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
5) CENTRIFUGE & LOAD CASE SENARIOS
    - L/B=20
    - L/B=10
    - L/B=1
    - CONCENTRIC LOADING
    - ECCENTRIC LOADING
    - INCLINED LOADING
    - INCLINED-ECCENTRIC LOADING
6) MEASURED RESULTS
    - L/B=20 (Verify Nq & Nγ)
    - L/B=20 (Verify shape and depth factors)
    - L/B=10 (Df=0 & 0.5B, Very Dense, L/A=0.10 & 0.25)
    - L/B=10 (Df=0 & 0.5B, Medium Dense, L/A=0.10 & 0.25)
    - L/B=10 (Verify eccentricity, iγ & iq)
7) CONCLUSIONS

BACKGROUND AND MOTIVATION

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

BACKGROUND AND MOTIVATION

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 AND TASKS

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

TASK 1: METHODS OF BEARING CAPACITY

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

General bearing capacity equation recommended by AASHTO (2016)

$$q_n = cN_{cm}(0) + \gamma D_f N_{qm} C_{wq}(1) + 0.5\gamma B N_{\gamma m} C_{w\gamma}(1) \quad \text{Eq.1}$$

$$q_n = \gamma D_f N_{qm} + 0.5\gamma B N_{\gamma m} \quad \text{Eq.2}$$

$$N_{qm} = N_q S_q d_q i_q \quad \text{Eq.3}$$

$$N_{\gamma m} = N_\gamma S_\gamma i_\gamma \quad \text{Eq.4}$$

$$N_q = e^{\pi \tan \phi_f} tan^2\left(45^\circ + \frac{\phi_f}{2}\right) \quad \text{Eq.5}$$

$$N_\gamma = 2(N_q + 1)tan(\phi_f) \quad \text{Eq.6}$$

B = Foundation width

γ = Soil unit weight

D_f = Embedment depth

S_q, S_γ = Shape correction factor

d_q = Depth correction factor

i_q, i_γ = Inclination correction factors

TASK 2: TEST SOIL

AASHTO CLASS: A-3

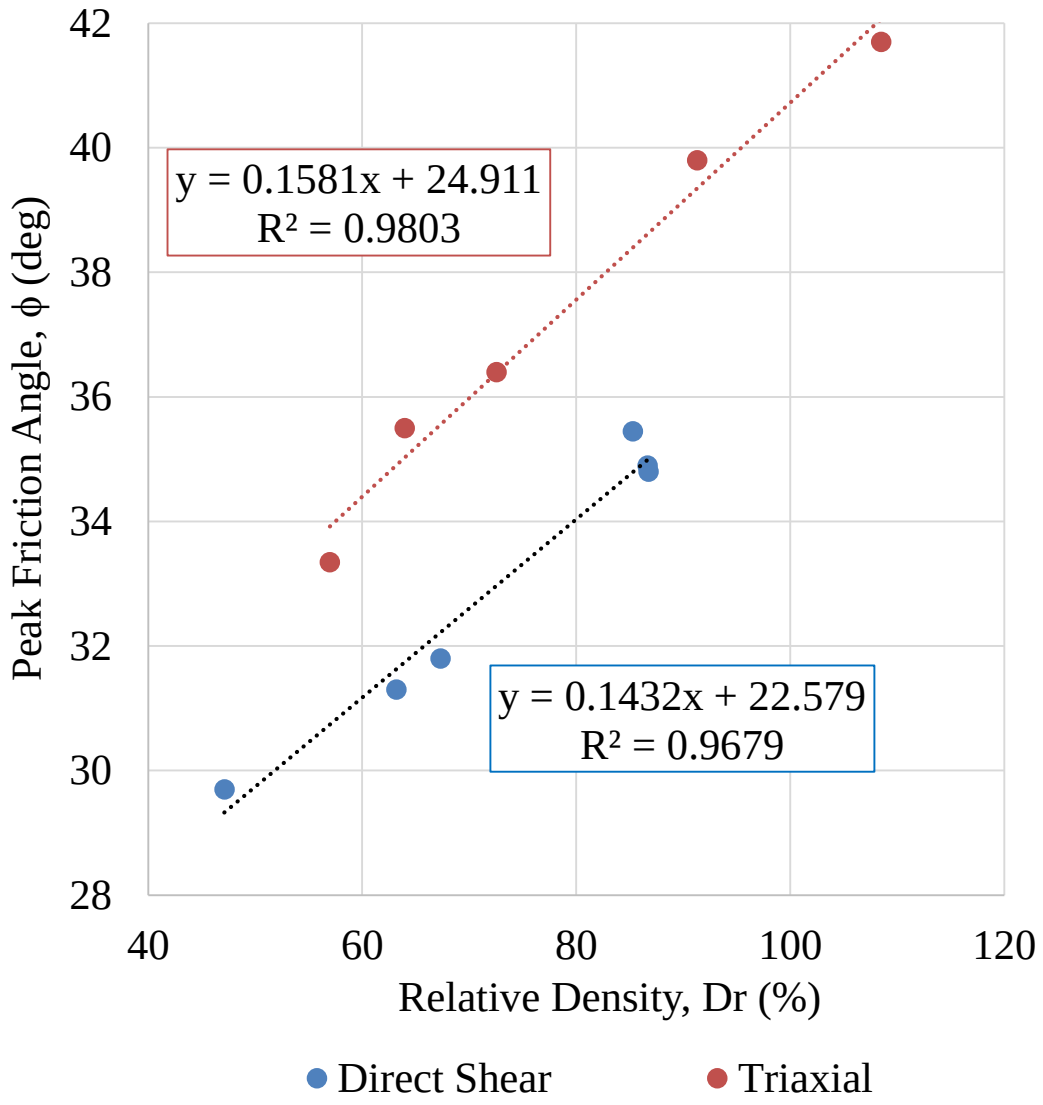
- Max unit weight: 108.9 pcf
- Min unit weight: 90.7 pcf
- 2.5% Passing #200
- 97.5% Sand
- Coefficient of Uniformity: 1.67
- Coefficient of Curvature: 1.35
- Specific gravity: 2.67
- e_{min}: 0.53
- e_{max}: 0.84
- SP Unified Soil Classification

DIRECT SHEAR TEST:

- D_r = 55 – 93%
- ϕ = 29.5° - 34°

TRIAXIAL CD-TEST:(c=0)

- D_r = 61 – 94%
- ϕ = 36.0° - 41.2°



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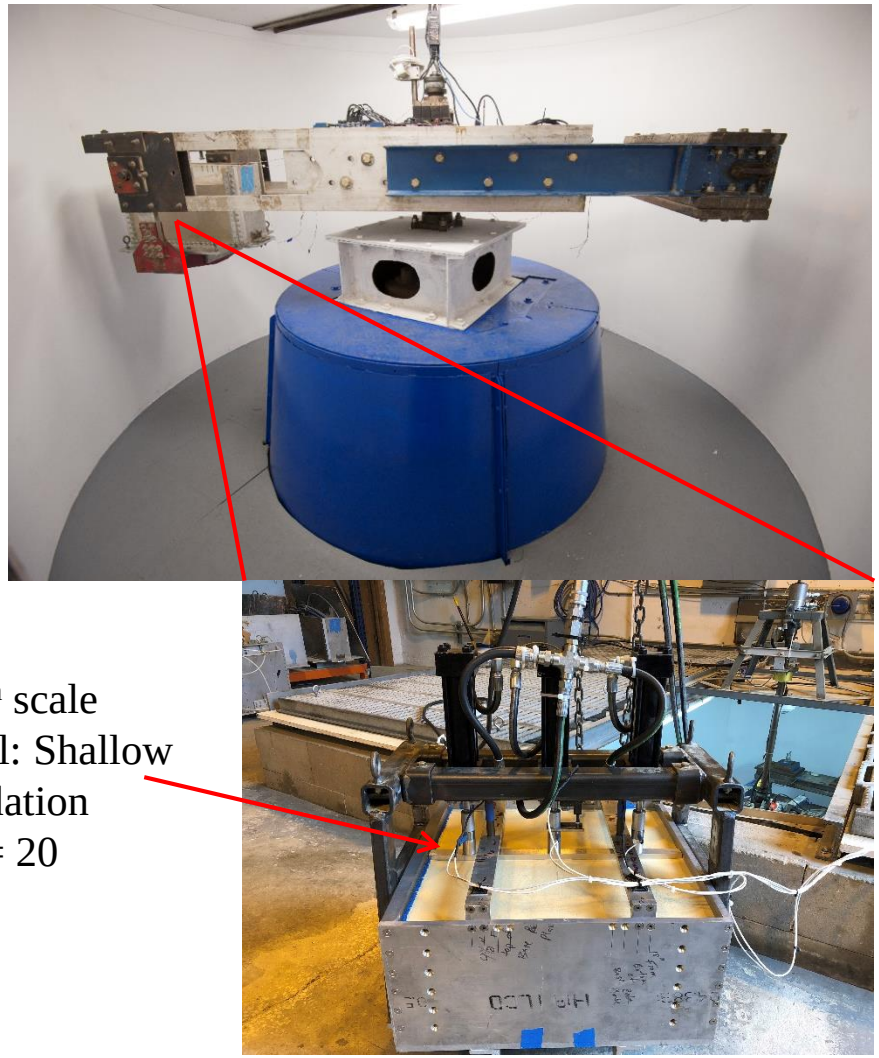
TASK 3: GEOTECHNICAL CENTRIFUGE TESTS

- 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

3 meter diameter centrifuge



$1/36^{th}$ scale model: Shallow foundation
L/B = 20

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

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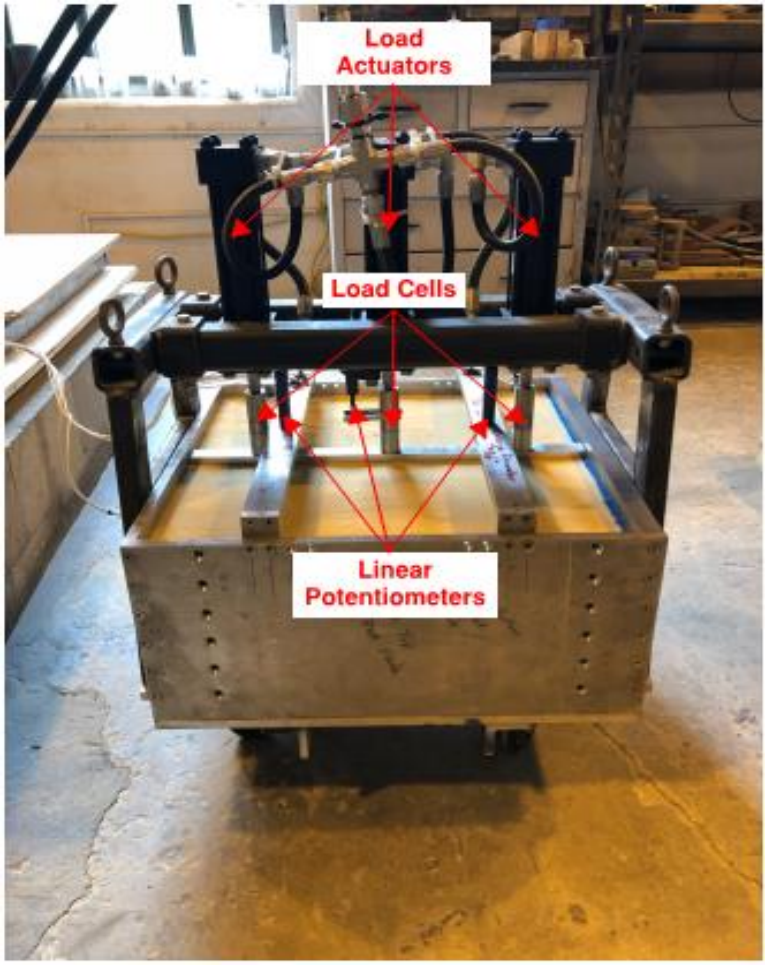
TASK 3: TEST CONDITIONS

Test Apparatus			
L/B Ratio	20	10	1
Interior container width (in.)	20		
Interior container length (in.)	20	15	20
Interior container height (in.)	9.5		
Soil height (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



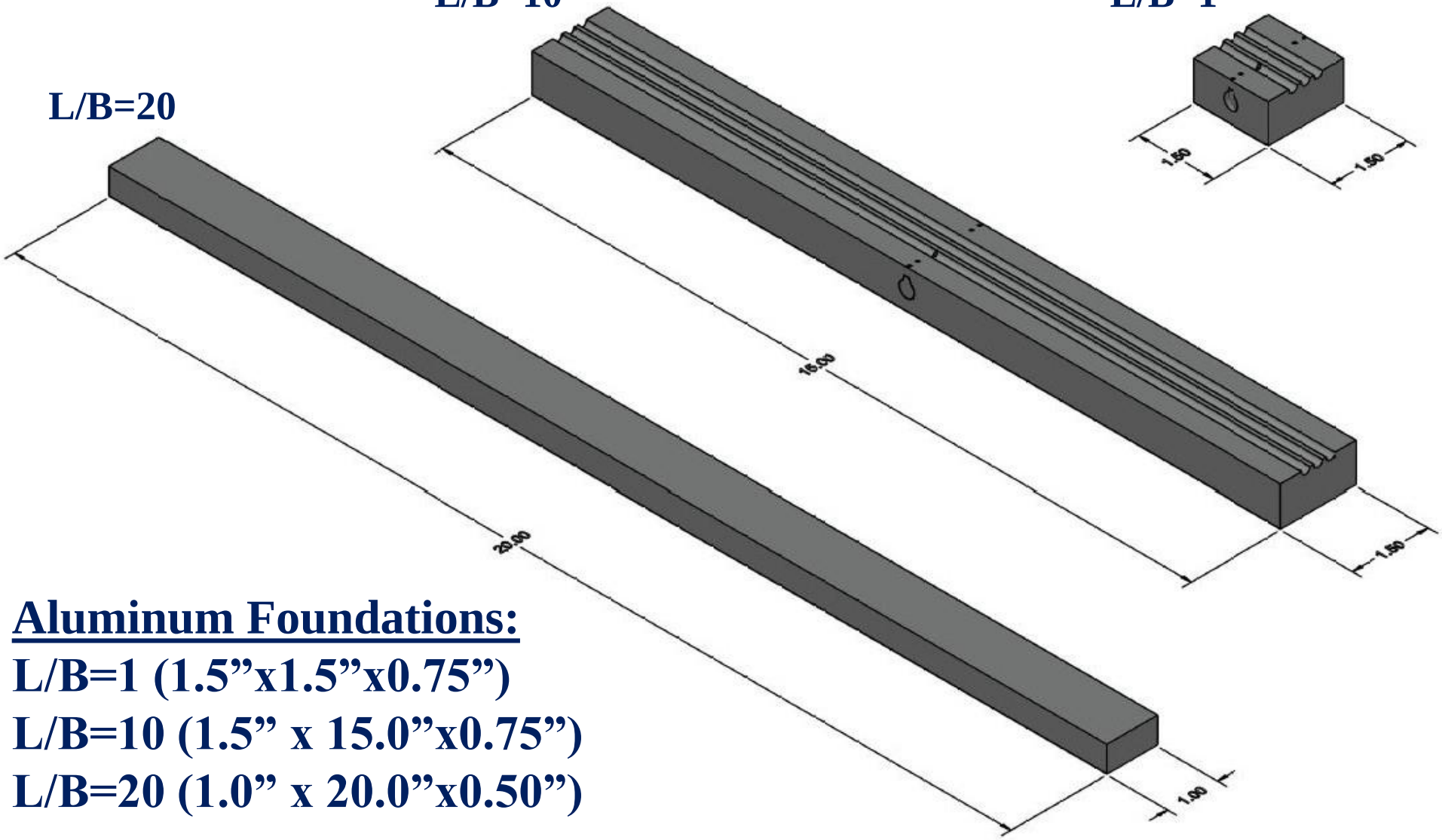
* Container designed to accommodate max load for ultimate bearing capacity and minimize boundary influences on failure surfaces.

