Bearing Capacity Factors for Shallow Foundations Subject to Combined Lateral and Axial Loading

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PRESENTATION OVERVIEW

1) BACKGROUND AND MOTIVATION

2) PROJECT TASKS

3) BEARING CAPACITY EQUATIONS

4) SOIL PROPERTIES
   • A-3 Soil

5) PLUVIATION PROCEDURE
   • Medium dense condition
   • Very dense condition

6) LOADING, FOOTINGS, AND SOIL CONDITIONS TO BE TESTED
   • Foundation size, L/B ratio, Embedment Depth, Relative Density, G-Level, etc.

7) CENTRIGUE MODEL EXPERIMENT SETUP
   • Test apparatus
   • Instrumentation

8) TEST RESULTS AND ANALYSIS
   • General or Local shear failure
   • Bearing capacity
   • $N_\gamma$
1) AASHTO Specifications (10.6.3.1.2) make allowance for load inclination
   • Meyerhof (1953), Vesić (1973) and Hansen (1973) are considered
   • Based on small scale experiments
   • Derived for footings without embedment

2) AASHTO commentary (C10.6.3.1.2a) suggest inclination factors may be overly conservative
   • Footing embedment \((D_f) = B\) or greater
   • Footing with modest embedment may omit load inclination factors

3) FHWA GEC No.6 indicates load inclination factors can be omitted if lateral and vertical load checked against their respective resistances

4) Resistance factors included in the AASHTO code were derived for vertical loads
   • Applicability to combined lateral/axial loads are currently unknown
   • Up to 75% reduction in Nominal Bearing Resistance computed with AASHTO load inclination factors
5) NCHRP 651 on LRFD Design and Construction of Shallow Foundations for Highway Bridges
   • Identify and propose the concept of a combined failure state
   • Similar to beam/column interaction diagram

6) FDOT research project BDK75-977-22 completed in December 2013
   • Limited set of combined vertical and horizontal loads
   • Results indicated the inclination of resultant load had an experimentally proven effect on the bearing capacity of MSE walls
OBJECTIVES
Measure bearing capacity of representative shallow foundations in centrifuge tests to identify the influence of embedment, lateral/axial concentric and eccentric loads through experimentally determined load factors.

TASKS
1) Task-1: Collect data on current practice through online survey
2) Task-2: Select foundation scenarios to test and design experimental program
3) Task-3: Conduct centrifuge tests on model foundations for bearing capacity
4) Task-4: Compare measured bearing capacity to predictions
5) Tasks-5 and 6: Closeout Teleconference and Final Report
FDOT recommends analysis of shallow foundations be done in accordance with AASHTO LRFD Bridge Design Specifications

**General bearing capacity equation recommended by AASHTO (2016)**

\[
q_n = cN_{cm} + \gamma D_f N_{qm} C_{wq} + 0.5\gamma B N_{\gamma m} C_{w\gamma}
\]

Eq. 1

\[
q_n = \gamma D_f N_{qm} + 0.5\gamma B N_{\gamma m}
\]

Eq. 2

\[
N_{qm} = N_q S_q d_q i_q
\]

Eq. 3

\[
N_{\gamma m} = N_{\gamma} S_{\gamma} i_{\gamma}
\]

Eq. 4

\[
N_q = e^{\pi \tan \phi_f \tan^2 \left(45^\circ + \frac{\phi_f}{2}\right)}
\]

Eq. 5

\[
N_{\gamma} = 2(N_q + 1) \tan(\phi_f)
\]

Eq. 6

Symbols:
- \( q_n \): Bearing capacity
- \( c \): Cohesion
- \( N_{cm} \): Bearing capacity factor
- \( \gamma \): Soil unit weight
- \( D_f \): Embedment depth
- \( N_{qm} \): Bearing capacity
- \( N_{\gamma m} \): Bearing capacity
- \( S_q \): Shape correction factor
- \( S_{\gamma} \): Shape correction factor
- \( d_q \): Depth correction factor
- \( i_q \), \( i_{\gamma} \): Inclination correction factors
- \( B \): Foundation width

