Development and Validation of a Unified Equation for Drilled Shaft Foundations

Presenter - Tom Brown P.E.  Bridge Foundation Engineer
Bob Meyers P.E.  State Geotechnical Engineer
New Mexico Department of Transportation

In memoriam
of
Koon Meng Chua P.E., Ph.D., M.ASCE UNM
Why Does NMDOT need Research on a Unified Design Approach?

Why so many different methods for different soil conditions?

1. Current methods are developed empirically for certain soil types and densities.

2. As a result, designs are either over-conservative ($$$) or designs require expensive field load testing to validate ($$$).

3. It is documented on major projects (i.e., Big-I; I40-Coors) that millions of dollars were at risk due to need of current design equations.
How has the Unified Equation Benefited NMDOT?

- $1.5 Million Savings in Foundation Construction Costs Documented on Big-I Interchange

- $750K Savings in Foundation Construction Costs Documented on I40-Coors
<table>
<thead>
<tr>
<th>Clay</th>
<th>Loose to medium dense sand</th>
<th>Dense sand</th>
<th>Intermediate geo-materials (gravel/cobbles/weathered rock cemented soils?)</th>
</tr>
</thead>
</table>

| Unified Equation 2002 |

<table>
<thead>
<tr>
<th>FHWA1999</th>
<th>FHWA1988</th>
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<tbody>
<tr>
<td>0°</td>
<td>17°</td>
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<tr>
<td>c'=21 kPa</td>
<td>35° c'= 0</td>
</tr>
</tbody>
</table>

| 42° c'= 0 |

| Mayne & Harris 1993 |
| (?|)
Mayne & Harris (1993) Method

\[ f_{\text{max}} = K_0 \tan \phi' \sigma_{ovrb}' \quad \text{where} \quad K_0 = \left( 1 - \sin \phi' \right) \text{OCR} \sin \phi' \]

\[ \phi' \left( N_{60}', \sigma_{ovrb}' \right) \]

\[ \text{OCR} \left( \sigma_{ovrb}', N_{60} \right) \]

\[ q_{\text{max}} = 9.33 S_u \quad \text{where} \quad S_u = 0.23 \sigma_{ovrb}' \text{OCR}^{0.8} \]
**Equation for Shaft Resistance**

\[ f_s' = c' + \left[ K_o + (K_p^* - K_o) (1 + z)^{-0.5} \right] \sigma_{ovrb}' \tan \phi' \]

**Phase I**

**Cohesionless**

\[ K_p^* = \frac{2c'}{\sigma_{ovrb}' \tan \phi' \sqrt{1 - \sin \phi'}} \left[ 1 + \frac{\sin \phi'}{1 - \sin \phi'} \right] \]

where

- \( z = \text{depth} \)
- \( \sigma_{ovrb}' = \text{overburden pressure at depth } z \)

[ NC soil ]

\( 1 - \sin \phi' \)

\( (1 - \sin \phi') \sqrt{\text{OCR}} \)

[ OC soil ]

\( 1 - \sin \phi' \)
Comparing Side Resistance for Cohesionless Soils

RESULTS

Unified equation $\phi' = 35^\circ$

FHWA Sand $\phi' = 35^\circ$

Unified equation $\phi' = 42^\circ$

FHWA Sand/Gravel

$\frac{f_s'}{\sigma_{ovrb}'}$ vs. depth (ft)
Using the Unified Equation for Different Soils

- $c' = 0$ psi
- $\phi' = 40^\circ$ (sand)
- $20$ psi $10^\circ$
- $30$ psi $0^\circ$ (clay)
- $10$ psi $20^\circ$
- $5$ psi $30^\circ$
Cohesionless Soil

\[ f_{s'} = K \tan \phi' \sigma_{ovrb}' \]

What is \( K = \)?