TASK 3: TEST FOUNDATIONS

L/B=10

L/B=1

L/B=20



Aluminum Foundations:

L/B=1 (1.5”x1.5”x0.75”)

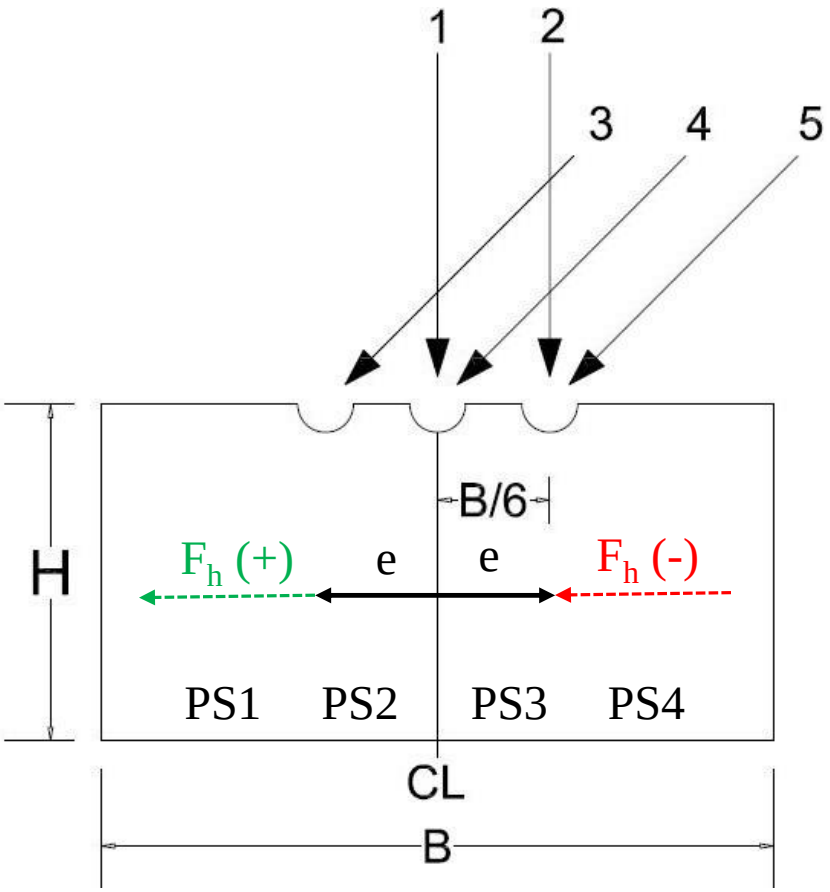
L/B=10 (1.5” x 15.0”x0.75”)

L/B=20 (1.0” x 20.0”x0.50”)

LOAD CASE SCENARIOS & NUMBER OF TEST

Load Cases – 5 (Positions 1-5)
Relative Density – 2 (Medium & Very dense)
Embedment Depth – 2 (Surface condition & Df=0.5B)
Inclination Angles -2 (L/A=0.1 & 0.25)
L/B Ratios -2 (1 & 10)
Test Repeatability -2

<u>Load Case Scenarios: Meyerhof (1953)</u>
Load Case-1: Concentric
Load Case-2: Eccentric
Load Case-3: Eccentric-inclined, horizontal component positive (+), to the direction of the eccentricity
Load Case-4: Inclined
Load Case-5: Eccentric-inclined, horizontal component negative (-), to the direction of the eccentricity



<u>Footing loading scenarios:</u>

Where B = width, H = Height, a = angle of inclination (not to scale) and eccentricity = B/6.

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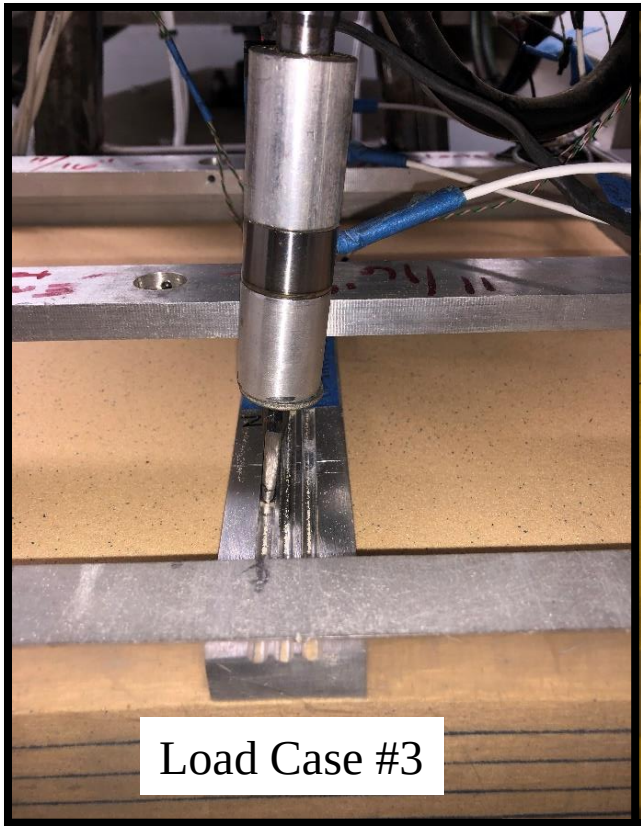
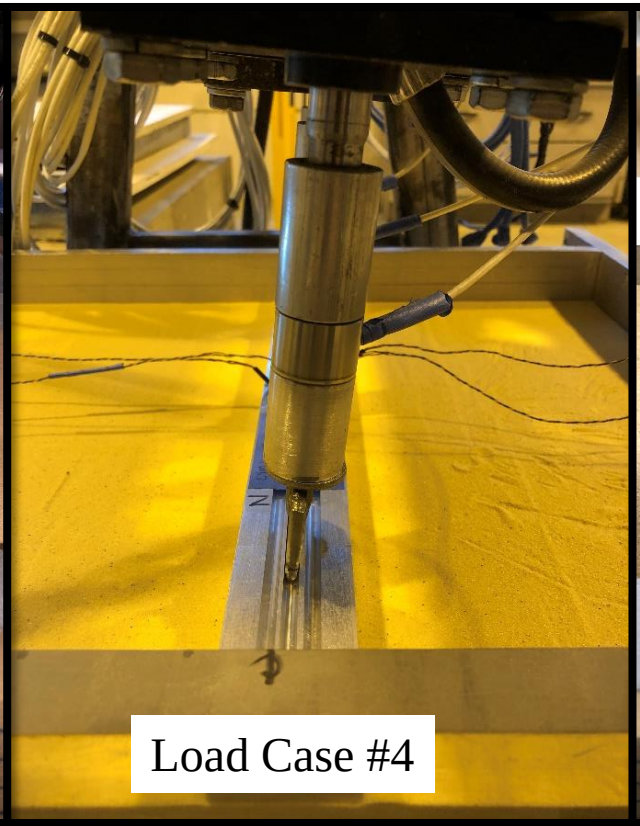
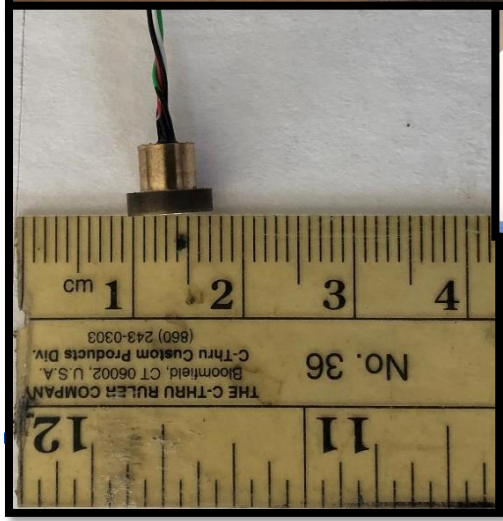
INCLINED LOAD SCENARIOS (L/B = 1 & 10)


Load Case #3


Load Case #4


Load Case #5



Manufacture	Tokyo Measuring Instruments Lab.)
Type	PDB-3MPB
Capacity	62 ksf (3MPa)
Rated Output	1mV/V (2000x10^{-6} strain)

CONCENTRIC LOADING ON STRIP FOUNDATION (L/B=20)

FOR THE PURPOSE OF THIS STUDY:

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

STRIP FOUNDATION AT SURFACE:

$q_n = 0.5\gamma B N_{\gamma m}$ 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 1.04 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

CONCENTRIC LOADING ON STRIP FOUNDATION (L/B=20)

Name	D_r (%)	γ (pcf)	ϕ (degree)	Measured-qu (psf)	Embedment Depth (D_f)	Eccentricity	Inclination	Series #
LT-01*	86.82	106.09	35.01	14,480	0	0	0	1
LT-02*	86.71	106.07	35.00	14,570	0	0	0	2
LT-03*	63.97	101.56	31.74	10,012	0	0	0	1
LT-04*	62.81	101.34	31.57	10,880	0	0	0	2
LT-05*	63.72	101.51	31.70	12,000	0.5B	0	0	1
LT-06*	63.75	101.52	31.71	11,780	0.5B	0	0	2
LT-07*	86.80	106.09	35.01	14,700	0.5B	0	0	1
LT-08*	86.07	105.94	34.90	11,800	0.5B	0	0	2
LT-09*	62.26	101.23	31.49	10,654	0.5B	0	0	3
LT-10*	88.47	106.44	35.25	14,938	0.5B	0	0	3
LT-11*	86.61	106.05	34.98	13,816	0.5B	0	0	4
LT-12*	88.83	106.51	35.30	16,500	0.5B	0	0	5
LT-13*	91.11	106.99	35.63	17,500	0.5B	0	0	6
LT-14	94.16	107.64	36.06	19,700	0.5B	0	0	7
LT-15**	-	-	-	-	0	0	0	3
LT-16	94.31	107.67	36.08	24,540	B	0	0	1
LT-17	95.37	107.90	36.24	14,160	0	0	0	4
LT-18	94.88	107.79	36.17	13,780	0	0	0	5
LT-19**	-	-	-	-	0.5B	0	0	8
LT-20	95.02	107.82	36.19	20,150	0.5B	0	0	9
LT-21	95.55	107.94	36.26	26,080	B	0	0	2
* Vacuumed Soil Samples								
** Load test excluded from analysis due to instrumentation malfunction								

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
Paikowsky et. Al (2010)	1.03	0.99
Meyerhof (1963)	1.02	1.02
Perau (1995, 1997)	1.06	0.95
Zhu and Michalowski (2005)	-	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)

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

$$d_\gamma = d_q$$

MEASURED Nq and Nγ (L/B=20)

$$q_u = \gamma(D_f + \delta)N_{qm} + (1/2)\gamma B N_{\gamma m}$$

or in a normalized form as

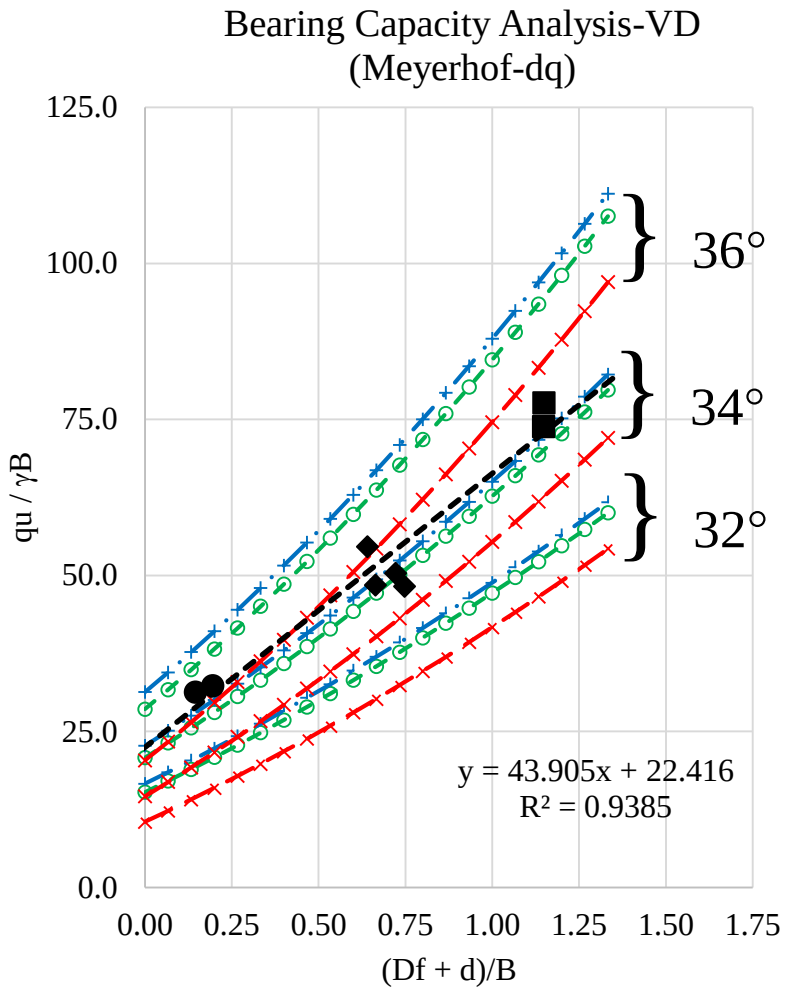
$$\frac{q_u}{\gamma B} = \left(\frac{D_f + \delta}{\delta B}\right)N_{qm} + (1/2)N_{\gamma m}$$

$y = m\,x + b$

Nq = slope

Nγ = 2 * intercept

Density	Nq (slope)	Nγ (2 * intercept)	Reissner - Nq	Vesic'- Nγ
MD	21.38	25.97	24.83	28.05
VD-Vac	23.69	43.37	39.82	48.53
VD	43.91	44.83	44.65	56.78



Prediction Methods:

Vesic'-Nγ Zhu-Nγ Hansen-Nγ

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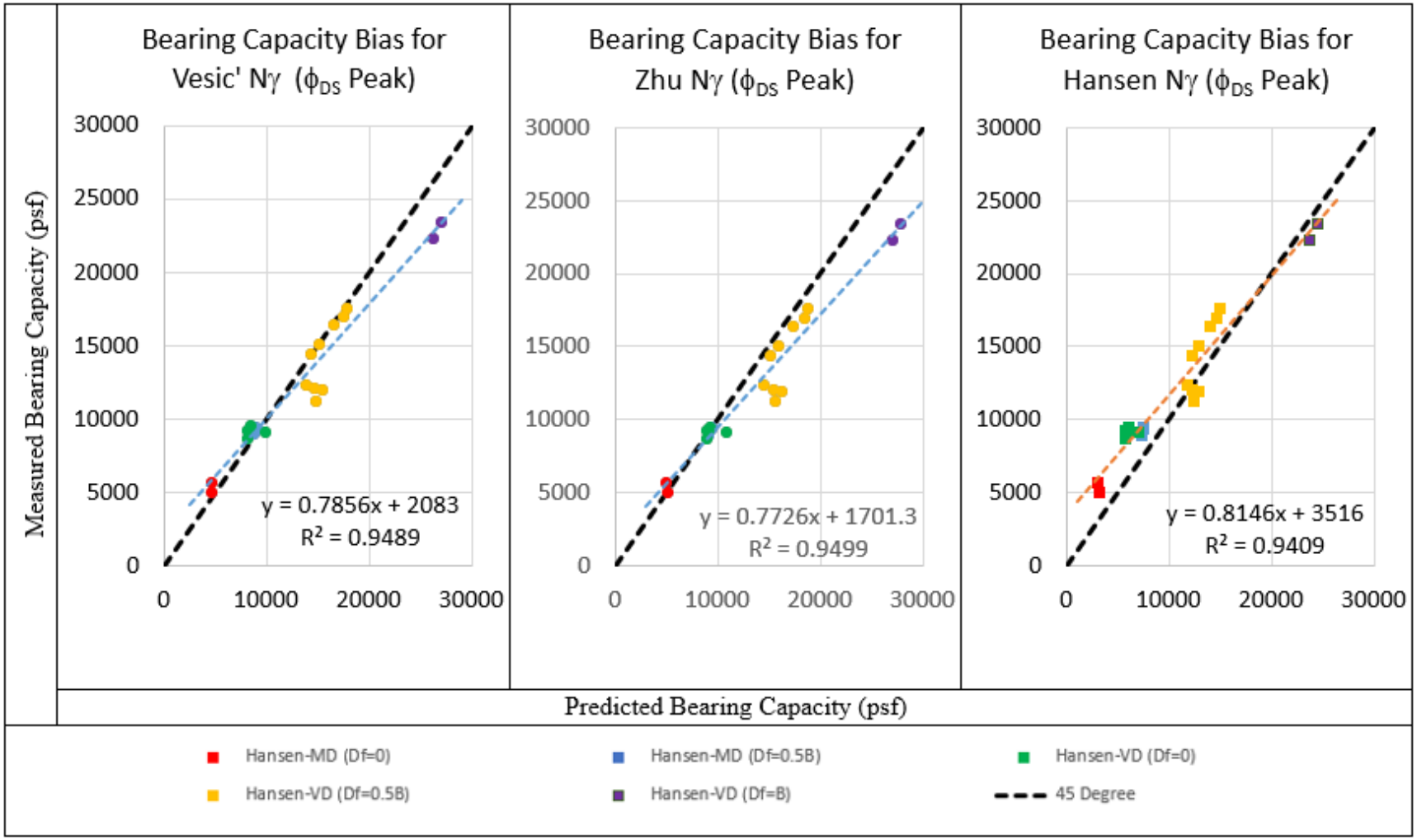
BEARING CAPACITY BIAS PLOT (L/B=20)



