Development of CPT Driven Pile Direct Design Methodology for ODOT

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ODOT CPT Rig

Manufactured by A.P. Van den Berg

- Track-Mounted CPT unit Hyson 200 kN
- VTS-D4-3550-700-TM30 Crawler
- John Deere diesel engine, 93kW = 125 hp
- 40 1039mm CPT Rods = 41.56m = 136.36’
- Maximum Push = 200 kN = 45 kips
- 15cm² Type 2 Piezo-Cone w/ Seismic Module
- Seismic Hammer Trigger Beam on jacks
ODOT CPT Rig
ODOT CPT Rig
ODOT CPT Rig
CPT Exploration
CPT Exploration
CPT Exploration
CPT Probe
CPT Probe
CPT Probe
CPT Probe

164 mm

43.7 mm

60°

15 cm²
CPT Probe

- $A_c = \text{projected area of cone}$
  - (not surface area of cone)
- $A_s = \text{area of friction sleeve}$
- $A_n = \text{cross-sectional area of load cell or shaft}$
- $a$ or $a_n = \text{Cone Net Area Ratio}$
  - $q_c/u_2$ from laboratory triaxial cell calibration
  - (this is not $A_n/A_c$)
CPT Probe Readings

- $Q_c = \text{force acting on the cone}$
  - measured by load cell

- $F_s = \text{force acting on the friction sleeve}$
  - measured by load cell

- $u_2 = \text{Pore Water Pressure}$
  - measured by transducer behind the cone
CPT Probe Readings
CPT Probe Readings

- $u_0 = \text{Equilibrium Pore Water Pressure}$
  - calculated based on water table location
- $u_1 = \text{Pore Water Pressure}$
  - measured by transducer in the cone
- $u_2 = \text{Pore Water Pressure}$
  - measured by transducer behind the cone
- $u_3 = \text{Pore Water Pressure}$
  - measured by transducer behind the sleeve
CPT Probe Readings

- \( q_c = \text{Cone (Tip) Resistance} \)
  \[ = \frac{Q_c}{A_c} \] (typically in MPa)

- \( f_s = \text{Sleeve Friction} \)
  \[ = \frac{F_s}{A_s} \] (typically in MPa or kPa)

- \( u_2 = \text{Pore Water Pressure} \)
  \[ \text{from transducer (typically in kPa)} \]
Tip Area Ratio, $a$

\[ a = \frac{q_c}{u_2} = 0.65 \]
CPT Cone (Tip) Net Area Ratio
$q_c$ is not necessarily directly useful

Need to correct for pore water pressure

$q_t = \text{Corrected Tip Resistance}$

$= q_c + u_2(1-a)$
CPT Probe Data

- **Direct Readings**
  - $Q_c$, $F_s$, $u_2$

- **Primary (Derived) Values**
  - $q_c$, $f_s$

- **Secondary (Derived) Values**
  - $q_t$, $R_f = \text{Friction Ratio} = \left(\frac{f_s}{q_t}\right) \times 100\%$

- **Tertiary (or further) Correlations**
  - $S_u$, $\phi'$, $\gamma$, $Q_t$, $F_r$, $I_c$, Soil Behavior Type, etc.
CPT Probe Data

Correlations exist for the following:

- $S_u$, undrained shear strength
- $\phi'$, effective internal friction angle
- $\gamma$, soil unit weight
- Soil Behavior Type (SBT)
- $Q_t$, Normalized Cone Resistance
- $F_r$, Normalized Friction Ratio
- $I_c$, Soil Behavior Type Index
- $N_{60}$, SPT blow count normalized at ER 60%
CPT Probe Data

Correlations exist for the following:

- $S_t$, soil sensitivity
- OCR, overconsolidation ratio
- $K_o$, in-situ stress ratio
- $D_r$, Relative Density
- $\psi$, state parameter
- $E$, Young’s modulus
- $k$, coefficient of permeability
- consolidation characteristics ($c_v$, $c_h$, $M$)
CPT Direct Design

