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

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 (3) – MSE Wall Construction with Two Designated Relative Compaction Efforts
- Task (4) – Draft Final and Closeout Teleconference
- Task (5) – Final Report

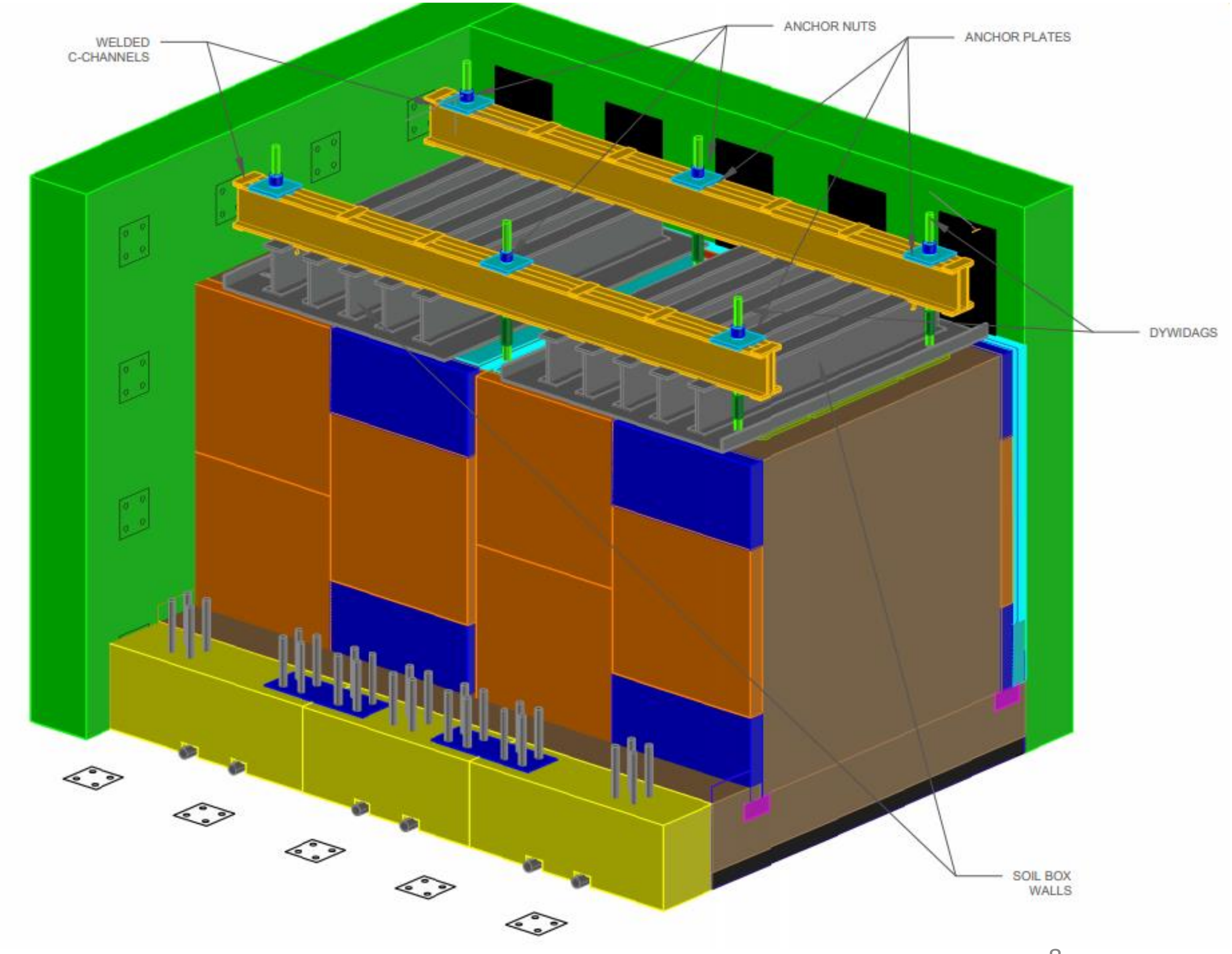
MSE Wall LRFD Final Design

- 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 k_{rS}	σ_h (psf) Unfactored	Load Factors $\gamma_{P\text{-}EV}$	Load Factors $\gamma_{P\text{-}ES}$	σ_h (psf) Factored	Unfactored T_{max} (lbf)	Factored T_{max} (lbf)	Factored $T_{con.}$ (lbf)	Unfactored $T_{con.}$ (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 k_{rCG}	σ_h (psf) Unfactored	Load Factors $\gamma_{P\text{-}EV}$	Load Factors $\gamma_{P\text{-}ES}$	σ_h (psf) Factored	Unfactored T_{max} (lbf)	Factored T_{max} (lbf)	Factored $T_{con.}$ (lbf)	Unfactored $T_{con.}$ (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 k_0	σ_h (psf) Unfactored	Load Factors $\gamma_{P\text{-}EV}$	Load Factors $\gamma_{P\text{-}ES}$	σ_h (psf) Factored	Unfactored T_{max} (lbf)	Factored T_{max} (lbf)	Factored $T_{con.}$ (lbf)	Unfactored $T_{con.}$ (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 k_a	σ_h (psf) Unfactored	Load Factors $\gamma_{P\text{-}EV}$	Load Factors $\gamma_{P\text{-}ES}$	σ_h (psf) Factored	Unfactored T_{max} (lbf)	Factored T_{max} (lbf)	Factored $T_{con.}$ (lbf)	Unfactored $T_{con.}$ (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 k_{rSH}	σ_h (psf) Unfactored	Load Factors $\gamma_{P\text{-}EV}$	Load Factors $\gamma_{P\text{-}ES}$	σ_h (psf) Factored	Unfactored T_{max} (lbf)	Factored T_{max} (lbf)	Factored $T_{con.}$ (lbf)	Unfactored $T_{con.}$ (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

