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

FDOT Contract No. BDV31-977-66

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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_γ

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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

<u>OBJECTIVES</u>

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.

<u>TASKS</u>

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)

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

($cN_{cm} \rightarrow 0$, $C_{wq} \rightarrow 1$, $C_{w\gamma} \rightarrow 1$)

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

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

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

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

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

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

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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:

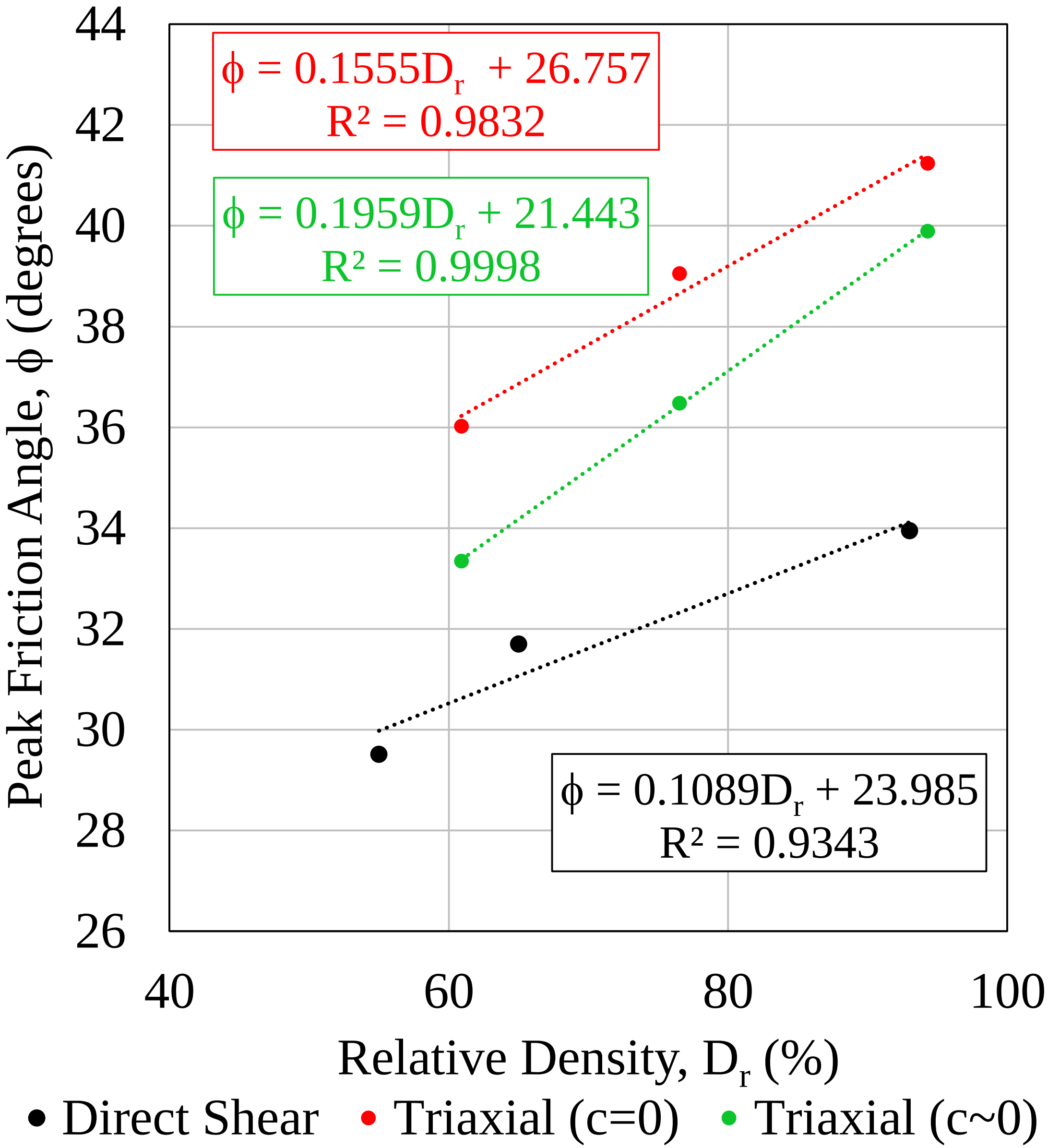
- D_r = 55 – 93%
- ϕ = 29.5° - 34°

TRIAXIAL CD-TEST:(c=0)

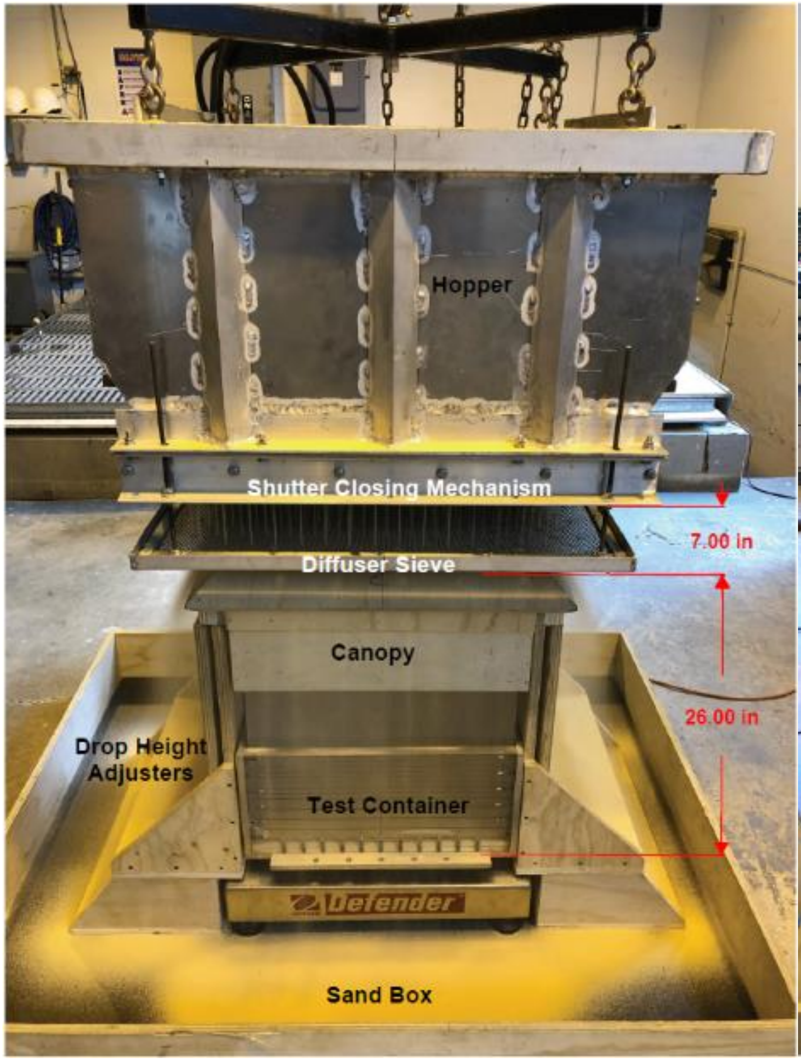
- D_r = 61 – 94%
- ϕ = 36.0° - 41.2°

TRIAXIAL CD-TEST:(c≠0)