**Note:**
- FDOT recommends analysis of shallow foundations be done in accordance with AASHTO LRFD Bridge Design Specifications.
AASHTO CLASS: A-3
- Max unit weight: 108.9 pcf
- Min unit weight: 90.7 pcf
- 2.5% Passing #200
- 97.5% Sand
- Coefficient of Uniformity: 1.67
- Coefficient of Curvature: 1.35
- Specific gravity: 2.67
- $e_{\text{min}}$: 0.53
- $e_{\text{max}}$: 0.84
- SP Unified Soil Classification

DIRECT SHEAR TEST:
- $D_r = 55 - 93\%$
- $\phi = 29.5^\circ - 34^\circ$

TRIAXIAL CD-TEST: (c=0)
- $D_r = 61 - 94\%$
- $\phi = 36.0^\circ - 41.2^\circ$

TRIAXIAL CD-TEST: (c≠0)
- $D_r = 61 - 94\%$
- $\phi = 33.3^\circ - 39.9^\circ$

\[ \phi = 0.1555D_r + 26.757 \quad R^2 = 0.9832 \]
\[ \phi = 0.1959D_r + 21.443 \quad R^2 = 0.9998 \]
\[ \phi = 0.1089D_r + 23.985 \quad R^2 = 0.9343 \]
TASK 2: SOIL PLUVIATION

Front View

Side View
TASK 2: SOIL PLUVIATION

MEDIUM DENSE CONDITION:
• Relative density range: 35%-65%
• Drop height: 26 in
• Area: 0.065 in²
• Flow rate: 0.12 ft³/min
• Relative density achieved: 63%

VERY DENSE CONDITION:
• Relative density range: 85% & UP
• Drop height: 26 in
• Area: 0.024 in²
• Flow rate: 0.015 ft³/min
• Relative density achieved: 85%
• Useful to study geotechnical problems (capacity of foundations) at a fraction of the cost of prototype study
• Soil has non-linear mechanical properties dependent on effective stress and stress history
• Spinning model in centrifuge increases the “gravitational” acceleration model which produces identical self-weight stresses between model and prototype ($\sigma_{\text{model}} / \sigma_{\text{prototype}} = 1$)
• Scale other properties for testing ex. $L_{\text{model}} / L_{\text{prototype}} = 1/N$

<table>
<thead>
<tr>
<th>Property</th>
<th>Scale Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>$1/N$</td>
</tr>
<tr>
<td>Area</td>
<td>$1/N^2$</td>
</tr>
<tr>
<td>Volume</td>
<td>$1/N^3$</td>
</tr>
<tr>
<td>Force</td>
<td>$1/N^2$</td>
</tr>
<tr>
<td>Unit Weight</td>
<td>$N$</td>
</tr>
<tr>
<td>Stress</td>
<td>$1$</td>
</tr>
<tr>
<td>Strain</td>
<td>$1$</td>
</tr>
</tbody>
</table>

- In flight load application and monitoring of foundation response (displacement and soil pressure)
**TASK 3: TEST CONDITION-1**

**Strip Foundation: (L/B = 20)**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Interior container width (in.)</td>
<td>20</td>
</tr>
<tr>
<td>Interior container length (in.)</td>
<td>20</td>
</tr>
<tr>
<td>Interior container height (in.)</td>
<td>9.5</td>
</tr>
<tr>
<td>Soil height (in.)</td>
<td>8.5</td>
</tr>
<tr>
<td>Scale factor (N)</td>
<td>36</td>
</tr>
<tr>
<td>Foundation material</td>
<td>Aluminum</td>
</tr>
<tr>
<td>Model width (in)</td>
<td>1</td>
</tr>
<tr>
<td>Model length (in.)</td>
<td>20</td>
</tr>
<tr>
<td>Model thickness (in.)</td>
<td>0.5</td>
</tr>
<tr>
<td># of Hyd. load actuators</td>
<td>3</td>
</tr>
<tr>
<td># of Omega load cells</td>
<td>3</td>
</tr>
<tr>
<td># of BEI linear potentiometers</td>
<td>3</td>
</tr>
<tr>
<td>Enerpac P464 hand pump</td>
<td>1</td>
</tr>
</tbody>
</table>

