7th Quarterly Progress Report

Ohio DOT Research

Seventh Quarter Ending on September 31, 2019

“Quarterly Report: State Job #31347”

For Quarter Ending:	September 31, 2019
Date Submitted:	**October 31, 2019**

Project Title:	Structural Design Methodology for Spray Applied Pipe Liners in Gravity Storm Water Conveyance Conduits				
Research Agency:	CUIRE/The University of Texas at Arlington				
Principal Investigator(s):	PI: Mohammad Najafi, Ph.D., P.E., F. ASCE, Professor and Director, CUIRE Co-PI: Xinbao Yu, Ph.D., P.E., Associate Professor				
State Job Number:	5501.03		Agreement Number:		31347
Project Start Date:	20 December 2017		Contract Funds Approved:		25 September 2017
Project Completion Date:	20 December 2020		Spent to Date:		$401,484.39
% Funds Expended:	76%	% Work Done:	80%	% Time Expired:	59%

List the ODOT Technical Liaisons and other individuals who should receive a copy of this report:

1. Jeffrey E. Syer, P.E. – Ohio DOT
2. Brian R. Carmody, P.E. – NYSDOT
3. Matthew S. Lauffer, P.E. and Charles Smith P.E. – NCDOT
4. Paul Rowekamp and Aislyn Ryan – MnDOT
5. Sheri Little – PennDOT
6. Carlton Spirio – FDOT
7. Jonathan Karam and Nicholas Dean – DelDOT

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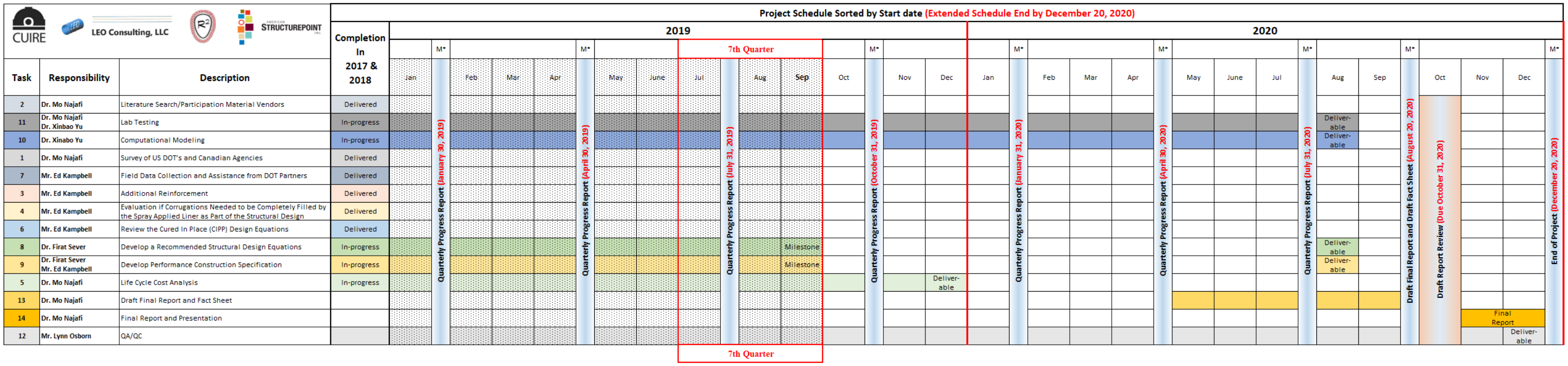
Schedule of Research Activities Tied to Each Task Defined in the Proposal and Percentage Completion of the Research

Table 1: SAPL Research Project Schedule



Ohio Department of Transportation

Structural Design Methodology for Spray Applied Pipe Liners in Gravity Storm Water Conveyance Conduits

			Completion In 2017 & 2018	Project Schedule Sorted by Start date (Extended Schedule End by December 20, 2020)																																
				2019																2020																
					M*				M*			7th Quarter	M*				M*				M*				M*				M*			M*				M*
Task	Responsibility	Description		Jan		Feb	Mar	Apr		May	June	Jul		Aug	Sep	Oct		Nov	Dec	Jan		Feb	Mar	Apr		May	June	Jul		Aug	Sep		Oct	Nov	Dec	
2	Dr. Mo Najafi	Literature Search/Participation Material Vendors	Delivered		Quarterly Progress Report (January 30, 2019)				Quarterly Progress Report (April 30, 2019)				Quarterly Progress Report (July 31, 2019)				Quarterly Progress Report (October 31, 2019)				Quarterly Progress Report (January 31, 2020)				Quarterly Progress Report (April 30, 2020)				Quarterly Progress Report (July 31, 2020)			Draft Final Report and Draft Fact Sheet (August 20, 2020)	Draft Report Review (Due October 31, 2020)			End of Project (December 20, 2020)
11	Dr. Mo Najafi Dr. Xinbao Yu	Lab Testing	In-progress	▨		▨	▨	▨		▨	▨	▨		▨	▨	▨		▨	▨	▨		▨	▨	▨		▨	▨	▨		Deliverable						
10	Dr. Xinabo Yu	Computational Modeling	In-progress	▨		▨	▨	▨		▨	▨	▨		▨	▨	▨		▨	▨	▨		▨	▨	▨		▨	▨	▨		Deliverable						
1	Dr. Mo Najafi	Survey of US DOT's and Canadian Agencies	Delivered																																	
7	Mr. Ed Kampbell	Field Data Collection and Assistance from DOT Partners	Delivered																																	
3	Mr. Ed Kampbell	Additional Reinforcement	Delivered																																	
4	Mr. Ed Kampbell	Evaluation if Corrugations Needed to be Completely Filled by the Spray Applied Liner as Part of the Structural Design	Delivered																																	
6	Mr. Ed Kampbell	Review the Cured In Place (CIPP) Design Equations	Delivered																																	
8	Dr. Firat Sever	Develop a Recommended Structural Design Equations	In-progress	▨		▨	▨	▨		▨	▨	▨		▨	Milestone															Deliverable						
9	Dr. Firat Sever Mr. Ed Kampbell	Develop Performance Construction Specification	In-progress	▨		▨	▨	▨		▨	▨	▨		▨	Milestone															Deliverable						
5	Dr. Mo Najafi	Life Cycle Cost Analysis	In-progress	▨		▨	▨	▨		▨	▨	▨		▨	▨	▨		▨	Deliverable																	
13	Dr. Mo Najafi	Draft Final Report and Fact Sheet																								▨	▨	▨		▨	▨					
14	Dr. Mo Najafi	Final Report and Presentation																																Final Report		
12	Mr. Lynn Osborn	QA/QC		▨		▨	▨	▨		▨	▨	▨		▨	▨	▨		▨	▨	▨		▨	▨	▨		▨	▨	▨		▨	▨			▨	Deliverable	

7th Quarter

Table 2: Completion Percentage of SAPL Research Project Tasks over the 1st, 2nd, 3rd, 4th, 5th, 6th and 7th Quarters

Structural Design Methodology for Spray Applied Pipe Liners in Gravity Storm Water Conveyance Conduits

UNIVERSITY OF TEXAS ARLINGTON · R² · AMERICAN STRUCTUREPOINT INC. · LEO · LEO Consulting, LLC · CUIRE

Task Number	Task Description	Percentage Completed by the end of:						
		1st Quarter	**2nd Quarter**	**3rd Quarter**	**4th Quarter**	**5th Quarter**	**6th Quarter**	**7th Quarter**
		Dec 2017 through Mar 2018	*Apr 2018 through Jun 2018*	*Jul 2018 through Sep 2018*	*Oct 2018 through Dec 2018*	*Jan 2019 through Mar 2019*	*April 2019 through Jun 2019*	*Jul 2019 through Sep 2019*
1	Survey of US DOT's and Canadian Agencies	29%	71%	100%	100%	100%	100%	100%
2	Literature Search/Participation Material Vendors	57%	100%	100%	100%	100%	100%	100%
3	Additional Reinforcement	0%	67%	95%	100%	100%	100%	100%
4	Evaluation if Corrugations Needed to be Completely Filled by the Spray Applied Liner as Part of the Structural Design	0%	67%	90%	100%	100%	100%	100%
5	Life Cycle Cost Analysis	0%	0%	0%	0%	35%	50%	75%
6	Review the Cured in Place (CIPP) Design Equations	0%	0%	67%	80%	100%	100%	100%
7	Field Data Collection and Assistance from DOT Partners	0%	40%	100%	100%	100%	100%	100%
8	Develop a Recommended Structural Design Equations	0%	0%	0%	20%	30%	80%	52%*
9	Develop Performance Construction Specification	0%	0%	0%	0%	30%	82%	55%*
10	Computational Modeling	19%	38%	57%	60%	65%	70%	66%*
11	Lab Testing	19%	38%	43%	45%	50%	70%	66%*
12	QA/QC	17%	29%	38%	54%	65%	75%	59%*

**Percentages are changed based on the budget and time extension.*

Comparative Status of Actual Versus Estimated Expenditures

Table 3: The 7th Quarterly Progress Work of SAPL Research Project

Structural Design Methodology for Spray Applied Pipe Liners in Gravity Storm Water Conveyance Conduits

UNIVERSITY OF TEXAS ARLINGTON · STRUCTUREPOINT · LEO Consulting, LLC · CUIRE

Task Number	Task Description	Total Duration (Months)	Duration Completed (Months)	Budgeted Amount ($)	Percentage of Total Budget (%)	Percentage of Completion Based on Schedule (%)	Percentage Completed This Quarter (%)	Actual Amount Completed this Quarter ($)
1	Survey of US DOT’s and Canadian Agencies	7	7	$25,751	5.09	100	0	0
2	Literature Search/Participation Material Vendors	7	7	$21,875	4.32	100	0	0
3	Additional Reinforcement	3	3	$2,100	0.41	100	0	0
4	Evaluation if Corrugations Needed to be Completely Filled by the Spray Applied Liner as Part of the Structural Design	4	4	$3,900	0.77	100	0	0
5	Life Cycle Cost Analysis	12	9	$29,123	5.75	75	25	7,280.75
6	Review the Cured in Place (CIPP) Design Equations	5	6	$13,751	2.72	100	0	0
7	Field Data Collection and Assistance from DOT Partners	5	5	$71,704	14.17	100	0	0
8	Develop a Recommended Structural Design Equations	21	11	$34,081	6.73	52	10	$9,125.52
9	Develop Performance Construction Specification	22	12	$27,392	5.41	55	14	$3,834.88
10	Computational Modeling	32	21	$60,013.44	11.86	66	10	$20,814.17
11	Lab Testing	32	21	$115,137.94	22.75	66	10	$61,771.51
12	QA/QC	36	21	$13,000	2.57	59	9	$1,800.00
13	Draft Final Report and Fact Sheet	7	Not Started	$88,270	17.44	0	0	0
14	Final Report and Presentation	3	Not Started					
Total				$506,098.38**	100	-	-	$104,626.79

* Percentages are changed based on the budget and time extensions.

** The total budget does not reflect the indirect cost of additional budget.

Table 4: Expenditures Summery of SAPL Research Project in the 7th Quarter

Structural Design Methodology for Spray Applied Pipe Liners in Gravity Storm Water Conveyance Conduits	
Summary of Expenditures for the 7th Quarter (July through September 2019)	
Description	**Sum Amount**
Salaries and Benefits	
Students Salaries and Benefits	$14,097.65
Faculty Salaries will be Paid During Summer Months	$60,602.96
Subtotal	$74,700.61
Partner Companies	
American Structurepoint, Inc.	$9,125.52
Rehabilitation Resource Solutions	-
LEO Consulting	$1,800.00
Subtotal	$10,925.52
Supplies	
Bracket flat straight, bracket corner, bracket angle, Hex bolt, atomic charge, spade vinyl, tape, STRUT channel gold, USB cable extension, AC power supply adapter, HDMI cable, display port to HDMI adapter, construction carpenter scaffolding-2, 3M Scotch, KwikSafety (Charlotte, NC) SCORPION safety harness w/attached 6ft. tubular lanyard on back, Prime KD SYP-4, work light, flat washers-2, security camera power extension cable, Duracell batteries, APC Back-UPS, TIE-DOWN 12' GRN 100, DISPLAY Port to DVI-1, Digital Camera – 3, Mini USB Cable 50Ft-3, TKDY Adapter Charger and DC Coupler Kit-2 and DEWALT 1/2" BLCK-2, DEWALT 3/8" BLCK-2	$7,063.05
Subtotal	$7,063.05
Other Indirect Costs	
Indirect Costs	$37,903.16
Total	**$130,592.34**

Brief Description of the Activities Accomplished by Each Member of the Research Team as Listed in the Project Budget

Principal Investigator: Dr. Mohammad Najafi

Task 5: Life Cycle Cost Analysis

- Scrubbed, cleaned, and prepared all collected data for analysis.
- Conducted the multiple linear regression analysis of the mean construction cost of SAPL in compared to CIPP, and sliplining.
- Developed the preliminary model to forecast the construction cost of SAPL projects.
- Conducted the sensitivity analysis of the construction cost to the diameter for SAPL, CIPP, and sliplining projects.