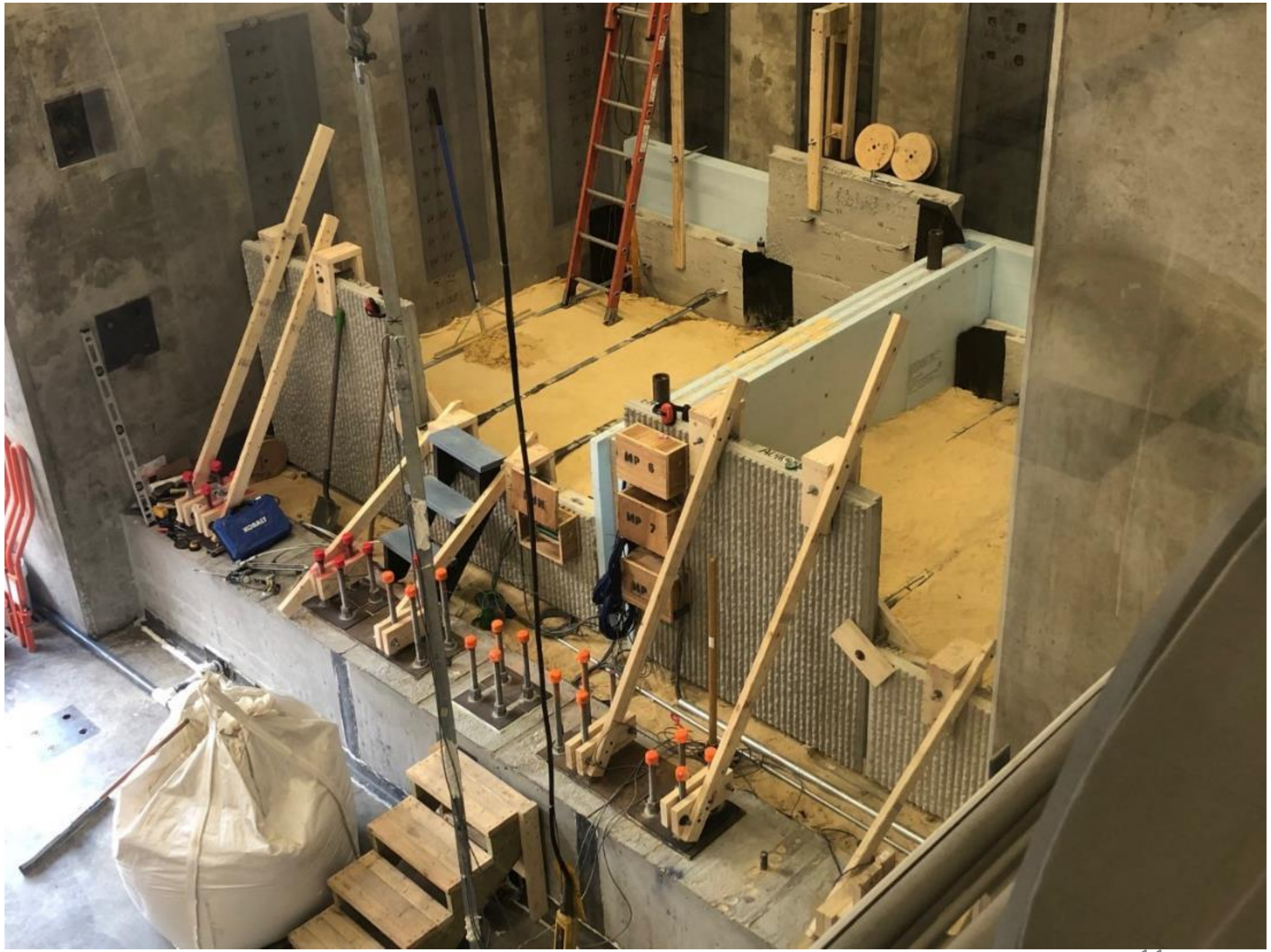
LRFD Design – Internal Stability

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

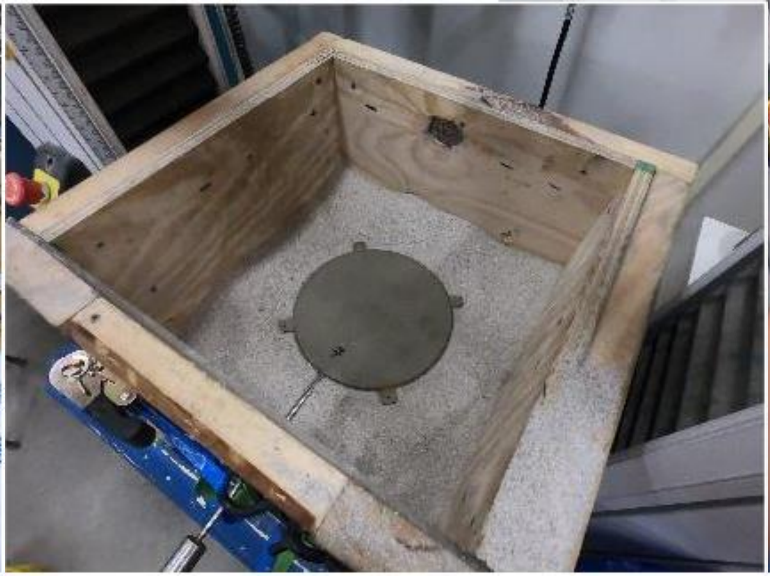
Construction Plan - Instrumentation

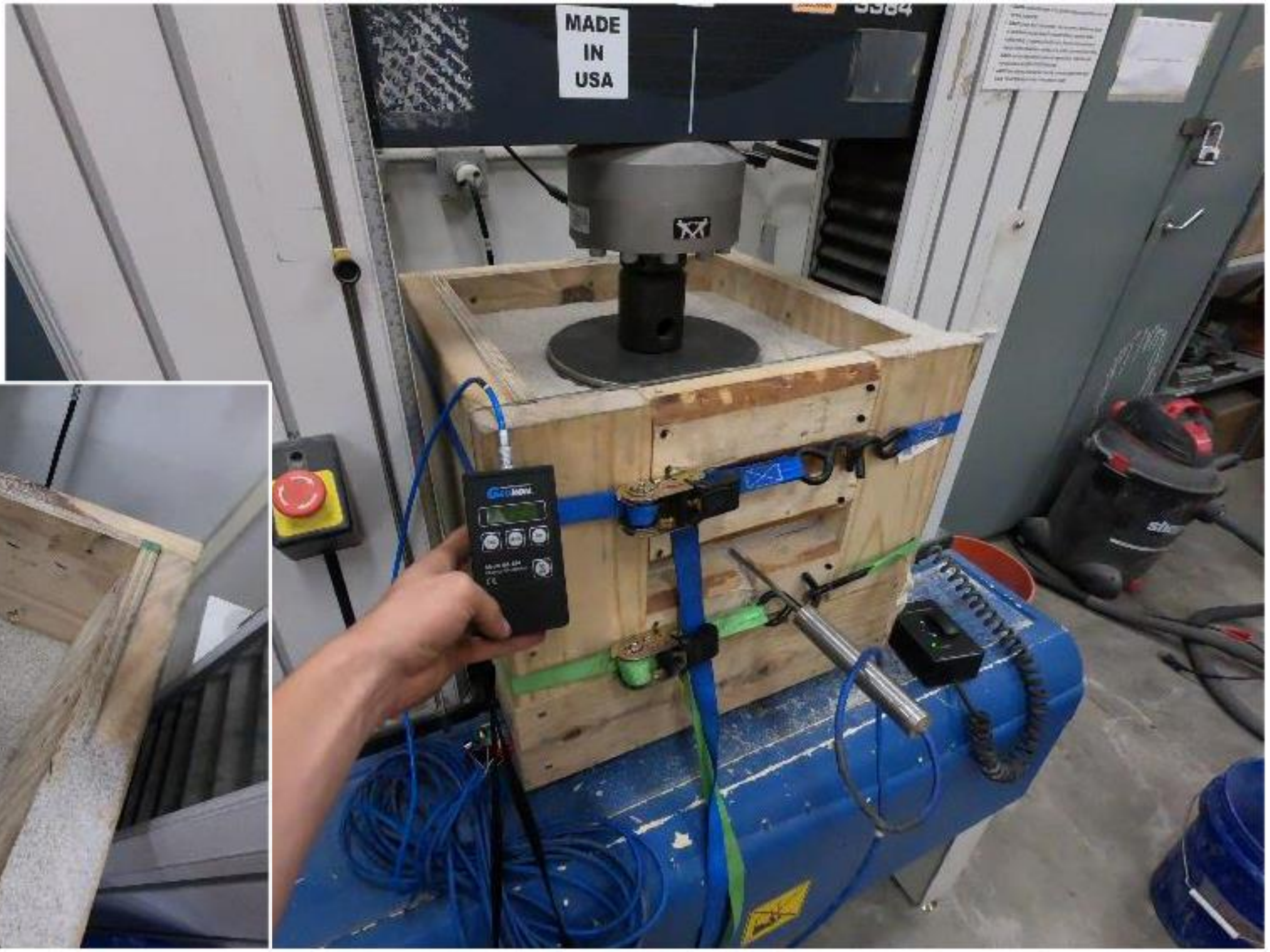
- 80 full bridge strain gauge locations
  - 4 Instrumented strips per reinforcement level
  - 5 locations per strip
  - 320 Strain gauges total
- 36 horizontal EPC's
  - Soil embedded in quadrants
  - 8 at each reinforcement level
  - 1 EPC under each leveling pad
- 16 vertical EPC's
  - Wall mounted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



Construction - Instrumentation Preparation

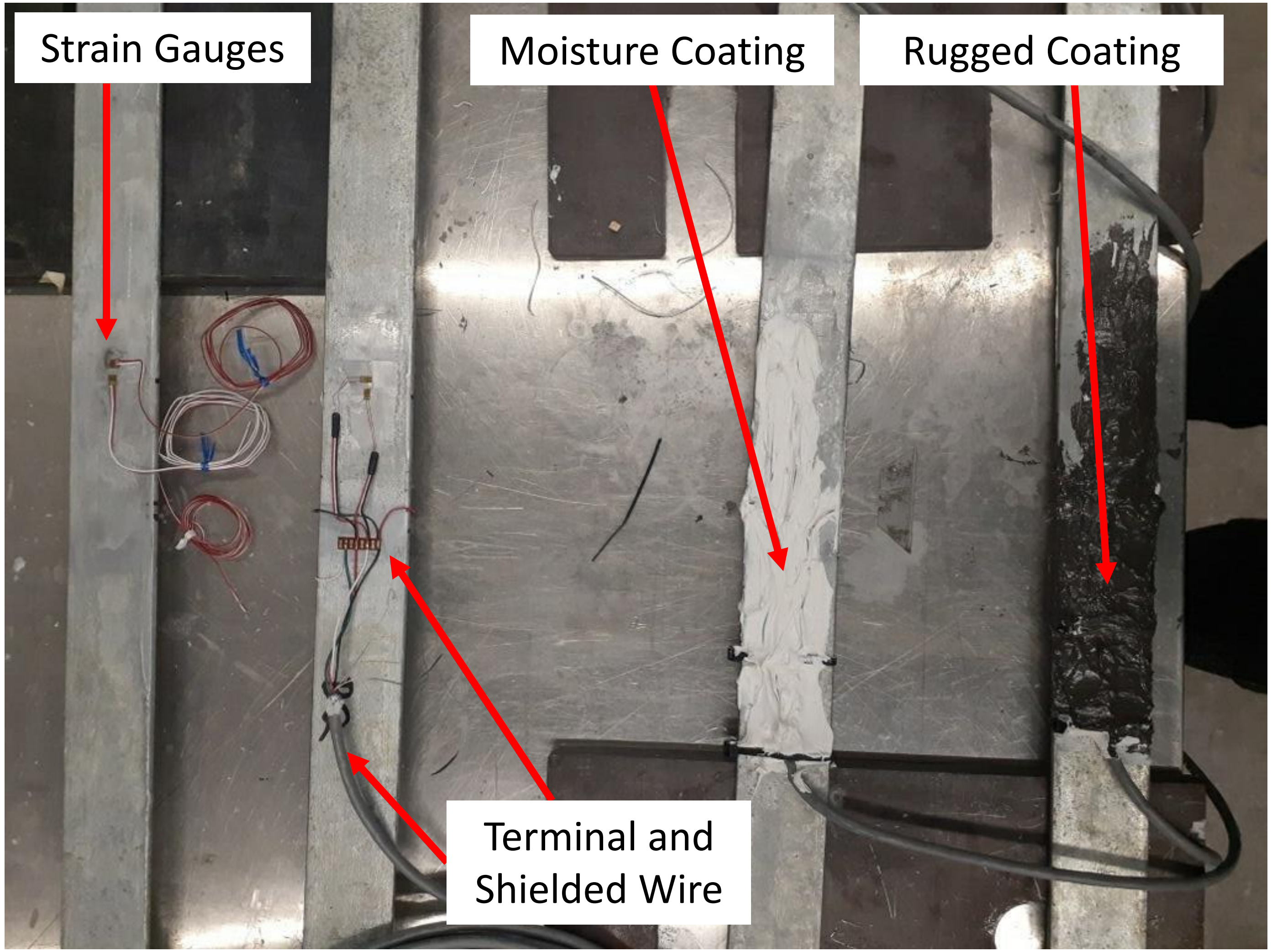
- Earth Pressure Cells – Vibrating Wire
  - 32 horizontal EPC’s (GeoKon 4800-1-100)
    - Purchased 2001/Last used around 2012
    - Gauge Calibrations checked on Instron
    - New cable spliced to EPCs
  - 16 Wall-mounted EPC’s (GeoKon 4810-350)
    - Purchased New





