Estimating Soil Pressure Against Unyielding Surfaces

(BDV31-977-89)

FDOT GRIP Meeting

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Introduction

- Mechanically Stabilized Earth (MSE) Walls are a cost-effective option for earth retention systems
  - Bridge abutments, highway separations, and when construction space is limited
- Reinforced strips or grids are placed between layers of compacted soil and mechanically attached to the wall facing
- Lateral earth pressures exerted on the wall facing by granular backfill are opposed by frictional resistance developed along the surface of the reinforcement

Background

- In general design, the lateral earth pressure imposed on a retaining wall is approximately equal to the active lateral earth pressure
  - Conventional earth pressure theory
  - Reinforcement embedded in soil provides resistance
- In certain cases, the reinforcement ties two walls together resulting in an unyielding condition.
  - Widening conditions (new wall tied to existing wall)
  - Acute corners
- The actual soil pressure that results behind an unyielding surface is not well defined

Background

- FHWA GEC #11 acknowledges that “much higher” tension develops in the reinforcement when walls are tied together
- Minor deformations that typically occur in conventional MSE walls are prevented
- While GEC #11 recognizes the problem, it does not provide a clear recommendation for estimating the pressure of compacted soils

Reinforcing strips are tied to both walls preventing minor deformations.

Objectives

- Investigate the resulting earth pressure coefficients derived from an approved MSE wall configuration
  - MSE reinforcement is tied to an unyielding structure
    - Prevents minor wall deformations in the yielding MSE wall
  - Two states of soil density (95% and 104% of T-180)
    - Half of the wall constructed at 95% and half at 104%
- The outcome can be used to adequately address design methodology and earth pressure coefficients
  - Earthen fill compacted behind unyielding structures

Tasks

- Task (1) – Literature Review and Preliminary Design ✓
- Task (2) – Final Design, Site Preparation, and Materials Purchasing ✓
- Task (3a) – MSE Wall Construction with Two Designated Relative Compaction Efforts ✓
- Task (3b) – Simulated Earth Surcharge and Deriving Earth Pressure Coefficients ✓
- Task (3c) – MSE Wall Deconstruction
- Task (4) – Draft Final and Closeout Teleconference
- Task (5) – Final Report

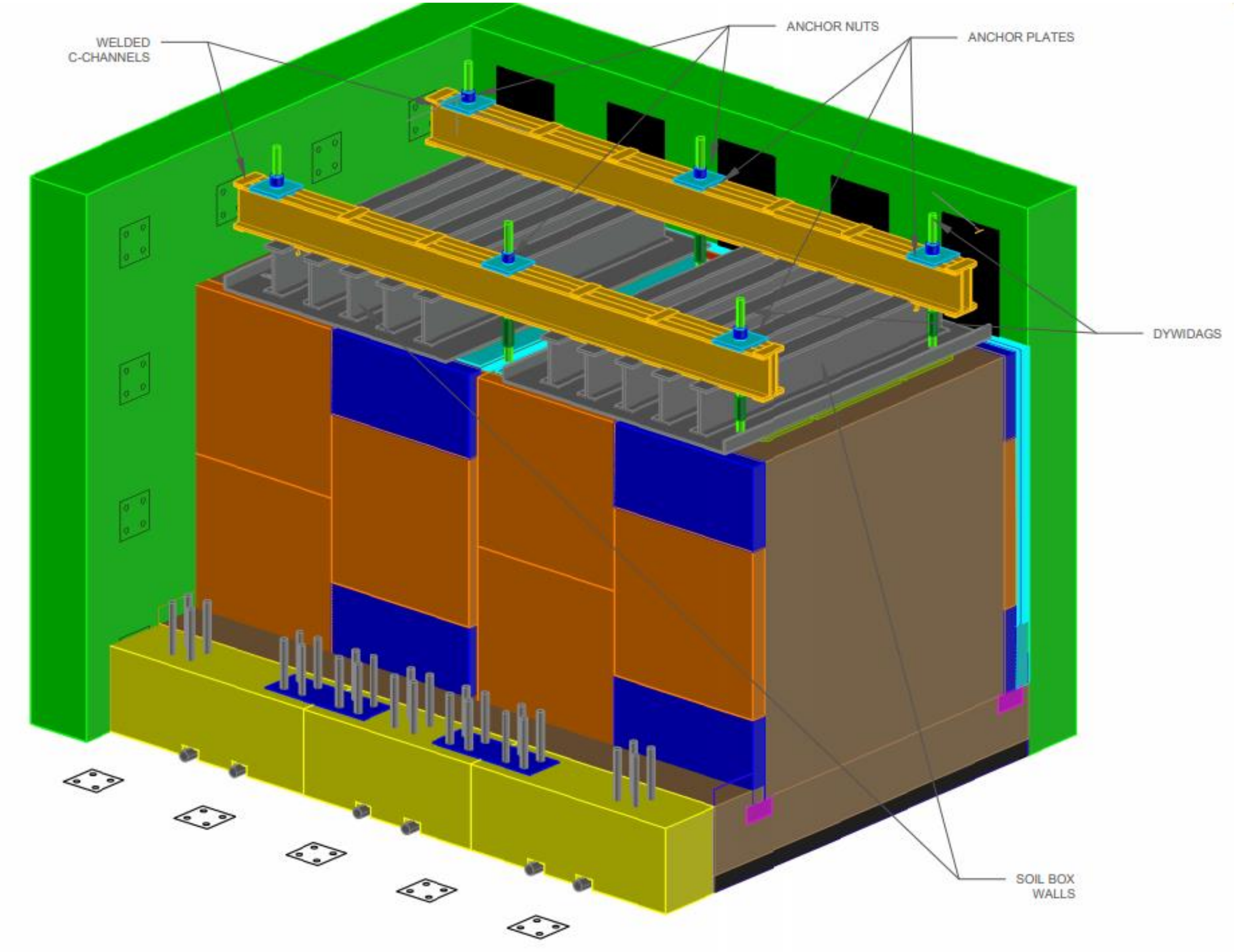
MSE Wall LRFD Final Design

- List and quantities of instrumentation
- Geometry
- Loading conditions
- Performance criteria
- Project parameters
- Wall embedment depth, design height, and reinforcement length
- Nominal loads
- Load combinations, load factors, and resistance factors
- External stability design
- Facing elements
- Overall/global stability
- Wall drainage system

- Internal stability design
  - Soil reinforcement
  - Critical failure surface
  - Unfactored loads
  - Vertical layout of reinforcements
  - Factored horizontal stress and maximum tension (each level)
  - Grade and number of soil reinforcement elements
  - Nominal and factored pullout resistance of soil reinforcements
  - Connection resistance at MSE wall facing
  - Connection resistance at Strong Wall
  - Estimated lateral wall movement
  - Vertical movement and bearing pads

MSE Wall Surcharge Design

- RECo indicated initial reinforcement/wall height ratio was not representative of practice
  - Wall height 10 ft plus 2 ft surcharge
  - Reinforcement length 10 ft
  - B/H ≈ 0.83
- Need a B/H ≈ 0.3
  - Must simulate around 23 ft of overburden
  - Total height of 33 ft
  - Not possible with dead weight and available lab overhead clearance
- Utilize parts of Soil Box to create reaction frame
  - Soil Box walls, soil plates, chain link fence, and Matjack airbag system
- Use Dywidag threaded bar system tied to Strong Floor



Connection Strength Stability Check

- Stability checks were performed using five different earth pressure coefficients for each state of soil density at each reinforcement level
    - Simplified Method
        - AASHTO Recommended
    - Coherent Gravity Method
    - At-rest Condition
    - Active State
    - Spangler and Handy
        - Silo Effect
- Surcharge equivalent to 23 feet of overburden
- 95% of T-180 estimates displayed

Simplified Method

Depth (ft)	σ_v (psf)	$\Delta\sigma_v$ (psf)	Simplified	σ_h (psf)	Load Factors		σ_h (psf)	Unfactored	Factored	Factored	Unfactored
			k_{rS}	Unfactored	γ_{P-EV}	γ_{P-ES}	Factored	T_{max} (lbf)	T_{max} (lbf)	$T_{con.}$ (lbf)	$T_{con.}$ (lbf)
1.23	139	2,603	0.534	1,465	1.35	1.5	2,187	8,866	13,232	11,340	15,120
3.69	418	2,603	0.515	1,554	1.35	1.5	2,299	9,407	13,915	11,340	15,120
6.15	696	2,603	0.495	1,633	1.35	1.5	2,397	9,881	14,509	11,340	15,120
8.61	974	2,603	0.475	1,700	1.35	1.5	2,481	10,289	15,012	11,340	15,120

Coherent Gravity Method

Depth (ft)	σ_v (psf)	$\Delta\sigma_v$ (psf)	Coherent	σ_h (psf)	Load Factors		σ_h (psf)	Unfactored	Factored	Factored	Unfactored
			k_{rCG}	Unfactored	γ_{P-EV}	γ_{P-ES}	Factored	T_{max} (lbf)	T_{max} (lbf)	$T_{con.}$ (lbf)	$T_{con.}$ (lbf)
1.23	139	2,603	0.475	1,302	1.35	1.5	1,943	7,879	11,759	11,340	15,120
3.69	418	2,603	0.455	1,373	1.35	1.5	2,031	8,308	12,290	11,340	15,120
6.15	696	2,603	0.434	1,433	1.35	1.5	2,104	8,669	12,730	11,340	15,120
8.61	974	2,603	0.414	1,481	1.35	1.5	2,161	8,962	13,077	11,340	15,120

At-rest Condition

Depth (ft)	σ_v (psf)	$\Delta\sigma_v$ (psf)	At-Rest	σ_h (psf)	Load Factors		σ_h (psf)	Unfactored	Factored	Factored	Unfactored
			k_0	Unfactored	γ_{P-EV}	γ_{P-ES}	Factored	T_{max} (lbf)	T_{max} (lbf)	$T_{con.}$ (lbf)	$T_{con.}$ (lbf)
1.23	139	2,603	0.485	1,330	1.35	1.5	1,985	8,047	12,010	11,340	15,120
3.69	418	2,603	0.485	1,465	1.35	1.5	2,167	8,864	13,113	11,340	15,120
6.15	696	2,603	0.485	1,600	1.35	1.5	2,349	9,681	14,216	11,340	15,120
8.61	974	2,603	0.485	1,735	1.35	1.5	2,531	10,498	15,319	11,340	15,120

Active State

Depth (ft)	σ_v (psf)	$\Delta\sigma_v$ (psf)	Active	σ_h (psf)	Load Factors		σ_h (psf)	Unfactored	Factored	Factored	Unfactored
			k_a	Unfactored	γ_{P-EV}	γ_{P-ES}	Factored	T_{max} (lbf)	T_{max} (lbf)	$T_{con.}$ (lbf)	$T_{con.}$ (lbf)
1.23	139	2,603	0.320	878	1.35	1.5	1,310	5,312	7,927	11,340	15,120
3.69	418	2,603	0.320	967	1.35	1.5	1,430	5,851	8,655	11,340	15,120
6.15	696	2,603	0.320	1,056	1.35	1.5	1,551	6,390	9,383	11,340	15,120
8.61	974	2,603	0.320	1,145	1.35	1.5	1,671	6,929	10,111	11,340	15,120

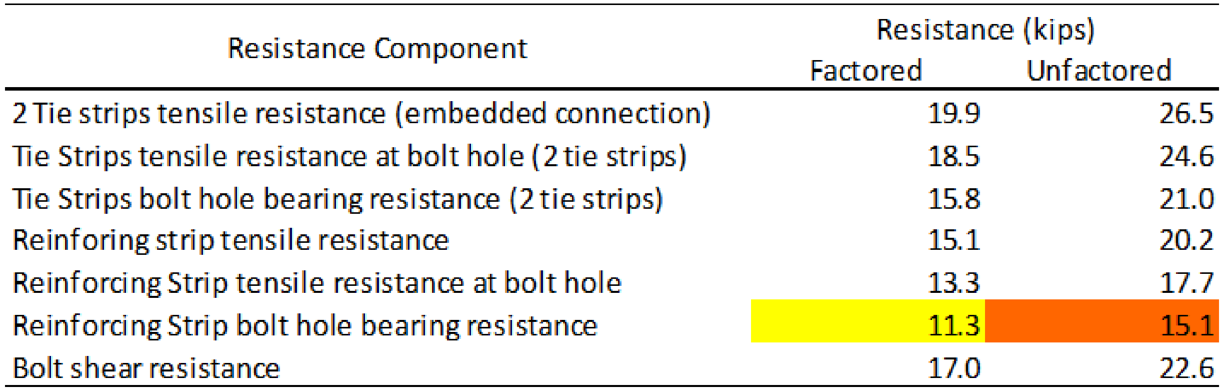
Spangler and Handy – “Silo Effect”

Depth (ft)	σ_v (psf)	$\Delta\sigma_v$ (psf)	S & H	σ_h (psf)	Load Factors		σ_h (psf)	Unfactored	Factored	Factored	Unfactored
			k_{rSH}	Unfactored	γ_{P-EV}	γ_{P-ES}	Factored	T_{max} (lbf)	T_{max} (lbf)	$T_{con.}$ (lbf)	$T_{con.}$ (lbf)
1.23	139	2,603	0.469	1,285	1.35	1.5	1,918	7,776	11,606	11,340	15,120
3.69	418	2,603	0.438	1,323	1.35	1.5	1,958	8,008	11,847	11,340	15,120
6.15	696	2,603	0.410	1,353	1.35	1.5	1,987	8,190	12,026	11,340	15,120
8.61	974	2,603	0.385	1,376	1.35	1.5	2,008	8,330	12,154	11,340	15,120

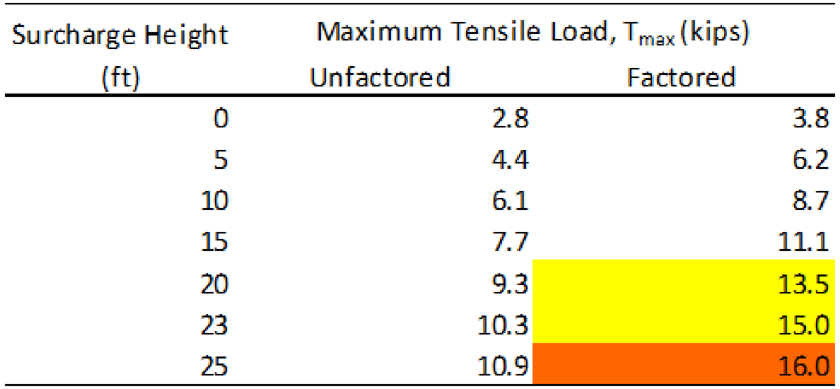
Incremental Surcharge Loading

- Incremental surcharge loading will be applied to the reinforced zone
  - Worst case load scenario presented
  - 95% of T-180 @ lowest reinforcement level
- Factored and unfactored resistances calculated for each reinforcement component
- Factored and unfactored loads calculated for each incremental surcharge height
- On-site monitoring will determine final simulated surcharge height applied
  - Increase in reinforcement tension is expected for unyielding MSE wall scenario

LRFD Design – Internal Stability



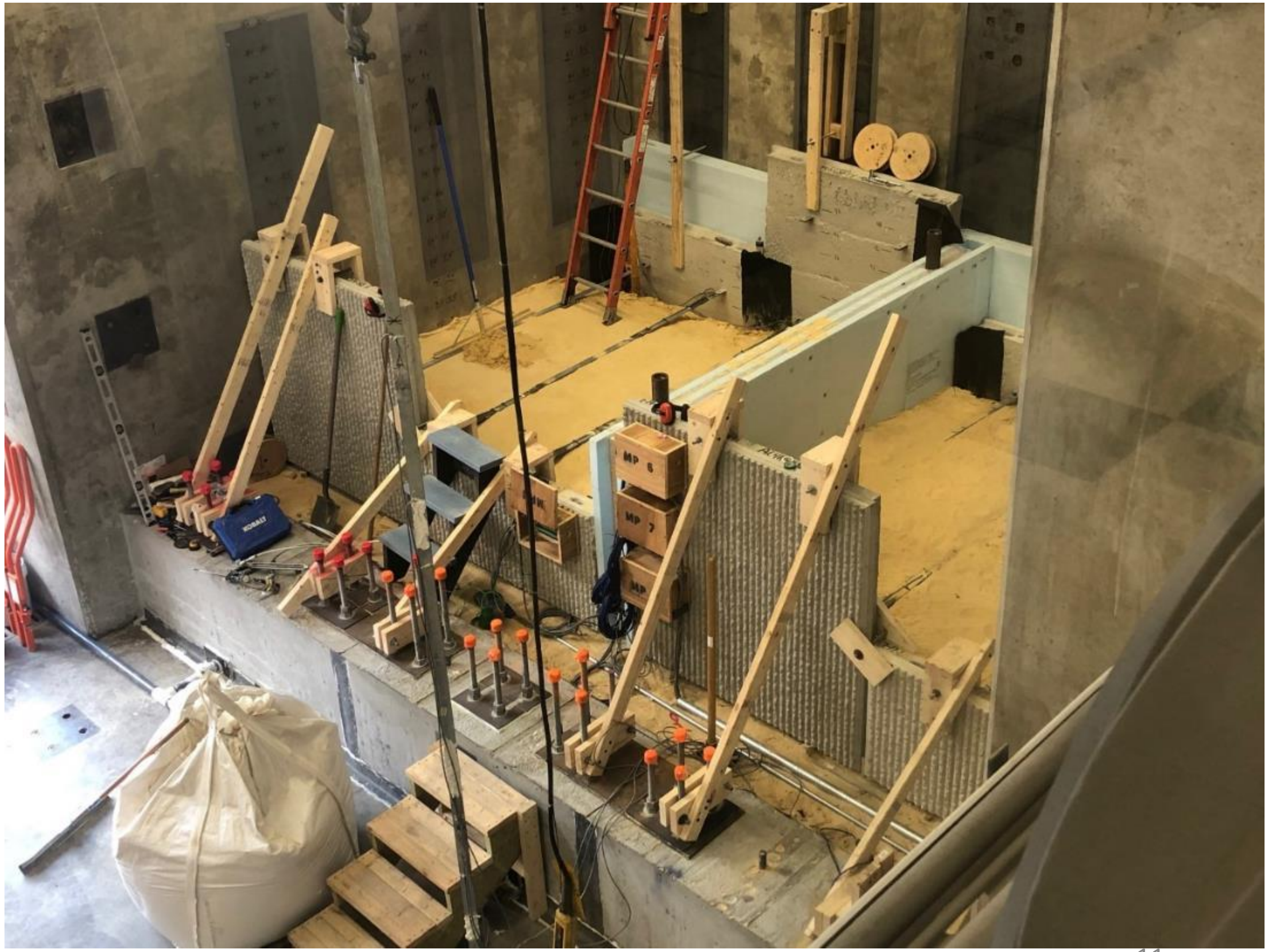
Resistance Component	Resistance (kips)	
	Factored	Unfactored
2 Tie strips tensile resistance (embedded connection)	19.9	26.5
Tie Strips tensile resistance at bolt hole (2 tie strips)	18.5	24.6
Tie Strips bolt hole bearing resistance (2 tie strips)	15.8	21.0
Reinforing strip tensile resistance	15.1	20.2
Reinforcing Strip tensile resistance at bolt hole	13.3	17.7
Reinforcing Strip bolt hole bearing resistance	11.3	15.1
Bolt shear resistance	17.0	22.6



Surcharge Height (ft)	Maximum Tensile Load, T_{max} (kips)	
	Unfactored	Factored
0	2.8	3.8
5	4.4	6.2
10	6.1	8.7
15	7.7	11.1
20	9.3	13.5
23	10.3	15.0
25	10.9	16.0

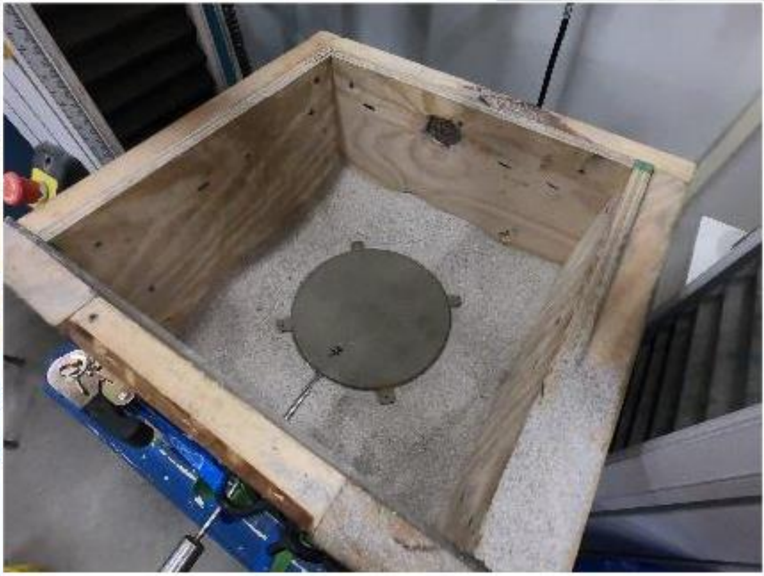
Construction Plan - Instrumentation

- 80 full bridge strain gauge locations on strips
    - 4 Instrumented strips per reinforcement level
    - 5 locations per strip
    - 320 Strain gauges total
- 36 horizontal EPC's
    - Soil embedded in quadrants
    - 8 at each reinforcement level
    - 1 EPC under each leveling pad
- 16 vertical EPC's
    - Wall mounted in quadrants
    - 4 at each reinforcement level
- 2 String Potentiometers
- 6 Reaction rods with strain gauges in full bridge
- 9 Multiplexers
- 1 Campbell CR6 Datalogger
- 1 Campbell CR10X Datalogger



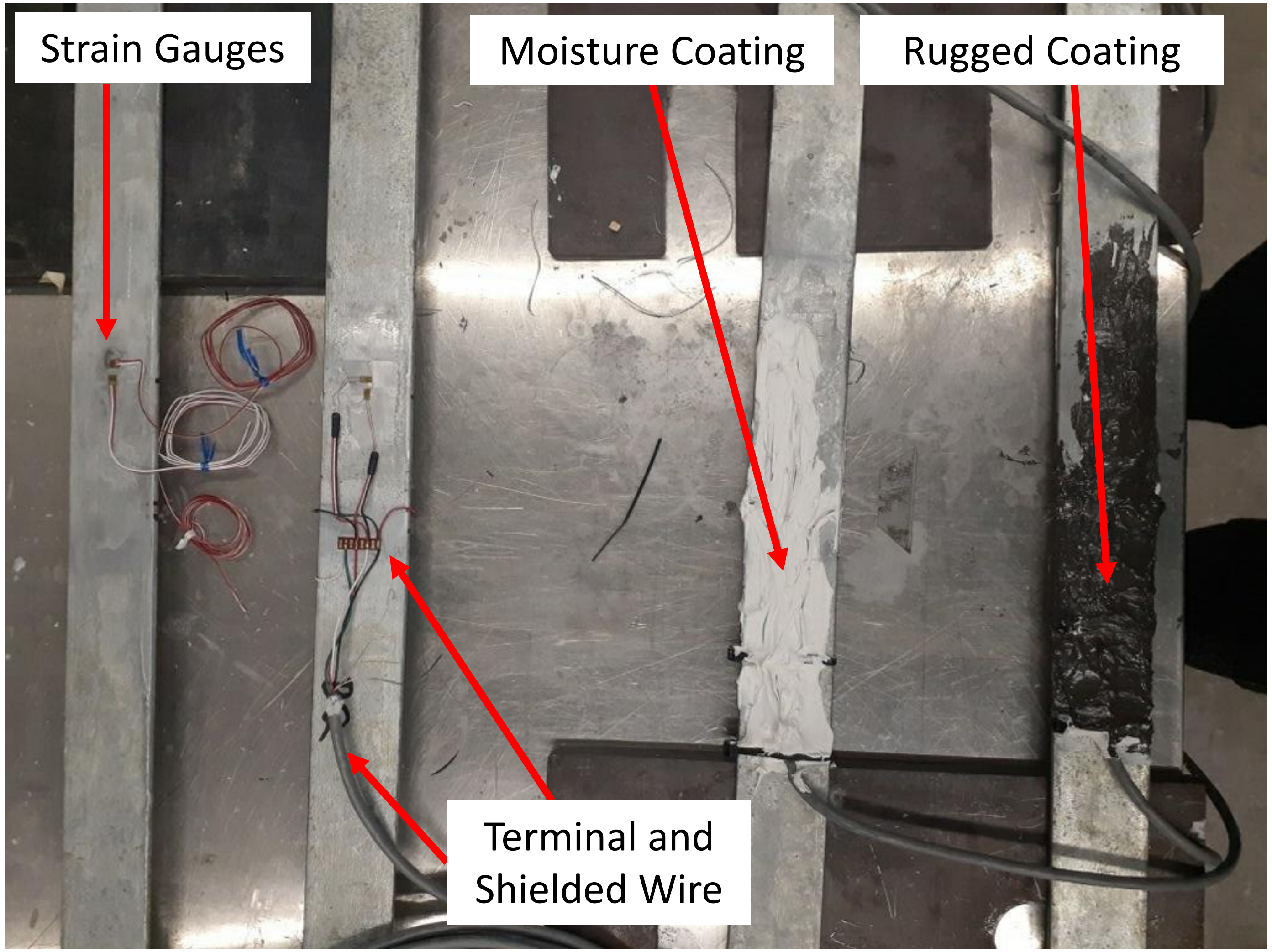
Construction - Instrumentation Preparation

