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

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FDOT Project Manager: Larry Jones

Principal Investigator: Scott Wasman, Ph.D.

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

Research Assistant: Stephen Crawford

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PRESENTATION OUTLINE

1) Introduction
2) Background
3) Objectives
4) Research Tasks
5) Research Conclusions
6) Recommendations
7) Project Benefits
8) Future Research

INTRODUCTION

Numerous structures have been built on shallow foundations subjected to combined axial and lateral loads (MSEW, Cast in place walls, etc.).

In general, there isn't a consensus among state practitioners as to if and how combined axial/lateral loads should be included in predictions of bearing capacity.

BACKGROUND

1) AASHTO Specifications (10.6.3.1.2) make allowance for load inclination
   - Meyerhof (1953), Brinch Hansen (1970), and Vesić (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

OBJECTIVES

- Collect data of L/B, embedment, eccentricity, lateral /axial load combinations, and sand densities of shallow foundations in Florida
- Select 1 average B, 2 loading locations, 3.5 lateral/axial load ratios, and 2 sand densities for centrifuge testing (56 cases x 2 repetitions = 112 total tests)
- Repeat 3 of the above cases with embedment = B
- Build load frame for centrifuge tests to accommodate all cases
- Conduct centrifuge tests of all cases and obtain the measured ultimate bearing capacity, measured lateral/axial load inclinations, and eccentricity factors
- Compare measured results with AASHTO methods and other existing methods
- Identify which combination of bearing factors are representative and recommended for FDOT

RESEARCH TASKS

TASKS

1) Task-1: Survey of FDOT shallow foundation design and construction practices

2) Task-2: Construct centrifuge container and load frame for variable embedment, eccentricity and load inclination test on shallow foundations

3) Task-3: Centrifuge testing of shallow foundations

4) Task-4: Comparison of AASHTO, and published bearing capacity factors with centrifuge results

5) Task-5: Draft final and closeout teleconference

6) Task-6: Final report.

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TASK 1

Survey of FDOT Shallow Foundation Design and Construction Practice

Online survey of FDOT engineers showed:

- Commonly used for single and multi-story structures, retaining walls, and bridges
- Less commonly used for sign structures, toll gantry, sounds walls, and light poles
- Widths, B, ranges from 3 – 12 ft, with most 3 and 8 ft as the most common
- L/B = 1 was most common followed by 2, 6, then 10
- Embedment = 4 ft was most common, followed by 3, 2, and 5 ft
- Only eccentricity provided was B/6
- Lateral/axial load inclination factor has been used in design; however, only 2 ratios were provided: 0.1 and 0.25
- A3 and A-2-4 were most common soil types used beneath foundation
- Soil most frequently compacted to 100% max dry density, less frequently to 95%

TASK 1

FDOT recommends analysis of shallow foundations be done in accordance with AASHTO LRFD Bridge Design Specifications

General bearing capacity equation recommended by AASHTO (2016)

$$q_n = \cancelto{0}{c}N_{cm} + \gamma D_f N_{qm} \cancelto{1}{C_{wq}} + 0.5\gamma B N_{\gamma m} \cancelto{1}{C_{w\gamma}} = \gamma D_f N_{qm} + 0.5\gamma B N_{\gamma m}$$

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

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

$N_q = e^{\pi \tan \phi_f} tan^2\left(45^\circ + \frac{\phi_f}{2}\right)$ (Reissner, 1924)

$N_\gamma = 2(N_q + 1) tan(\phi_f)$ (Vesić, 1973)

B = Foundation width

γ = Soil unit weight

D_f = Embedment depth

ϕ_f = Soil friction angle

S_q, S_γ = Shape correction factor (Vesić, 1973)

d_q = Depth correction factor

i_q, i_γ = Inclination correction factors (Vesić, 1973)

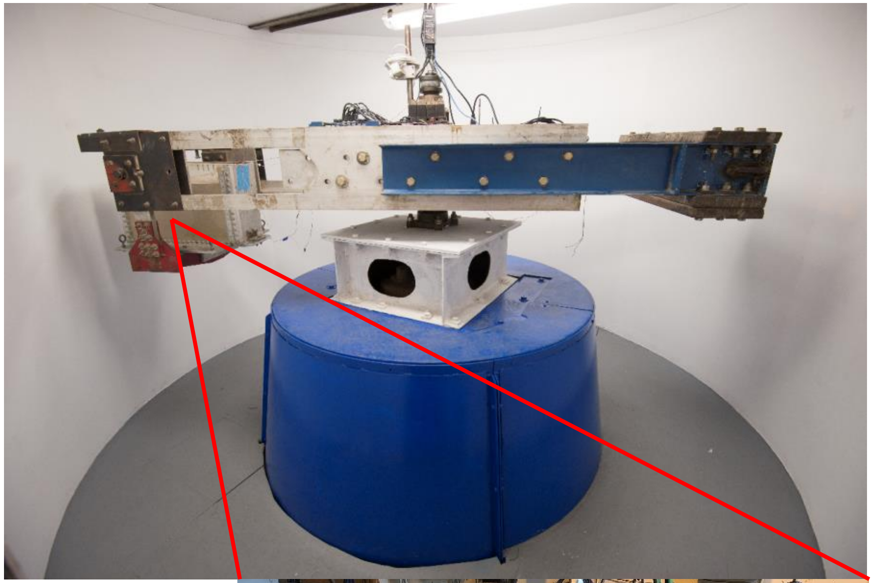
TASK 2: GEOTECHNICAL CENTRIFUGE

- 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 ($\sigma_{model}/\ \sigma_{prototype} = 1$)
- Scale other properties for testing
  ex. $L_{model}/\ L_{prototype} = 1/N$

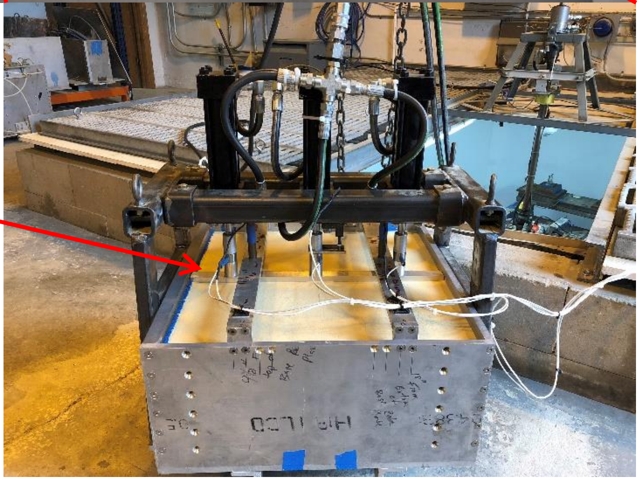
Property	Scale Factor
Length	1/N
Area	$1/N^2$
Volume	$1/N^3$
Force	$1/N^2$
Unit Weight	N
Stress	1
Strain	1

- In flight load application and monitoring of foundation response (displacement and soil pressure)

3 meter diameter centrifuge



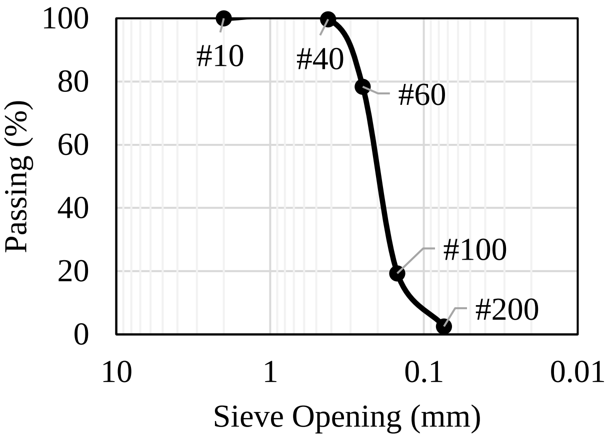
1/36th scale model: Shallow foundation L/B = 20

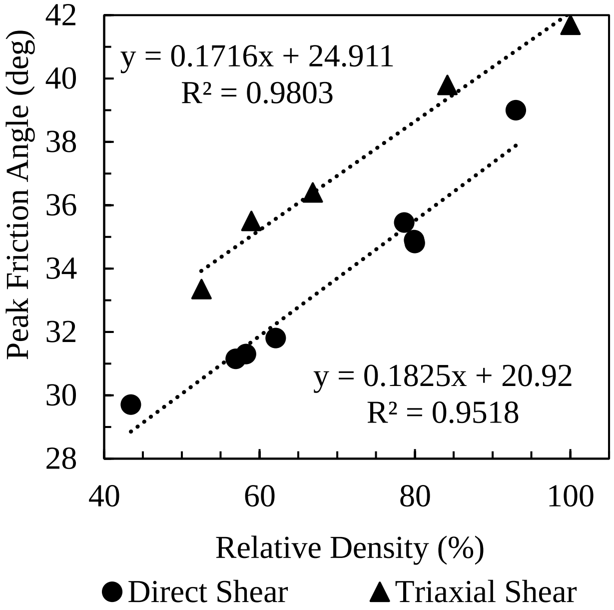


TASK 2: TEST SOIL

A-3 (Fine Sand)

- 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_{min}: 0.53
- e_{max}: 0.84
- Subangular-subrounded
- USCS: SP





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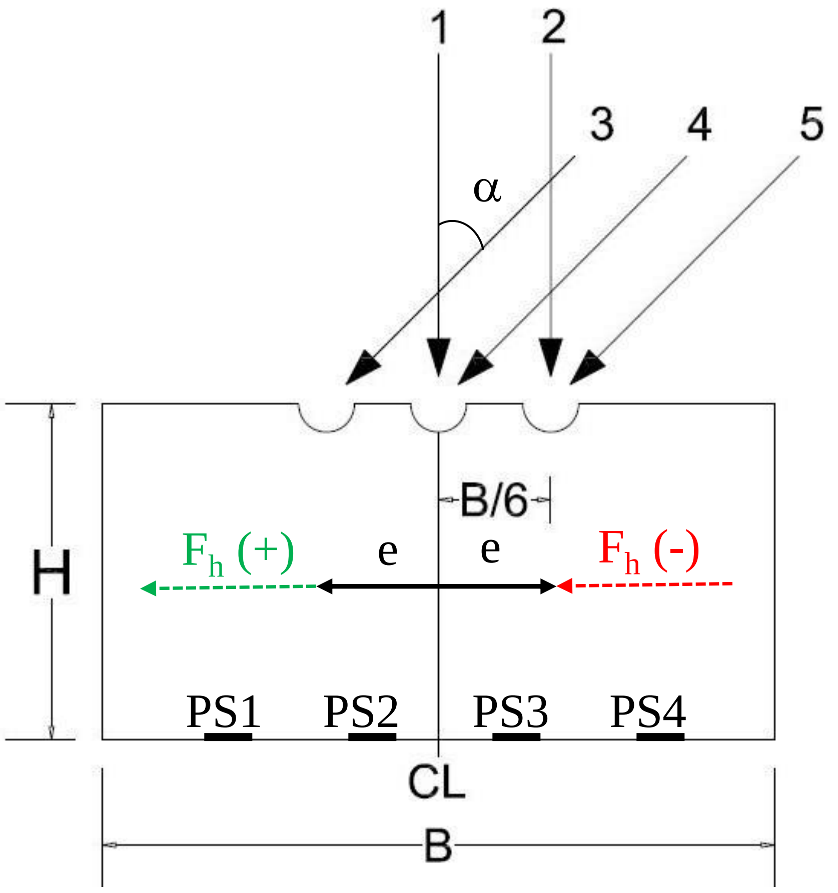
LOAD CASE SCENARIOS

Load Case Scenarios

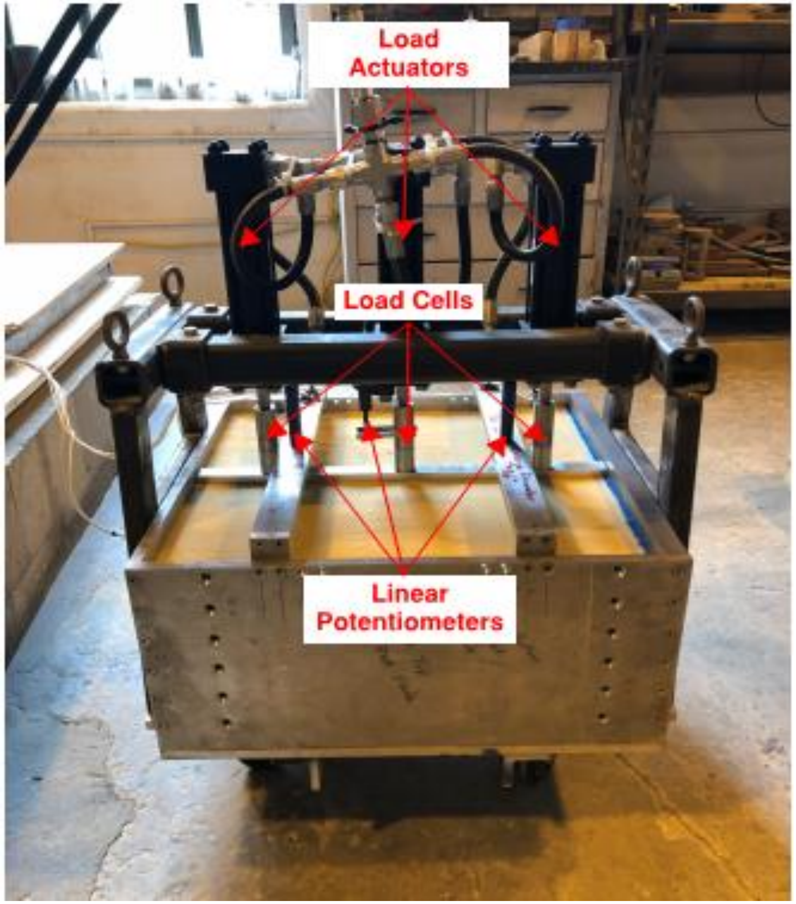
- **Load Case-1: Vertical-centric**
- **Load Case-2: Vertical-eccentric**
- **Load Case-3: Inclined-eccentric, horizontal component in direction of eccentricity, positive (+)**
- **Load Case-4: Inclined-centric**
- **Load Case-5: Inclined-eccentric, horizontal component opposite direction of eccentricity, negative (-)**



B = width, H = Height, α = angle of inclination, 5.7° and 14° (not to scale) and eccentricity = B/6.

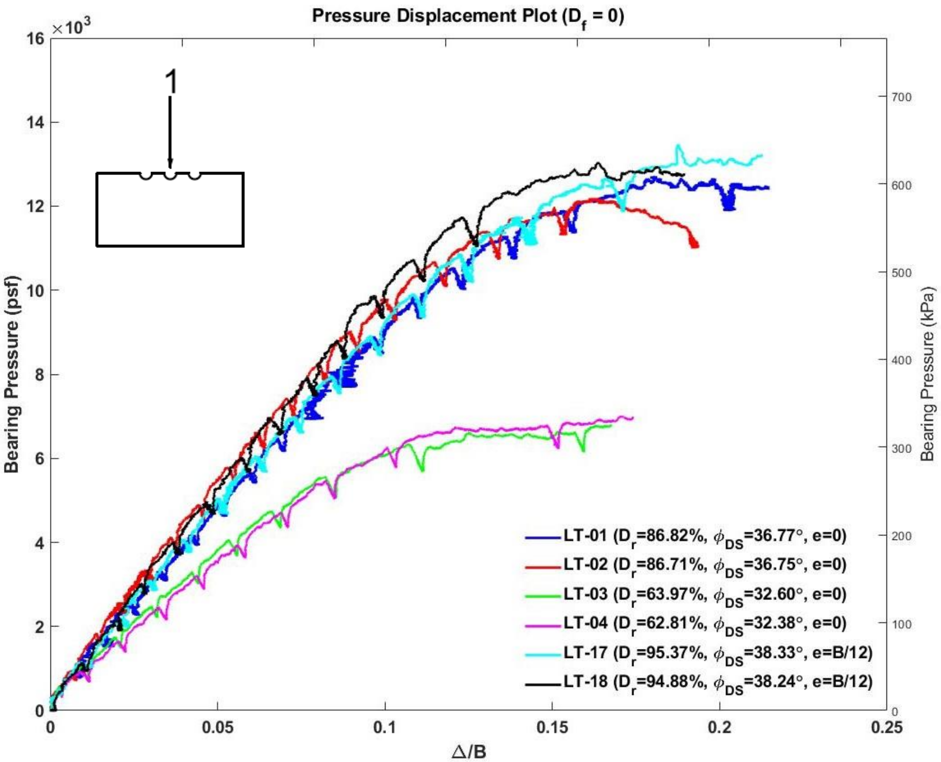
TASK 2: CENTRIFUGE CONTAINER AND LOAD FRAME