Task 11: Laboratory Testing

Soil Box Test Setup

- Placed CMPs inside the soil box for the control tests.
- External instrumentation including (18 strain gauges for each pipe) surface preparation, installation, physical and chemical protection attachment, wiring and system setup (control tests).
- Earth Pressure cell installation (control tests).
- CMPs embedment and backfilling (control tests).
- Invert section detachment (control tests).
- Internal instrumentation including development of a frame to carry the sensors, installation of LVDTs, CDSs, DICs, and their required data acquisition system (control tests).
- Initial setup of instrumentations, preliminary testing and calibration.
- Loading the CMPs and monitoring (control tests).
- Completed soil box control tests of invert cut CMPs for both circular and arch shapes.
- Completed soil box control test of intact circular CMP.
- Performed data analysis and interpretation on the results of soil box control tests of CMPs.
- Performed Digital Image correlation model development.
- Prepared report for the control tests.
- Detached all the inside instrumentation (LVDTs and cable displacement sensors).
- Detached all the wires and sensors from external surface.
- Excavated the first set of soil box and removed the earth pressure cells.
- Removed CMPs.
- Stored the CMPs.
- Prepared the soil box test setup for polymeric SAPL material from Sprayroq.
- Placed a bedding layer at top of the foundation.

Participation in the Meetings during Conferences, Internal Meetings, Progress Meetings

- Attended three monthly progress meetings with DOTs.
- Held internal meetings with CUIRE team and research partners (Dr. Xinbao Yu, Dr. Firat Sever, Mr. Ed Kampbell and Mr. Lyn Osborn).
- Submitted two journal papers to Canadian Journal of Civil Engineering and Thin-Walled Structures Journal.
- Submitted two abstracts to No-Dig Show Conference 2020.
- Submitted two abstracts to ASCE Pipeline Conference 2020.

Co-Principal Investigator: Dr. Xinbao Yu

The following are the tasks performed this quarter:

Task 10: Computational Modeling

- Completed and calibrated the FEM modeling of intact circular CMP.

Subcontractor: Mr. Ed Kampbell
Rehabilitation Resource Solutions, LLC

- In the past quarter Rehabilitation Resource Solution did not perform any work on the project except to participate in the required meetings. I have continued to peruse the literature for additional thoughts on the design equations development.

Subcontractor: Dr. Firat Sever
American Structurepoint, Inc. (ASI)

American Structurepoint's progress in this period is included in Lynn Osborn's report as they work jointly on the performance specification development. Dr. Firat Sever has performed the following tasks in this quarter:

- Attended conference calls with UTA and ODOT.
- Created a spreadsheet based on Seide (shell approach) for cementitious liners.

Subcontractor: Mr. Lynn Osborn
LEO Consulting, LLC

Task 9: Prepare Performance Construction Specifications

Activities for Q7 include:

- Received draft cementitious specification from American Structurepoint.
- Prepared cementitious specification outline and sent to Dr. Najafi.
- Cementitious specification outline made available to DOTs for comment.
- Made numerous modifications to the draft cementitious specification.
- Received draft polymer specification from American Structurepoint.

Task 12. QA/QC

As QA/QC Reviewer, much of my work depends upon the work and progress of other team members and items that require quality checks.

Activities for Q7 include:

- Reviewed draft performance construction specifications from American Structurepoint (see Task 9).
- Attended ODOT update calls 8/13/19 and 9/11/19.

Proposed Work for New Quarter

Table 5: SAPL Research Project Tasks for 8th Quarter (October 1 through December 31, 2019)

<table>
<tr><th colspan="6">Structural Design Methodology for Spray Applied Pipe Liners in Gravity Storm Water Conveyance Conduits</th></tr>
<tr><th rowspan="3">Task Number</th><th rowspan="3">Responsibility</th><th rowspan="3">Task Description</th><th colspan="3">Percentage of Work to be Completed by the end of 8th Quarter</th></tr>
<tr><th colspan="3">October 1st through December 31st</th></tr>
<tr><th>October</th><th>November</th><th>December</th></tr>
<tr><td>5</td><td>Dr. Mo Najafi</td><td>Life Cycle Cost Analysis</td><td colspan="3">To be Completed</td></tr>
<tr><td>8</td><td>Dr. Firat Sever
Mr. Ed Kampbell</td><td>Develop a Recommended Structural Design Equations</td><td colspan="3">To be Continued</td></tr>
<tr><td>9</td><td>Dr. Firat Sever
Mr. Lyn Osborn</td><td>Develop Performance Construction Specification</td><td colspan="3">To be Continued</td></tr>
<tr><td>10</td><td>Dr. Xinabo Yu</td><td>Computational Modeling</td><td colspan="3">To be Continued</td></tr>
<tr><td>11</td><td>Dr. Mo Najafi</td><td>Lab Testing</td><td colspan="3">Circular Polymeric SAPL Test to be Started</td></tr>
<tr><td>12</td><td>Mr. Lynn Osborn</td><td>QA/QC</td><td colspan="3">To be Continued</td></tr>
</table>

Principal Investigator: Dr. Mohammad Najafi

Task 5: Life Cycle Cost Analysis

- To complete development of a model to forecast the construction cost of SAPL, CIPP, and sliplining.
- To complete the analysis of life-cycle cost for SAPL compared to CIPP and sliplining.

Task 11: Soil Box Testing

- To complete soil box tests of polymeric SAPL material from Sprayroq for circular CMPs.
- To perform data analysis on the results of soil box tests of polymeric SAPL for circular CMPs.
- To start the test setup of polymeric SAPL material from Sprayroq for arch CMPs.
- To prepare journal papers out of the results of soil box tests of polymeric SAPL for circular CMPs.

Co-Principal Investigator: Dr. Xinbao Yu

Planned Task for the Next Quarter

Following are the tasks planned for the coming quarter:

Task 10: Computational Modeling

- The FEM work on the invert-cut circular, and arch CMP are to be continued and will be reported in next quarterly report.

Subcontractor: Mr. Ed Kampbell
Rehabilitation Resource Solutions, LLC

- Rehabilitation Resource Solutions will not be engaging in any meaningful tasks towards the development of the design equations until sometime in the 9th quarter when the data becomes available.

Subcontractor: Dr. Firat Sever
American Structurepoint, Inc. (ASI)

The following tasks are to be performed by Firat Sever in the next quarter:

- To work with Ed Kampbell on establishing the overall design approach with the base equations.
- To modify the current base equations based on experimental data from this study, NTPET, and computational modeling with FEA being performed by UTA.
- To attend periodic team conference calls as requested.
    - Review any interim work and reports

Subcontractor: Mr. Lynn Osborn
LEO Consulting, LLC

Task 9: Prepare Performance Construction Specifications

- To make draft cementitious specification available to the project team for review.
- To address comments on draft cementitious specification.
- To begin detailed review of draft polymer specification.

Task 12. QA/QC.

QA/QC reviews will continue on design and development planning, inputs, control and outputs. This will include general project oversight as required.

Implementation (if any):

N/A

Problems & Recommended Solutions (if applicable):

N/A

Equipment Purchased (if any):

N/A

Contacts and Meetings

Progress Meeting

Table 6: SAPL Progress Meeting during the 7th Quarter
July 1 through September 31

No.	Progress Meeting Agenda	Date
18	• Schedule Update • Task 11: Soil Box - Embedment Compaction - Loading Rate - Instrumentation - Testing Schedule • Task 8: Develop a Recommended Structural Design Equations • Time Extension & Additional Budget	July 16, 2019
19	• Schedule Update • Task 9: Performance Construction Specification Layout • Task 11: Soil Box Testing - Intact Circular CMP Sample - Invert-cut Arch CMP Sample • Task 5: Life Cycle Cost Analysis	August 13, 2019
20	• Schedule Update • Task 11: Soil Box Testing - Update on 1st Control Test Setup - Preparation of 2nd Polymeric SAPL Test Setup for Circular CMPs • Task 5: Life Cycle Cost Analysis	September 11, 2019

Appendix A

Report of Soil Box Testing
CMP Control Tests

Structural Design Methodology for Spray Applied Pipe Liners (SAPLs) in Gravity Storm Water Conveyance Conduits

Task 11

SAPL Laboratory Testing

Control Test Report (Draft)

Prepared by:
Amin Darabnoush Tehrani
and
Zahra (Ellie) Kohankar Kouchesfehani
Ph.D. Students

Center for Underground Infrastructure Research and Education (CUIRE)
Director: Dr. Mohammad Najafi, P.E.
The University of Texas at Arlington
Department of Civil Engineering
September 11, 2019

Center for Underground Infrastructure Research and Education (CUIRE)

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Summary of 1^{st} Soil Box Testing (Control Test)

Table A7: Summary of 1^{st} Soil Box Test Setup

Test No.	**Date**	**Corrugated Metal Pipe (CMP)**			**Load Pad Size**	**Load Rate (in./min)**	**Load at Failure (kips)**	**Maximum Pipe Displacement at Crown (in.)**	**Maximum Soil Displacement (in.)**
		Shape	**Size**	**Condition**					
1	7/31/2019	Circular	60 in.	Intact	10 in. × 20 in.	0.03	24.9	4.87	13.699
2	08/08/2019	Arch	47 in. × 71 in.	Invert-cut	20 in. × 40 in.	0.03	26.9	8.15	10
3	08/15/2019	Circular	60 in.	Invert-cut	20 in. × 40 in.	0.03	39.92	7.65	8.98

Control Test Procedure:

The 1^{st} series of soil box tests (control test) contains three CMPs: a 60 in. circular intact CMP, a 47 in. × 71 in. arch invert-cut CMP and a 60 in. circular invert-cut CMP. The CMPs were prepared, instrumented and tested at the center for underground infrastructure research and education (CUIRE) at the University of Texas at Arlington's civil engineering laboratory building (CELB). The tests were conducted according to the testing plan according to the following procedures:

1. A 24 in. foundation layer for the circular CMPs and 37 in. for the arch CMP was placed at the bottom the soil box using concrete sand. The foundation was placed in lifts of 8 in. and compacted using two passes of a vibratory plate compacter.
2. The top 4 in. of the foundation was disturbed to provide bedding for the CMPs.
3. An earth pressure cell, measuring vertical stress, was installed below the bottom of each CMP. The earth pressure cell was placed 4 inches away from the CMP surface to provide proper backing and eliminate the effect of point load on them.
4. The CMPs were placed on top of the bedding layer.
5. Strain gauges were installed on the CMPs at the predefined locations (circumferentially at the middle section of the CMPs).
6. For the backfilling, the poorly graded sand (SP) was dumped into the soil box and levelled to achieve 8 in. lifts. No additional compaction was done, and no effort was made to pack soil into the haunch areas (just by dumping, the 85% required compaction rate was achieved). This represents cases of poor installation or cases where loss of invert and resulting seepage has disturbed the soil support.
7. Compaction was measured using nuclear density gauge after each lift at four locations around each CMP.
8. Two earth pressure cells measuring horizontal pressure were installed on both sides at the level of springline, and one earth pressure cell measuring vertical pressure was installed on top of the CMP. Each earth pressure cell was installed 4 in. away from the CMP surface to provide proper backing and eliminate the effect of point load on them.
9. Concrete sand was placed to a height of 1 ft. above the top of the CMP. An additional 1 ft. of gravel layer was added to the top to prevent the soil failure.
10. After completion of backfill, the LVDT platform was installed inside the CMP and cable displacement sensors were installed to measure vertical and horizontal displacement.
11. For case of invert-cut CMPs, after removing the invert, the CMP had a significant movement which was monitored at the crown by using the cable displacement sensor.
12. LVDTs and cable displacement sensors were installed inside the CMPs to measure diagonal, horizontal and vertical changes of CMP diameter.
13. All the sensors were connected to their respective data acquisition systems.
14. Load was applied at a rate of 0.03 in./min. and the system response was monitored.

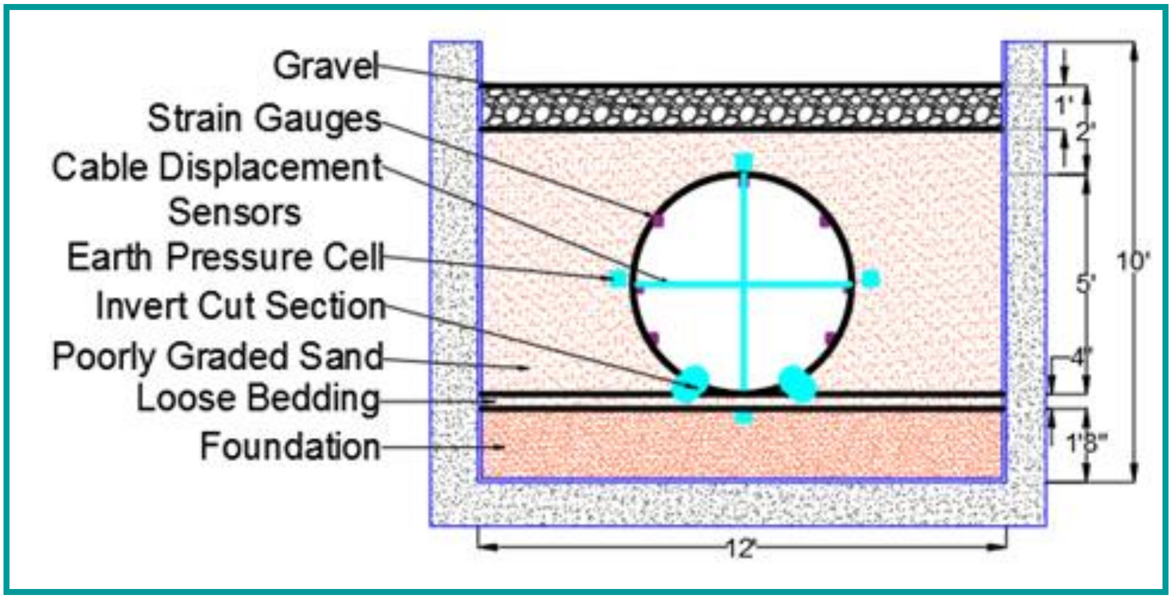

Figure A1: Soil Box Test Setup for 60 in. Circular CMP.

