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

FDOT Contract No. BDV31-977-66

FDOT Project Manager: Larry Jones

Principal Investigator: Scott Wasman, Ph.D.

Co-Principal Investigator: Michael McVay, Ph.D.

Research Assistant: Stephen Crawford

UF UNIVERSITY of FLORIDA

OUTLINE

1) BACKGROUND
2) OBJECTIVES
3) SURVEY OF CURRENT PRACTICE
   - Typical uses, lateral/axial load ratios, widths, embedment depths, etc.
4) GOVERNING BEARING CAPACITY EQUATIONS
5) SOIL
   - A-3
6) THEORETICAL FAILURE SURFACE
7) PROPOSED TEST SET-UP
   - L/B=20, L/B=10, L/B=1
   - Limitations
   - Failure loads & G-Levels
   - Foundation design
   - Sensor placement (pressure transducers)
8) ECCENTRICITIES & INCLINATION SENARIOS

BACKGROUND:

1) AASHTO Specifications (10.6.3.1.2) make allowance for load inclination
   - Meyerhof (1953), Vesić (1973) and Hansen (1973) are considered, however based small scale experiments

2) AASHTO commentary (C10.6.3.1.2a) suggest inclination factors may be overly conservative
   - Embedment of $D_f/B = 1$ or deeper
   - Load inclination factors were derived for footings without embedment
   - 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

BACKGROUND:

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

PROJECT OBJECTIVES:

1) Task-1: Collect data on current practice (online survey)
   - B (width), L/B (length/width), embedment (Df), eccentricity
   - lateral/axial load combinations, soil types, unit weights
2) Task-2: Select foundation scenarios to test, design experiments and test apparatus
   - Select soil
   - Container and load frame
   - Plan experiments
3) Task-3: Conduct centrifuge tests
   - Experimentally measure bearing capacity through general shear failure

Soil Density	B, Width	L, Lengths	D, Depths	Axial/Lateral Load Ratios	Loading Locations	Repetitions
2	1	2	2	2	2	2
Med Dense & Dense	Average width	L/B =1 and L/B>3	Near Surface, Near B/2	2 ratios at center and eccentric	Center & Near Edge (eccentric)	Repeat each test (at a minimum)

UF UNIVERSITY of FLORIDA

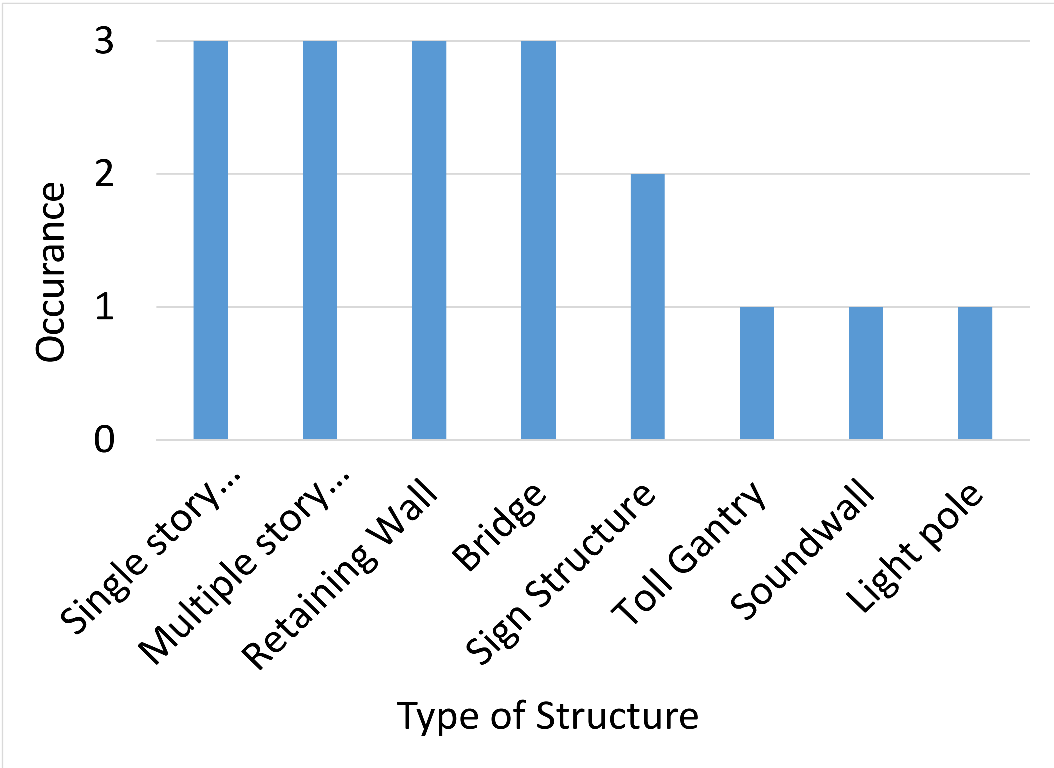
PROJECT OBJECTIVES:

4) Task-4: Compare measured bearing capacity to predictions
   - AASHTO recommended equations
   - Other recommended equations in literature (NCHRP 651)
   - Identify equations/methods recommended for FDOT use