- Earth Pressure Cells – Vibrating Wire
  - 32 horizontal EPC's (GeoKon 4800-1-100)
    - Purchased 2001/Last used around 2012
    - Gauge Calibrations checked on Instron
    - New cable spliced to EPCs
  - 16 Wall-mounted EPC's (GeoKon 4810-350)
    - Purchased New



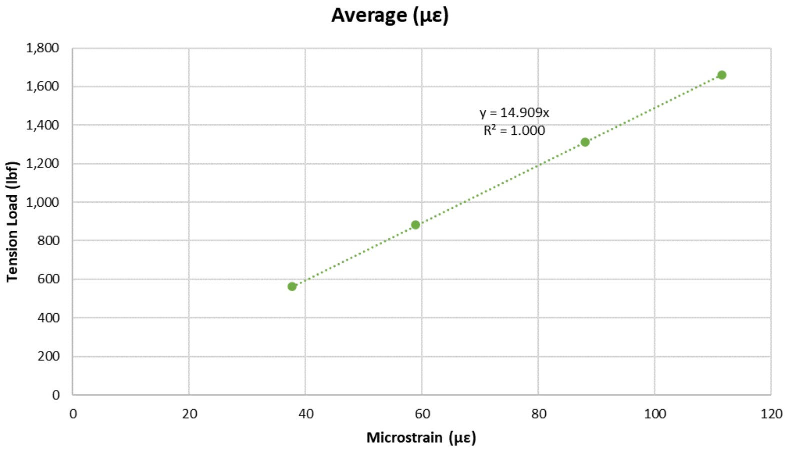
Instrumented Reinforcement Strips

- Gauges are placed on both sides of the strip
  - 5 locations on 16 strips
- Soldered onto bondable terminal in full bridge
  - Compensates for bending and thermal effects
- 4-strand shielded wire soldered onto terminal
  - Connects to DAQ system
- Load test at 4 loads
- Moisture protective coating added
  - Load tested at 4 loads
- Rugged protective coating added
  - Load tested at 4 loads
- Each strip is load tested 3 times
- 48 total load tests

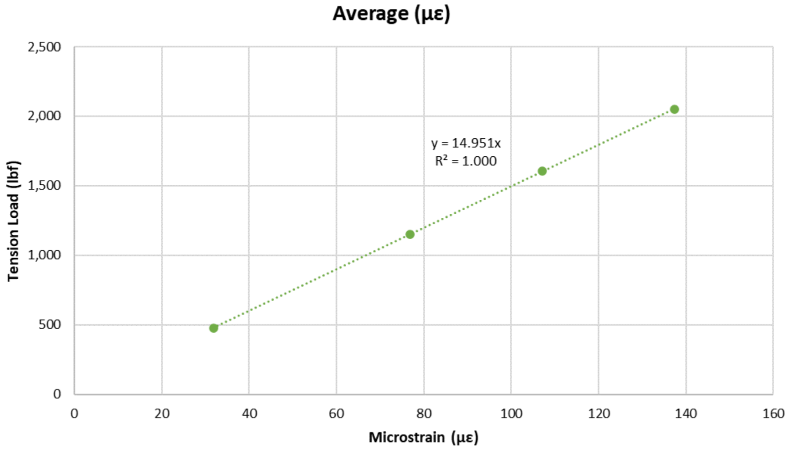


Reinforcement Strip Load Testing

Before Protective Coatings



After Applying Both Coatings



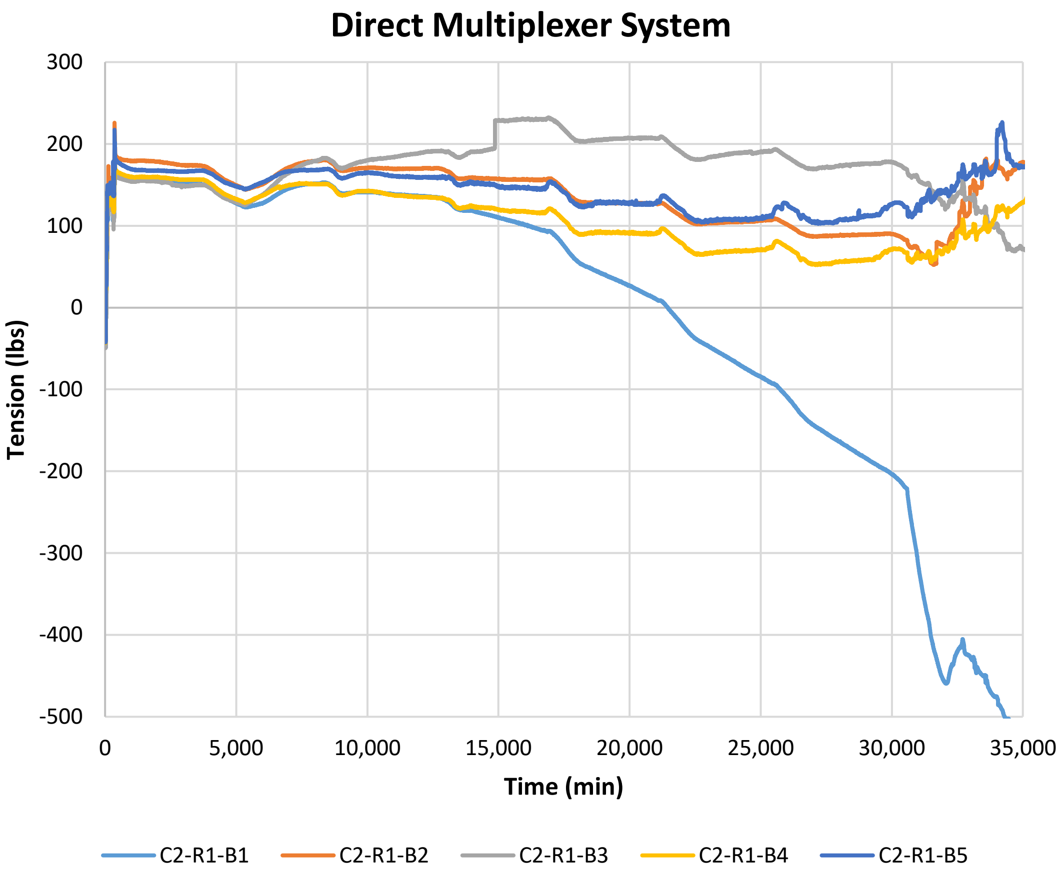
- 0.3% difference in average strain readings before and after coatings were applied

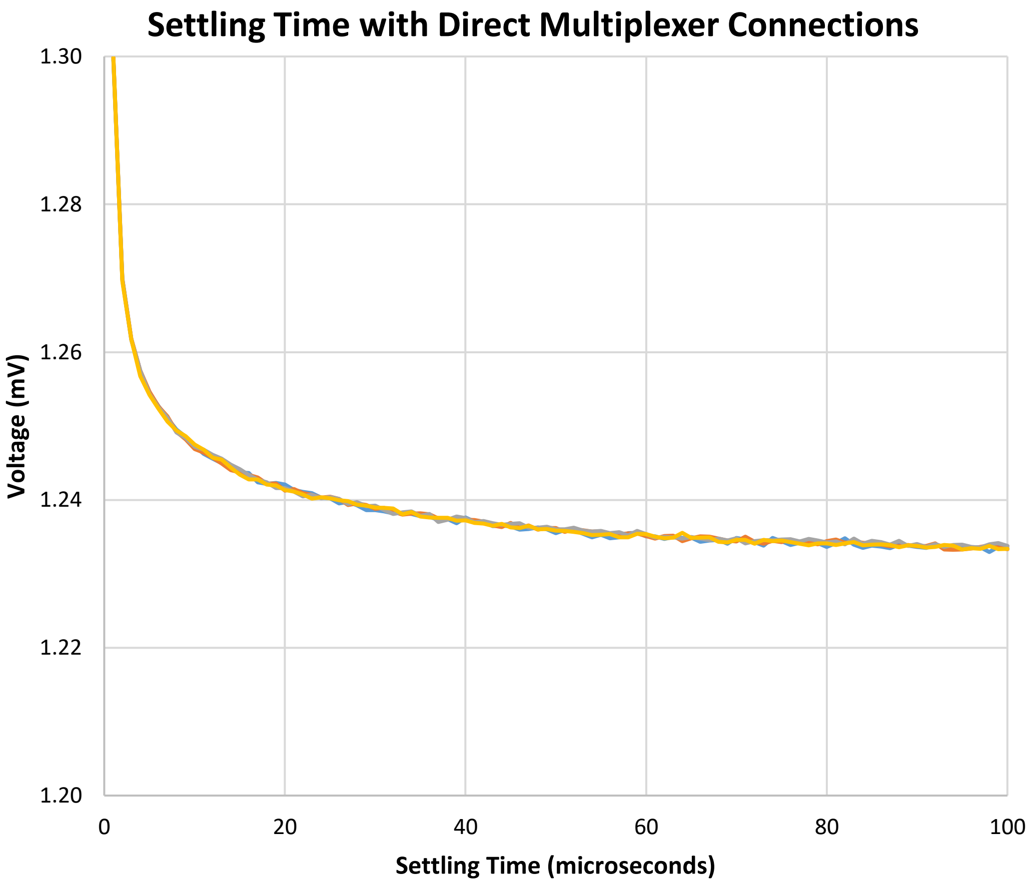
Additional Instrumentation

Draw-wire Sensors – Wall Displacement

FB Strain Gauges – Reaction Loads

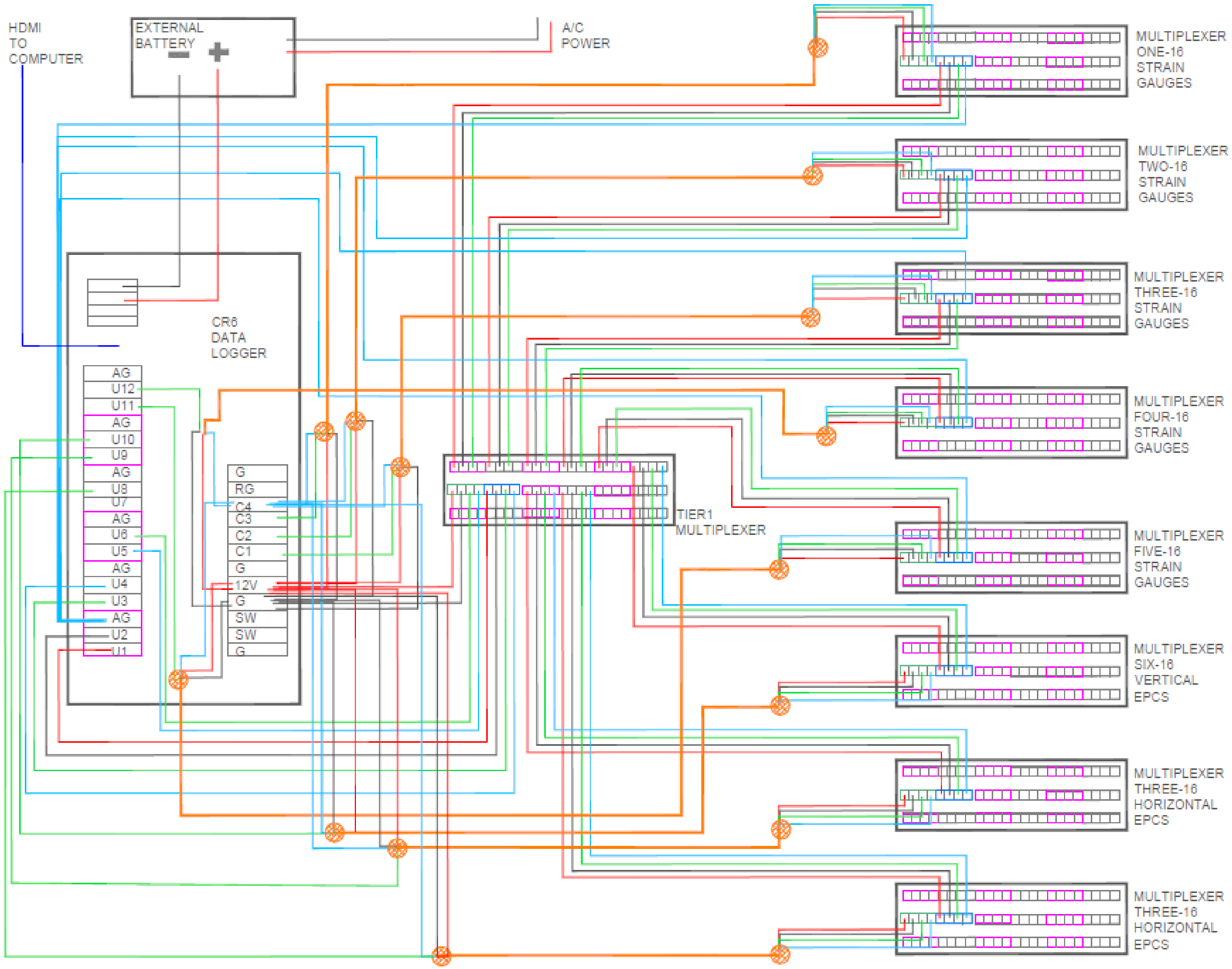
Residual Voltage Buildup



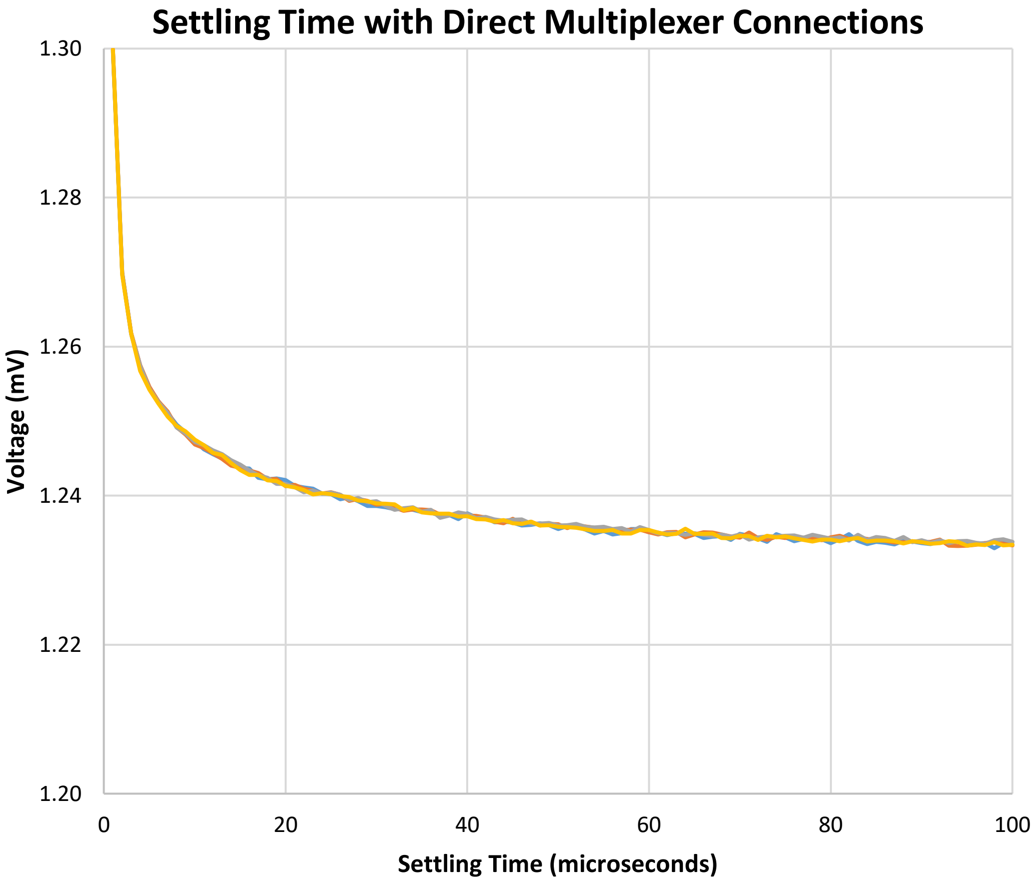


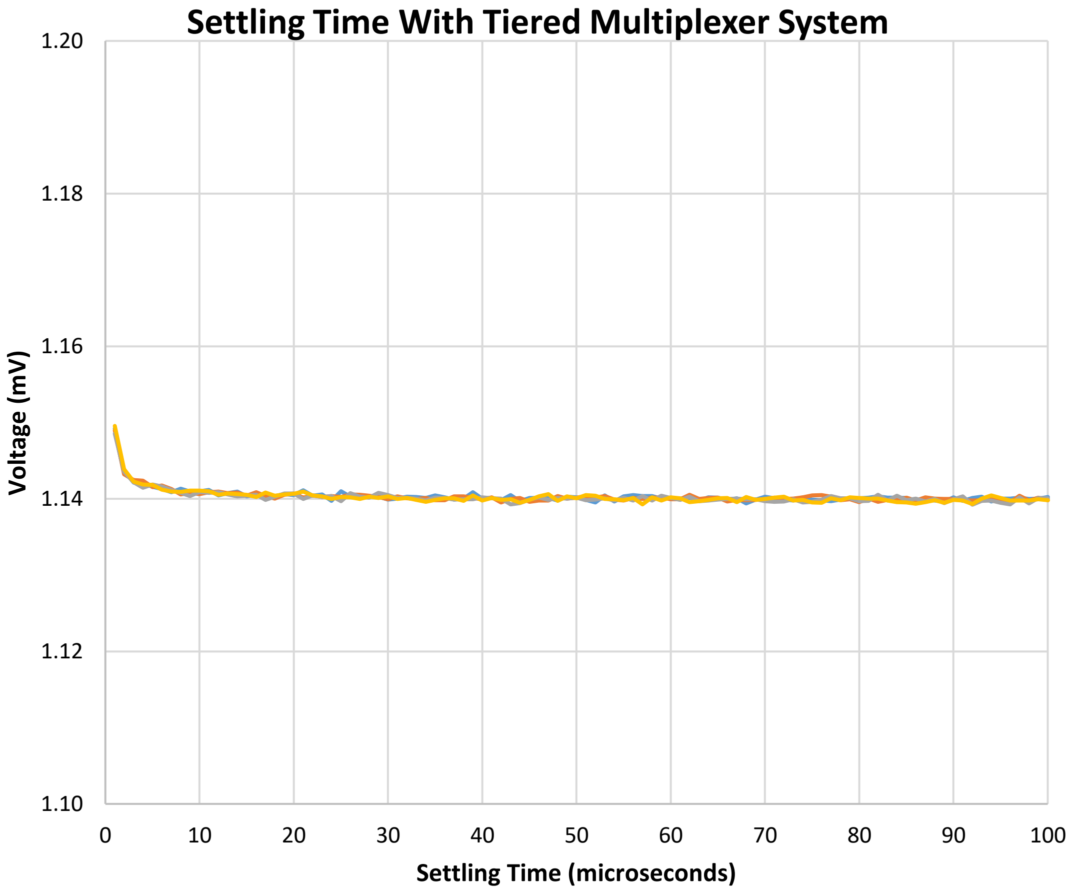
CR6

- Multitiered system
- 5 multiplexers collect strain gauge data
- 1 multiplexer collects vertical EPC data
- 2 multiplexers collect horizontal EPC data
- Tier 1 collects data from 8 multiplexers
- Tier 1 data is then routed into CR6 DAQ