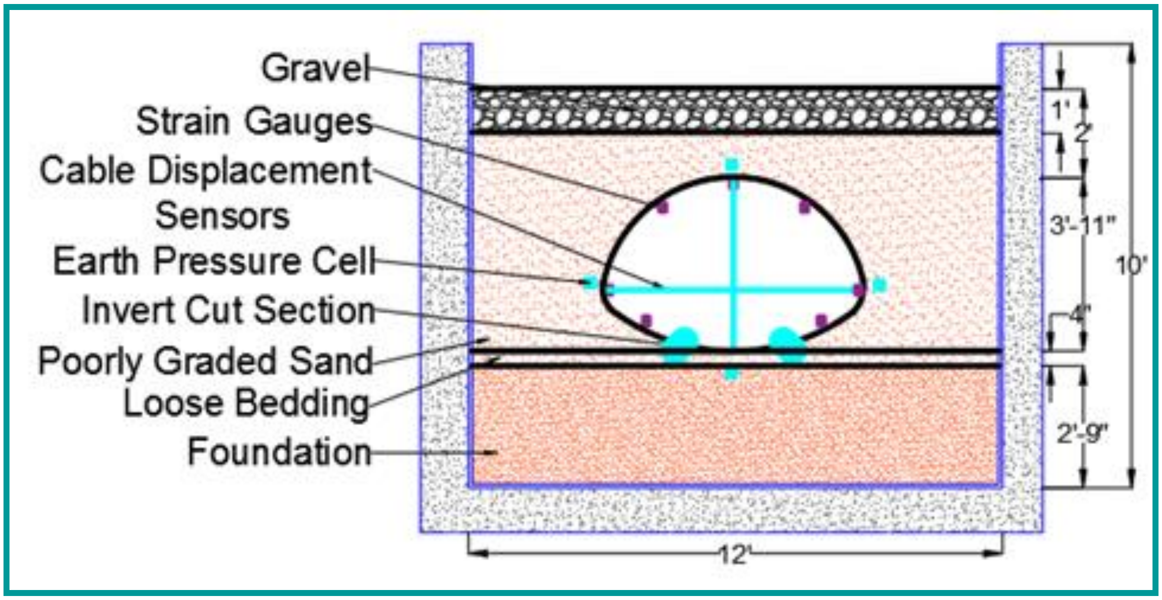

Figure A2: Soil Box Test Setup for 47 in. × 71 in. Arch CMP.

Preparation of Control Test Setup and Instrumentation

Figure A3: Nuclear Density Measurement to Check the Compaction Rate.

Figure A4: Outside View of CMPs for Control Test Setup.

Figure A5: Inside View of CMPs for Control Test Setup.

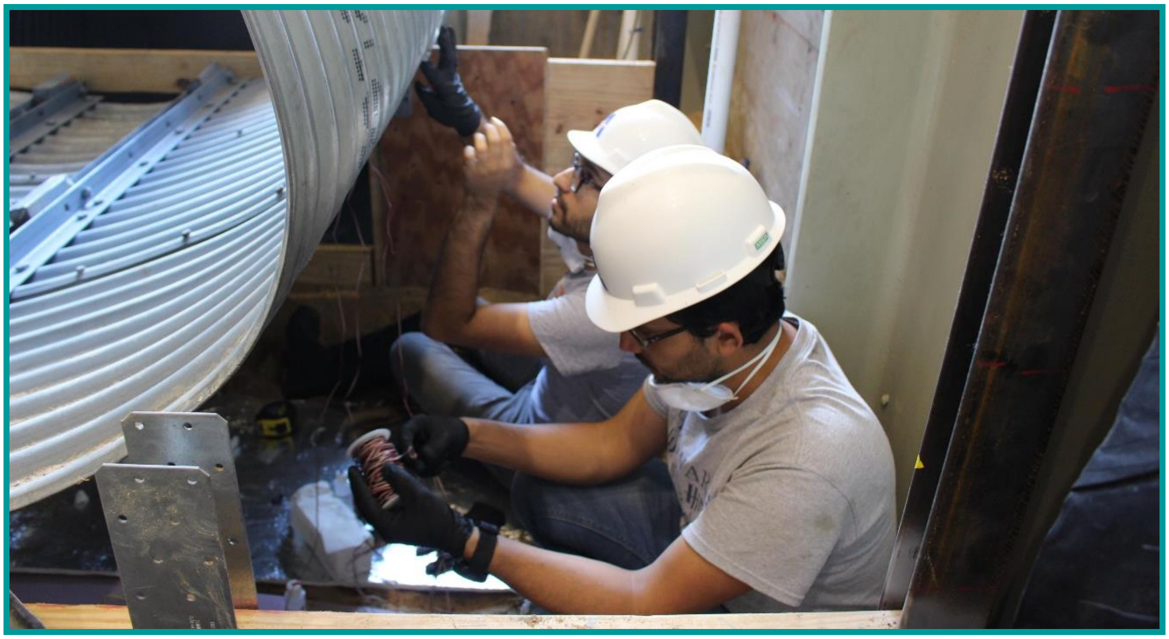

Figure A6: CMP Outside Instrumentation – Attaching Strain Gauges.

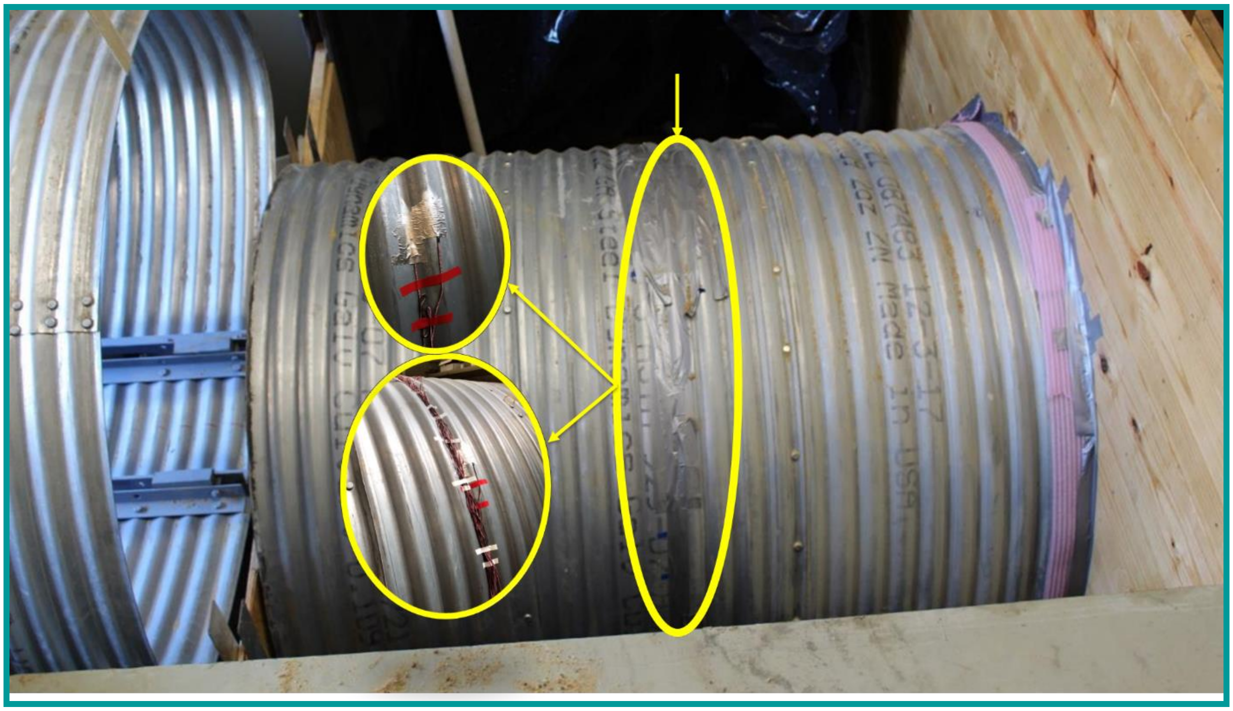

Figure A7: Physical Protection of Strain Gauges by Aluminum Tape.

Figure A8: Partition Walls Opening.

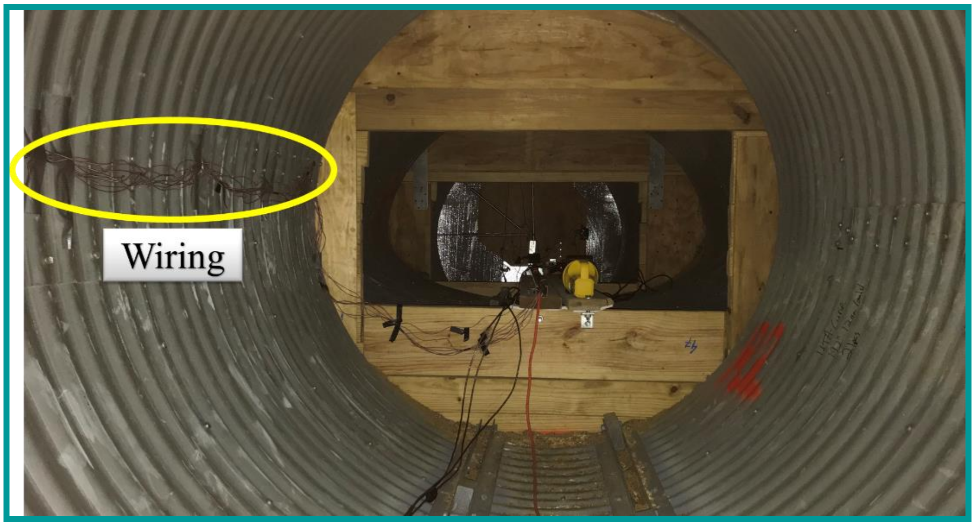

Figure A9: Partition Walls Opening and Wiring inside the CMPs.

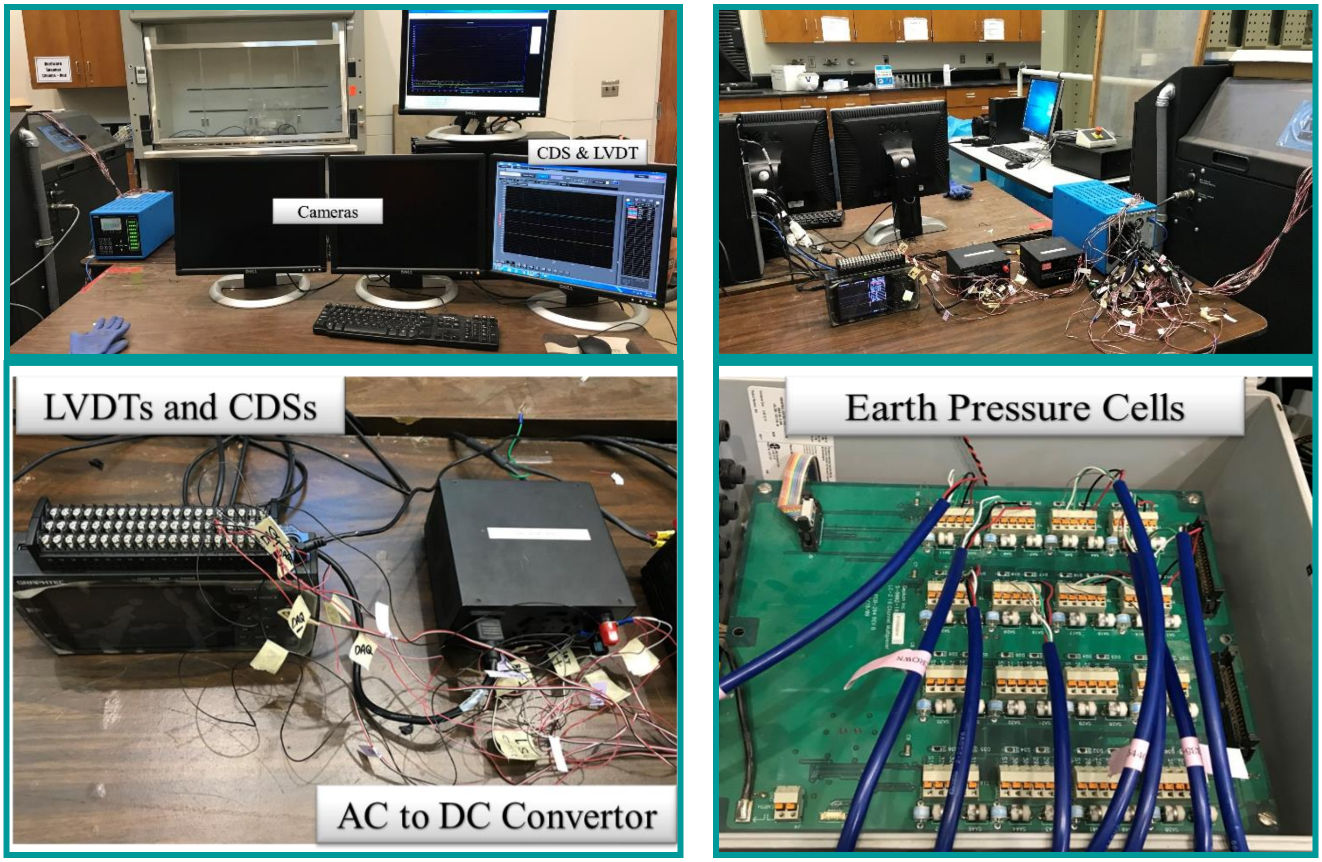

Figure A10: Data Acquisition System.