5) Tasks-5 and 6: Closeout Teleconference and Final Report

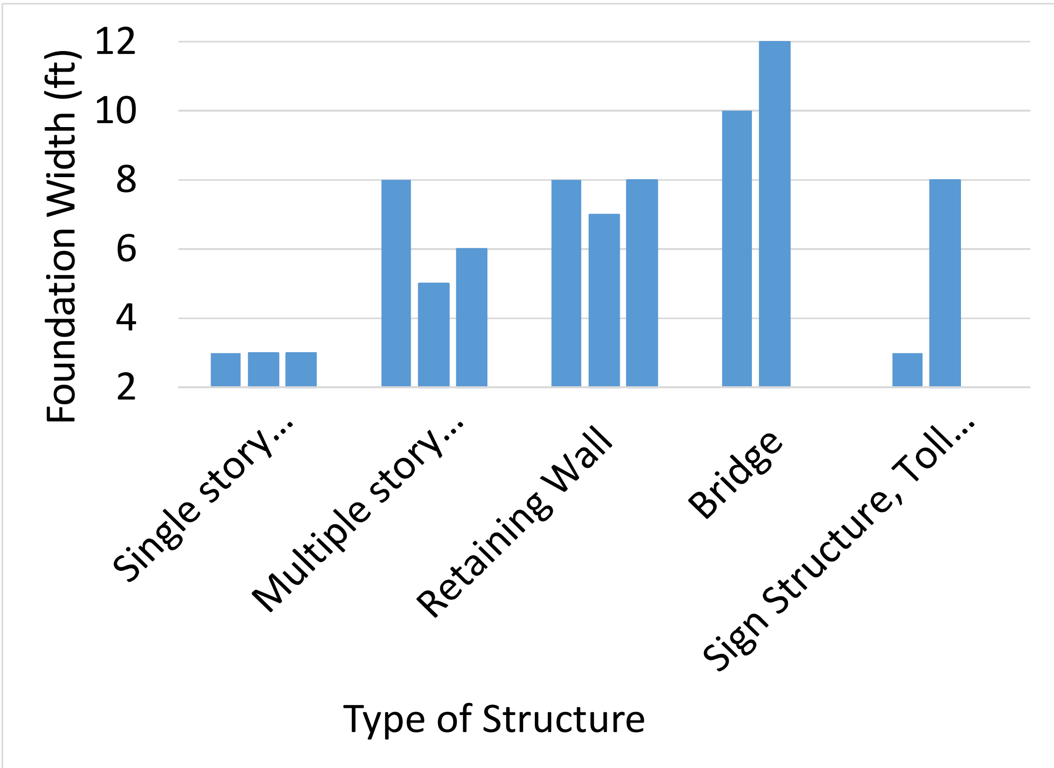
SURVEY OF CURRENT PRACTICE

TYPICAL USE OF SHALLOW FOUNDATIONS



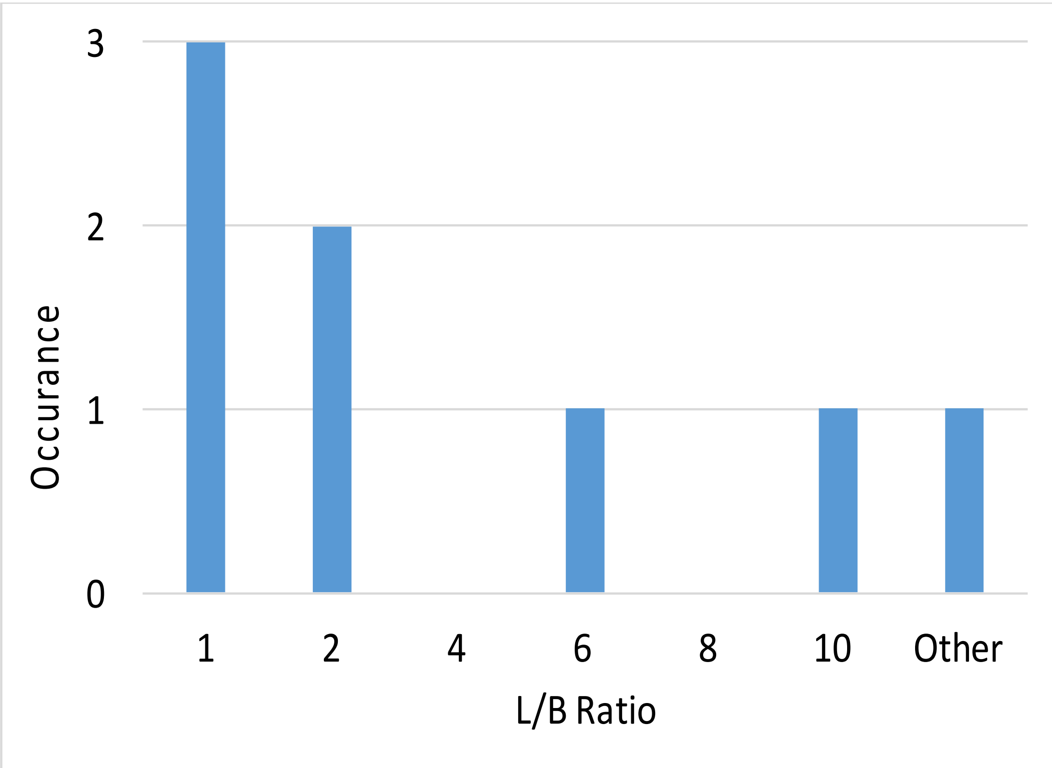
SURVEY OF CURRENT PRACTICE

TYPICAL FOUNDATION WIDTH (B)



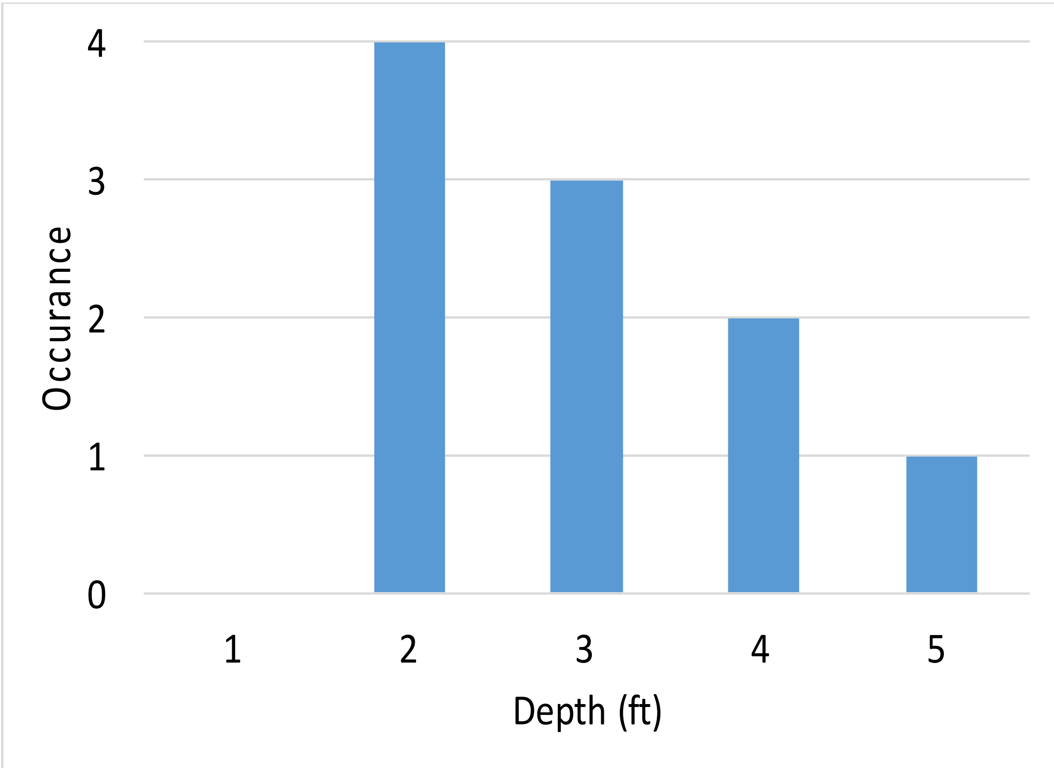
SURVEY OF CURRENT PRACTICE

TYPICAL FOUNDATION LENGTH/WIDTH (L/B) RATIOS



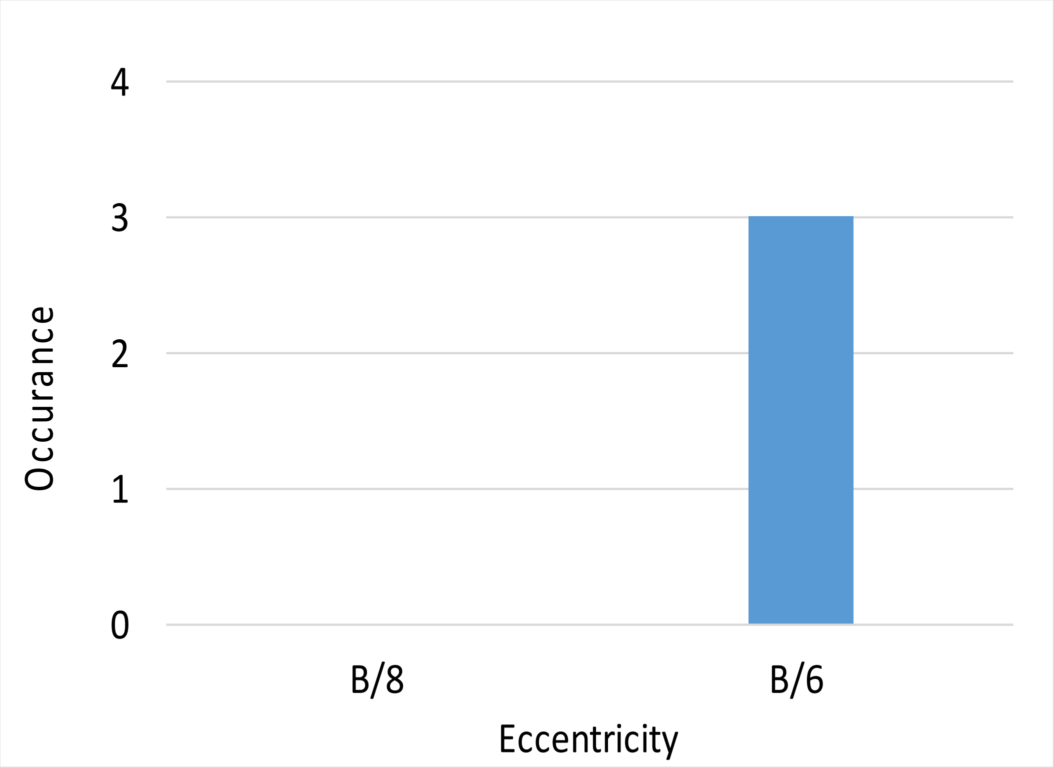
SURVEY OF CURRENT PRACTICE

TYPICAL FOUNDATION EMBEDMENT DEPTH (D_f)