Model Parameters			
L/B Ratio	20	10	1
Interior container width (in.)	20		
Interior container length (in.)	20	15	20
Interior container depth (in.)	9.5		
Soil depth (in.)	8.5		
Scale factor (N)	36	40	40
Foundation material	Alum.		
Model width (in)	1	1.5	1.5
Model length (in.)	20	15	1.5
Model thickness (in.)	0.5	0.75	0.75
# of Hyd. load actuators	3	3	1
# of Omega load cells	3	3	1
# of BEI linear potentiometers	3	3	1
# of Pressure sensors	0	4	4



- All prototypes to be tested:
  - D_r of medium dense and very dense A3 fine sand
  - D_f of 0 and 0.5B
  - Vertical centric loads
- L/B = 20 tests only vertical centric loads for N_γ and N_q, d_q, and d_γ with negligible shape effects (S_q, S_γ)
- L/B = 10 and 1 all load combinations

TASK-3: PRESSURE vs. DISPLACEMENT PLOT
Strip Footing-MD & VD (D_f=0 & D_f=0.5B)

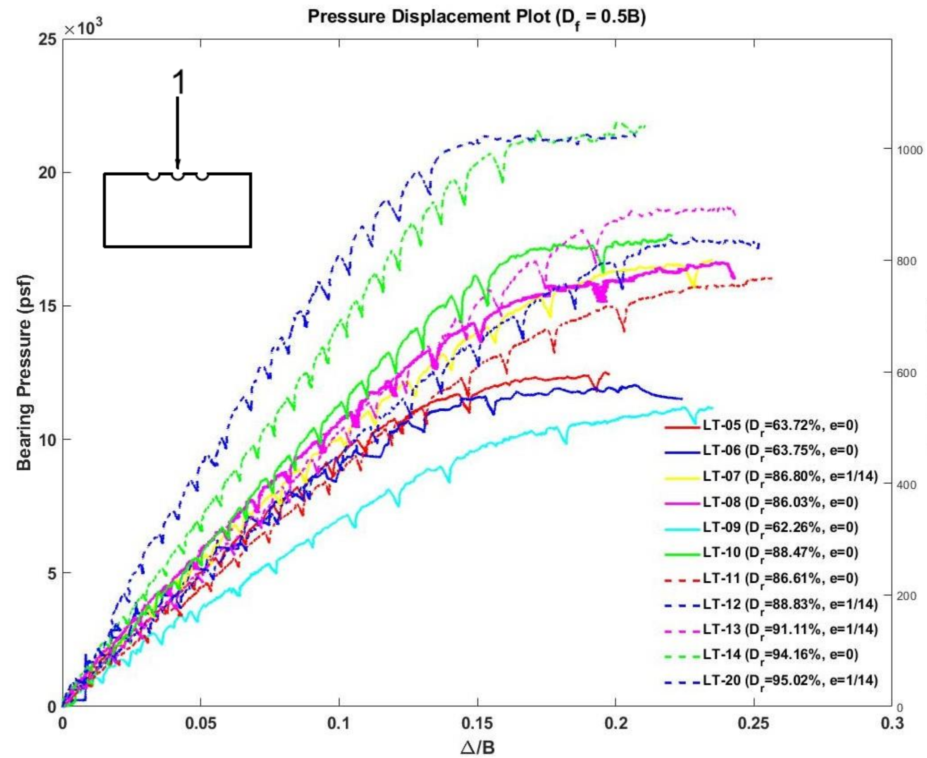


Bearing Capacity Equation:

$$q_n = 0.5\gamma B N_\gamma$$

Bearing Capacity Equation:

$$q_n = \gamma D_f N_q d_q + 0.5\gamma B N_\gamma$$



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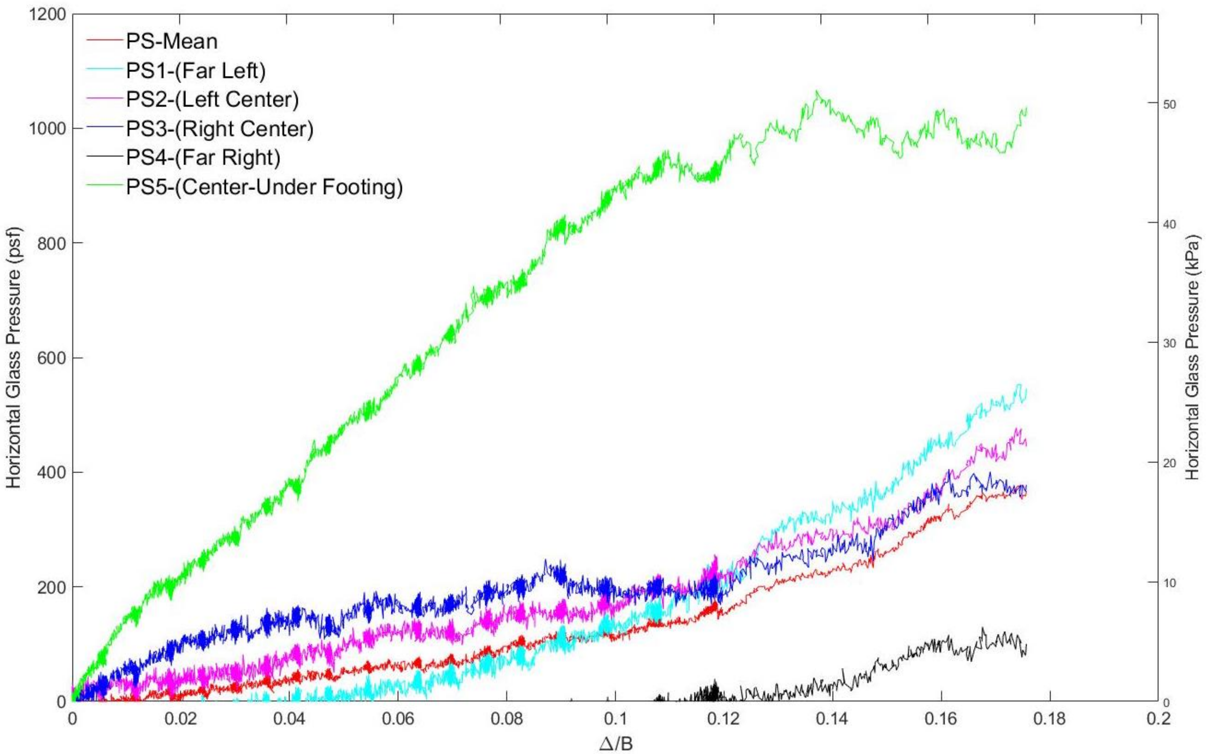
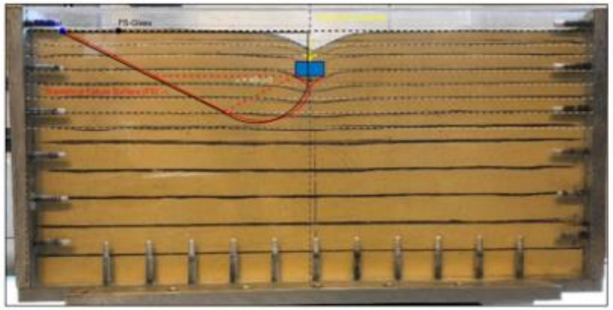
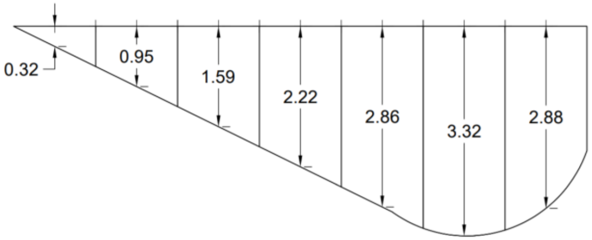
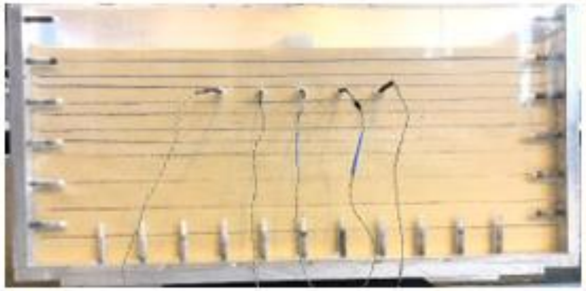
TASK-3: EXPERIMENTAL VERIFICATION
Boundary Conditions

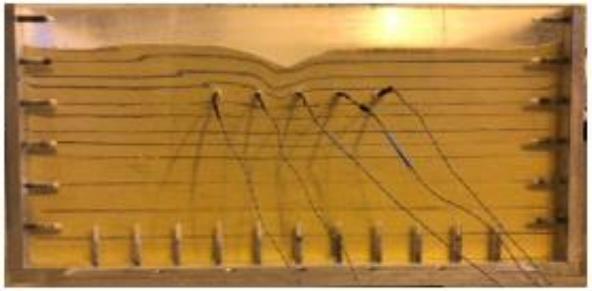
$$\tau = \sigma_h tan(\delta) \;\therefore\; \sigma_h = K_o \gamma h$$



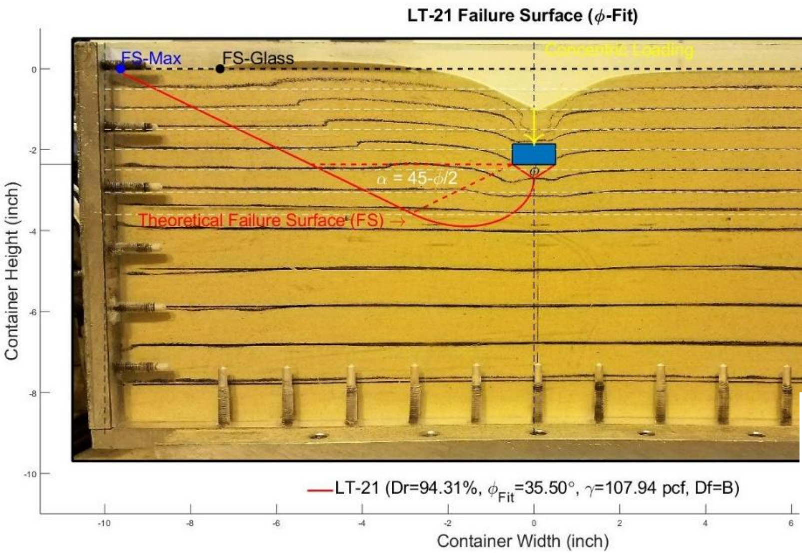


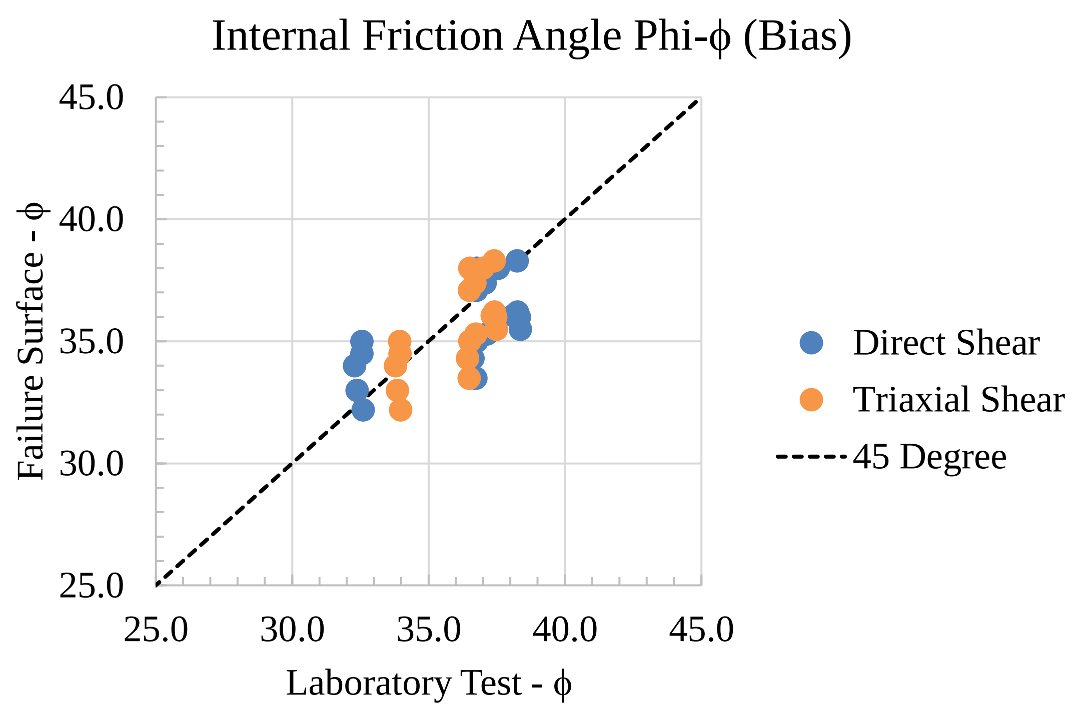






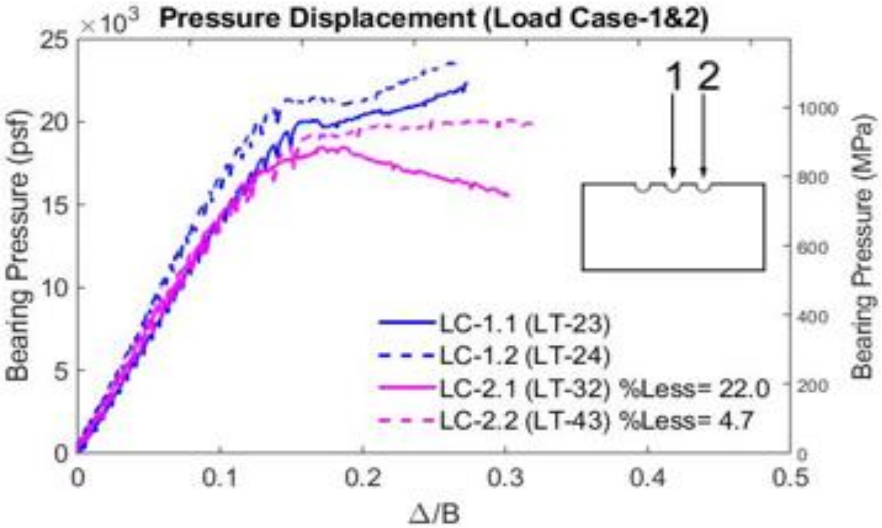
TASK-3:EVALAUTION OF ϕ

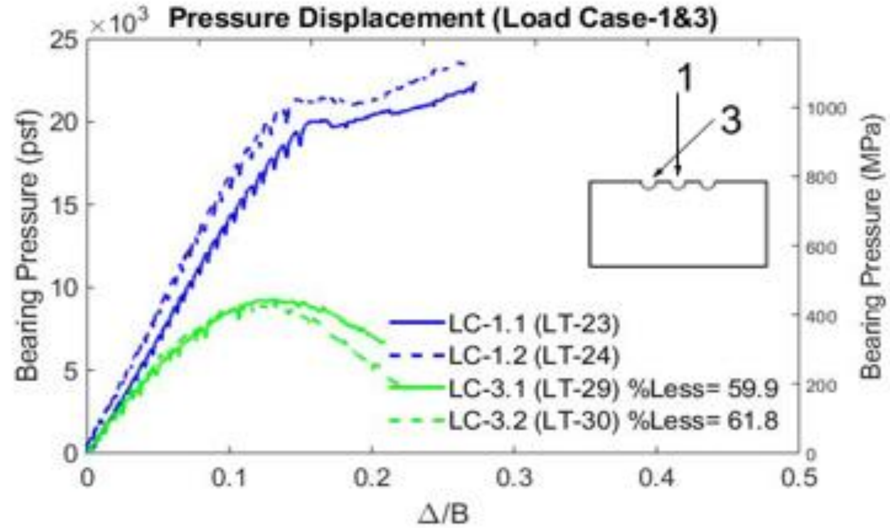


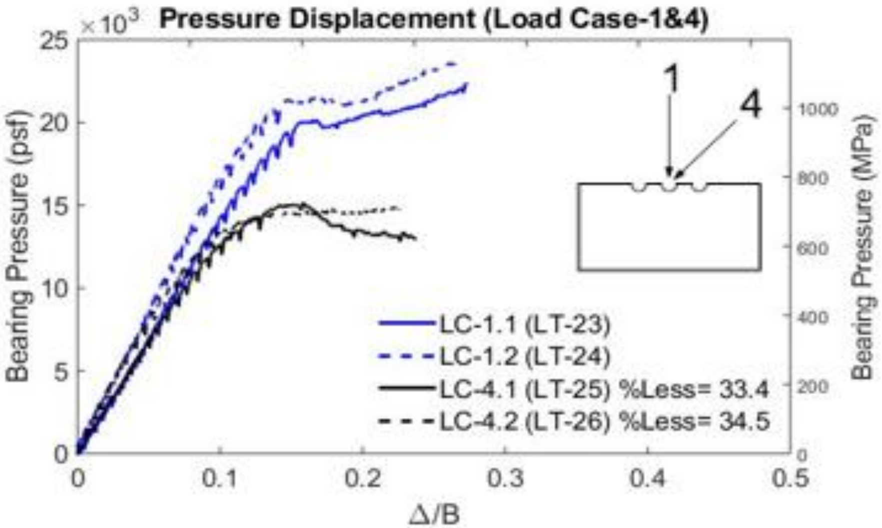


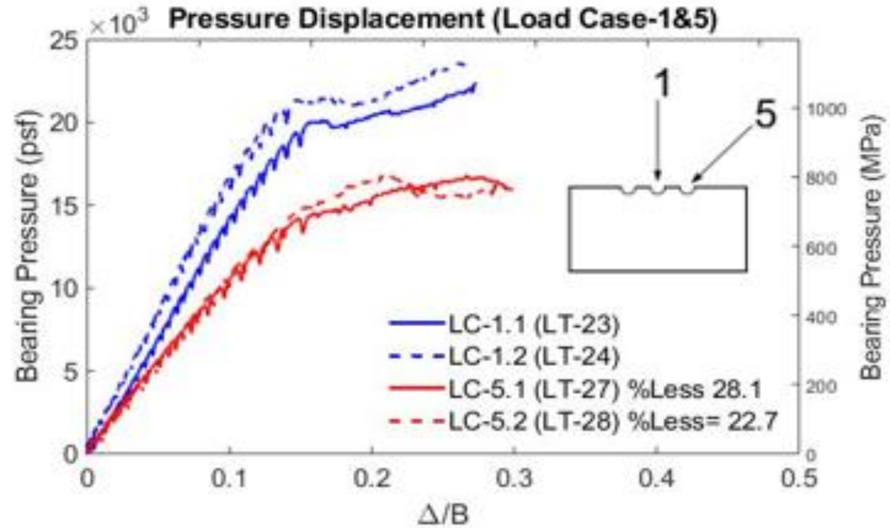
TASK-3: PRESSURE vs. DISPLACEMENT PLOT
Rectangular-VD (Df=0 and L/A=0.10)