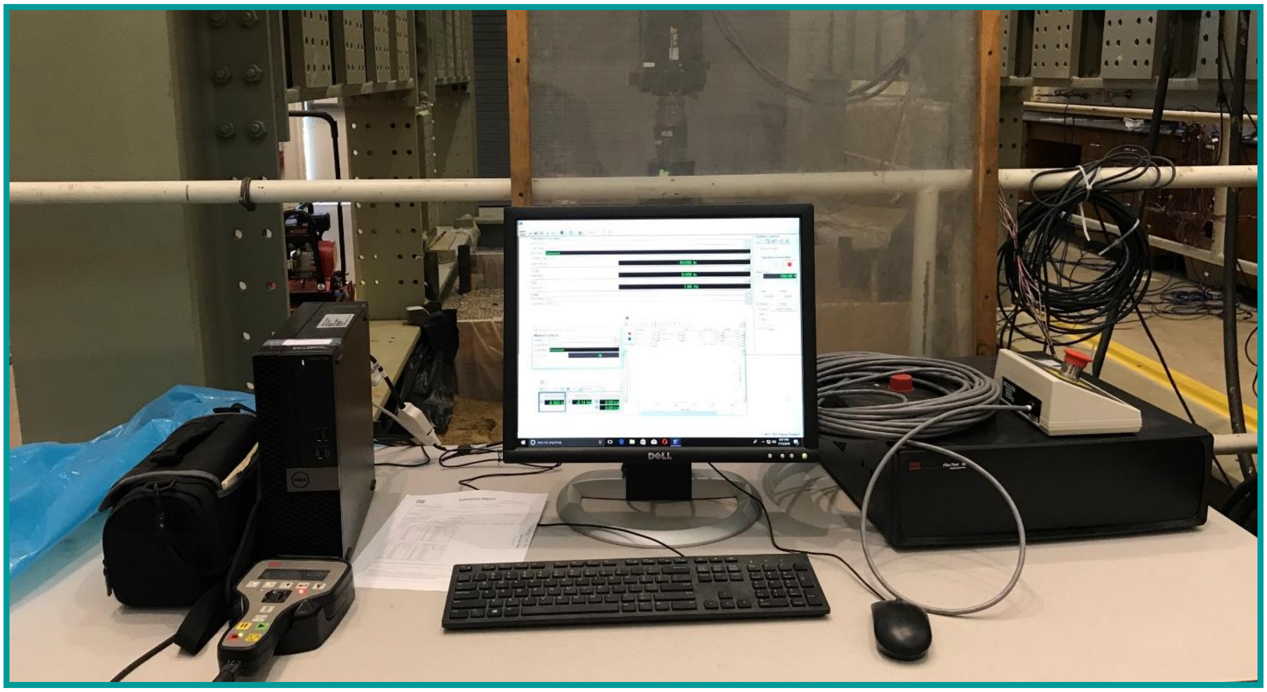

Figure A11: MTS Actuator Control Station.

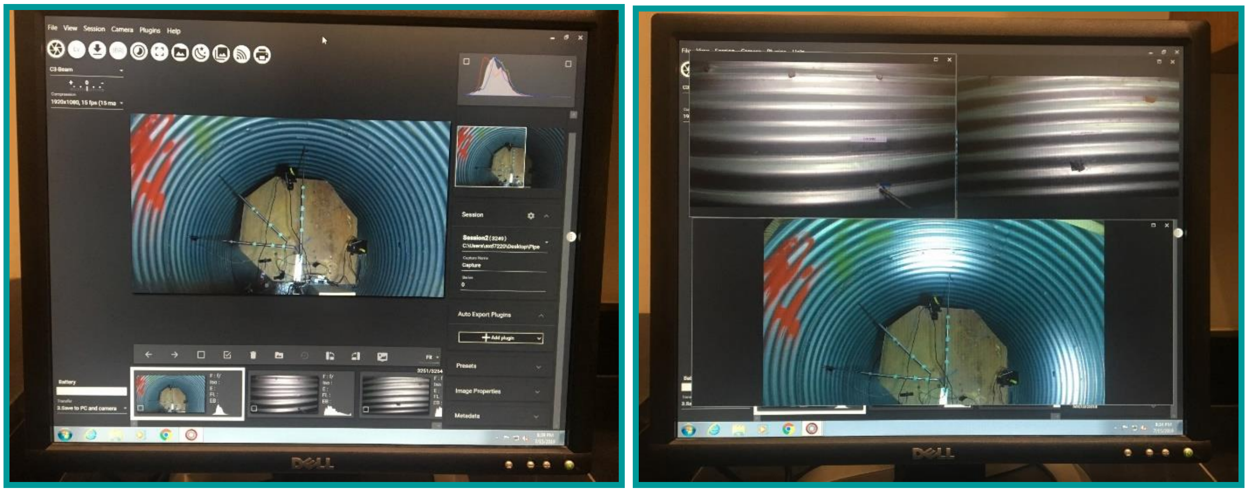

Figure A12: Live View from Cameras inside the CMP.

Results of 1st Control Test Setup: Intact 60 in. Circular CMP

60 in. Intact Circular CMP

The first test was conducted on a sample of 60 in. intact circular CMP. Load was applied using the hydraulic MTS actuator at a rate of 0.03 in./min and the system response was monitored using the instrumentation discussed in previous section.

Initially, the load required to induce the prescribed displacement (14 in. which is the stroke length of actuator) was high and a steep rise in load-displacement curve was seen; the top gravel layer started to resist the load. As the soil layers started to get to plastic state, the slope of the load-displacement curve started to reduce. At this state, a peak load of approximately 21 kips was seen beyond which, the bearing failure of soil cover occurred, and the load was transferred directly to the CMP. It resulted in second increase in slope of the load-displacement plot and an eventual second peak in the curve. The results of 1st control test setup (60 in. intact circular CMP) are illustrated in Figures 13 to 32.

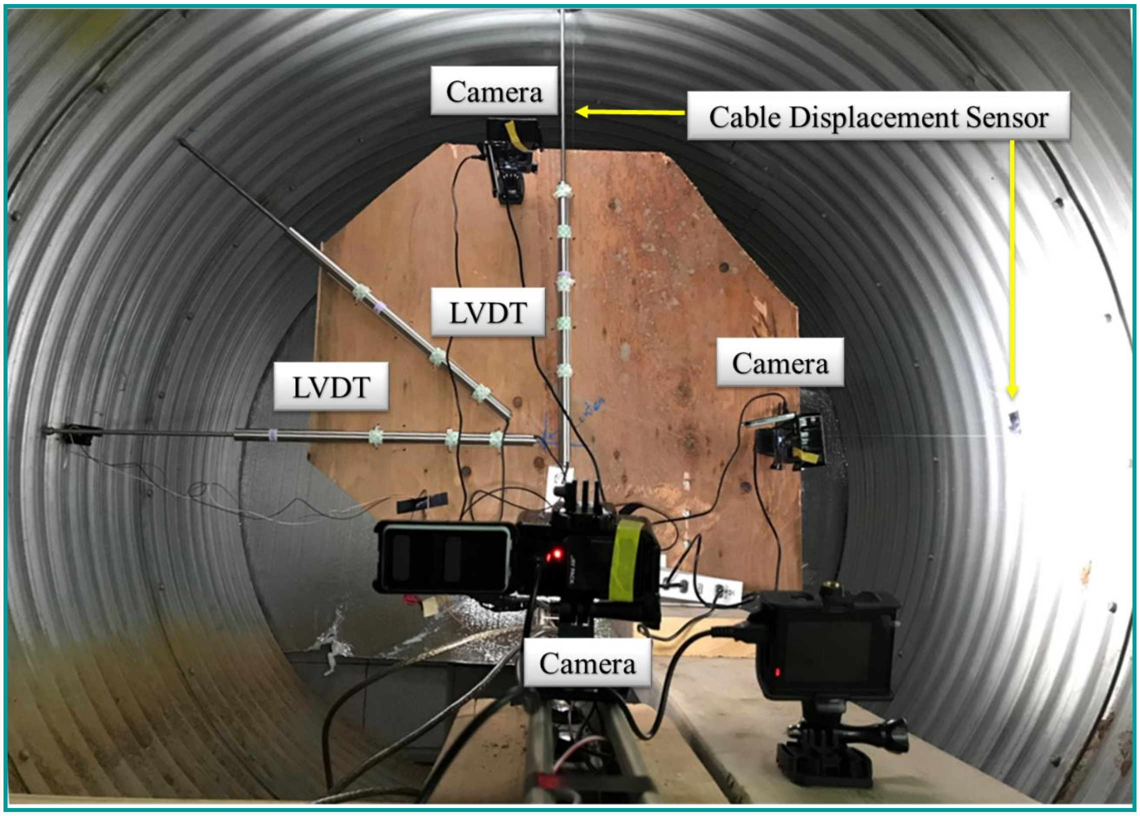

Figure A13: 1st Control Test Setup – 60 in. Intact Circular CMP – Inside Instrumentation

Figure A14: Load Pad (10 in. × 20 in.) Configuration on the soil at: (a) 16,650 lb. Service Load, (b) and (c) both at the Soil Failure Initiation.

Figure A15: Load Pad Penetration into the Soil due to the Soil Failure at the Ultimate Load.