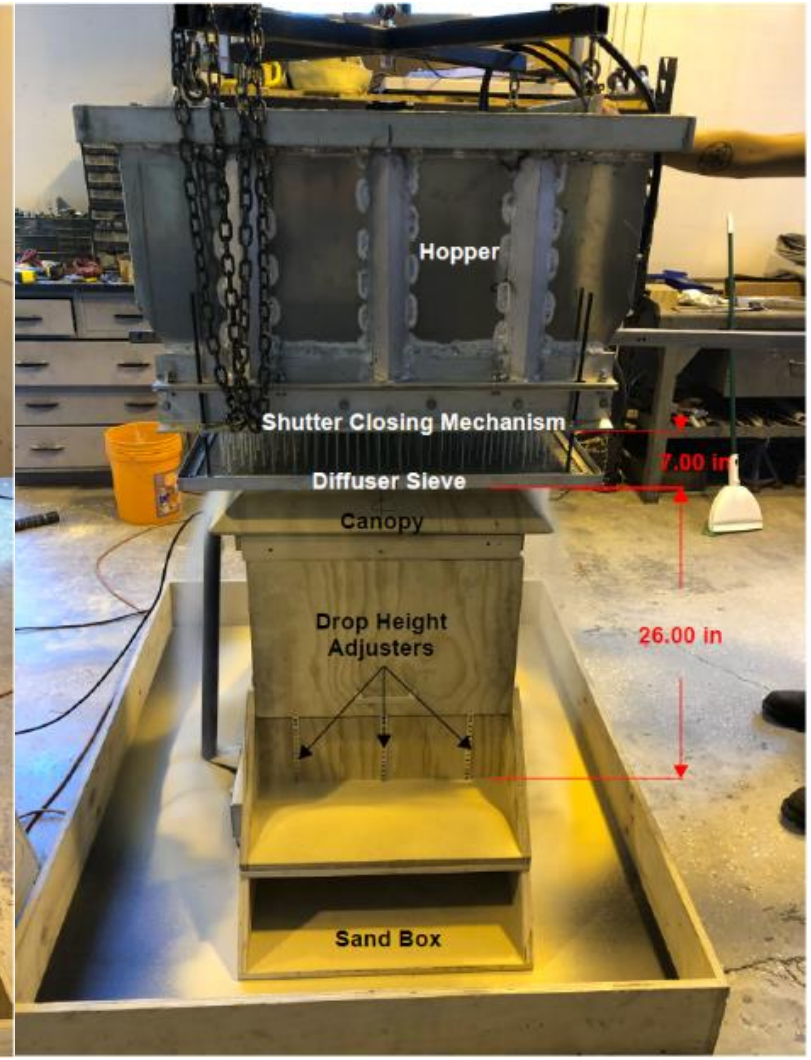
- D_r = 61 – 94%
- ϕ = 33.3° - 39.9°



TASK 2: SOIL PLUVIATION



Front View



Side View

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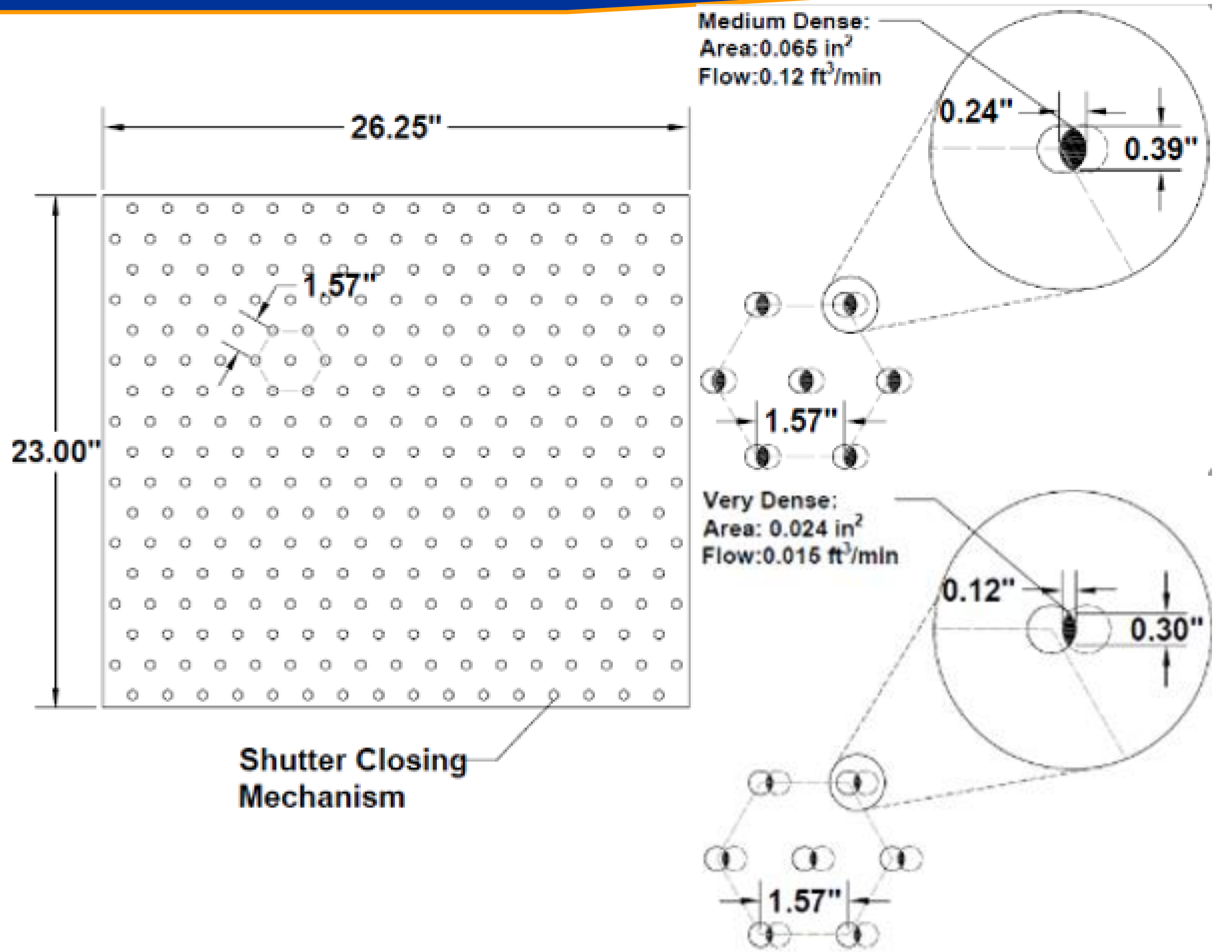
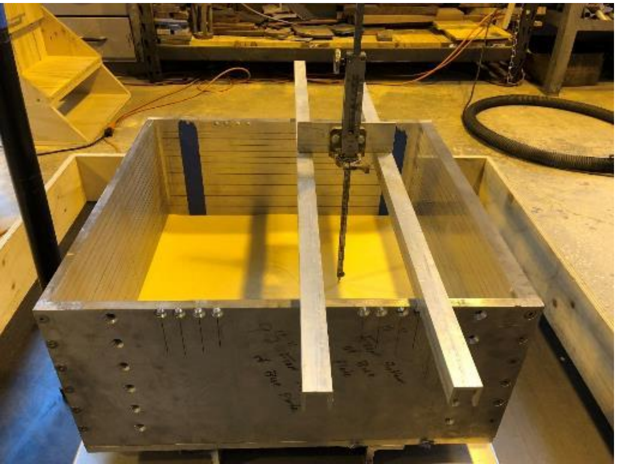
TASK 2: SOIL PLUVIATION

MEDIUM DENSE CONDITION:
- Relative density range: 35%-65%
- Drop height: 26 in
- Area: 0.065 in^2
- Flow rate: 0.12 ft^3/min
- Relative density achieved: 63%

VERY DENSE CONDITION:
- Relative density range: 85% & UP
- Drop height: 26 in
- Area: 0.024 in^2
- Flow rate: 0.015 ft^3/min
- Relative density achieved: 85%





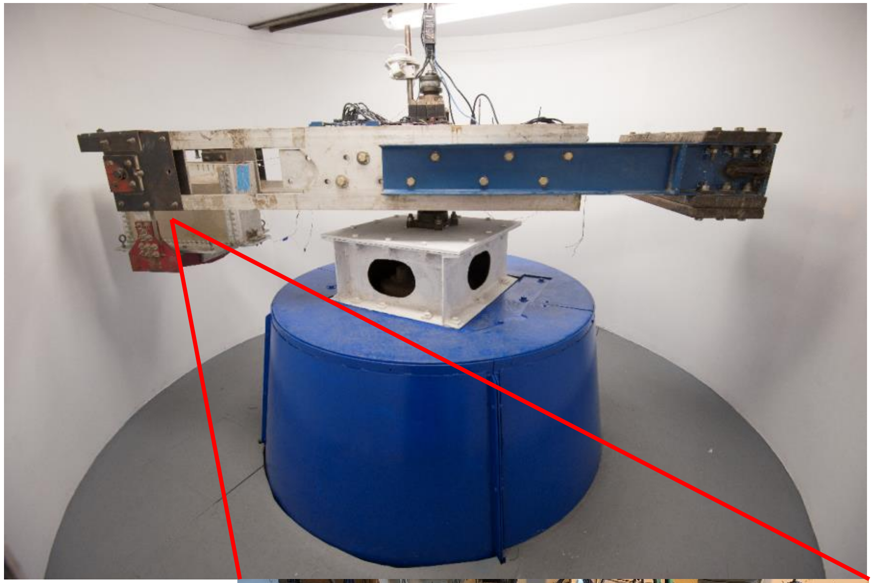
TASK 3: GEOTECHNICAL CENTRIFUGE TESTS

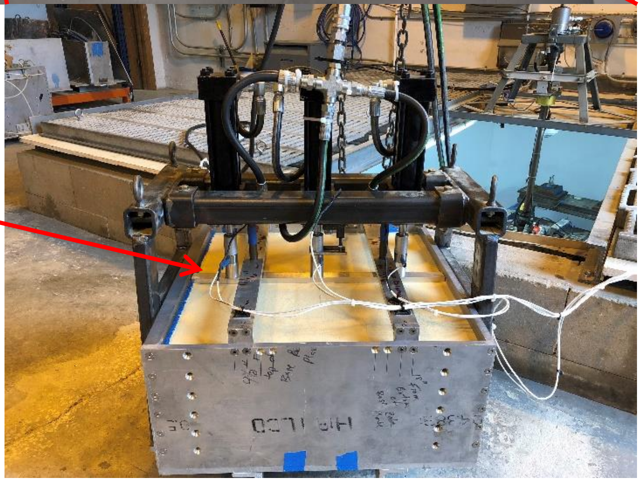
- Useful to study geotechnical problems (capacity of foundations) at a fraction of the cost of prototype study
- Soil has non-linear mechanical properties dependent on effective stress and stress history
- Spinning model in centrifuge increases the "gravitational" acceleration model which produces identical 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

- 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

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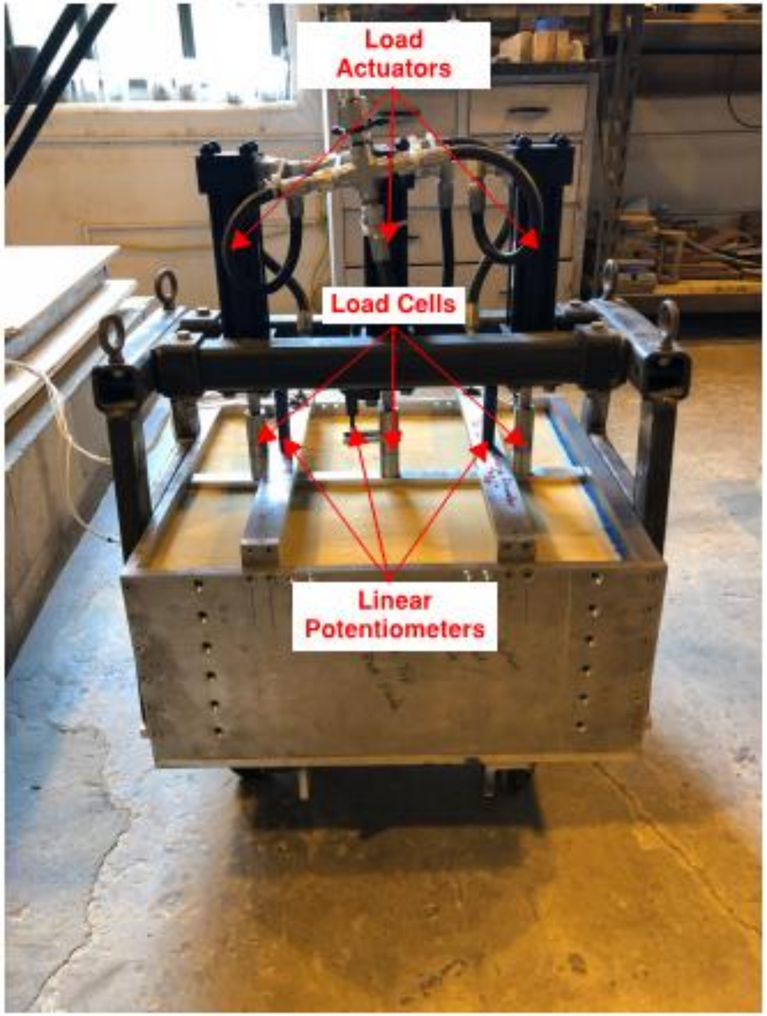
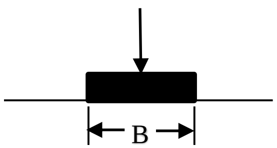
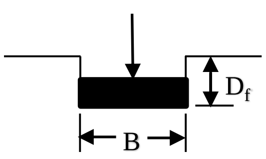
TASK 3: TEST CONDITION-1

Strip Foundation: (L/B = 20)	
Interior container width (in.)	20
Interior container length (in.)	20
Interior container height (in.)	9.5
Soil height (in.)	8.5
Scale factor (N)	36
Foundation material	Aluminum
Model width (in)	1
Model length (in.)	20
Model thickness (in.)	0.5
# of Hyd. load actuators	3
# of Omega load cells	3
# of BEI linear potentiometers	3
Enerpac P464 hand pump	1