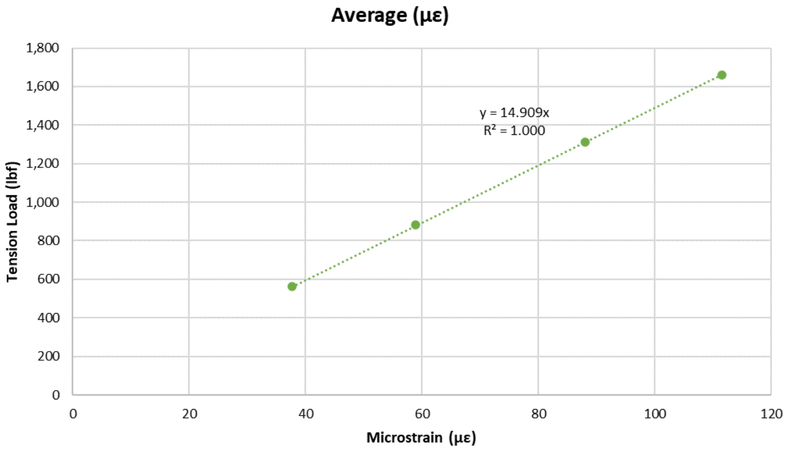
Instrumented Reinforcement Strips

- 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

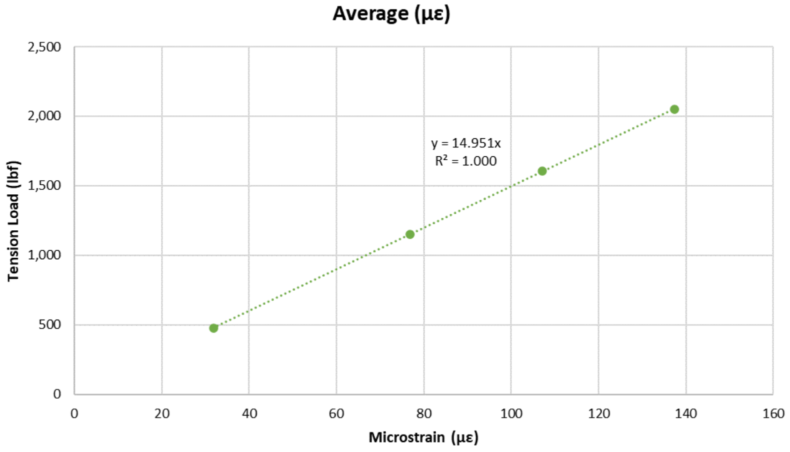


Reinforcement Strip Load Testing

Before Protective Coatings

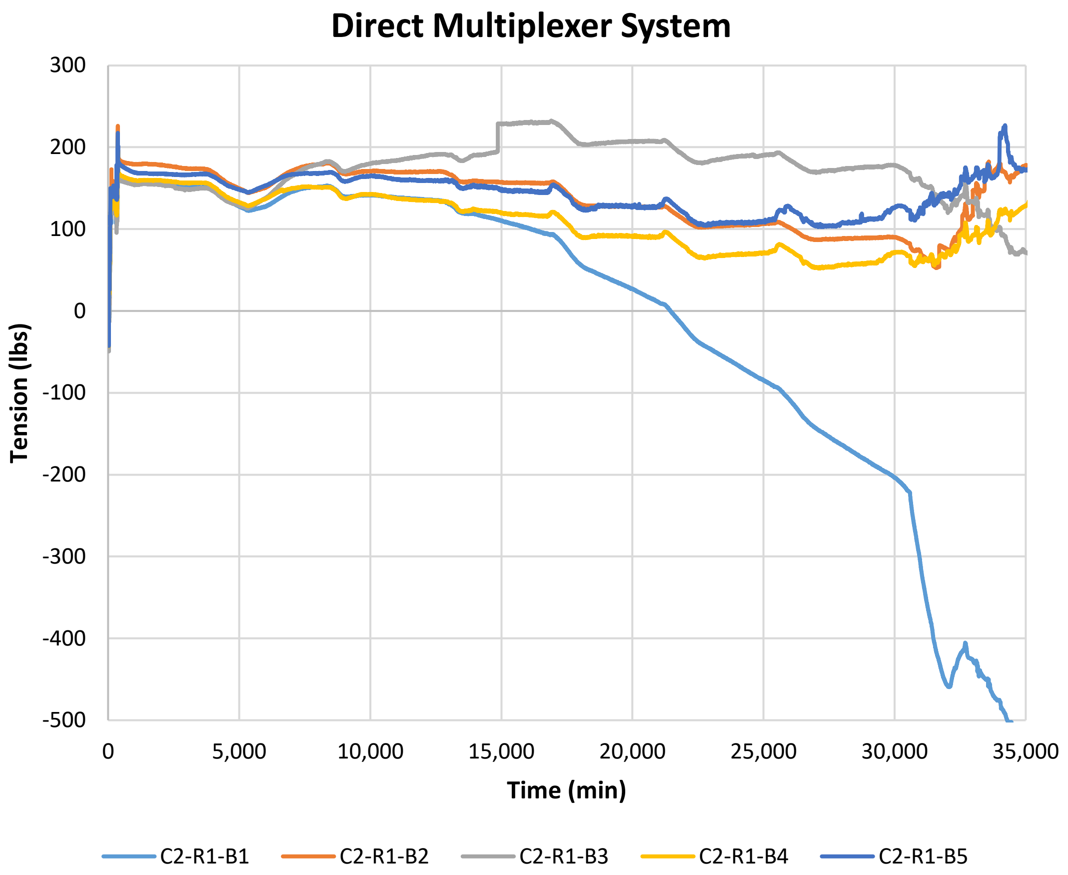


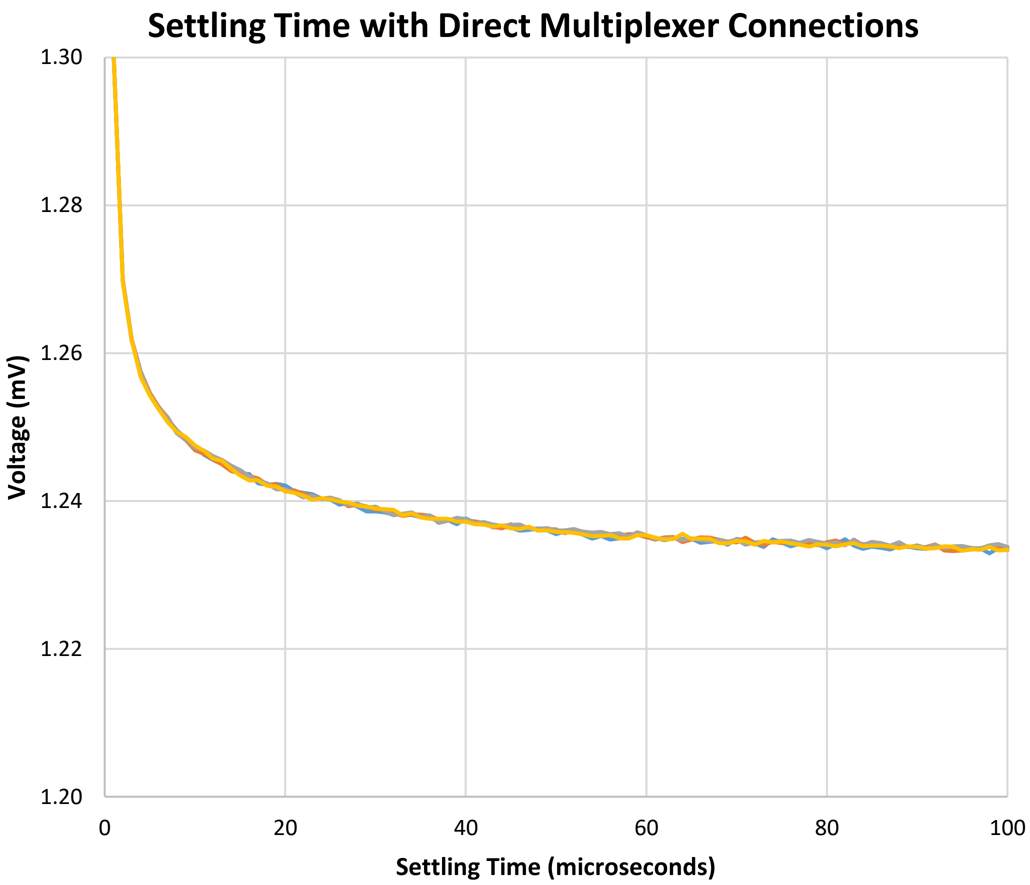
After Applying Both Coatings



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