Test Results

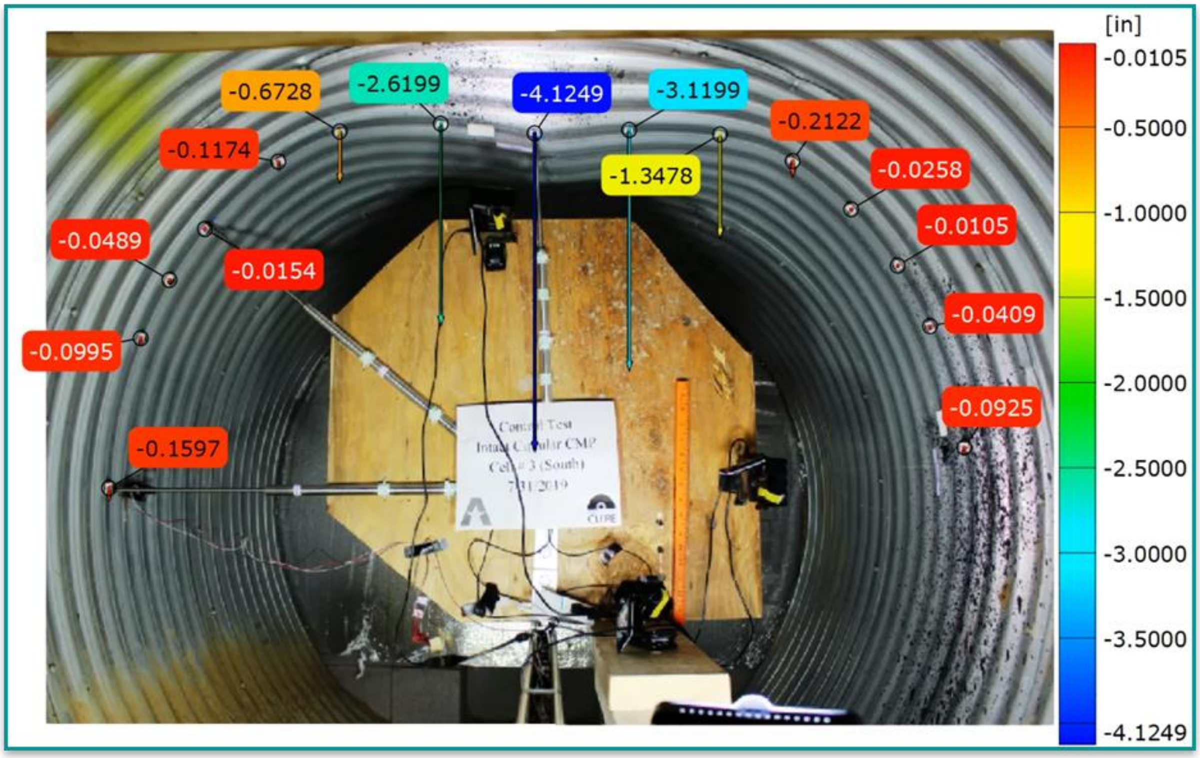

Figure A16: The Result of Digital Image Correlation (DIC) at the Ultimate Load

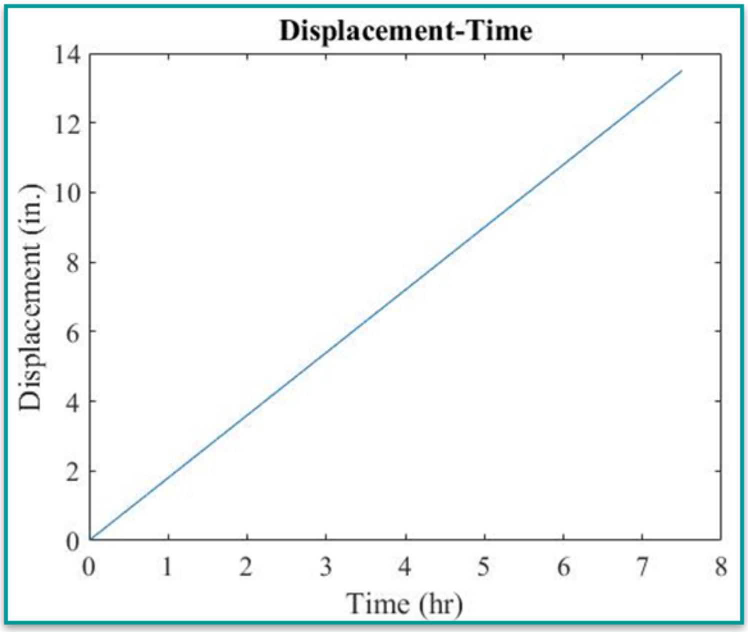

Figure A17: Load Rate of the Test (0.03 in./min) – Intact 60 in. Circular CMP

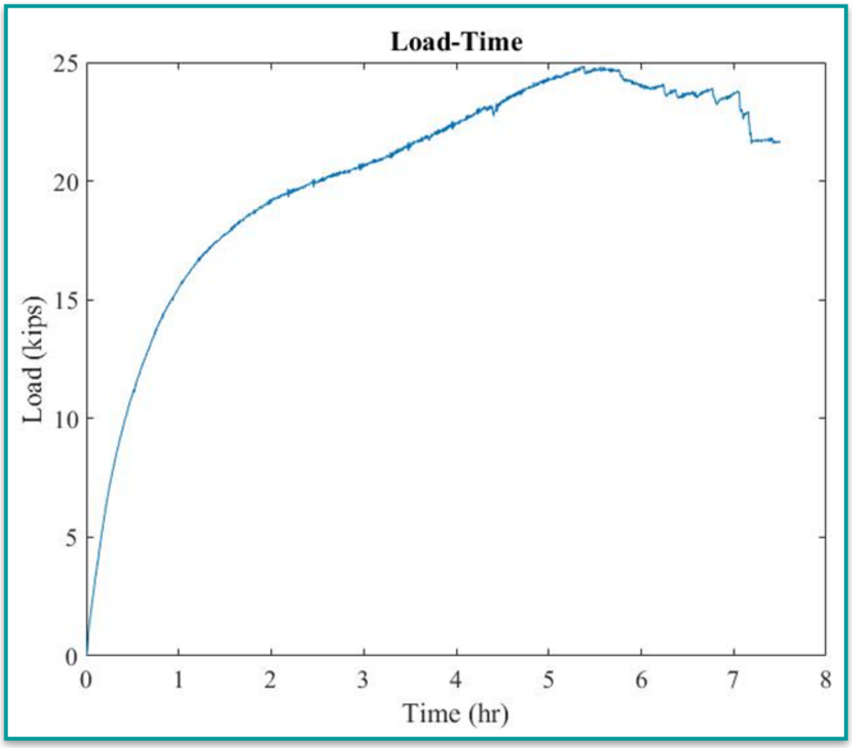

Figure A18: Load vs. Test Duration – Intact 60 in. Circular CMP

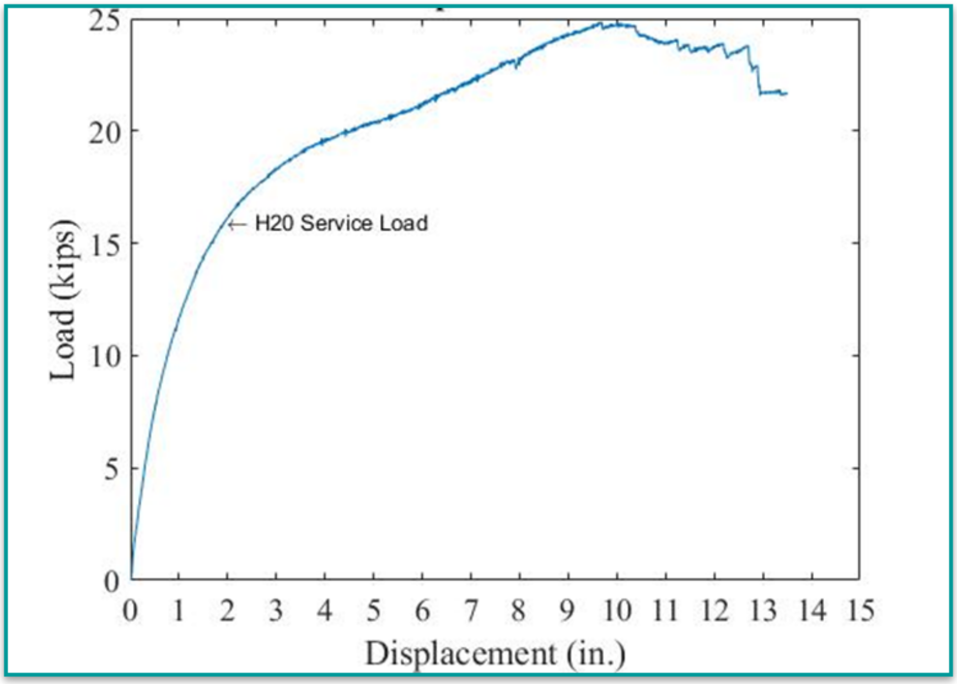

Figure A19: Load vs. Displacement on Soil Surface – Intact 60 in. Circular CMP

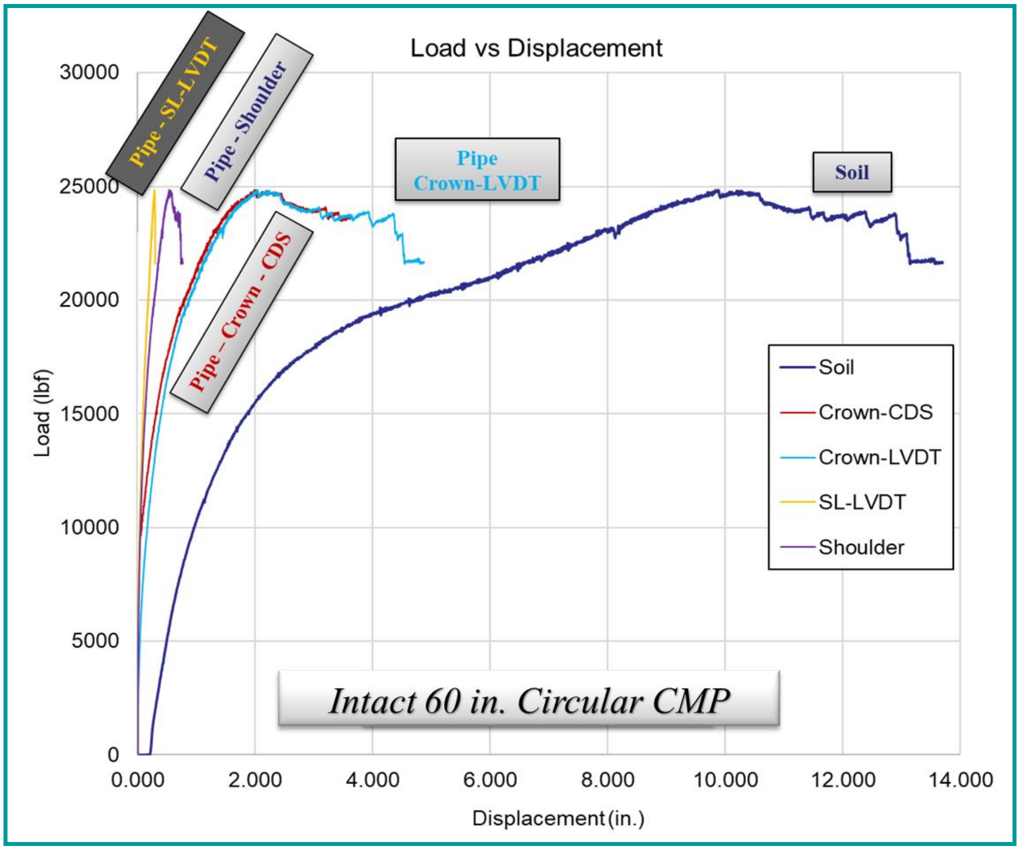

Figure A20: Load vs. Displacement – Intact 60 in. Circular CMP

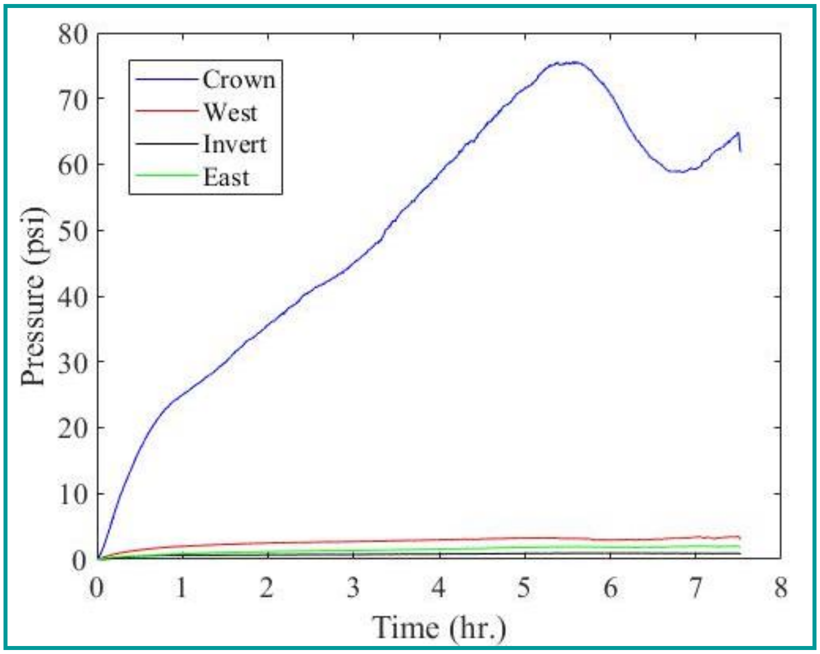

Figure A21: Earth Pressure Cells Results around the CMP vs. Time – Intact 60 in. Circular CMP

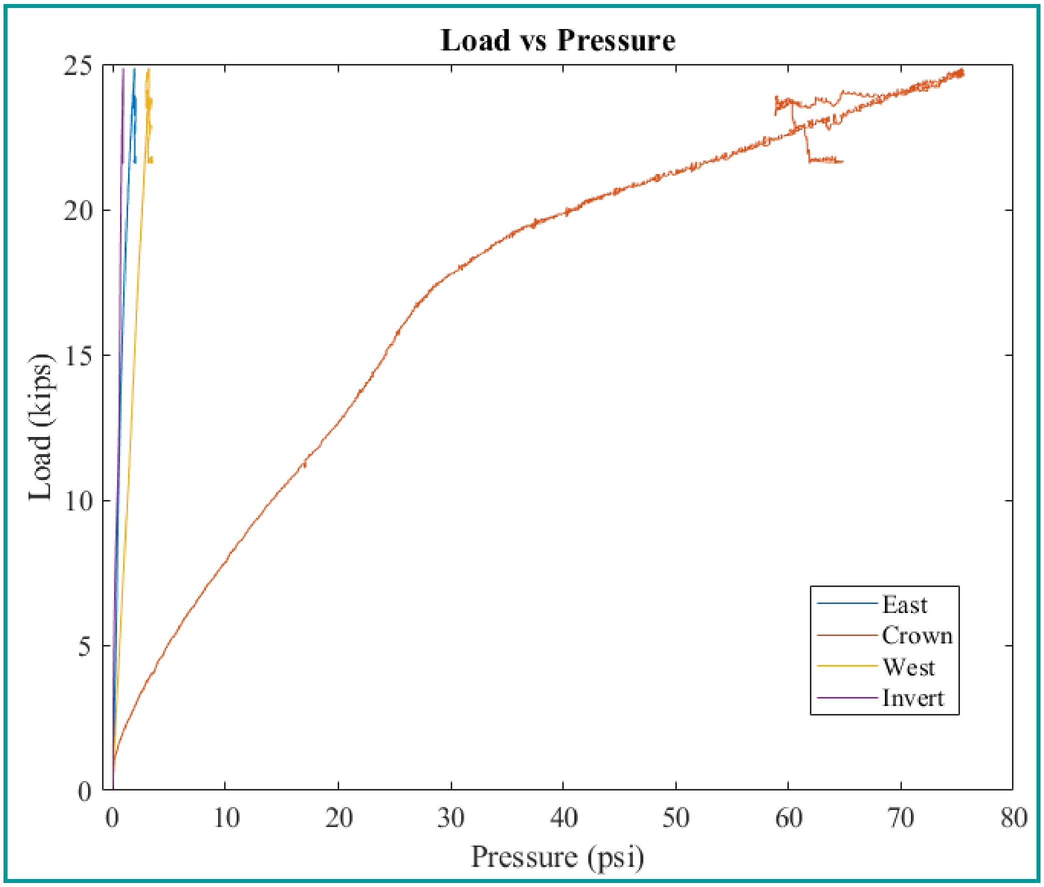

Figure A22: Vertical Load vs. Pressure around the Pipe – Intact 60 in. Circular CMP.