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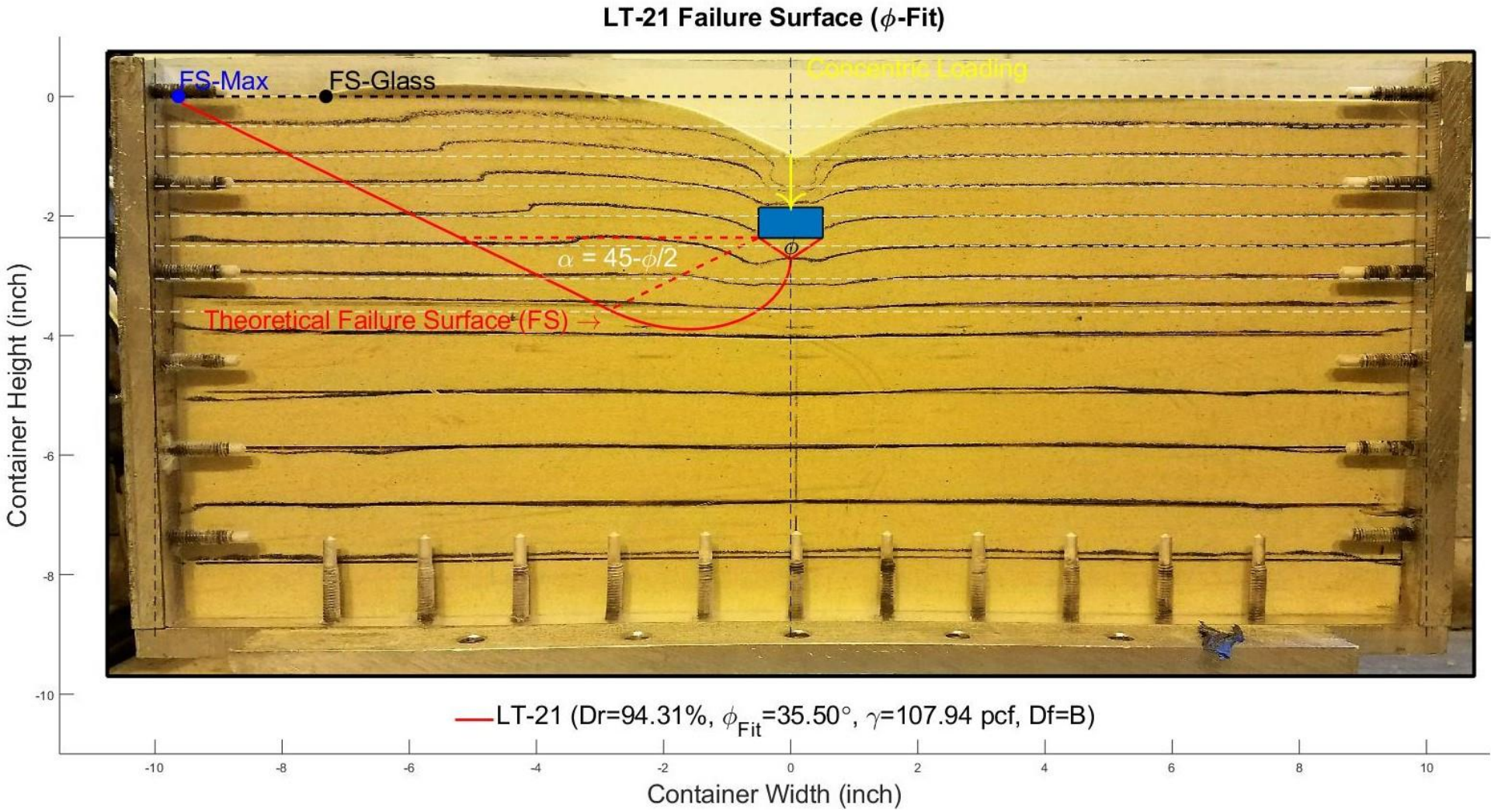
THEORETICAL FAILURE SURFACE (LT-21)



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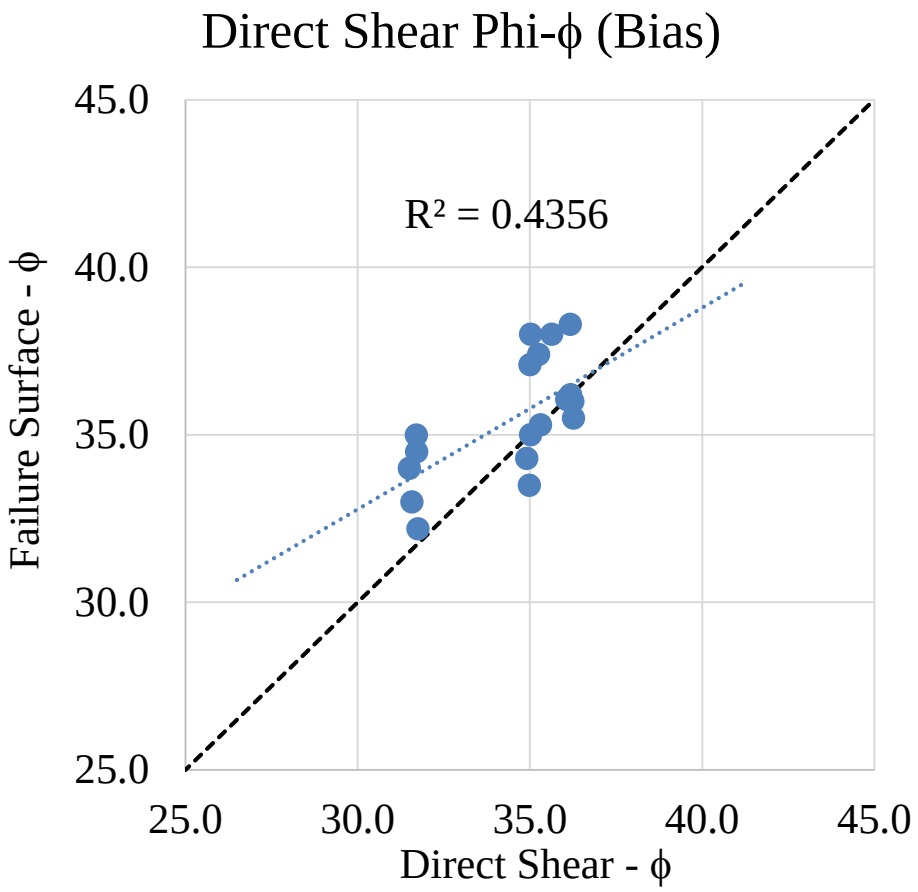
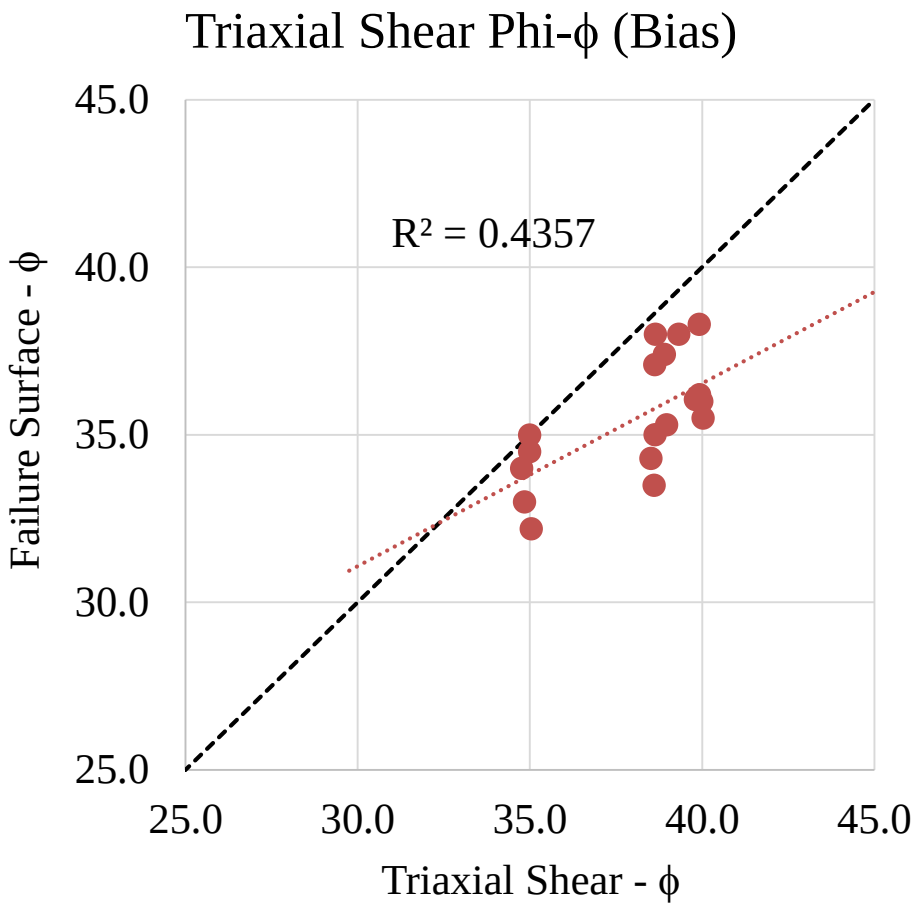
DIRECT SHEAR & TRIAXIAL Phi-ϕ (Bias plot)





LOADING ON RECTANGULAR FOUNDATION (L/B=10)

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

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

LOAD TEST ON RECTANGULAR FOUNDATION (L/B=10)-VD

Name	Load Case	D_r (%)	γ (pcf)	ϕ (degree)	Measured-qu (psf)	Embedment Depth (D_f)	Eccentricity	Inclination	Series #
LT-22**	1	-	-	-	-	-	-	-	-
LT-23	1	95.82	108.00	36.30	18860	0	0	0	2
LT-24	1	96.73	108.20	36.43	19060	0	0	0	3
LT-25	4	90.63	106.90	35.56	13750	0	B/6	0.10	1
LT-26	4	94.20	107.65	36.07	12460	0	B/6	0.10	2
LT-27	5	94.67	107.75	36.14	15970	0	B/6	-0.10	1
LT-28	5	96.60	108.16	36.41	17070	0	B/6	-0.10	2
LT-29	3	95.07	107.84	36.19	8612	0	B/6	0.10	1
LT-30	3	95.10	107.84	36.20	7944	0	B/6	0.10	2
LT-31	2	98.89	108.66	36.74	14790	0	B/6	0	1
LT-32	2	98.29	108.53	36.65	18670	0	B/6	0	2
LT-33	2	95.40	107.91	36.24	22060	0.5B	B/6	0	1
LT-34	2	95.65	107.96	36.28	24080	0.5B	B/6	0	2
LT-35	1	92.99	107.39	35.9	21762	0.5B	0	0	1
LT-36	1	95.60	107.95	36.27	25900	0.5B	0	0.10	2
LT-37	4	96.54	108.15	36.4	22900	0.5B	0	0.10	1
LT-38	4	95.89	108.01	36.31	21090	0.5B	0	0.10	2
LT-39	5	97.02	108.25	36.47	26520	0.5B	B/6	-0.10	1
LT-40	5	97.58	108.38	36.55	24830	0.5B	B/6	-0.10	2

** Load test excluded from analysis due to instrumentation malfunction

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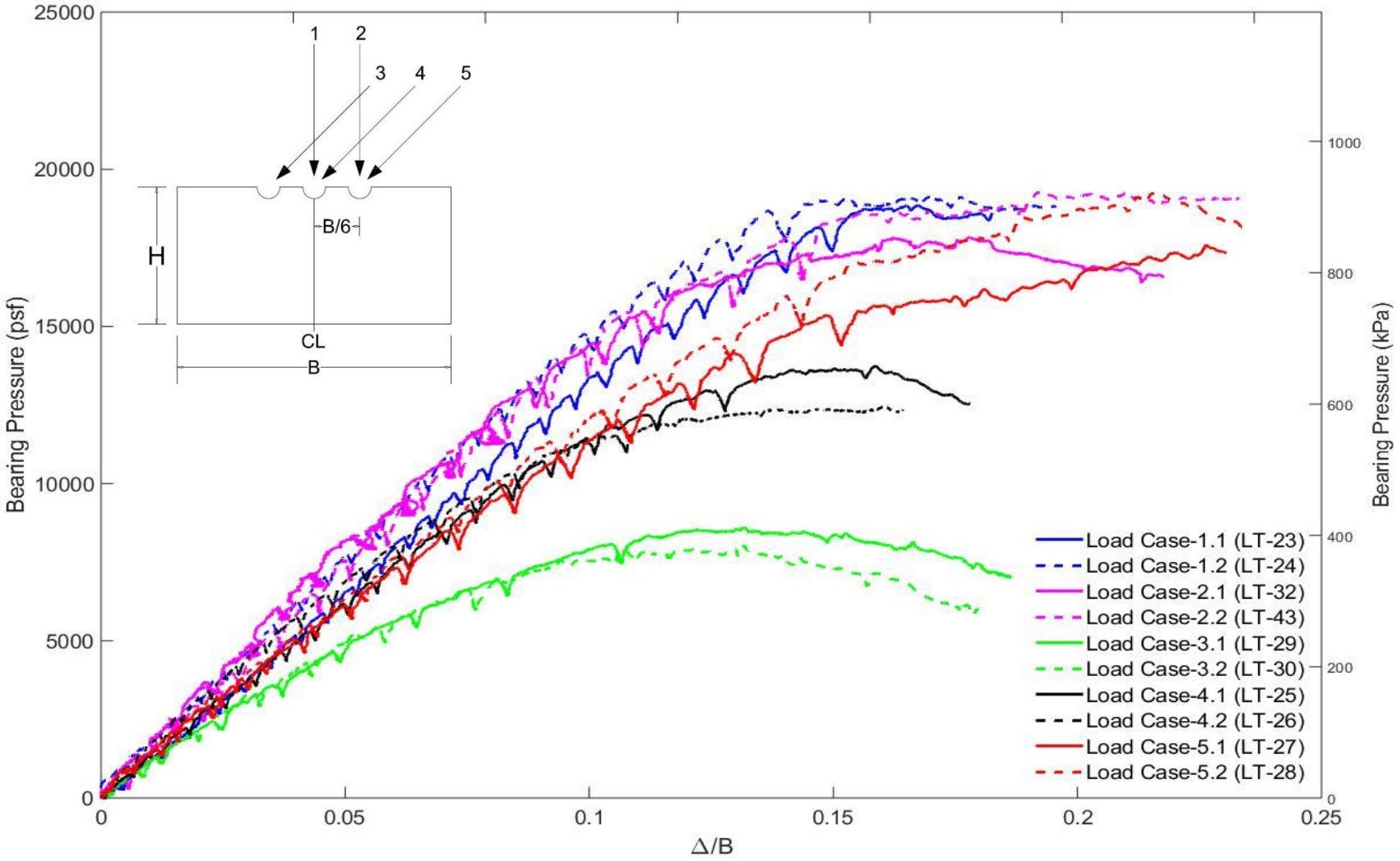
LOAD TEST ON RECTANGULAR FOUNDATION (L/B=10)-VD

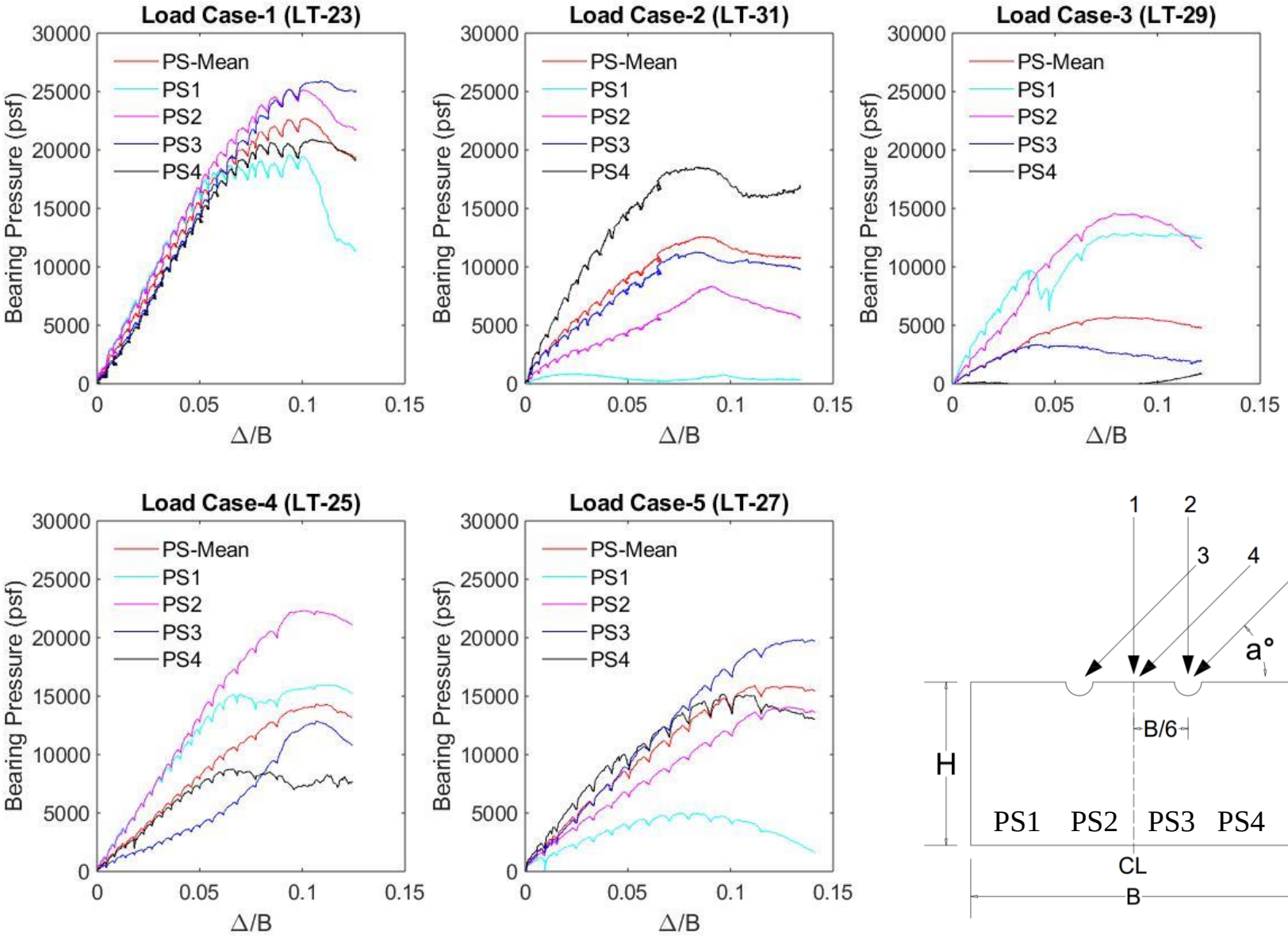
Name	Load Case	D_r (%)	γ (pcf)	ϕ (degree)	Measured-qu (psf)	Embedment Depth (D_f)	Eccentricity	Inclination	Series #
LT-41	3	96.65	108.17	36.42	10460	0.5B	B/6	0.10	1
LT-42	3	97.10	108.27	36.48	13400	0.5B	B/6	0.10	2
LT-43	2	96.71	108.19	36.43	17830	0	B/6	0	3
LT-44	1	95.70	107.97	36.28	29540	0.5B	0	0	3
LT-45	4	95.70	107.97	36.28	7596	0	0	0.25	1
LT-46	4	96.41	108.12	36.39	5681	0	B/6	0.25	2
LT-47	5	95.22	107.87	36.21	14590	0	B/6	-0.25	1
LT-48	5	94.99	107.82	36.18	13740	0	B/6	-0.25	2
LT-49	3	95.89	108.01	36.31	3547	0	B/6	0.25	1
LT-50*	3	-	-	-	-	-	-	-	-
LT-51	4	94.63	107.74	36.13	12800	0.5B	B/6	0.25	1
LT-52	4	97.06	108.26	36.48	12650	0.5B	B/6	0.25	2
LT-53	5	95.56	107.94	36.26	25410	0.5B	B/6	-0.25	1
LT-54	5	95.22	107.87	36.21	22660	0.5B	B/6	-0.25	2
LT-55	3	95.77	107.98	36.29	7242	0.5B	B/6	0.25	1
LT-56	3	94.94	107.81	36.17	9037	0.5B	B/6	0.25	2
LT-57	3	95.00	107.82	36.18	3684	0	B/6	0	3
** Load test excluded from analysis due to instrumentation malfunction									