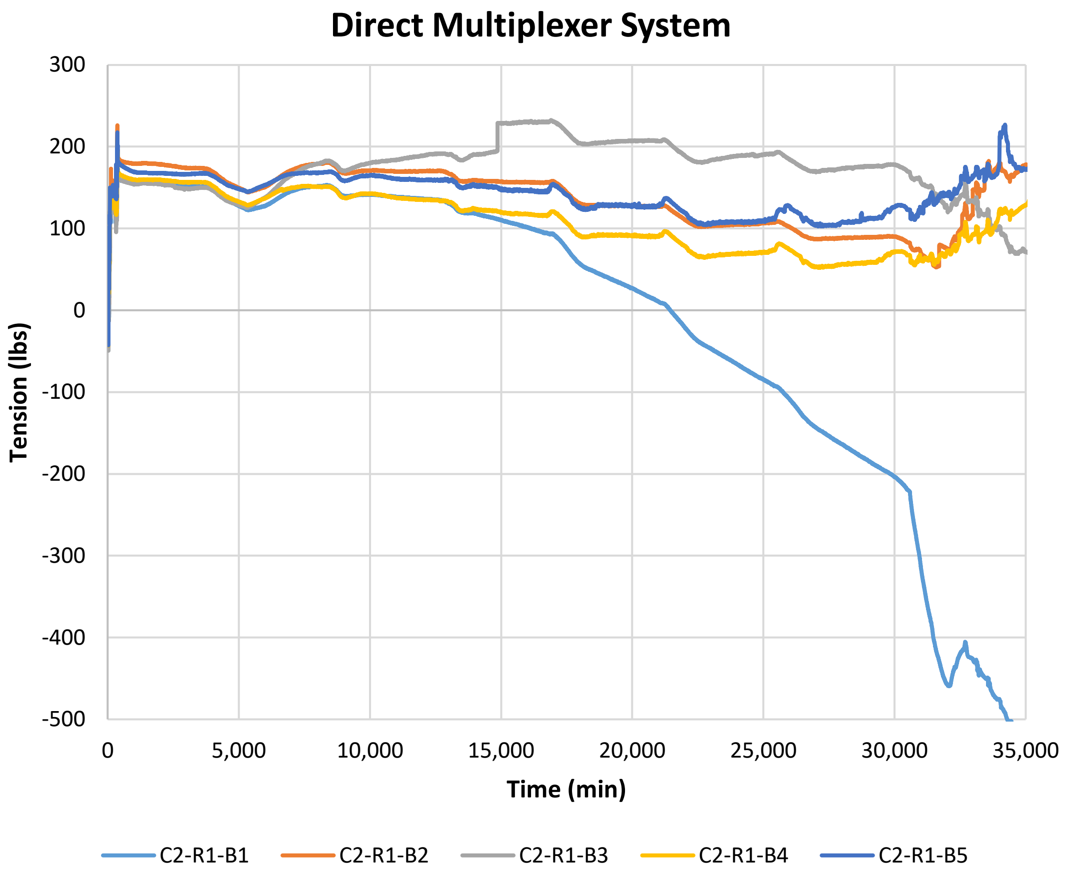


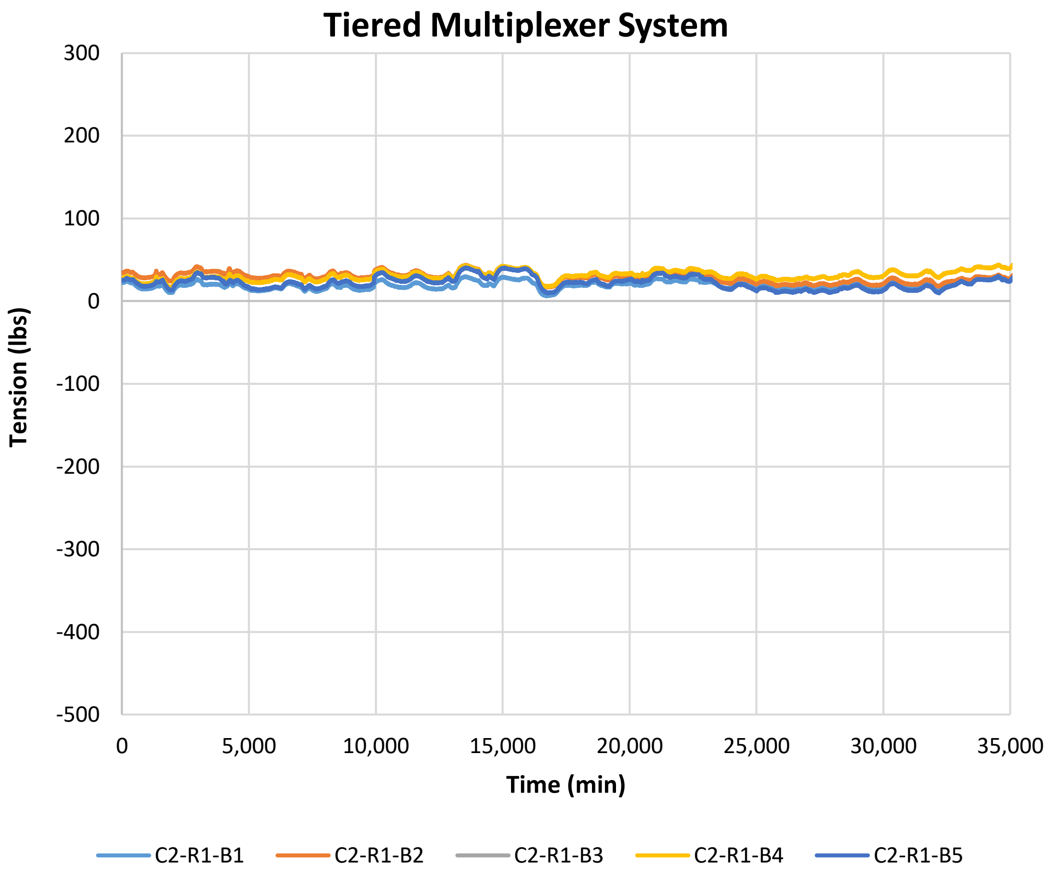
Resolving Settling Time Issues





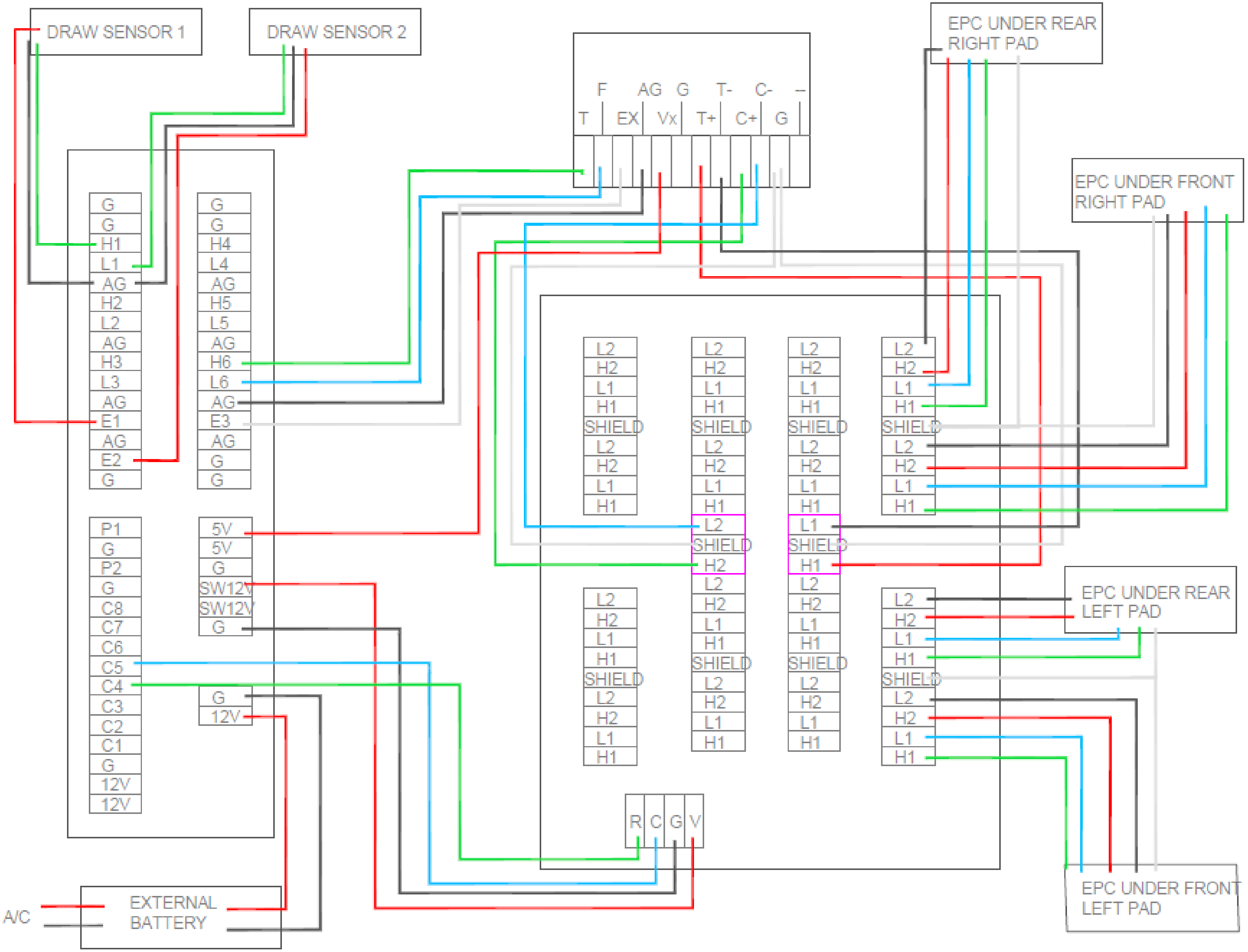
Resolving Residual Voltage Buildup





CR-10X

- 2 draw wire sensors
  - 1 sensor per compaction effort
  - Measures wall movement
- 4 EPCs
  - Underneath each leveling pad
- 6 Strain gauge locations
  - Placed on threadbar for load test monitoring



MSE Wall Construction Sequence

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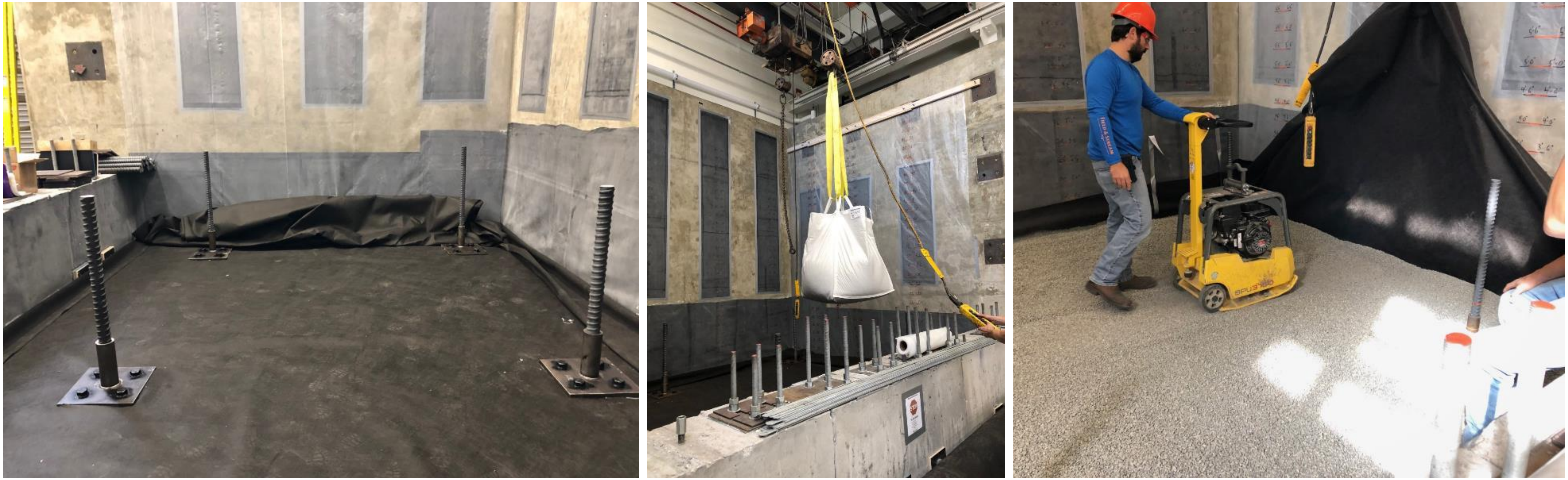

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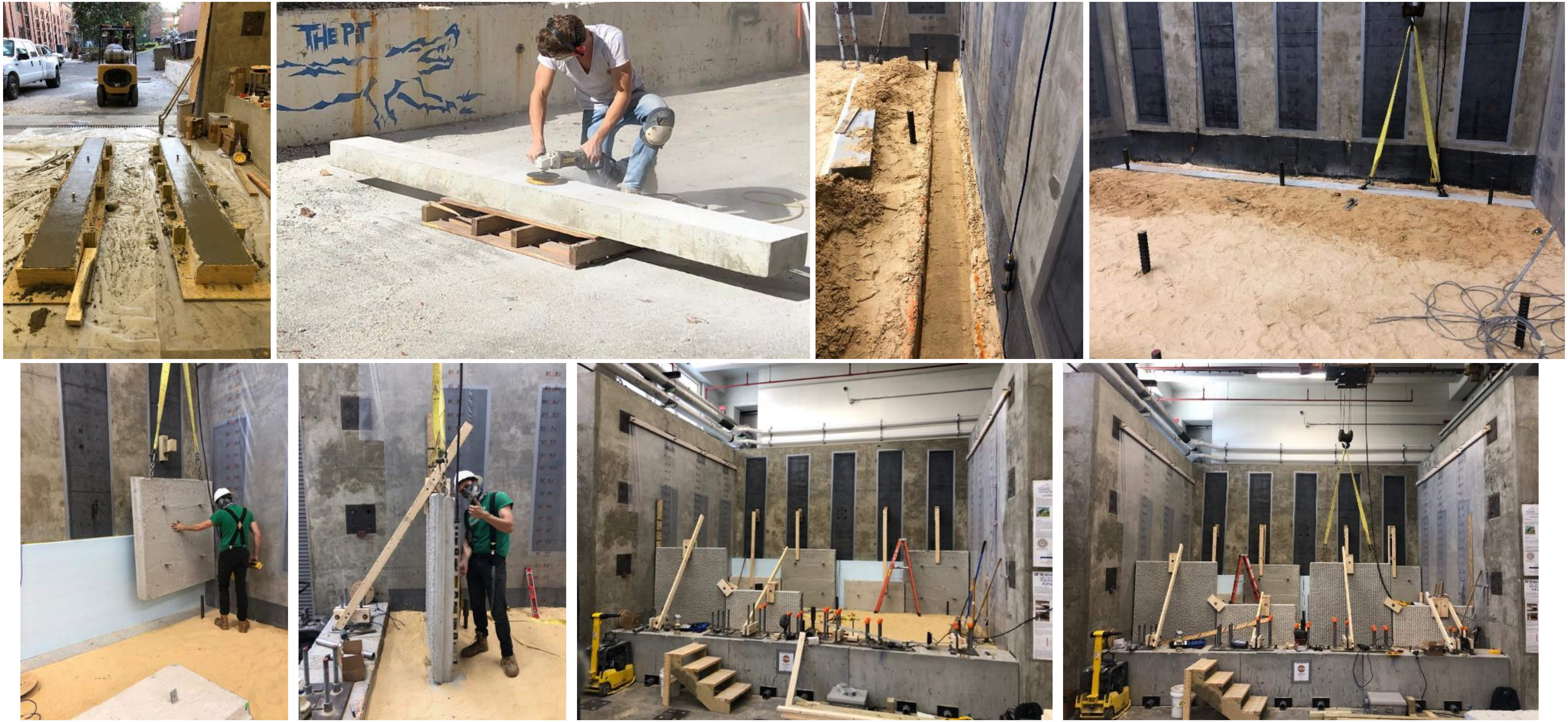

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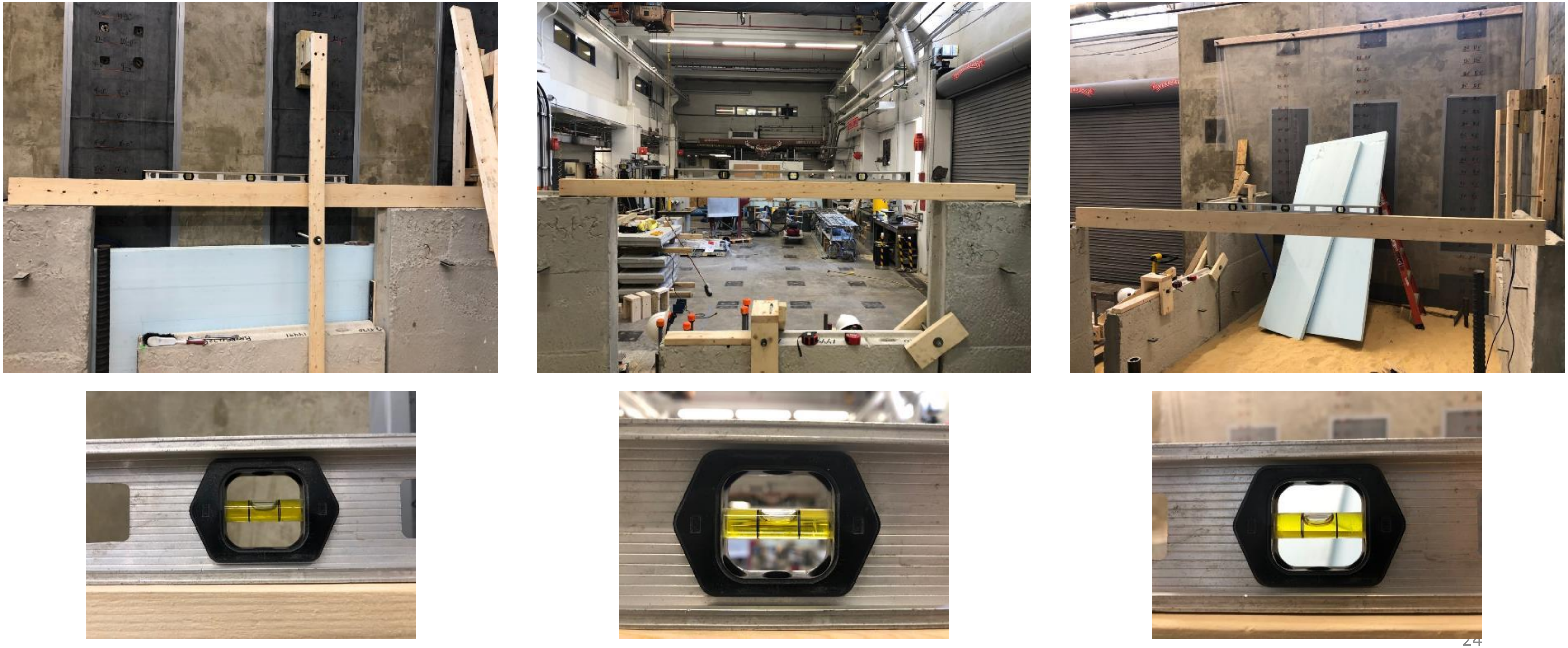

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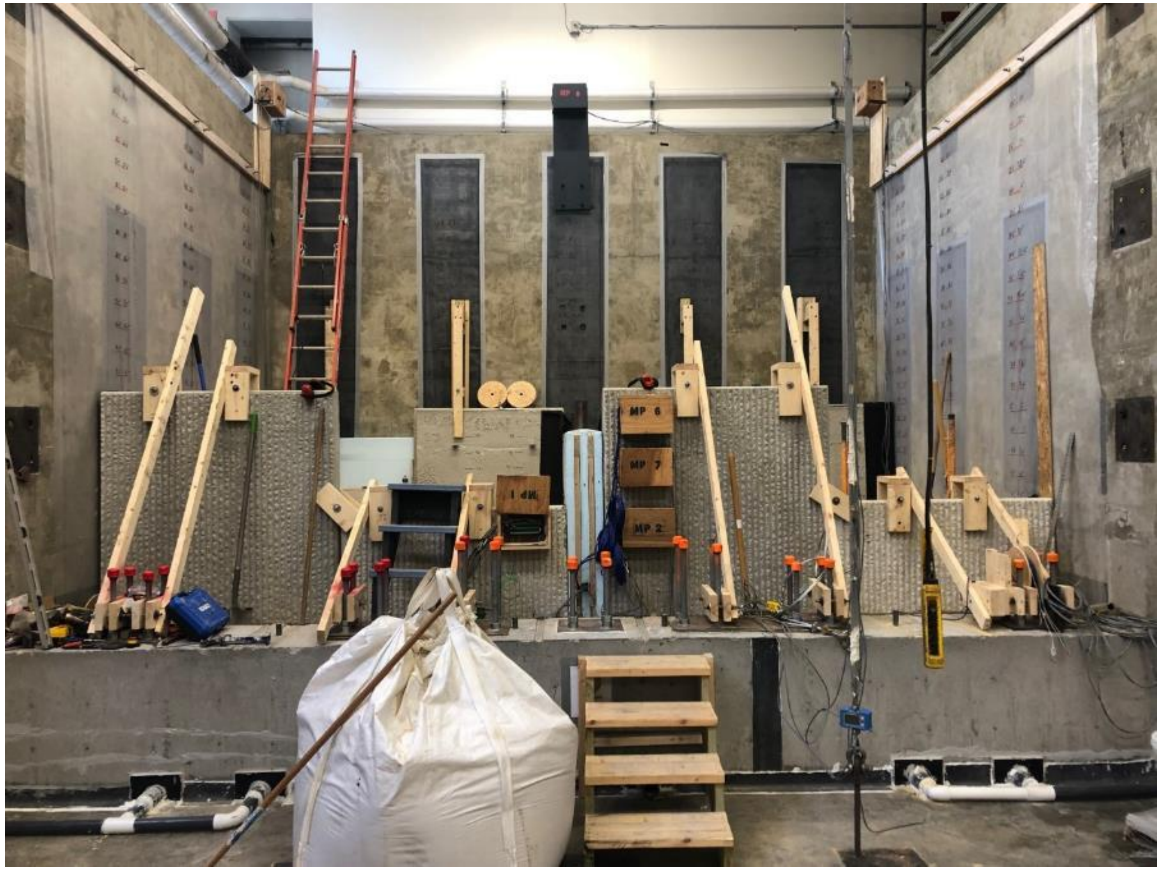

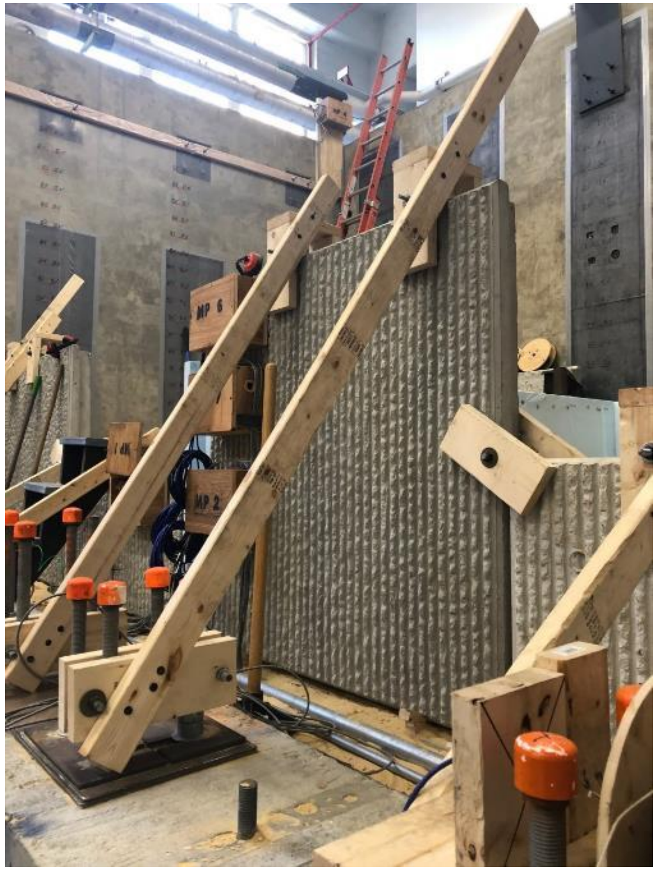

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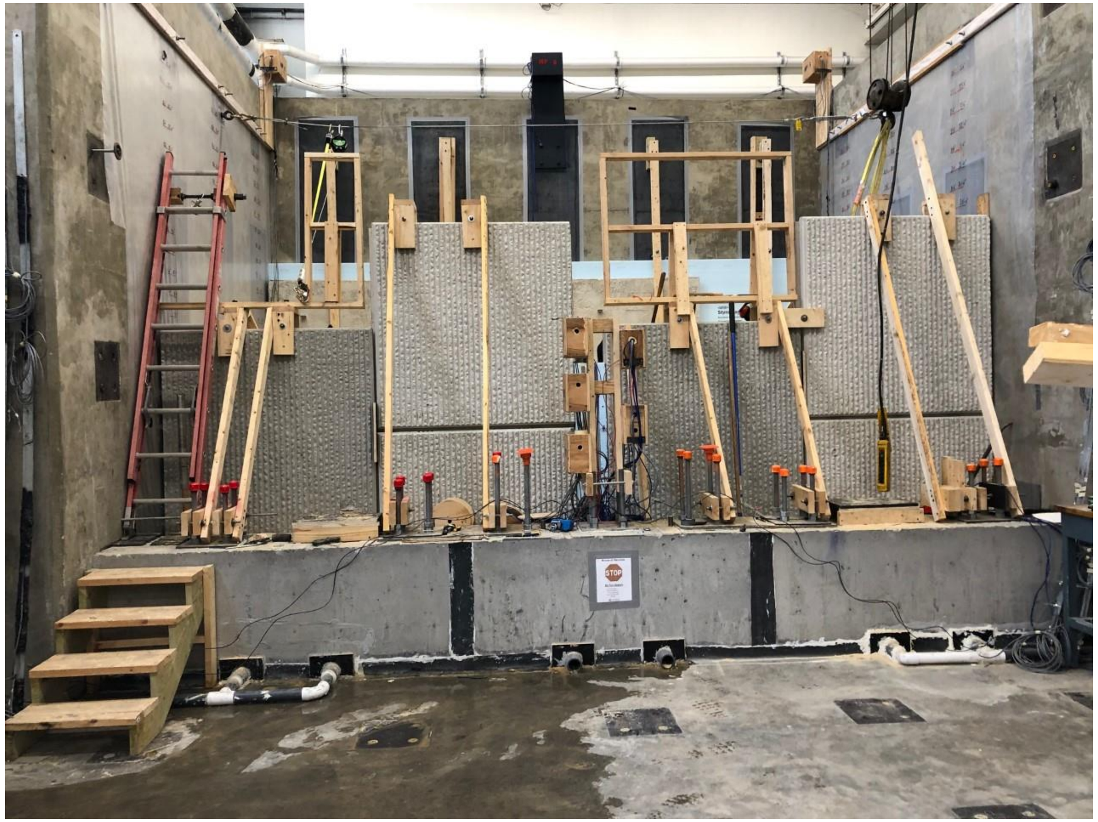