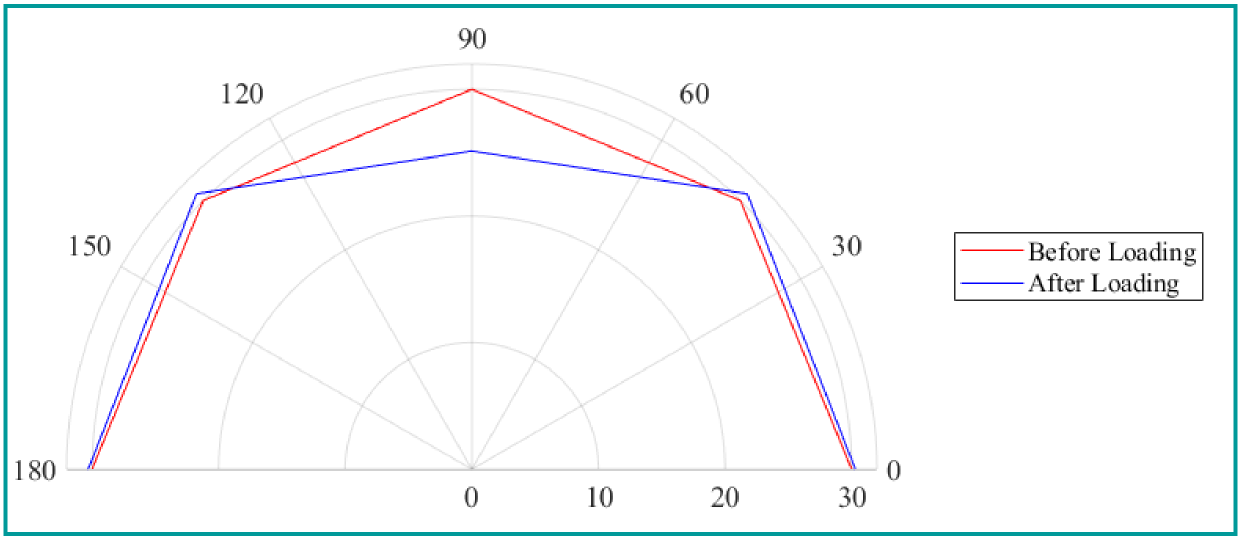

Figure A23: Pipe Profile at the end of the Test vis LVDTs – Intact 60 in. Circular CMP.

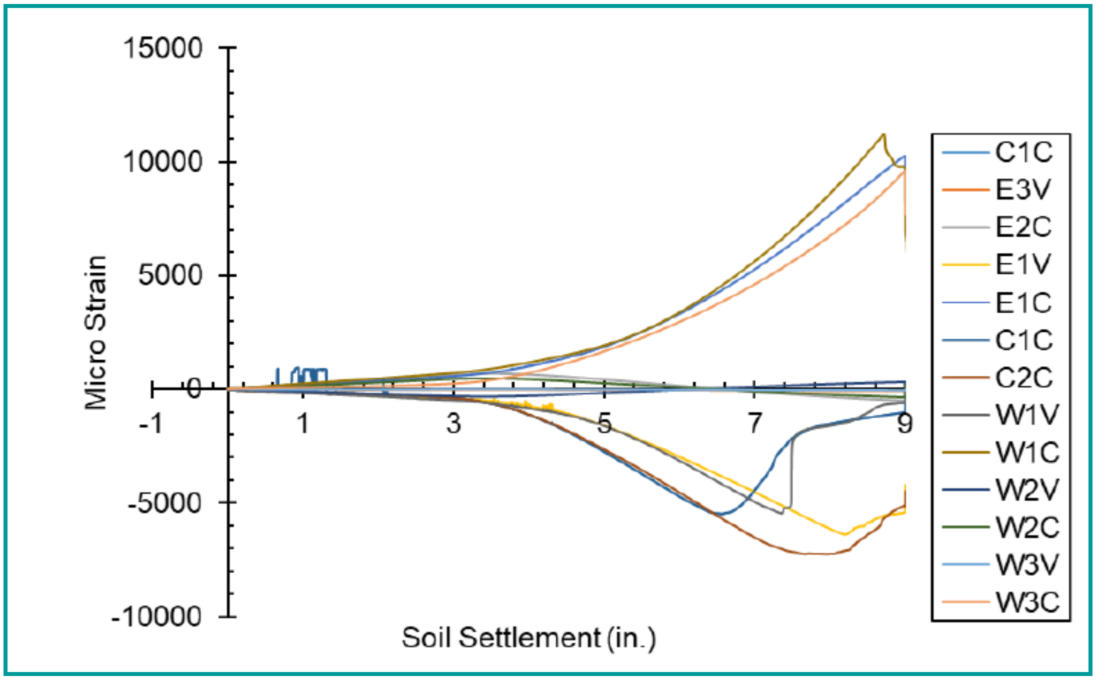

Figure A24: Strain Distribution Circumferentially around the CMP (Middle Cross Section) – Intact 60 in. Circular CMP.

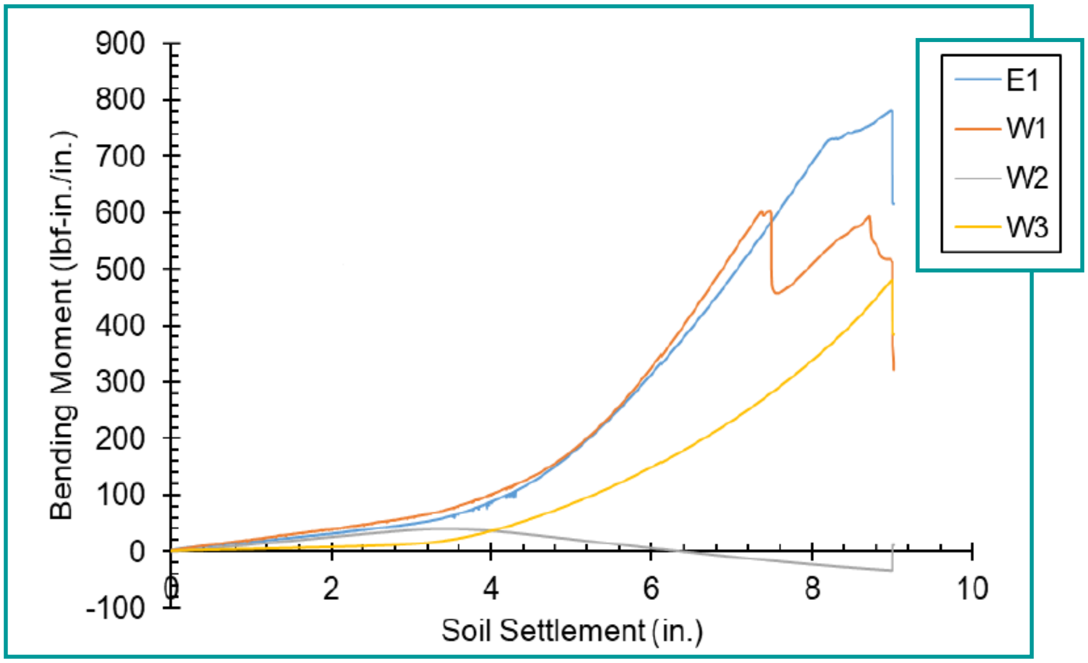

Figure A25: Circumferential Bending Moment (Middle Cross Section) – Intact 60 in. Circular CMP.

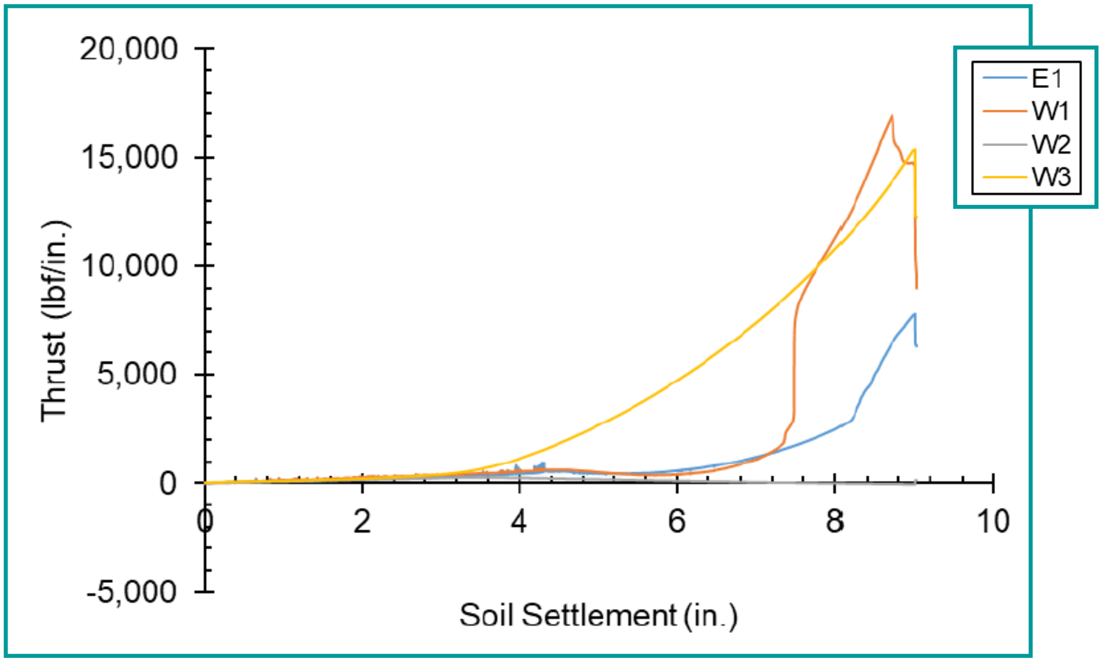

Figure A26: Circumferential Thrust Forces (Middle Cross Section) – Intact 60 in. Circular CMP.

Finite Element Modeling (FEM) Results vs. Soil Box Testing Results

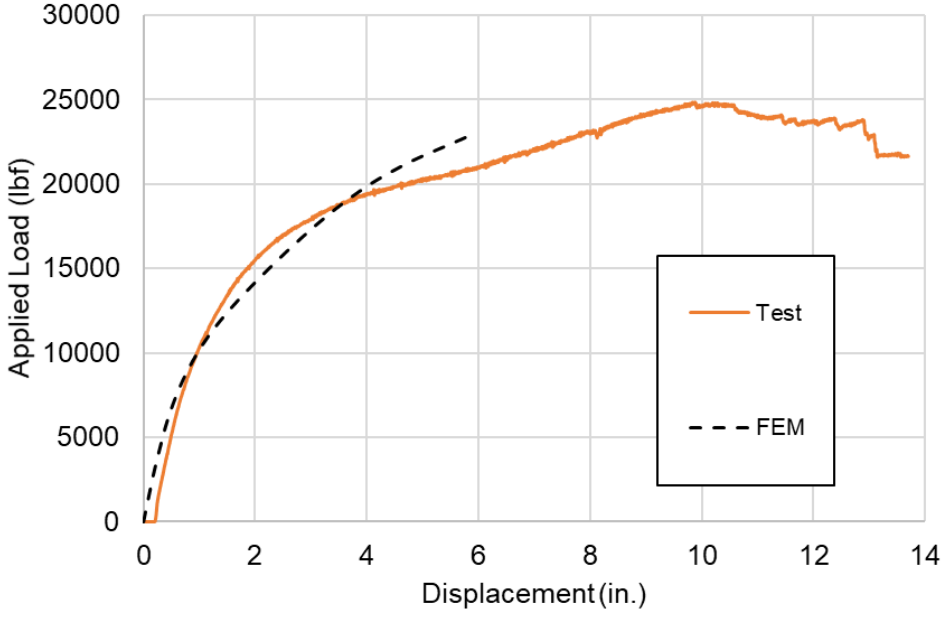

Figure A27: Load vs. Displacement of Soil, Comparison of FEM and Test Results – Intact 60 in. Circular CMP.

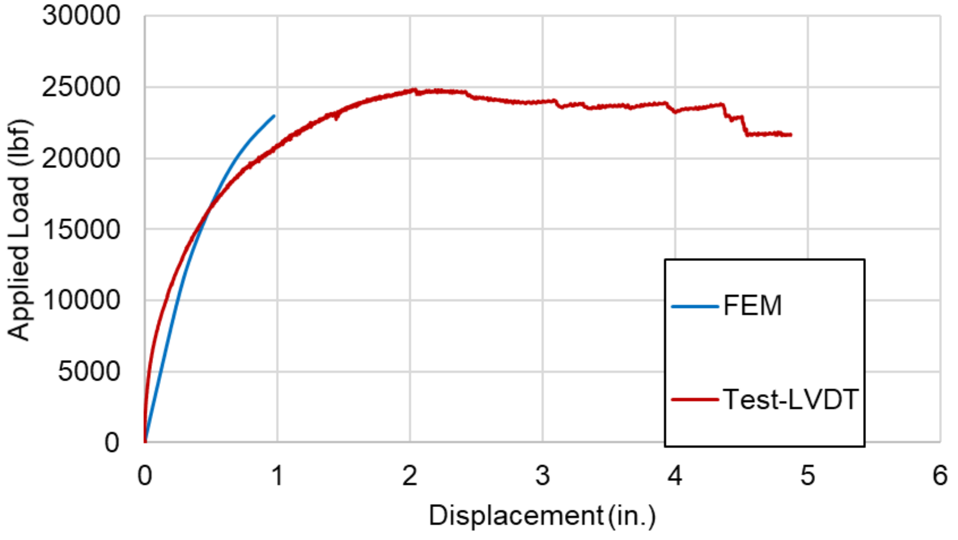

Figure A28: Load vs. Displacement of CMP, Comparison of FEM and Test Results – Intact 60 in. Circular CMP.