Bearing Capacity Equation: $q_n = 0.5\gamma B N_\gamma S_\gamma \boldsymbol{i_\gamma}$

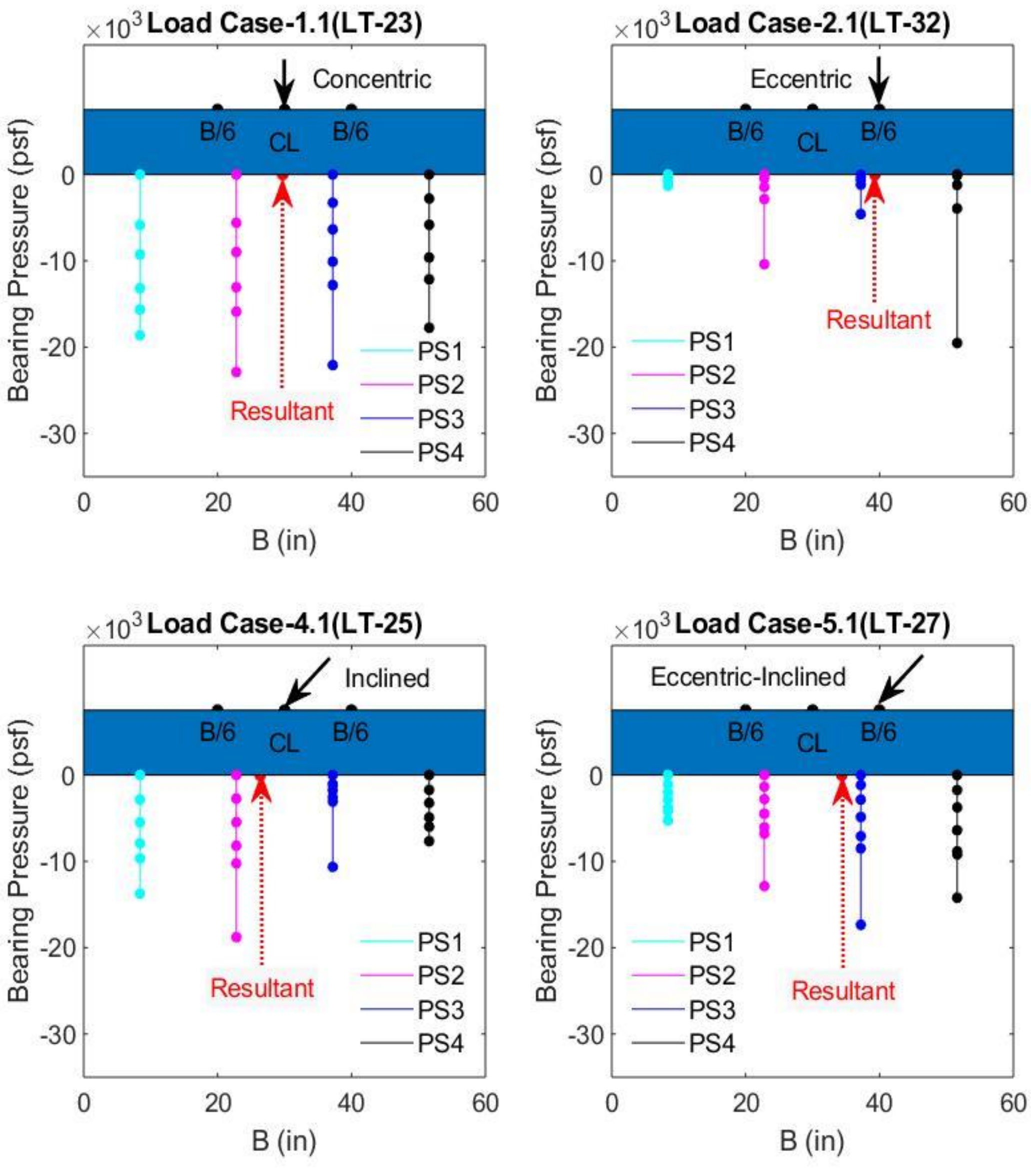


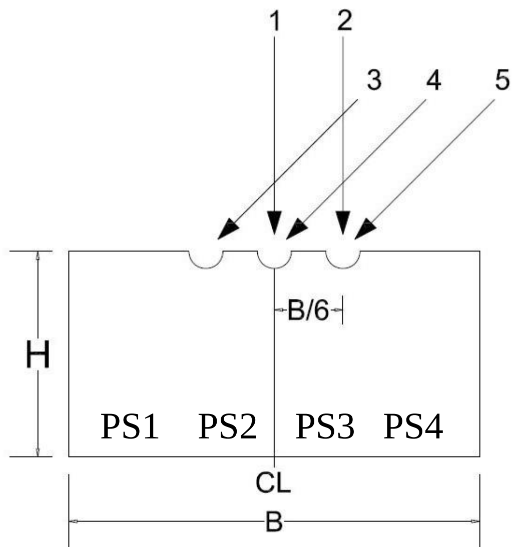






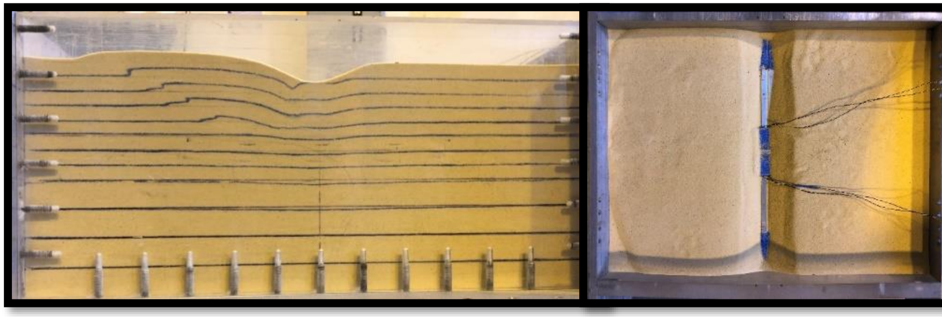
TASK-3: PRESSURE vs. DISTRIBUTION PLOT
Rectangular-VD (Df=0 and L/A=0.10)





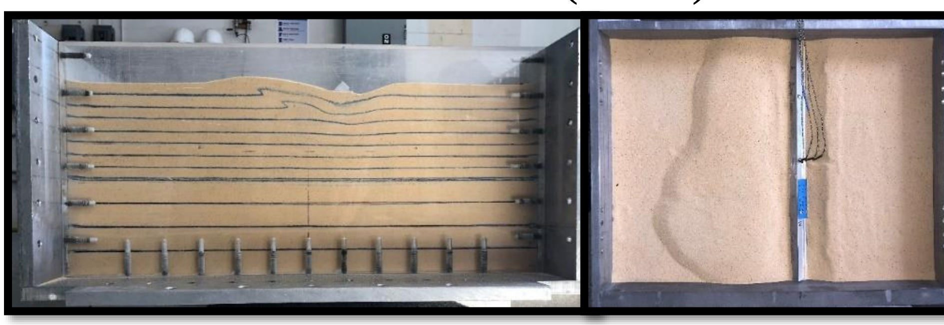
TASK-3: FAILURE SURFACE IMAGES- Rectangular-VD (Df=0 and L/A=0.10)

Load Case -1 (LT-24) Df=0

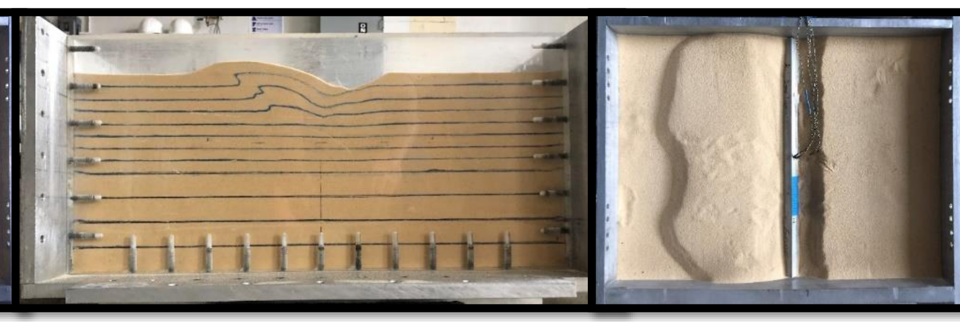


Load Case -4 (LT-26)

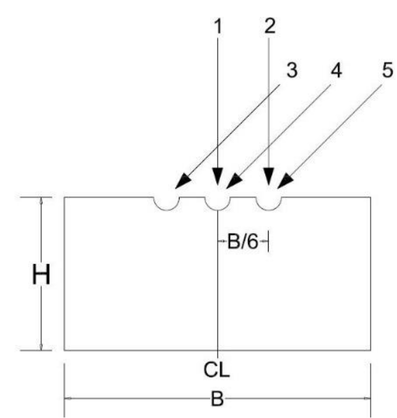
Load Case -2 (LT-31)



Load Case -5 (LT-28)

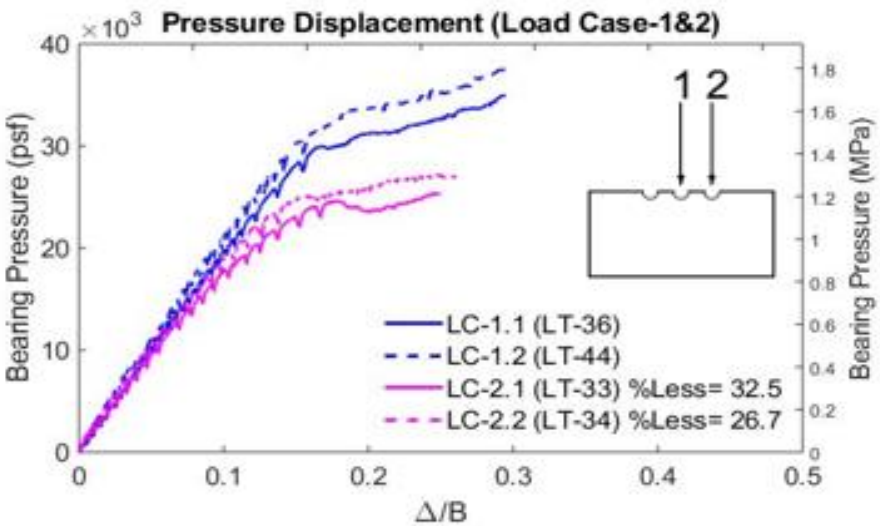


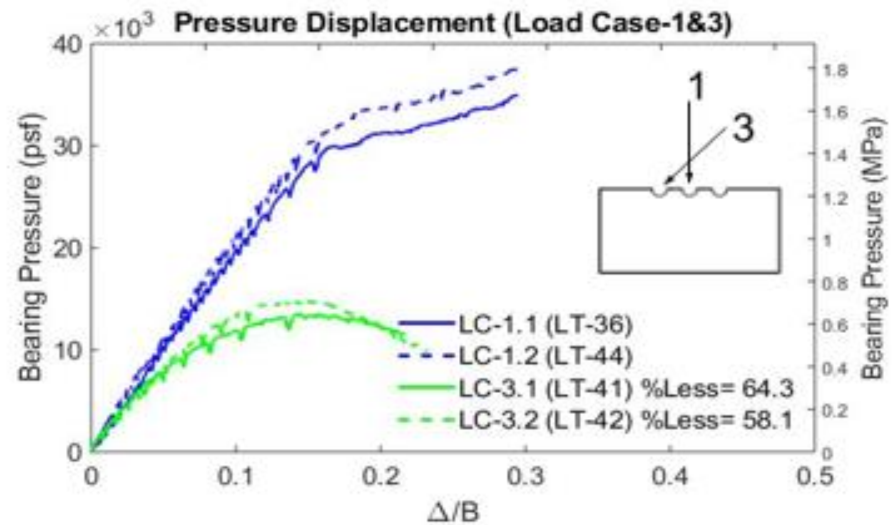
Load Case -3 (LT-30)

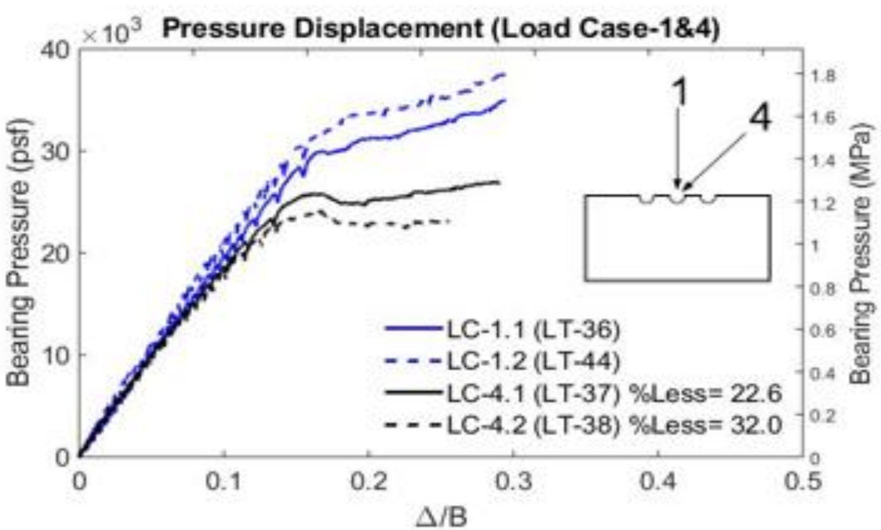


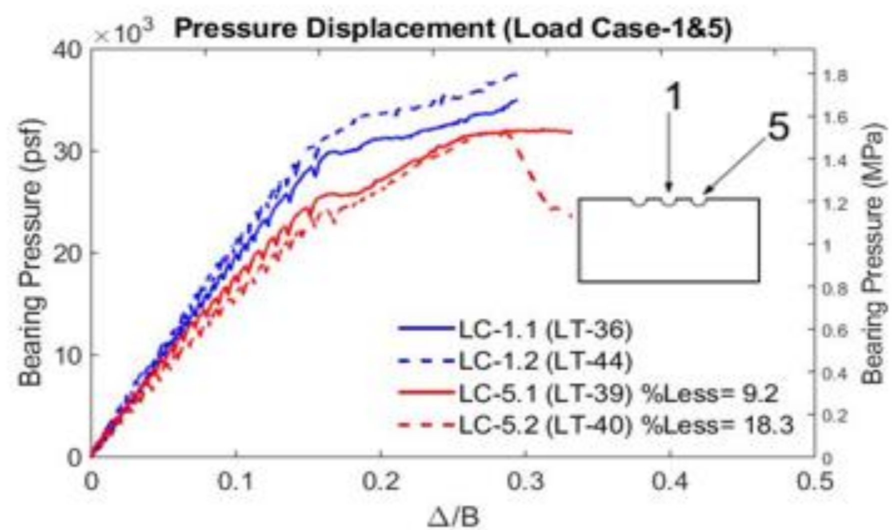
TASK-3: PRESSURE vs. DISPLACEMENT PLOT
Rectangular-VD (Df=0.5B and L/A=0.10)