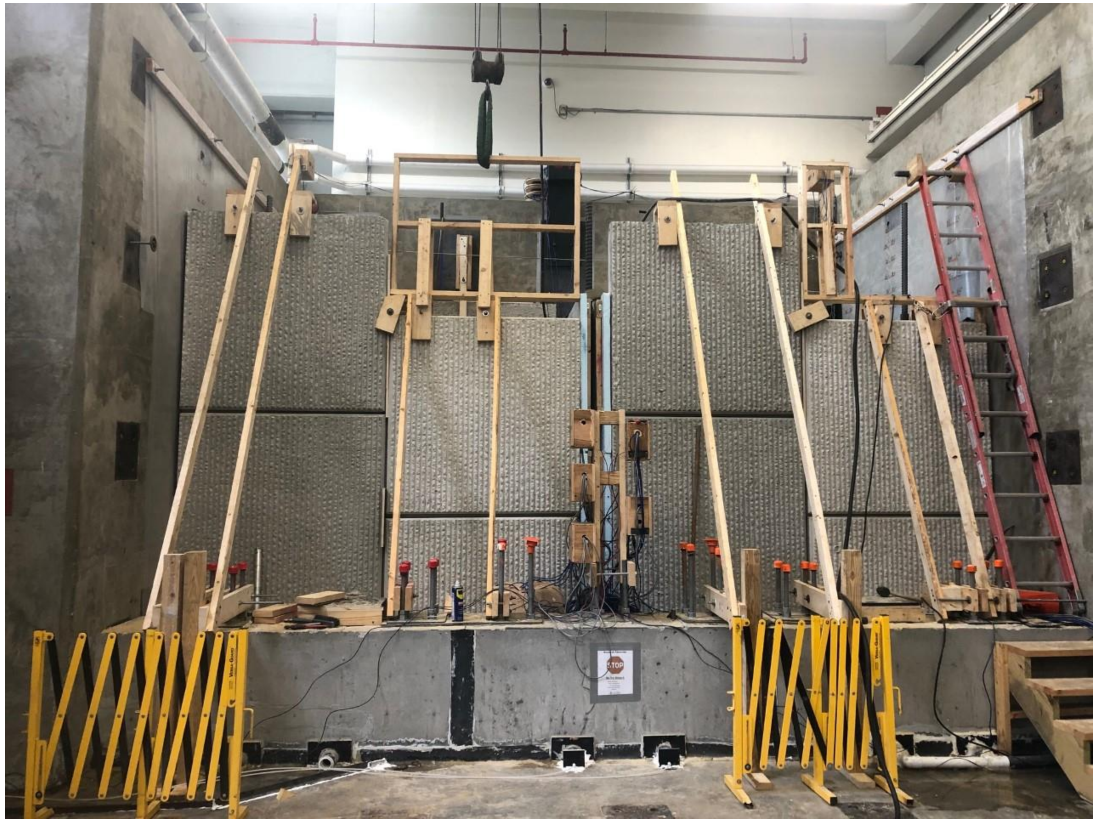

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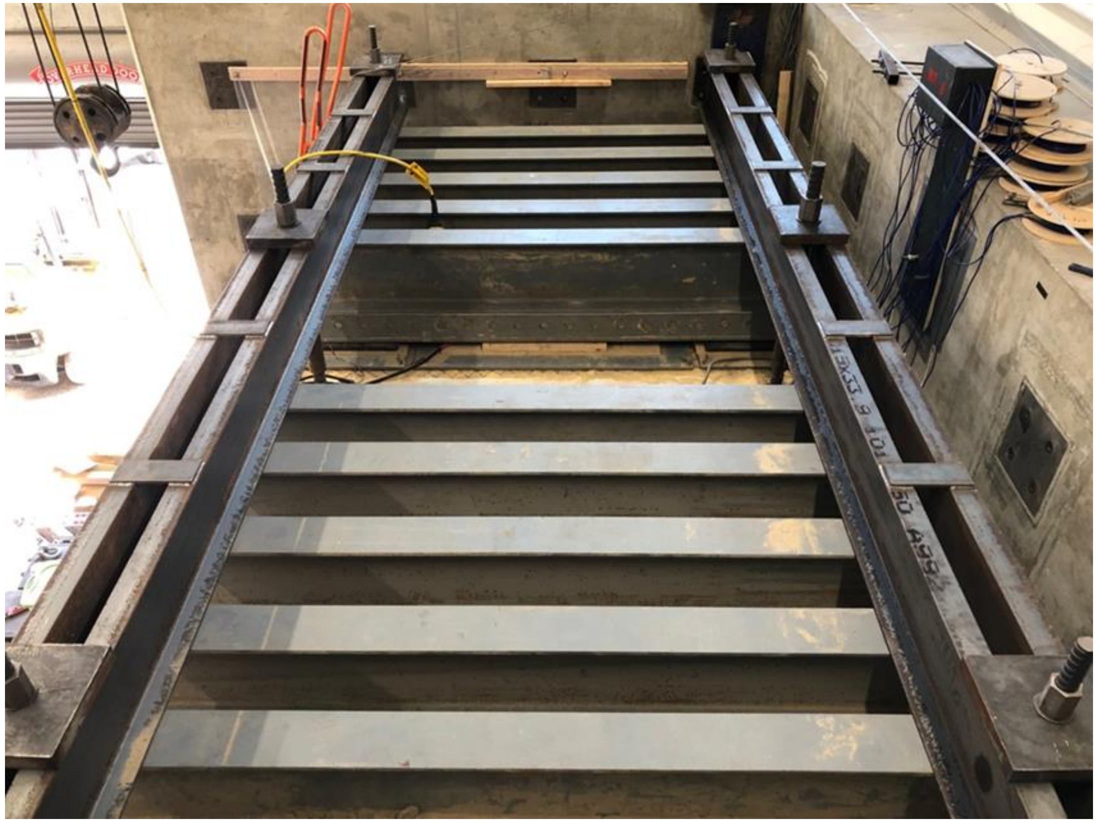
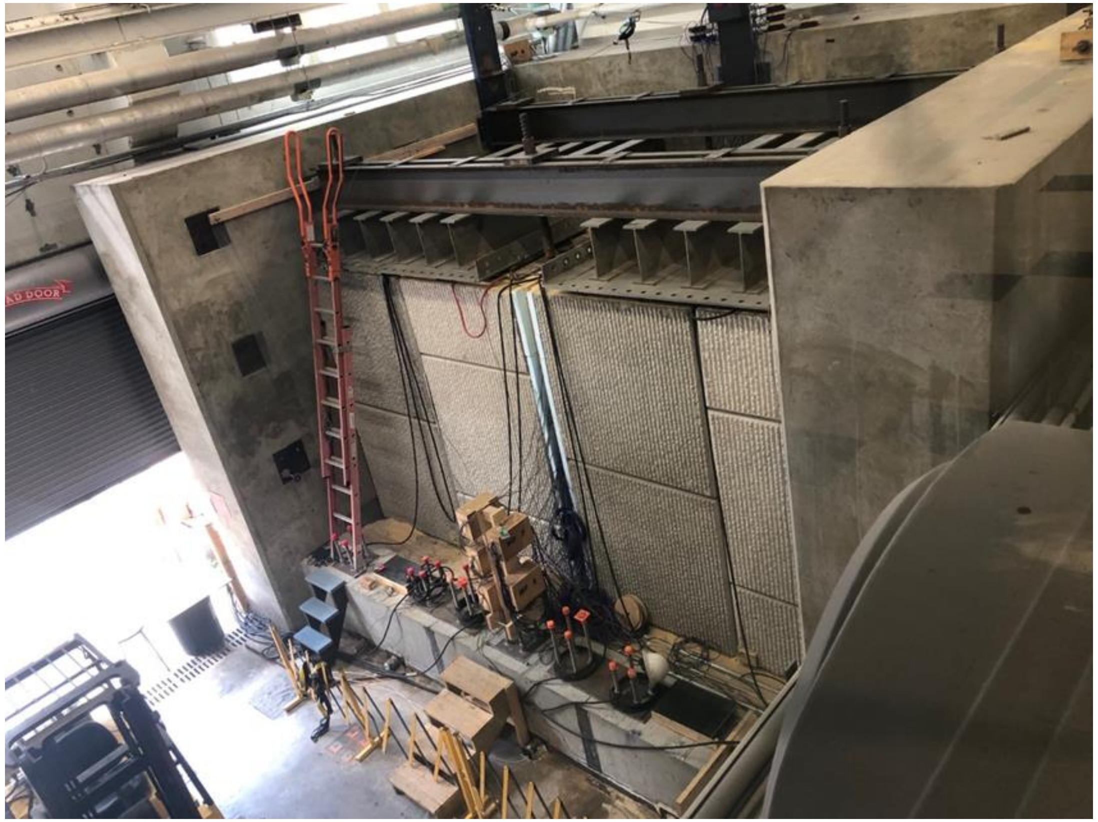




MSE Wall Construction Sequence

95% of T-180

103% of T-180

Col 1

Col 2

Col 3

Col 4

Row 4

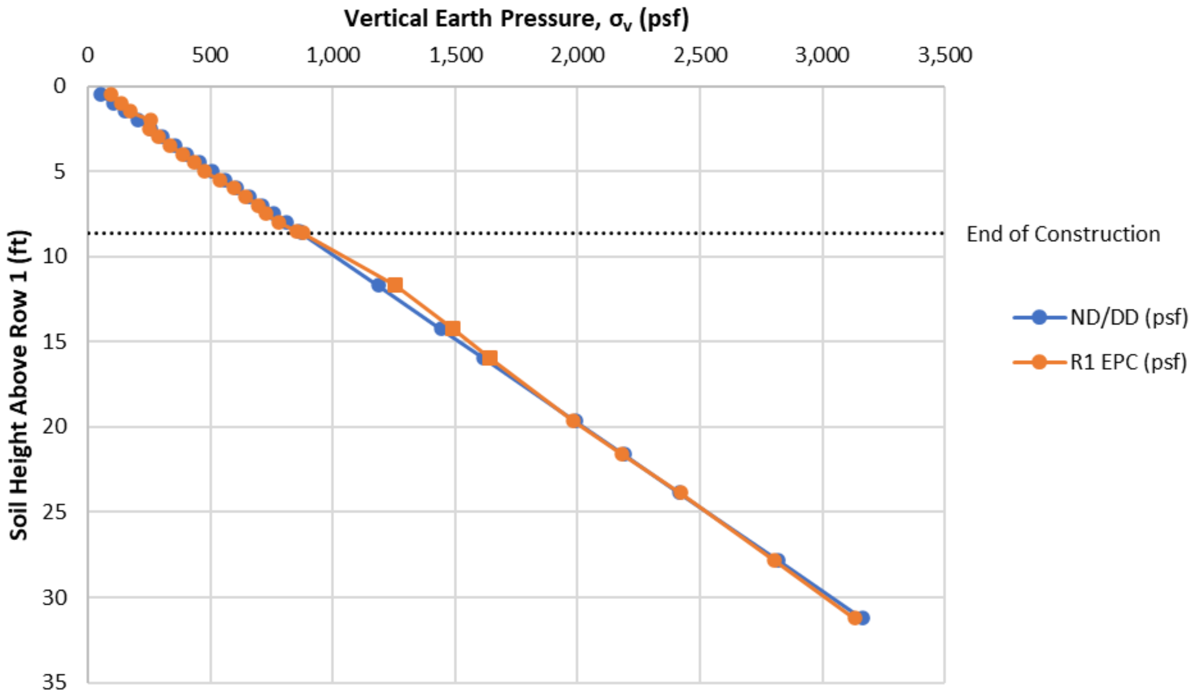
Row 3

Row 2

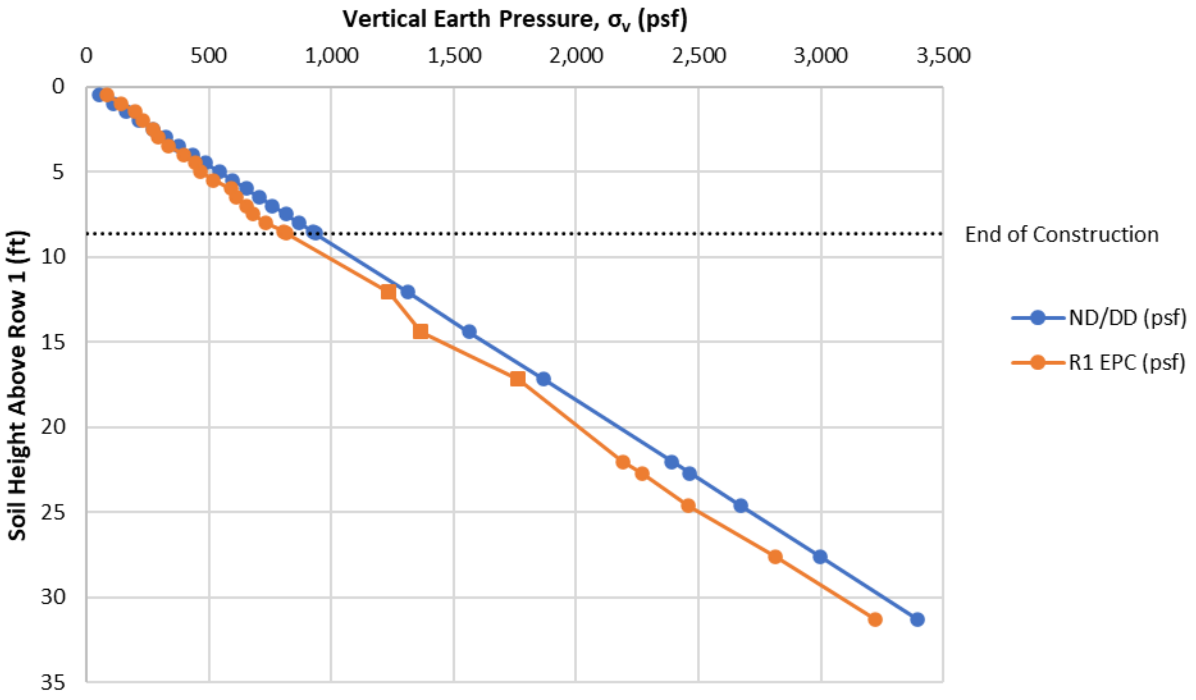
Row 1

Applied Overburden vs. Measured Vertical Stress

95% of T-180

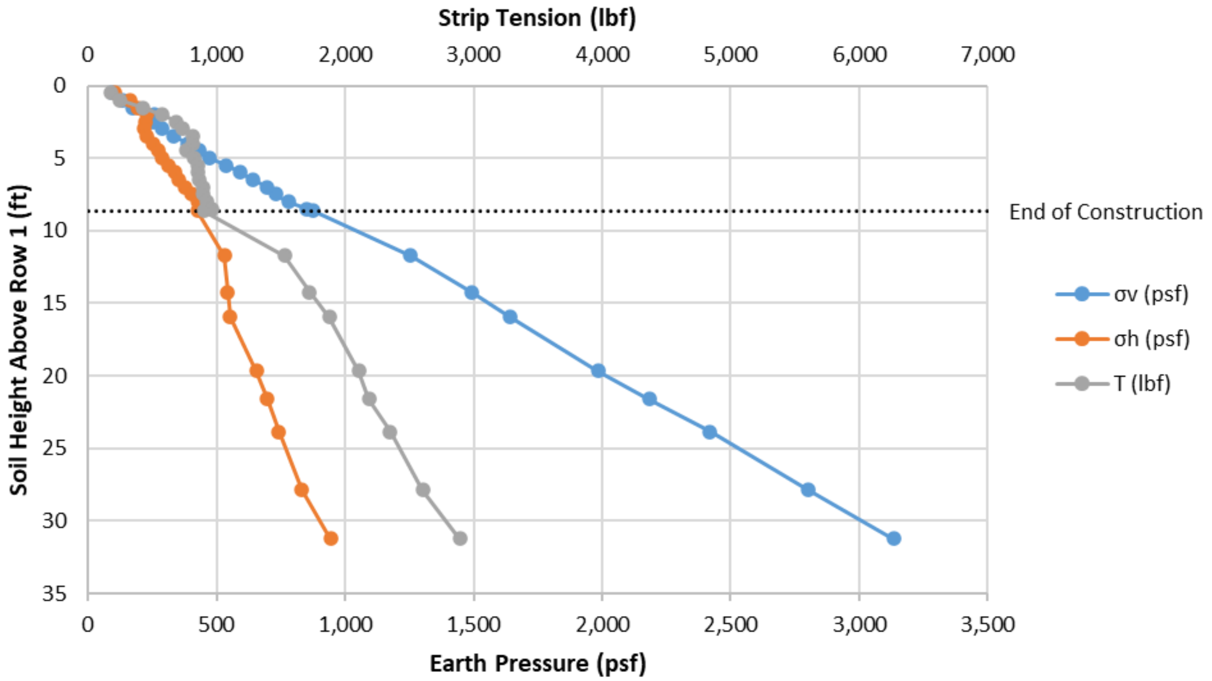


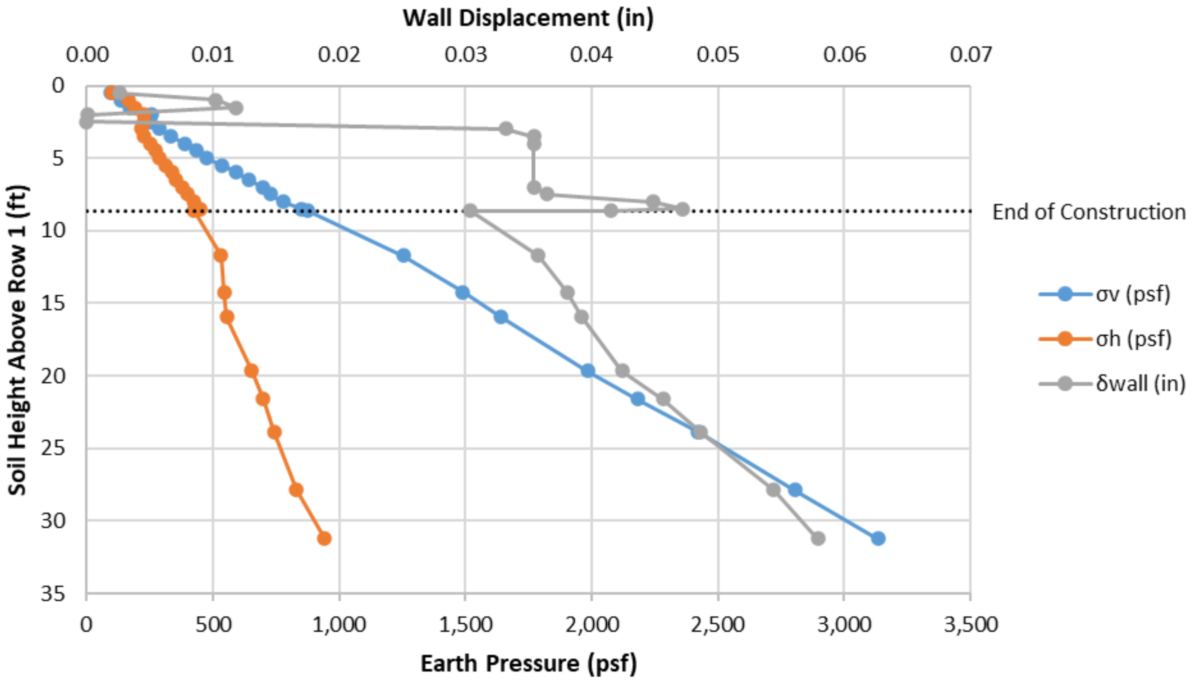
103% of T-180



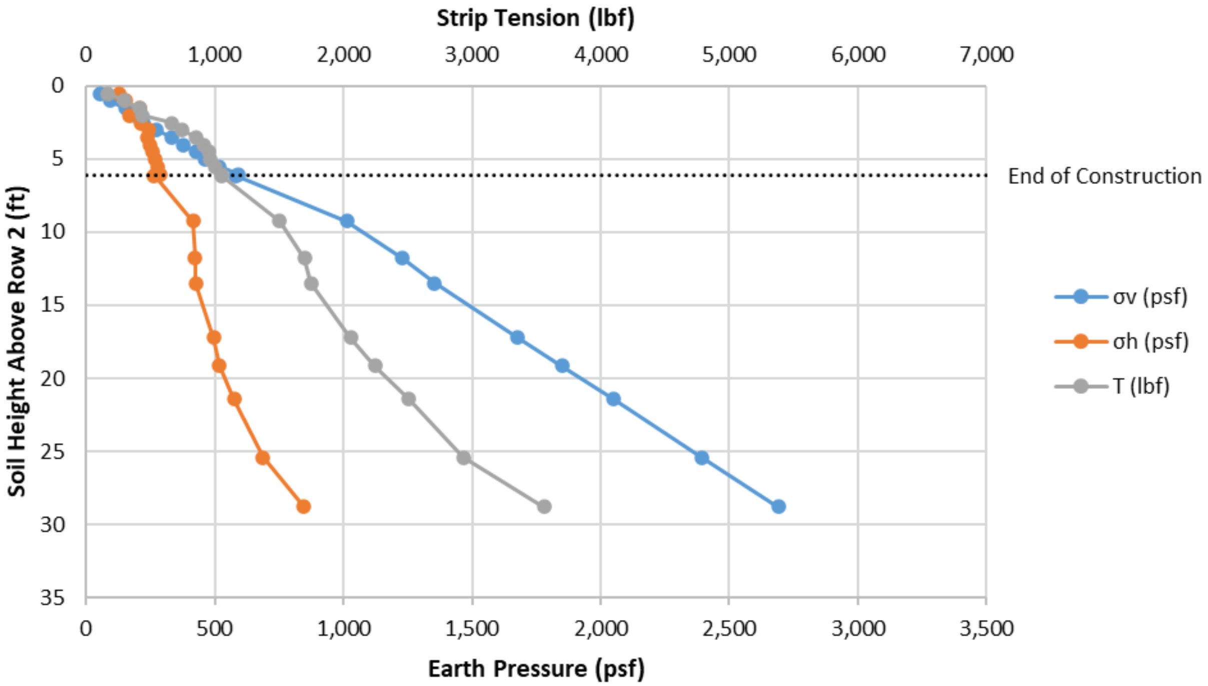
- Row 1 EPCs on the 95% side are similar to the applied overburden pressure with a small reduction
- Row 1 EPCs on the 103% side are noticeably reduced compared to the applied overburden pressure