Methods Under Consideration:
- Schmertmann, 1978
- De Ruiter and Beringen, 1979
- Bustamante and Gianeselli (LCPC), 1982, The "French Method"
- Aoki and De Alencar, 1975
- Penpille (MissDOT), Clisby et al., 1978
- Philipponnat, 1980
- Price and Wardle, 1982
CPT Direct Design

Methods Under Consideration:
- Tumay and Fakhroo, 1982
- Almeida et al., 1996
- Eslami and Fellenius, 1997
- Jardine and Chow (MTD), 1996
- Powell et al., 2001
- UWA-05 (Lehane et al.), 2005
- Zhou et al., 1982
CPT Direct Design
Percent Prediction within 10% Test Capacity

- Schneitmann
- De Ruiter and Beringen
- Aoki and De Alencar
- Penpil
- Philipponnat
- Price and Wardle
- Tumay and Fakhroo
- Almeida et al.
- Eslami and Fellenius
- Jardine and Chow (MTD)
- Powell et al.
- UWA-05
- Zhou et al.
What do we really want?

Accuracy is nice, but getting CLOSE to the target “only counts in horseshoes and hand-grenades!”

If you are CLOSE to safety, but not quite there, you still have a failure!

Overprediction = Unconservatism!
Mean Prediction of Percent Capacity
CPT Direct Design

What do we really want?

- Best predictor of driven pile quantities!
- Spot-on prediction is the best…but unlikely.
- Overprediction of capacity = quantity underrun
- Underprediction of capacity = excess quantity
- Underruns cost \( \approx 2.5 \times \) the cost of overruns
- We want to waste the least cost in failure to predict the exact capacity (least wastage)
Total Wastage in Percent Capacity

- Schmertmann
- De Ruiter and Beringen
- Aoki and De Alencar
- Penpine
- Philippennat
- Price and Wardle
- Tumay and Fakhroo
- Almeida et al.
- Eslami and Fellenius
- Jardine and Chow (MFD)
- Powell et al.
- UWA 05
- Zhou et al.
CPT Direct Design

Methods we cut out right away:

- Tumay and Fakhroo, 1982
- Almeida et al., 1996
- Eslami and Fellenius, 1997

All 3 tend to greatly over-predict capacity

- Zhou et al., 1982

Does not predict ultimate capacity; assumes a drilled shaft load-deflection behavior
CPT Direct Design

Methods we cut out right away:

- Jardine and Chow (MTD), 1996
- UWA-05 (Lehane et al.), 2005

Both are quite complicated, and are not really CPT direct design methods. They both require additional inputs that cannot be derived through CPT probing, but need additional soil testing.
CPT Direct Design

Methods using minimum path rule:
- Schmertmann, 1978
- De Ruiter and Beringen, 1979
- Tumay and Fakhroo, 1982

The Minimum Path Rule is a graphical method that cannot be easily computerized, and is nearly impossible to implement in a spreadsheet solution.
Minimum Path Rule

\[ q_t = \frac{q_{c1} + q_{c2}}{2} \]

- \( q_{c1} \): Average \( q_c \) over a distance of \( yD \) below the pile tip (path a-b-c). Sum \( q_c \) values in both the downward (path a-b) and upward (path b-c) directions. Use actual \( q_c \) values along path a-b and the minimum path rule along path b-c. Compute \( q_{c1} \) for \( y \) values from 0.7 and 4.0 and use the minimum \( q_{c1} \) values obtained.