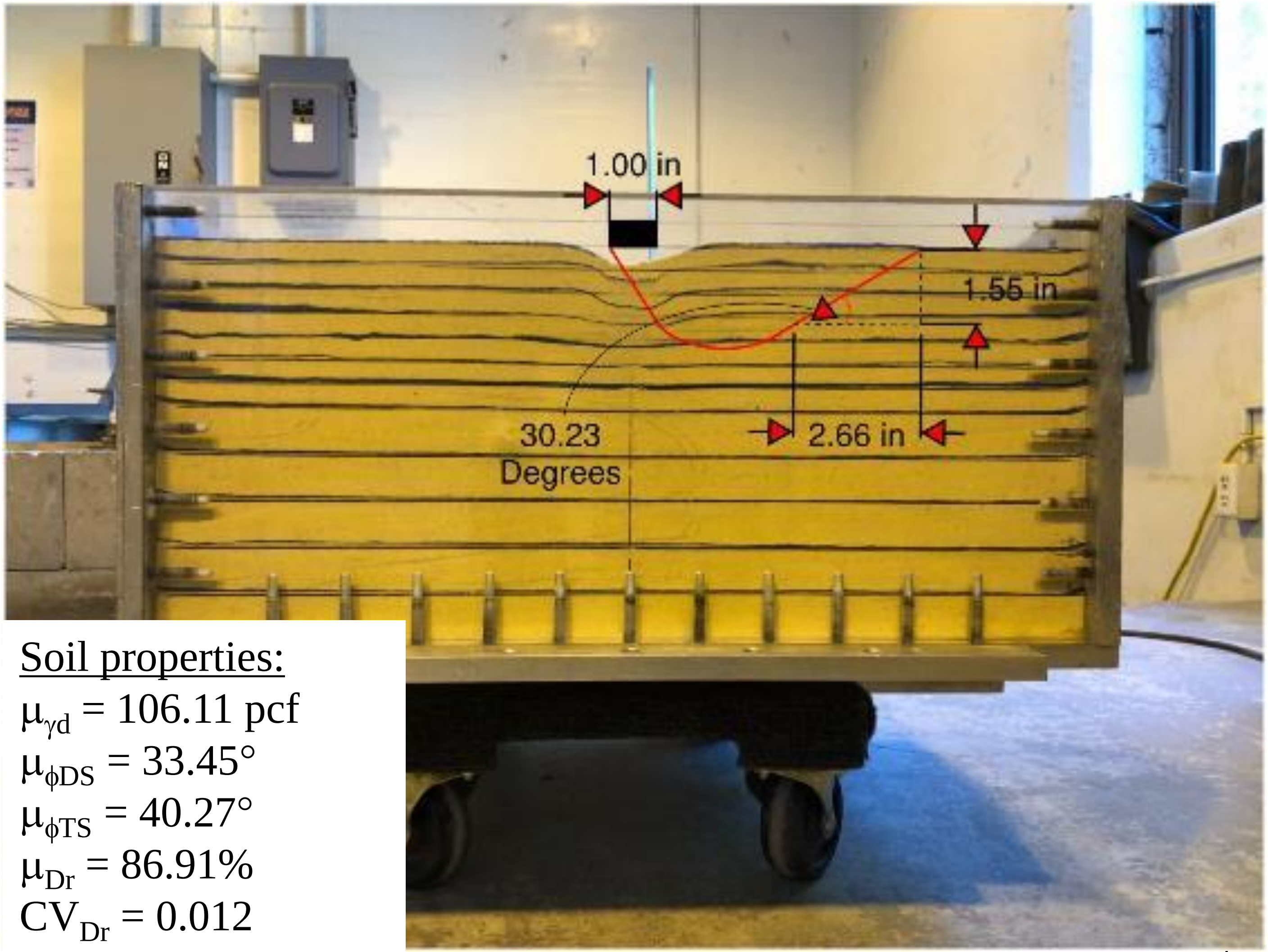


* Container designed to accommodate max load for ultimate bearing capacity and eliminate boundary influences on failure surfaces.

TASK 3: TESTS PERFORMED

Loading and Foundation Scenario	Name	Date	Density (D_r)	Embedment Depth (D_f)	Eccentricity	Inclination	Series #
	LT-1	7/5/2018	Very Dense	0	0	0	1
	LT-2	7/7/2018	Very Dense	0	0	0	2
	LT-3	7/12/2018	Medium Dense	0	0	0	1
	LT-4	7/13/2018	Medium Dense	0	0	0	2
	LT-5	7/14/2018	Medium Dense	0.5B	0	0	1
	LT-6	7/16/2018	Medium Dense	0.5B	0	0	2
	LT-7	7/17/2018	Very Dense	0.5B	0	0	1
	LT-8	7/18/2018	Very Dense	0.5B	0	0	2

TASK 3: LT-1 SOIL PROFILE VIEW



Post-test soil stratigraphy

Soil properties:

$\mu_{\gamma d}$ = 106.11 pcf
$\mu_{\phi DS}$ = 33.45°
$\mu_{\phi TS}$ = 40.27°
μ_{Dr} = 86.91%
CV_{Dr} = 0.012

$$\alpha = 45° - \frac{\phi}{2} \therefore \alpha = 30.23°$$

$$\phi = 29.54°$$

TASK 3: LT-1 SOIL PLAN VIEW

Post-test soil plan view

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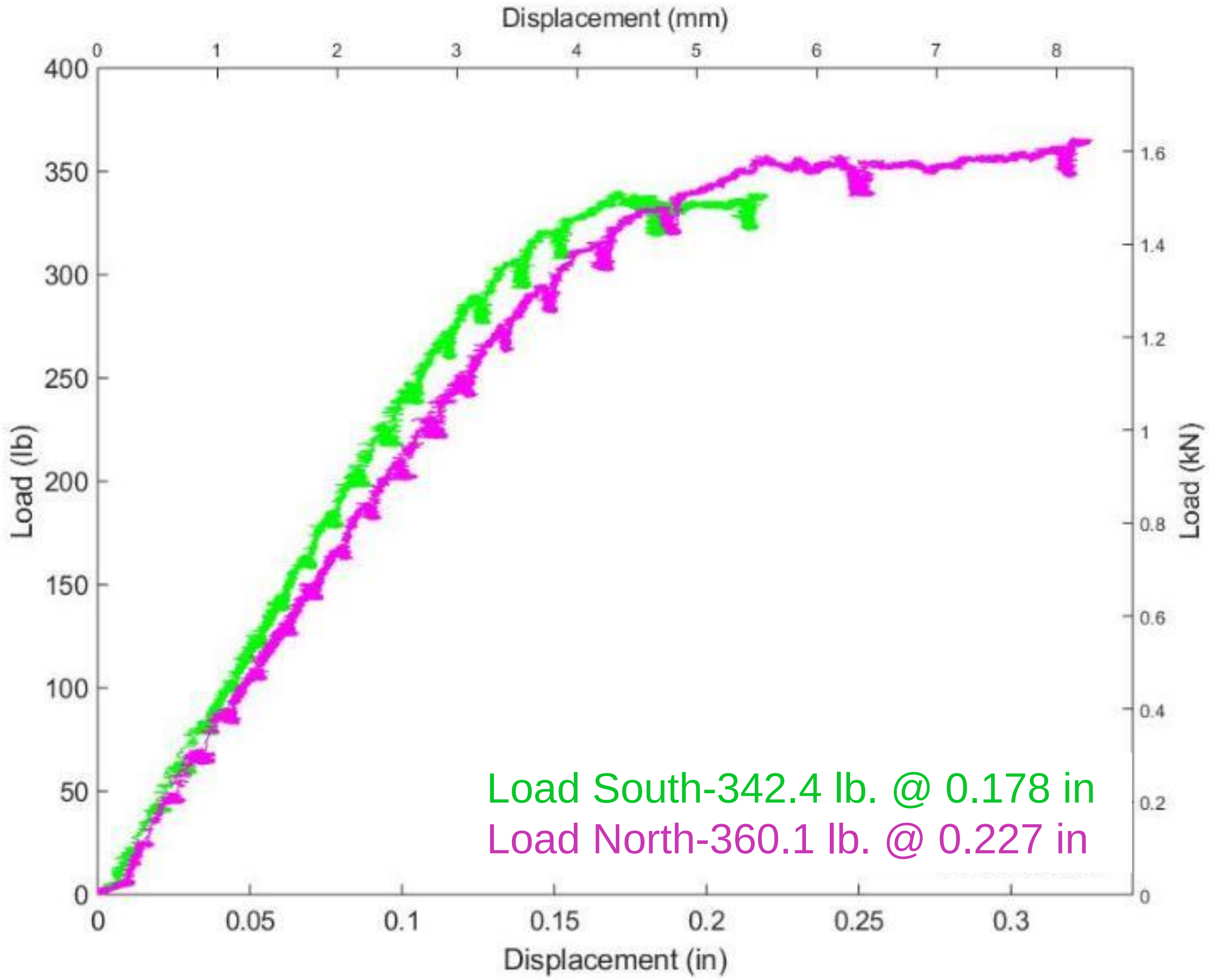
TASK 3: LT-1 LOAD vs. DISPLACEMENT (model scale)



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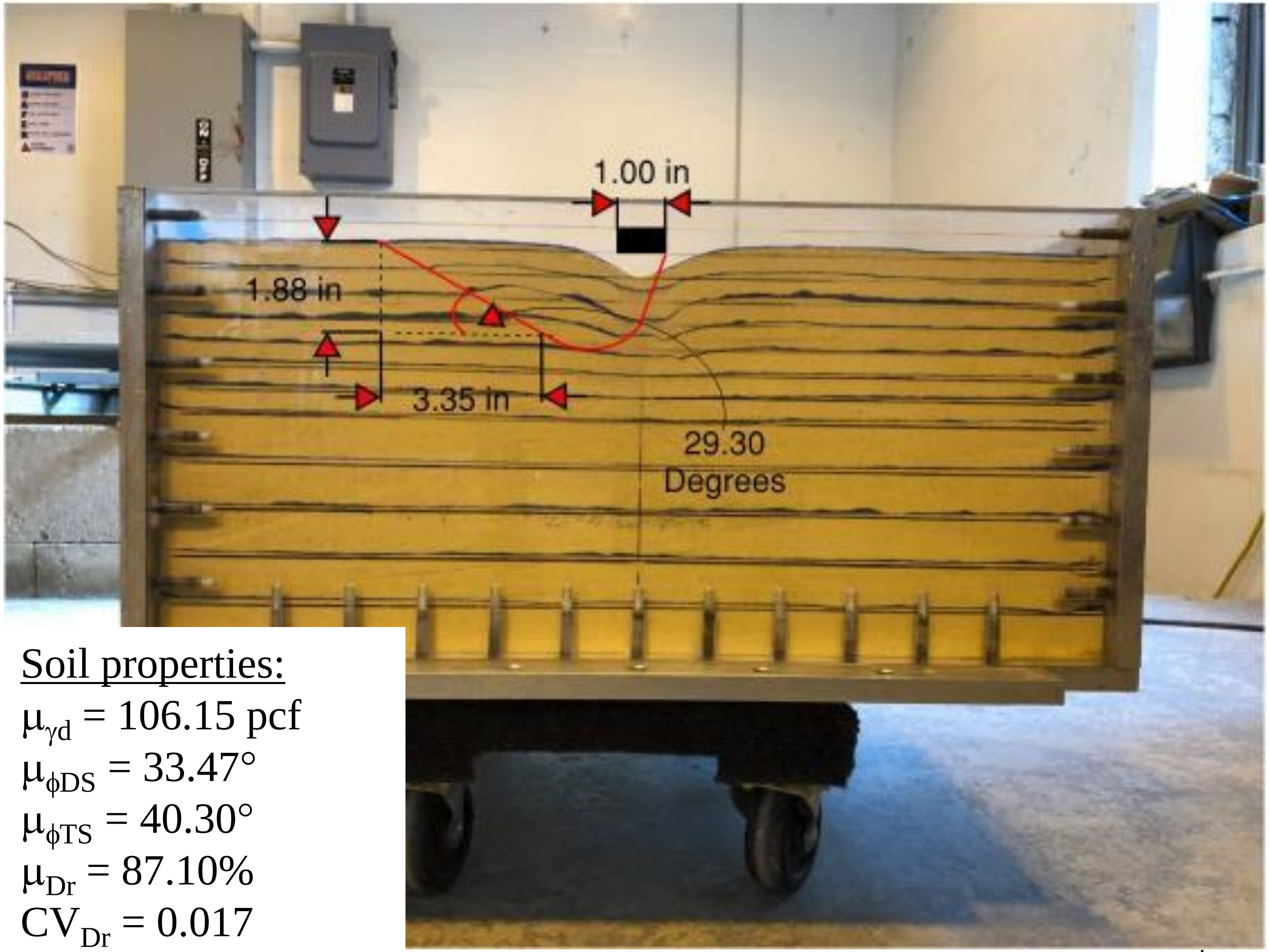
TASK 3: LT-2 SOIL PROFILE VIEW