Bearing Capacity Equation: $q_n = \gamma D_f N_q S_q d_q i_q + 0.5\gamma B N_\gamma S_\gamma i_\gamma$



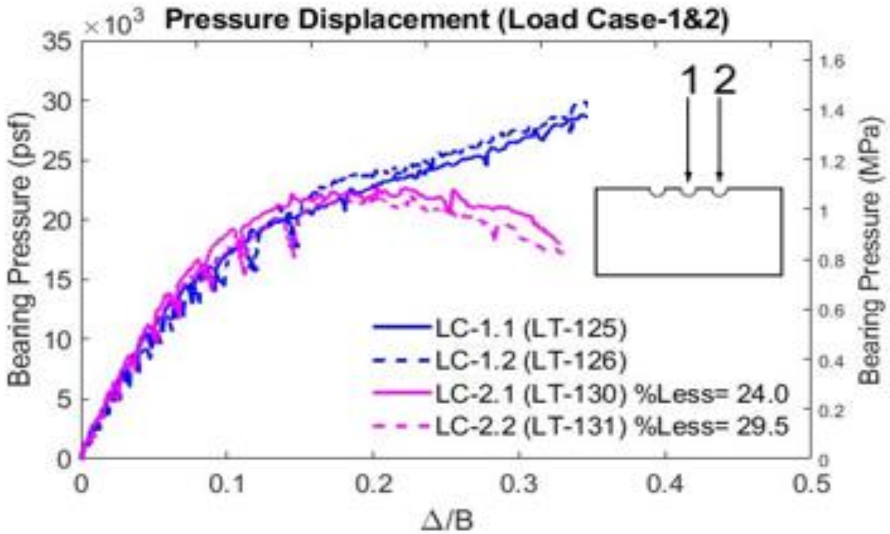


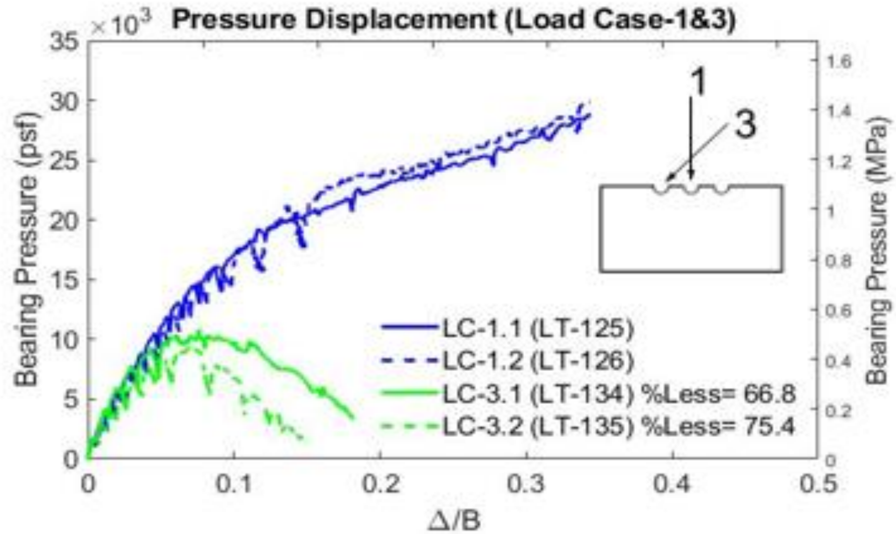


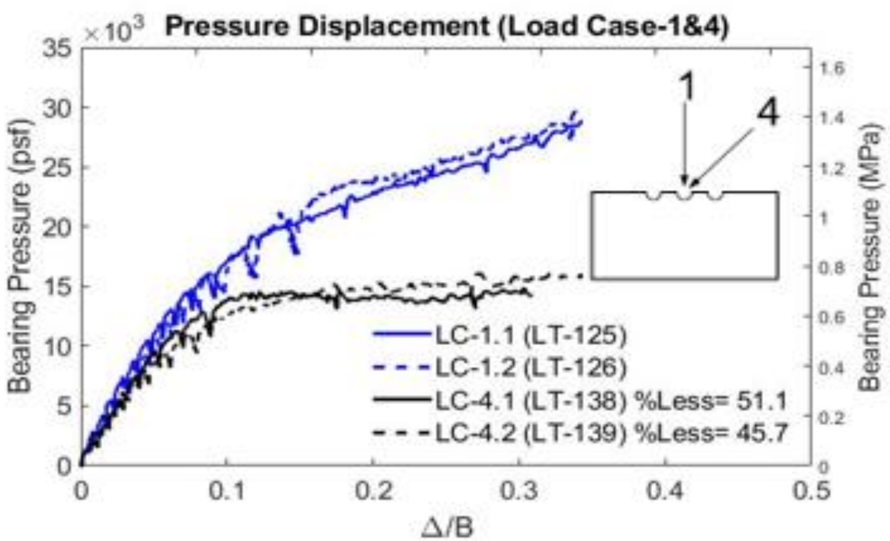


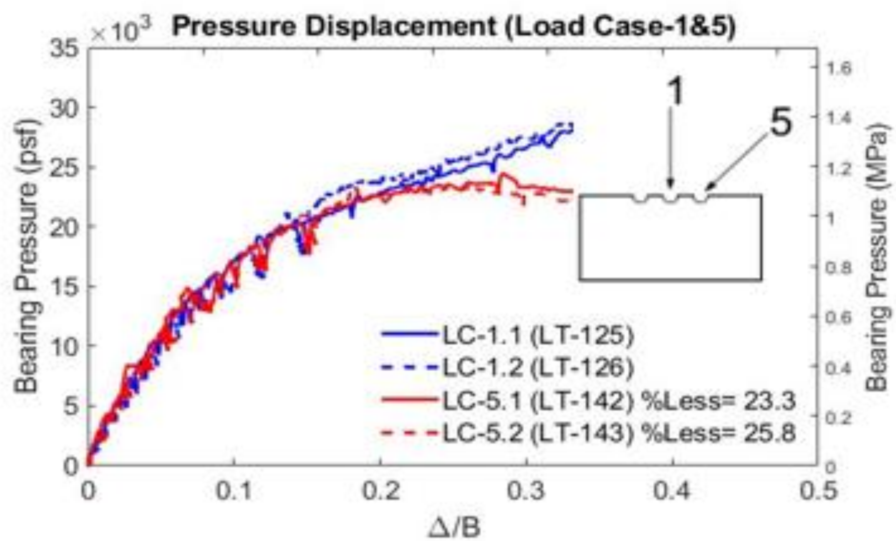
TASK-3: PRESSURE vs. DISPLACEMENT PLOT
Square-VD (Df=0 and L/A=0.10)

Bearing Capacity Equation: $q_n = 0.5\gamma B N_\gamma S_\gamma \boldsymbol{i_\gamma}$







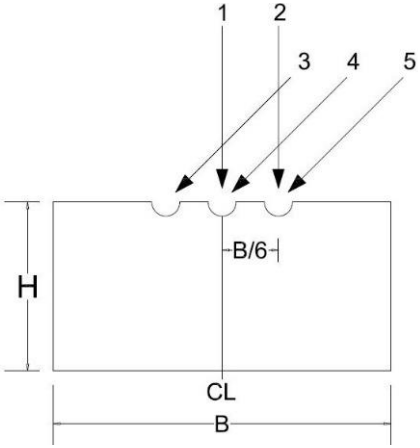


TASK-3: FAILURE SURFACE IMAGES
Square Footing- (Df=0 and L/A=0.10)

Load Case -1

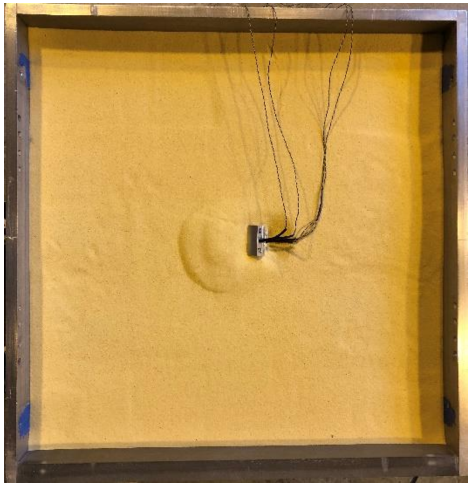
Load Case -2

Load Case -3



Load Case -4

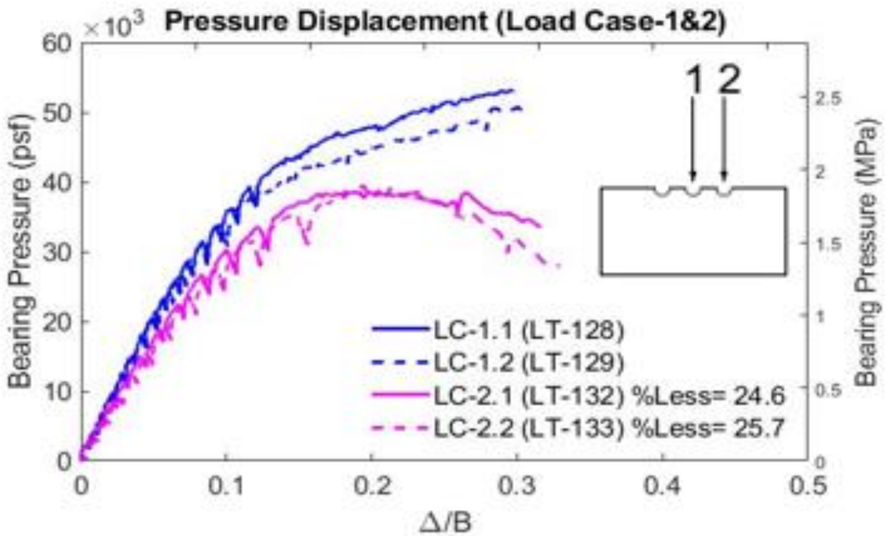
Load Case -5

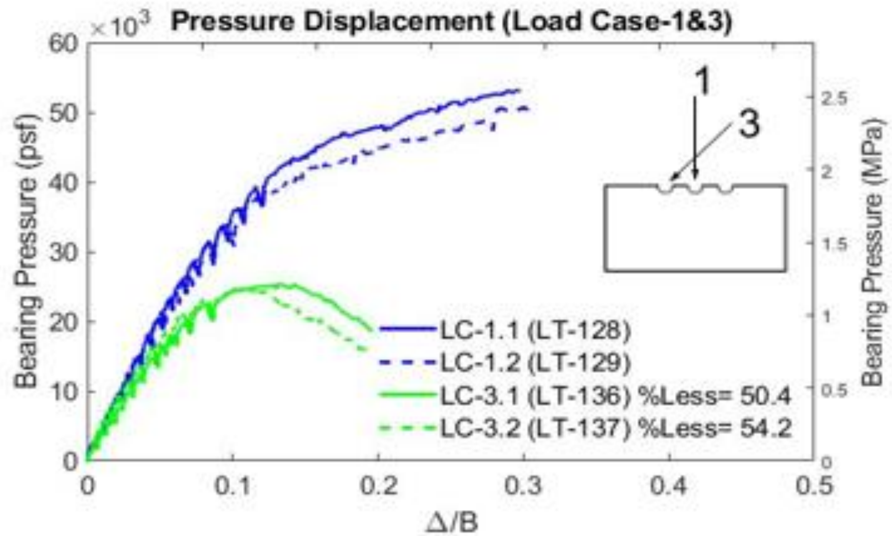


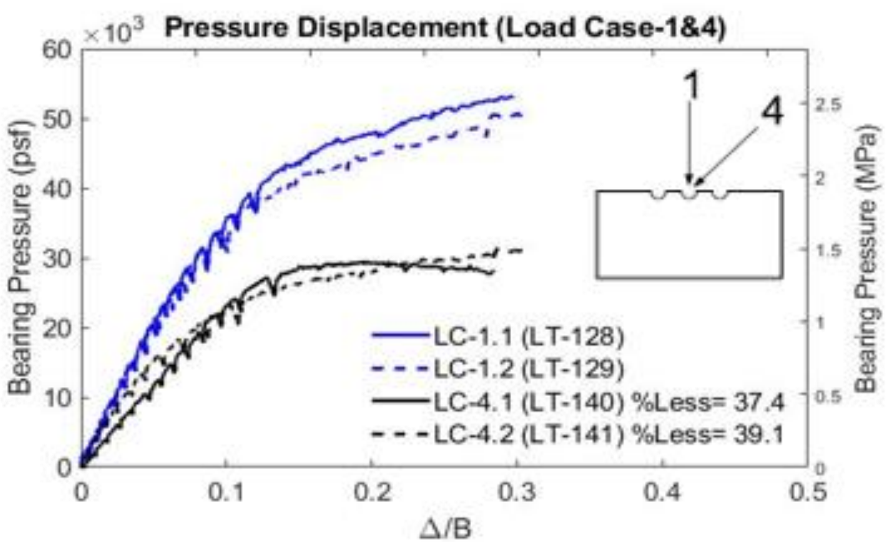
Load Case -5

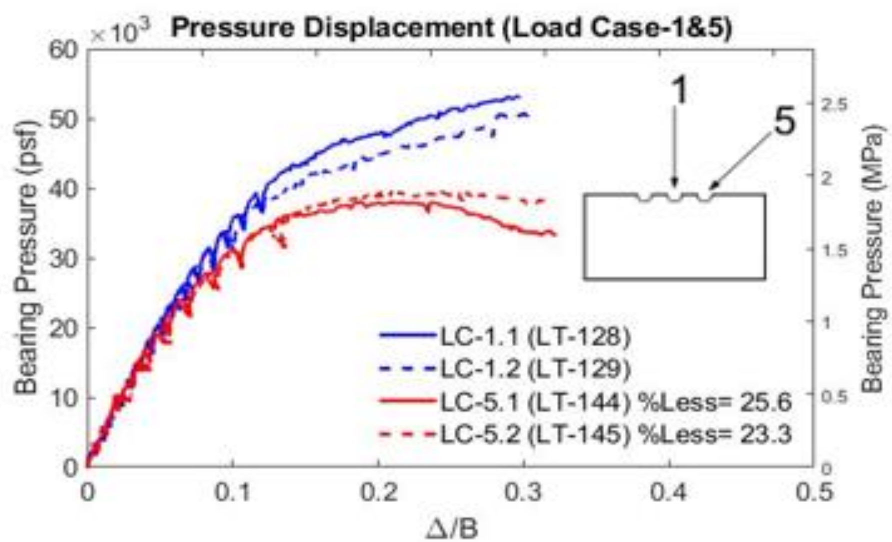
TASK-3: PRESSURE vs. DISPLACEMENT PLOT
Square-VD (Df=0.5B and L/A=0.10)

Bearing Capacity Equation: $q_n = \gamma D_f N_q S_q d_q i_q + 0.5\gamma B N_\gamma S_\gamma i_\gamma$



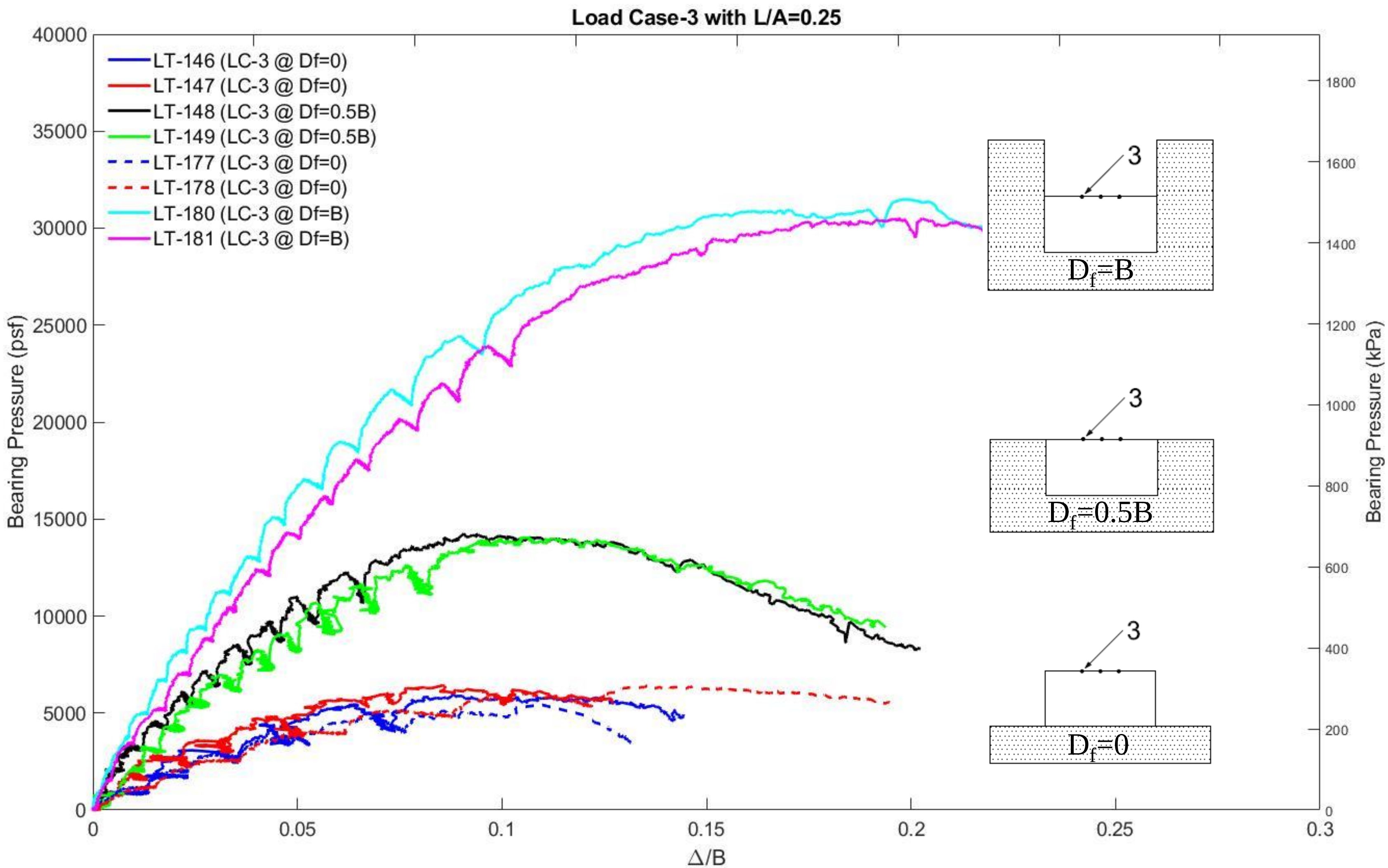






TASK-3: PRESSURE vs. DISPLACEMENT PLOT
Square-VD (Df=B with L/A=0.25)