* Container designed to accommodate max load for ultimate bearing capacity and eliminate boundary influences on failure surfaces.*
### TASK 3: TESTS PERFORMED

<table>
<thead>
<tr>
<th>Loading and Foundation Scenario</th>
<th>Name</th>
<th>Date</th>
<th>Density (D_d)</th>
<th>Embedment Depth (D_f)</th>
<th>Eccentricity</th>
<th>Inclination</th>
<th>Series #</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LT-1</td>
<td>7/5/2018</td>
<td>Very Dense</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>LT-2</td>
<td>7/7/2018</td>
<td>Very Dense</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>LT-3</td>
<td>7/12/2018</td>
<td>Medium Dense</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>LT-4</td>
<td>7/13/2018</td>
<td>Medium Dense</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>LT-5</td>
<td>7/14/2018</td>
<td>Medium Dense</td>
<td>0.5B</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>LT-6</td>
<td>7/16/2018</td>
<td>Medium Dense</td>
<td>0.5B</td>
<td>0</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>LT-7</td>
<td>7/17/2018</td>
<td>Very Dense</td>
<td>0.5B</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>LT-8</td>
<td>7/18/2018</td>
<td>Very Dense</td>
<td>0.5B</td>
<td>0</td>
<td>0</td>
<td>2</td>
</tr>
</tbody>
</table>
Soil properties:
- \( \mu_{\gamma_d} = 106.11 \text{ pcf} \)
- \( \mu_{\phi_{DS}} = 33.45^\circ \)
- \( \mu_{\phi_{TS}} = 40.27^\circ \)
- \( \mu_{Dr} = 86.91\% \)
- \( CV_{Dr} = 0.012 \)

Post-test soil stratigraphy:

\[
\alpha = 45^\circ - \frac{\phi}{2} \quad \therefore \alpha = 30.23^\circ \\
\phi = 29.54^\circ 
\]
Post-test soil plan view
TASK 3: LT-1 LOAD vs. DISPLACEMENT (model scale)

Load South - 342.4 lb. @ 0.178 in
Load North - 360.1 lb. @ 0.227 in
Soil properties:
\[ \mu_{\gamma_d} = 106.15 \text{ pcf} \]
\[ \mu_{\phi_{DS}} = 33.47^\circ \]
\[ \mu_{\phi_{TS}} = 40.30^\circ \]
\[ \mu_{Dr} = 87.10\% \]
\[ CV_{Dr} = 0.017 \]

Post-test soil stratigraphy
\[ \alpha = 45^\circ - \frac{\phi}{2} \quad \therefore \alpha = 29.30^\circ \]
\[ \phi = 31.40^\circ \]
Post-test soil plan view
TASK 3: LT-2 LOAD vs. DISPLACEMENT (model scale)

Load South - 346.2 lb. @ 0.135 in
Load North - 355.2 lb. @ 0.164 in
TASK 3: LT-1 & LT-2 LOAD vs. DISPLACEMENT (prototype scale)

Bearing capacity, $q = 7,383$ psf @ 7.852 in

Bearing capacity, $q = 7,402$ psf @ 5.849 in
Soil properties:
\[
\begin{align*}
\mu_{\gamma_d} &= 101.45 \text{ pcf} \\
\mu_{\phi_{DS}} &= 30.89^\circ \\
\mu_{\phi_{TS}} &= 36.62^\circ \\
\mu_{\text{Dr}} &= 63.42\% \\
\text{CV}_{\text{Dr}} &= 0.025
\end{align*}
\]