Soil properties:

$\mu_{\gamma d}$ = 106.15 pcf

$\mu_{\phi DS}$ = 33.47°

$\mu_{\phi TS}$ = 40.30°

μ_{Dr} = 87.10%

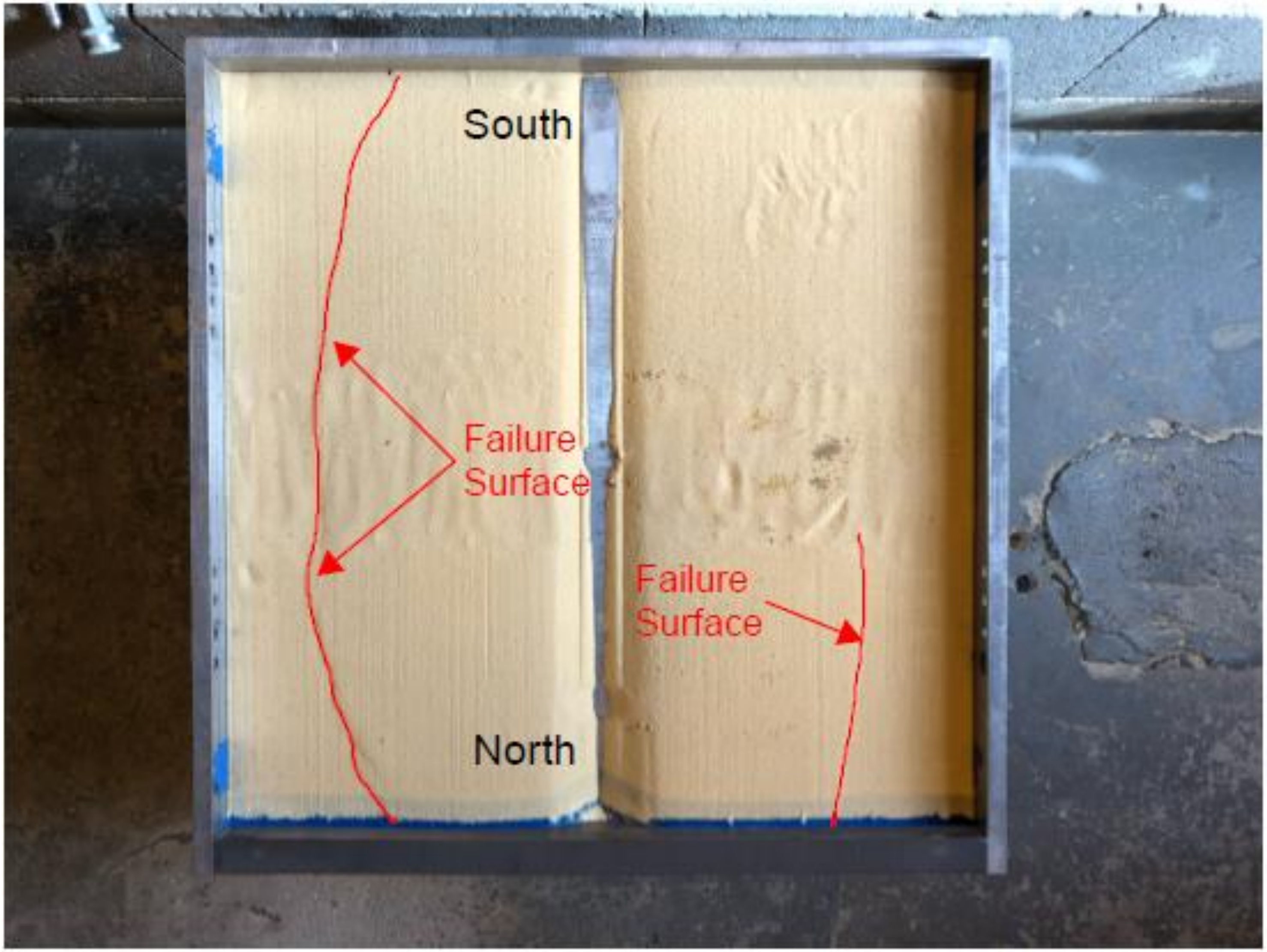
CV_{Dr} = 0.017

Post-test soil stratigraphy

$\alpha = 45° - \frac{\phi}{2} \therefore \alpha = 29.30$

ϕ = 31.40°

TASK 3: LT-2 SOIL PLAN VIEW



Post-test soil plan view

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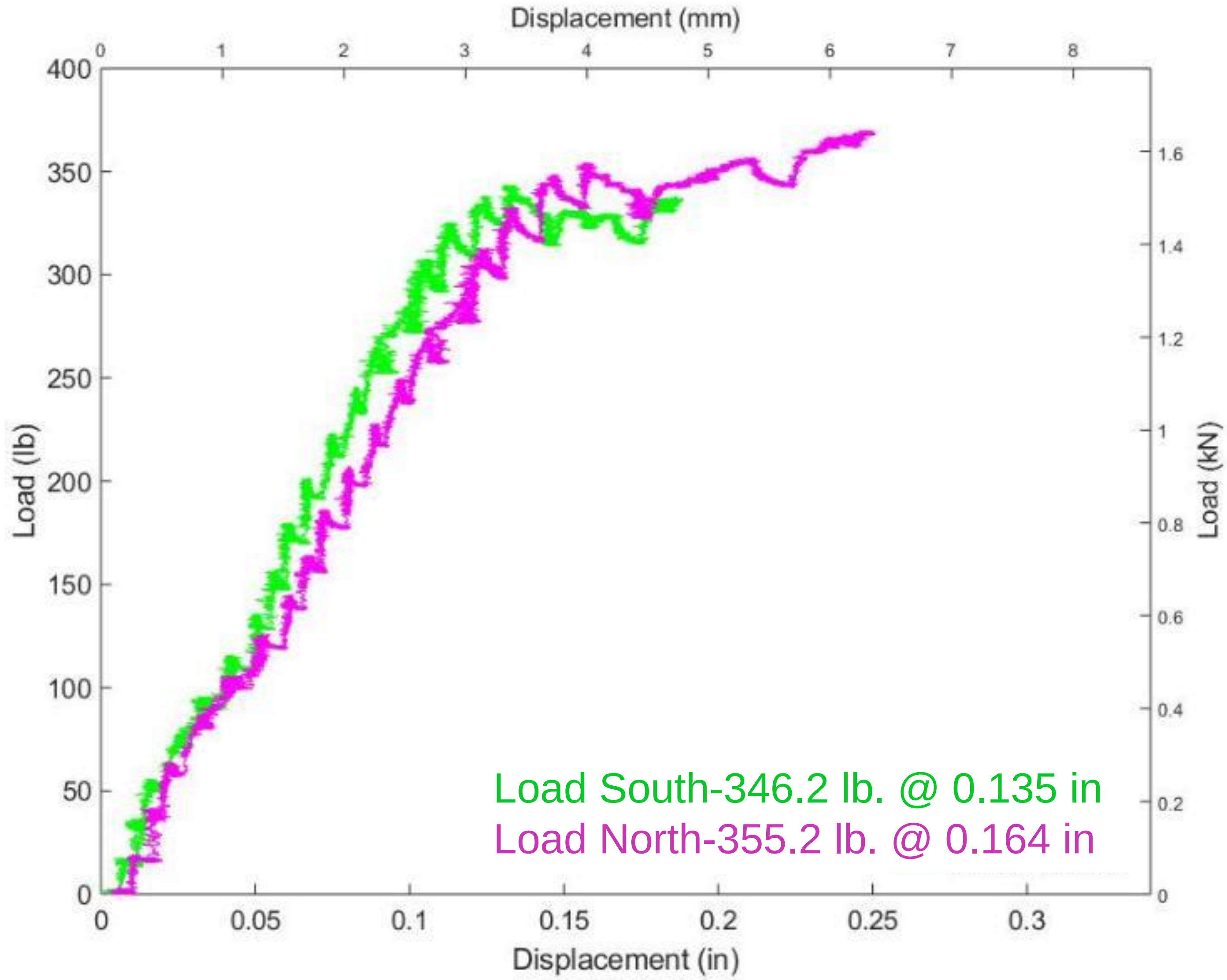
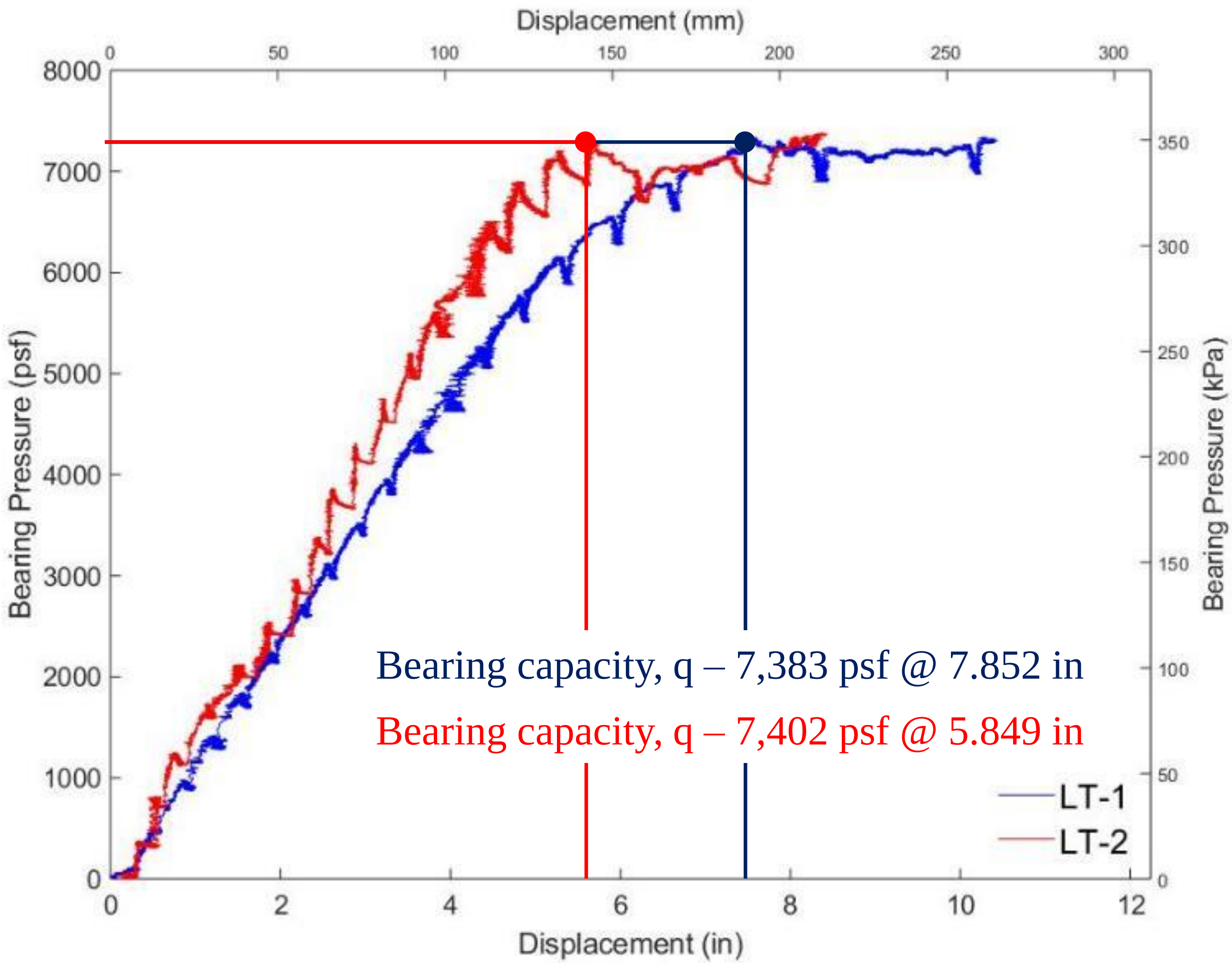
TASK 3: LT-2 LOAD vs. DISPLACEMENT (model scale)