Bearing Capacity Equation: $q_n = \gamma D_f N_q S_q d_q i_q + 0.5\gamma B N_\gamma S_\gamma i_\gamma$



TASK-4: CONCENTRIC LOADING ON STRIP FOUNDATION

FOR THE PURPOSE OF THIS STUDY:

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

STRIP FOUNDATION AT SURFACE:

$q_n = 0.5\gamma B N_{\gamma m}$

- $D_f = 0$
- Measured $N_{\gamma m}$ Term
- L/B = 20 the shape factors s_q and s_γ are 1.04 and 0.98 (<4% error)

STRIP FOUNDATION AT $D_f = B$:

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

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

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TASK-4: LOADING ON RECTANGULAR & SQUARE FOUNDATION

RECTANGLE & 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

RECTANGLE & SQUARE FOUNDATION 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
- $B' = B - 2 \cdot e_B$

RECTANGLE & 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

TASK-4: BEARING CAPACITY FACTORS- N_q & N_γ

Bearing Capacity Factor for Overburden:

Reissner, (1924): AASHTO recommended:

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

Bearing Capacity Factor for Soil Unit Weight (Analytical Derivation):

Vesić (1973): AASHTO recommended:

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

Zhu et al. (2001):

$$N_\gamma = 2\left(N_q + 1\right) tan\left(1.07\phi_f\right)$$

Bearing Capacity Factor for Soil Unit Weight (Empirical Relationships):

Meyerhof (1963):

$$N_\gamma = \left(N_q - 1\right) \tan\left(1.4\phi_f\right)$$

Hansen (1970):

$$N_\gamma = 1.5\left(N_q - 1\right) tan\left(\phi_f\right)$$

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TASK-4: SHAPE & DEPTH FACTORS (L/B=20)

Shape Factors considered in analysis:

(L/B=20 < 4% error for the factors used)

Reference	S_q	S_γ
DeBeer (1970) as modified by Vesić (1973)	1.04	0.98
EuroCode (2005)	1.03	0.99
Meyerhof (1963)	1.02	1.02
Perau (1995, 1997)	1.06	0.95
Zhu and Michalowski (2005)	1.17	1.00

Depth Factors considered in analysis:

Hansen (1970):

$$d_q = 1 + 2\tan\phi_f \cdot \left(1 - \sin\phi_f\right)^2 \left(\frac{d_f}{B}\right) \text{ for } \frac{d_f}{B} \leq 1$$

$$d_\gamma = 1$$

Meyerhof (1963)*

$$d_q = 1 + 0.1\sqrt{K_p}\left(\frac{d_f}{B}\right) \text{ for } \phi_f > 10^\circ$$

$$d_\gamma = d_q$$

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TASK-4: MEASURED N_q and N_γ (L/B=20)

$$q_u = \gamma(D_f + \delta)N_q + (1/2)\gamma B N_\gamma$$

or in a normalized form as

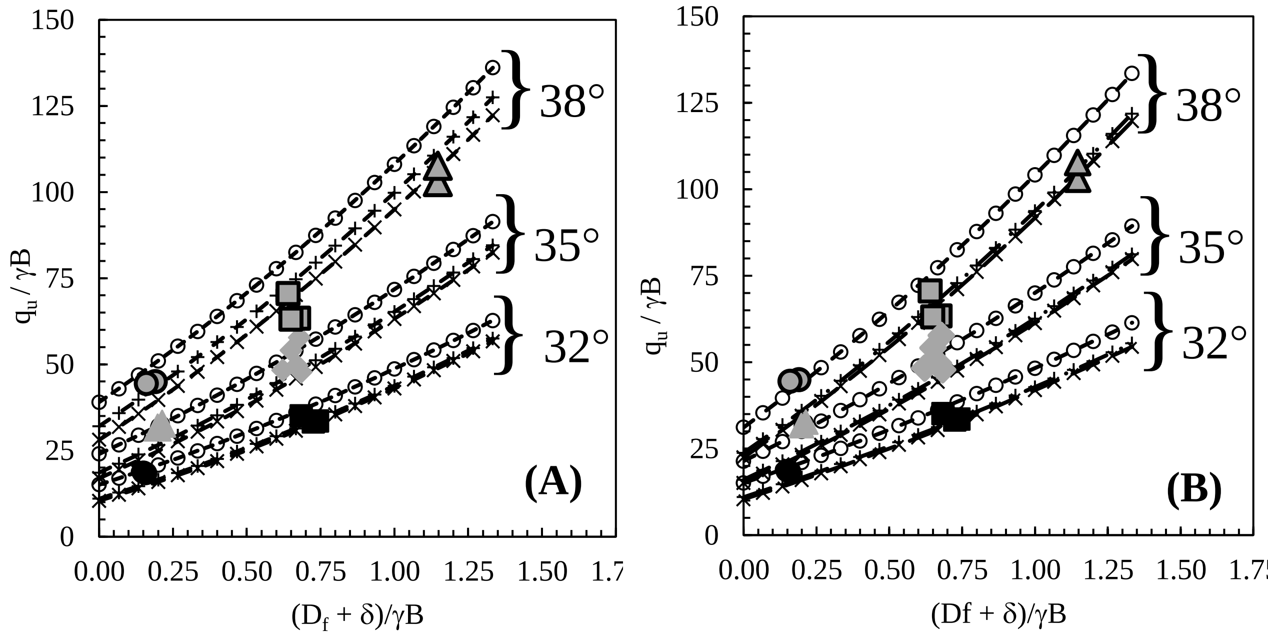
$$\frac{q_u}{\gamma B} = \left(\frac{D_f + \delta}{\gamma B}\right)N_q + (1/2)N_\gamma$$

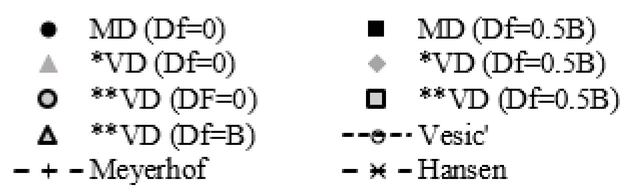
$$y = m\,x + b$$

N_q = slope

N_γ = 2 * intercept

Density	Nq (slope)	Nγ (2 * intercept)	Reissner N_q	Vesić N_γ	Hansen N_γ
MD	27.29	28.87	24.88	33.10	22.91
VD*	39.03	48.53	34.44	50.12	35.47
VD**	61.98	56.75	49.59	72.43	57.15
*Relative Density, D_r=85-90%, **Relative Density, D_r=91-96%					





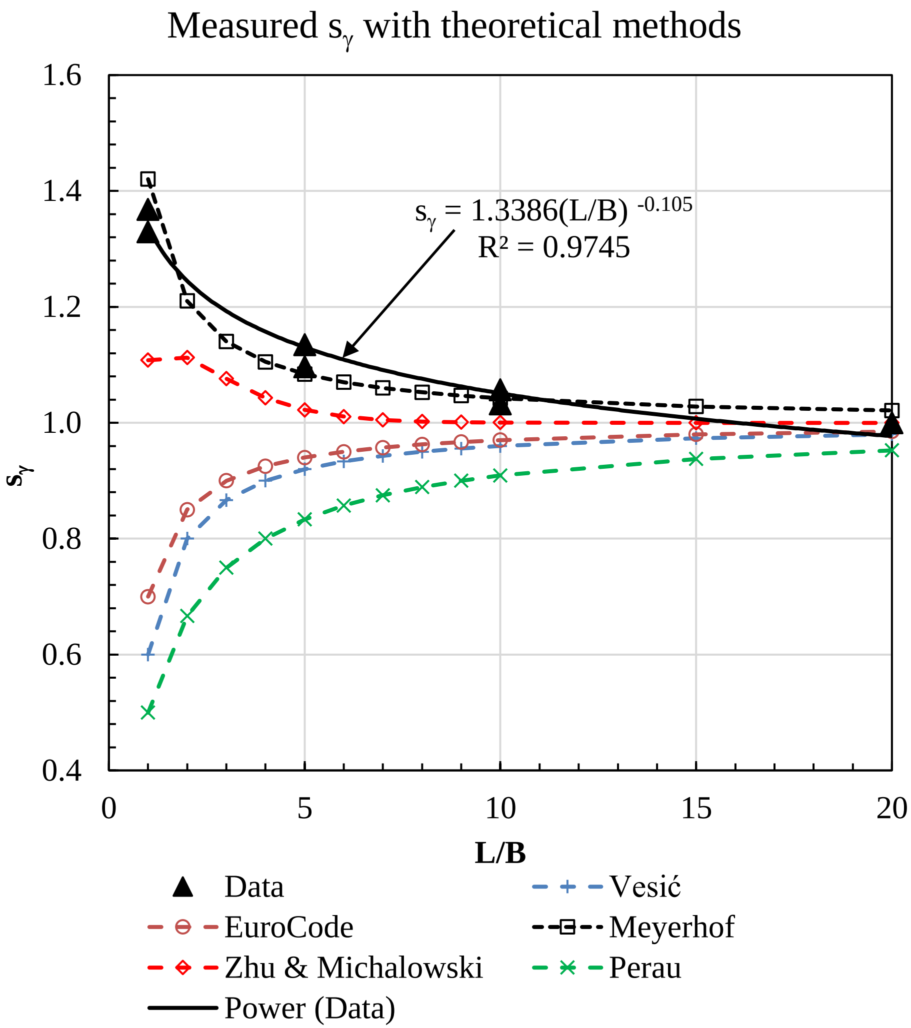
(A) Hansen (1970) and Vesic' (1973) d_q and d_γ

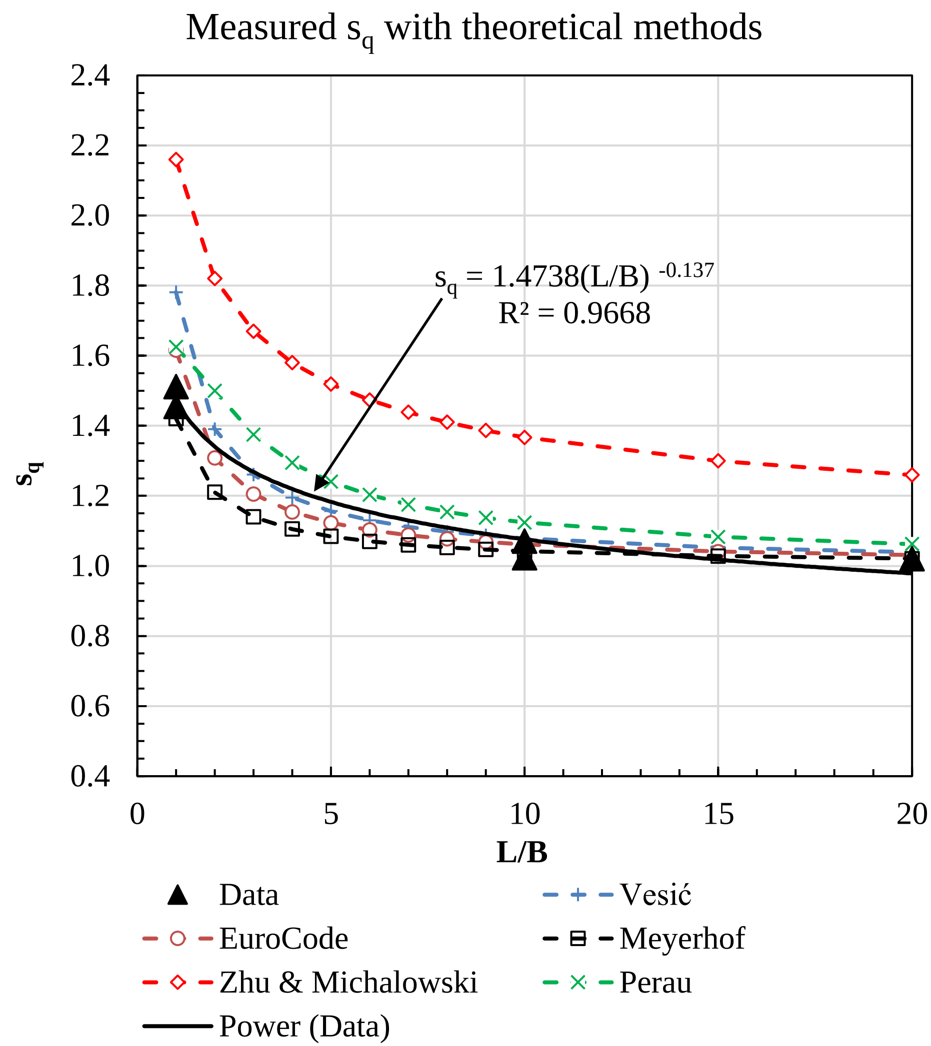
(B) Meyerhof (1963) d_q and d_γ

*VD (D_r=85-90%)

**VD (D_r=91-96%)

TASK-4: SHAPE FACTORS





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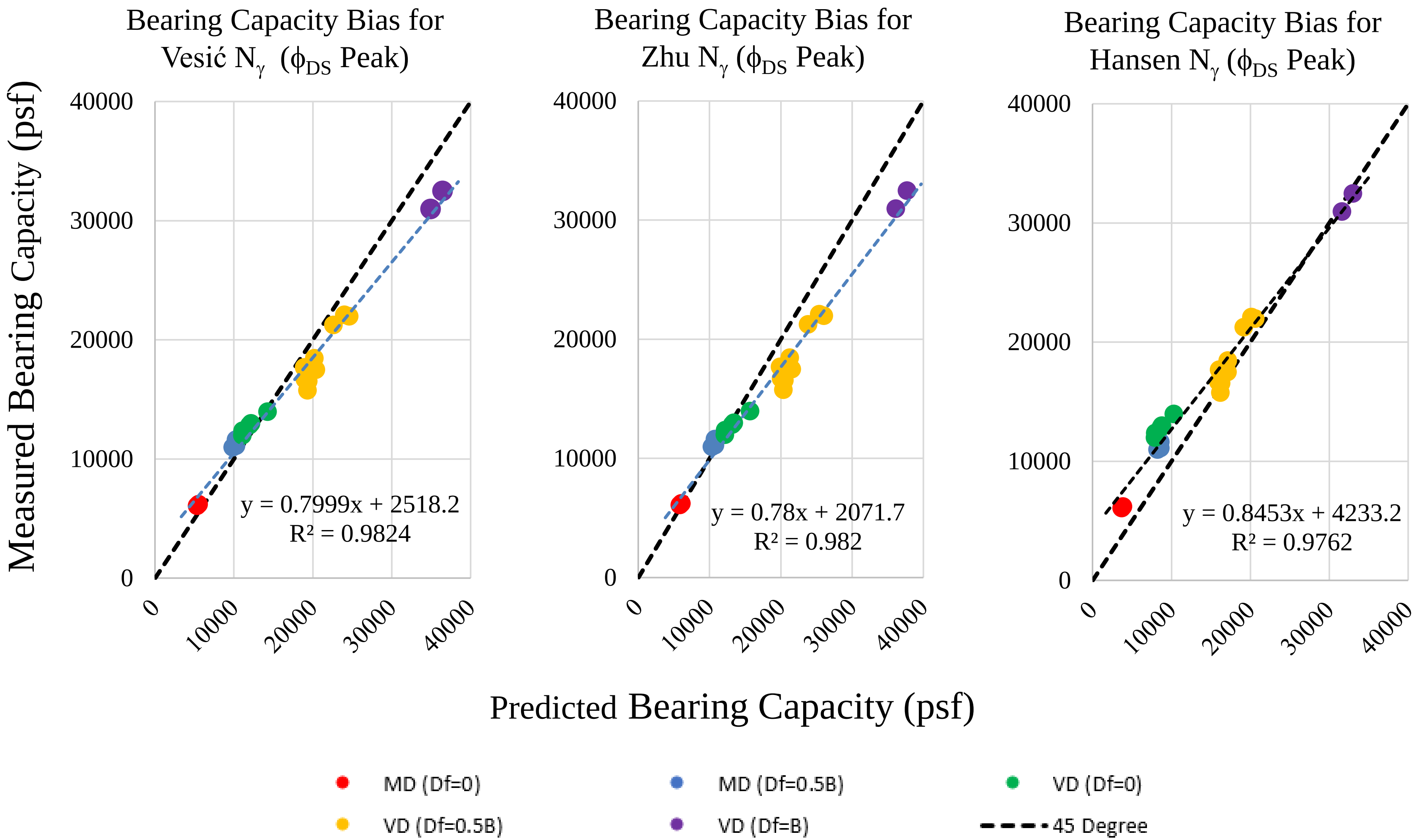
TASK-4: BEARING CAPACITY BIAS PLOT (L/B=20)