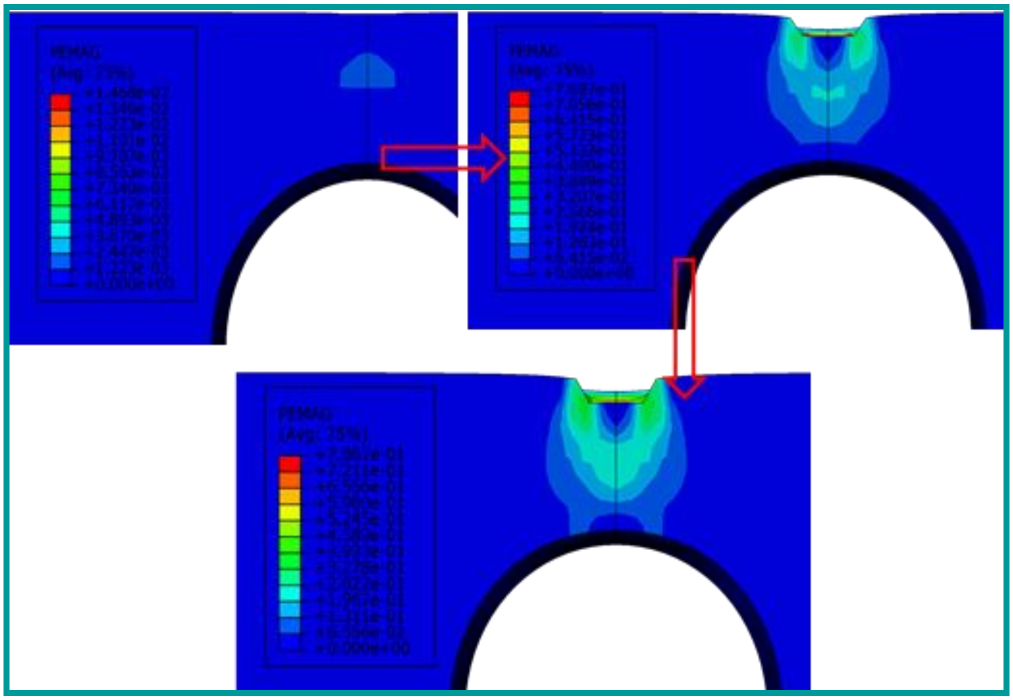

Figure A29: FEM Result for Stress Distribution in the Soil at Different Stages of Loading – Intact 60 in. Circular CMP.

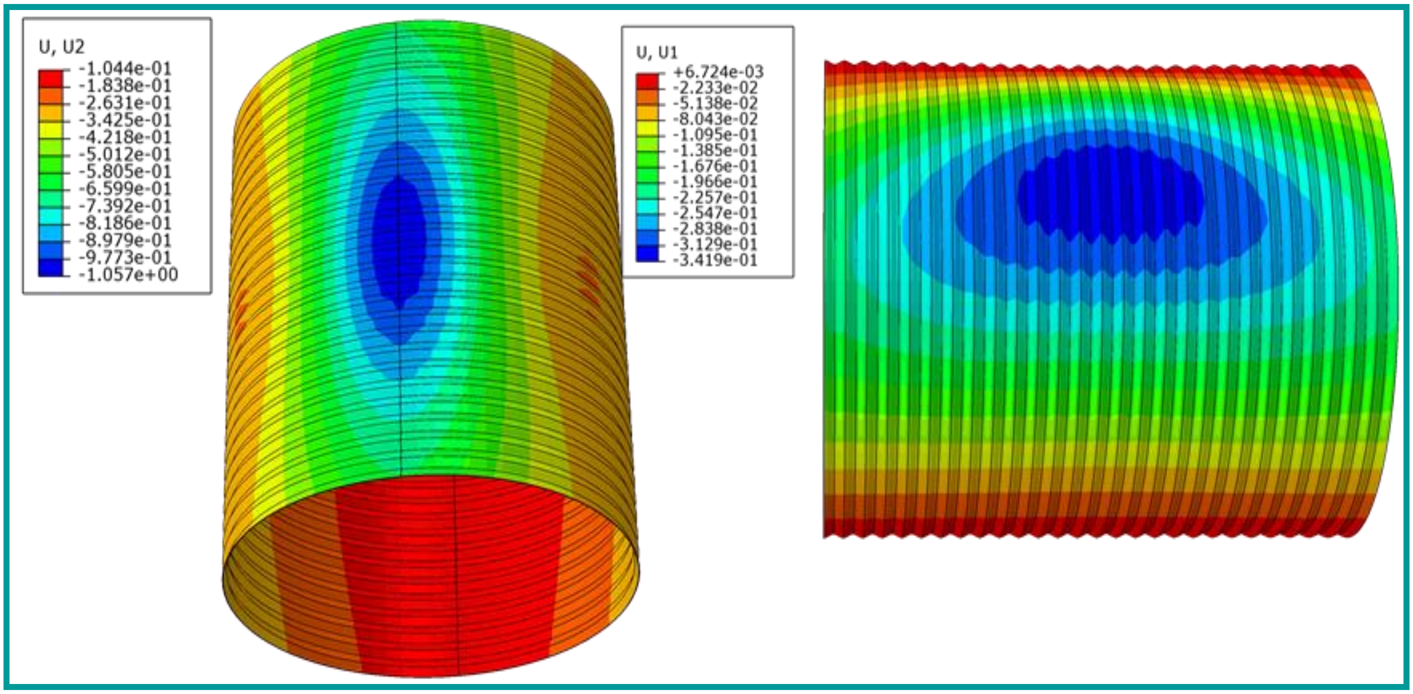

Figure A30: FEM Result for Stress Distribution – Intact 60 in. Circular CMP.

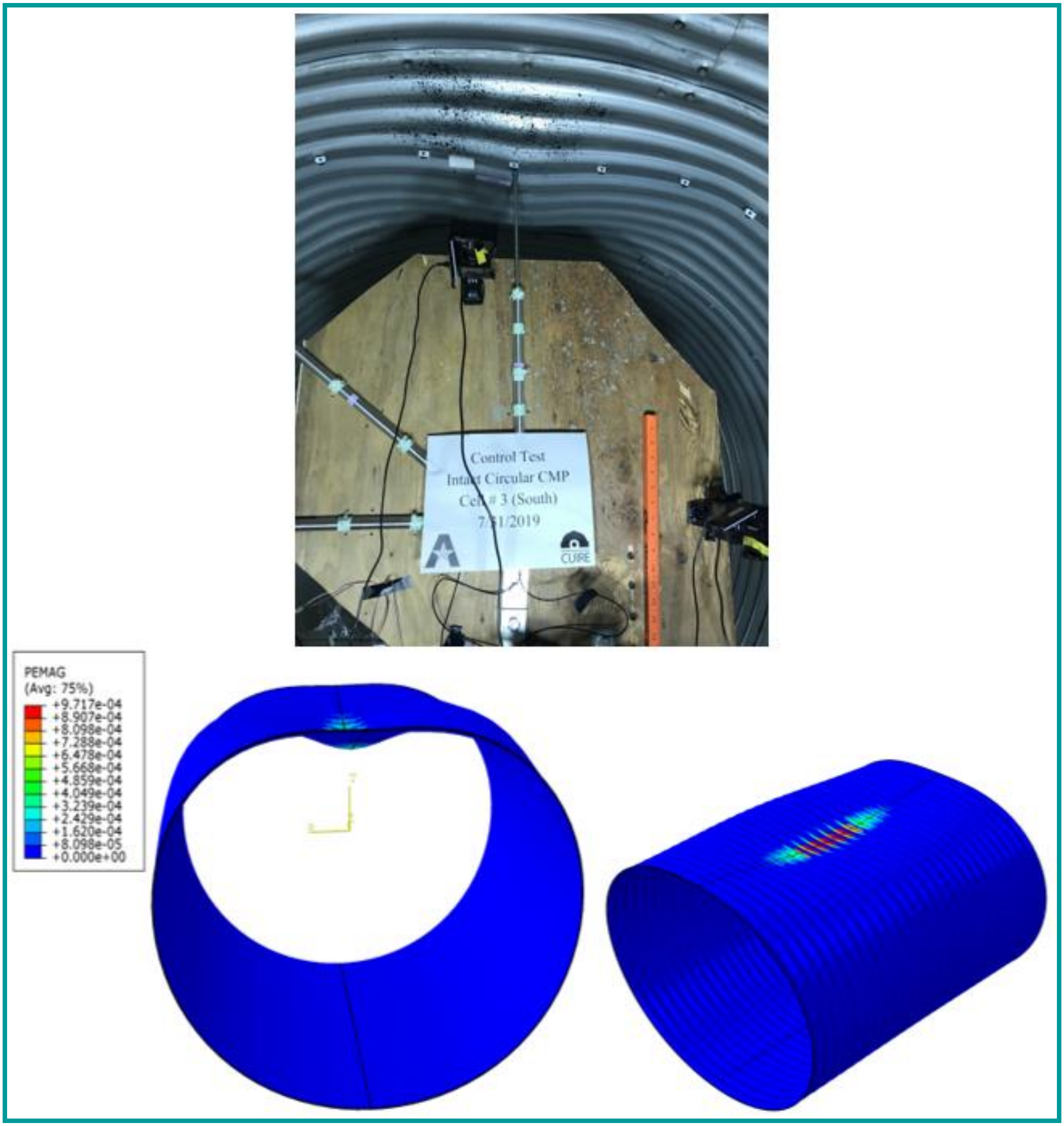

Figure A31: FEM result for pipe failure mode verification – Intact 60 in. Circular CMP.

Figure A32: Pipe Exhumation and Storage – Intact 60 in. Circular CMP.

Results of 2nd Control Test Setup: Intact 60 in. Circular CMP

47 in. × 71 in. Invert-cut Arch CMP

The second test was conducted on a sample of 47 in. × 71 in. invert-cut arch CMP. Load was applied using the hydraulic MTS actuator at a rate of 0.03 in./min and the system response was monitored using the instrumentation discussed in previous section. The results of 2nd control test setup (47 in. × 71 in. invert-cut arch CMP) are illustrated in Figures 33 to 46.

Figure A33: Initial Measurement and Instrumentation Installation for the invert-cut 47 in. × 71 in. Arch CMP.

Figure A34: Invert-cut Detachment of 47 in. × 71 in. Arch CMP.

Test Results

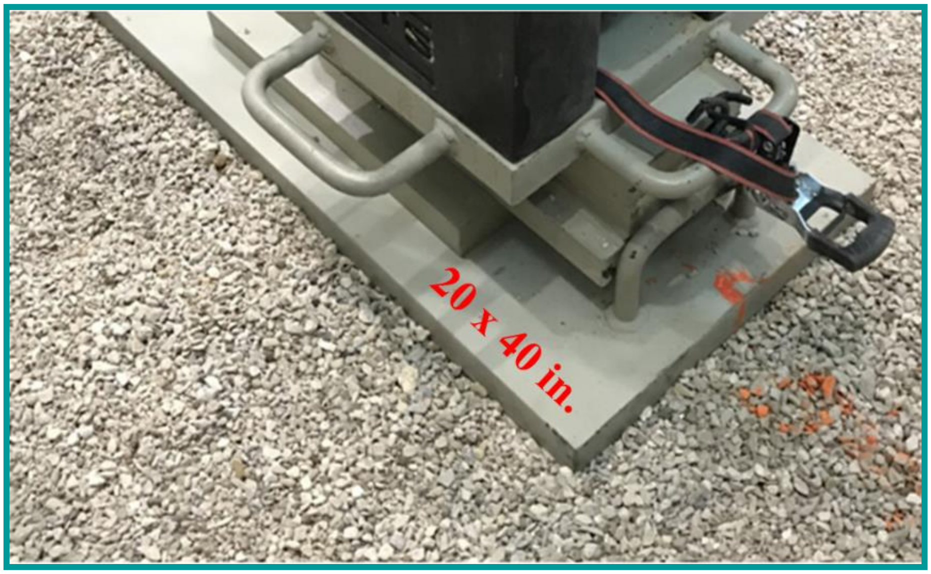

Figure A35: Load Pad Configuration on Soil at 16,000 lb. – 47 in. ⨯ 71 in. Invert-cut Arch CMP.

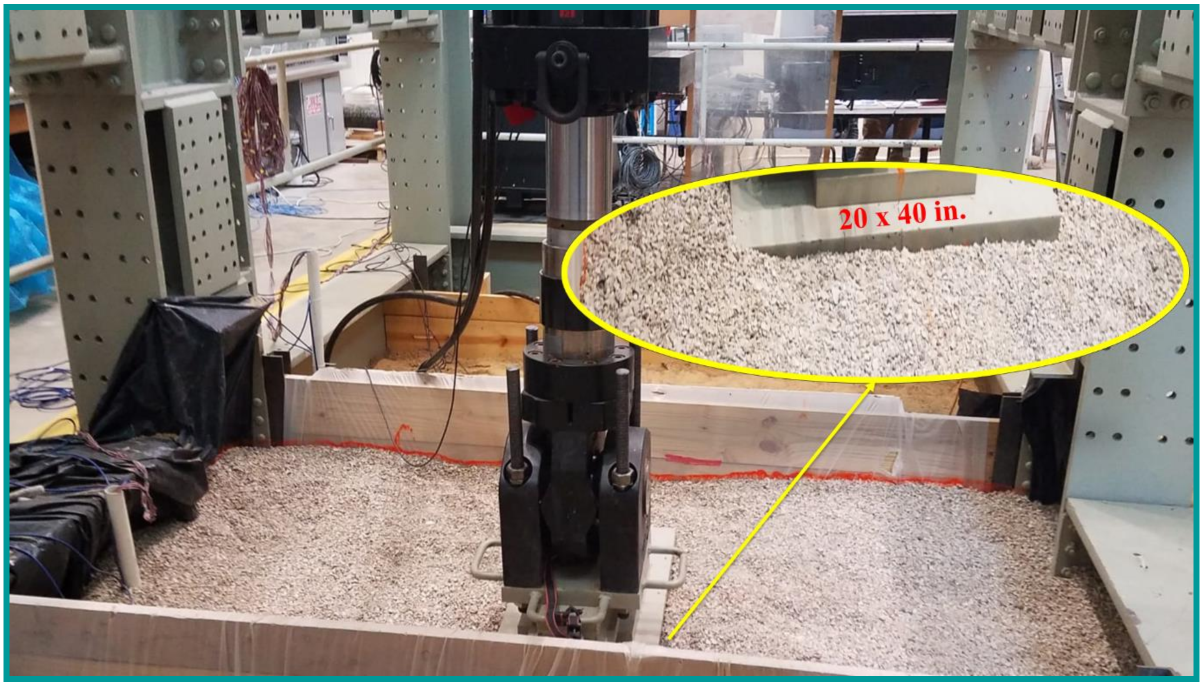

Figure A36: Load Pad Configuration on Soil at Failure – 47 in. ⨯ 71 in. Invert-cut Arch CMP.