Post-test soil stratigraphy

\[
\alpha = 45^\circ - \frac{\phi}{2} \therefore \alpha = 29.36^\circ \\
\phi = 31.28^\circ
\]
Soil properties:
\( \mu_{\gamma d} = 101.44 \) pcf
\( \mu_{\phi DS} = 30.89^\circ \)
\( \mu_{\phi TS} = 36.61^\circ \)
\( \mu_{Dr} = 63.36\% \)
\( CV_{Dr} = 0.017 \)

Post-test soil stratigraphy
\[ \alpha = 45^\circ - \frac{\phi}{2} \Rightarrow \alpha = 29.44^\circ \]
\[ \phi = 31.12^\circ \]
 TASK 3: LT-3 & LT-4 LOAD vs. DISPLACEMENT (prototype scale)

Bearing capacity, $q = 5,000$ psf @ 5.75 in
Bearing capacity, $q = 5,050$ psf @ 4.20 in
**TASK 3: INVESTIGATION OF N_γ**

**Bearing Factor for Surcharge and Soil Unit Weight:**

\[ N_q = e^{\pi \tan \phi_f \tan^2 \left(45^\circ + \frac{\phi_f}{2}\right)} \]

\[ N_γ = 2(N_q + 1)\tan(\phi_f) - \text{(Vesic')} \]

\[ N_γ = 2(N_q + 1)\tan(1.07\phi_f) - \text{(Zhu et al method)} \]

**Simplified form of Bearing Capacity Equation:**

\[ q_n = \gamma D_f N_{qm} C_{wq} + 0.5\gamma B N_{γm} \]

\[ N_{γm} = \frac{q_n}{0.5\gamma B} \text{ (Measured)} \]

**Evaluate N_γ with various φ-values:**

- φ-Direct shear test
- φ-Triaxial shear test
- φ-Measured failure surface
## TASK 3: INVESTIGATION OF $N_\gamma$

### $\phi$-Direct Shear Test

<table>
<thead>
<tr>
<th>Test</th>
<th>Density</th>
<th>$\phi$-Direct Shear (degree)</th>
<th>$N_\gamma$ - Measured</th>
<th>$N_\gamma$ - Vesic' method</th>
<th>%-Difference (Vesic')</th>
<th>$N_\gamma$ - Zhu et al method</th>
<th>%-Difference (Zhu et al method)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LT-1</td>
<td>86.91</td>
<td>33.45</td>
<td>45.24</td>
<td>37.71</td>
<td>18.2</td>
<td>41.15</td>
<td>9.5</td>
</tr>
<tr>
<td>LT-2</td>
<td>87.10</td>
<td>33.47</td>
<td>45.22</td>
<td>37.83</td>
<td>17.8</td>
<td>41.28</td>
<td>9.1</td>
</tr>
<tr>
<td>LT-3</td>
<td>63.42</td>
<td>30.89</td>
<td>32.86</td>
<td>25.57</td>
<td>25.0</td>
<td>27.81</td>
<td>16.6</td>
</tr>
<tr>
<td>LT-4</td>
<td>63.36</td>
<td>30.89</td>
<td>32.86</td>
<td>25.57</td>
<td>25.0</td>
<td>27.81</td>
<td>16.6</td>
</tr>
</tbody>
</table>