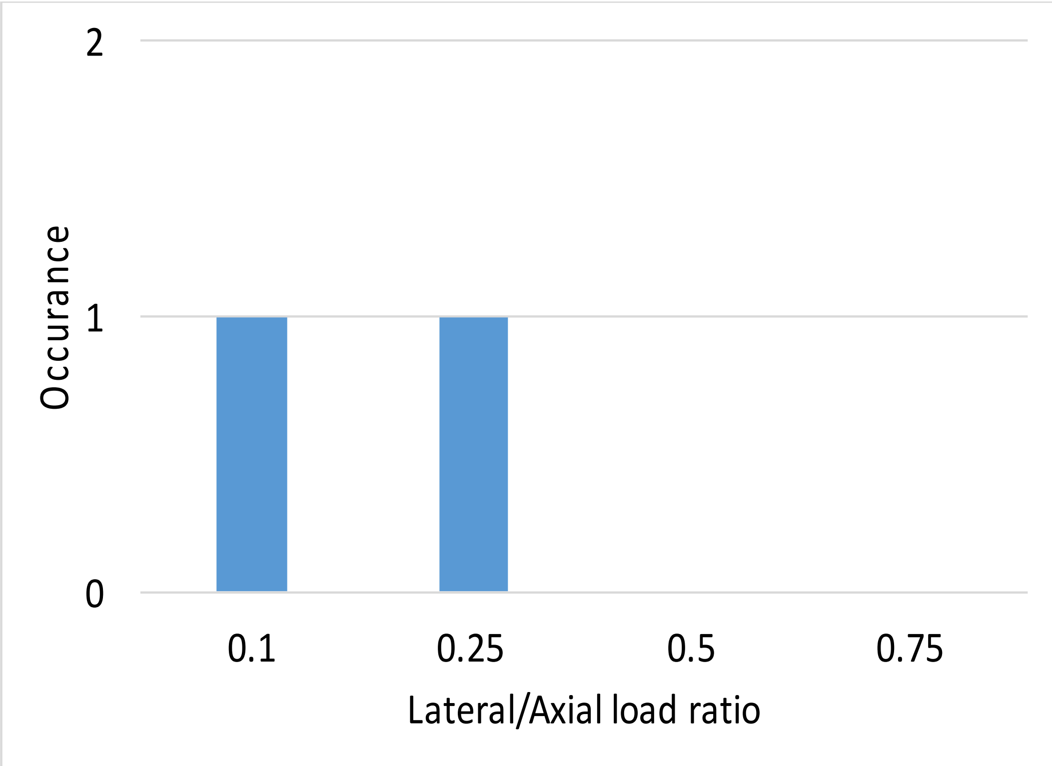
SURVEY OF CURRENT PRACTICE

TYPICAL ECCENTRICITIES OBSERVED



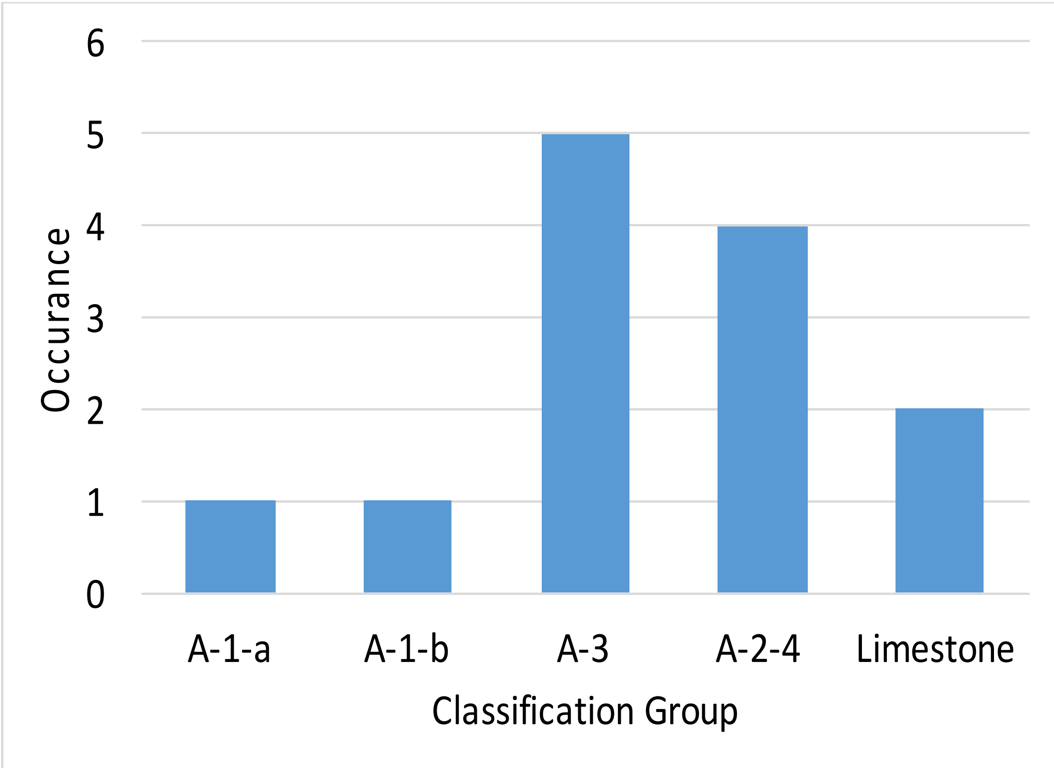
SURVEY OF CURRENT PRACTICE

TYPICAL LATERAL/AXIAL LOAD RATIOS



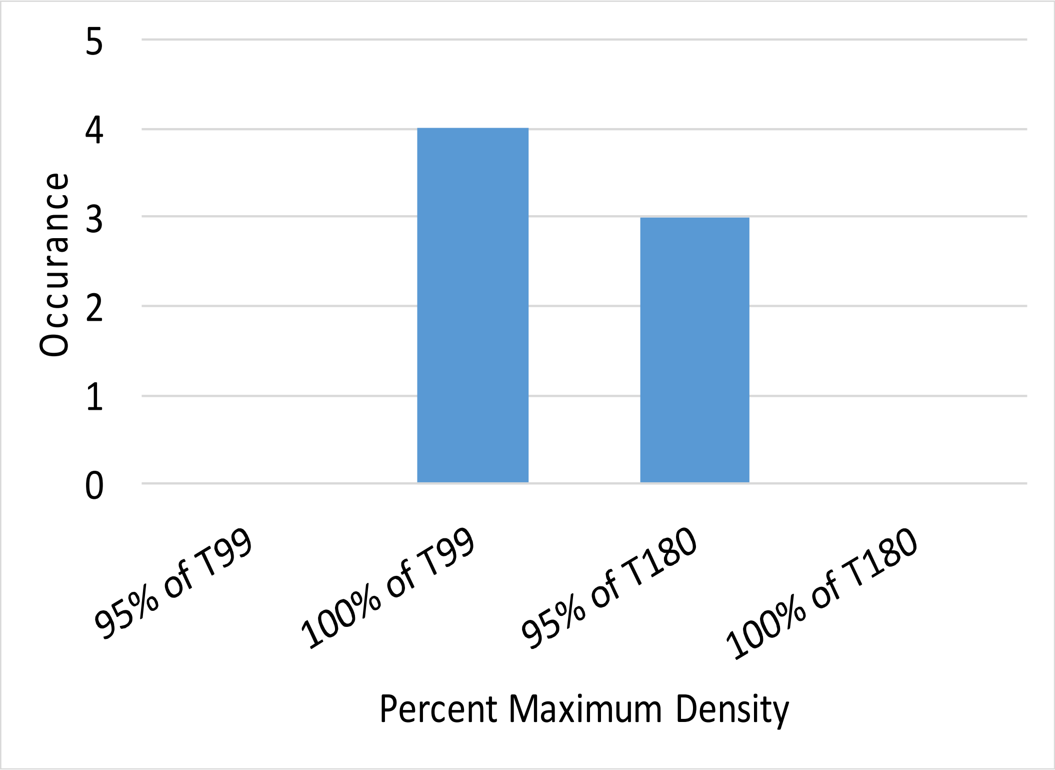
SURVEY OF CURRENT PRACTICE

TYPICAL SOILS BENEATH THE FOOTINGS



SURVEY OF CURRENT PRACTICE

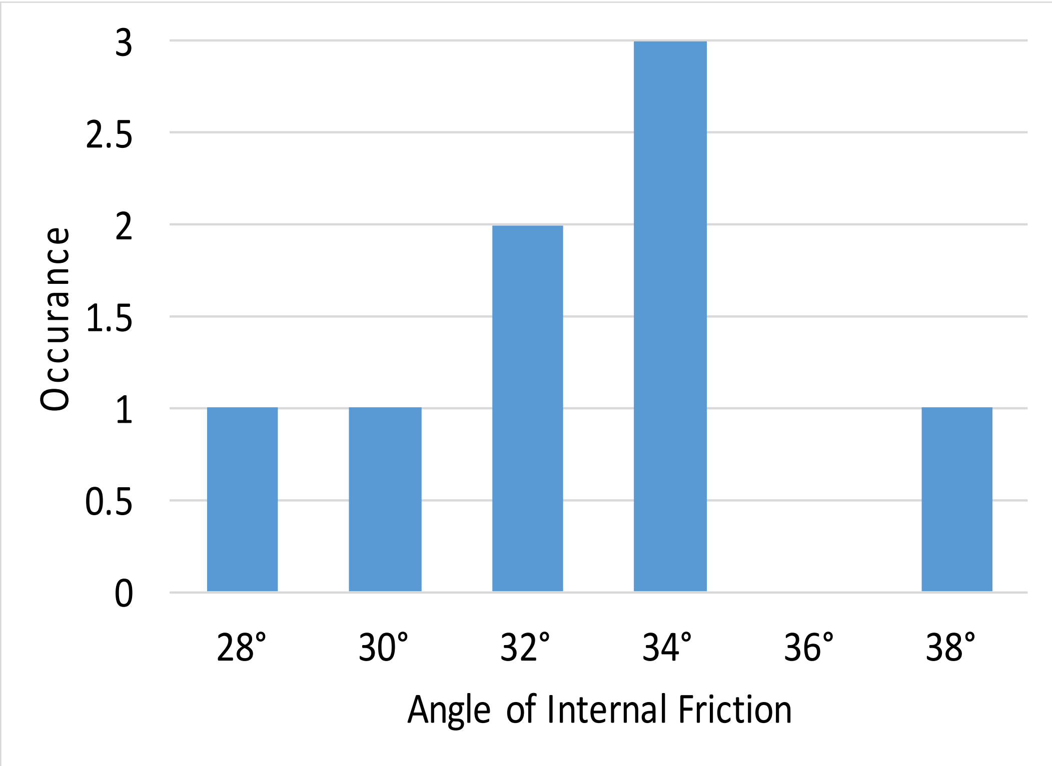
TYPICAL SOILS DENSITY REQUIRMENT BENEATH FOOTINGS



UF UNIVERSITY of FLORIDA

SURVEY OF CURRENT PRACTICE

TYPICAL SOIL FRICTION ANGLE (ϕ) BENEATH THE FOOTING



UF UNIVERSITY of FLORIDA

GOVERNING BEARING CAPACITY EQUATIONS

METHODS OF BEARING CAPACITY ESTIMATION

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

$$N_{cm} = N_c S_c i_c$$ 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

$$N_\gamma = 2\left(N_q + 1\right) tan\left(\phi_f\right)$$ Eq.6

FOUNDATION SCENARIOS (STRIP)

FOR THE PURPOSE OF THIS STUDY (cohesionless soil):

$$q_n = \gamma D_f N_{qm} + 0.5\gamma B N_{\gamma m} \quad \text{Eq.7}$$

STRIP FOUNDATION AT SURFACE:

$$q_n = 0.5\gamma B N_{\gamma m} \quad \text{Eq.8}$$

- $D_f = 0$
- Measured $N_{\gamma m}$ Term
- Fcs, Fqs & $F_{\gamma s} \approx 1.00$
- L/B = 20 the shape factors S_q and S_γ are 1.03 and 0.98 (< 3% error)

STRIP FOUNDATION AT $D_f = B$:

$$q_n = \gamma D_f N_{qm} + 0.5\gamma B N_{\gamma m} \quad \& \quad N_{qm} = N_q S_q d_q i_q$$

- $D_f = B$
- Measured N_{qm} & depth corrections, d_q
- N_q & N_γ are only functions of ϕ

UF | UNIVERSITY of FLORIDA

FOUNDATION SCENARIOS (RECTANGLE)

RECTANGLE FOUNDATION AT $D_f = 0$ & $D_f = B$:

$N_{qm} = N_q S_q d_q i_q$ & $N_{\gamma m} = N_\gamma S_\gamma i_\gamma$

- $D_f = 0$ & $D_f = B$
- Measured N_{qm} & depth corrections, d_q
- N_q & N_γ are only functions of ϕ

RECTANGLE FOUNDATION with load inclination:

$N_{qm} = N_q S_q d_q i_q$ & $N_{\gamma m} = N_\gamma S_\gamma i_\gamma$

- $D_f = 0$ & $D_f = B$
- Lateral/Axial load ratios: 0.1 & 0.25
- Isolate the inclination factors

RECTANGLE FOUNDATION AT with eccentricity:

$N_{qm} = N_q S_q d_q i_q$ & $N_{\gamma m} = N_\gamma S_\gamma i_\gamma$

- $D_f = 0$ & $D_f = B$
- Lateral/Axial load ratios: 0.1 & 0.25
- Maximum eccentricity: B/6
- $B' = B - 2 \cdot e_B$ Eq.9

FOUNDATION SCENARIOS (SQUARE)

SQUARE FOUNDATION AT $D_f = 0$ & $D_f = B$:

$N_{qm} = N_q S_q d_q i_q$ & $N_{\gamma m} = N_\gamma S_\gamma i_\gamma$

- $D_f = 0$ & $D_f = B$
- Measured N_{qm} & depth corrections, d_q
- N_q & N_γ are only functions of ϕ

SQUARE FOUNDATION with load inclination:

$N_{qm} = N_q S_q d_q i_q$ & $N_{\gamma m} = N_\gamma S_\gamma i_\gamma$

- $D_f = 0$ & $D_f = B$
- Lateral/Axial load ratios: 0.1 & 0.25
- Isolate the inclination factors

SQUARE FOUNDATION AT with eccentricity:

$N_{qm} = N_q S_q d_q i_q$ & $N_{\gamma m} = N_\gamma S_\gamma i_\gamma$

- $D_f = 0$ & $D_f = B$
- Lateral/Axial load ratios: 0.1 & 0.25
- Maximum eccentricity: B/6
- $B' = B - 2 \cdot \mathrm{e}_B$

UF UNIVERSITY of FLORIDA

PROTOTYPE FOUNDATION SELECTION

Prototype Size			
L/B	Width-B (ft)	Length- L (ft)	q_u (psf)
1	5	5	29990
10	5	50	24112
20	3	60	14272

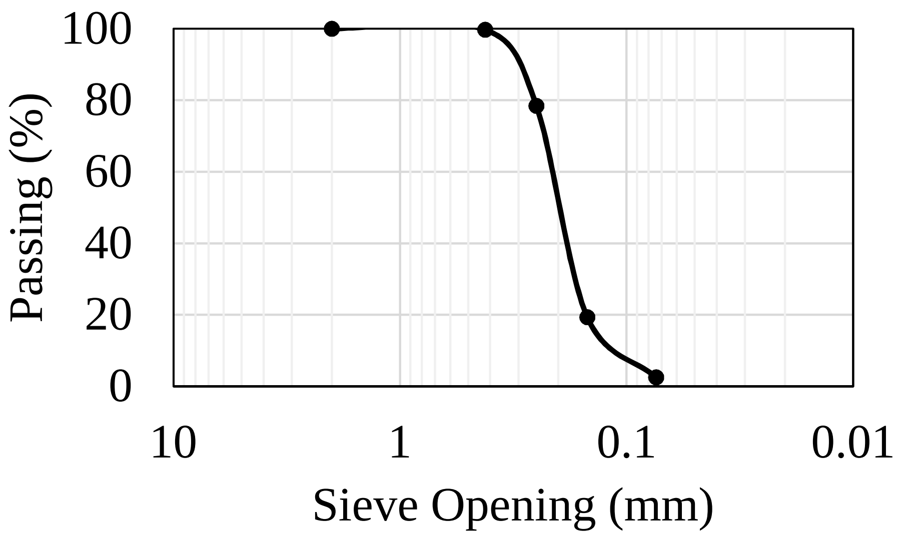
SELECTION PROCESS:

- **Survey results (most common or average response)**
- **Test apparatus limitations**
- **Boundary conditions**
- **Ultimate bearing capacity calculation**
  - **Unit weight: 105 pcf**
  - **Friction angle: 32 deg**

PROPOSED TEST SOIL

AASHTO CLASS: A-3

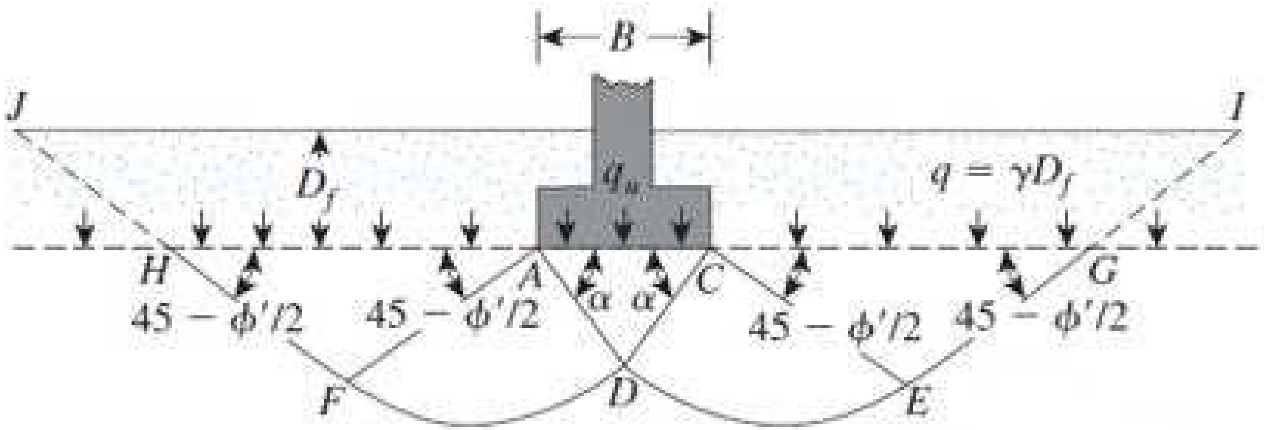
- Poorly graded sand
- Sand: 97.5%
- Silt: 2%
- Clay: 0.5%
- C_u: 1.67
- C_c: 1.35
- G_s: 2.67
- e_{min}: 0.53
- e_{max}: 0.84
- γ_{min}: 90.7 pcf
- γ_{max}: 108.9 pcf
- ϕ: 30° - 34° for D_r: 60% to > 85%
- USCS class: SP