Pressure vs. Displacement Plot-VD (Df=0 and L/A=0.10)

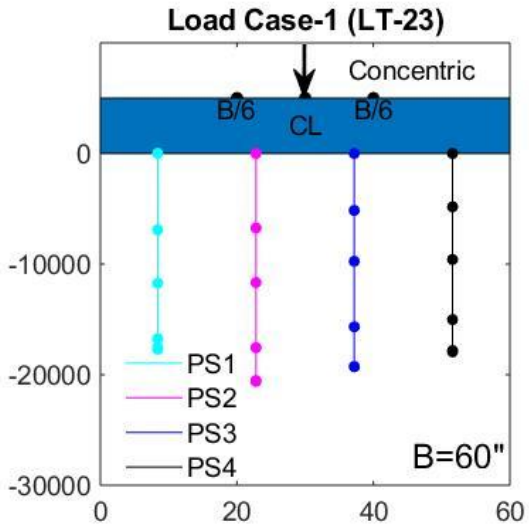
Bearing Capacity Equation: $q_n = 0.5\gamma B N_\gamma S_\gamma \boldsymbol{i_\gamma}$

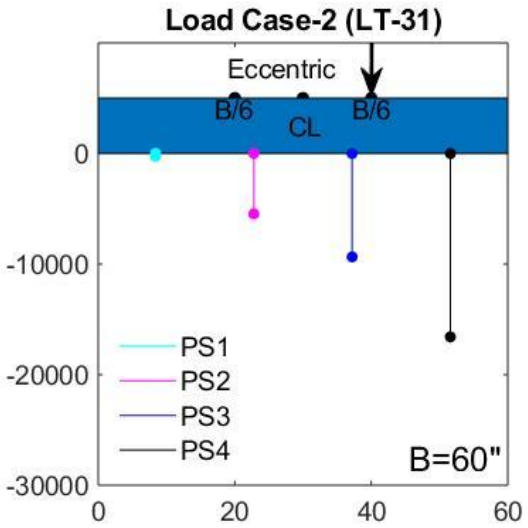


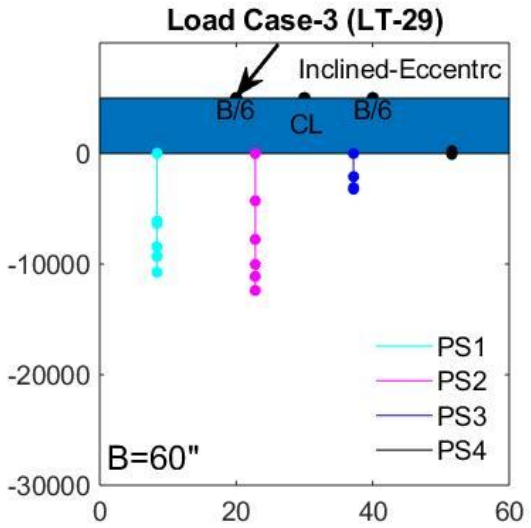
Pressure vs. Displacement Plot (Df=0 and L/A=0.10)

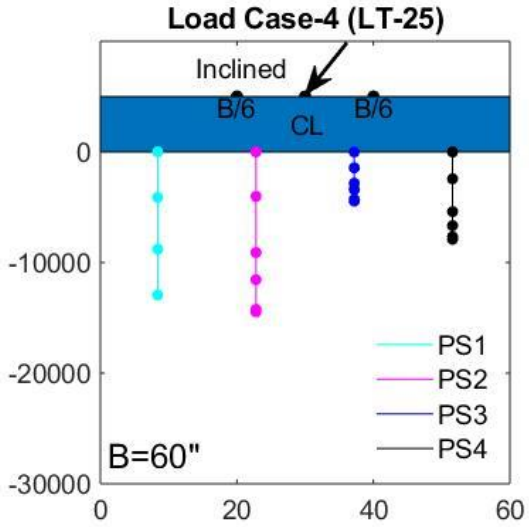


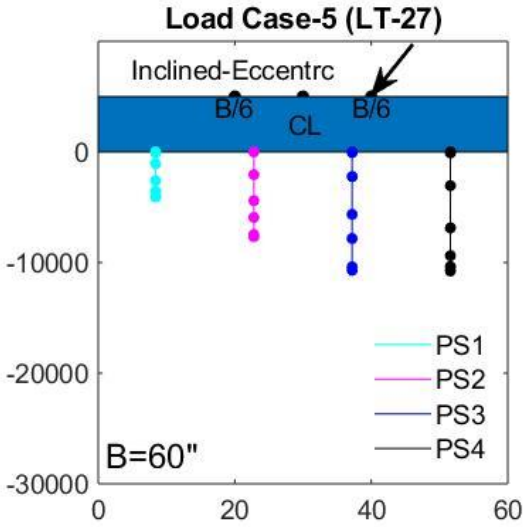
Pressure Distribution Plot-VD (Df=0 and L/A=0.10)

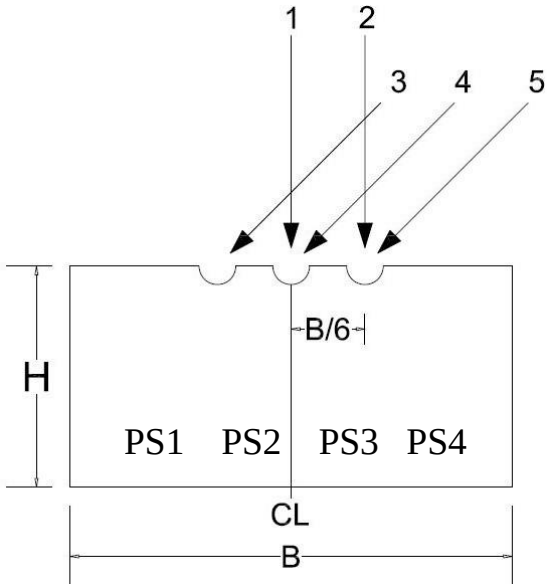






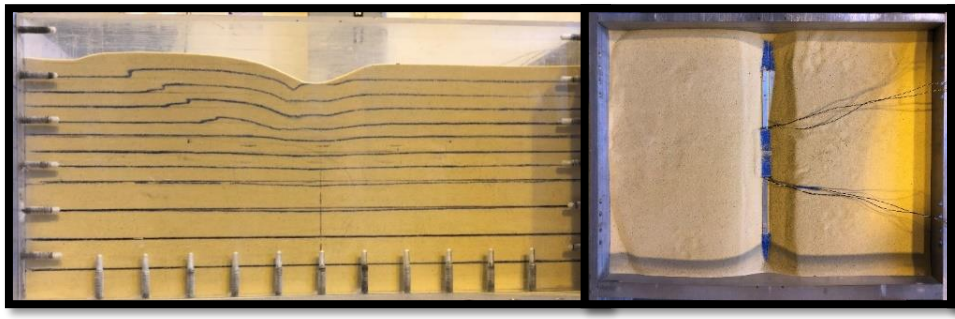






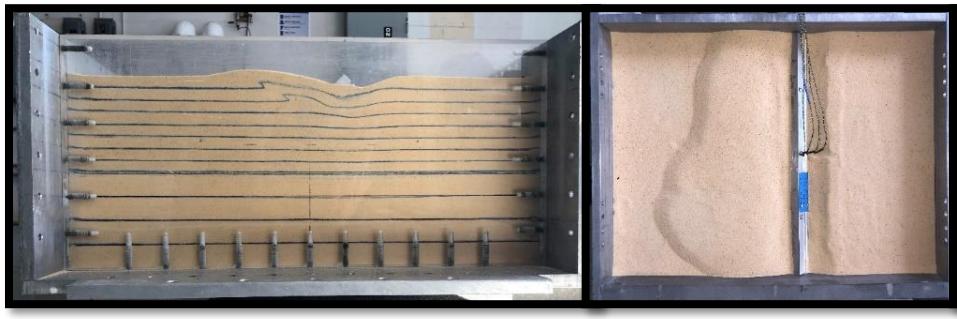
FAILURE SURFACE IMAGES-VD (Df=0 and L/A=0.10)

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

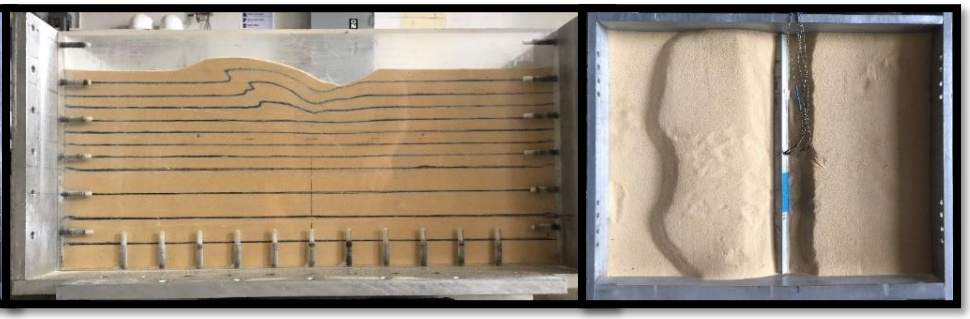


Load Case -4 (LT-26)

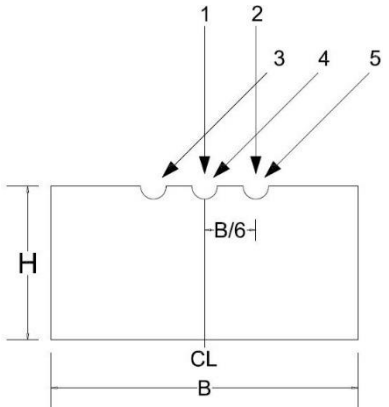
Load Case -2 (LT-31)



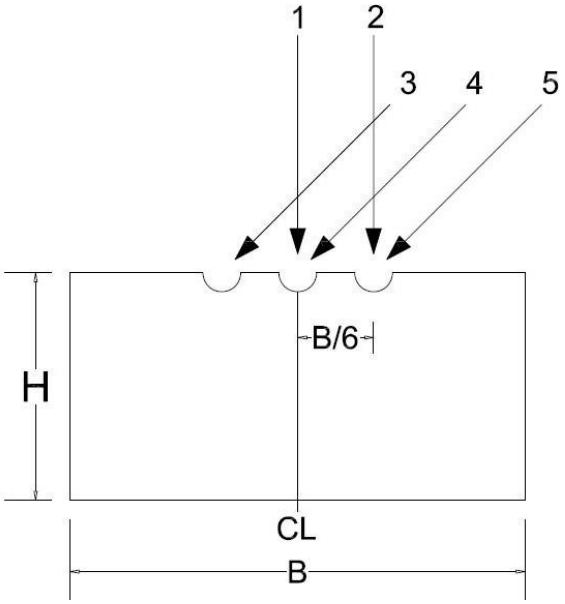
Load Case -5 (LT-28)

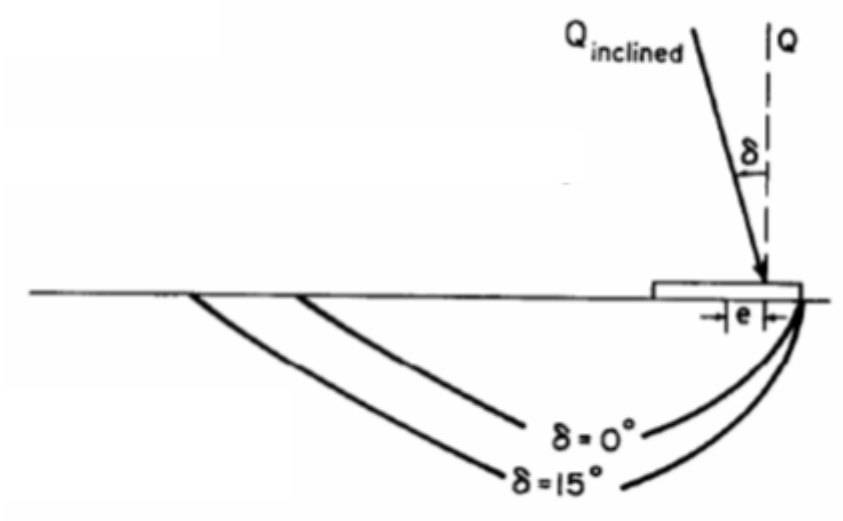


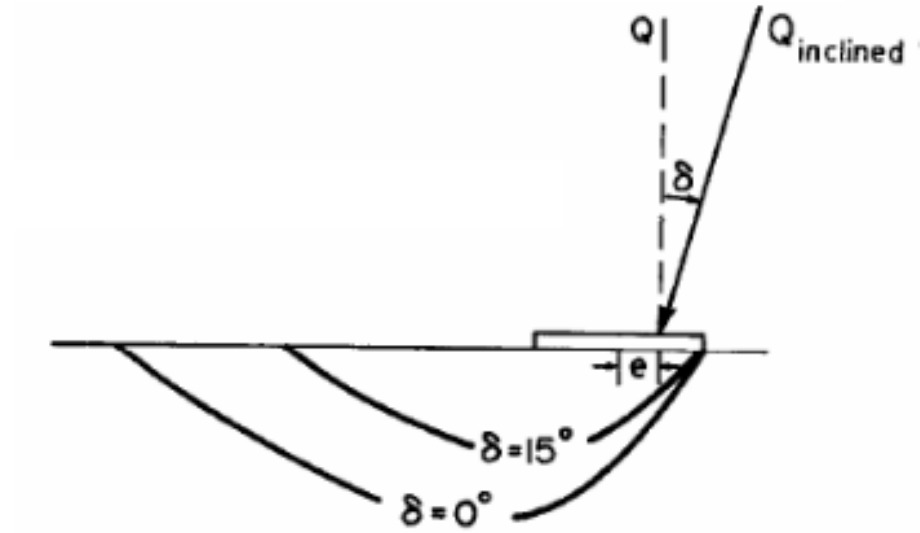
Load Case -3 (LT-30)