- \( q_{c2} \): Average \( q_c \) over a distance of 8\( D \) above the pile tip (path c-e). Use the minimum path rule as for path b-c in the \( q_{c1} \) computations. Ignore any minor 'x' peak depressions if in sand, but include in minimum path if in clay.
CPT Direct Design

Methods we reviewed further:

- Bustamante and Gianeselli (LCPC), 1982
- Aoki and De Alencar, 1975
- Philipponnat, 1980
- Penpile (MissDOT), Clisby et al., 1978
- Price and Wardle, 1982
- Powell et al., 2001
CPT Direct Design

Equations tend to be in the form of:

- \( q_s = \alpha q_c \) or \( \alpha f_s \) for Side Resistance
- \( q_p = kq_c \) for Tip Resistance

\( \alpha \) and \( k \) are generally functions of soil type and/or pile type
## CPT Direct Design

### Methods and Equations:

<table>
<thead>
<tr>
<th>Method</th>
<th>Factors</th>
<th>( q_s )</th>
<th>( q_p )</th>
</tr>
</thead>
<tbody>
<tr>
<td>LCPC</td>
<td>( q_c )</td>
<td>( q_c/\alpha )</td>
<td>( k_c q_{ca} )</td>
</tr>
<tr>
<td>Aoki and De Alencar</td>
<td>( q_c )</td>
<td>( q_c \alpha_s/F_s )</td>
<td>( q_{ca}/F_b )</td>
</tr>
<tr>
<td>Philipponnat</td>
<td>( q_c )</td>
<td>( q_c \alpha_s/F_s )</td>
<td>( k_b q_{ca} )</td>
</tr>
<tr>
<td>Penpilie</td>
<td>( q_c, f_s )</td>
<td>( f_s/(1.5+0.1f_s) ) (in psi)</td>
<td>( 0.25q_{ca} ) in clay, ( 0.125q_{ca} ) in sand</td>
</tr>
<tr>
<td>Price and Wardle</td>
<td>( q_c, f_s )</td>
<td>( 0.53f_s )</td>
<td>( 0.35q_{ca} )</td>
</tr>
<tr>
<td>Powell et al.</td>
<td>( q_c, f_s, u_2 )</td>
<td>( (q_c-\sigma_{vo})/k_1 )</td>
<td>( (q_c-\sigma_{vo})/k_2 )</td>
</tr>
</tbody>
</table>
POR-TR280-0.47 OBPP, C-001-1-14

12-inch CIP Pipe Pile Axial Geotechnical Resistance (kips)

Depth (ft)

LCPC UBV
Aoki/De Al. UBV
P&W UBV
Penpil UBV
Philipponnat UBV
DRIVEN CPT UBV
POR-TR280-0.47 OBPP, C-001-1-14

12-inch CIP Pipe Pile Axial Geotechnical Resistance (kips)

Depth (ft)

DRIVEN End Bearing
DRIVEN Skin Friction
DRIVEN UBV
P&W End Bearing
P&W Skin Friction
P&W UBV

CPT Direct Design
POR-TR280-0.47 OBPP, C-001-1-14

12-inch CIP Pipe Pile Axial Geotechnical Resistance (kips)

Depth (ft)

P&W UBV
DRIVEN CPT UBV

CPT Direct Design
CPT Direct Design

- Uses scaling of direct in-situ test data

- However, $\phi_{\text{cpt}} = ?$

- Right now, AASHTO gives $\phi_{\text{stat}} = 0.50$ for CPT direct design with the Schmertmann method

- However, $\phi_{\text{stat}} = 0.50 < \phi_{\text{dyn}} = 0.70$ which penalizes CPT direct design compared to conventional design using SPT.
CPT Indirect Design

- Uses correlation to soil properties
- Eliminates the advantages of CPT Direct Design through multiple levels of correlation
- We consider this to be approximately equal to conventional design using SPT
- Use $\phi_{\text{dyn}} = 0.70$ per ODOT Bridge Design Manual Section 202.2.3.2.b
CPT Indirect Design

We are utilizing the following items:

- Soil Behavior Type (SBT)
- $I_c$, Soil Behavior Type Index
- $S_u$, undrained shear strength
- $\phi'$, effective internal friction angle
- $N_{60}$, SPT blow count normalized at ER 60%
- $\gamma$, total soil unit weight
- Axial Resistance Software: DRIVEN, APILE, etc.
CPT Indirect Design

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**CONE RESISTANCE, \( q_p \)**