UF UNIVERSITY of FLORIDA

CENTRIFUGE CONTAINER DESIGN

- **NO BOUADARY INFLUENCES ON BEARING CAPACITY**
- **CONTAINER DIMENSIONS > EXTENTS OF FAILURE SURFACE**



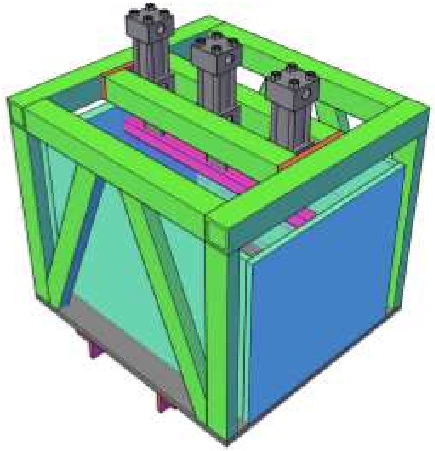
FAILURE SURFACE IS A FUNCTION OF:

- Foundation width: B
- Soil friction angle: ϕ
- Foundation embedment depth: D_f

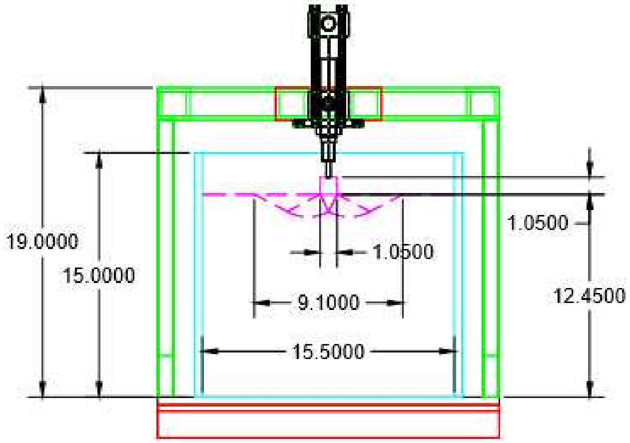
UF UNIVERSITY of FLORIDA

PROPOSED TEST CONDITION-1 (L/B =20)

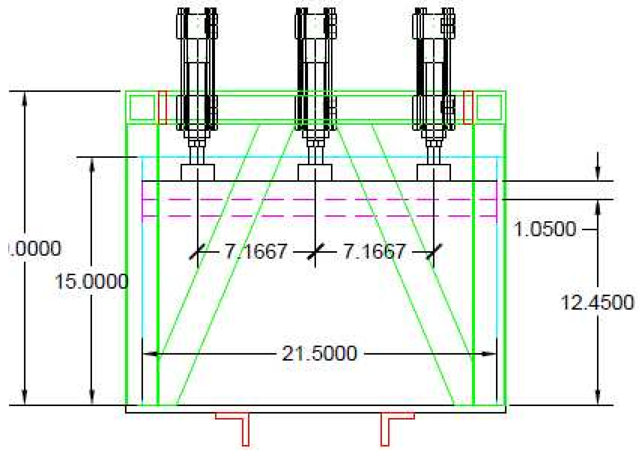
Isometric View



Transverse Elevation

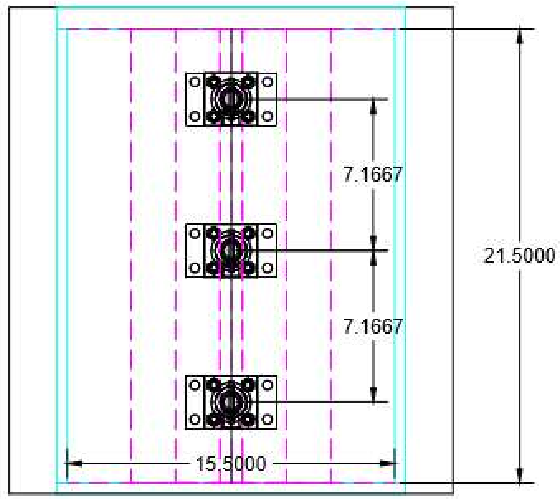


Longitudinal Elevation



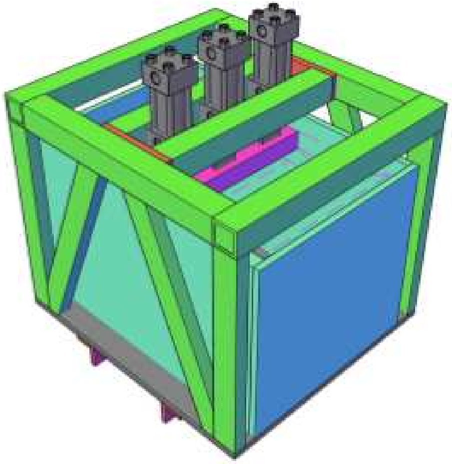
STRIP FOUNDATION	
Interior container width, B (in)	15.5
Interior container length, L (in)	21.5
Interior container height, $H_{cont.}$ (in)	15
Soil height, H_{soil} (in)	13.5
Failure surface length, (in)	9.10
Total load on model foundation (lb)	2290
Total design weight of test apparatus (lb)	600
G-Level (G)	34

Plan View

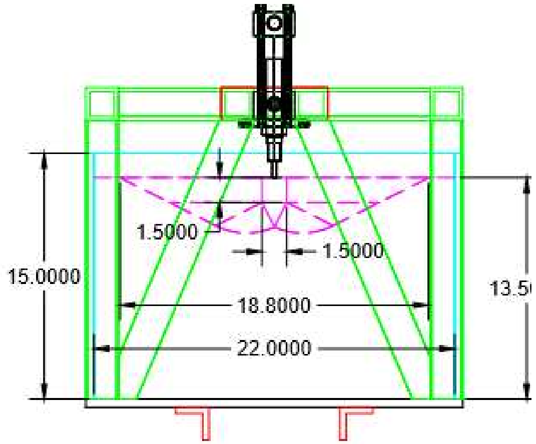


PROPOSED TEST CONDITION-2 (L/B =10)

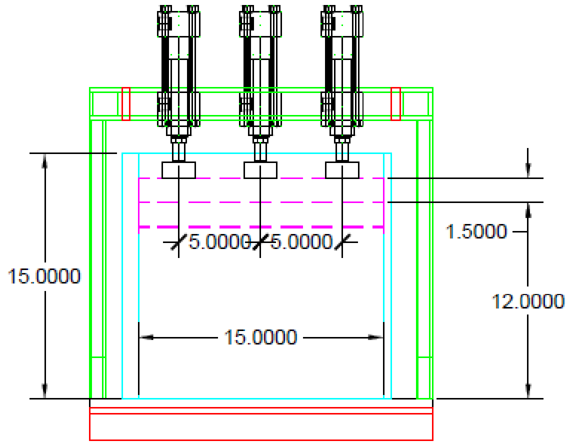
Isometric View



Transverse Elevation

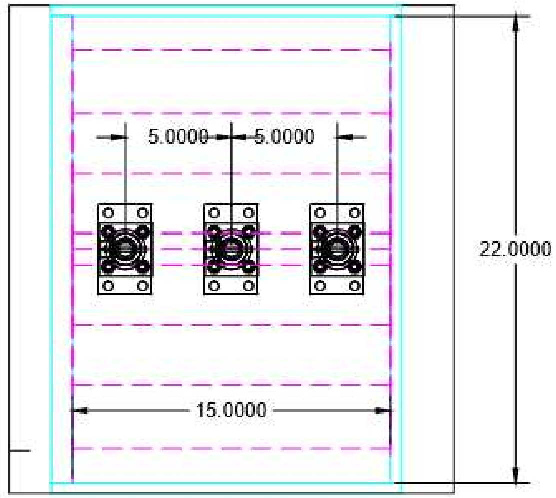


Longitudinal Elevation



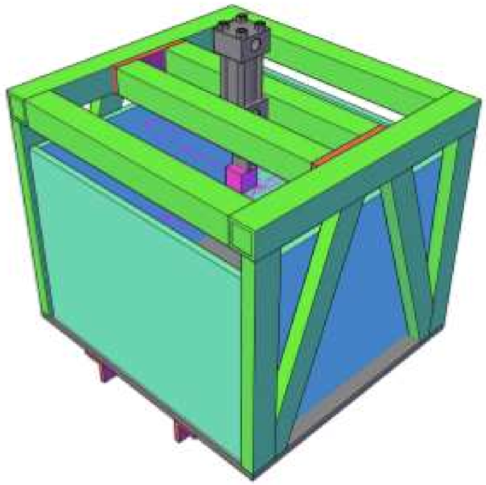
RECTANGLE FOUNDATION	
Interior container width, B (in)	15.0
Interior container length, L (in)	22.0
Interior container height, $H_{cont.}$ (in)	15
Soil height, H_{soil} (in)	13.5
Failure surface length, (in)	18.8
Total load on model foundation (lb)	3767
Total design weight of test apparatus (lb)	600
G-Level (G)	40