THEORECTICAL FAILURE SURFACE



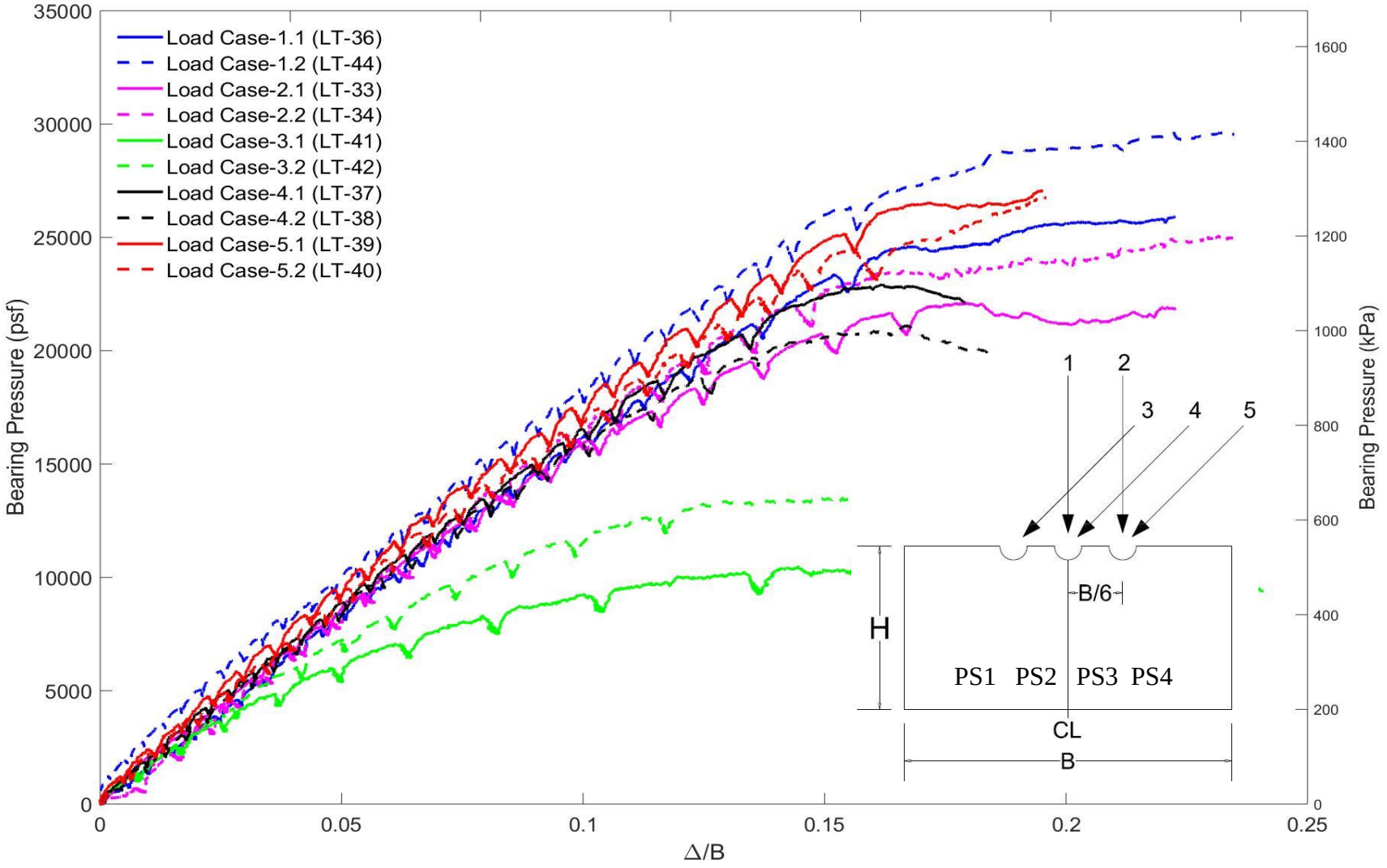




Perloff and Baron, 1976

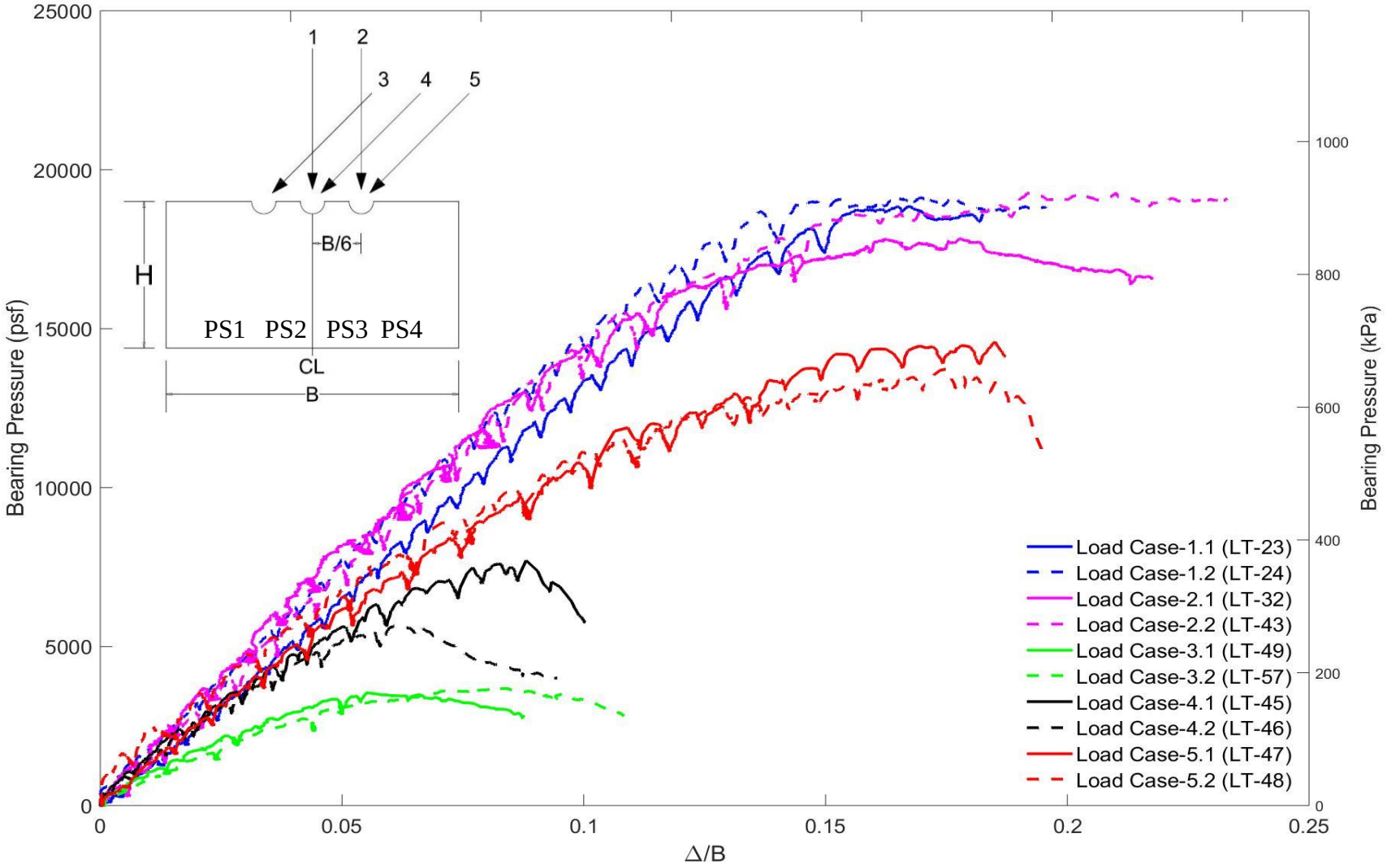
Pressure vs. Displacement Plot-VD (Df=0.5B and L/A=0.10)

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



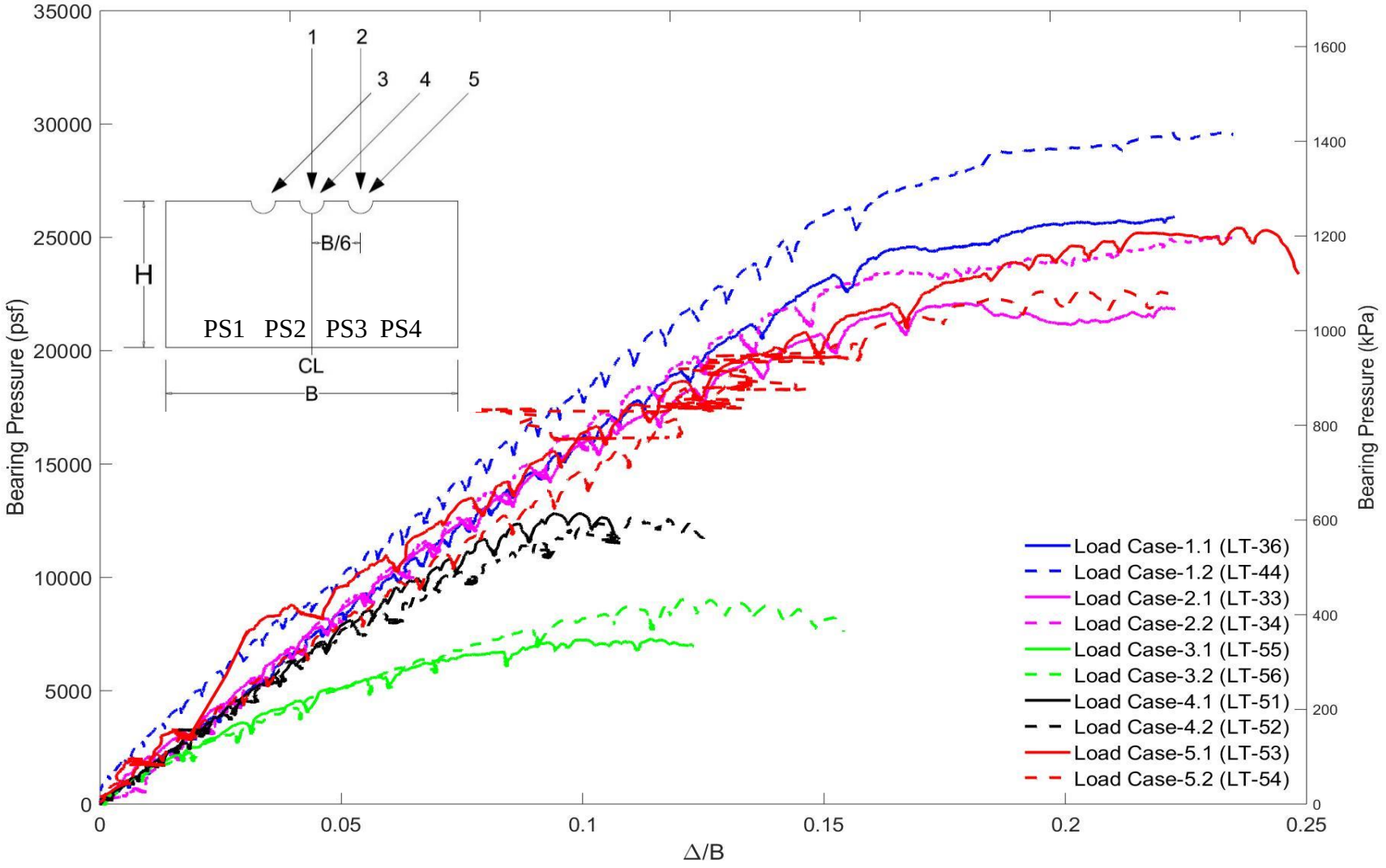
Pressure vs. Displacement Plot-VD (Df=0 and L/A=0.25)

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



Pressure vs. Displacement Plot-VD (Df=0.5B and L/A=0.25)

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



LOAD TEST ON RECTANGULAR FOUNDATION (L/B=10)-MB

Name	Load Case	D_r (%)	γ (pcf)	ϕ (degree)	Measured-qu (psf)	Embedment Depth (D_f)	Eccentricity	Inclination	Series #
LT-58	1	63.65	101.50	31.69	10360	0	0	0	1
LT-59	1	64.08	101.58	31.75	10670	0	0	0	2
LT-60	1	63.79	101.52	31.71	14120	0.5B	0	0	1
LT-61	1	63.40	101.45	31.66	15360	0.5B	0	0	2
LT-62	2	63.80	101.53	31.71	11280	0	B/6	0	1
LT-63	2	64.16	101.59	31.77	11420	0	B/6	0	2
LT-64	2	63.88	101.54	31.73	15780	0.5B	B/6	0	1
LT-65	2	64.37	101.63	31.8	15240	0.5B	B/6	0	2
LT-66	3	64.56	101.67	31.82	6080	0	B/6	0.10	1
LT-67	3	64.26	101.61	31.78	6503	0	B/6	0.10	2
LT-68	3	64.23	101.61	31.78	10050	0.5B	B/6	0.10	1
LT-69	3	63.17	101.41	31.62	8315	0.5B	B/6	0.10	2
LT-70	4	64.25	101.61	31.78	6155	0	0	0.10	1
LT-71	4	63.27	101.42	31.64	6531	0	0	0.10	2
LT-72	4	63.52	101.47	31.68	11070	0.5B	0	0.10	1
LT-73	4	64.03	101.57	31.75	12570	0.5B	0	0.10	2
LT-74	5	64.39	101.64	31.80	11880	0	B/6	-0.10	1
LT-75	5	64.08	101.58	31.76	11380	0	B/6	-0.10	2
LT-76	5	63.85	101.54	31.72	16650	0.5B	B/6	-0.10	1
LT-77	5	63.74	101.51	31.71	17540	0.5B	B/6	-0.10	2

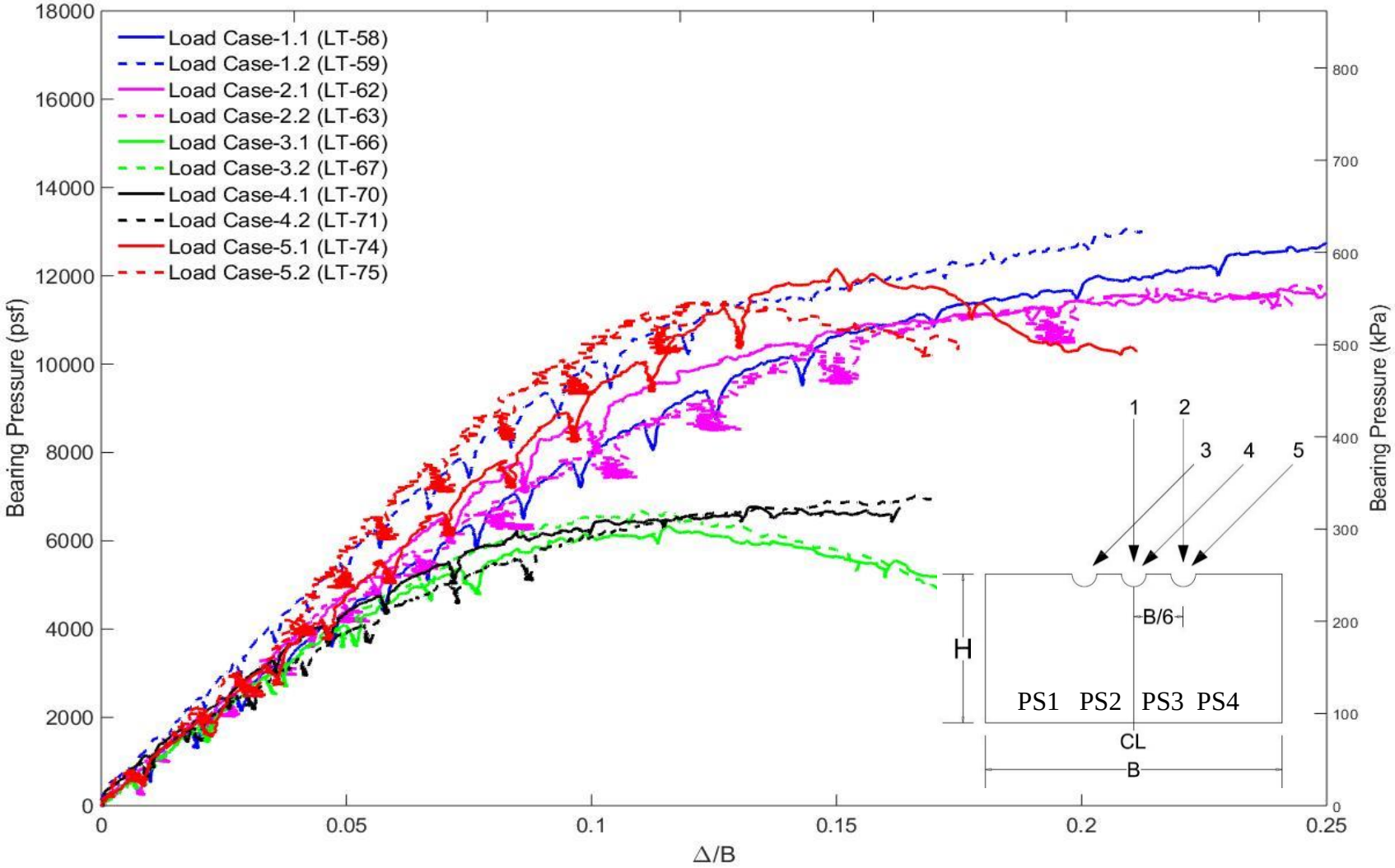
** Load test excluded from analysis due to instrumentation malfunction

LOAD TEST ON RECTANGULAR FOUNDATION (L/B=10)-MB

Name	Load Case	D_r (%)	γ (pcf)	ϕ (degree)	Measured-qu (psf)	Embedment Depth (D_f)	Eccentricity	Inclination	Series #
LT-78	3	63.53	101.47	31.68	3140	0	B/6	0.25	1
LT-79	3	63.74	101.51	31.71	2124	0	B/6	0.25	2
LT-80	3	64.24	101.61	31.78	8012	0.5B	B/6	0.25	1
LT-81	3	63.59	101.49	31.68	6356	0.5B	B/6	0.25	2
LT-82	4	63.32	101.43	31.65	3023	0	0	0.25	1
LT-83	4	63.69	101.51	31.7	2612	0	0	0.25	2
LT-84	4	64.19	101.6	31.77	9322	0.5B	0	0.25	1
LT-85	4	64.06	101.58	31.75	8969	0.5B	0	0.25	2
LT-86	5	63.74	101.51	31.71	9169	0	B/6	-0.25	1
LT-87	5	63.66	101.5	31.7	9818	0	B/6	-0.25	2
LT-88	5	63.34	101.44	31.65	13210	0.5B	B/6	-0.25	1
LT-89	5	63.92	101.55	31.73	12630	0.5B	B/6	-0.25	2
** Load test excluded from analysis due to instrumentation malfunction									