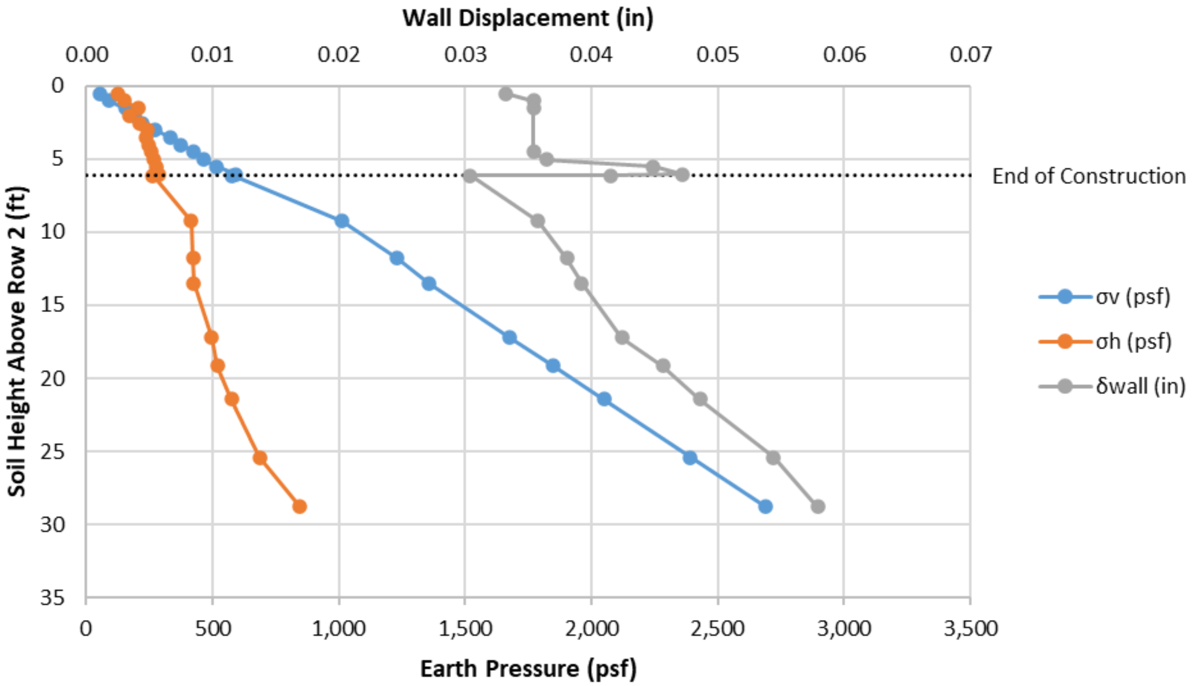
95% of T-180 – Row 1



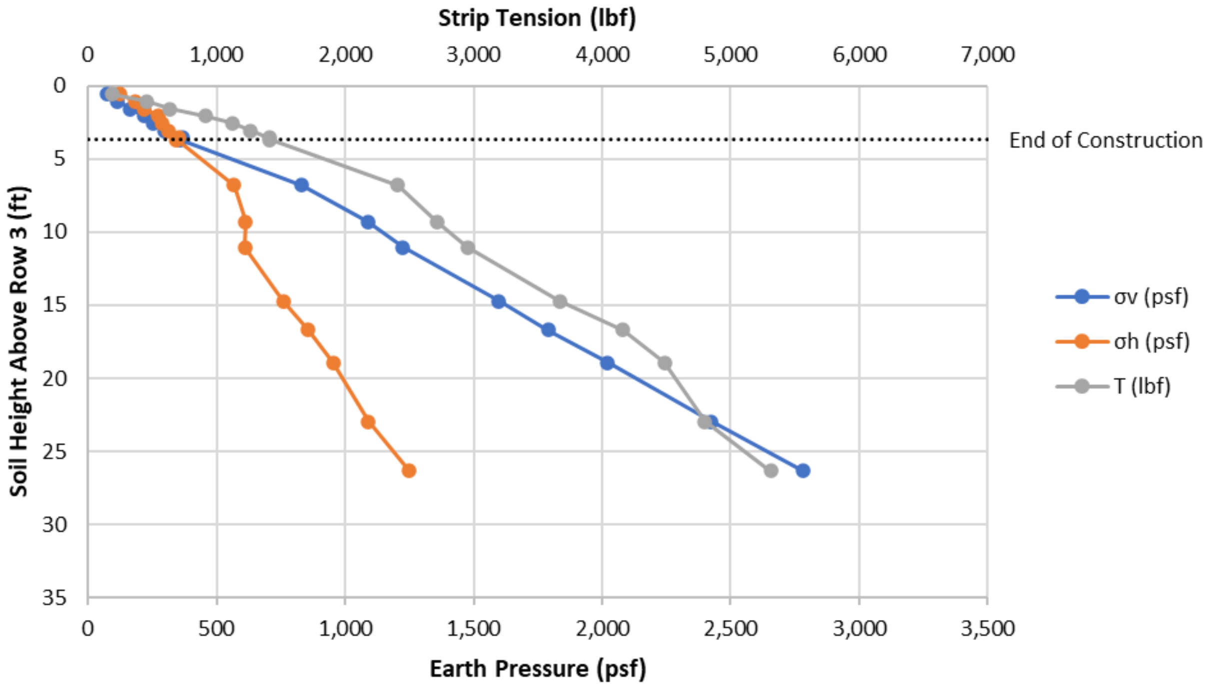


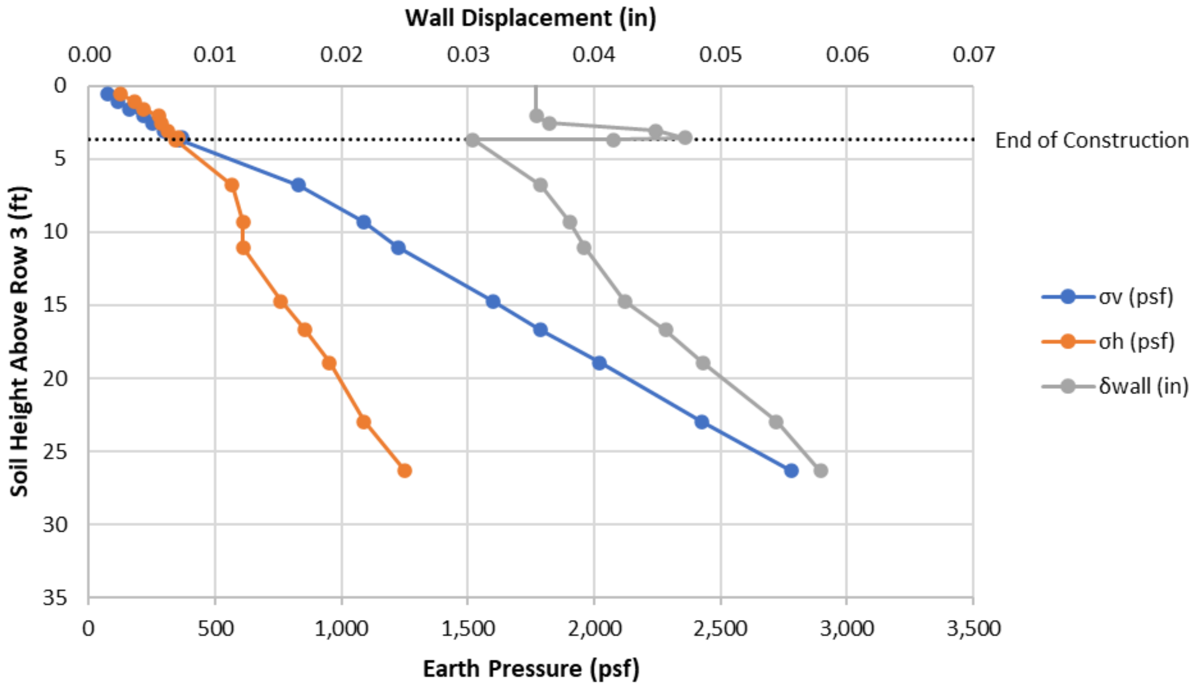
95% of T-180 – Row 2



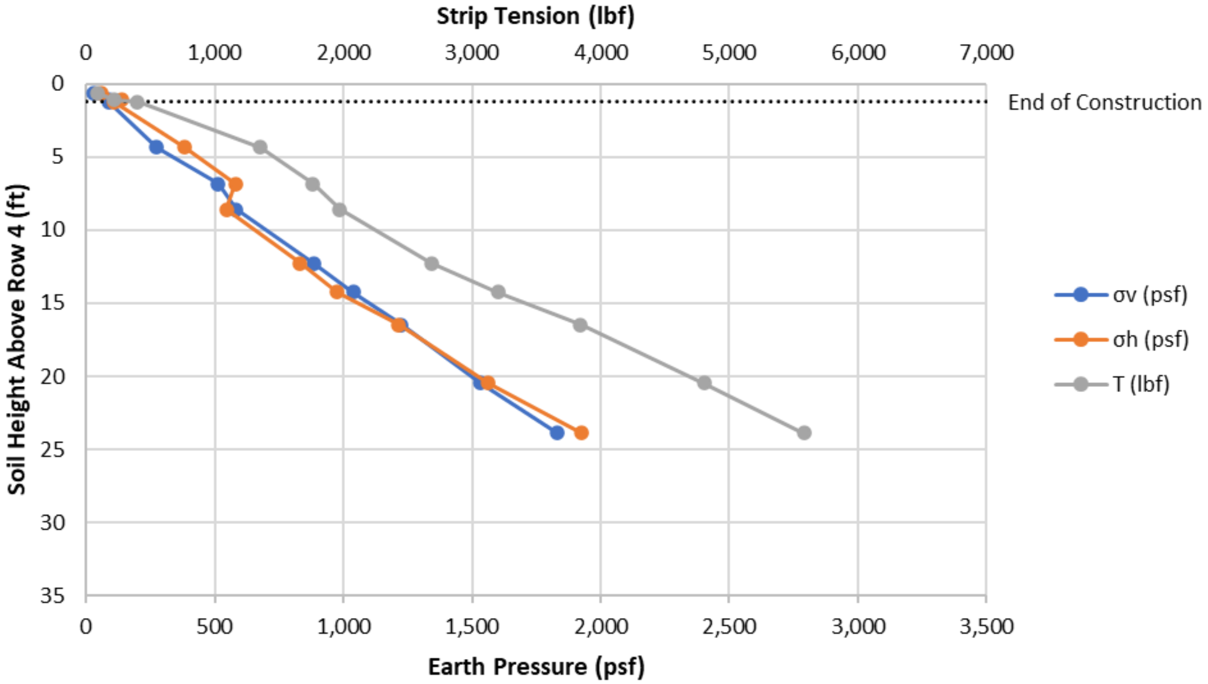


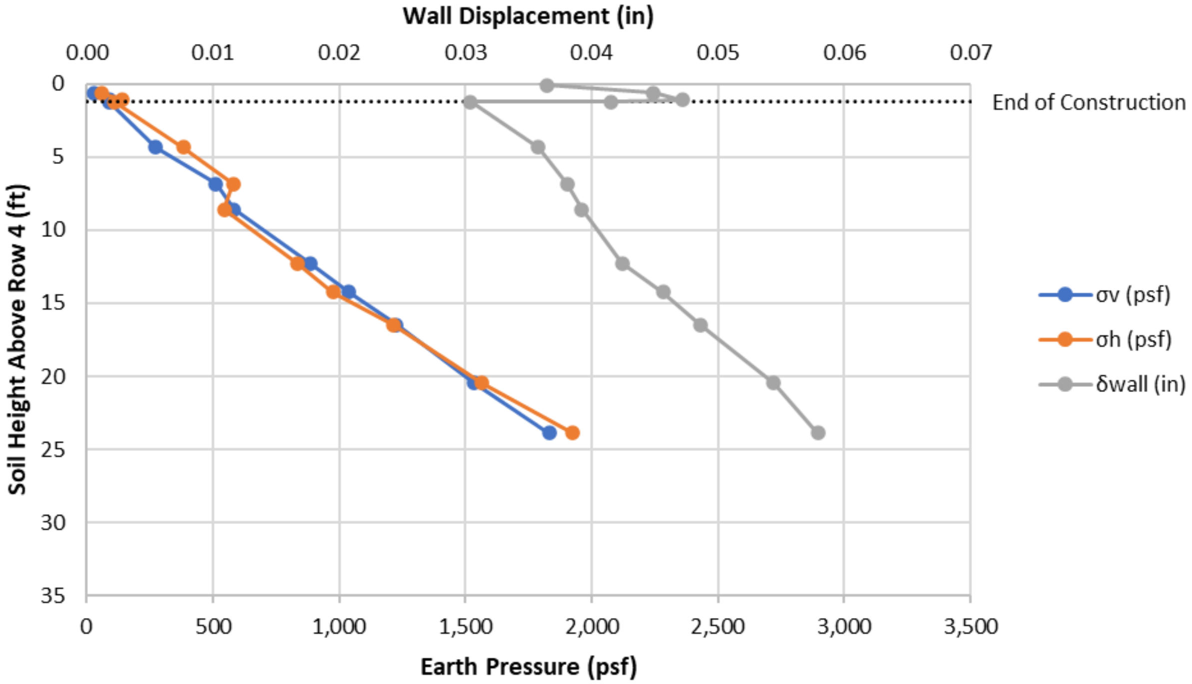
95% of T-180 – Row 3



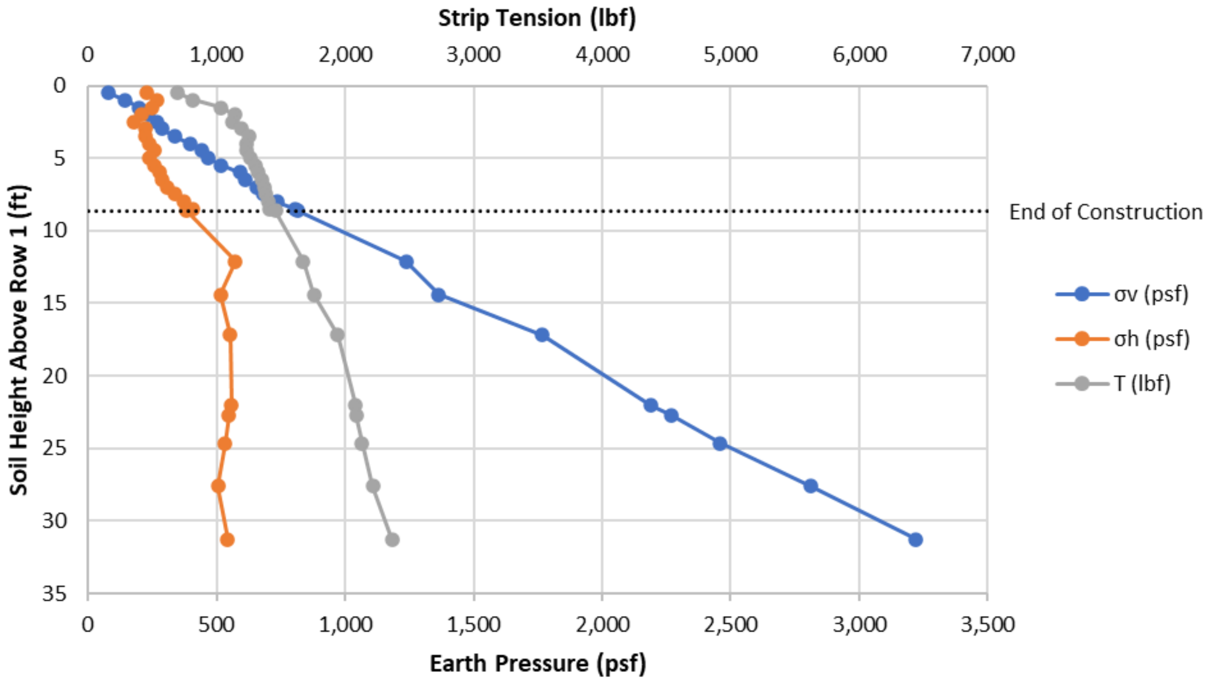


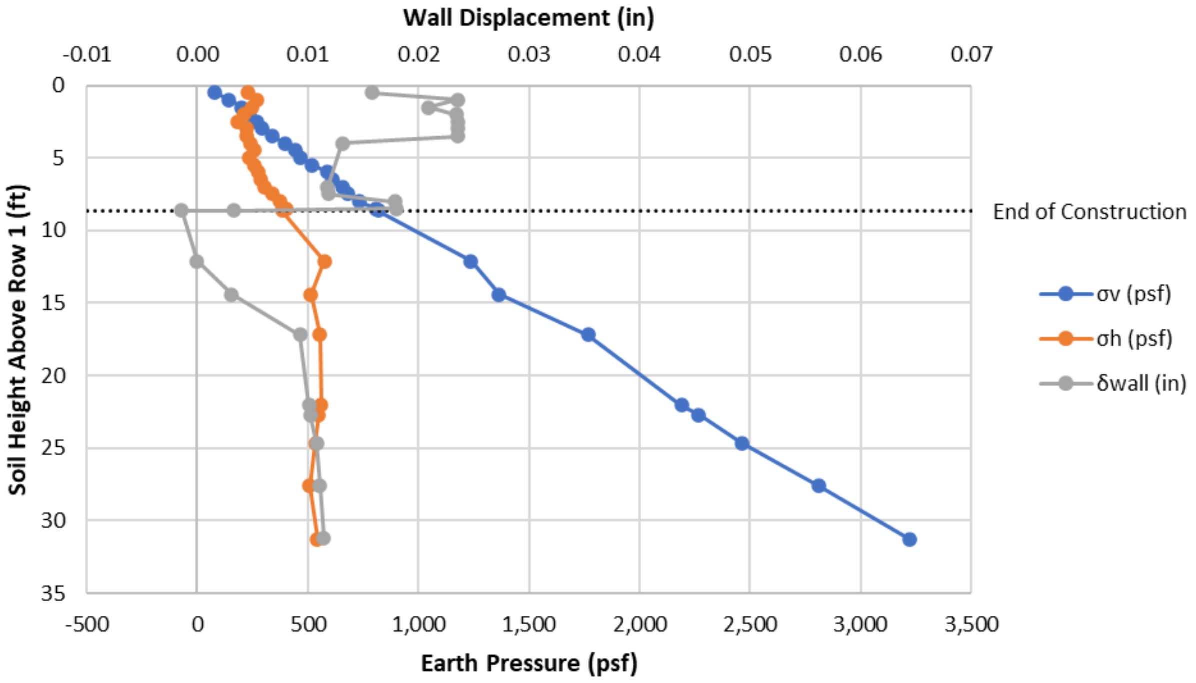
95% of T-180 – Row 4



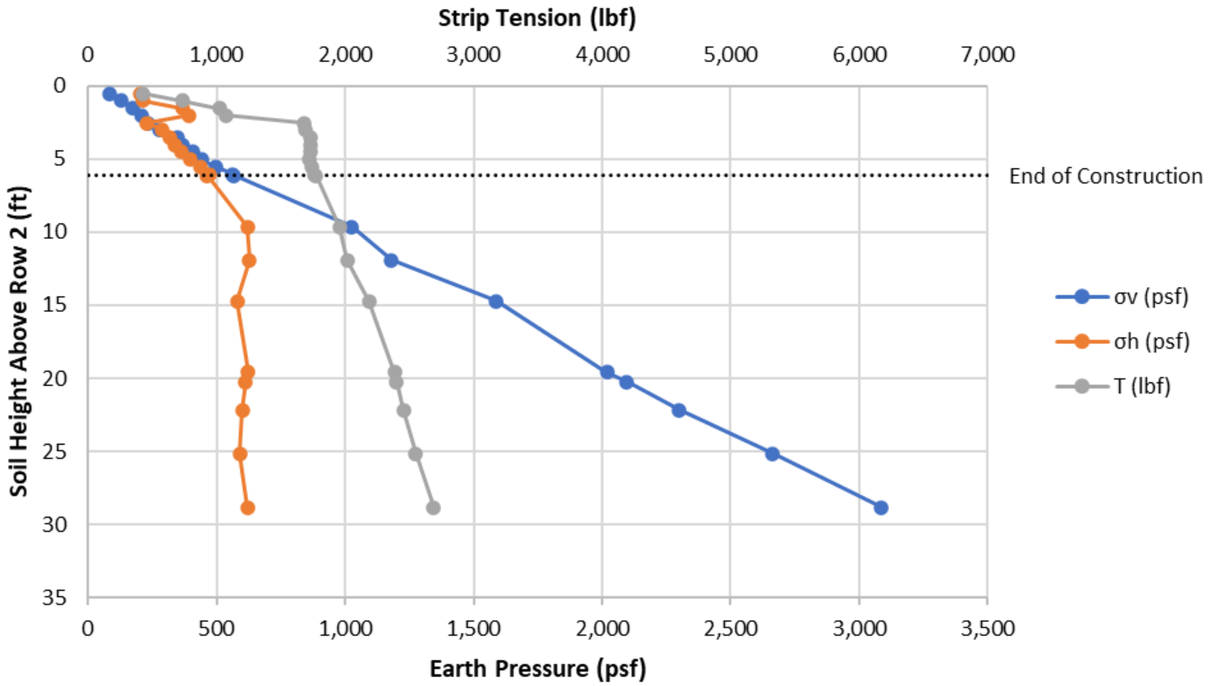


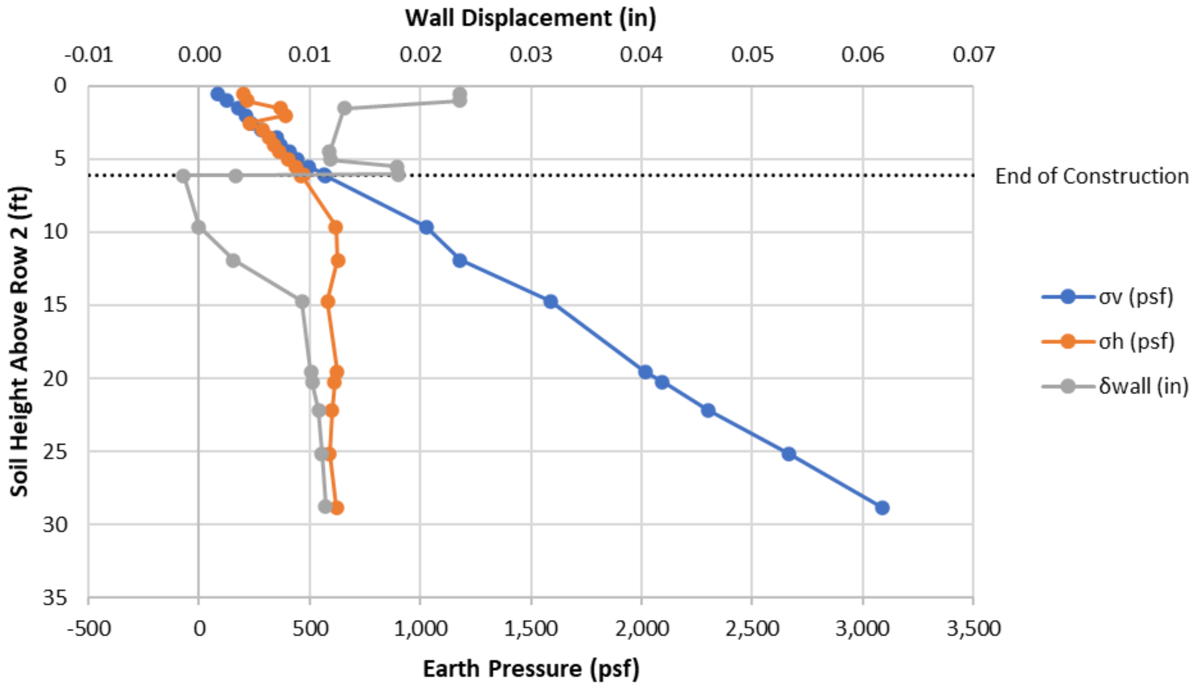
103% of T-180 – Row 1



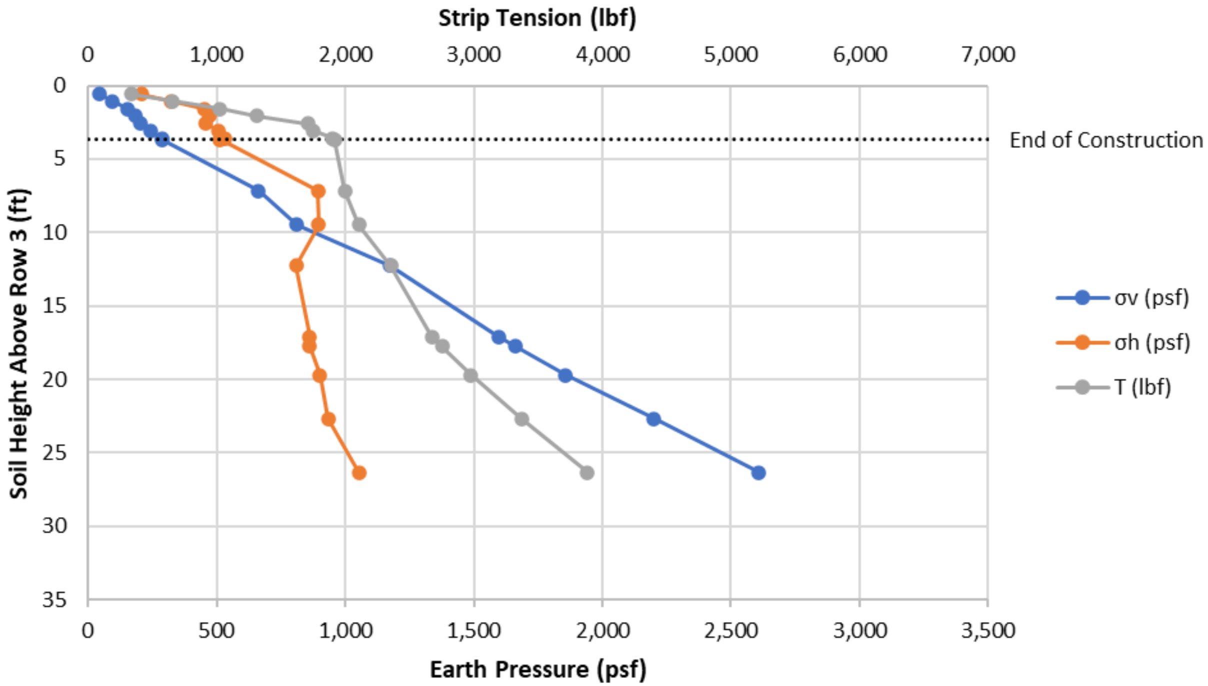


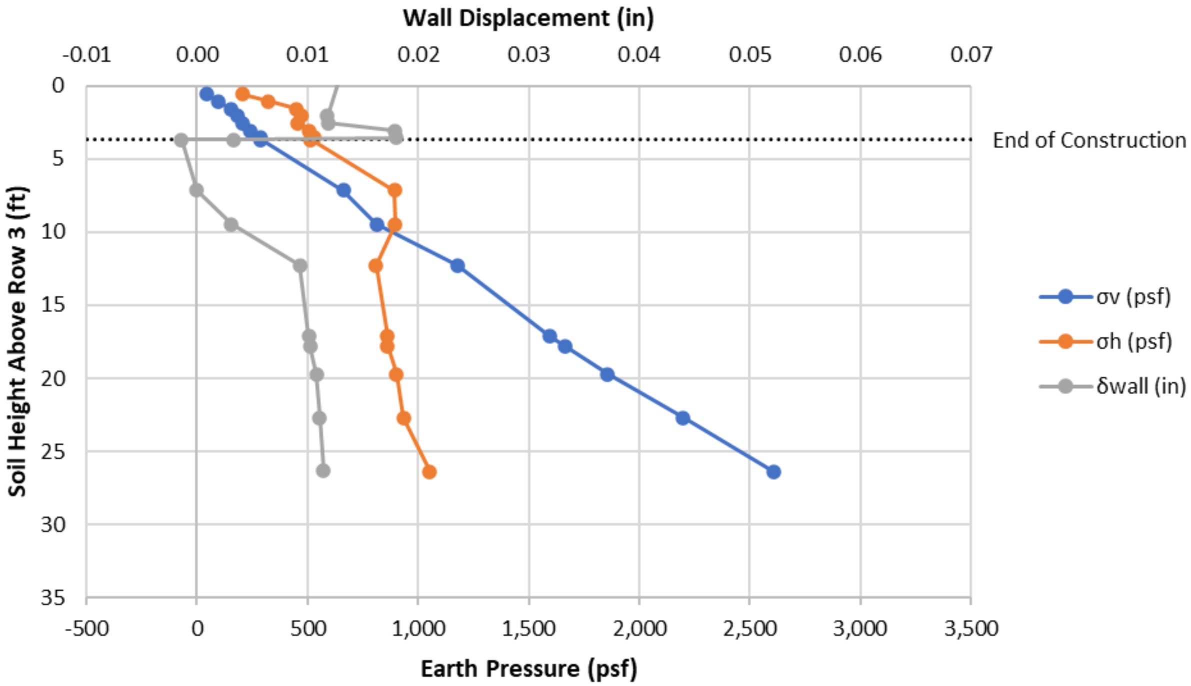
103% of T-180 – Row 2



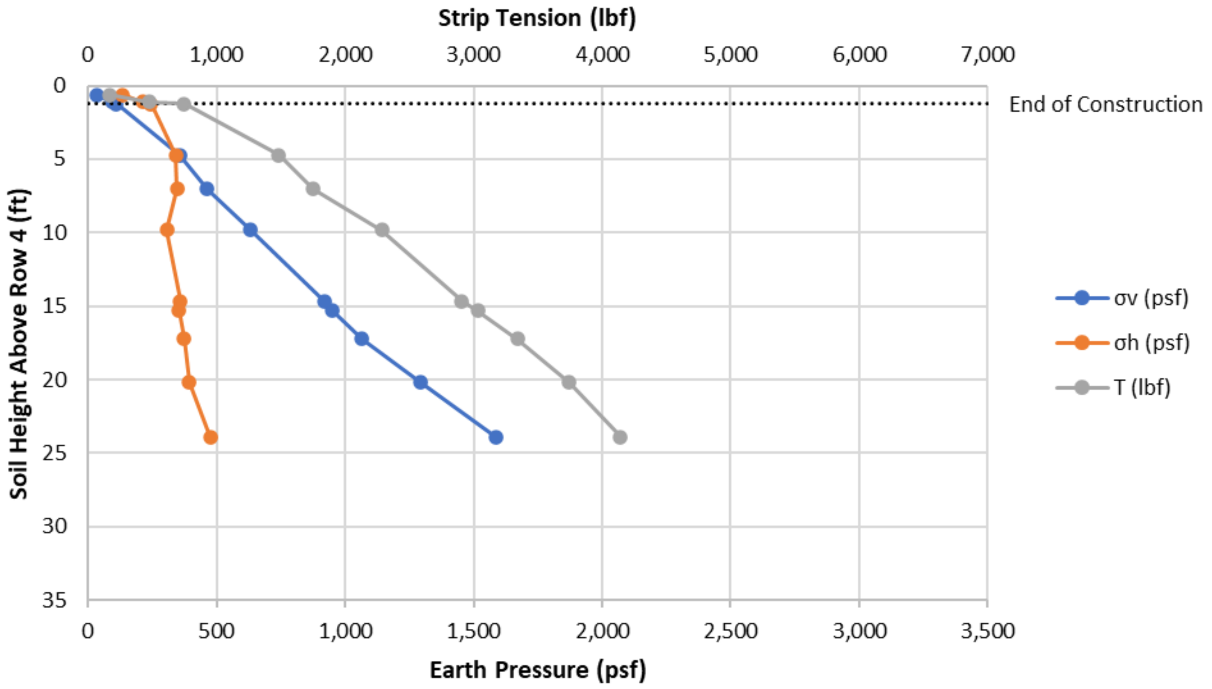


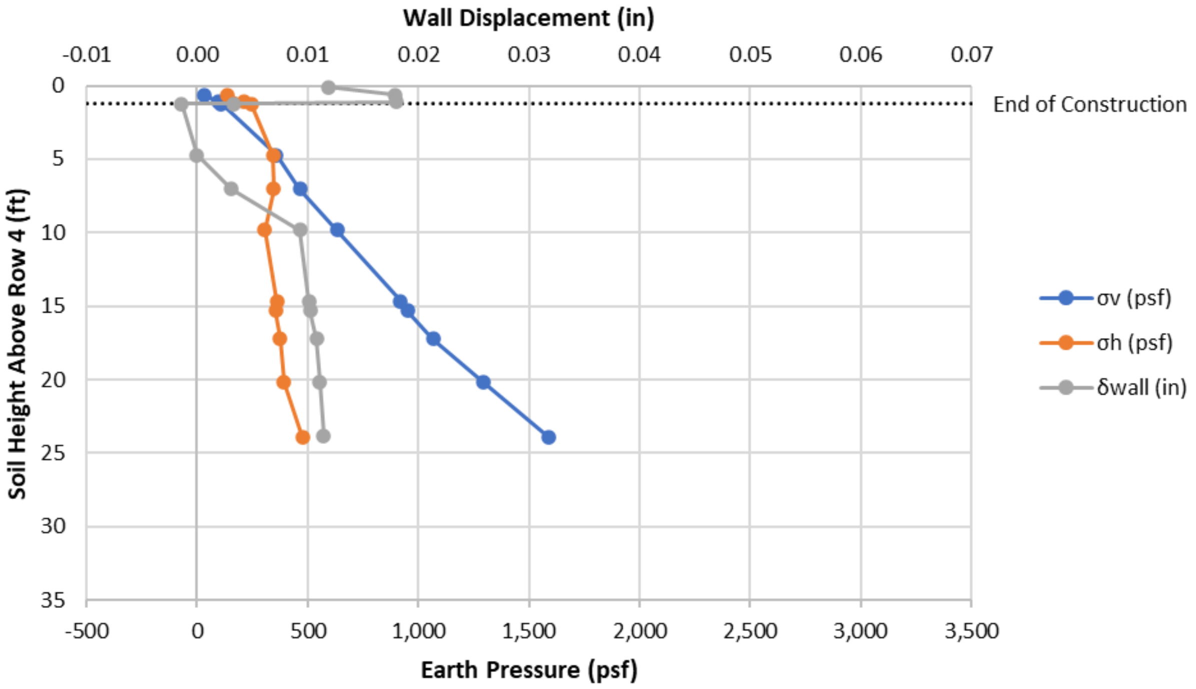
103% of T-180 – Row 3





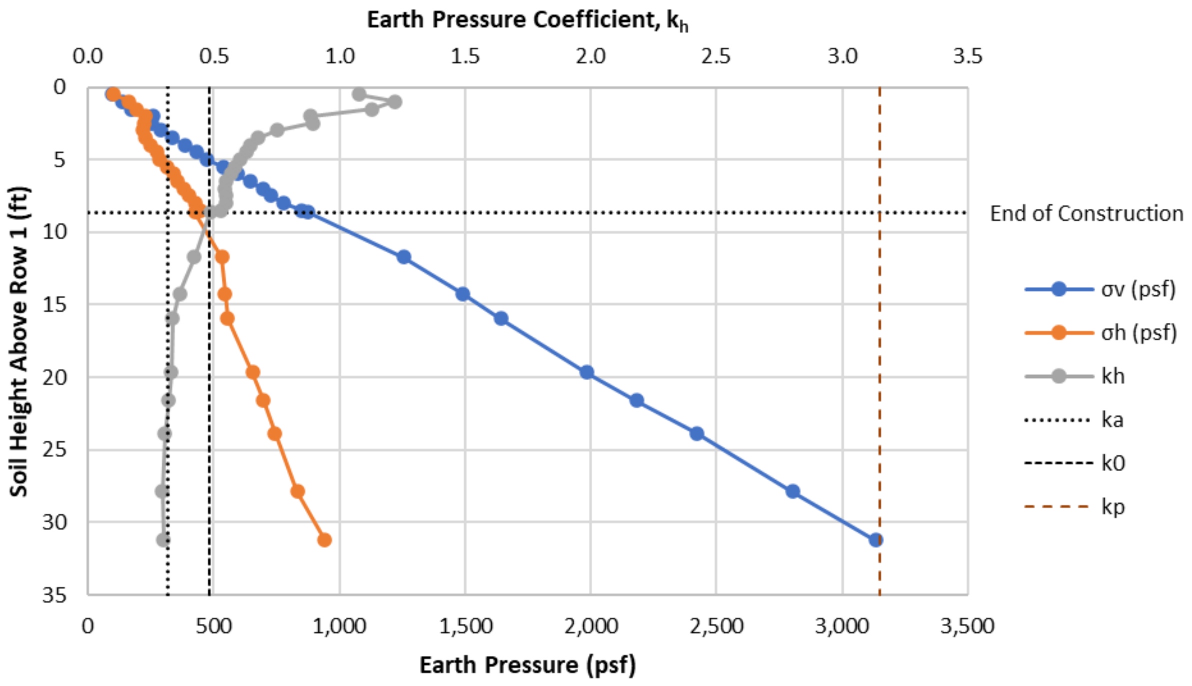
103% of T-180 – Row 4



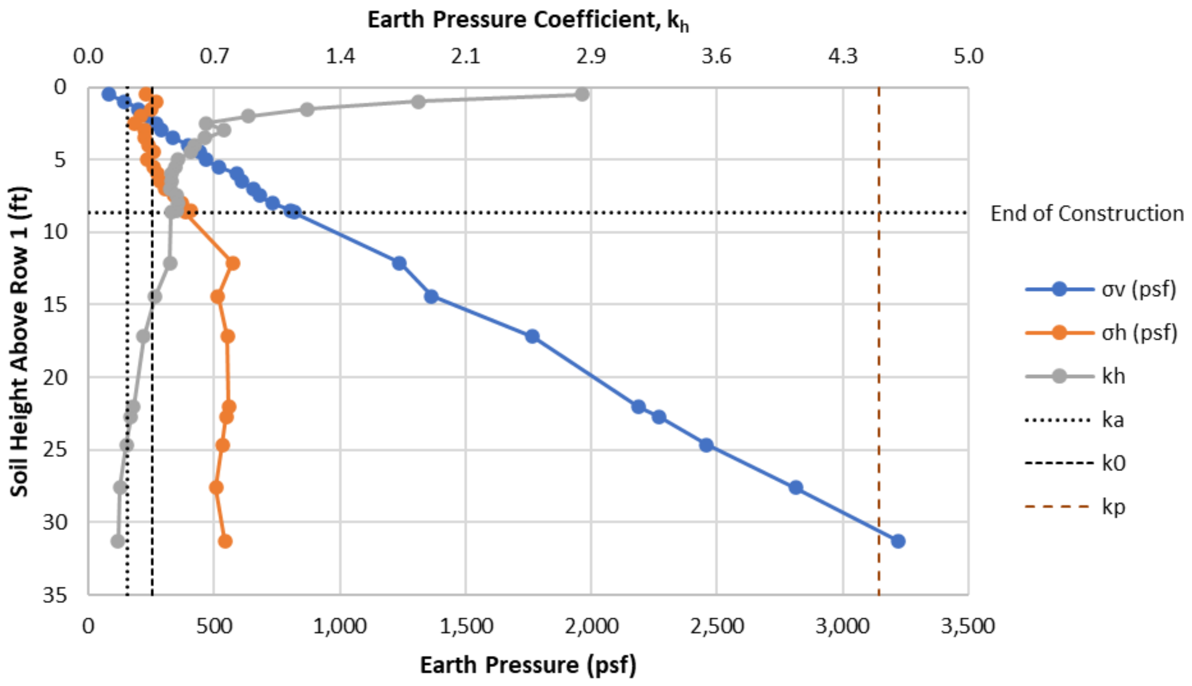


Earth Pressure Coefficients – Row 1

95% of T-180 ⇒ ϕ = 31.2 degrees

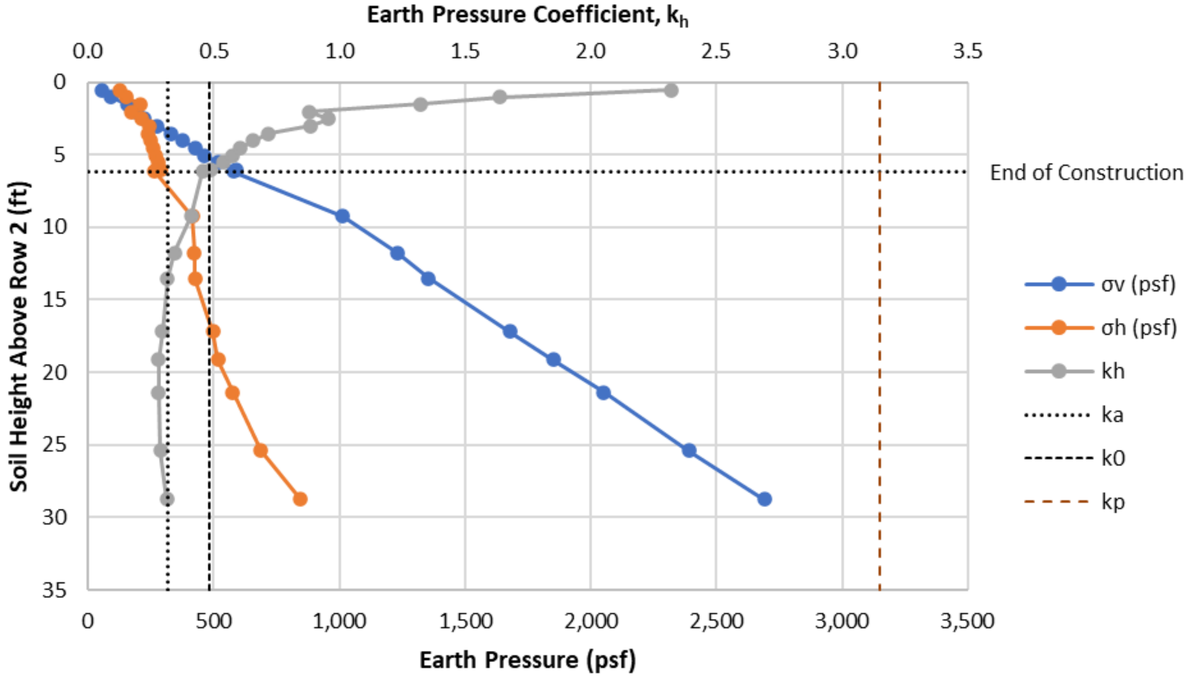