### $\phi$-Triaxial Shear Test (c=0)

<table>
<thead>
<tr>
<th>Test</th>
<th>Density</th>
<th>$\phi$-Triaxial (degree)</th>
<th>$N_\gamma$ - Measured</th>
<th>$N_\gamma$ - Vesic' method</th>
<th>%-Difference (Vesic')</th>
<th>$N_\gamma$ - Zhu et al method</th>
<th>%-Difference (Zhu et al method)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LT-1</td>
<td>86.91</td>
<td>40.27</td>
<td>45.24</td>
<td>114.64</td>
<td>86.8</td>
<td>126.58</td>
<td>94.7</td>
</tr>
<tr>
<td>LT-2</td>
<td>87.10</td>
<td>40.30</td>
<td>45.22</td>
<td>115.23</td>
<td>87.3</td>
<td>127.25</td>
<td>95.1</td>
</tr>
<tr>
<td>LT-3</td>
<td>63.42</td>
<td>36.62</td>
<td>32.86</td>
<td>62.13</td>
<td>61.6</td>
<td>68.25</td>
<td>70.0</td>
</tr>
<tr>
<td>LT-4</td>
<td>63.36</td>
<td>36.61</td>
<td>32.86</td>
<td>62.13</td>
<td>61.6</td>
<td>68.14</td>
<td>69.9</td>
</tr>
</tbody>
</table>

### $\phi$-Measured Failure Surface

<table>
<thead>
<tr>
<th>Test</th>
<th>Density</th>
<th>$\phi$-Failure surf. (degree)</th>
<th>$N_\gamma$ - Measured</th>
<th>$N_\gamma$ - Vesic' method</th>
<th>%-Difference (Vesic')</th>
<th>$N_\gamma$ - Zhu et al method</th>
<th>%-Difference (Zhu et al method)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LT-1</td>
<td>86.91</td>
<td>29.54</td>
<td>45.24</td>
<td>20.93</td>
<td>73.5</td>
<td>22.73</td>
<td>66.2</td>
</tr>
<tr>
<td>LT-2</td>
<td>87.10</td>
<td>31.40</td>
<td>45.22</td>
<td>27.6</td>
<td>48.4</td>
<td>30.04</td>
<td>40.3</td>
</tr>
<tr>
<td>LT-3</td>
<td>63.42</td>
<td>31.28</td>
<td>32.86</td>
<td>27.11</td>
<td>19.2</td>
<td>29.50</td>
<td>10.8</td>
</tr>
<tr>
<td>LT-4</td>
<td>63.36</td>
<td>31.12</td>
<td>32.86</td>
<td>26.47</td>
<td>21.5</td>
<td>28.79</td>
<td>13.2</td>
</tr>
</tbody>
</table>
TASK 3: LT-5 SOIL PROFILE VIEW

Soil properties:
\( \mu_{\gamma_d} = 101.58 \text{ pcf} \)
\( \mu_{\phi_{DS}} = 30.96^\circ \)
\( \mu_{\phi_{TS}} = 36.72^\circ \)
\( \mu_{Dr} = 64.07\% \)
\( CV_{Dr} = 0.029 \)

Post-test soil stratigraphy
\[ \alpha = 45^\circ - \frac{\phi}{2} \therefore \alpha = 27.75^\circ \]
\[ \phi = 34.50^\circ \]
Soil properties:
\[ \mu_{\gamma_d} = 101.38 \text{ pcf} \]
\[ \mu_{\phi_{DS}} = 30.85^\circ \]
\[ \mu_{\phi_{TS}} = 36.56^\circ \]
\[ \mu_{\text{Dr}} = 63.05\% \]
\[ CV_{\text{Dr}} = 0.029 \]

Post-test soil stratigraphy

\[ \alpha = 45^\circ - \frac{\phi}{2} \quad \therefore \alpha = 29.93^\circ \]
\[ \phi = 30.14^\circ \]
TASK 3: LT-5 & LT-6 LOAD vs. DISPLACEMENT (prototype scale)

Bearing capacity, $q$ - 6,000 psf @ 4.900 in
Bearing capacity, $q$ - 5,900 psf @ 7.800 in
Soil properties:
\[ \mu_{\gamma_d} = 105.97 \text{ pcf} \]
\[ \mu_{\phi_{DS}} = 33.37^\circ \]
\[ \mu_{\phi_{TS}} = 40.16^\circ \]
\[ \mu_{Dr} = 86.21\% \]
\[ CV_{Dr} = 0.012 \]

\begin{align*}
\alpha &= 45^\circ - \frac{\phi}{2} \quad \therefore \alpha = 27.64^\circ \\
\phi &= 34.72^\circ
\end{align*}
Soil properties:
\[ \mu_{\gamma_d} = 105.85 \text{ pcf} \]
\[ \mu_{\phi_{DS}} = 33.31^\circ \]
\[ \mu_{\phi_{TS}} = 40.07^\circ \]
\[ \mu_{Dr} = 85.65\% \]
\[ CV_{Dr} = 0.008 \]