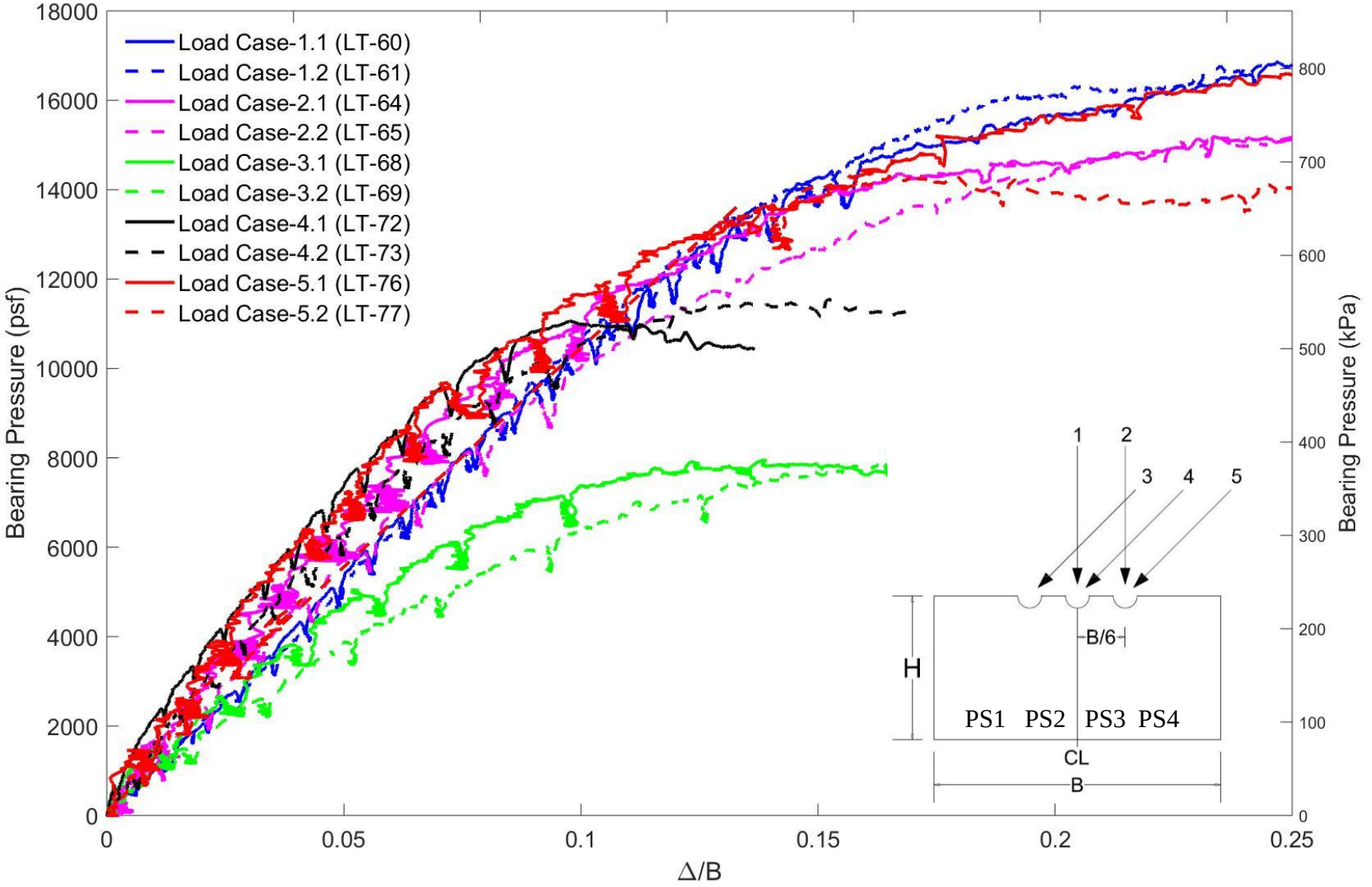
Pressure vs. Displacement Plot-MD (Df=0 and L/A=0.1)

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



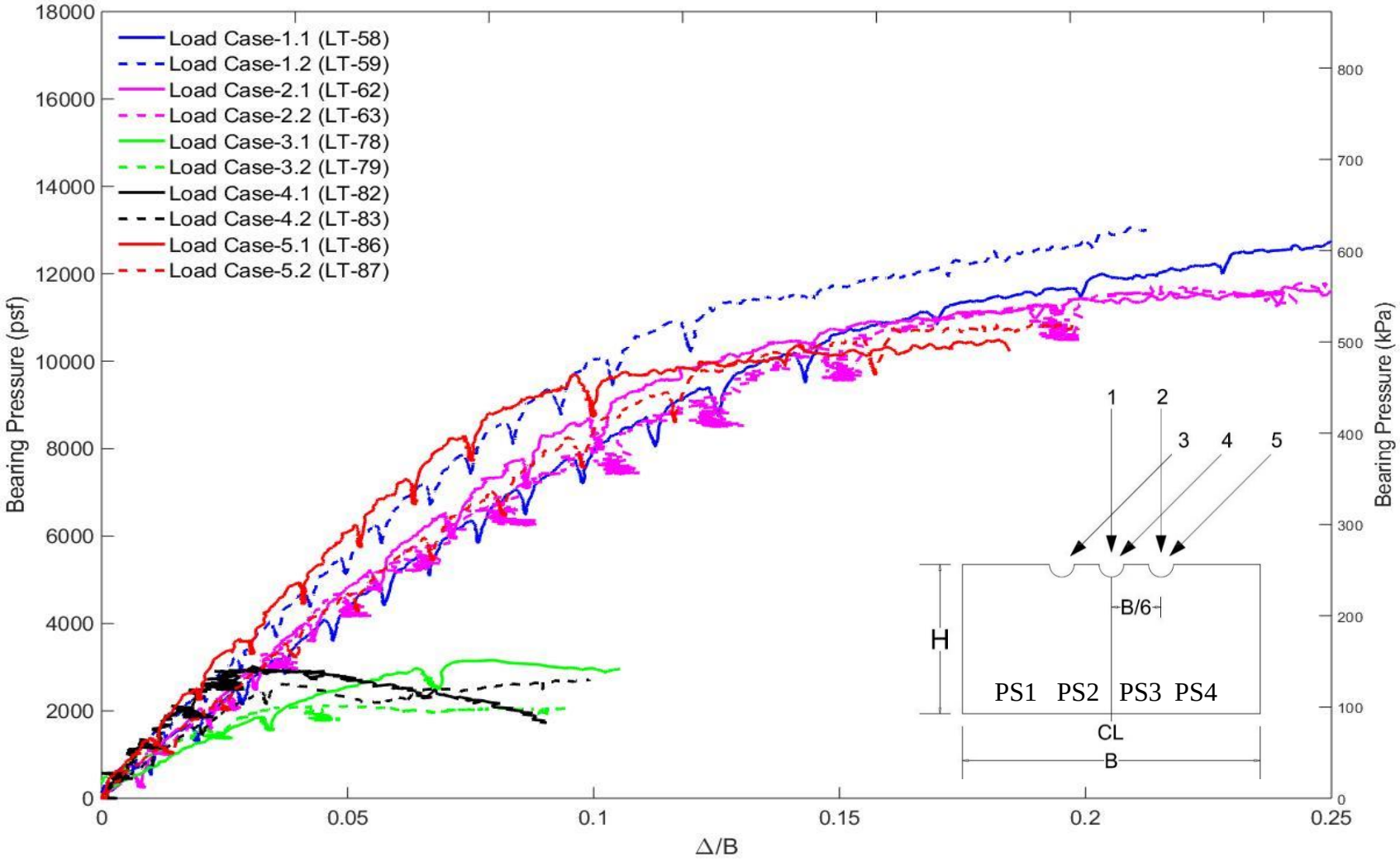
Pressure vs. Displacement Plot-MD (Df=0.5B and L/A=0.10)

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



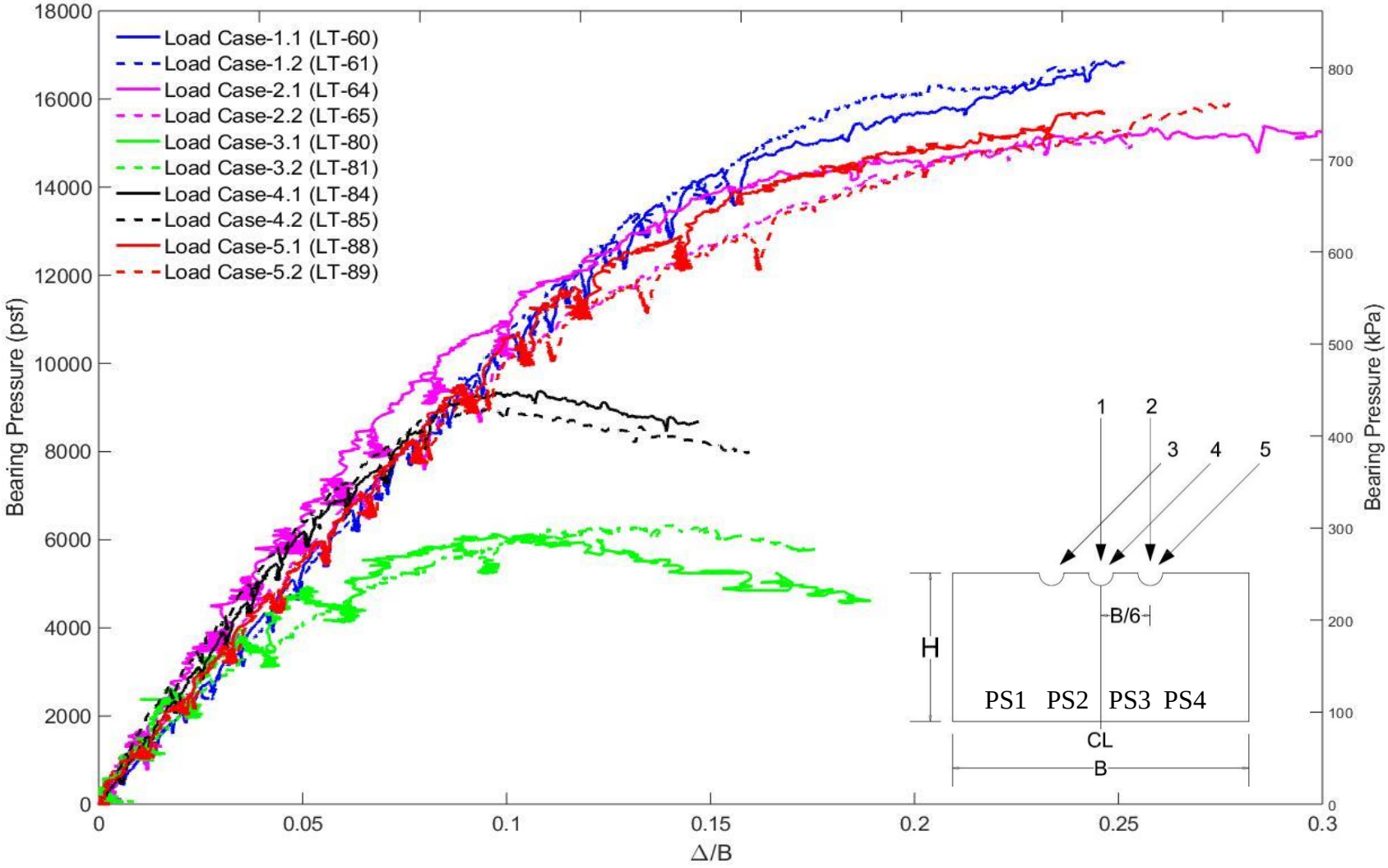
Pressure vs. Displacement Plot-MD (Df=0 and L/A=0.25)

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

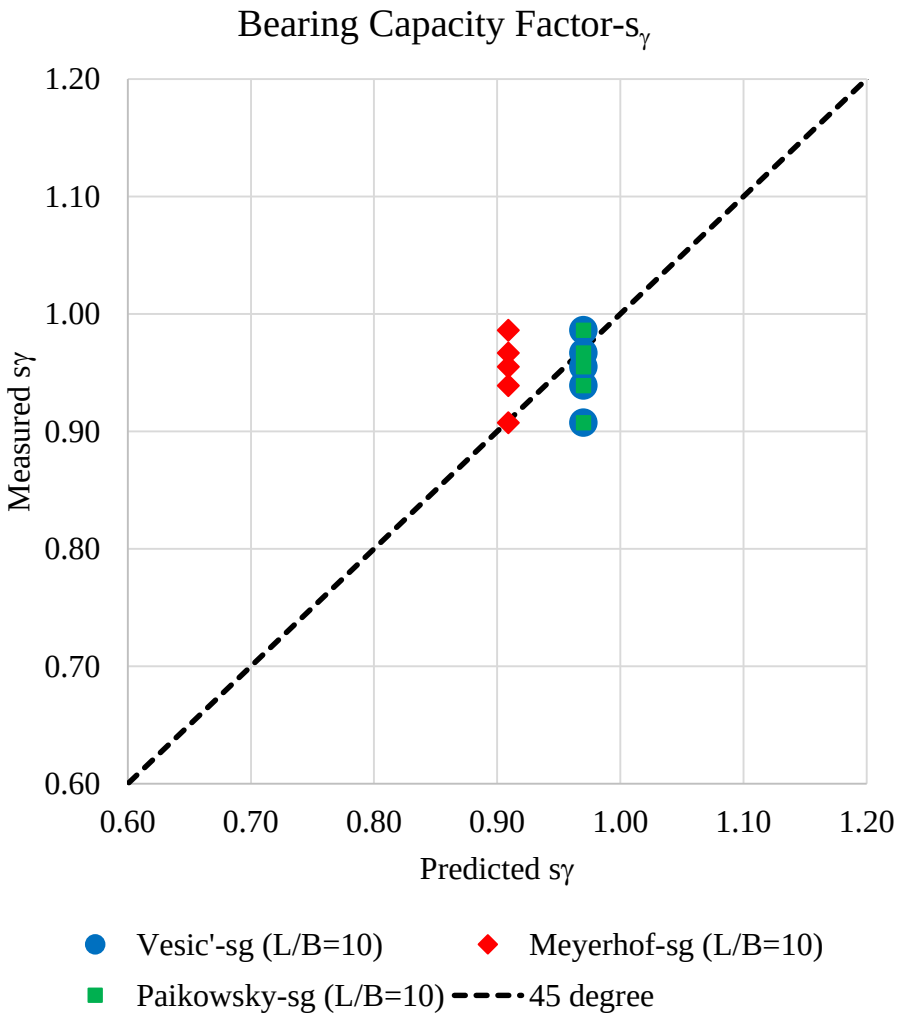


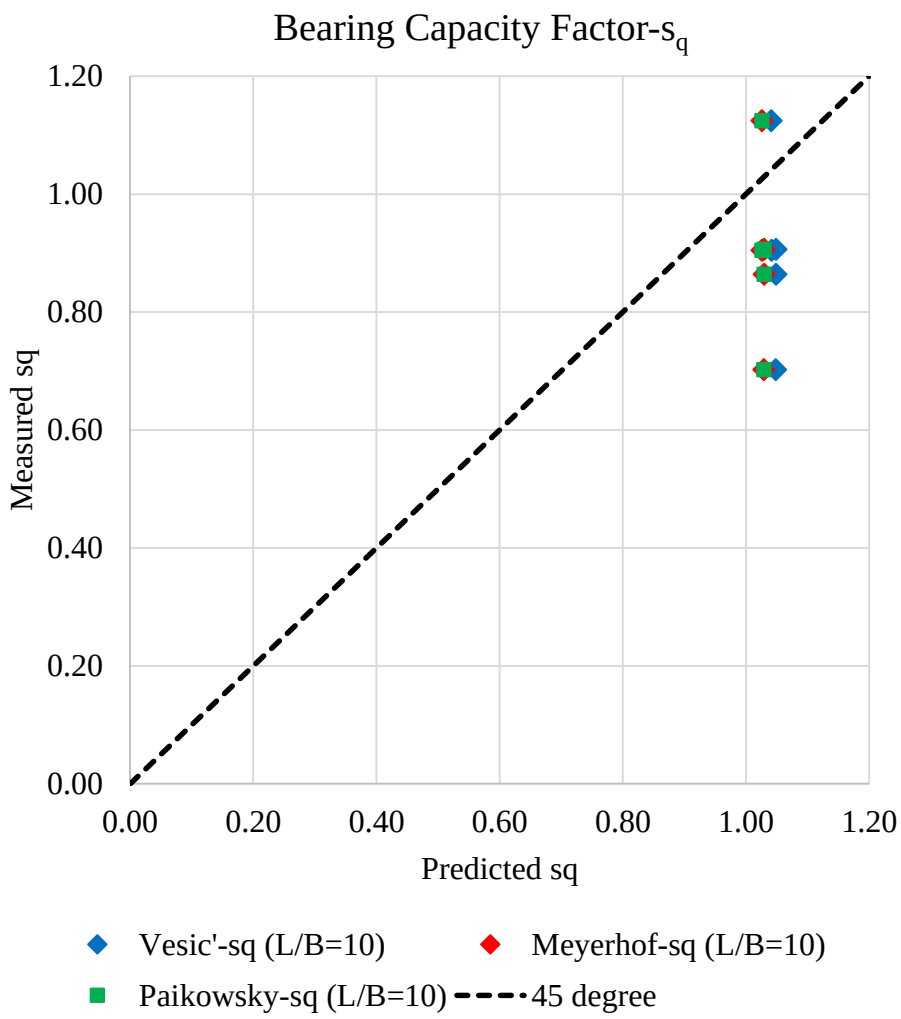
Pressure vs. Displacement Plot-MD (Df=0.5B and L/A=0.10)