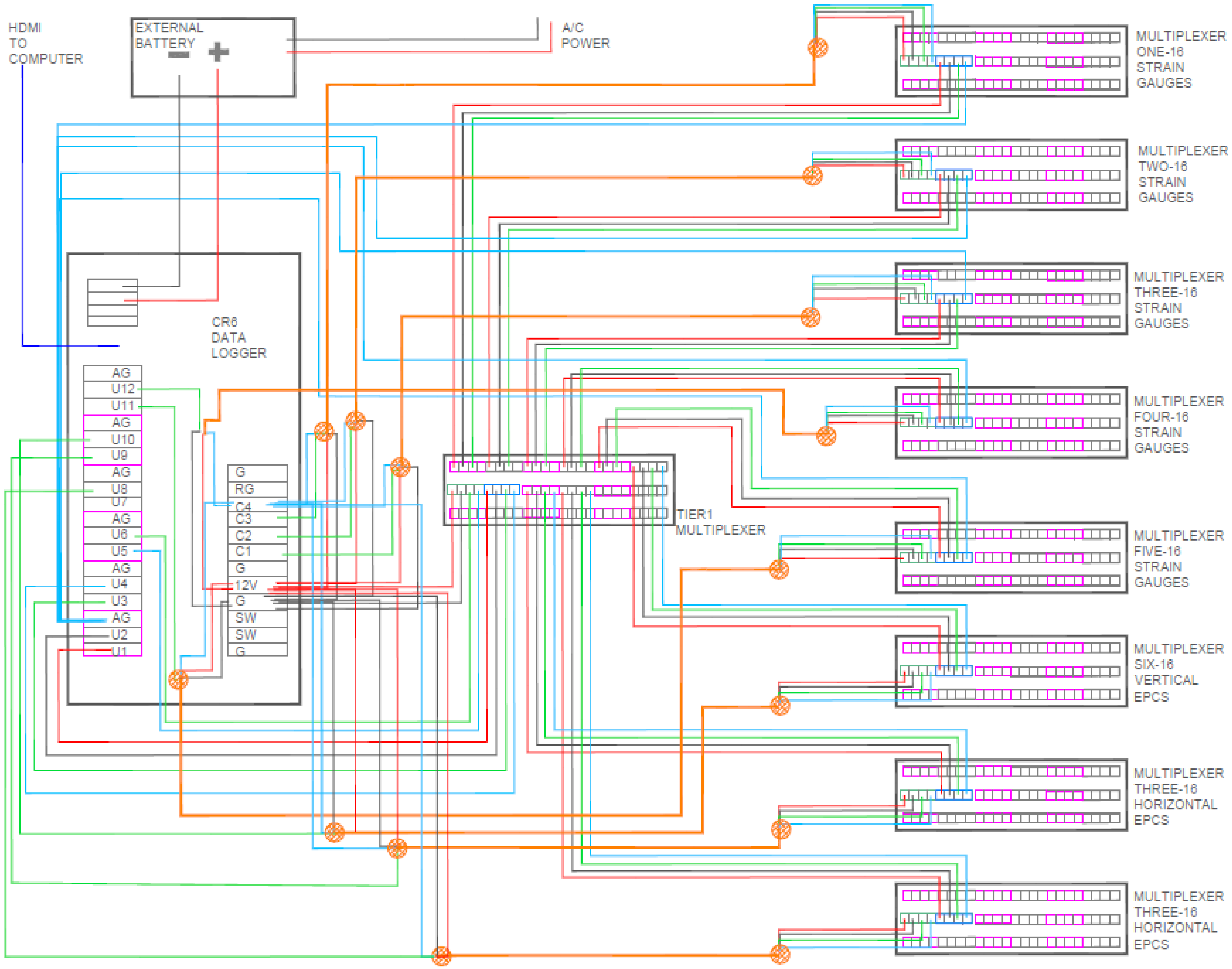
Residual Voltage Buildup



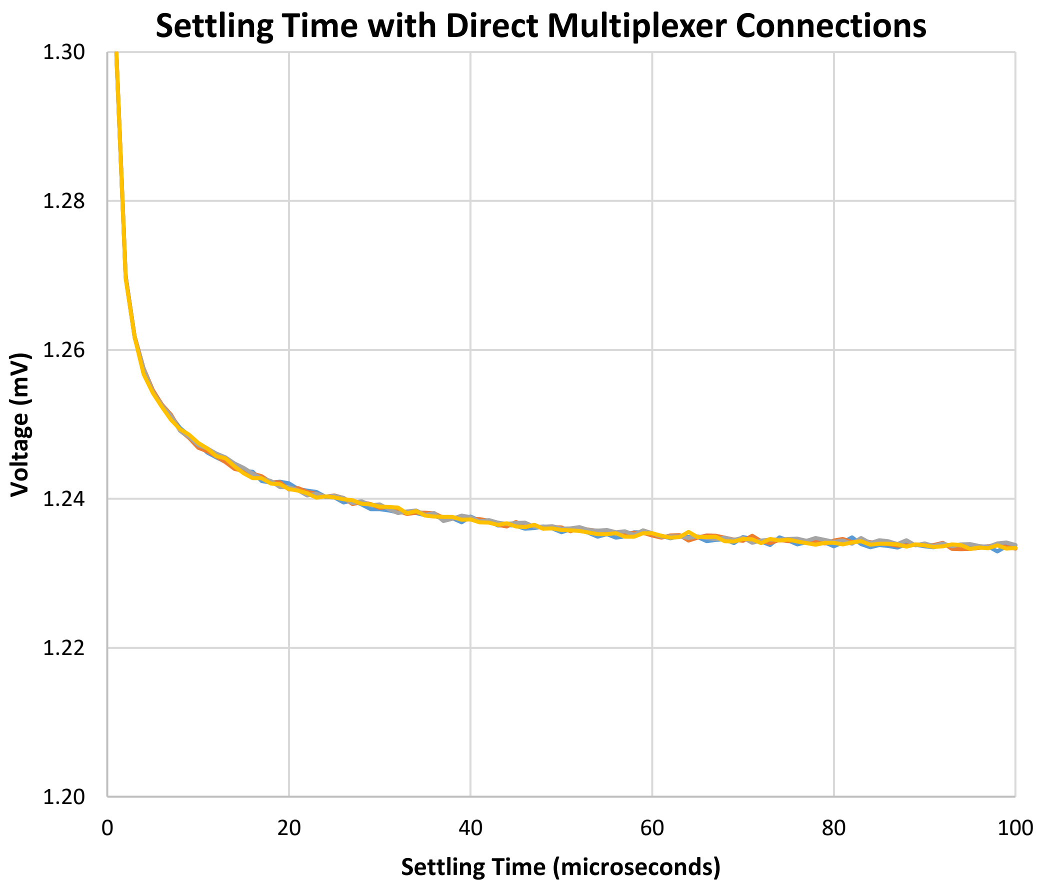


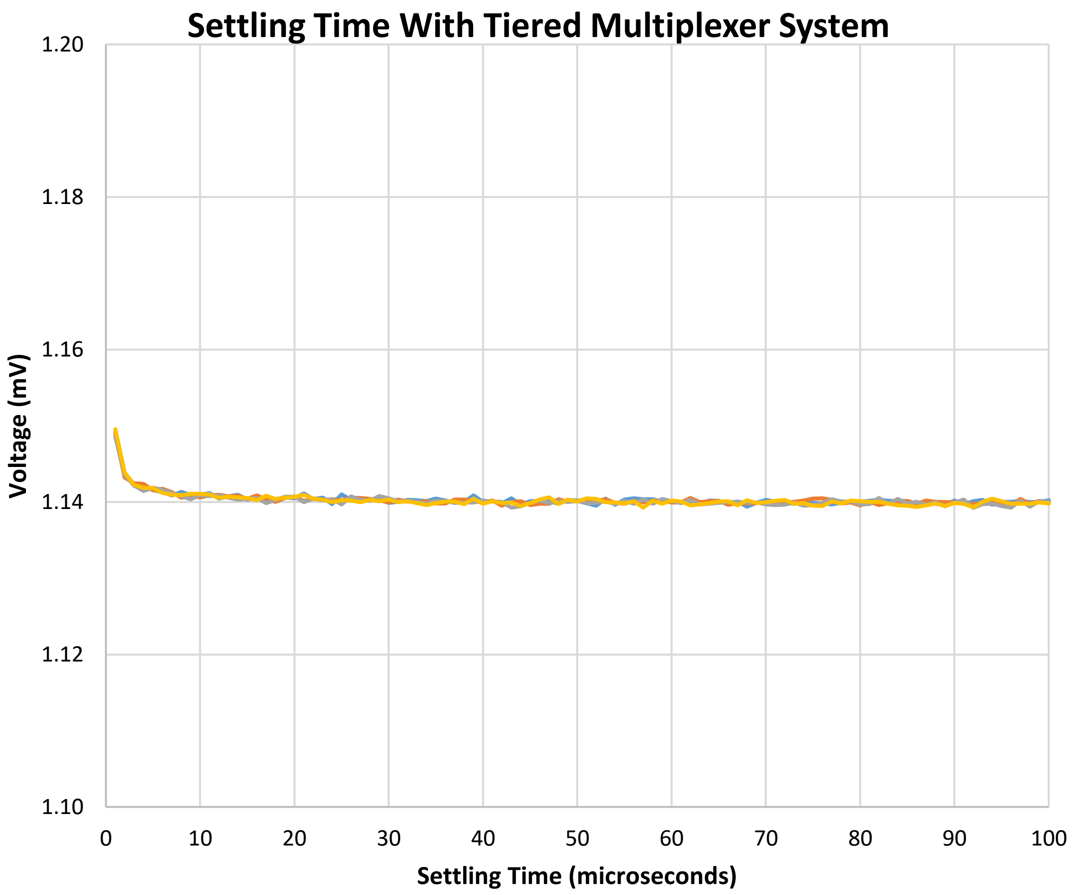
CR6

- 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

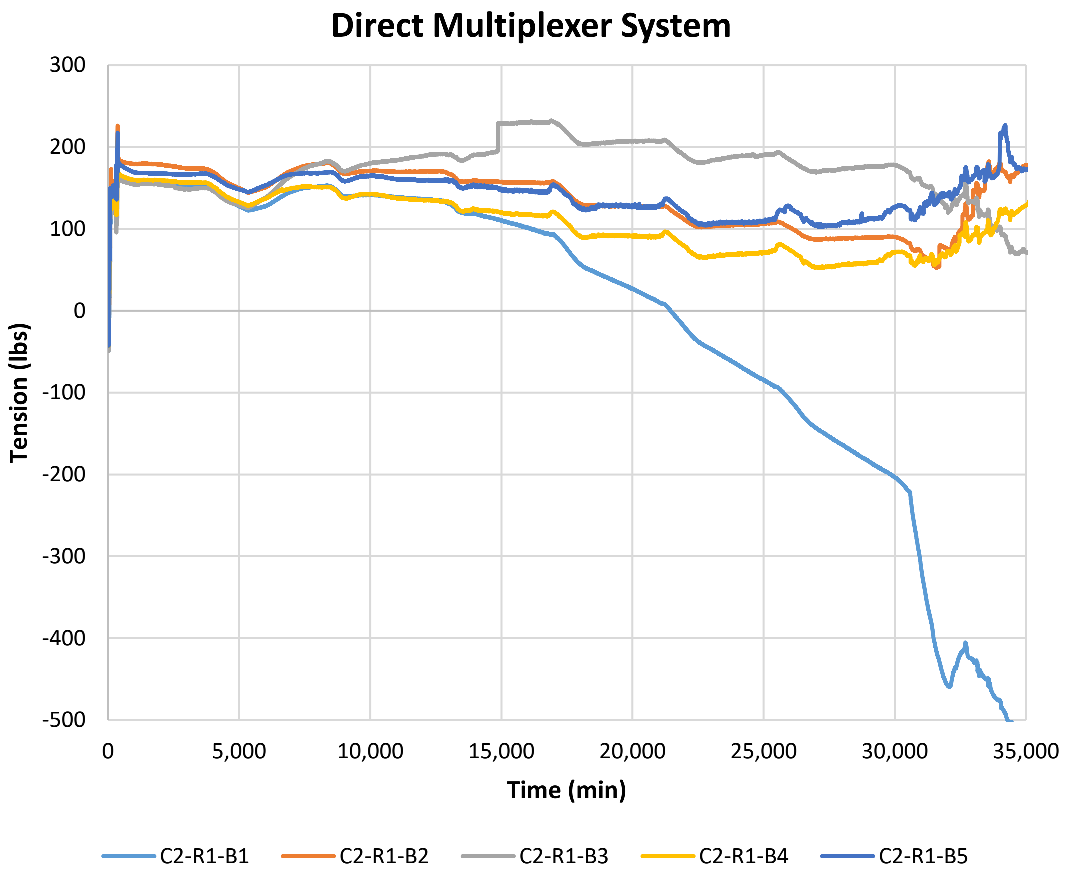


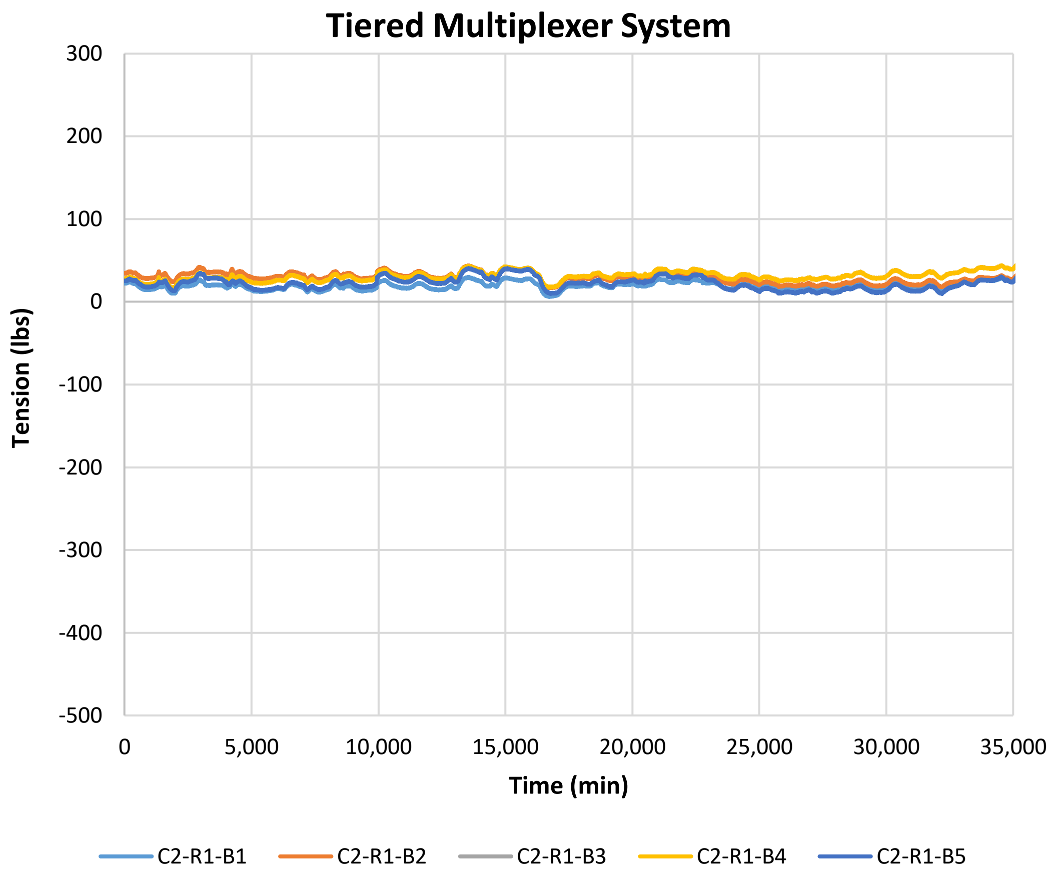
Resolving Settling Time Issues





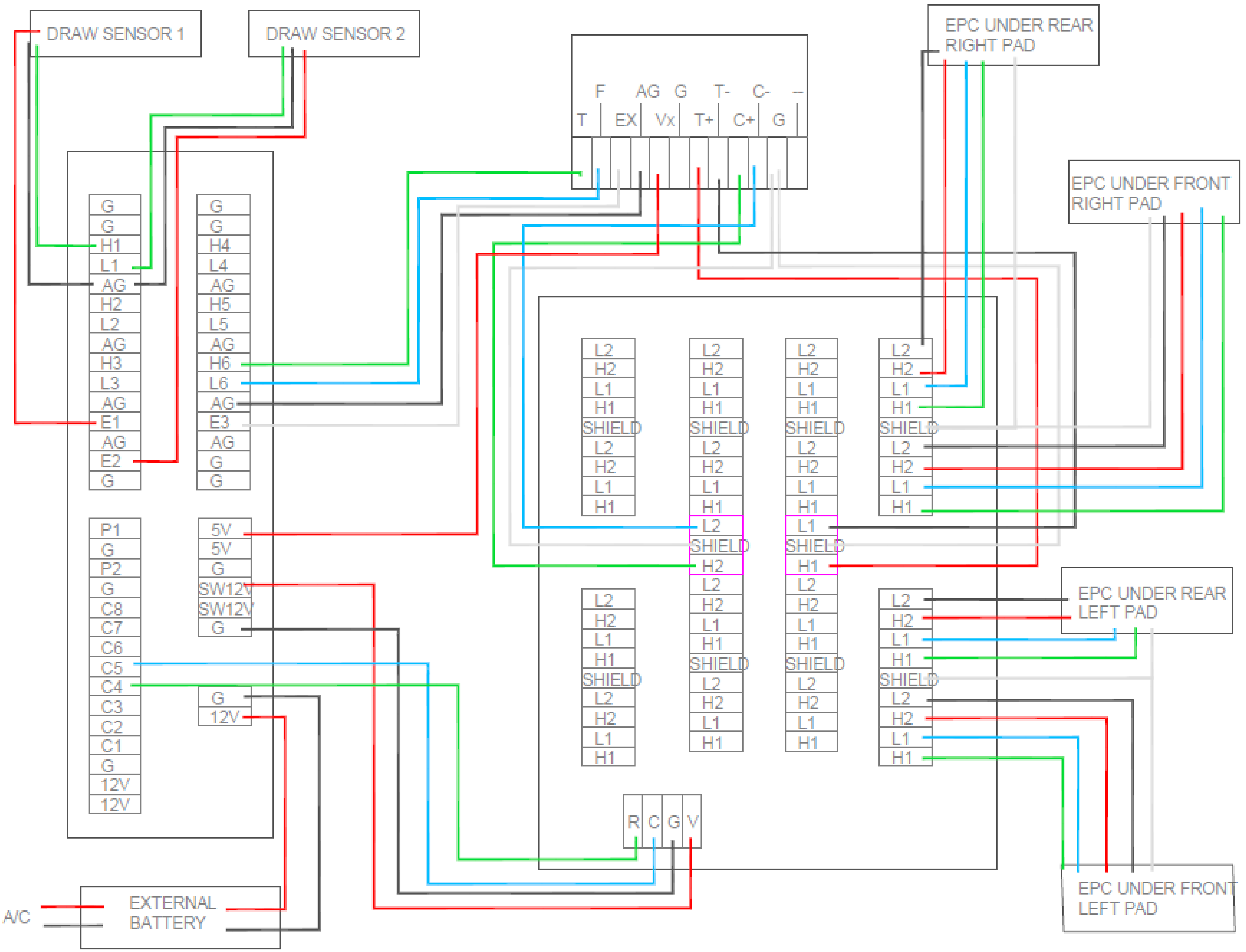