TASK 3: LT-1 & LT-2 LOAD vs. DISPLACEMENT (prototype scale)



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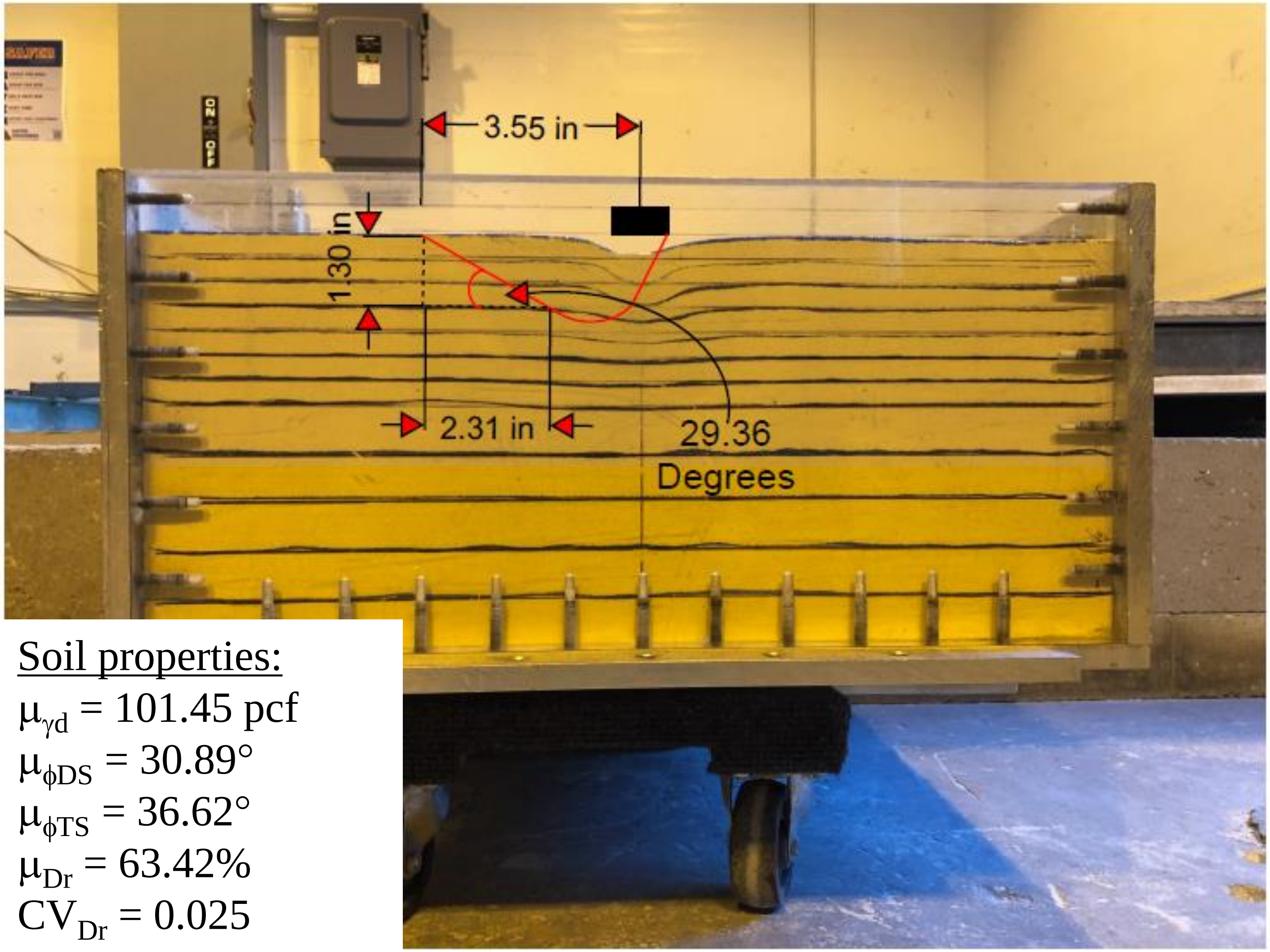
TASK 3: LT-3 SOIL PROFILE VIEW



Soil properties:

$\mu_{\gamma d}$ = 101.45 pcf

$\mu_{\phi DS}$ = 30.89°

$\mu_{\phi TS}$ = 36.62°

μ_{Dr} = 63.42%

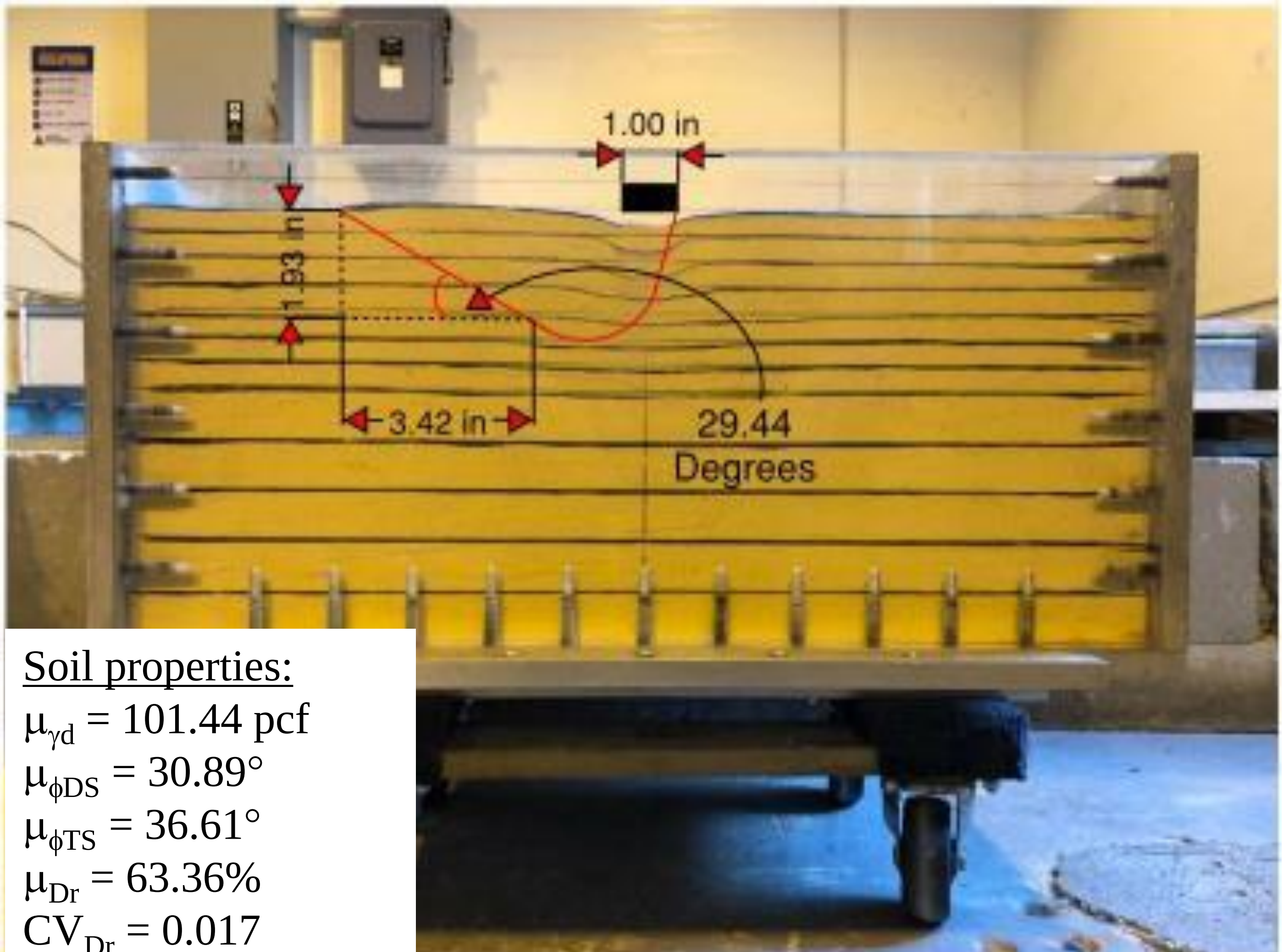
CV_{Dr} = 0.025

Post-test soil stratigraphy

$$\alpha = 45° - \frac{\phi}{2} \therefore \alpha = 29.36$$

$$\phi = 31.28°$$

TASK 3: LT-4 SOIL PROFILE VIEW



<u>Soil properties:</u>

$\mu_{\gamma d}$ = 101.44 pcf

$\mu_{\phi DS}$ = 30.89°

$\mu_{\phi TS}$ = 36.61°

μ_{Dr} = 63.36%

CV_{Dr} = 0.017

Post-test soil stratigraphy

$$\alpha = 45° - \frac{\phi}{2} \therefore \alpha = 29.44°$$

$$\phi = 31.12°$$

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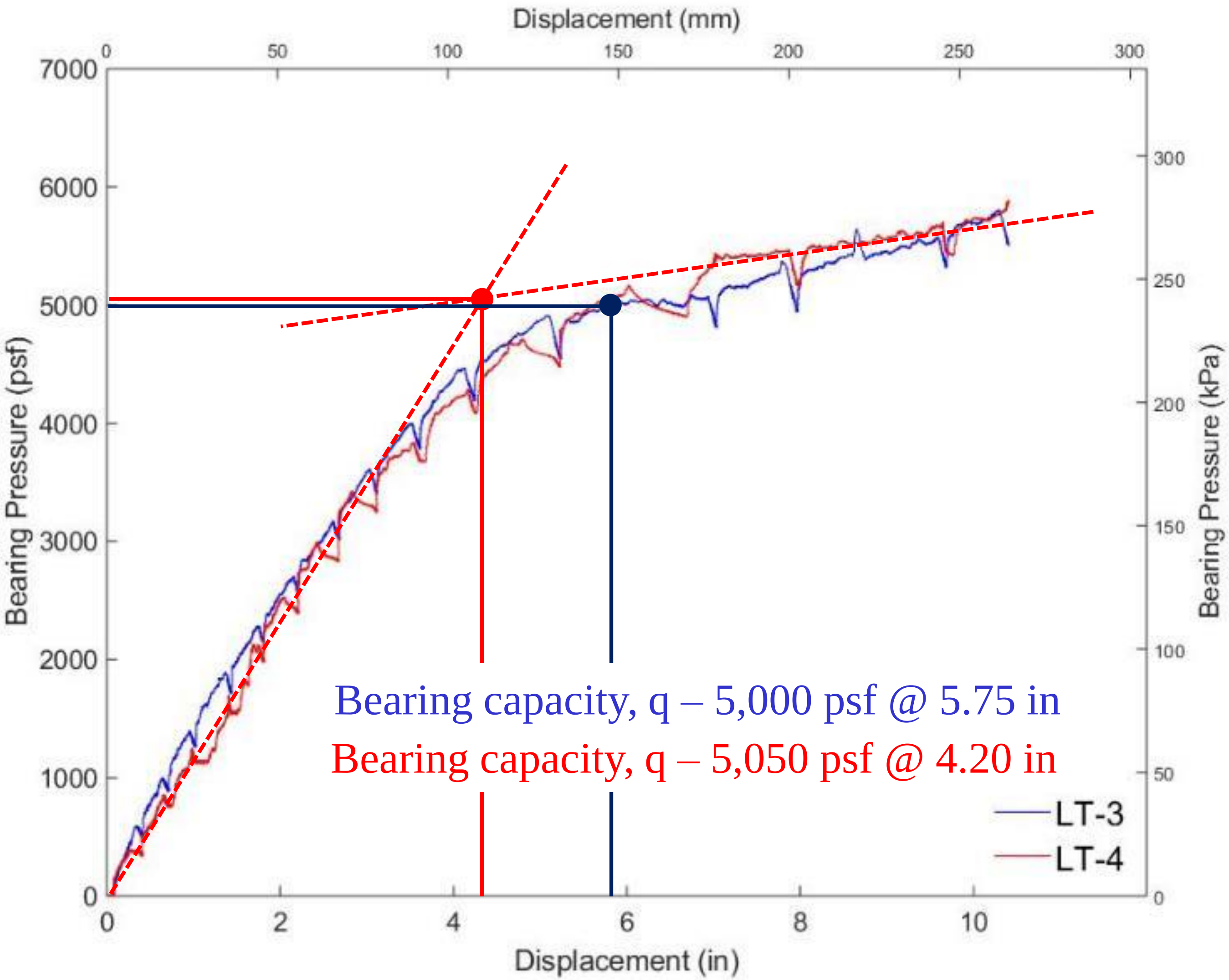
TASK 3: LT-3 & LT-4 LOAD vs. DISPLACEMENT (prototype scale)



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TASK 3: INVESTIGATION OF N_γ

Bearing Factor for Surcharge and Soil Unit Weight:

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

$$N_\gamma = 2(N_q + 1)tan(\phi_f)$$ - (Vesic')

$$N_\gamma = 2(N_q + 1)tan(1.07\phi_f)$$ – (Zhu et al method)

Simplified form of Bearing Capacity Equation:

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

($\gamma D_f N_{qm}$ → 0)

$$N_{\gamma m} = \frac{q_n}{0.5\gamma B}$$ (Measured)

Evaluate N_γ with various ϕ-values:

- ϕ-Direct shear test
- ϕ-Triaxial shear test
- ϕ-Measured failure surface

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TASK 3: INVESTIGATION OF N_γ

ϕ-Direct Shear Test

Test	Density	ϕ-Direct Shear (degree)	N_γ - Measured	N_γ - Vesic' method	%-Difference (Vesic')	N_γ - Zhu et al method	%-Difference (Zhu et al method)
LT-1	86.91	33.45	45.24	37.71	18.2	41.15	9.5
LT-2	87.10	33.47	45.22	37.83	17.8	41.28	9.1
LT-3	63.42	30.89	32.86	25.57	25.0	27.81	16.6
LT-4	63.36	30.89	32.86	25.57	25.0	27.81	16.6

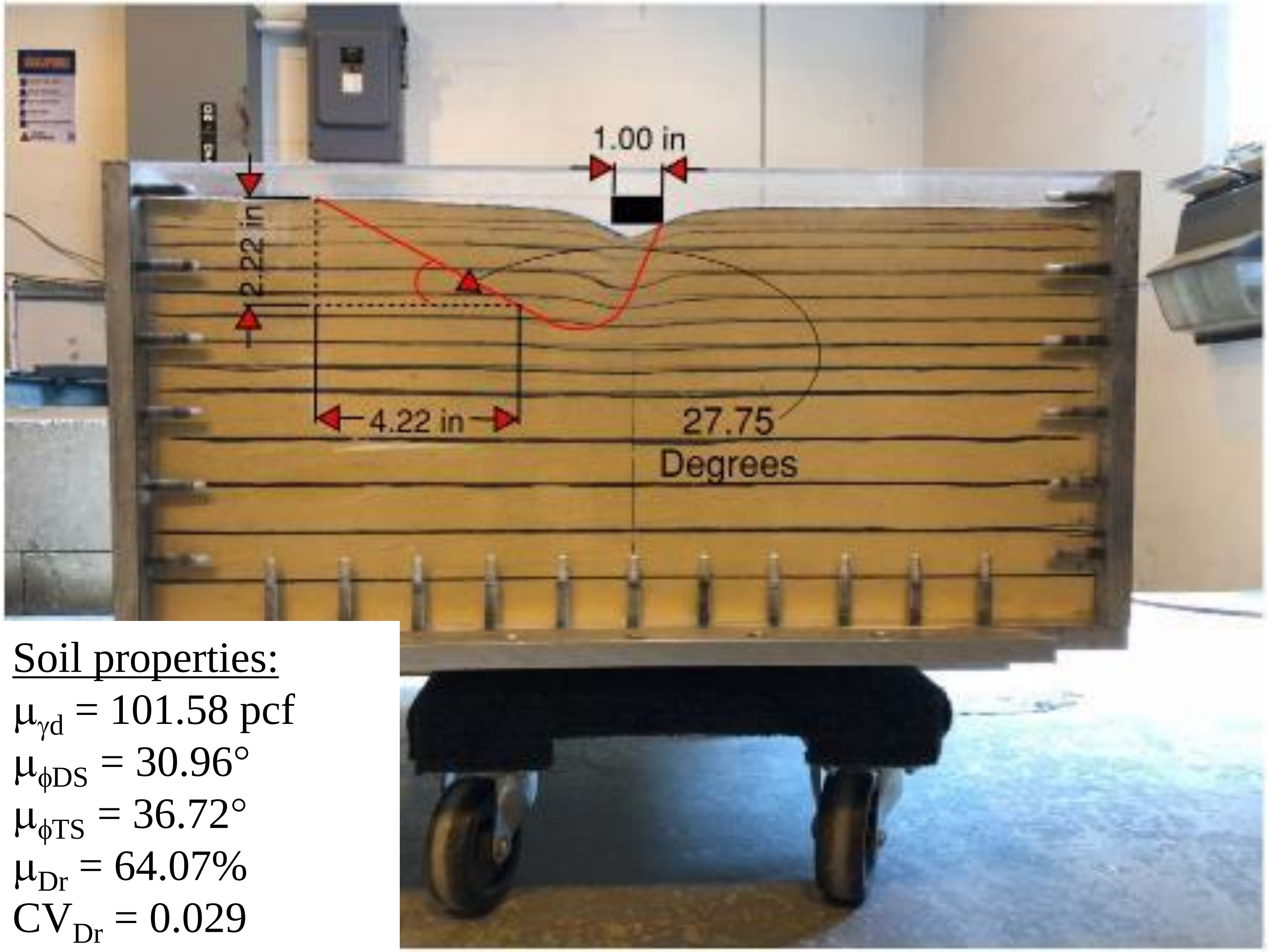
ϕ-Triaxial Shear Test (c=0)

Test	Density	ϕ-Triaxial (degree)	N_γ - Measured	N_γ - Vesic' method	%-Difference (Vesic')	N_γ - Zhu et al method	%-Difference (Zhu et al method)
LT-1	86.91	40.27	45.24	114.64	86.8	126.58	94.7
LT-2	87.10	40.30	45.22	115.23	87.3	127.25	95.1
LT-3	63.42	36.62	32.86	62.13	61.6	68.25	70.0
LT-4	63.36	36.61	32.86	62.13	61.6	68.14	69.9

ϕ-Measured Failure Surface

Test	Density	ϕ-Failure surf. (degree)	N_γ - Measured	N_γ - Vesic' method	%-Difference (Vesic')	N_γ - Zhu et al method	%-Difference (Zhu et al method)
LT-1	86.91	29.54	45.24	20.93	73.5	22.73	66.2
LT-2	87.10	31.40	45.22	27.6	48.4	30.04	40.3
LT-3	63.42	31.28	32.86	27.11	19.2	29.50	10.8
LT-4	63.36	31.12	32.86	26.47	21.5	28.79	13.2