Plan View

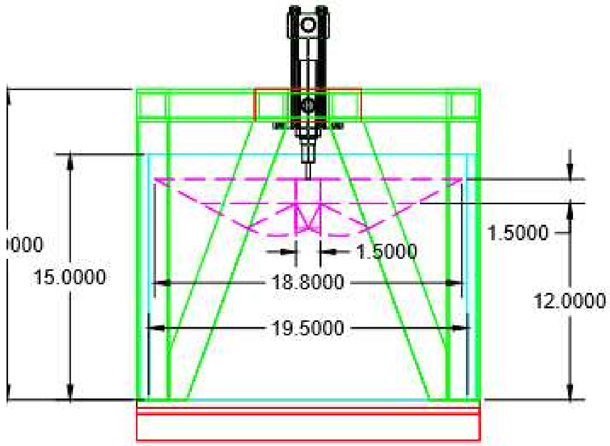


PROPOSED TEST CONDITION-3 (L/B =1)

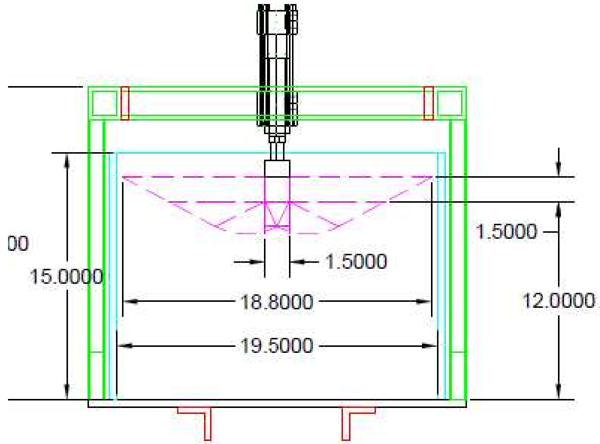
Isometric View



Transverse Elevation

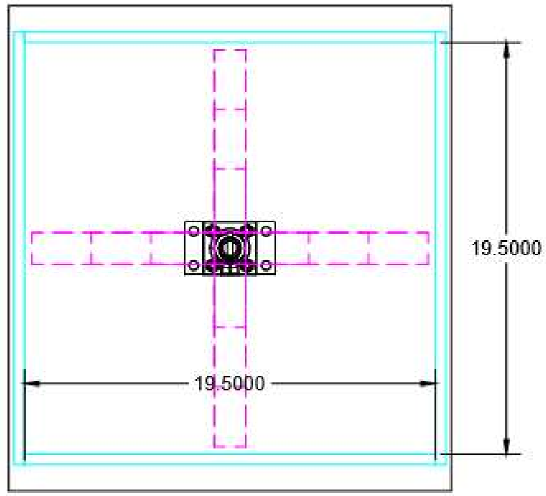


Longitudinal Elevation

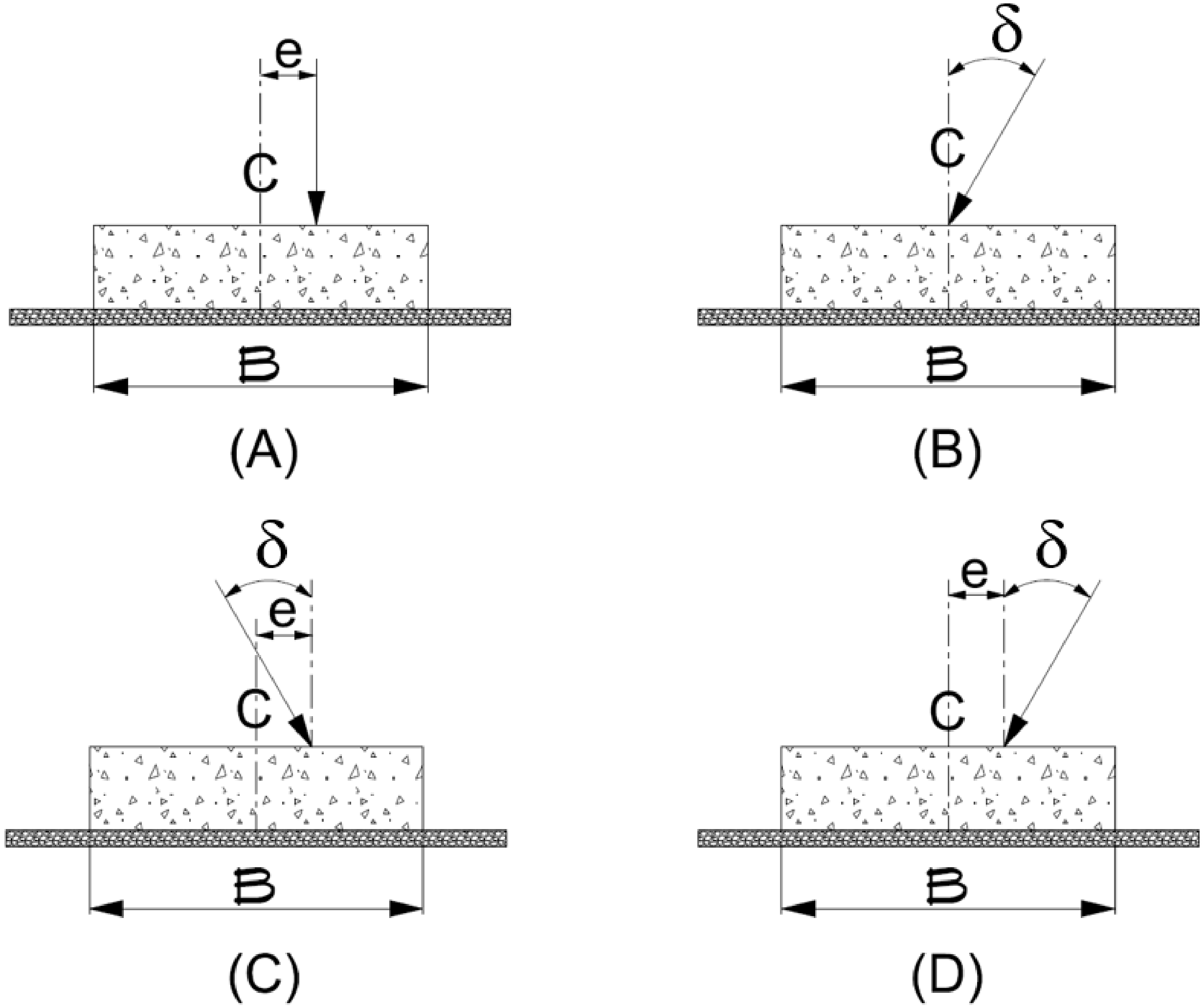


SQUARE FOUNDATION	
Interior container width, B (in)	19.5
Interior container length, L (in)	19.5
Interior container height, $H_{cont.}$ (in)	15
Soil height, H_{soil} (in)	13.5
Failure surface length, (in)	18.8
Total load on model foundation (lb)	469
Total design weight of test apparatus (lb)	600
G-Level (G)	40

Plan View



ECCENTRICITY & INCLINATION SCENARIOS



Lateral/Axial Load Ratio: 0.1 and 0.25
Eccentricity: B/6

PROPOSED TEST CONDITION-2 (L/B =10)

