]

- Modulus reduction factor (Fahey & Carter 1993):
  \[ \frac{E}{E_{\text{max}}} = 1 - f \left( \frac{q}{q_{\text{ult}}} \right)^g = 1 - (FS)^g \]
  where FS = \( q_{\text{ult}}/q \)
  Operational E = \( \left( \frac{E}{E_{\text{max}}} \right) \cdot E_{\text{max}} \)
  for "well-behaved" soils: \( f = 1 \) and \( g \approx 0.3 \)

Likely that “g” varies with \( K^*_G \)

Nonlinear Foundation Displacement Analyses

\[ S_{\text{center}} = \frac{q \cdot d \cdot I_G \cdot I_F \cdot I_E (1-\nu^2)}{E_{\text{MAX}} \left[ 1 - \left( \frac{q}{q_{\text{ult}}} \right)^{0.3} \right]} \]

where
- \( q \) = applied surface stress;
- \( q_{\text{ult}} \) = ultimate bearing stress; \( \text{from CPT} \)
- \( d \) = equivalent footing diameter
- \( I_G, I_F, I_E \) = elastic factors for modulus variation, rigidity, and embedment, respectively.
- \( \nu \) = Poisson’s ratio
- \( E_{\text{max}} \) = initial elastic modulus = \( 2G_{\text{max}} (1+\nu) \) \( \text{from SCPT} \)
- See Mayne & Poulos (ASCE J. Geot. Engrg. - Jan 2001)

After Mayne, 2018
SCPT for Foundation Load-Settlement

Class “A” Prediction – Texas A&M
ASCE and FHWA Symposium (1994)

European Foundation Prediction Symposium
GT Class “A” Prediction (July, 2001)

Belfast Footing Load Test

\[ K_i = f(V_s) \]

\[ q_{\text{ult}} = f(q_t) \]

\[ V_s = 210 \text{ m/s} \]
\[ \gamma_T = 15.5 \text{ kN/m}^3 \]
\[ \phi' = 39^0 \]

After Mayne, 2018
Links to Pre-bored Pressuremeter Test (PMT)

Pre-bored pressuremeter Test (Menard) - stiffness:

Initial Modulus, $E_M$ – Stiffness at large strains
Unload-reload Modulus, $E_{UR}$ - Stiffness at intermediate strains

Briaud (2013) $\gamma_{av.} \sim 0.3 \gamma_{PMT}$

$E_M$ at $\gamma_{av.} \sim 3$ to 5% and $E_{UR}$ at $\gamma_{av.} \sim 0.1$ to 0.5%
**MODULUS VARIES WITH STRAIN**

Generalized variation of Shear ($G$) and Youngs ($E$) modulus as a function of shear strain

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

$\nu \sim 0.33$

$E \sim 2.66G$
APPLICATION TO DESIGN

Measure $V_s$ (small strain) to get $G_o (E_o)$ and unload-reload Modulus ($E_{UR}$) from PMT to evaluate modulus degradation curve with strain.
Links to Pre-bored Pressuremeter Test (PMT)

Limit Pressure, \( P^*_{LM} \) – Shear strength at large strains

Net Limit Pressure, \( P^*_{LM} = P_{LM} - \sigma_{ho} \)

Normalized Net Limit Pressure = \( P^*_{LM} / \sigma'_{vo} \)

Experience in France (Bustamante & Gianselli, 1993)

<table>
<thead>
<tr>
<th>Clayey and silty soils</th>
<th>0</th>
<th>1.0</th>
<th>2.0</th>
<th>3.0</th>
<th>4.0</th>
<th>5.0</th>
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<tbody>
<tr>
<td>0</td>
<td>3</td>
<td>6</td>
<td>9</td>
<td>12</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>15</td>
<td>30</td>
<td>45</td>
<td>60</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sands and gravels</td>
<td>0</td>
<td>8</td>
<td>16</td>
<td>24</td>
<td>32</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>20</td>
<td>40</td>
<td>60</td>
<td>80</td>
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<tr>
<td>0</td>
<td>4</td>
<td>8</td>
<td>12</td>
<td>16</td>
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</tr>
<tr>
<td>0</td>
<td>6-12</td>
<td>12-24</td>
<td>18-36</td>
<td>24-48</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| Chalk                  | 0  | 3.5 | 7   | 10.5 | 15  |     |
| 0                      | 20 | 40  | 60  | 80  |     |     |

| Marl                   | 0  |     |     |     |     |     |
| 0                      |     |     |     |     |     |     |

\[
\frac{q_c}{P^*_{LM}}
\]

<table>
<thead>
<tr>
<th>( q_c [\text{MPa}] )</th>
<th>3</th>
<th>8</th>
<th>4</th>
<th>3.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>( N/0.3 \text{ m} )</td>
<td></td>
<td></td>
<td></td>
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</tbody>
</table>
Links to Pre-bored Pressuremeter Test (PMT)

*In clay-like soils* (Gibson & Anderson, 1961):

\[ \frac{P^*_{LM}}{\sigma'_{vo}} \sim 5.5 \frac{s_u}{\sigma'_{vo}} \sim 5.5 \frac{Q_t}{N_{kt}} \quad \text{(for } N_{kt} \sim 14) \]

\[ Q_t \sim 2.5 \left( \frac{P^*_{LM}}{\sigma'_{vo}} \right) \quad \text{(France Exp. } \sim 3) \]

*In sand-like soils* (Yu et al, 1996):

\[ P^*_{LM}/\sigma'_{vo} = 0.1 \text{ to } 0.2 \quad Q_t \]

\[ Q_t \sim 5 \text{ to } 10 \left( \frac{P^*_{LM}}{\sigma'_{vo}} \right) \quad \text{(France Exp. } \sim 8) \]
PROPOSED LINK BETWEEN CPT AND PMT

For soils with little to no microstructure

Contractive - Dilative boundary

\[ \frac{P^*_{LM}}{\sigma'_{vo}} \approx 5 \]
SUMMARY

• Significant developments made in use and application of SCPTu since first developed 40 years ago
• SCPTu can provide 7 measurements in one, cost effective in-situ test to produce near continuous profiles
• Role of soil microstructure is increasingly becoming recognized and SCPTu can identify soil microstructure
• Importance of non-linearity in soil stiffness recognized and SCPTu provides measure of the fundamental small strain stiffness $G_0$
• Combination of surface geophysics, such as the MASW (2D), with SCPTu and PMT has potential to provide insights into soil microstructure and non-linear soil stiffness for geotechnical design
Thank You

Questions?

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