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TASK-4: BEARING CAPACITY BIAS TABLE (L/B=20)

Load Test	L/B Ratio	Reissner-Nq Bias	Vesic'-N_γ Bias	Meyerhof-N_γ Bias	Hansen-N_γ Bias	Vesic'-N_γ Bias	Meyerhof-N_γ Bias	Hansen-N_γ Bias	Vesic'-N_γ Bias	Meyerhof-N_γ Bias	Hansen-N_γ Bias	Vesic'-N_γ Bias	Meyerhof-N_γ Bias	Hansen-N_γ Bias
D_f=0		-	Hansen and Vesic' Depth Factors (d_γ=1) & Vesic' Shape Factors			Meyerhof Depth Factors (d_γ=d_q) & Vesic' Shape Factors			Hansen and Vesic' Depth Factors (d_γ=1) & Meyerhof Shape Factors			Meyerhof Depth Factors (d_γ=dq) & Meyerhof Shape Factors		
LT-1	20	1.13	1.33	1.71	1.88	Same Results as Hansen Depth Factors (d_γ=d_q=1) & Vesic' Shape Factors			1.28	1.65	1.81	Same Results as Hansen Depth Factors (d_γ=d_q=1) & Vesic' Shape Factors		
LT-2	20	1.14	1.29	1.66	1.83				1.24	1.60	1.76			
LT-3	20	1.10	1.15	1.56	1.67				1.11	1.51	1.61			
LT-4	20	1.13	1.17	1.59	1.69				1.13	1.54	1.63			
LT-17	20	1.21	1.09	1.32	1.51				1.05	1.27	1.46			
LT-18	20	1.23	1.09	1.32	1.52				1.06	1.28	1.46			
LT-23	10	1.20	0.93	1.13	1.29				0.86	1.04	1.19			
LT-24	10	1.17	0.97	1.17	1.34				0.89	1.08	1.24			
LT-125	1	1.25	1.90	2.31	2.64				0.80	0.98	1.11			
LT-126	1	1.19	1.84	2.22	2.55				0.77	0.93	1.07			
LT-165	5	1.22	1.08	1.31	1.50				0.92	1.11	1.28			
LT-167	5	1.23	1.07	1.29	1.48				0.90	1.10	1.25			
D_f=0.5B		-	Hansen and Vesic' Depth Factors (d_γ=1) & Vesic' Shape Factors			Meyerhof Depth Factors (d_γ=d_q) & Vesic' Shape Factors			Hansen and Vesic' Depth Factors (d_γ=1) & Meyerhof Shape Factors			Meyerhof Depth Factors (d_γ=dq) & Meyerhof Shape Factors		
LT-5	20	1.10	1.15	1.33	1.37	1.12	1.31	1.35	1.13	1.32	1.36	1.10	1.29	1.34
LT-6	20	1.10	1.10	1.27	1.31	1.07	1.25	1.29	1.08	1.26	1.30	1.05	1.24	1.28
LT-7	20	1.13	1.06	1.20	1.26	1.01	1.16	1.22	1.04	1.19	1.25	1.00	1.15	1.21
LT-8	20	1.15	1.11	1.26	1.32	1.06	1.22	1.28	1.09	1.25	1.30	1.05	1.21	1.26
LT-9	20	1.14	1.13	1.31	1.35	1.10	1.29	1.33	1.12	1.30	1.34	1.08	1.28	1.32
LT-10	20	1.09	1.07	1.21	1.27	1.02	1.17	1.23	1.05	1.20	1.26	1.01	1.16	1.22
LT-11	20	1.14	1.08	1.23	1.28	1.03	1.19	1.24	1.06	1.21	1.27	1.02	1.17	1.23
LT-12	20	1.08	1.14	1.29	1.34	1.08	1.23	1.29	1.13	1.28	1.34	1.07	1.22	1.28
LT-13	20	1.34	0.92	1.03	1.09	0.87	0.97	1.03	0.92	1.02	1.08	0.86	0.96	1.02
LT-14	20	1.25	0.93	1.04	1.11	0.88	0.99	1.06	0.92	1.02	1.10	0.87	0.98	1.05
LT-20	20	1.22	0.95	1.05	1.12	0.89	0.99	1.06	0.94	1.04	1.11	0.88	0.98	1.05
LT-36	10	1.21	0.83	0.92	0.98	0.79	0.88	0.94	0.80	0.89	0.96	0.76	0.85	0.92
LT-44	10	1.20	0.90	1.00	1.07	0.86	0.95	1.02	0.87	0.97	1.04	0.82	0.92	1.00
LT-128	1	1.20	1.17	1.24	1.29	1.14	1.21	1.26	0.89	0.99	1.07	0.84	0.94	1.02
LT-129	1	1.21	1.14	1.21	1.26	1.11	1.19	1.23	0.87	0.97	1.04	0.82	0.92	1.00
D_f=B		-	Hansen and Vesic' Depth Factors (d_γ=1) & Vesic' Shape Factors			Meyerhof Depth Factors (d_γ=d_q) & Vesic' Shape Factors			Hansen and Vesic' Depth Factors (d_γ=1) & Meyerhof Shape Factors			Meyerhof Depth Factors (d_γ=dq) & Meyerhof Shape Factors		
LT-16	20	1.24	0.89	0.95	0.99	0.84	0.90	0.94	0.89	0.95	0.99	0.83	0.90	0.94
LT-21	20	1.21	0.92	0.98	1.02	0.85	0.91	0.95	0.92	0.98	1.02	0.84	0.90	0.95

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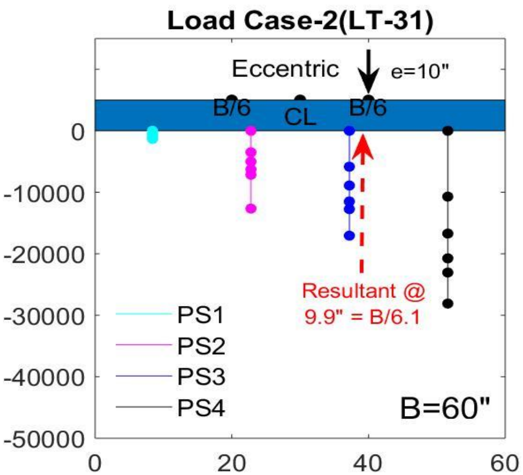
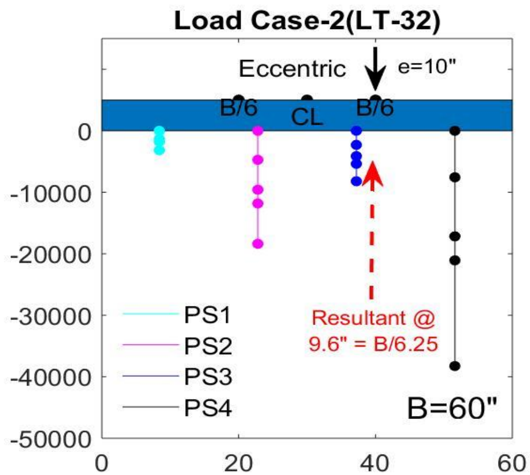
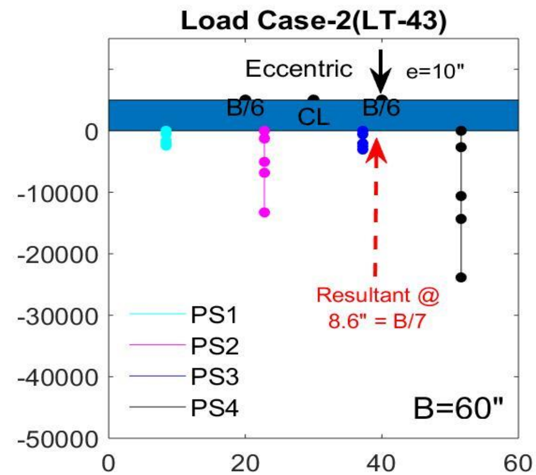
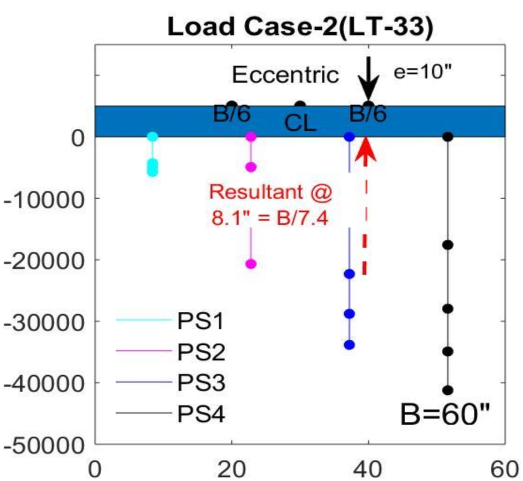
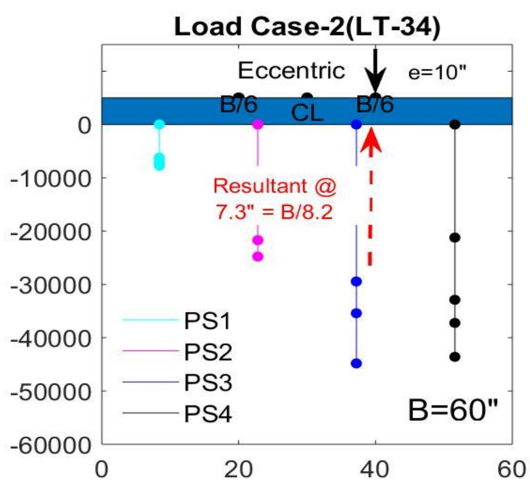
TASK-4: PRESSURE DISTRIBUTION
Eccentric Load Case









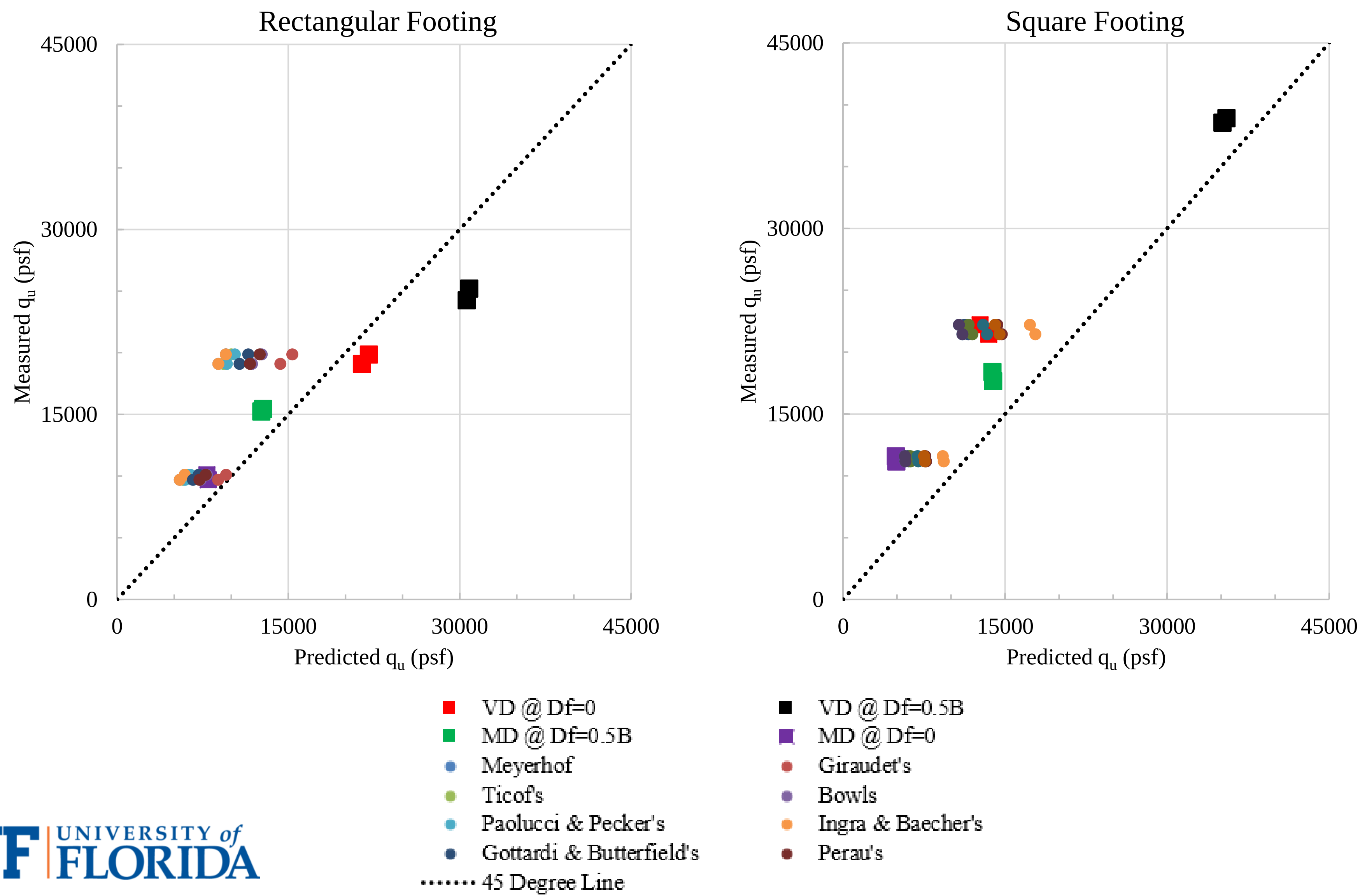


$$B' = B - 2 \cdot e_B$$

Measured Eccentricity	Design Eccentricity	Foundation Rotation (degree)
B/6.1	B/6	6.65
B/6.25	B/6	7.06
B/7	B/6	6.54
B/7.4	B/6	9.13
B/8.2	B/6	8.46