Resolving Residual Voltage Buildup





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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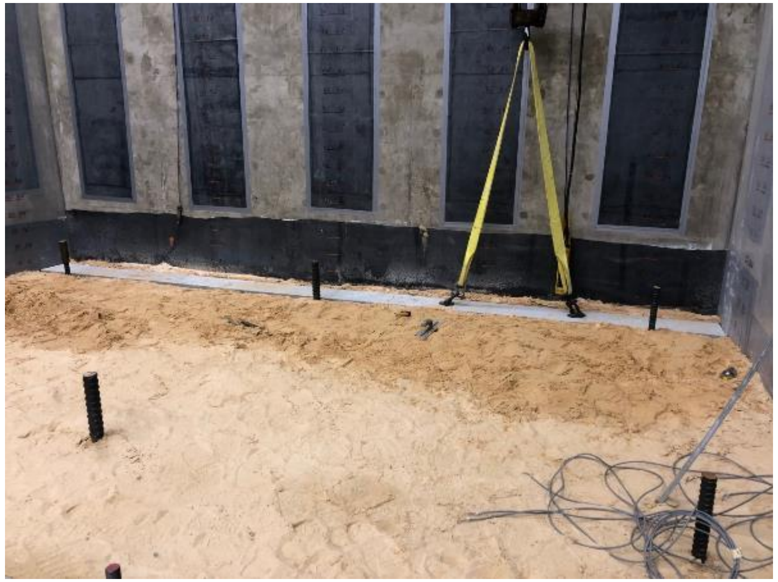

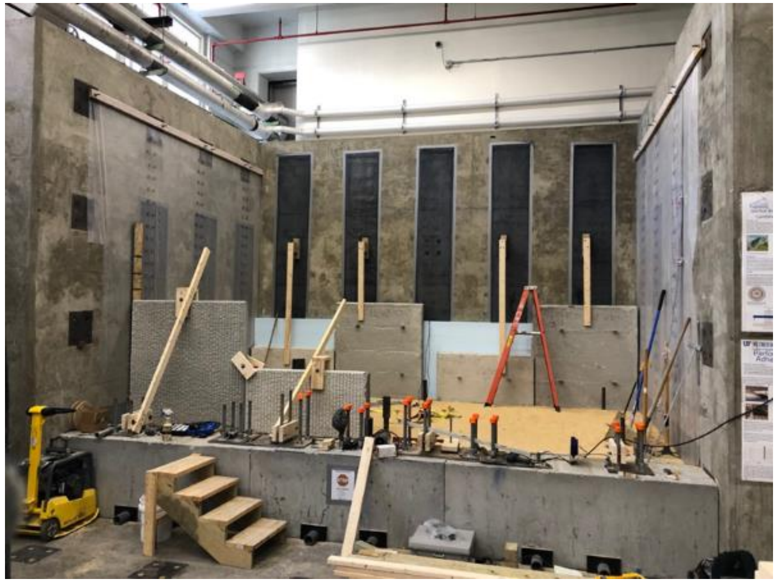

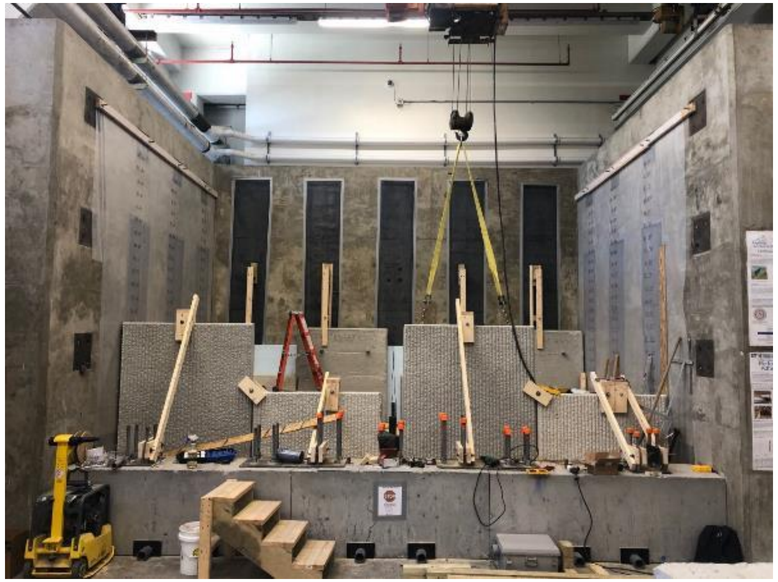

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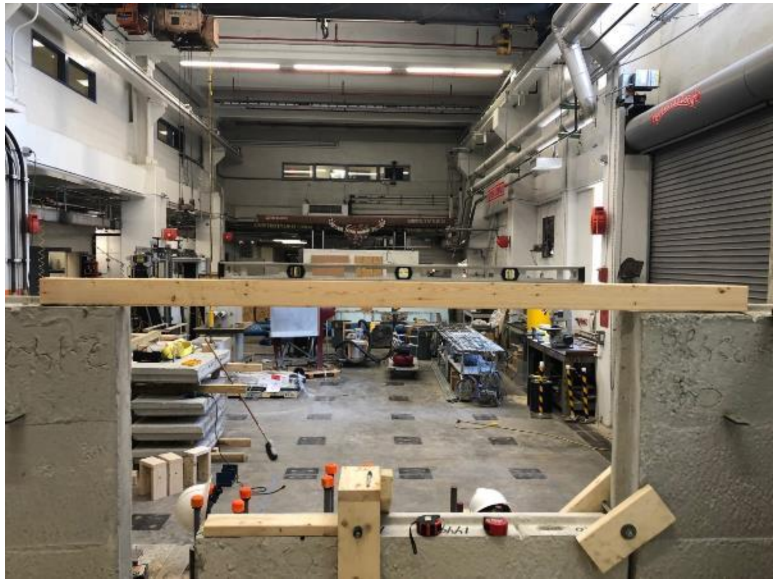