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

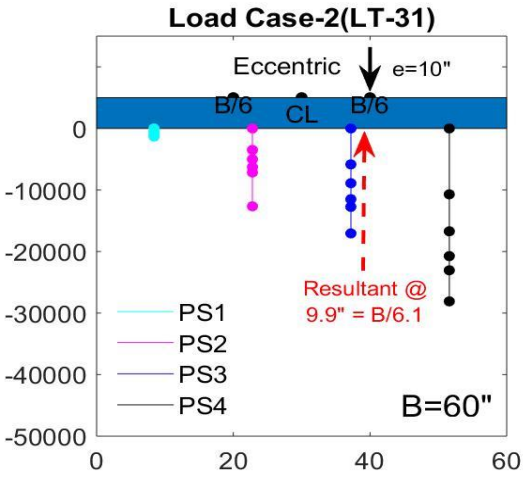


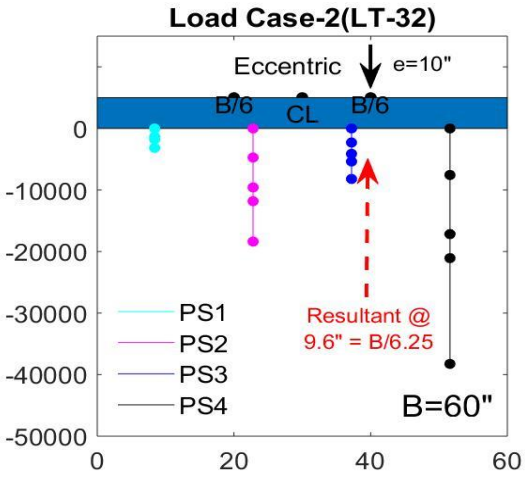
SHAPE & DEPTH FACTORS (L/B=10)

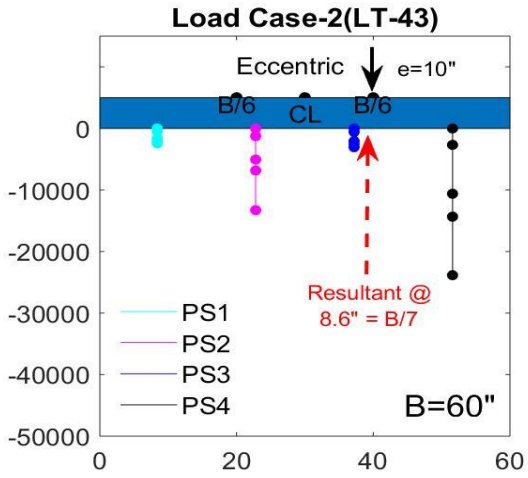


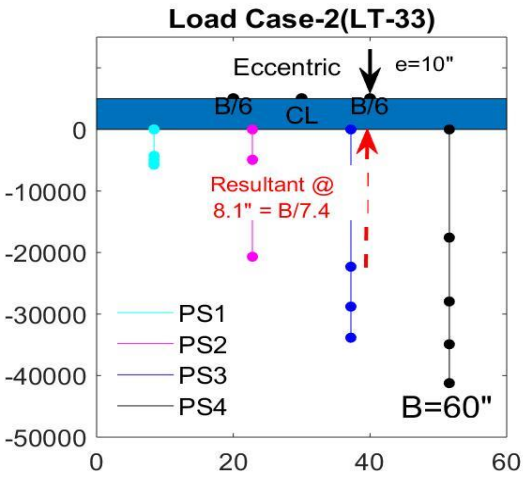


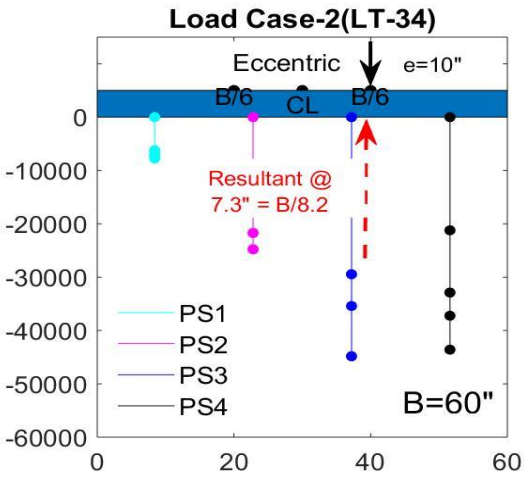
Pressure Distribution for Eccentric Load Case







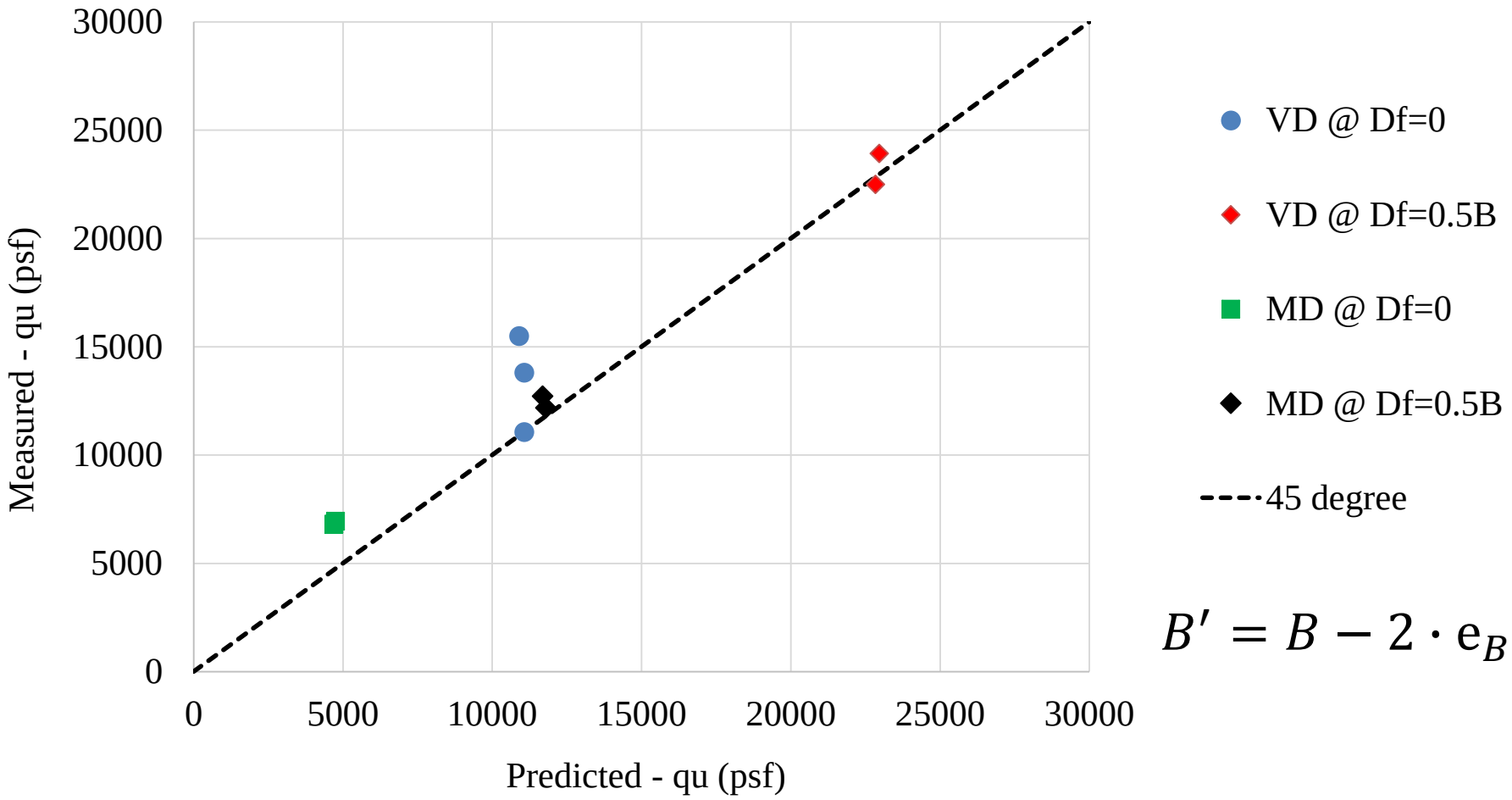




$$B' = B - 2 \cdot e_B$$

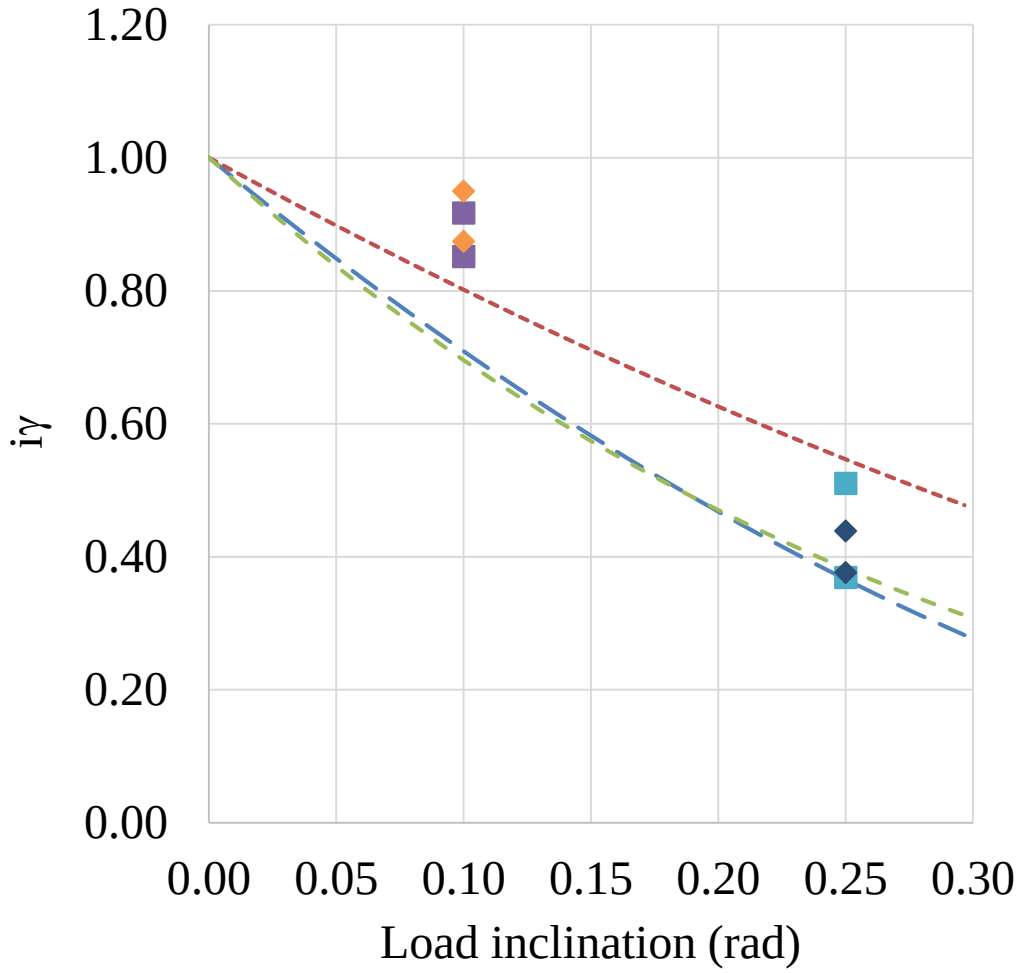
Measured Eccentricity	Design Eccentricity	Foundation Rotation (degree)
B/6.1	B/6	5.65
B/6.25	B/6	4.41
B/7	B/6	4.69
B/7.4	B/6	4.51
B/8.2	B/6	4.60

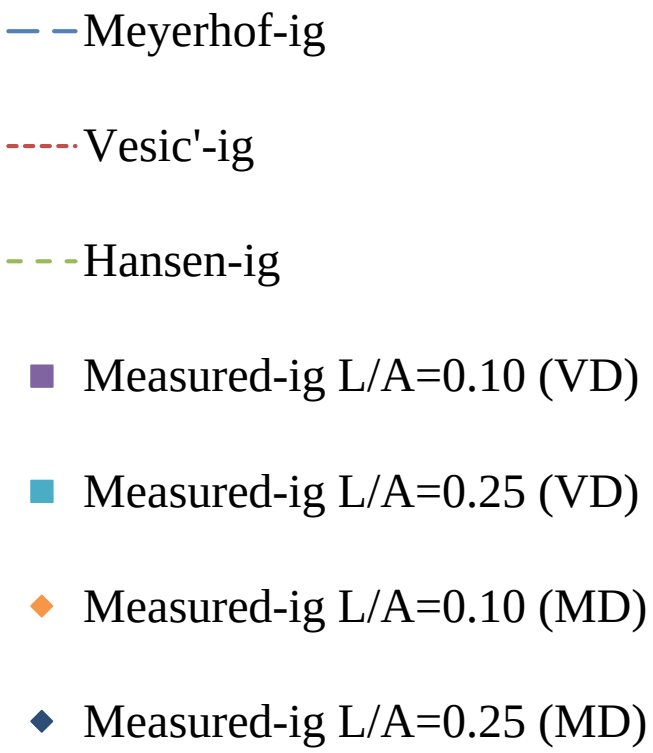
Effect of Eccentricity on Surface & Embedded Footing



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

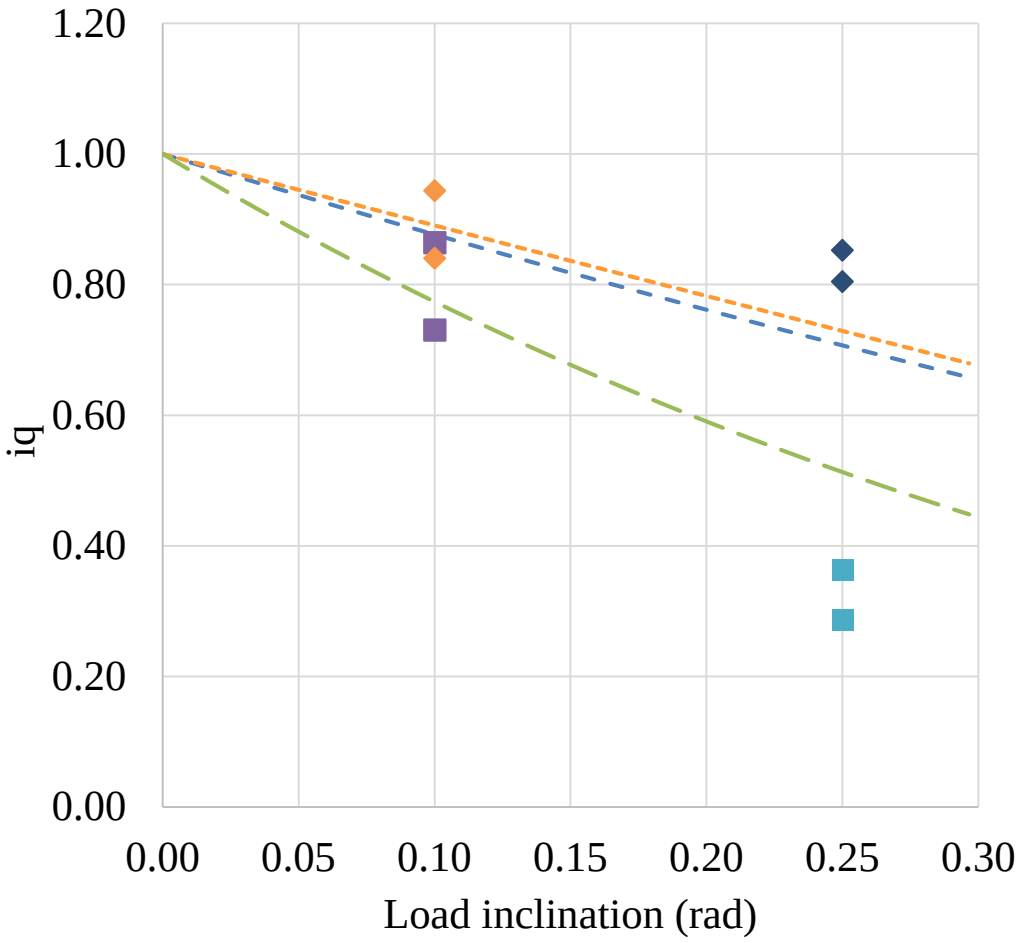
Effect of Load Inclination on Surface Footing