$$\$$
Development of a “K” Database

CLAY

LOOSE SAND

DENSE SAND

SAND

SAND/GRAVEL

GRAVEL
Development of a “K” Database

Conventional Load Frame Testing
Development of a “K” Database

Osterberg Cell Load Testing
### Verification of “K” on Big-I

**Recommended Values of k & α and End-Bearing for Use in Shaft Design**

<table>
<thead>
<tr>
<th>Layer Description</th>
<th>Soil Classification</th>
<th>USCS Classification</th>
<th>Friction Angle, $\phi$ (degrees) (3)</th>
<th>Undrained Strength, $s_u$ (kPa)</th>
<th>Stress Ratio, $k$ (4)</th>
<th>Adhesion Factor, $\alpha$ (4)</th>
<th>Ultimate End-Bearing Pressure (kPa/tsf)</th>
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</thead>
<tbody>
<tr>
<td><strong>Fill</strong></td>
<td>F&lt;sub&gt;1&lt;/sub&gt;</td>
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<td>28</td>
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<td>SM, SP-SM</td>
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<td>0.6 (4)</td>
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<tr>
<td></td>
<td>F&lt;sub&gt;3&lt;/sub&gt;</td>
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<td>1 (4)</td>
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<td>5,750/60</td>
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<td>200</td>
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</table>

**NOTES:**
1. Soil layers which do not have USCS classifications were not encountered at the test shaft sites.
2. Friction angle values were estimated using the Standard Penetration Test data (N-values) from the borings performed at the test shaft locations.
3. Values of “k” and “α” for soil layers not encountered at the test shaft sites are estimates only.
4. Based on review and analysis of load test data.
Analytic Methods Compared with Load Test Results

Saturated Sands (SP,SM,SW)
Dr = 20% - 50%

I-40 Rio Grande

Predicted Ultimate Capacity, Kips

Observed Ultimate Capacity, Kips
(Static Load Test)

US - 70 TEST PILE

I-40 TEST SHAFT

CAPWAP (EOD)
CAPWAP (RESTRIKE)
BETA METHOD
DAVISSON (STATIC)
STATNAMIC TEST
NORDLUND
## NM74 Rio Grande

### Comparison of Analytic Methods and Measured Values

<table>
<thead>
<tr>
<th>Method</th>
<th>Beta(^{(1)})</th>
<th>K(^{(2)})</th>
<th>(f_{sz})(^{(3)}) (ksf)</th>
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<tbody>
<tr>
<td>Beta Method (Predicted)</td>
<td>0.94(^{(4)})</td>
<td>1.0</td>
<td>1.0</td>
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<td>LPC Method (Predicted)</td>
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<td>2.5</td>
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<td>Bentonite Shaft (Measured)</td>
<td>2.58</td>
<td>2.87</td>
<td>3.0</td>
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<tr>
<td>Polymer Shaft (Measured)</td>
<td>3.75</td>
<td>4.15</td>
<td>4.5</td>
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</table>

\(^{(1)}\) \(\beta = K \tan \phi\)

\(^{(2)}\) Based on \(\phi = 42^\circ\)

\(^{(3)}\) \(f_{sz} = \beta p'_o\)

\(^{(4)}\) \(\beta = 1.5 - 0.135 z^{0.5}\) (Reese & O’Neill, 1988)

\(^{(5)}\) (Bustamante and Gianeselli, 1982; Briaud et. al., 1986)
O-Cell Testing at Sunland Park

Get a GRIP
**O-Cell Testing at Sunland Park**

**N.M.S.H. T.D. - Geology & Foundation Exploration**

**BORING L G SUMMARY**

<table>
<thead>
<tr>
<th>MATERIAL CHARACTERISTICS</th>
<th>MATERIAL TYPE</th>
<th>ELEV.</th>
<th>SAMPLE ELEV.</th>
<th>DEPTH SAMPLE</th>
<th>SPL NO.</th>
<th>SPL TYP.</th>
<th>SPL REC.</th>
<th>SPT N. VALUE</th>
<th>SOIL CLASSIFICATION</th>
<th>UNCONFINED COMP. STRENGTH</th>
<th>NATURAL DRY DENSITY</th>
<th>WATER CONTENT %</th>
<th>LL PI</th>
<th>GRADUATION % PASSING</th>
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**GROUND WATER DEPTH - at C completion:**
- 4.8' after 0.5 hours