Post-test soil stratigraphy
\[ \alpha = 45^\circ - \frac{\phi}{2} \therefore \alpha = 28.64^\circ \]
\[ \phi = 32.72^\circ \]
TASK 3: LT-7 & LT-8 LOAD vs. DISPLACEMENT (prototype scale)

Bearing capacity, $q = 6,000$ psf @ 4.90 in
Bearing capacity, $q = 5,500$ psf @ 4.00 in
**TASK 3: SUMMARY OF $D_f = 0.5B$ TESTS**

<table>
<thead>
<tr>
<th>Name</th>
<th>Date</th>
<th>Density (D_r)</th>
<th>Embedment Depth (D_f)</th>
<th>Eccentricity</th>
<th>Inclination</th>
<th>Measured Bearing Pressure (psf)</th>
<th>Vesic’ Bearing Pressure (psf)</th>
<th>Percent Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LT-5</td>
<td>7/14/2018</td>
<td>Medium Dense</td>
<td>0.5B</td>
<td>0</td>
<td>0</td>
<td>6000</td>
<td>7537</td>
<td>22.7</td>
</tr>
<tr>
<td>LT-6</td>
<td>7/16/2018</td>
<td>Medium Dense</td>
<td>0.5B</td>
<td>0</td>
<td>0</td>
<td>5900</td>
<td>7414</td>
<td>22.7</td>
</tr>
<tr>
<td>LT-7</td>
<td>7/17/2018</td>
<td>Very Dense</td>
<td>0.5B</td>
<td>0</td>
<td>0</td>
<td>6000</td>
<td>10878</td>
<td>57.8</td>
</tr>
<tr>
<td>LT-8</td>
<td>7/18/2018</td>
<td>Very Dense</td>
<td>0.5B</td>
<td>0</td>
<td>0</td>
<td>5500</td>
<td>10776</td>
<td>64.8</td>
</tr>
</tbody>
</table>

\[ q_n = \gamma D_f N_{qm} + 0.5\gamma B N_{\gamma m} \]

\[ N_{qm} = N_q d_q \quad : \quad N_q = e^{\pi \tan \phi_f \tan^2 (45^\circ + \frac{\phi_f}{2})} \]

\[ N_{\gamma m} = N_{\gamma} \quad : \quad N_{\gamma} = 2(N_q + 1)\tan(\phi_f) \]

\[ N_{\gamma m} = \text{Measured value (once confirmed)} \]

\[ d_q = 1 + 2 \tan \phi_f \cdot (1 - \sin \phi_f)^2 \left( \frac{d_f}{B} \right) \text{ for } \frac{d_f}{B} \leq 1 \]
1) LT-1 through LT-4: ($D_f = 0$)
   - $\phi$-direct shear test appears representative of $\phi$-measured failure surface.
   - Plane strain condition
   - $N_y = 2(N_q + 1)\tan(1.07\phi_f)$ – Zhu et al method is best estimate of test results

2) LT-5 through LT-8: ($D_f = 0.5B$)
   - Re-evaluate LT-7 & LT-8 at higher relative density to ensure general shear failure (higher bearing capacity).
   - $q_{\text{measured}}$ vs. $q_{\text{estimated}}$ (confirm $N_y$ & $d_q$)
1) Future tests
   - Evaluate inclined and inclined-eccentric loading on L/B = 1 & L/B = 10 foundations $D_f = 0$ and $D_f > 0$
Thank You