103% of T-180 ⇒ ϕ = 39.5 degrees

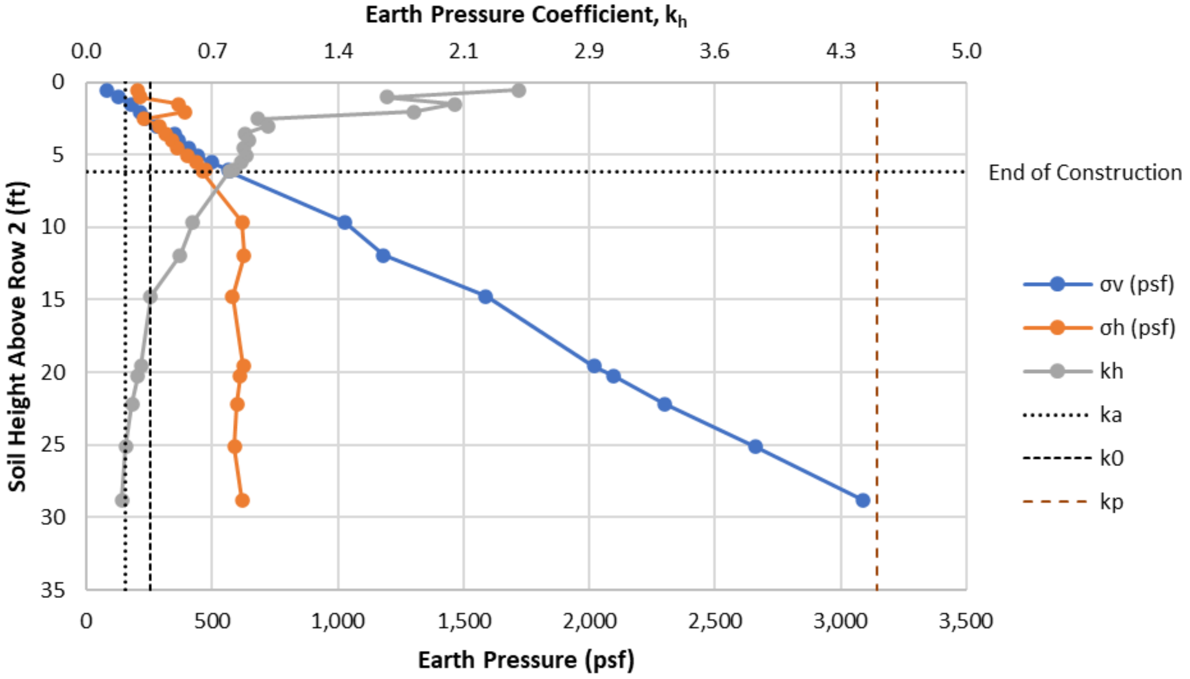


Earth Pressure Coefficients – Row 2

95% of T-180 ⇒ ϕ = 31.2 degrees

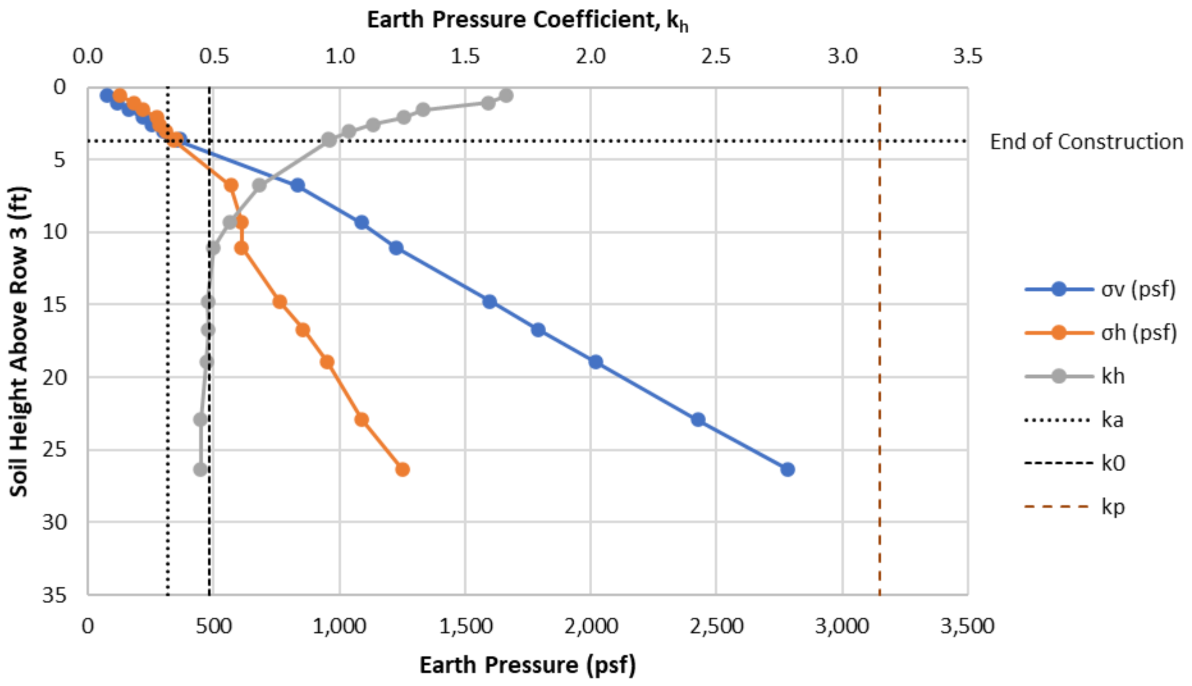


103% of T-180 ⇒ ϕ = 39.5 degrees

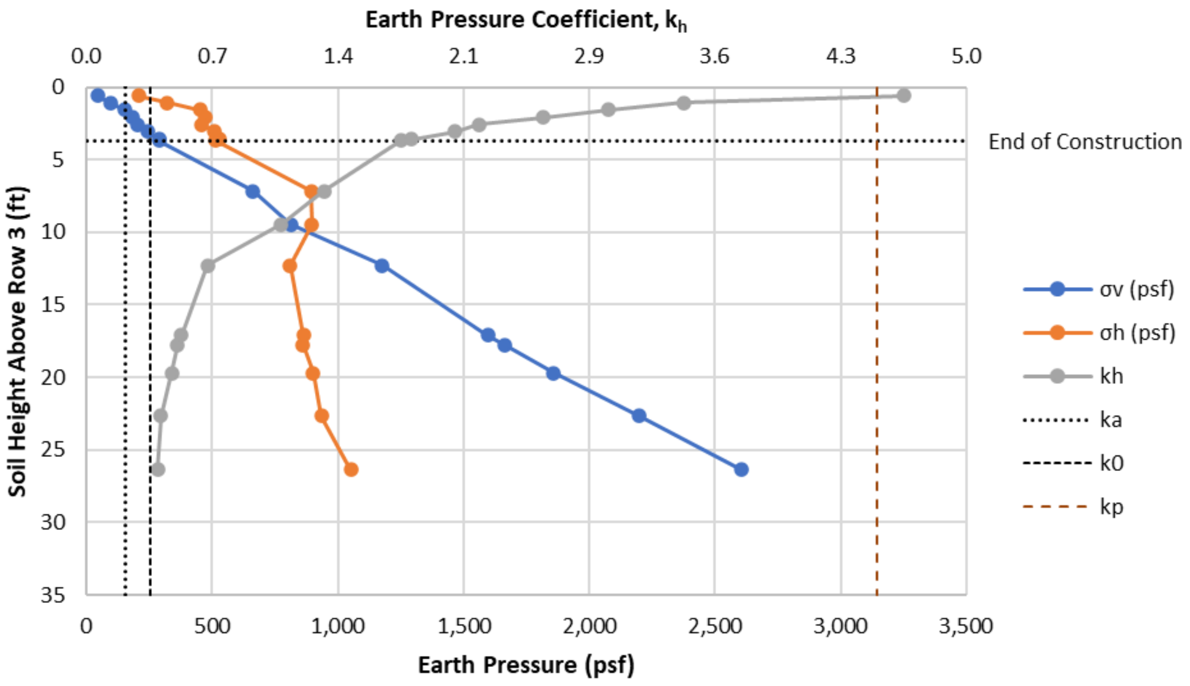


Earth Pressure Coefficients – Row 3

95% of T-180 ⇒ ϕ = 31.2 degrees

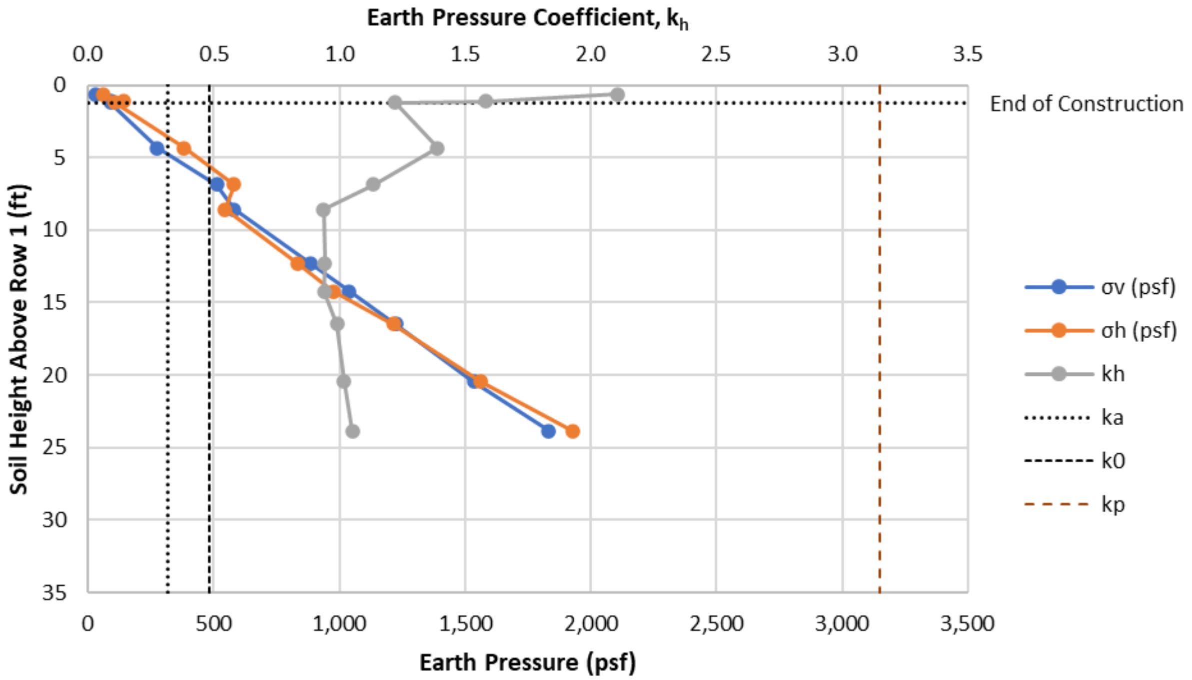


103% of T-180 ⇒ ϕ = 39.5 degrees

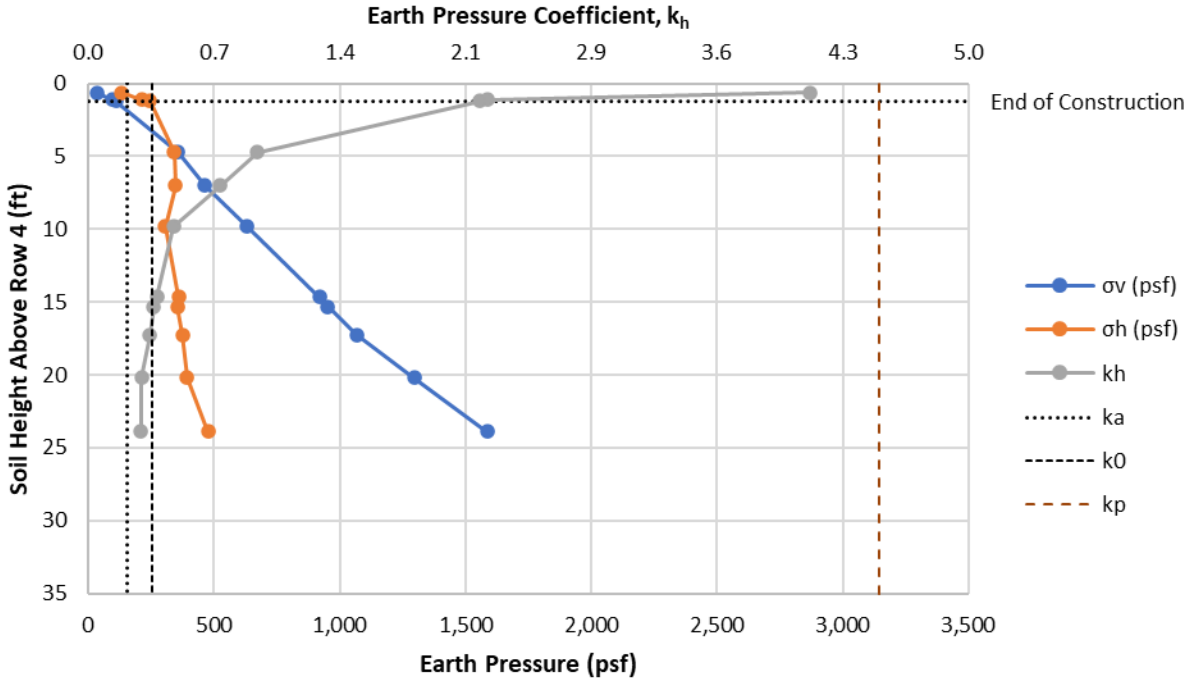


Earth Pressure Coefficients – Row 4

95% of T-180 ⇒ ϕ = 31.2 degrees



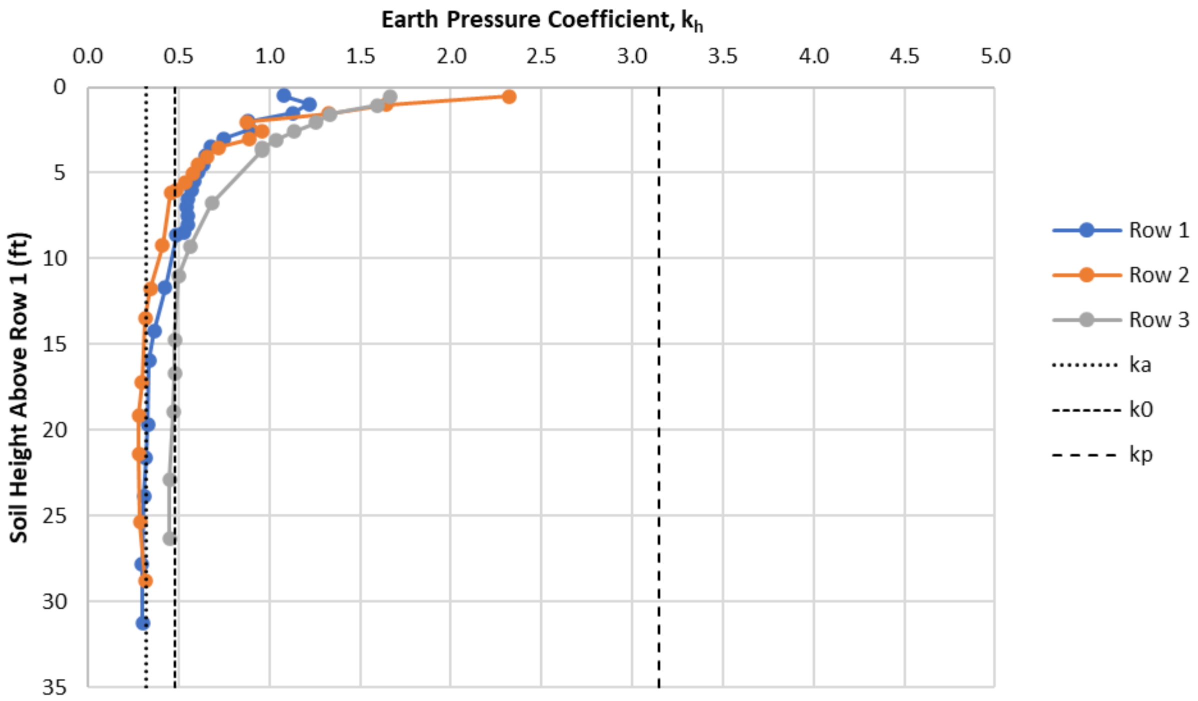
103% of T-180 ⇒ ϕ = 39.5 degrees



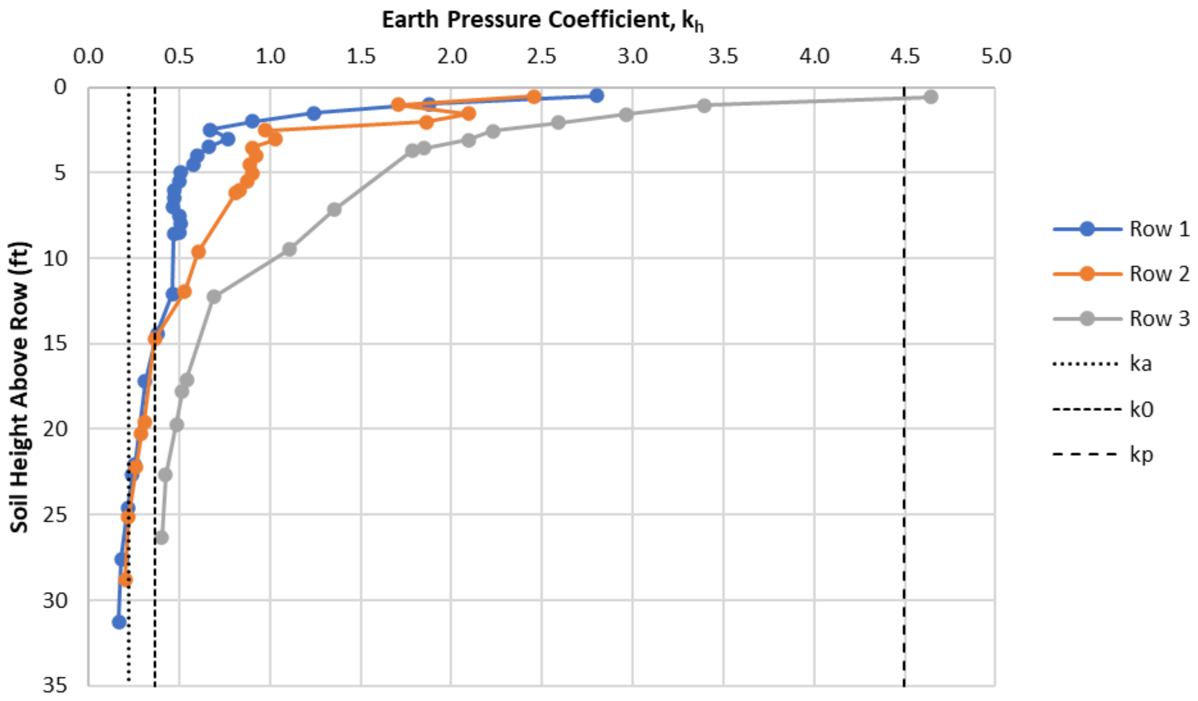
- Top of the divider was the weakest structural point of the experimental component
- Higher surcharge applied on the 103% side caused the divider to bow inward toward the 95% side
  - $q_{s@95\%}$ = 2,291 psf vs. $q_{s@103\%}$ = 2,459 psf
- At Row 4, 95% side shows passive condition developing and 103% side shows active condition developing