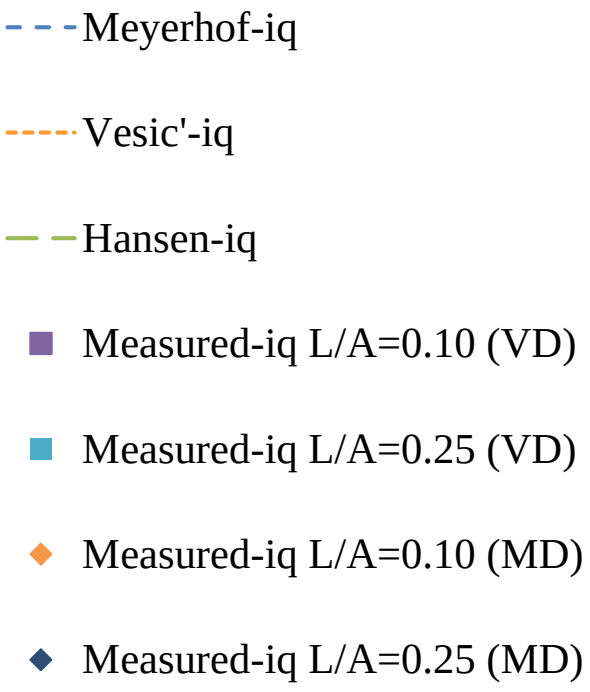




$$i_\gamma = \frac{q_u}{0.5\gamma B N_\gamma s_\gamma d_\gamma}$$

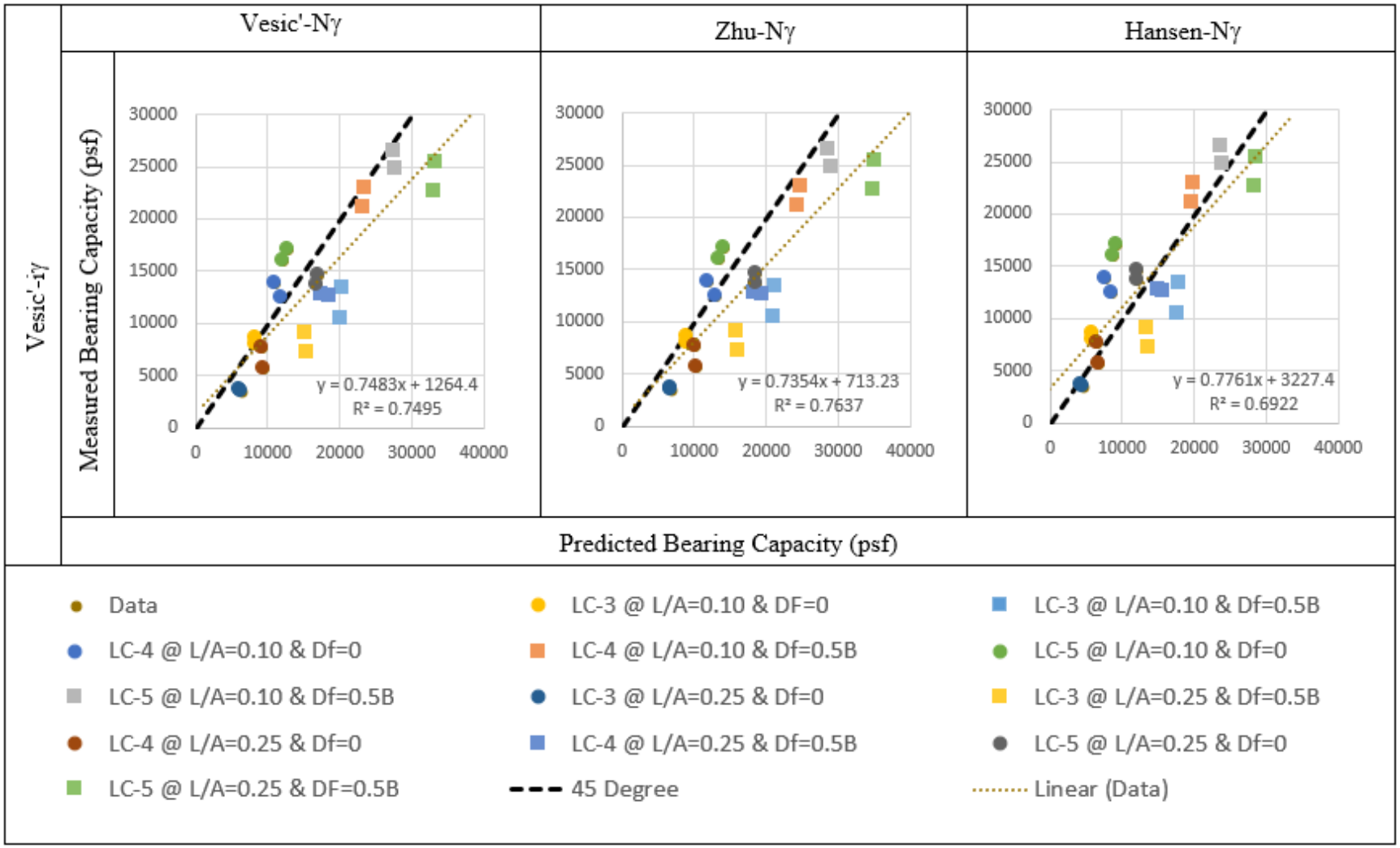
Effect of Load Inclination on Surface Footing





$$i_q = \frac{q_u - 0.5\gamma B N_\gamma s_\gamma d_\gamma i_\gamma}{D_f \gamma N_q s_q d_q}$$

Bearing Capacity Bias Plot for Vesic' - iγ (VD)



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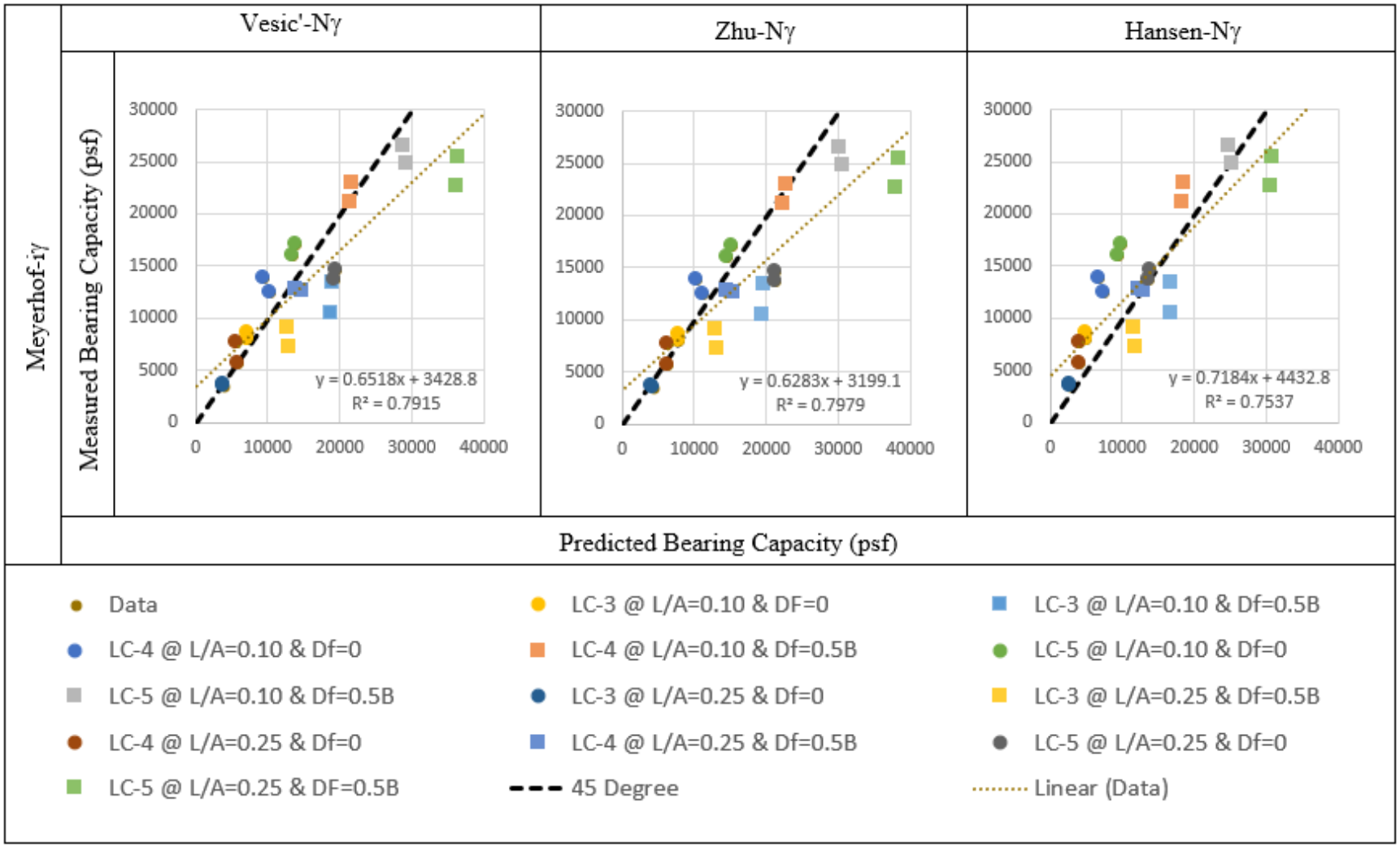
Bearing Capacity Bias Plot for Meyerhof - iγ (VD)



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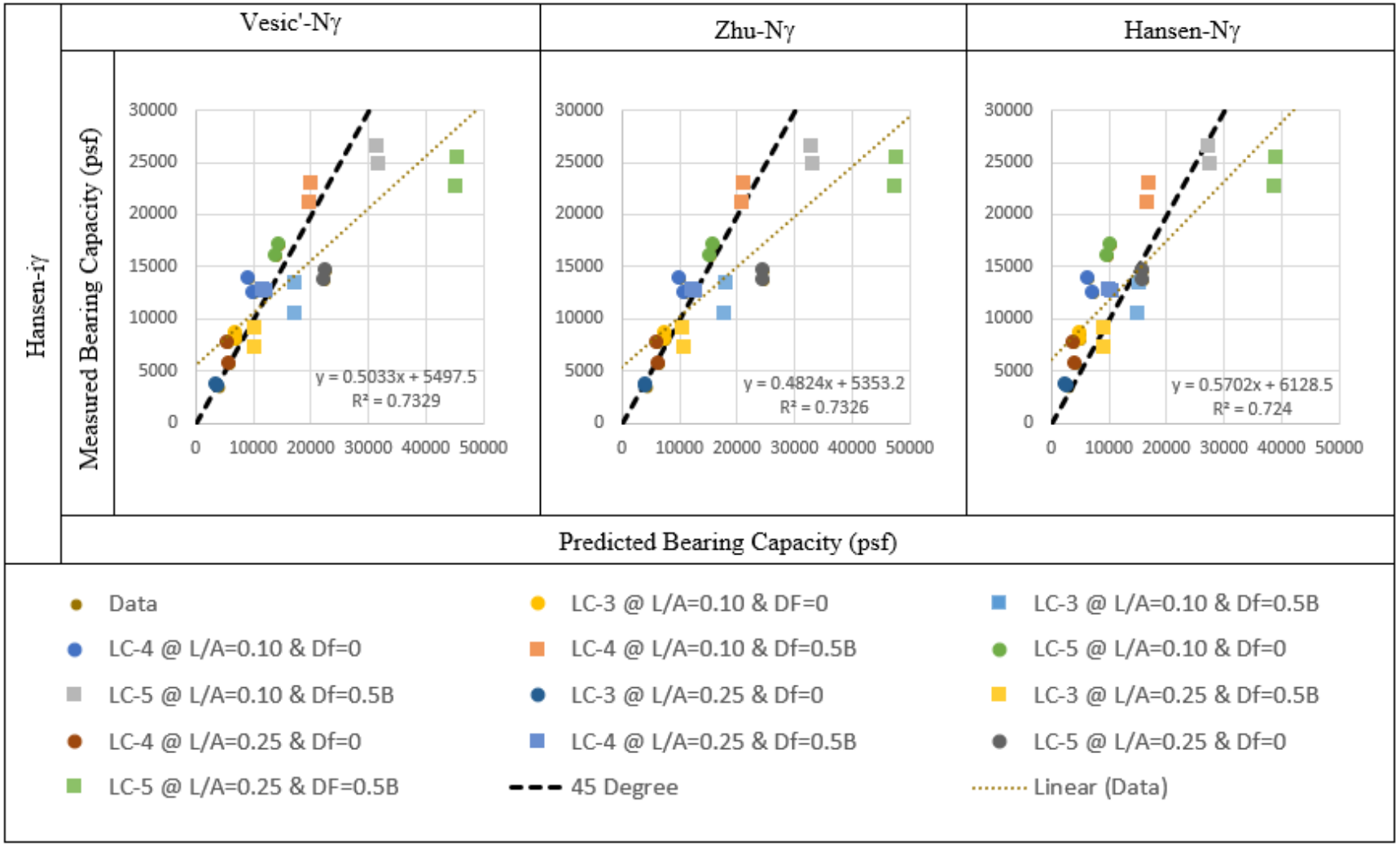
Bearing Capacity Bias Plot for Hansen - iγ (VD)



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CONCLUSIONS

Strip Foundation: (L/B=20)

- Bearing capacity factor-Nq presented by Reissner, AASHTO Recommended is representative (Mean - 13% difference)

- Bearing capacity factor-Nγ presented by Vesic' (1973), AASHTO Recommended and Zhu et al.(2001) are representative (Mean - 9.7% and 10.3% difference)

- Shape factors-sγ presented by Vesic' (1973), AASHTO Recommended are representative (< 4% error)

- Depth factors-dq and dγ presented by Meyerhof (1963), AASHTO Recommended is representative (Mean - 9.3% difference)

CONCLUSIONS CONTINUED

Rectangular Footing L/B=10: (Very Dense)

- Load Case #1-Concentric loading
  - Df=0: **19,000 psf**
  - Df=0.5B: **29,000 psf**

- Load Case#2-Eccentric loading
  - Df=0: **17,800 psf** (93.7% of LC-1)
  - Df=0.5B: **23,400 psf** (80.7% of LC-1)

CONCLUSIONS CONTINUED

Rectangular Footing L/B=10: (Very Dense)

Load Case#3-Eccentric-Inclined loading, (+) to the direction of Inclination

- Df=0 & L/A=0.10: **8,150 psf** (42.9% of LC-1)
- Df=0.5B & L/A=0.10: **13,350 psf** (46.0% of LC-1)
- Df=0 & L/A=0.25: **3,500 psf** (18.4% of LC-1)
- Df=0.5B & L/A=0.25: **8,725 psf** (45.9% of LC-1)

- Load Case#4-Inclined loading
  - Df=0 & L/A=0.10: **12,500 psf** (65.8% of LC-1)
  - Df=0.5B & L/A=0.10: **21,600 psf** (74.5% of LC-1)
  - Df=0 & L/A=0.25: **7,500 psf** (39.5% of LC-1)
  - Df=0.5B & L/A=0.25: **12,800 psf** (44.1% of LC-1)
- Load Case#5-Eccentric-Inclined loading (-) to the direction of Inclination
  - Df=0 & L/A=0.10: **17,000 psf** (90.3% of LC-1)
  - Df=0.5B & L/A=0.10: **26,500 psf** (91.4% of LC-1)
  - Df=0 & L/A=0.25: **14,000 psf** (73.7% of LC-1)
  - Df=0.5B & L/A=0.25: **23,250 psf** (80.2 % of LC-1)

CONCLUSIONS CONTINUED

Rectangular Footing L/B=10: (Medium Dense)

- Load Case #1-Concentric loading
  - Df=0: **11,200 psf**
  - Df=0.5B: **14,750 psf**
- Load Case#2-Eccentric loading
  - Df=0: **10,700 psf** (95.5% of LC-1)
  - Df=0.5B: **12,120 psf** (82.2% of LC-1)

CONCLUSIONS CONTINUED

Rectangular Footing L/B=10: (Medium Dense)

- Load Case#3-Eccentric-Inclined loading (+) to the direction of Inclination
  - Df=0 & L/A=0.10: **6,300 psf** (54.3% of LC-1)
  - Df=0.5B & L/A=0.10: **9,180 psf** (62.3% of LC-1)
  - Df=0 & L/A=0.25: **2,630 psf** (23.5% of LC-1)
  - Df=0.5B & L/A=0.25: **7,180 psf** (48.7% of LC-1)
- Load Case#4-Inclined loading
  - Df=0 & L/A=0.10: **6,340 psf** (56.6% of LC-1)
  - Df=0.5B & L/A=0.10: **11,000 psf** (74.6% of LC-1)
  - Df=0 & L/A=0.25: **2,820 psf** (25.2% of LC-1)
  - Df=0.5B & L/A=0.25: **9,145 psf** (62.0% of LC-1)
- Load Case#5-Eccentric-Inclined loading (-) to the direction of Inclination
  - Df=0 & L/A=0.10: **11,000 psf (98.2**% of LC-1)
  - Df=0.5B & L/A=0.10: **14,200 psf** (96.3% of LC-1)
  - Df=0 & L/A=0.25: **9,493 psf** (84.8% of LC-1)
  - Df=0.5B & L/A=0.25: **12,920 psf** (87.7 % of LC-1)

Thank You