TASK 3: LT-5 SOIL PROFILE VIEW



Post-test soil stratigraphy

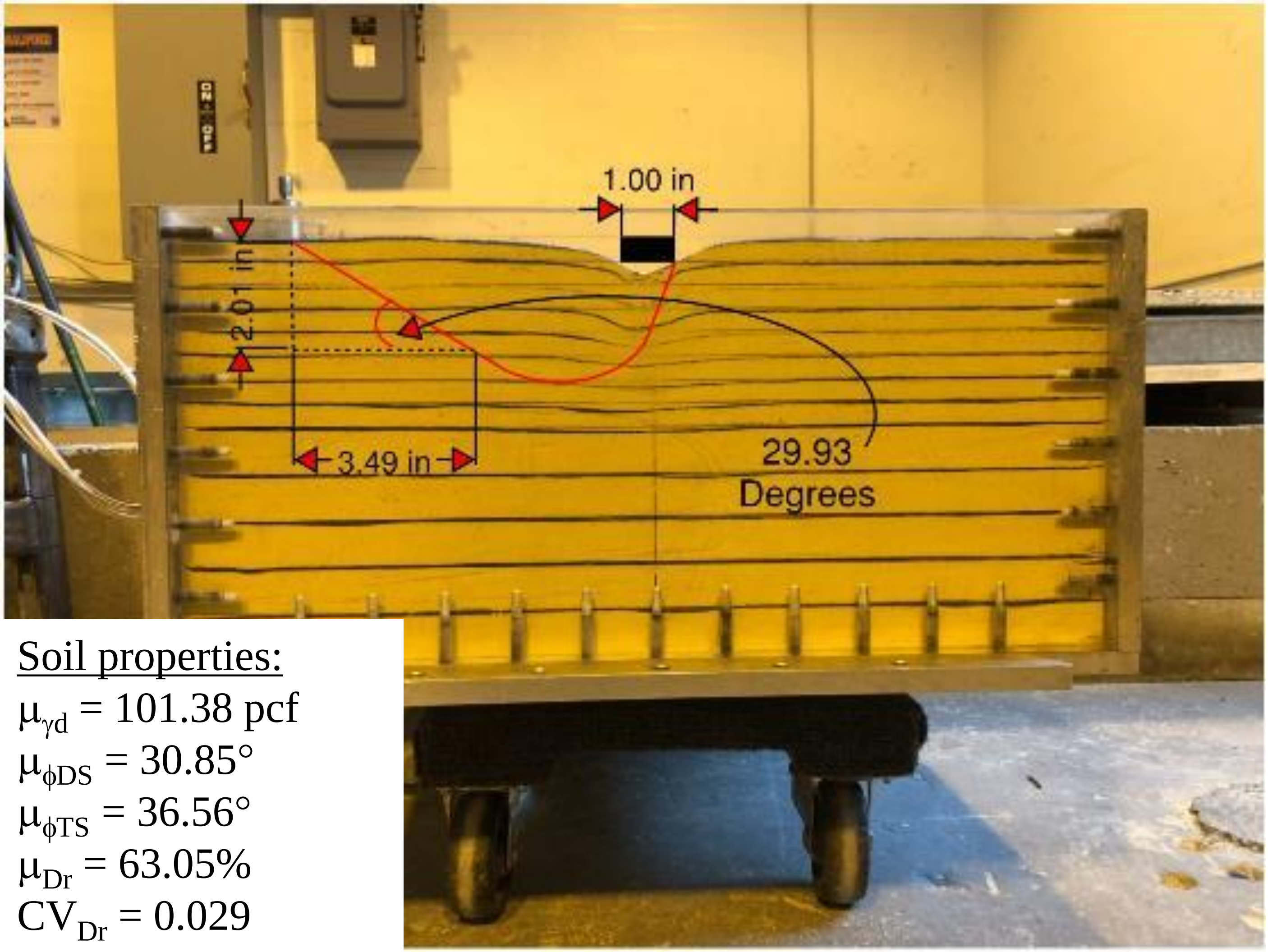
<u>Soil properties:</u>

$\mu_{\gamma d}$ = 101.58 pcf
$\mu_{\phi DS}$ = 30.96°
$\mu_{\phi TS}$ = 36.72°
μ_{Dr} = 64.07%
CV_{Dr} = 0.029

$$\alpha = 45° - \frac{\phi}{2} \therefore \alpha = 27.75°$$

$$\phi = 34.50°$$

TASK 3: LT-6 SOIL PROFILE VIEW



Soil properties:

$\mu_{\gamma d}$ = 101.38 pcf

$\mu_{\phi DS}$ = 30.85°

$\mu_{\phi TS}$ = 36.56°

μ_{Dr} = 63.05%

CV_{Dr} = 0.029

Post-test soil stratigraphy

$$\alpha = 45° - \frac{\phi}{2} \therefore \alpha = 29.93°$$

$$\phi = 30.14°$$

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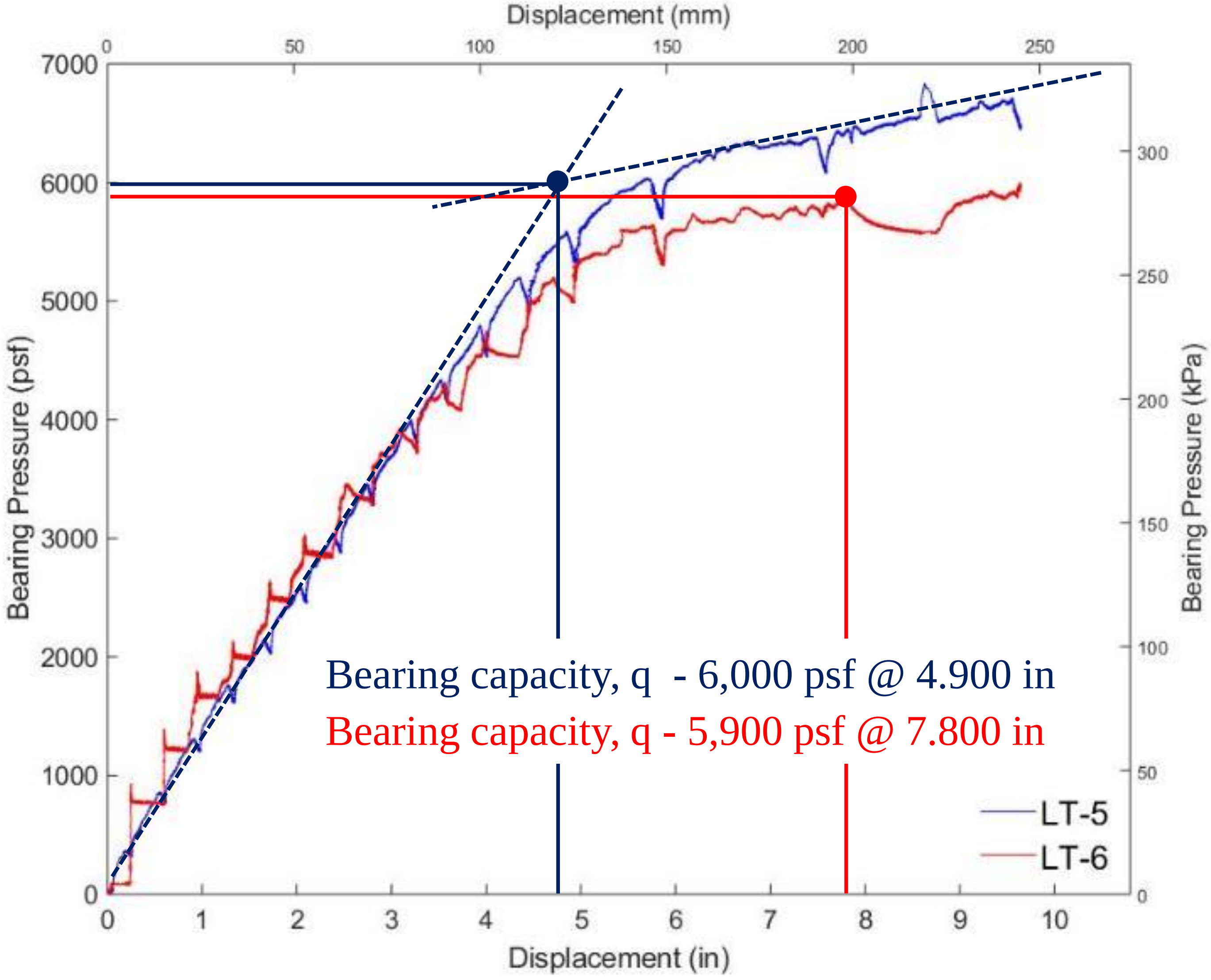
TASK 3: LT-5 & LT-6 LOAD vs. DISPLACEMENT (prototype scale)



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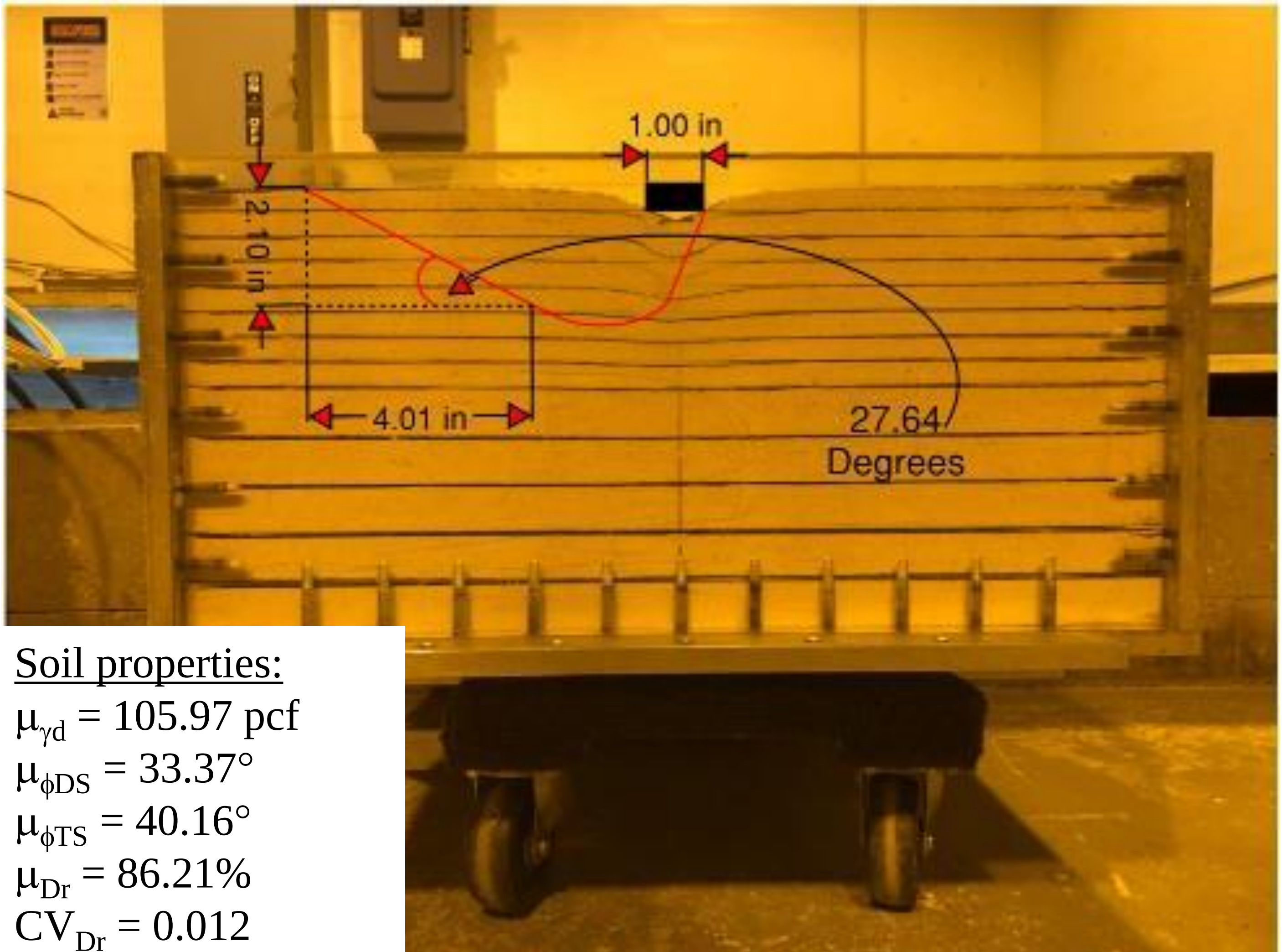
TASK 3: LT-7 SOIL PROFILE VIEW



Soil properties:

$\mu_{\gamma d}$ = 105.97 pcf

$\mu_{\phi DS}$ = 33.37°

$\mu_{\phi TS}$ = 40.16°

μ_{Dr} = 86.21%

CV_{Dr} = 0.012

Post-test soil stratigraphy

$$\alpha = 45° - \frac{\phi}{2} \therefore \alpha = 27.64°$$

$$\phi = 34.72°$$

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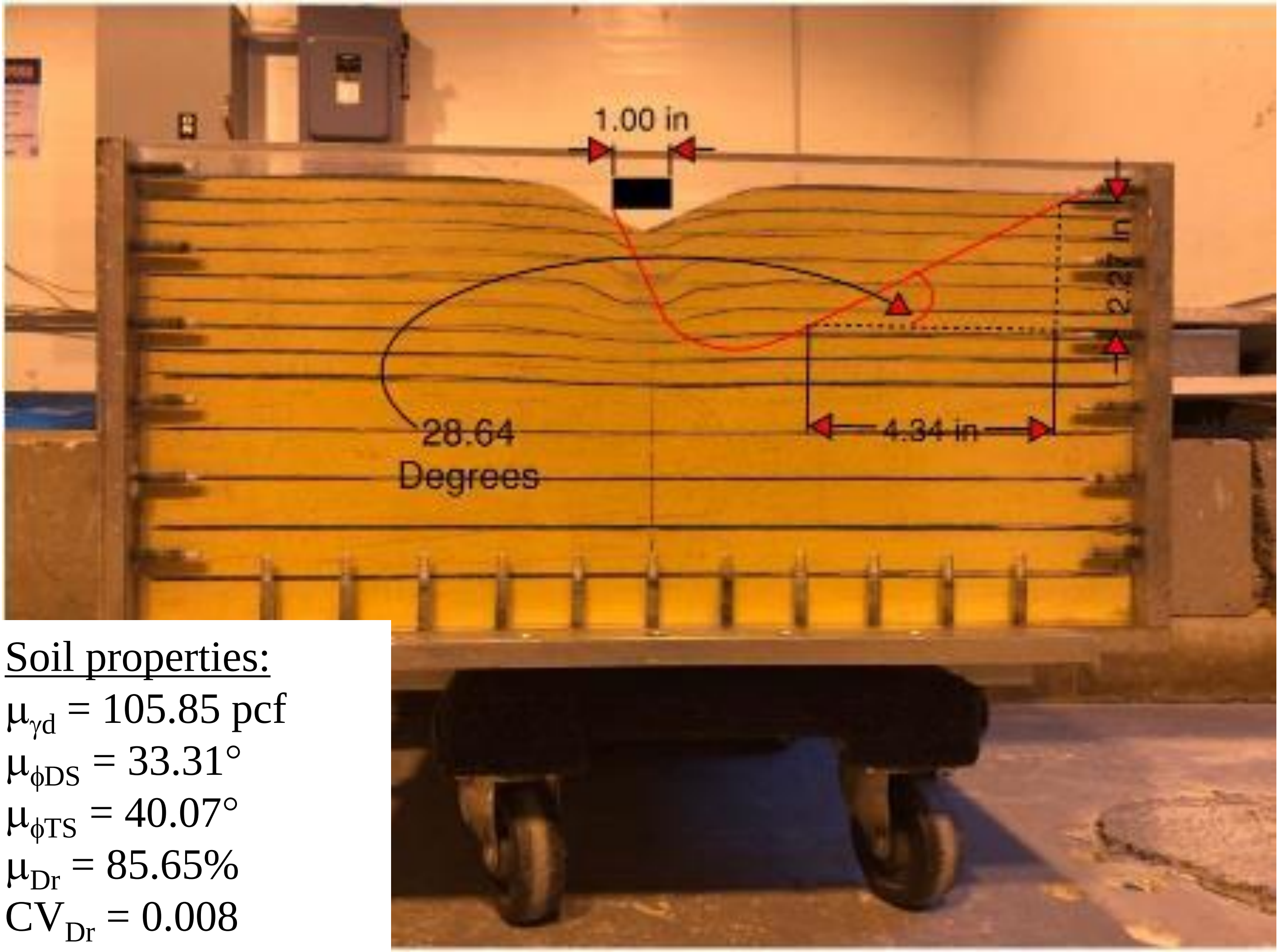
TASK 3: LT-8 SOIL PROFILE VIEW



Soil properties:

$\mu_{\gamma d}$ = 105.85 pcf

$\mu_{\phi DS}$ = 33.31°

$\mu_{\phi TS}$ = 40.07°

μ_{Dr} = 85.65%

CV_{Dr} = 0.008

Post-test soil stratigraphy

$$\alpha = 45° - \frac{\phi}{2} \therefore \alpha = 28.64°$$

$$\phi = 32.72°$$

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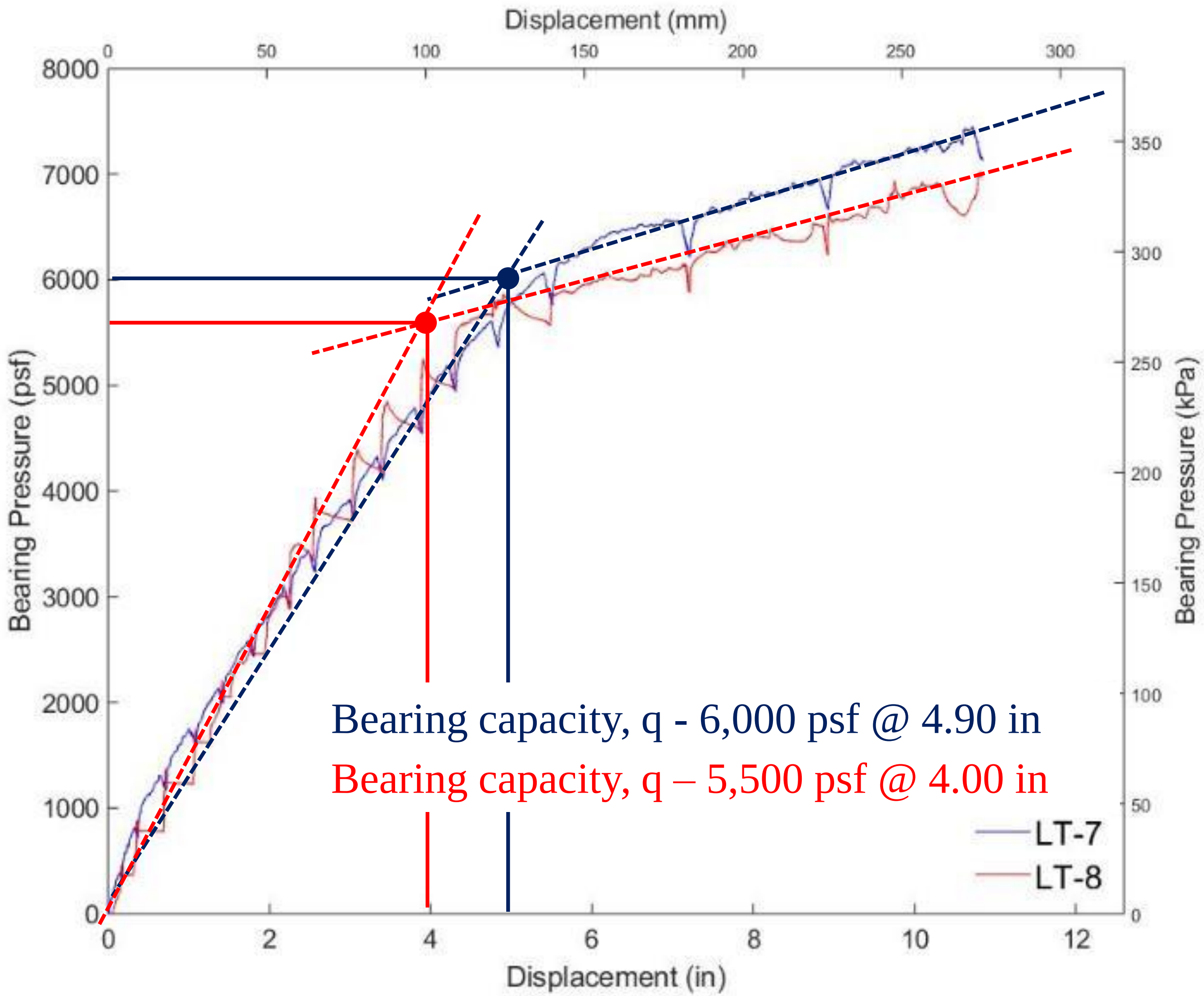
TASK 3: LT-7 & LT-8 LOAD vs. DISPLACEMENT (prototype scale)



TASK 3: SUMMARY OF D_f = 0.5B TESTS

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

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

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

$$N_{\gamma m} = N_\gamma \quad \therefore \quad N_\gamma = 2\left(N_q + 1\right) tan\left(\phi_f\right)$$

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

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

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TASK 3: CONCLUDING COMMENTS

1) **LT-1 through LT-4: (D_f = 0)**
   - **ϕ-direct shear test appears representative of ϕ-measured failure surface.**
   - **Plane strain condition**
   - $N_\gamma = 2(N_q + 1)tan(1.07\phi_f)$ **– 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).**
   - **$q_{Measured}$ vs. $q_{Estimated}$ (confirm N_γ & d_q)**

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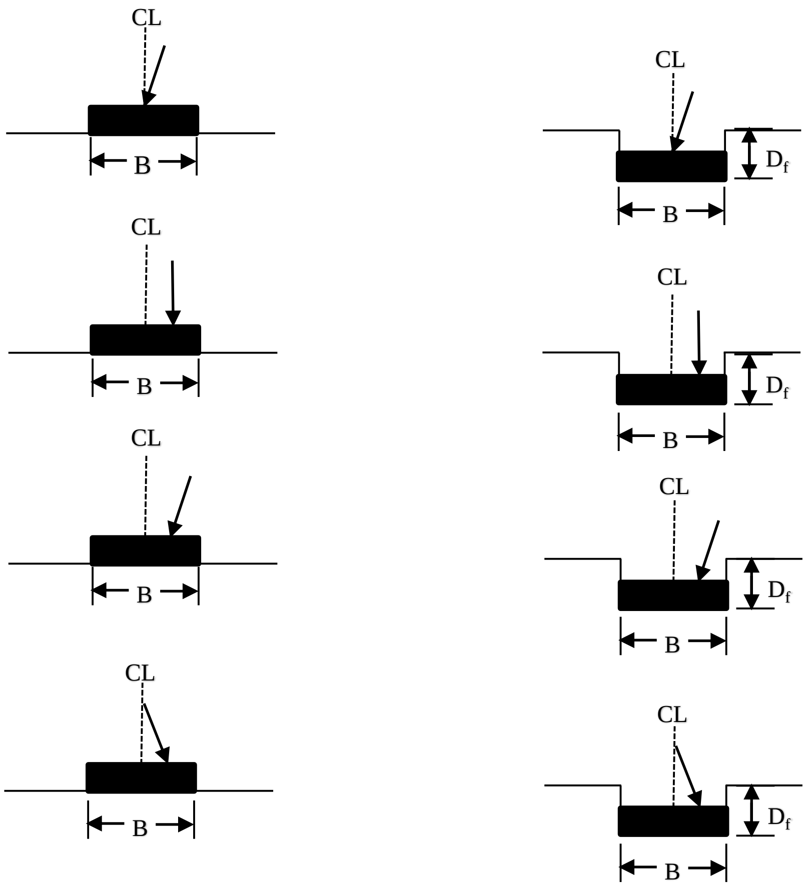
TASK 3: CONCLUDING COMMENTS

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