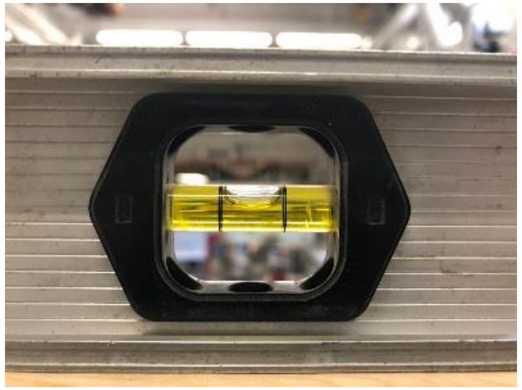

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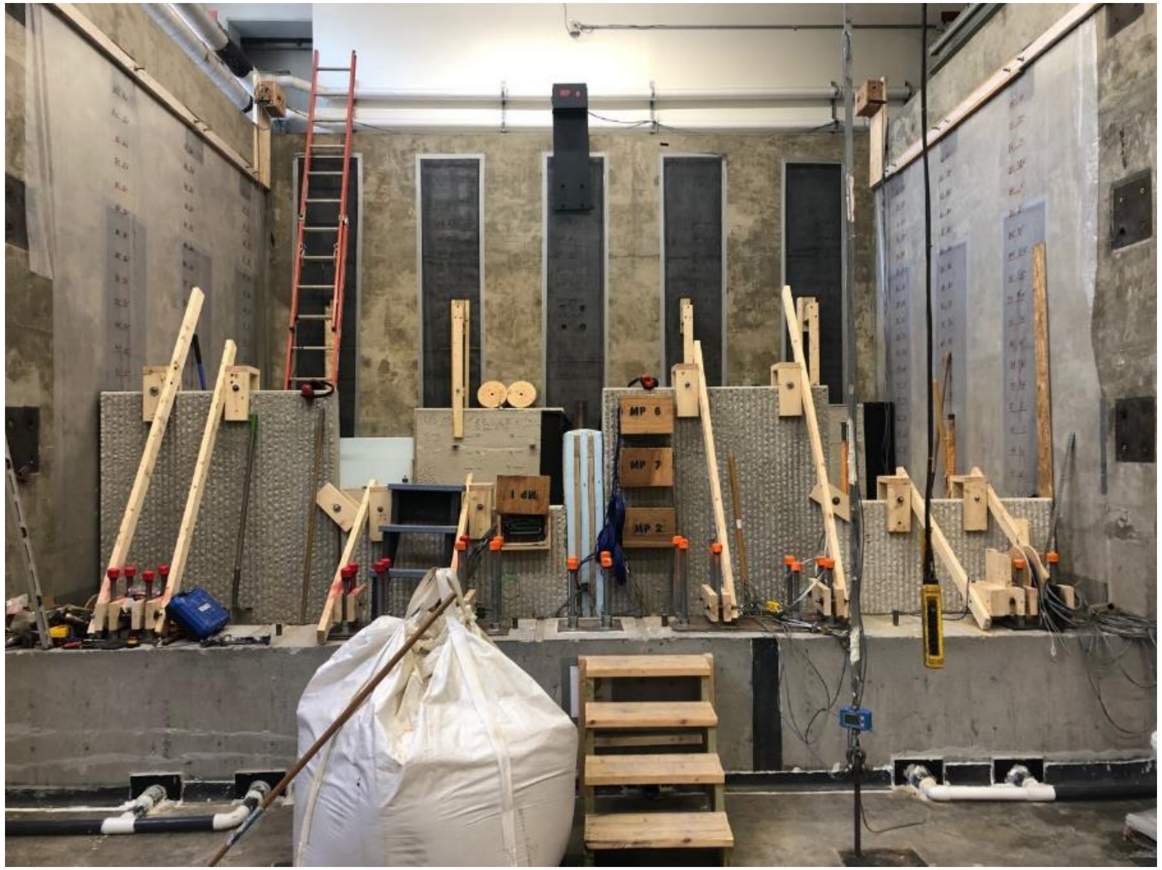

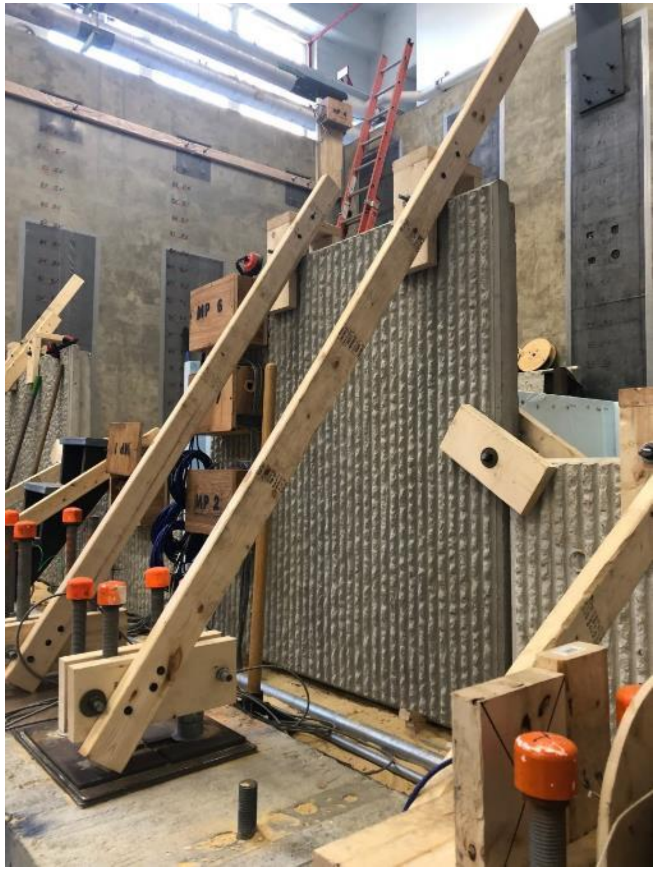

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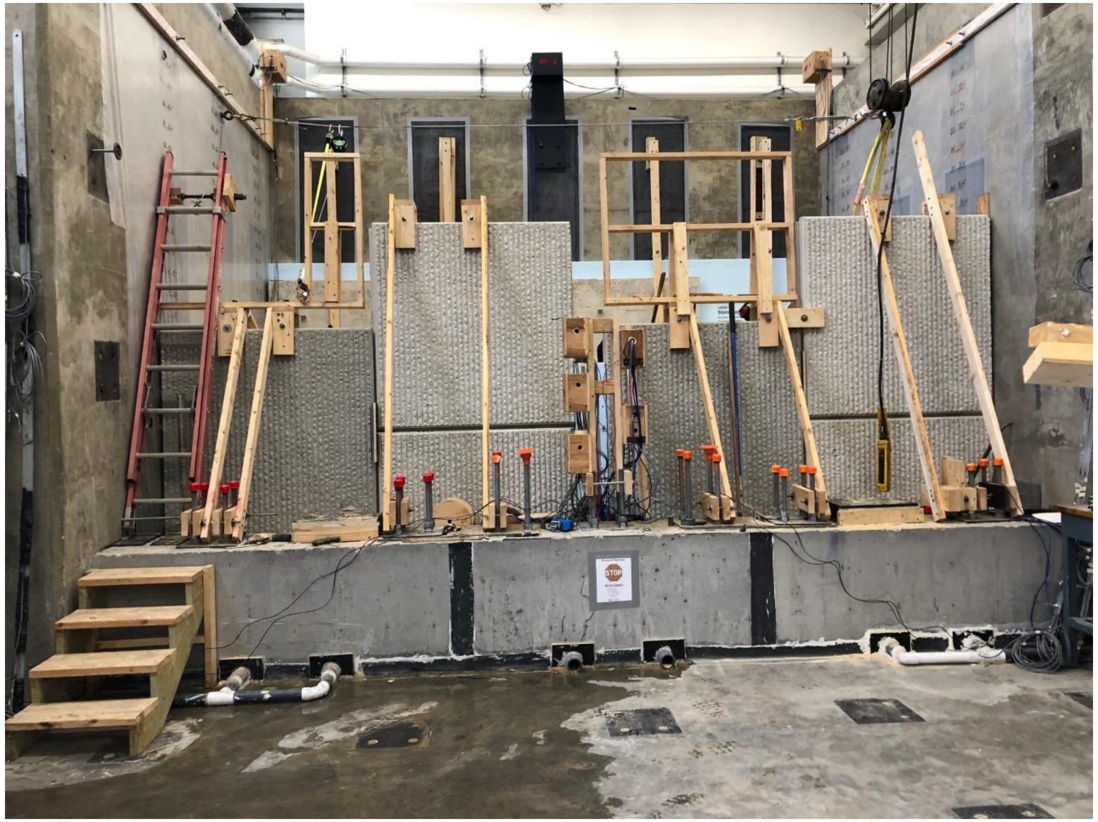
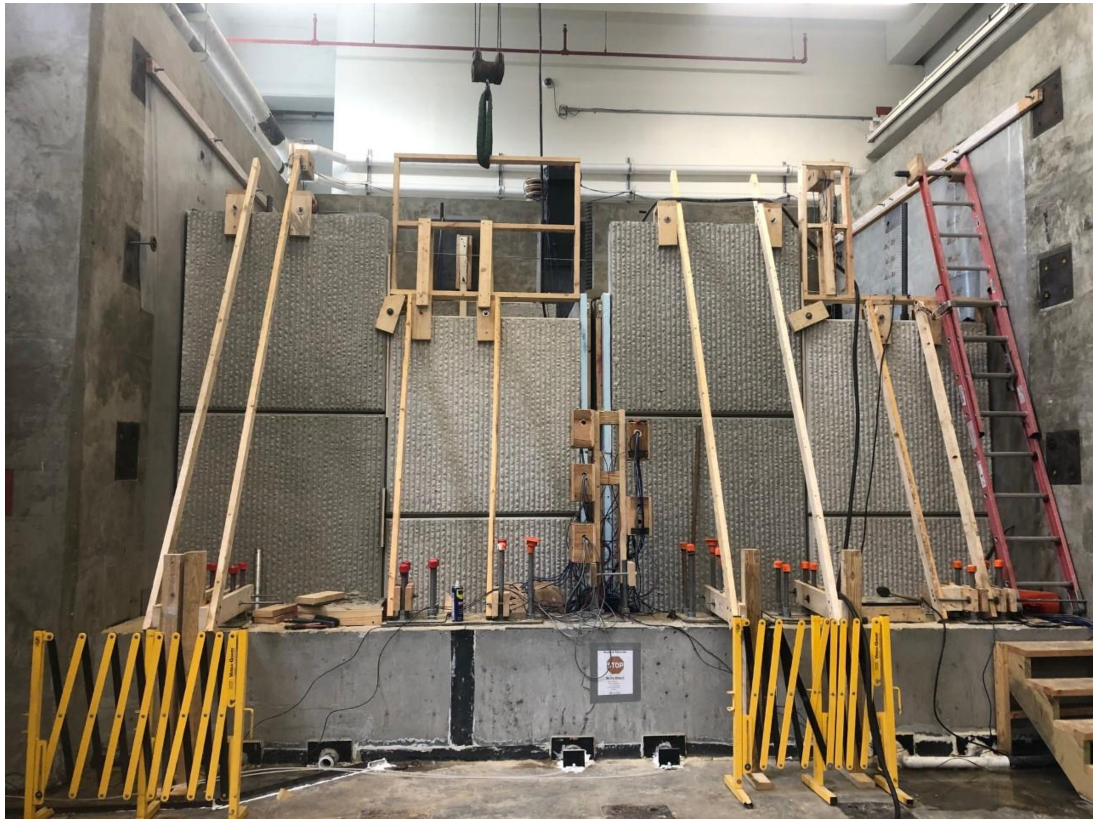
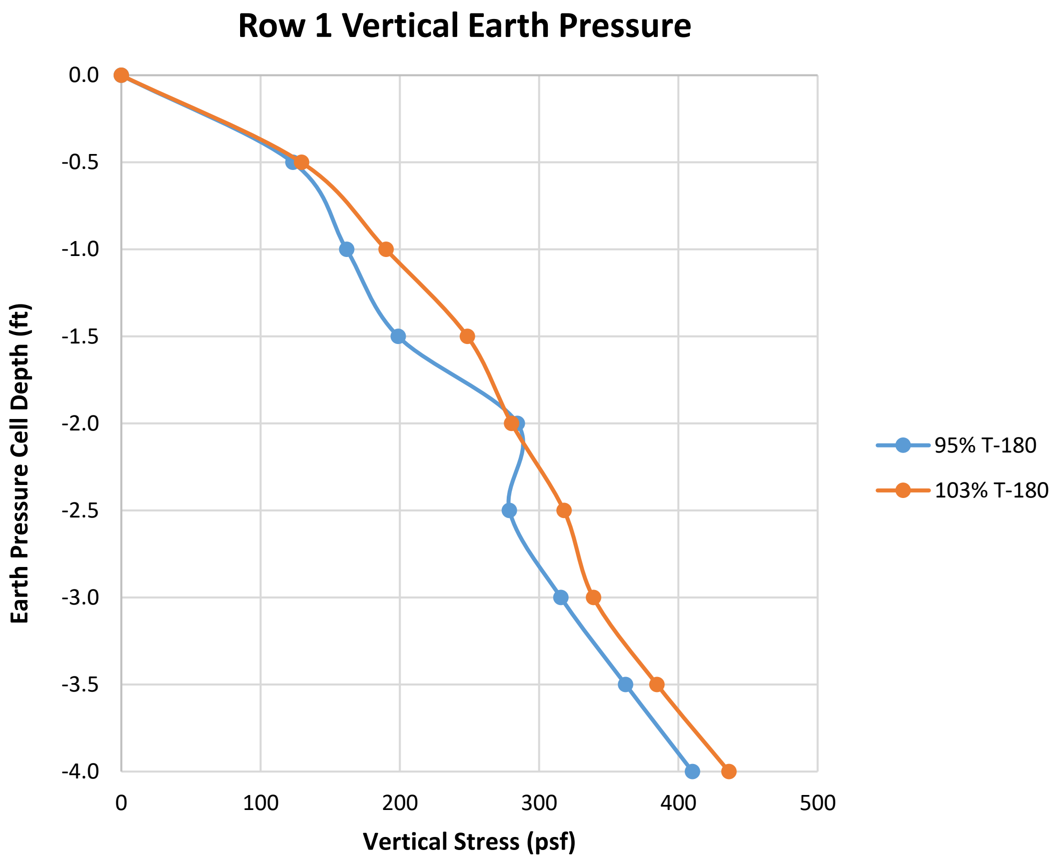
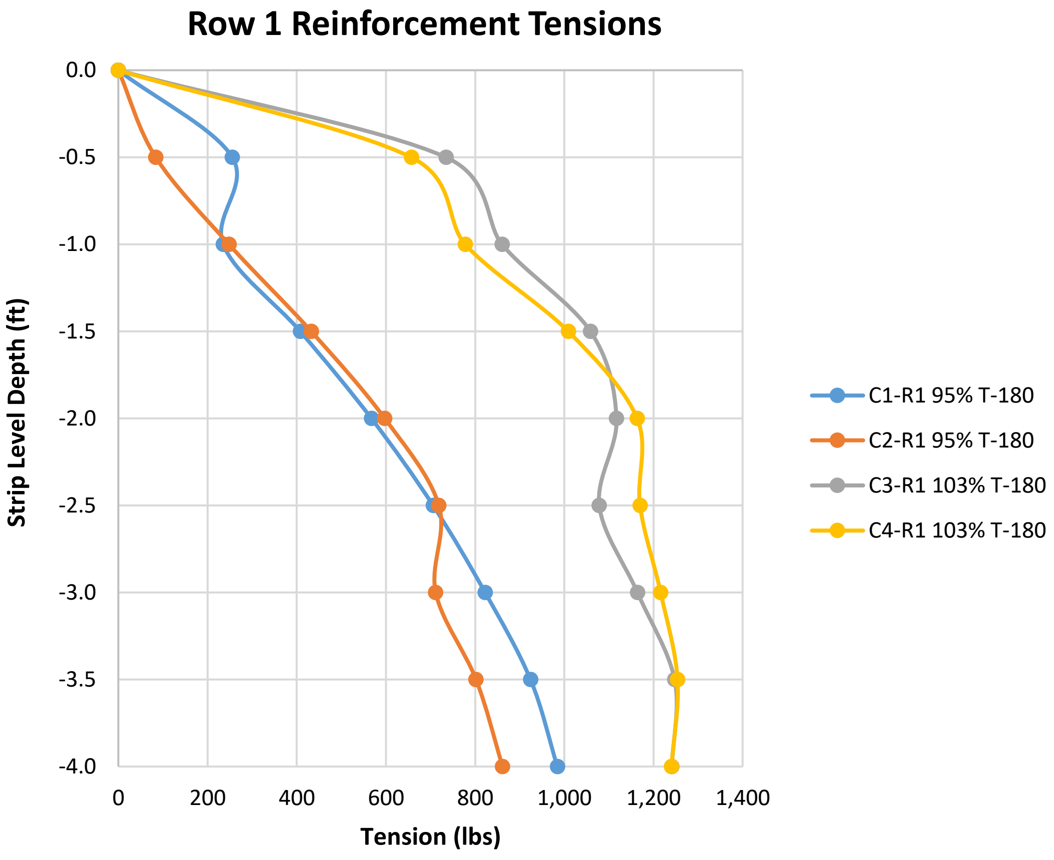