Earth Pressure Coefficient Analysis

95% of T-180 ⇒ ϕ = 31.2 degrees



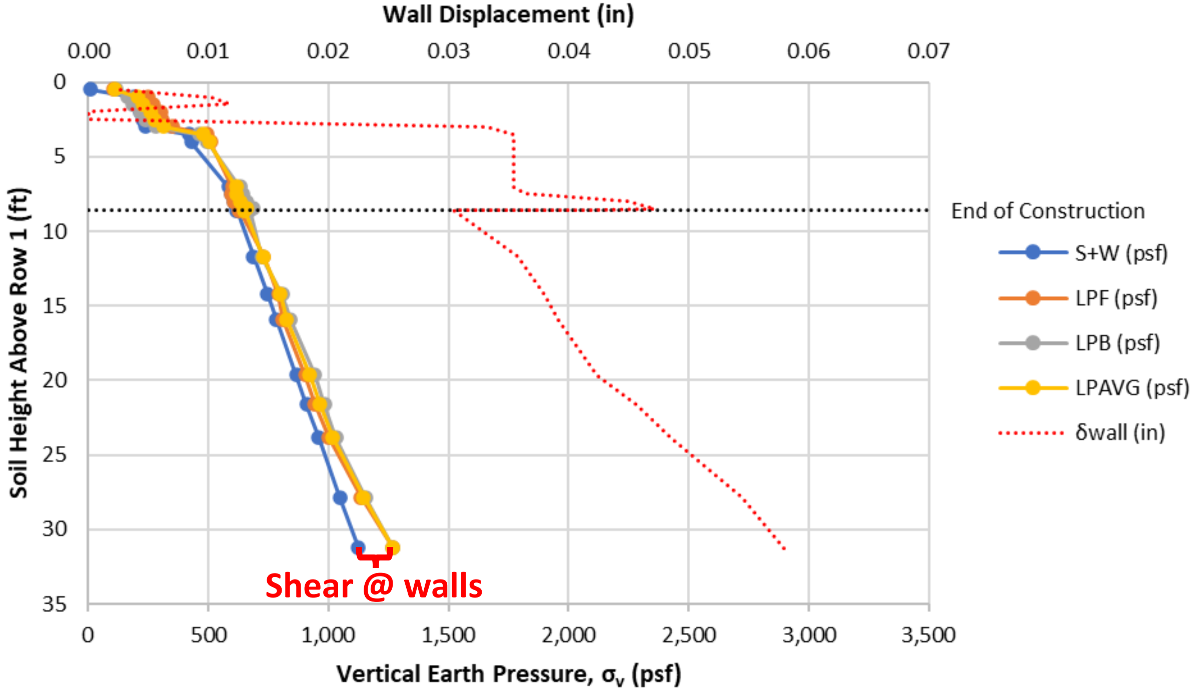
103% of T-180 ⇒ ϕ = 39.5 degrees



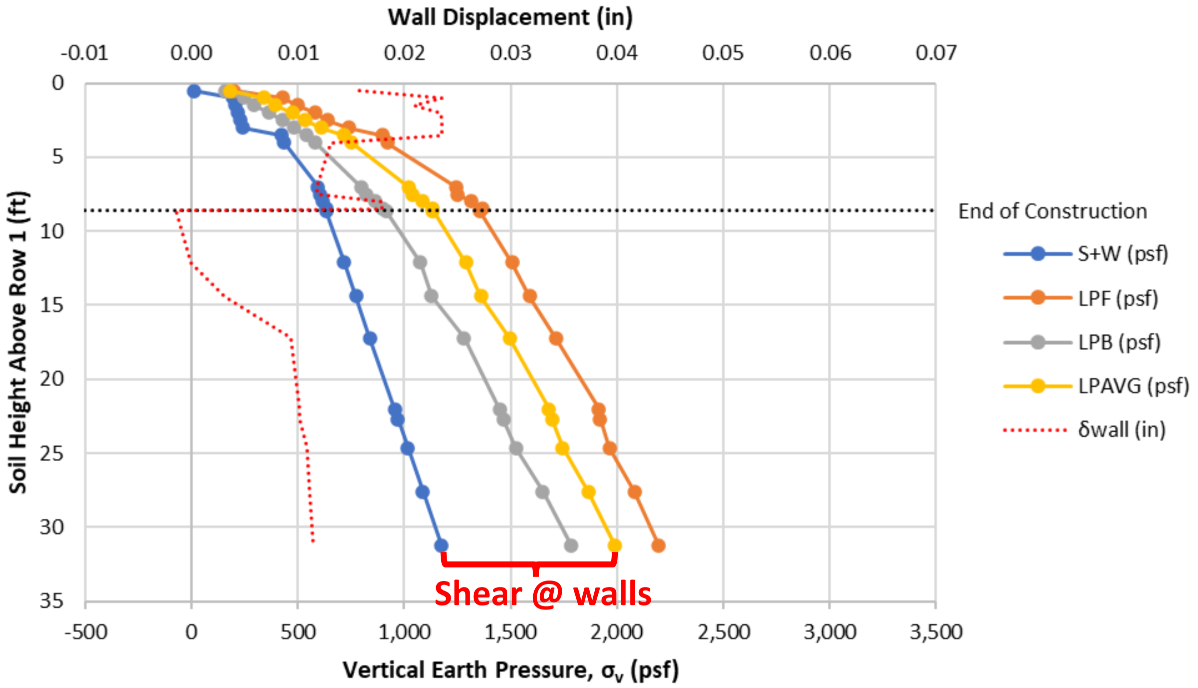
- Lower half of the wall moved from a passive to active condition for both compaction efforts
- Upper half of the wall moved from a passive to at-rest condition for both compaction efforts
- In all cases, the earth pressure coefficients were below $k_{0@95\%}$ w/ a soil height 20 ft above the row

Leveling Pad Pressure Analysis

95% of T-180 ⇒ ϕ = 31.2 degrees



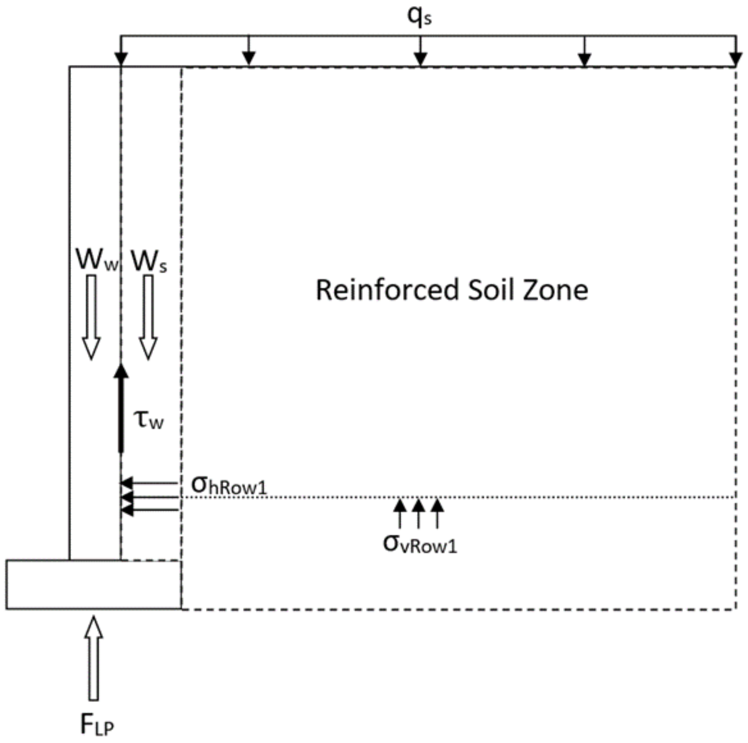
103% of T-180 ⇒ ϕ = 39.5 degrees



Increased leveling pad pressure beyond the weight of the MSE wall panels and soil column acting on the leveling pads indicates shear transfer to the wall → Soil arching → Overburden reduction in reinforced zone

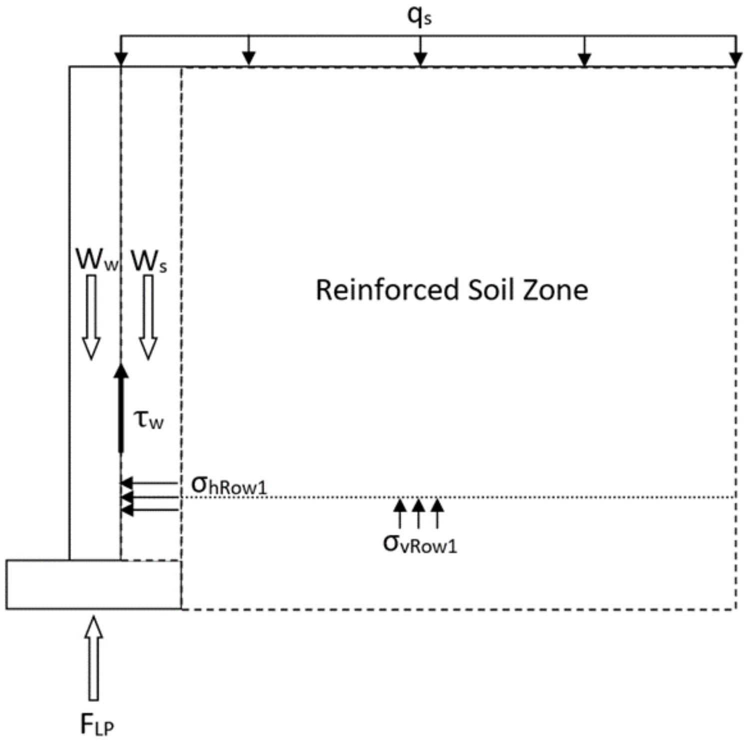
Force Equilibrium Analysis – 95% of T-180