TASK-4: EFFECT OF ECCENTRICITY
Surface & Embedded Footing

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



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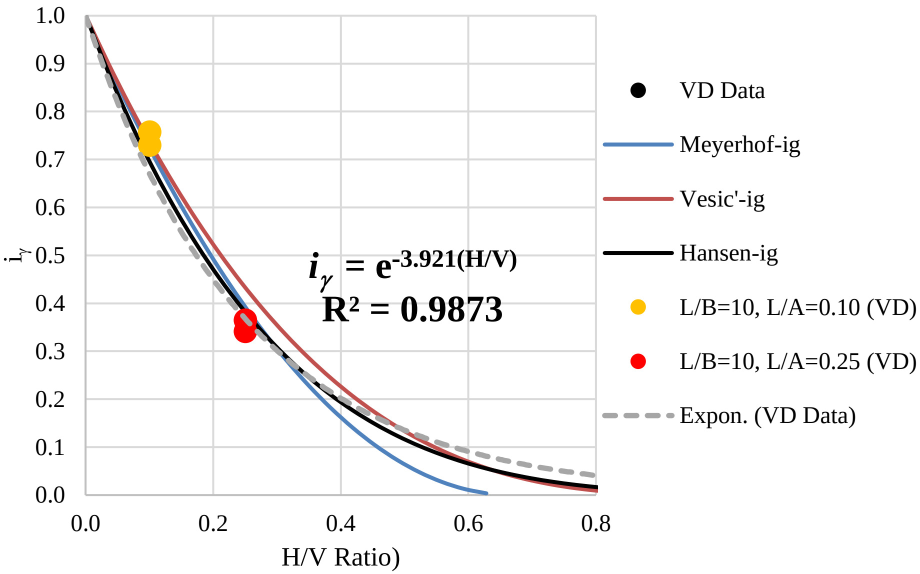
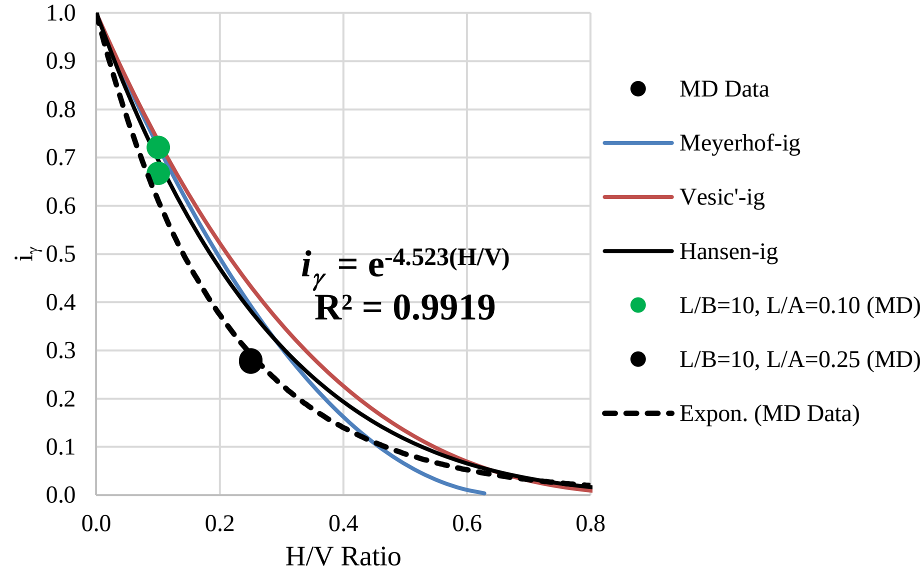
TASK-4: EFFECT OF LOAD INCLINATION-i_γ

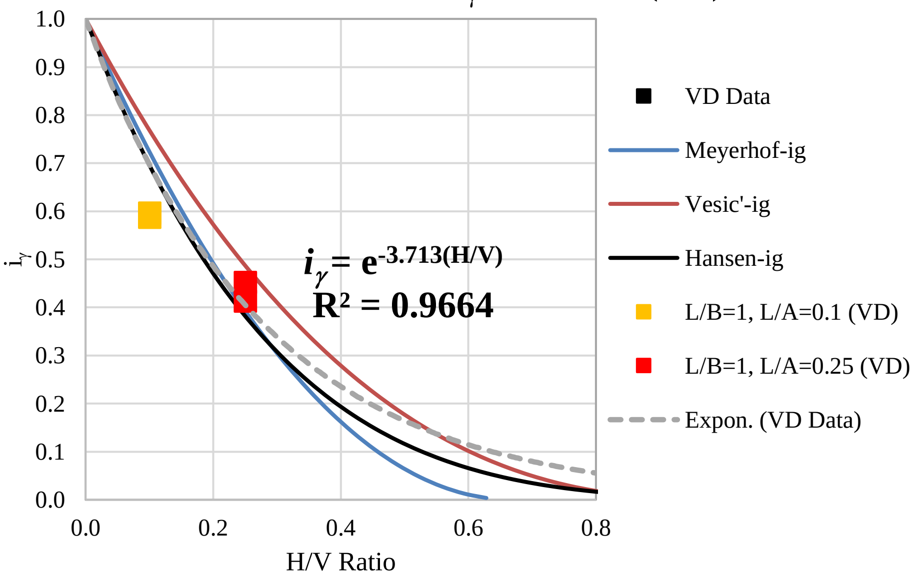
Inclination Factor-i_γ for L/B=10 (VD)



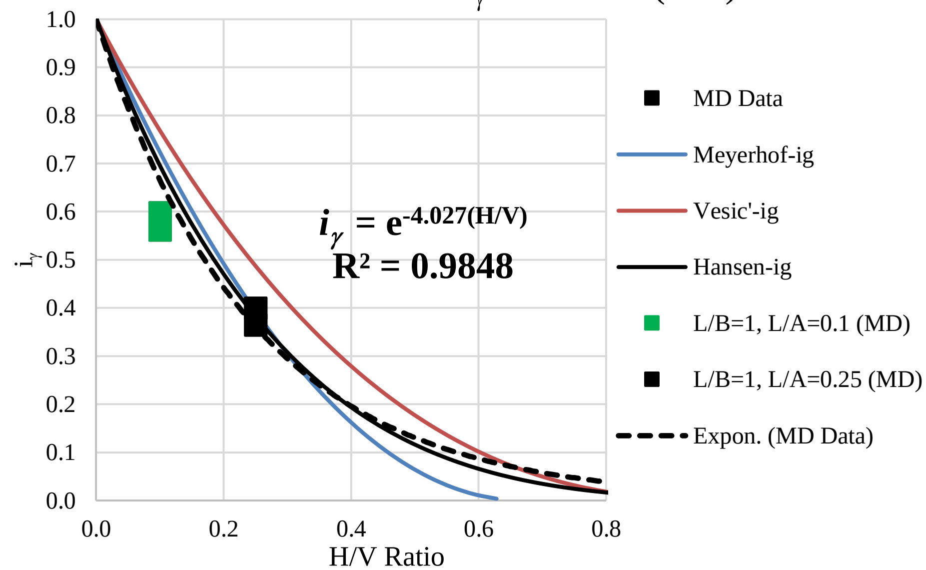
Inclination Factor-i_γ for L/B=10 (MD)



Inclination Factor-i_γ for L/B=1 (VD)

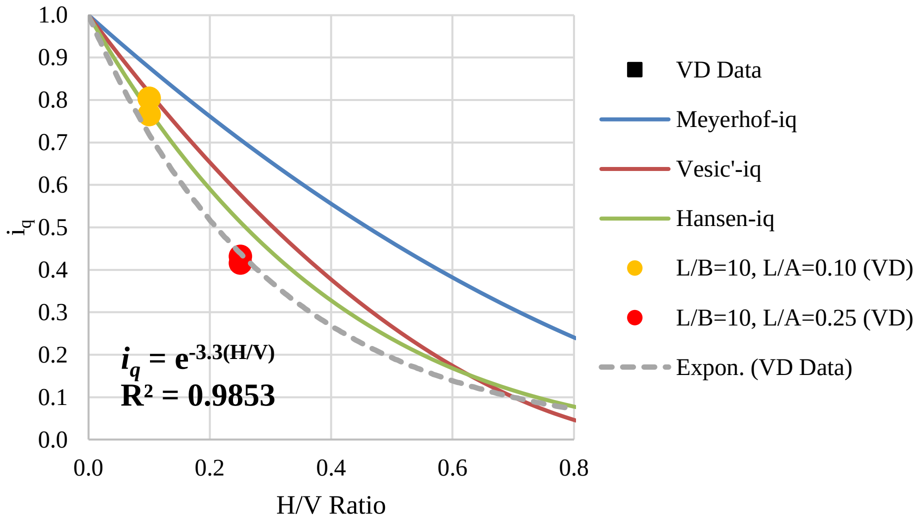


Inclination Factor-i_γ for L/B=1 (MD)

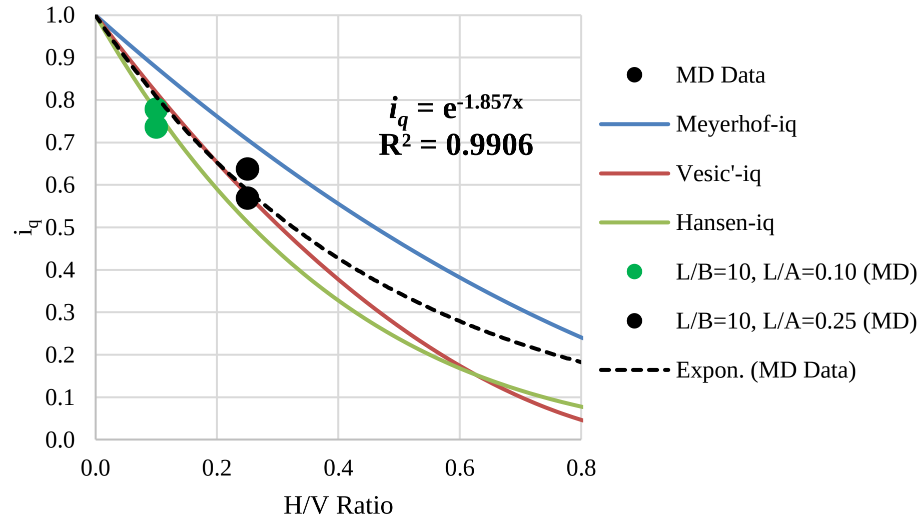


TASK-4: EFFECT OF LOAD INCLINATION-i_q

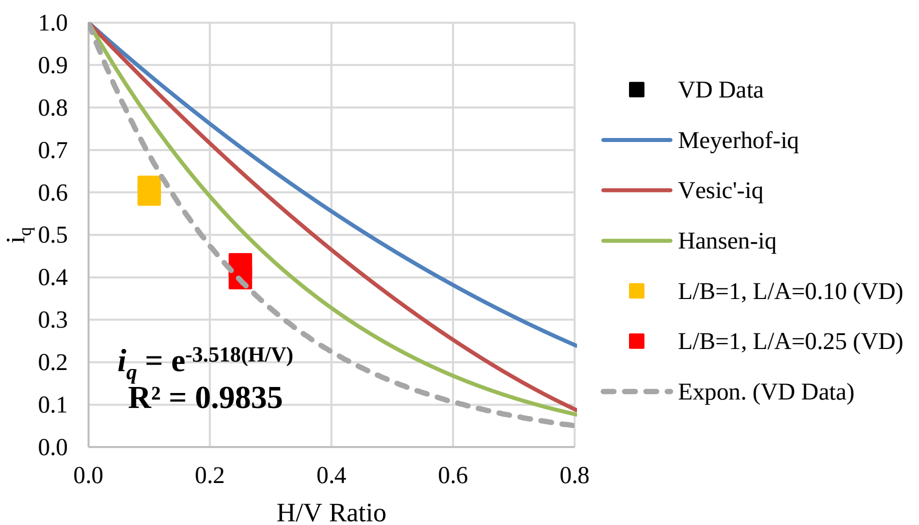
Inclination Factor-i_q for L/B=10 (VD)



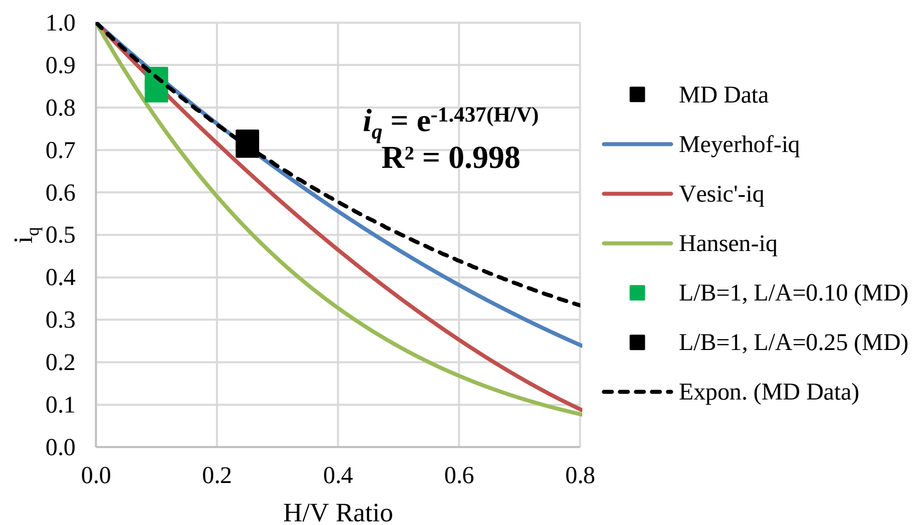
lination Factor-i_q for L/B=10 (MD)



Inclination Factor-i_q for L/B=1 (VD)

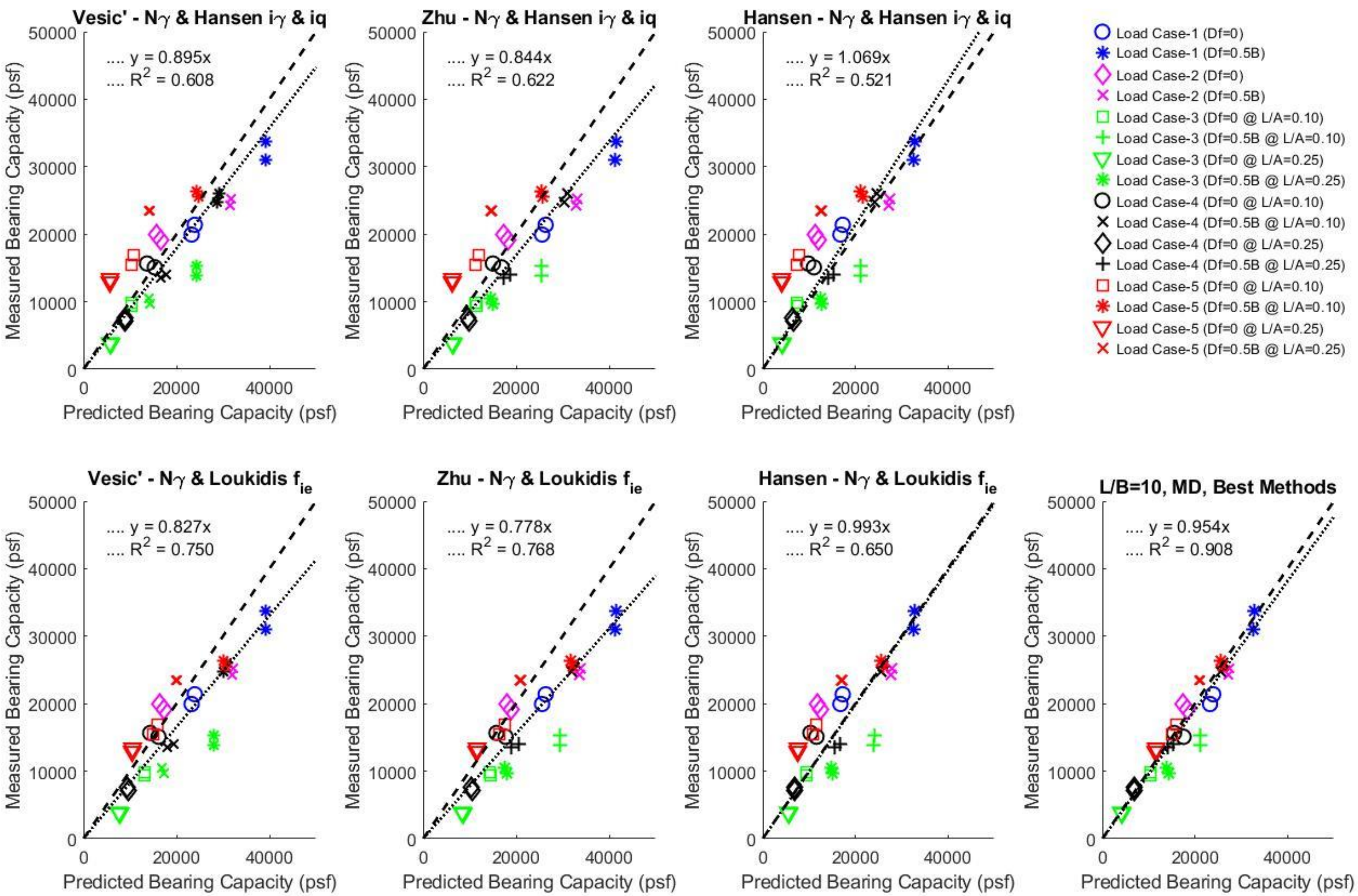


Inclination Factor-i_q for L/B=1 (MD)



TASK-4: BEARING CAPACITY BIAS PLOT
Rectangular Footing (VD)