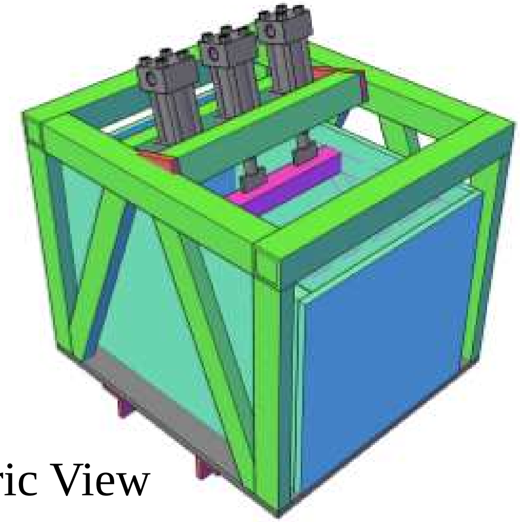
Cases A,B,C & D: Inclined & Eccen

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

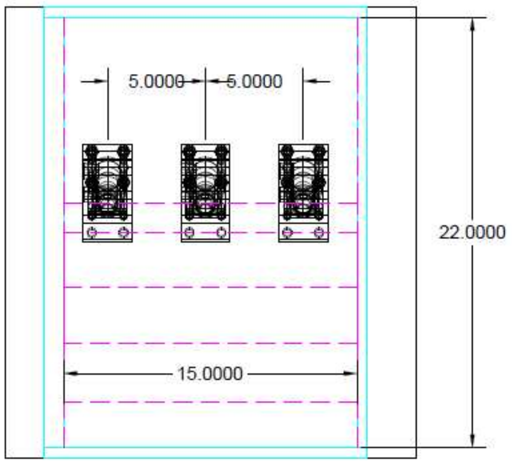
$$N_{qm} = N_q S_q d_q \boldsymbol{i_q}$$

$$N_{\gamma m} = N_\gamma S_\gamma \boldsymbol{i_\gamma}$$

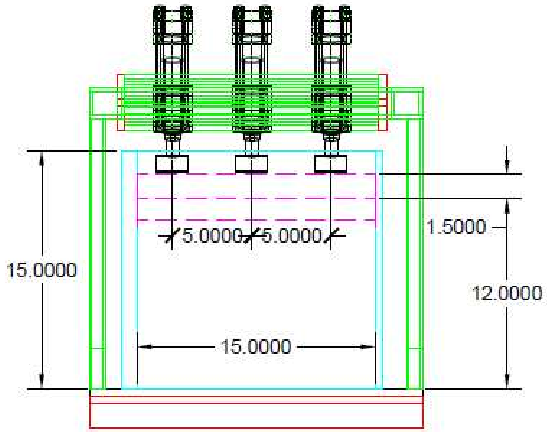
$$B' = B - 2 \cdot e_B$$



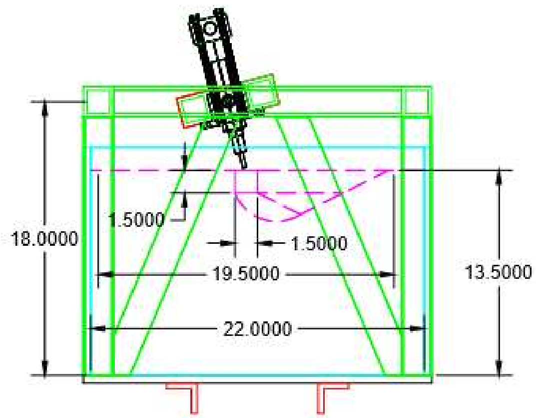
Isometric View



Plan View



Longitudinal Elevation
(Failure surface)



Transverse Elevation
(Failure surface)

UF UNIVERSITY of FLORIDA

PROPOSED TEST CONDITION-3 (L/B =1)

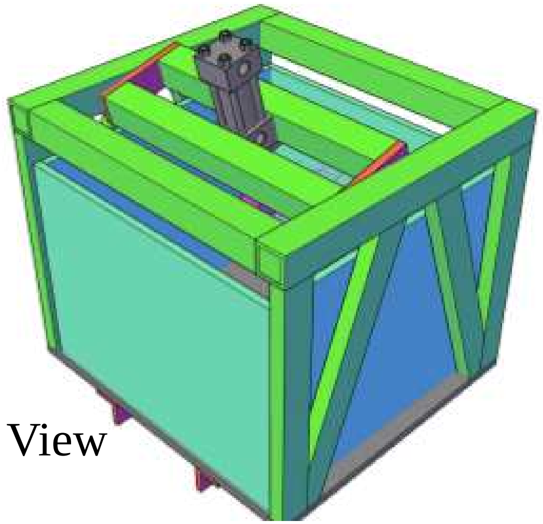
Cases A,B,C & D: Inclined & Eccentric

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

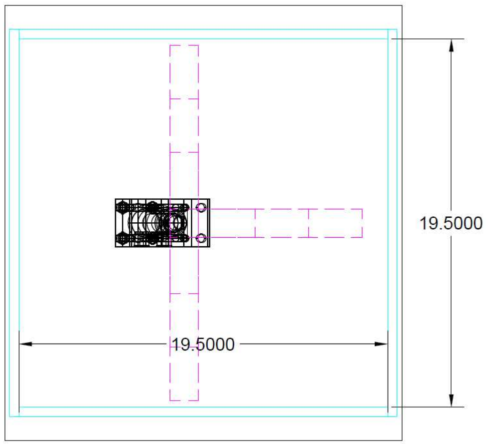
$$N_{qm} = N_q S_q d_q \boldsymbol{i_q}$$

$$N_{\gamma m} = N_\gamma S_\gamma \boldsymbol{i_\gamma}$$

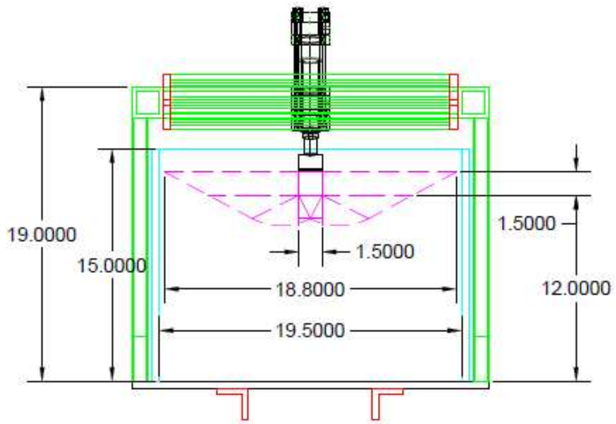
$$B' = B - 2 \cdot e_B$$



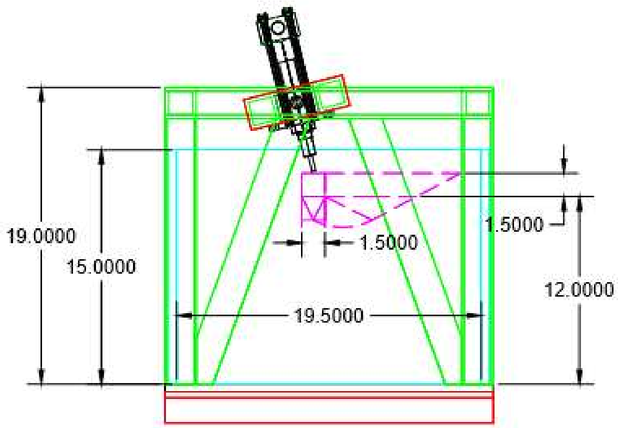
Isometric View



Plan View



Longitudinal Elevation
(Failure surface)



Transverse Elevation
(Failure surface)

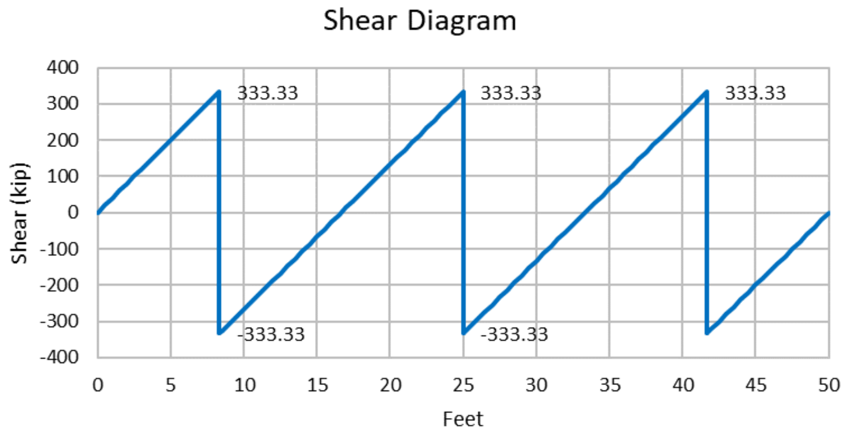
UF UNIVERSITY of FLORIDA

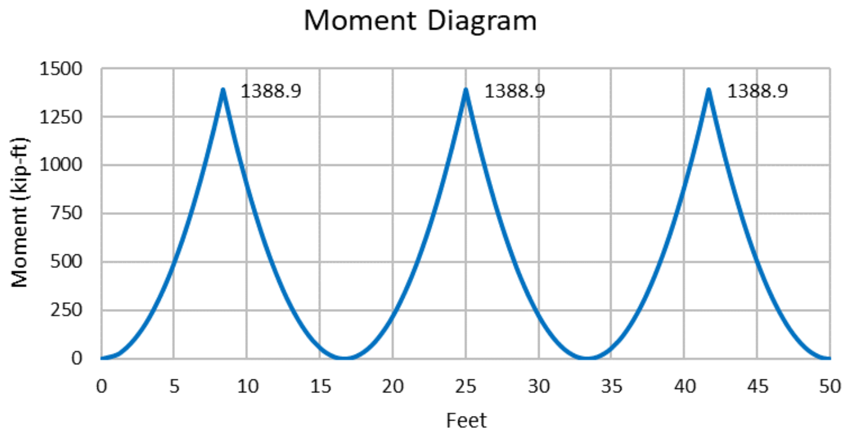
FOUNDATION DESIGN FOR STIFFNESS

TEST-2 Rectangle Foundation (L/B=10): q_u = 24 ksf

PROTOTYPE FOUNDATION:

- LRFD design
- Bearing capacity reduced by 2/3
- Bearing capacity = 8 ksf
- Effective moment of inertia determined for concrete
- Equivalent gross moment of inertia for aluminum
- Prototype aluminum foundation scaled to model size
- $E_c I_c = E_A I_A$





UF UNIVERSITY of FLORIDA

MODEL FOUNDATION DESIGN

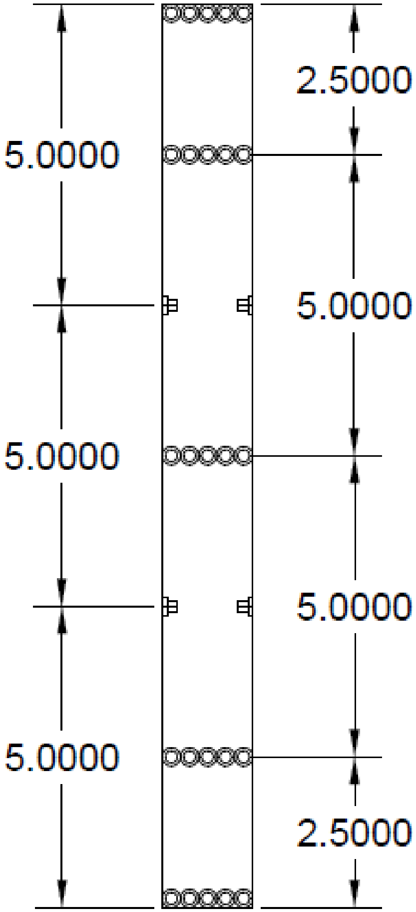
Model Foundation Size					
Type	L/B	Width-B (in)	Length- L (in)	Height (in)	# Pressure Transducers (proposed)
Square	1	1.5	1.5	0.75	5
Rectangle	10	1.5	15	0.75	5
Strip	20	1.075	21.5	0.5	3

LOAD ACTUATORS

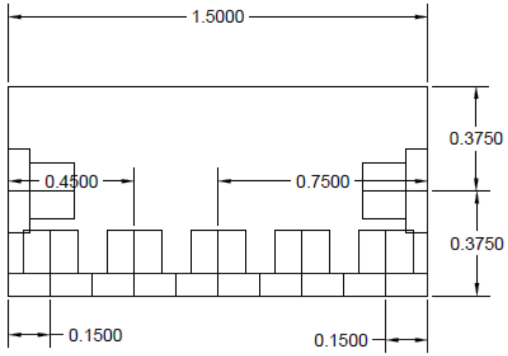
<table>
<tr><td colspan="5">HYDRUALIC LOAD ACUATORS</td></tr>
<tr><td colspan="4">Medium Duty (Max 1500 psi)</td><td>Applied pressure (1000 psi)</td></tr>
<tr><td>B (in)</td><td>Bore (in)</td><td>Rod Dia. (in)</td><td>Area (in^2)</td><td>Force (lb)</td></tr>
<tr><td rowspan="2">2.5</td><td rowspan="2">2.00</td><td>1.000</td><td rowspan="2">3.14</td><td rowspan="2">3142</td></tr>
<tr><td>1.375</td></tr>
<tr><td colspan="4">Heavy Duty (Max 3000 psi)</td><td>Applied pressure (2000 psi)</td></tr>
<tr><td>B (in)</td><td>Bore (in)</td><td>Rod Dia. (in)</td><td>Area (in^2)</td><td>Force (lb)</td></tr>
<tr><td rowspan="2">2.5</td><td>1.50</td><td>0.63</td><td rowspan="2">1.77</td><td rowspan="2">3534</td></tr>
<tr><td>1.50</td><td>1.00</td></tr>
</table>

PRESSURE TRANSDUCER PLACEMENT

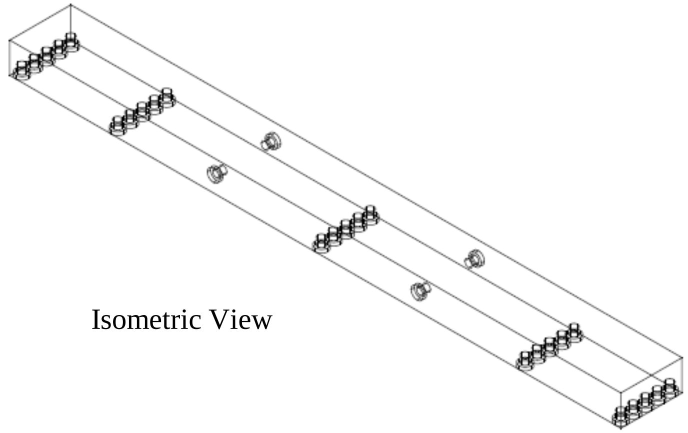
TEST-2 (L/B=10)



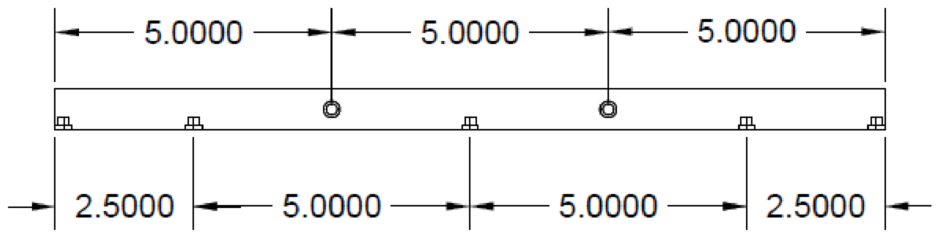
Plan View



Transverse Elevation



Isometric View

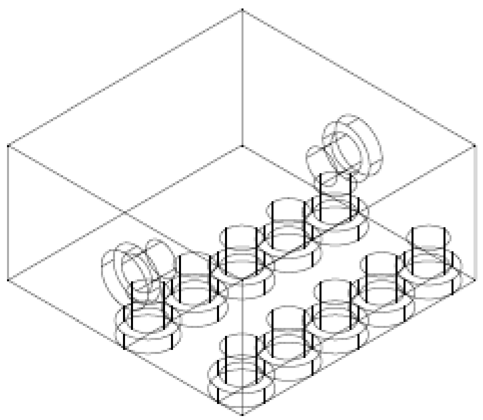


Longitudinal Elevation

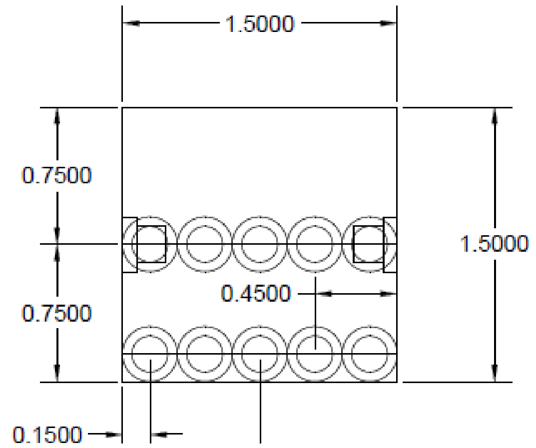
UF UNIVERSITY of FLORIDA

PRESSURE TRANSDUCER PLACEMENT

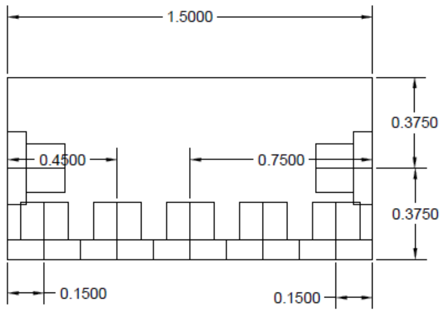
TEST-3 (L/B=1)



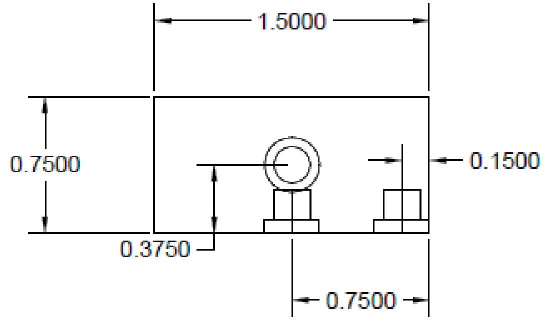
Isometric View



Plan View



Transverse Elevation



Longitudinal Elevation

UF UNIVERSITY of FLORIDA

Thank You