- $F_v = Overburden\ Reduction\ \times Plan\ View\ Soil\ Area$
- $F_v = 30.3\ psf\ \times 9.58\ ft \times 9.75\ ft = 2{,}827\ lbf$
- Equivalent average leveling pad pressure = $(F_v/2\ walls)/Leveling\ Pad\ Area$
- Equivalent average leveling pad pressure = $(2{,}827\ lbf/2)/10ft^2 = 141.3\ psf$
- Compare equivalent leveling pad pressure to leveling pad pressure beyond the weight of the MSE wall panels and soil column acting on the leveling pads
- 141.3 psf vs. 143.4 psf → 1.5% difference
- Agreement is found indicating force equilibrium
- Check shear transfer:
- $\tau_{wall} = \sigma_h \tan\delta = 943\ psf \times \tan 30 = 544\ psf$
- $\tau_{LP} = 1{,}434\ lbf \div (8.61\ ft \times 9.58\ ft) = 17.4\ psf$
- Measured equivalent shear stress was significantly less than the available shear stress
- Available shear stress at the soil-wall interface was not exceeded and the limited wall height to surcharge height had no effect on the shear transfer from soil arching



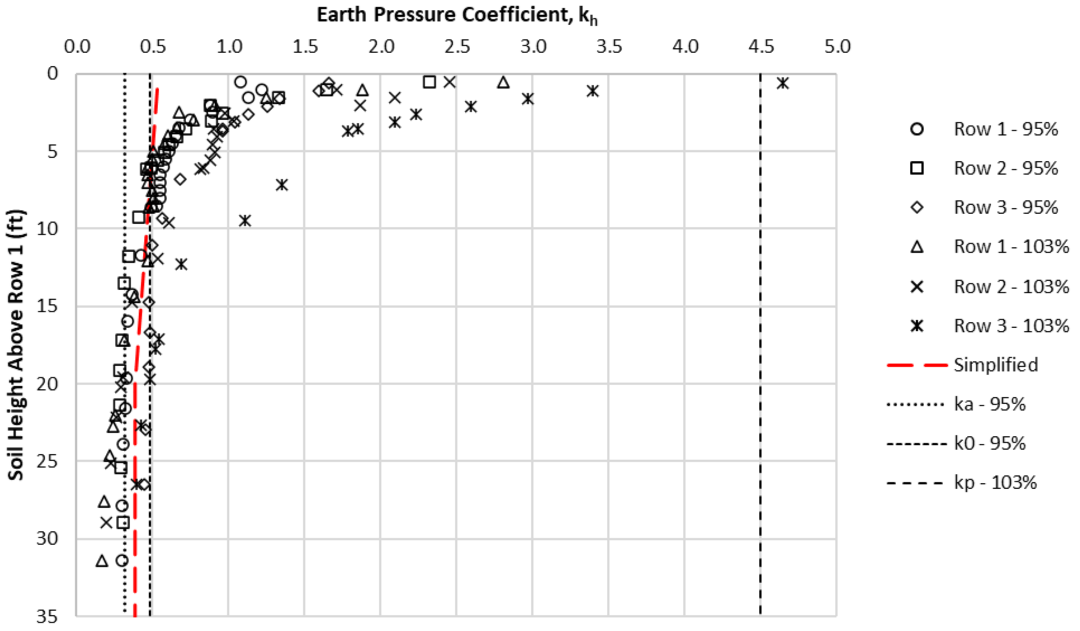
Force Equilibrium Analysis – 103% of T-180

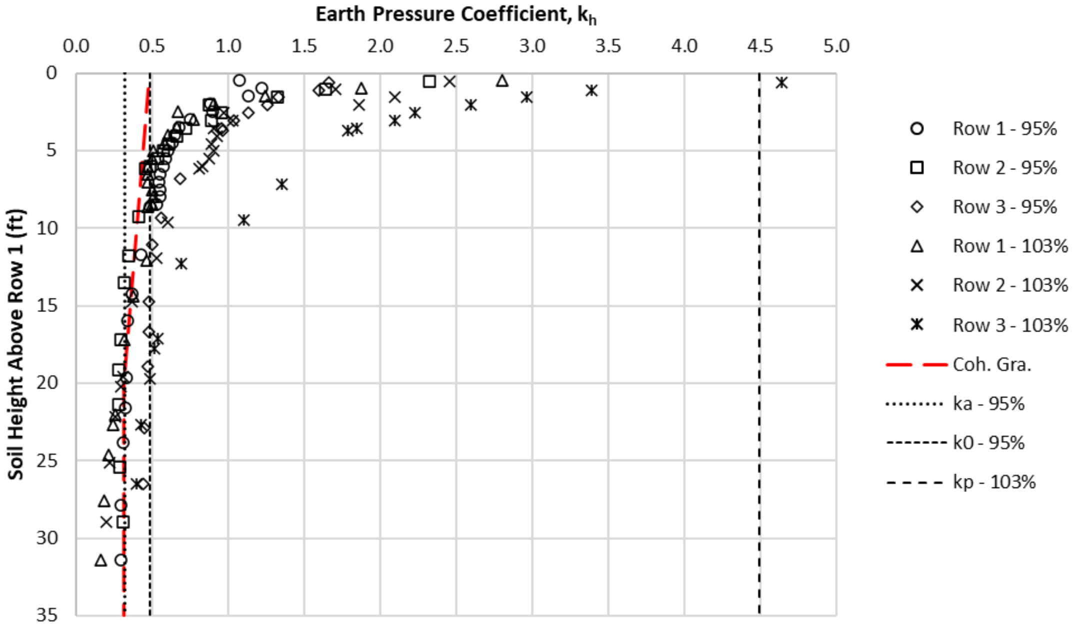
- $F_v = Overburden\ Reduction\ \times Plan\ View\ Soil\ Area$
- $F_v = 173.5\ psf\ \times 9.58\ ft \times 9.75\ ft = 16{,}202\ lbf$
- Equivalent average leveling pad pressure = $(F_v/2\ walls)/Leveling\ Pad\ Area$
- Equivalent average leveling pad pressure = $(16{,}202\ lbf/2)/10ft^2 = 810.1\ psf$
- Compare equivalent leveling pad pressure to leveling pad pressure beyond the weight of the MSE wall panels and soil column acting on the leveling pads
- 810.1 psf vs. 814.3 psf → 0.52% difference
- Agreement is found indicating force equilibrium
- Check shear transfer:
- $\tau_{wall} = \sigma_h \tan\delta = 542\ psf \times \tan 30 = 313.2\ psf$
- $\tau_{LP} = 8{,}143\ lbf \div (8.61\ ft \times 9.58\ ft) = 98.7\ psf$
- Measured equivalent shear stress was ≈1/3 of the available shear stress
- Available shear stress at the soil-wall interface was not exceeded and the limited wall height to surcharge height had no effect on the shear transfer from soil arching

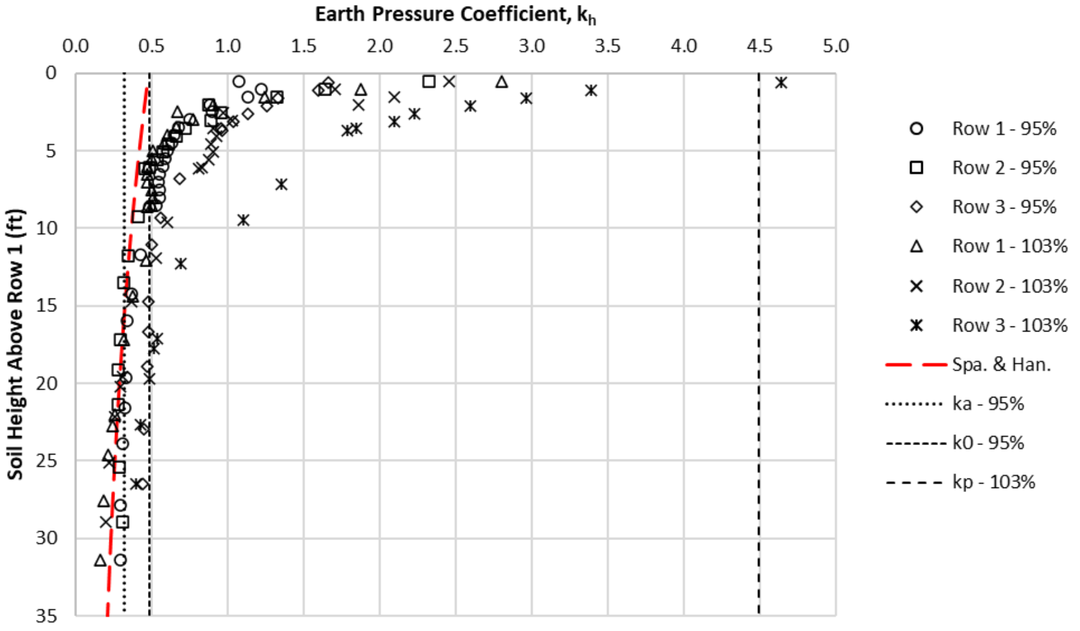


Conventional Methods

- AASHTO Simplified, Coherent Gravity, and Spangler & Handy (Silo Effect)
- None of the conventional methods quantified the higher locked-in stress due to tying two walls together







Equation Development

- Observed data indicated tying two walls together locks in higher lateral stress due to the compaction effort at relatively shallow soil heights above the reinforcement row
  - Data indicates k_h moves from a passive condition to an active or at-rest condition as the soil height increases above the reinforcement level
    - K_a or k_0 dependent on the location of the reinforcement strips (i.e., upper half of wall or lower half of wall)
- Developed a new EQN that considers a variable ϕ based on the construction compaction effort
- General EQN form is presented for k_h
- Set z (depth) equal to 20 feet
  - Data indicated k_h stabilization generally starts around 20 feet which agrees with the Coherent Gravity and Simplified methods
- Set k_h equal to k_a or k_0
- k_a or k_0 values obtained from 95% of T-180
  - Considers under-compaction within 3 feet of the wall
- k_p obtained from >100% of T-180
  - Considers possible over-compaction beyond 3 feet from the wall
  - Relative compaction of 103% of T-180 from N.D. used for the research

General Equation

$$k_h = k_{p@OC} \times z^b$$

b for active condition

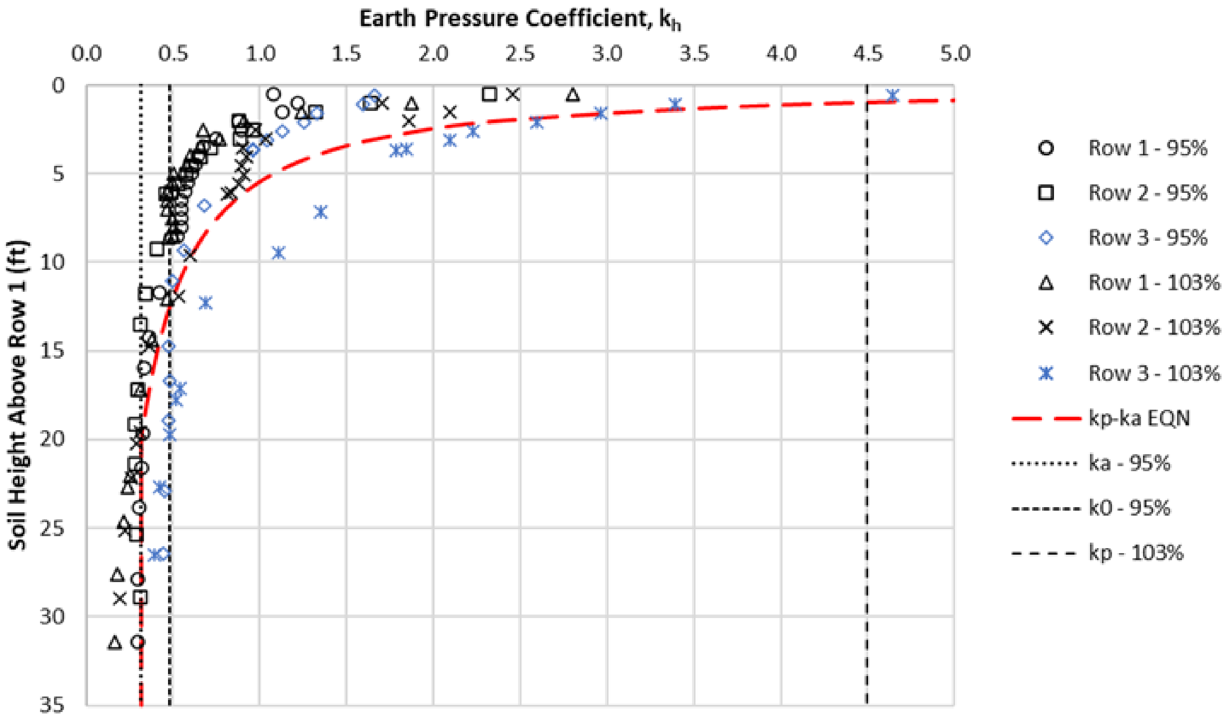
$$b = \frac{\log\left(\frac{k_{a@95}}{k_{p@103}}\right)}{\log(20)}$$

b for at-rest condition

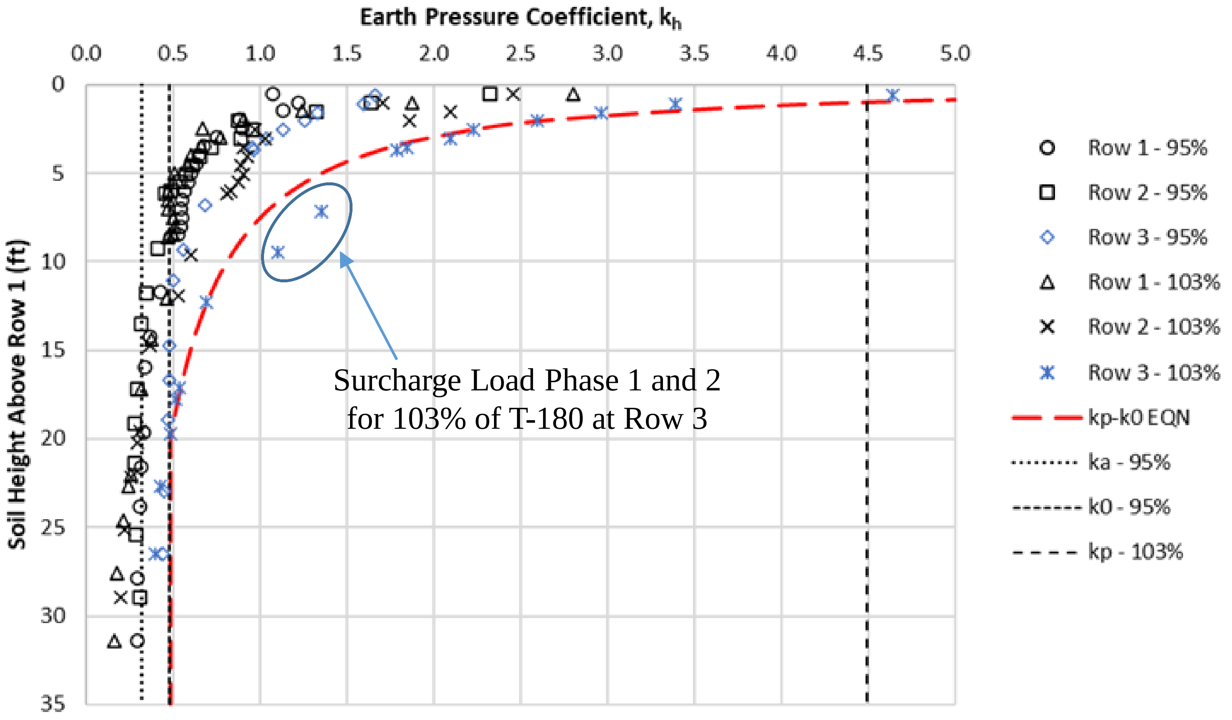
$$b = \frac{\log\left(\frac{k_{0@95}}{k_{p@103}}\right)}{\log(20)}$$

UF EQNs vs. Measured E.P. Coefficients

K_p – k_a Equation



K_p – k_0 Equation



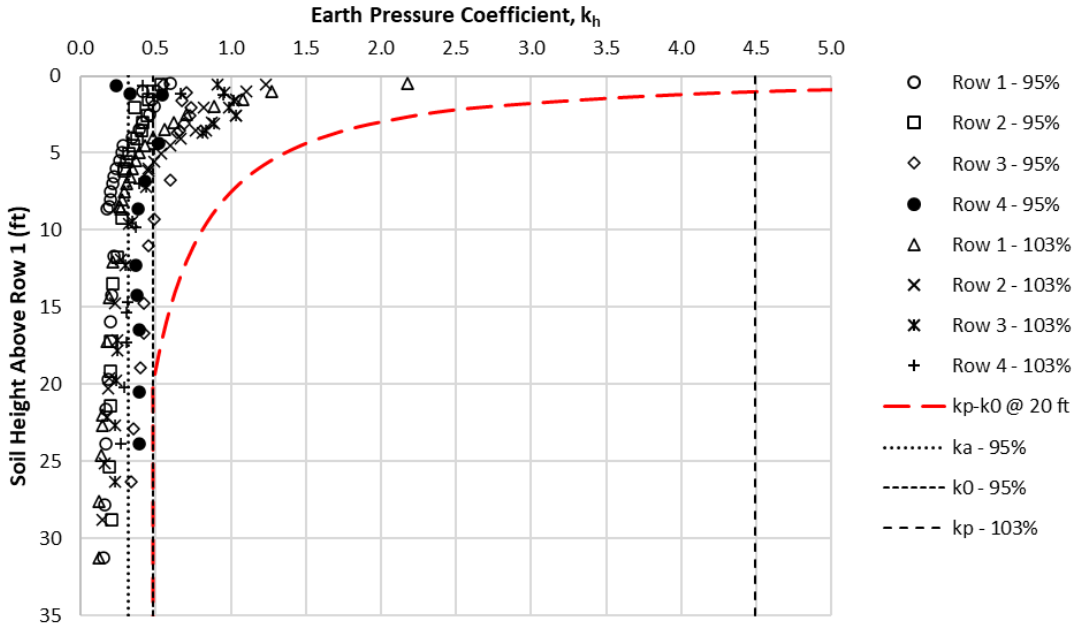
Surcharge Load Phase 1 and 2
for 103% of T-180 at Row 3

- Using k_a followed the trends of the data well for the bottom half of the wall but underestimated k_h in top half of wall
- Similar to coherent gravity method, data indicated higher locked in stresses in the top half of the wall
- UF recommends using k_0 for the entire wall as a conservative approach
- Use k_p-k_0 EQN for top 20 feet, use k_0 for depths below 20 feet
  - Similar to coherent gravity and AASHTO simplified methods

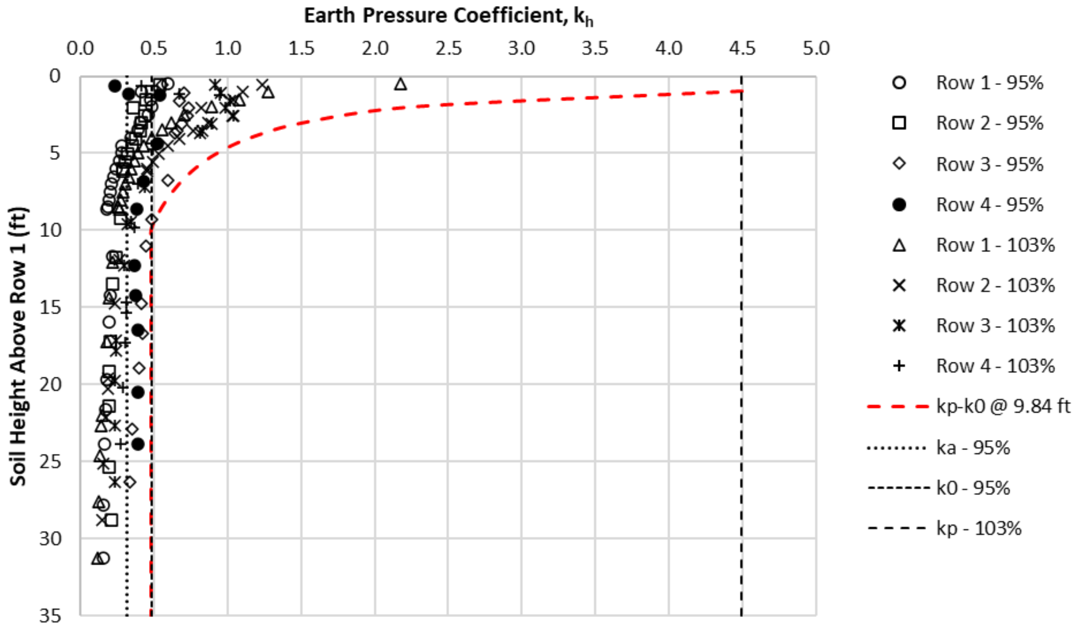
UF EQN vs. Strip Tension Earth Pressure Coefficients

- Reinforcement strip design based on lateral earth pressure at depth
- Important to compare UF EQN to strip tension earth pressure coefficients
  - Average strip tension / tributary area
- UF EQN w/ z = 20 feet appears overly conservative at shallower depths
- RECo stated that strip tension mostly develops during construction process
- UF research wall only constructed to 9.84 ft w/ 23 ft of wall height simulated
  - Set z = 9.84 feet → research wall height
- Good agreement is found between UF EQN and strip tension earth pressure coefficients
  - Including Row 4 data from both compaction efforts
- Lateral earth pressure at depth indicates the potential strip tension that could develop based on construction practices
- UF k_p-k_0 EQN with a 20 ft $k_{0@95\%}$ cutoff is appropriate

Z = 20 feet



Z = 9.84 feet



Conclusions

- The compaction equipment and techniques utilized throughout construction provided the necessary soil density to investigate an under compacted and over compacted state of soil density for an unyielding condition
- Using the Matjack-airbag system, approximately 23 feet of overburden soil was simulated in a controlled manner
    - This in combination with the constructed wall height produced a B/H ratio of 0.3 for both compaction efforts
- Higher lateral earth pressures develop during construction in an unyielding condition compared to conventional MSE wall design
- A higher compaction effort leads to increased soil arching and shear transfer to the retaining wall in an unyielding condition
    - The increased shear transfer at the soil-wall interface generates increased pressure on the leveling pads the MSE wall rest on
- Higher locked-in compaction forces were generated in the upper half of the constructed walls compared to the lower half as described by the Coherent Gravity and Simplified methods
    - This result was found when the soil was under compacted and over compacted
    - Due to the limited wall height of 9.84 feet, the distinctions made for the lower and upper halves of the wall should be treated with caution

Conclusions

- Increased shear transfer at the soil-wall interface leads to a reduction in lateral stress
    - Rows 1 and 2 on the 103% of T-180 side indicated the earth pressure coefficients were less than an active condition at the end of surcharge loading due to increased compaction and the unyielding condition,
    - Increased soil arching and reduced vertical and lateral stress as described by the Spangler and Handy (silo effect) method.
- The available shear stress at the wall was not exceeded for either compaction effort using a common soil-wall interface friction angle of $\delta = 30$ degrees
    - Limited wall height to surcharge height had no effect on shear transfer at the soil-wall interface, further validating the results
- Force equilibrium was achieved for both compaction efforts, indicating all stresses and forces were accounted for with minimal error
- When two MSE walls are tied together, earth pressure coefficients tend to move from a passive condition to either an active or at-rest condition as the soil height above the reinforcement level is increased
    - Different than conventional MSE wall design where the earth pressure coefficients tend to move from an at-rest condition to an active condition as detailed by the Coherent Gravity and Simplified methods
    - The earth pressure coefficients developed in the unyielding condition generally stabilized in either an active or at-rest condition at an approximate depth of 20 feet as suggested by the Coherent Gravity and Simplified methods.
- A new equation was developed that incorporates a variable friction angle (ϕ) based on the compaction effort for an unyielding condition, and FDOT design and construction requirements. When compared to the measured results, the new equation followed the trends of the data well.

Remaining Tasks

- Task (3c) – MSE Wall Deconstruction
- Task (4) – Draft Final and Closeout Teleconference
- Task (5) – Final Report

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Questions?