**FRICION RATIO, \( R_f \)**

<table>
<thead>
<tr>
<th>Zone</th>
<th>Soil Behavior Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Sensitive, fine grained</td>
</tr>
<tr>
<td>2</td>
<td>Organic soils - clay</td>
</tr>
<tr>
<td>3</td>
<td>Clay – silty clay to clay</td>
</tr>
<tr>
<td>4</td>
<td>Silt mixtures – clayey silt to silty clay</td>
</tr>
<tr>
<td>5</td>
<td>Sand mixtures – silty sand to sandy silt</td>
</tr>
<tr>
<td>6</td>
<td>Sands – clean sand to silty sand</td>
</tr>
<tr>
<td>7</td>
<td>Gravelly sand to dense sand</td>
</tr>
<tr>
<td>8</td>
<td>Very stiff sand to clayey sand*</td>
</tr>
<tr>
<td>9</td>
<td>Very stiff fine grained*</td>
</tr>
</tbody>
</table>

*Heavily overconsolidated or cemented

\[ P_a = \text{atmospheric pressure} = 100 \, \text{kPa} = 1 \, \text{tsf} \]
CPT Indirect Design

Granular, Coarse Grained

Cohesive, Fine Grained
I_c, Soil Behavior Type Index

\[ I_c = \left( (3.47 - \log Q_t)^2 + (\log F_r + 1.22)^2 \right)^{0.5} \]

- \( Q_t \) = normalized cone penetration resistance (dimensionless)
  \[ = \frac{q_t - \sigma_{vo}}{\sigma'_{vo}} \]
- \( F_r \) = Normalized Friction Ratio (%)
  \[ = \left( \frac{f_s}{(q_t - \sigma_{vo})} \right) \times 100\% \]

- \( I_c \) is used in various other correlations
I_c, Soil Behavior Type Index

Generally,

- I_c < 1.5 = Gravel to Sandy Gravel (A-1)
- I_c = 1.5-2.0 = Sand to Silty Sand (A-3)
- I_c = 2.0-2.5 = Sandy Silt to Silt (A-4)
- I_c = 2.5-3.0 = Silt and Clay to Silty Clay (A-6)
- I_c > 3.0 = Clay (A-7)
- I_c = 2.0 is the approximate dividing line between Granular and Cohesive soils
Cohesive Soils

Various correlations exist for $S_u$, "Peak Shear Strength"

However, we consider Peak Shear Strength to be unconservative for design of Driven Piles

Instead, we use Remolded Shear Strength

$S_u = f_s = $ Sleeve Friction

This gives a close agreement with conventional design using SPT correlations
Granular Soils

Various correlations exist for $\phi'$, “Peak Friction Angle”

However, we consider Peak Friction Angle to be unconservative for design of Driven Piles, giving values up to 166% of what could be expected with SPT correlations.

Instead, we are correlating $\phi'$, effective internal friction angle, to $N_{60}$ and $N_{160}$, based on AASHTO LRFD Bridge Design Specifications Article 10.4.6.2.4.
**SPT N_{60} Correlation**

- We use a correlation developed by Robertson (2012):

\[
\frac{(qt/pa)}{N_{60}} = 10^{(1.1268 - 0.2817I_c)}
\]

- \( q_t = \) Corrected Tip Resistance = \( q_c + u_2(1-a) \)
- \( p_a = \) Atmospheric Pressure
- \( I_c = \) Soil Behavior Type Index
γ, Total Soil Unit Weight

We use a correlation developed by Robertson (2010):

\[
\frac{\gamma}{\gamma_w} = 0.27 \left[ \log R_f \right] + 0.36 \left[ \log \left( \frac{q_t}{p_a} \right) \right] + 1.236
\]

\( R_f = \text{Friction Ratio} = \left( \frac{f_s}{q_t} \right) \times 100\% \)
\( \gamma_w = \text{Unit Weight of Water} \)
\( p_a = \text{Atmospheric Pressure} \)
References


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Thank You

🔗 Questions?
🔗 Comments?