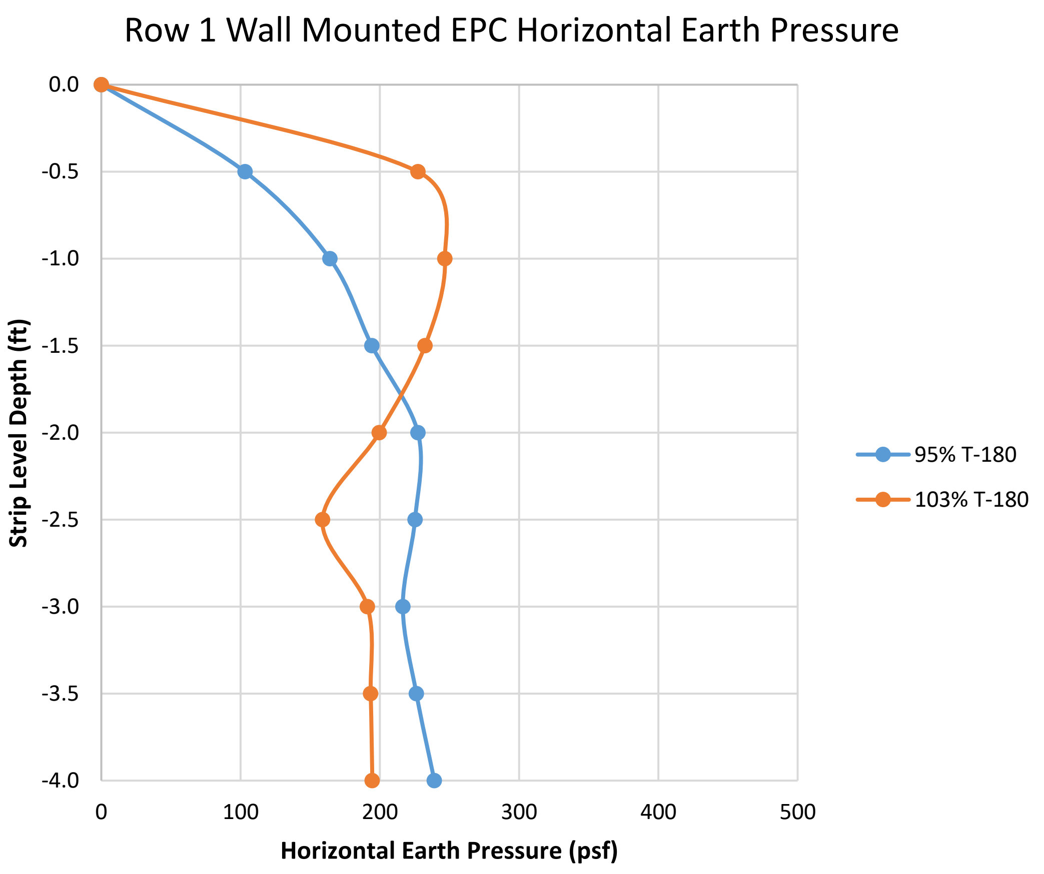


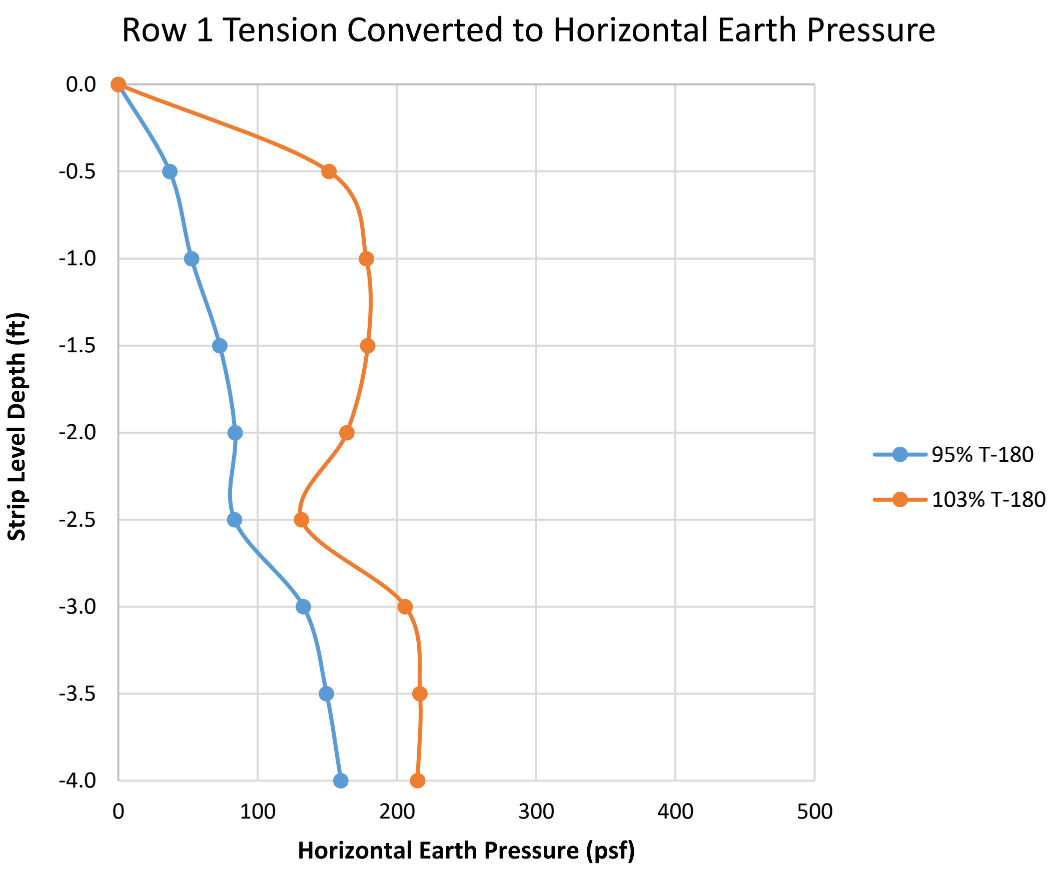
Vertical Stress and Reinforcement Strip Tension