Paired Methods & Best Methods



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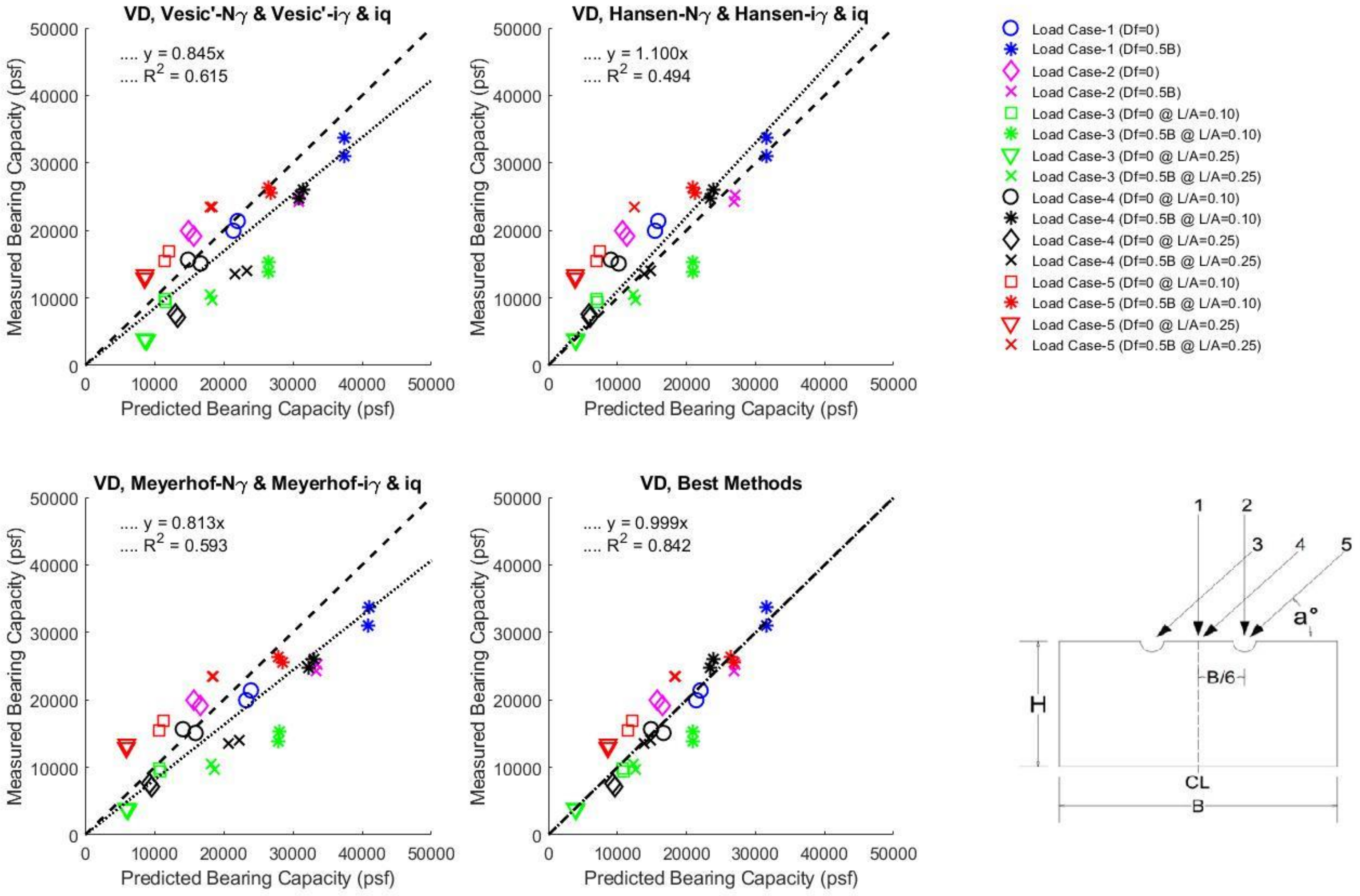
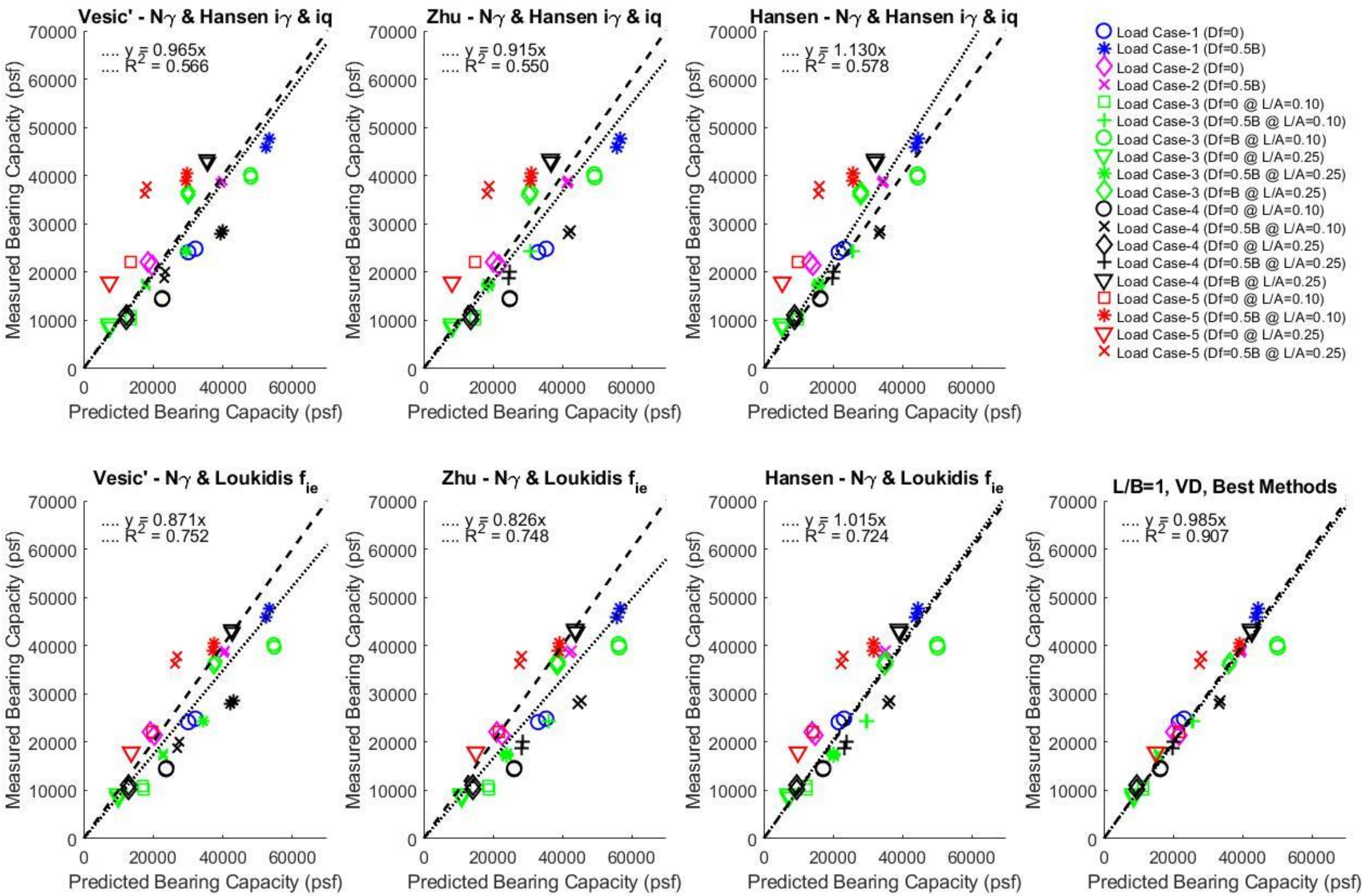
TASK-4: BEARING CAPACITY BIAS PLOT
Rectangular Footing (VD)

Match Methods



TASK-4: BEARING CAPACITY BIAS PLOT
Square Footing (VD)

Paired Methods & Best Methods



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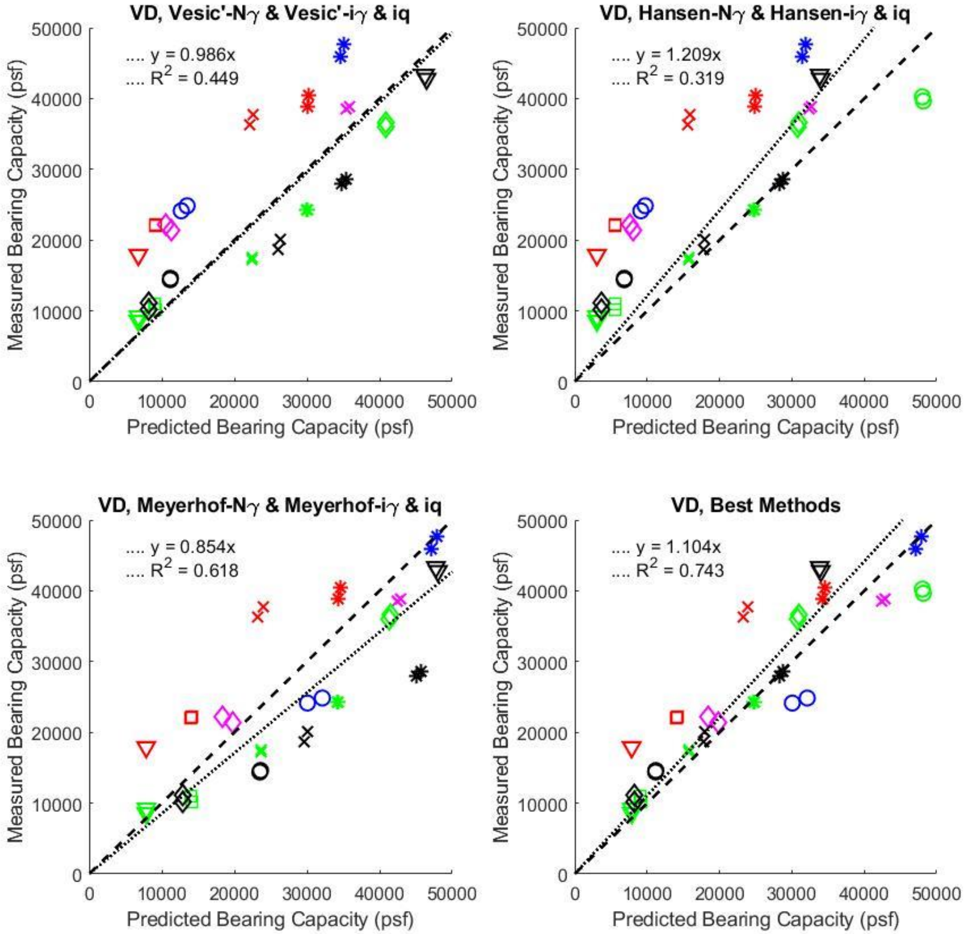
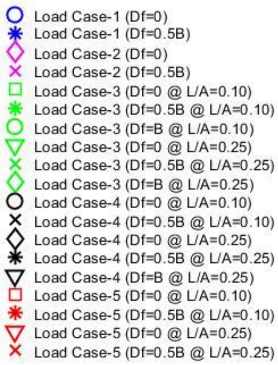
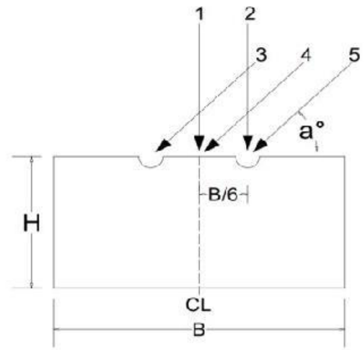
TASK-4: BEARING CAPACITY BIAS PLOT
Square Footing (VD)

Match Methods







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SUMMARY OF RESEARCH CONCLUSIONS

- Bearing capacities of L/B = 20 , 10, and 1 shallow foundations on sand subjected to centric, eccentric, and inclined loading measured in centrifuge tests.
- Bearing capacity factors N_γ and N_q validated against measured bearing capacity of strip foundations (shape factor = 1).
- Correction factors for depth, shape, and inclination independently validated against measured bearing capacities of L/B = 10 and 1 foundations in MD and VD sand.
- Based on comparison with measured bearing capacities, the combination of factors that lead to bias (measured/predicted) values closest to 1 are:
    - Soil overburden is well represented by N_q (Reissner, 1924)
    - Soil self weight is best predicted by N_γ Vesić (1973) method
    - Eccentricity is represented by B′
    - Effect of embedment is best predicted by d_q and d_γ Meyerhof (1963)
    - Effect of foundation shape is best predicted by S_q and S_γ Meyerhof (1963)
    - Effect of inclination in cases 3 and 4 best predicted by Hansen (1970) and Vesić (1973) i_q *and* i_γ with B′, Loukidis et al. (2008) f_{ie} with B does well
    - Effect of inclination in case 5: Loukidis et al. (2008) f_{ie} with B does well

SUMMARY OF RESEARCH CONCLUSIONS

- Foundation embedment had a marked effect on the measured bearing capacity:
  - D_f = 0.5B
    - Greatest improvement in capacity for lateral/axial load = 0.25
    - For MD and VD and L/B =10 and L/B = 1
    - Significant improvements (60 – 100%) for cases 3-5
    - Case 3 (most critical) improvements 62 – 90%
    - Significant improvement in capacity for lateral/axial load 0.1
    - 18-80% increase in capacity
  - D_f = B tests on L/B = 1 in VD sand with lateral/axial = 0.25
    - Improvements in capacity of 119% for cases 3 and 4 compared to Df = 0
  - D_f = B tests on L/B = 1 in VD sand with lateral/axial = 0.10
    - Improvements in capacity of 115% for case 3 compared to Df = 0
  - Based on the results, 38 – 70% reduction in measured bearing capacity for footings subjected to inclined loads (0.10 and 0.25)and when embedded up to Df = B.

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SUMMARY OF RESEARCH CONCLUSIONS

- Combination of load inclination and eccentricity is significant and direction of lateral component of load relative the direction of eccentricity should be considered
  - Case 3 (+ load combination) was the most critical for L/B = 10 and 1 and MD and VD sands
  - Capacity increased as load combination became less + and more – (case 5)
  - Same trend in results for Df = 0 and 0.5B tests
- AASHTO inclination factor methods don’t account for relative direction of inclined load – may overpredict bearing capacity

RECOMMENDATIONS

When estimating bearing capacity, the following methods in ASSHTO guidelines on shallow foundation design compared well with measured results and should continue to be used:

- N_q (Reissner, 1924)
- N_γ Vesić (1973) method
- $B' = B - 2e$
- d_q and d_γ Meyerhof (1963)
- For cases 3 and 4 loading, Vesić (1973) i_q *and* i_γ

- Hansen (1970) i_q *and* i_γ for L/B = 10 and 1 footings on sand
- Vesić (1973) S_q and S_γ are conservative (esp. for $L/B < 5$)
- Vesić (1973) i_q *and* i_γ are unconservative
- Effect of foundation shape is best predicted by S_q and S_γ Meyerhof (1963)
- When loading is like case 5, effect of inclination is best predicted by Loukidis et al. (2008) f_{ie} with B
- Inclination factor should not be omitted: 38 – 70% reduction in measured bearing capacity for embedded footings subjected to inclined loads (0.10 and 0.25).

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PROJECT BENEFITS

- Qualitative:
  - AASHTO methods to account for shape and inclination are conservative and commentary to account for effect of inclined load is ambiguous
  - The results of this research provide measured results of representative shallow foundation cases and independently assess the influence of soil weight, depth, shape, eccentricity, and inclination for comparison to current AASHTO methods
  - Experimental results and analysis in this research address the ambiguity and uncertainty in the design methods
- Quantitative:
  - Reducing conservancy in designs will result in more cost-efficient designs (smaller foundations)
  - Shallow foundations designed with appropriate load inclination factors to account for reduced bearing capacity may be assigned with less risk (probability of a foundation failure X the consequence of a failure ($)).

FUTURE RESEARCH

Shallow Foundations on/near Slopes

- AASHTO guidelines on bearing capacity of shallow foundations on or near slopes is based on Meyerhof (1957) charts for Df = 0 and 1.
- Recent work by Zerguine et al., (2017) looked at bearing capacity of eccentrically loaded strip footing near slopes through finite element modeling of the system in cohesionless soil.
- Yang at al., (2019) proposed modifying all factors to account for the influence of the slope proximity to shallow foundation in c-ϕ soil.

Bias and LRFD Resistance Factor Calibration

- NCHRP 24-31 Program compiled database of measured bearing capacity of shallow foundations on soil and rock.
- Vertical centric, eccentric, inclined, and eccentric inclined cases tested.
- Current work shows method bias for and N_γ 0.93 – 1.88 for Vesić, Hansen, Meyerhof methods.
- Can amend NCHRP database with new data to calibrate resistance factor for methods and cases (eccentric-inclined) in design.

LIST OF PUBLICATIONS

About to be Submitted:

- Experimental Verification of Bearing Capacity Factors for Shallow Foundations on Sand (2020): Stephen Crawford, Scott Wasman Ph.D., Michael McVay Ph.D., Larry Jones, Victor Steck

In-Draft:

- Centrifuge Modeling of Pressure Distributions Beneath Rectangular Shallow Foundations with Inclined-eccentric Loading on Sand (2020): Stephen Crawford, Scott Wasman Ph.D., Michael McVay Ph.D., Larry Jones

Planned:

- Centrifuge Modeling of Pressure Distributions Beneath Square Shallow Foundations with Inclined-eccentric Loading on Sand (2020): Stephen Crawford, Scott Wasman Ph.D., Michael McVay Ph.D., Larry Jones

- Resistance Factors for Shallow Foundations on Granular Soil Subjected to Centric, Eccentric, and Inclined Loads (2020): Scott Wasman Ph.D., Stephen Crawford, Michael McVay Ph.D., Andrea Tyrrell, Larry Jones

Thank You

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