**NS - No Sa ple**

**Sampler Type:** SS - Driven Split Spoon
- ST - Shelby Tube
- CS - Continuous Sampler
- DC - Driven Casing
- MD - Mud Drilling
- AD - Air Drill ng
- FD - Foa m Drilling

**Boring Method:** HSA - Hollow Stem Augers

**Reported By:** Daryl R. Beach
O-Cell Testing at Sunland Park

Osterberg Cell Load-Movement Curves
Test Shaft #1 - Sunland Park Drive - Sunland Park, NM

- Beta Predicted
- Beta + M&H Predicted (Or Unified Equation)

Displacement (mm)

O-cell Load (MN)
Validate the Unified Equation for use by NMDOT Geotechnical Section as covered by AASHTO LRFD Bridge Design Specifications 4th Edition 2007 with 2008 and 2009 Interim Revisions Section 10.1:

“The probabilistic LRFD basis of these Specifications, which produces an interrelated combination of load, load factor resistance, resistance factor, and statistical reliability, shall be considered when selecting procedures for calculating resistance other than that specified herein. Other methods, especially when locally recognized and considered suitable for regional conditions, may be used if resistance factors are developed in a manner that is consistent with the development of the resistance factors for the method(s) provided in these Specifications, and are approved by the Owner.”
RESEARCH QUESTION:

1. How can NMDOT improve current drilled shaft design methods from the FHWA manual, which are more empirically based and may not reflect the real behavior of drilled shafts in different soils and regions?

2. Is it possible to discover a unified mechanistic-based design method for drilled shafts?

3. Is the current proposed unified mechanistic-based design equation proposed by Chua & Meyers suitable for validation?

4. Can localized resistance factors be determined for Load and Resistance Factor Design (LRFD) for the proposed unified mechanistic-based design equation?
Reliability Analysis:

\[ \phi \] is mainly a Function of \( \lambda \) and COV

Figure from NCHRP Report 507
for Drilled Shafts:

- NCHRP Report 507

- FHWA-NHI-05-052 Publication

FHWA Resource Center

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TASKS

Task-1: *Literature Review:* comprehensive best-practice national perspective

Task-2: Research development drilled shaft design methods from FHWA manual
  - Weaknesses and suitability of empirically based FHWA equations
  - How equations compare to behavior of drilled shafts in different soils and regions

Task-3: Research development of proposed unified design equation (Chua, Meyers; 2002)
  - Current proposed unified design equation suitable for validation
  - Localized LRFD resistance factors for the unified design equation (statistically and reliability based method/ calibrate resistance factors)

Task-4: Provide:
  - **Final Report:**
  - **Implementation Plan:**
  - **Multimedia Presentation:**

---

**CLAY**
**LOOSE SAND**
**DENSE SAND**
**SAND/GRAVEL**
Research Bureau

Innovation in Transportation

Invitation To Propose

Development and Validation of a Unified Equation for Drilled Shaft Foundation Design in New Mexico

Project Number – NM10MSC-01

Naresh C. Samtani, PhD, PE
President, NCS Consultants, LLC

CLAY
LOOSE SAND
DENSE SAND
SAND/SAND/GRAVEL
GRAVEL
CONCLUDING REMARKS

The Unified Equation: Shaft Resistance

Logical Avenue...

...to Validate the Unified Equation

... FOR ADOPTION BY NMDOT

...Will we be ready for the next $300 Million Project...?
CONCLUDING REMARKS

The Unified Equation: Shaft Resistance

Any Questions??