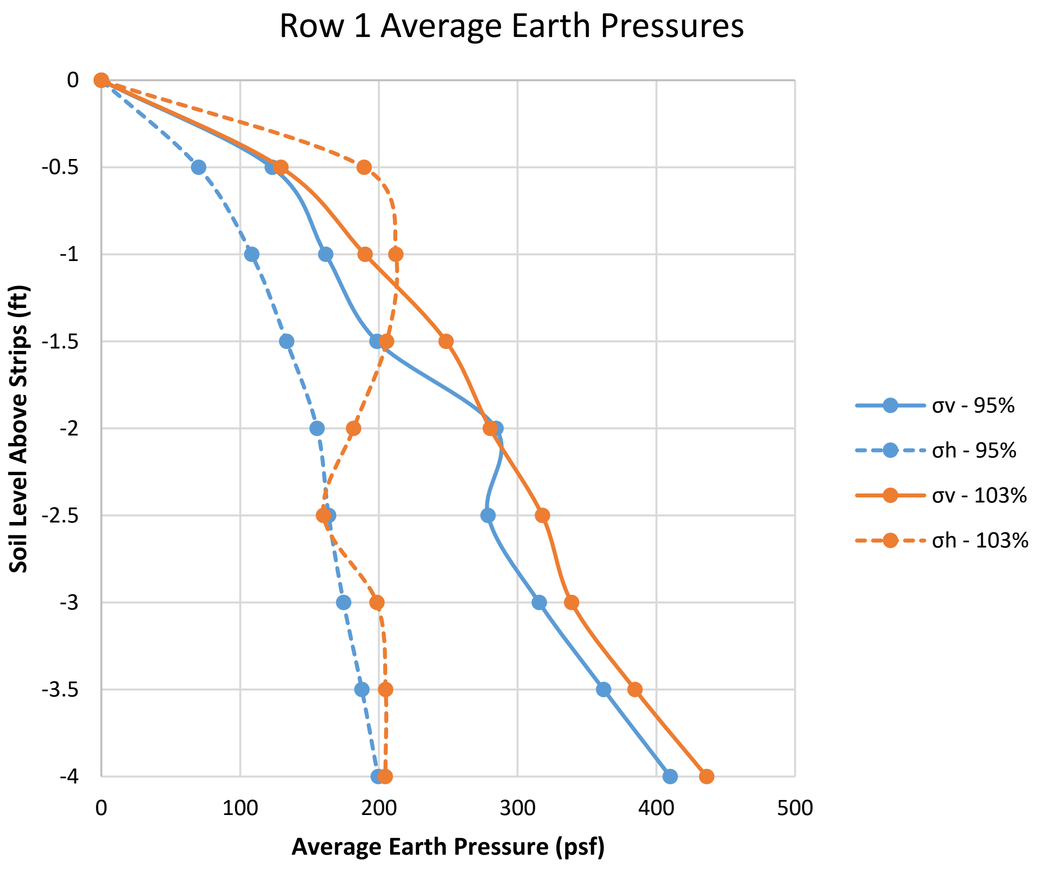


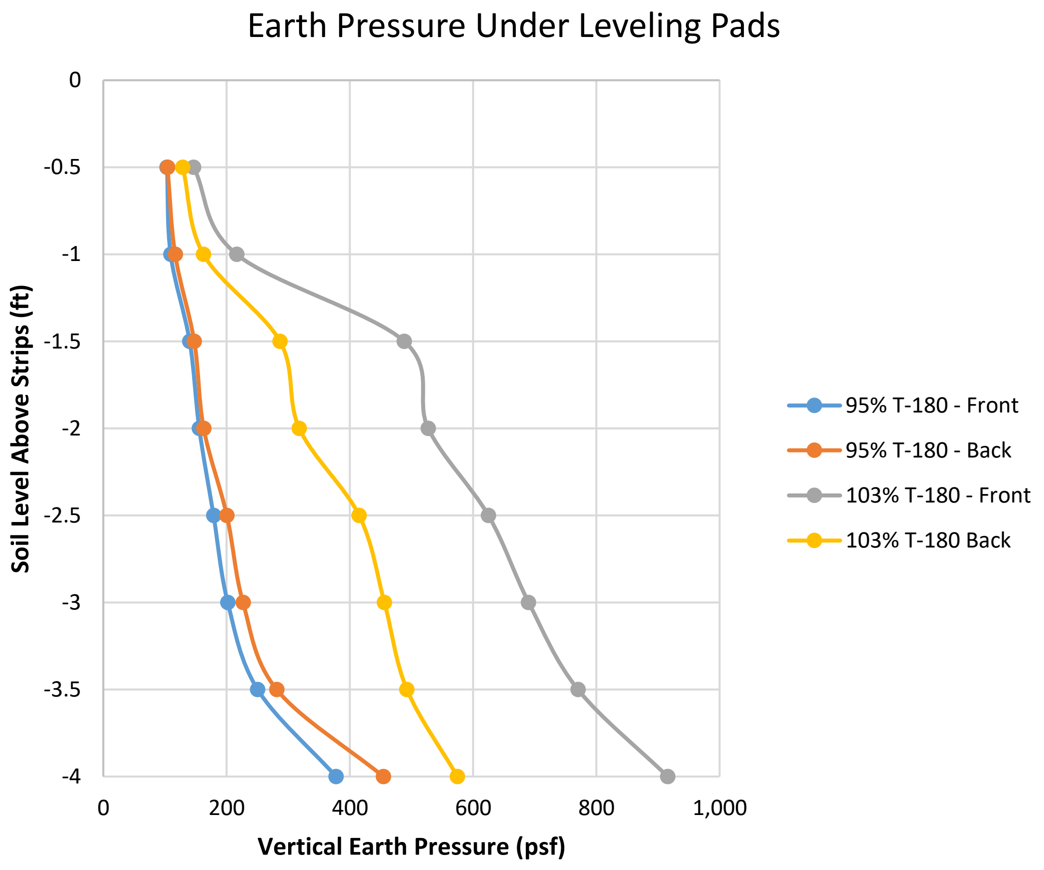
Row 1 Horizontal Earth Pressures





Earth Pressures





Remaining Tasks

- Task (3) – MSE Wall Construction with Two Designated Relative Compaction Efforts
- Task (4) – Draft Final and Closeout Teleconference
- Task (5) – Final Report

References

- AASHTO. “LRFD Bridger Design Specifications, 4th Edition”. American Association of State Highway and Transportation Officials. Washington, D.C. 2007.
- Allen T., Christopher B., Elias V., and DiMaggio J. “Development of the Simplified Method for Internal Stability Design of Mechanically Stabilized Earth Walls”. Report No. WA-RD 513.1, Washington State Department of Transportation, Olympia, Washington, July, 2001.
- Anderson P.L., Gladstone R.A, and Withiam J.L. "Coherent Gravity: The Correct Design Method for Steel-Reinforced MSE Walls." *Earth Retention Conference 3*.GSP 208. 2010.
- Anderson P.L., Gladstone R.A., and Sankey J.E. "State of the practice of MSE wall design for highway structures." *Geotechnical Engineering State of the Art and Practice: Keynote Lectures from GeoCongress 2012*. GSP 226. 2012.
- Baquelin F. "Construction and Instrumentation of Reinforced Earth Walls in French Highway Administration." *Symposium on Earth Reinforcement*. ASCE. 1978.
- Bilgin O. and Kim H. “Effect of Soil Properties and Reinforcement Length of Mechanically Stabilized Earth Wall Deformations”. *Earth Retention Conference 3.* GSP 208. 2010.
- Broms, B. “Lateral earth pressures due to compaction of cohesionless soils.” *Proc., 4th Int. Conf. Soil Mechanics*. Budapest, Hungary. 1971.
- Chalermyanont, Tanit, and Craig H. Benson. "Reliability-Based Design for Internal Stability of Mechanically Stabilized Earth Walls." *Journal of Geotechnical and Geoenvironmental Engineering*. 130.2: 163-173, 2004.
- Chalermyanont, Tanit, and Craig H. Benson. "Reliability-Based Design for External Stability of Mechanically Stabilized Earth Walls." *Journal of Geotechnical and Geoenvironmental Engineering*. Volume 5, Issue 3, September 2005.
- Chen T. and Yung-Show F. "Earth Pressure due to Vibratory Compaction." *Journal of Geotechnical and Geoenvironmental Engineering*. Volume 134, Issue 4. 2008.
- D’Appolonia D.J., Whitman R.V., and D’Appolonia E. "Sand compaction with vibratory rollers." *Journal of Soil Mechanics & Foundations Division*. Volume 95, Issue 1Pages 263-284. 1969.
- D’Appolonia Engineering. “LRFD Calibration of Coherent Gravity Method for Metallically Reinforced MSE Walls”. *Report for Association for Mechanically Stabilized Earth (AMSE)*. December 2007.
- Duncan, James M., and Raymond B. Seed. "Compaction-induced earth pressures under K_0-conditions." *Journal of Geotechnical Engineering*. 112.1: 1-22. 1986.
- Duncan, J. M., Williams G.W., Sehn A.L., Seed R.B. "Estimation earth pressures due to compaction." *ASCE Journal of geotechnical engineering*. Volume 117, Issue 12. 1991.
- FDOT. Standard Specifications for Road and Bridge Construction. Florida Department of Transportation. 2017.
- FHWA. Samtani N.C. and Nowatzki E.A. “Soils and Foundation Reference Manual – Volume I”. *Publication No. FHWA-NHI-06-088*, Federal Highway Administration. Washington, DC, 2006.
- FHWA. Samtani N.C. and Nowatzki E.A. “Soils and Foundation Reference Manual – Volume II”. *Publication No. FHWA-NHI-06-089*, Federal Highway Administration. Washington, DC, 2006.
- FHWA. Berg R.R., Christopher B.R., and Samtani N.C. “Design of Mechanically Stabilized Earth Walls and Reinforced Soil Slopes – Volume I”. *Publication No. FHWA-NHI-10-024, FHWA GEC 011-Vol II.* Federal Highway Administration. Washington, DC, 2009.
- FHWA. Berg R.R., Christopher B.R., and Samtani N.C. “Design of Mechanically Stabilized Earth Walls and Reinforced Soil Slopes – Volume II”. *Publication No. FHWA-NHI-10-025, FHWA GEC 011-Vol II.* Federal Highway Administration. Washington, DC, 2009.
- Kim D. and Salgado R. “Load and Resistance Factors for Internal Checks of Mechanically Stabilized Earth Walls”. *ASCE Journal of Geotechnical and Geoenvironmental Engineering*, Volume 138, Issue 8, August 2012.
- Kniss K.T., Wright S.G., Zornberg J., and Yang K. “Design Considerations for MSE Retaining Walls Constructed in Confined Spaces”. *Report No. FHWA/TX-08/0-5506-1*, Texas Department of Transportation (TxDOT). Austin, Texas, 2007.
- Lawson C.R. and Yee T.W. “Reinforced Soil Retaining Walls with Constrained Reinforced Fill Zones”. *Slopes and Retaining Structures Under Seismic and Static Conditions*, GSP 140, ASCE, Austin, Texas, 2005.
- Mitchell J.K. and Villet W.C.B. “Reinforcement of Earth Slopes and Embankments”. *NCHRP Report No. 290,* National Cooperative Highway Research Program. Washington, D.C. June, 1987.
- McKittrick, David P. “Reinforced Earth: Application of Theory and Research to Practice”. *Ground Engineering*. 1979.
- RECo. Documentation and Test Results for Clip Angle Connections used in Reinforced Earth Structures. 2003.
- RECo. Design Manual for Reinforced Earth Walls. 2011.
- WSDOT. “Geotechnical Design Manual”. *M-46-03.01*, Washington State Department of Transportation (WSDOT). January 2010.

Questions?