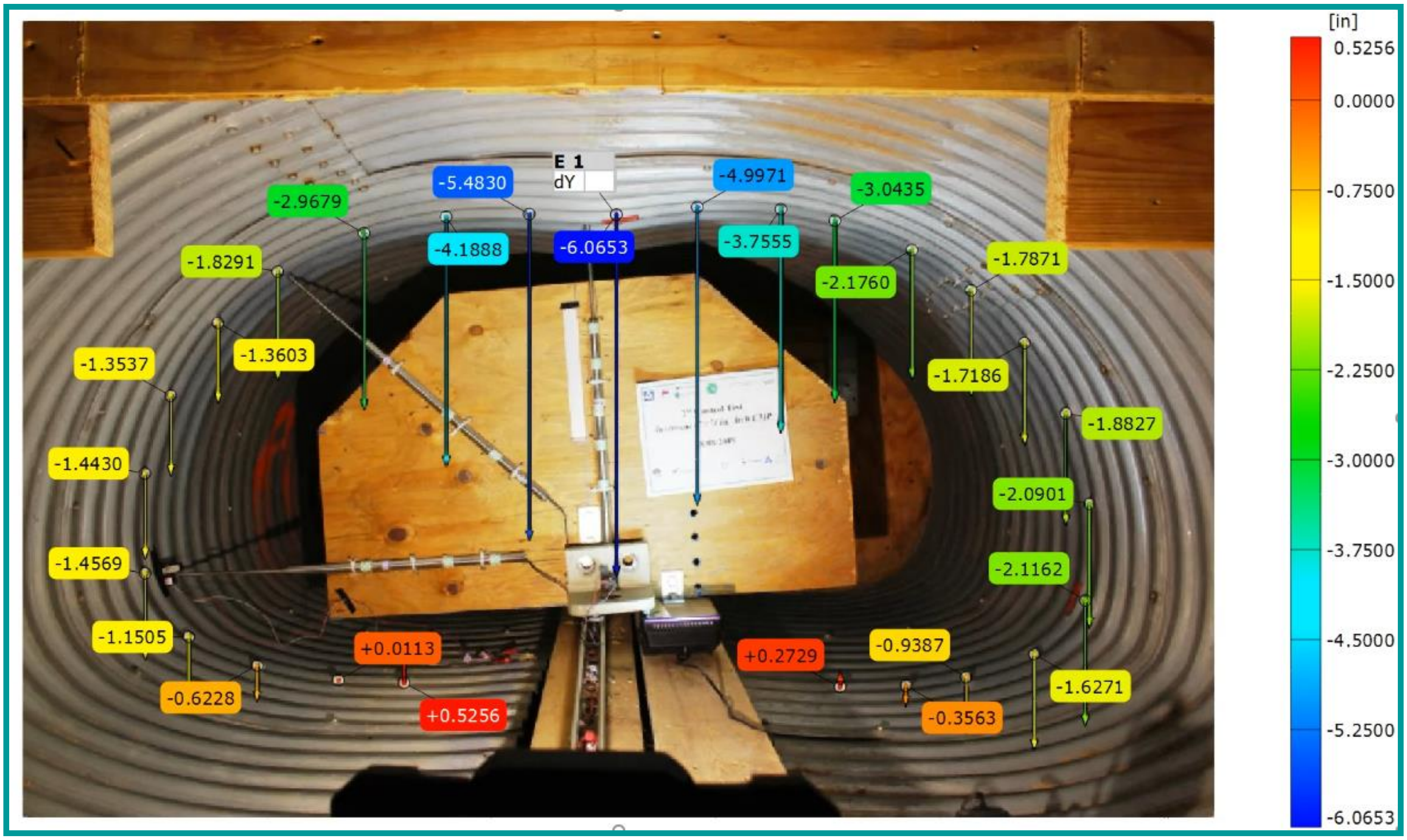

Figure A37: Result of DIC Measurement at the end of the Test – 47 in. ⨯ 71 in. Invert-cut Arch CMP.

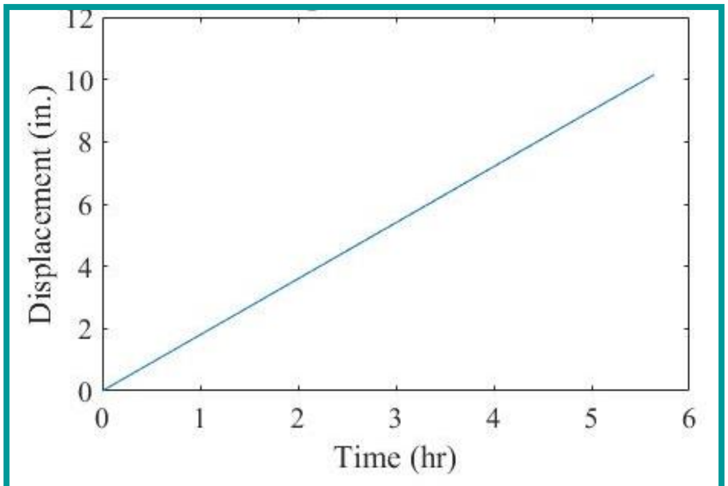

Figure A38. Test Load Rate (0.03 in./min) – 47 in. ⨯ 71 in. Invert-cut Arch CMP.

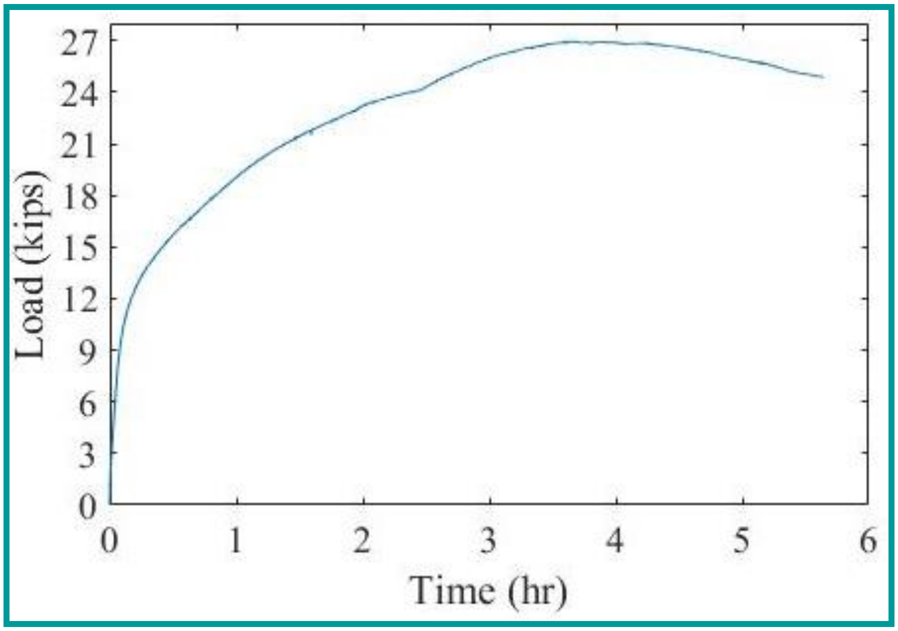

Figure A39: Load vs. Time for the Soil Surface – 47 in. × 71 in. Invert-cut Arch CMP.

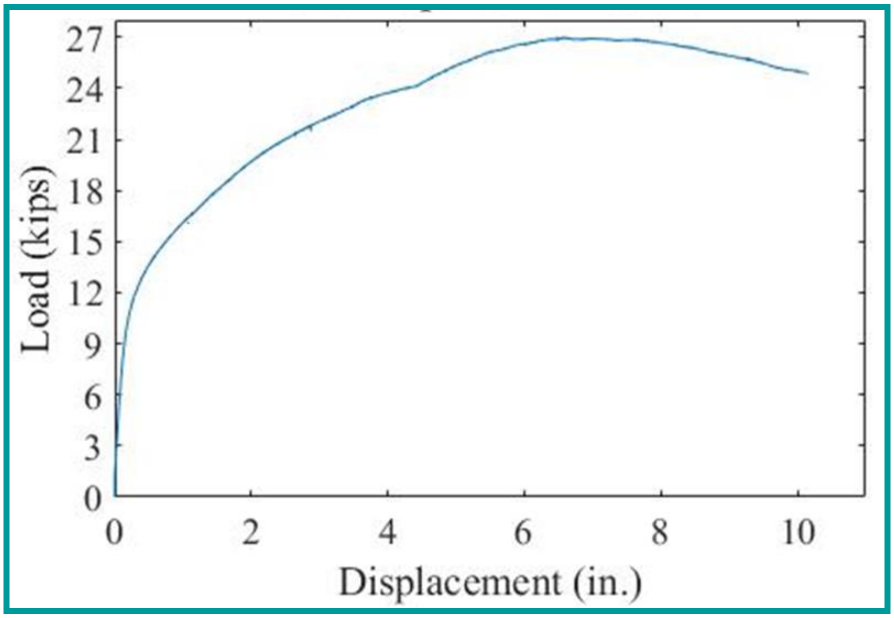

Figure A40: Load vs. Displacement of the Soil Surface – 47 in. × 71 in. Invert-cut Arch CMP.

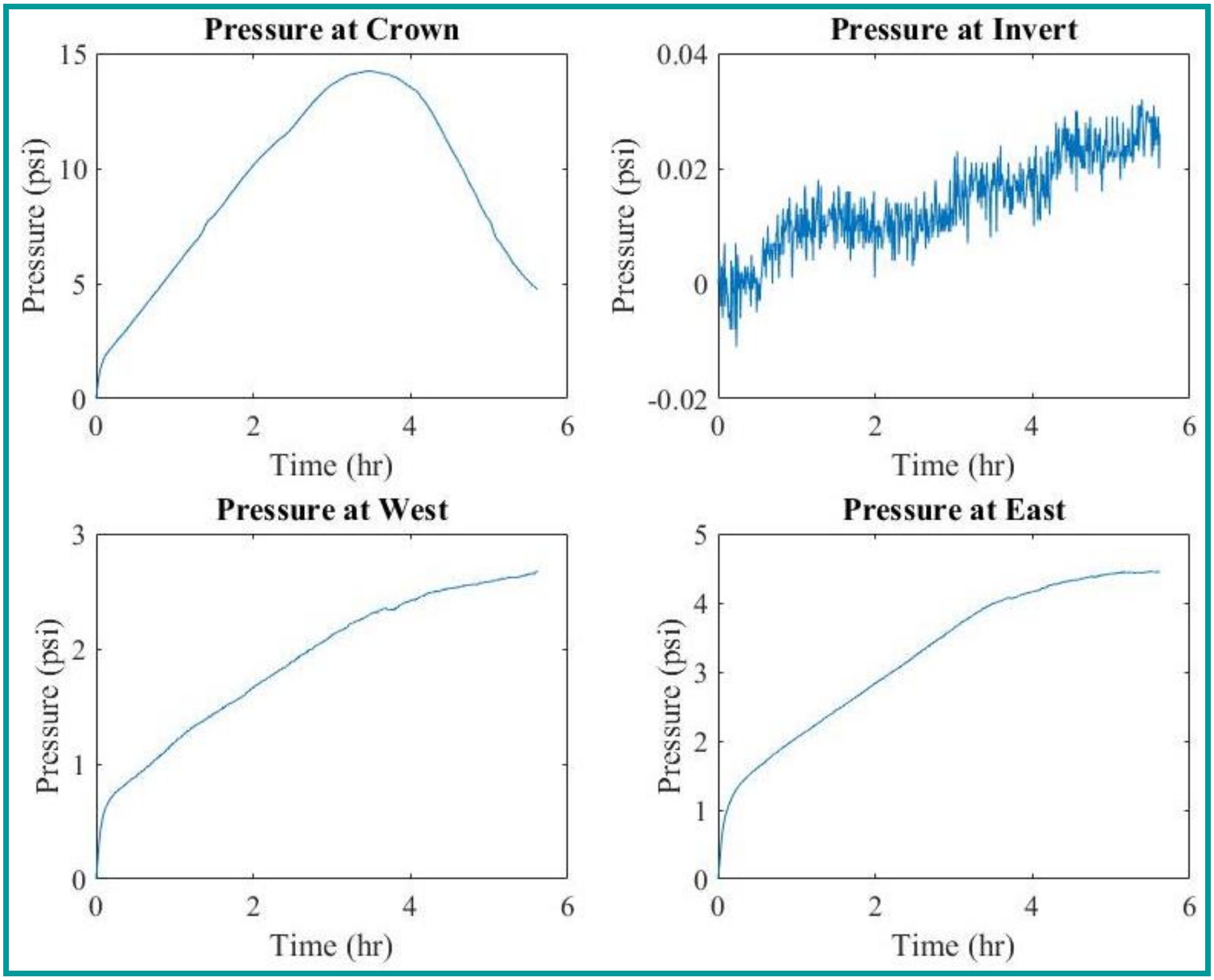

Figure A41: Results of Earth Pressure Cells around the CMP – 47 in. × 71 in. Invert-cut Arch CMP.

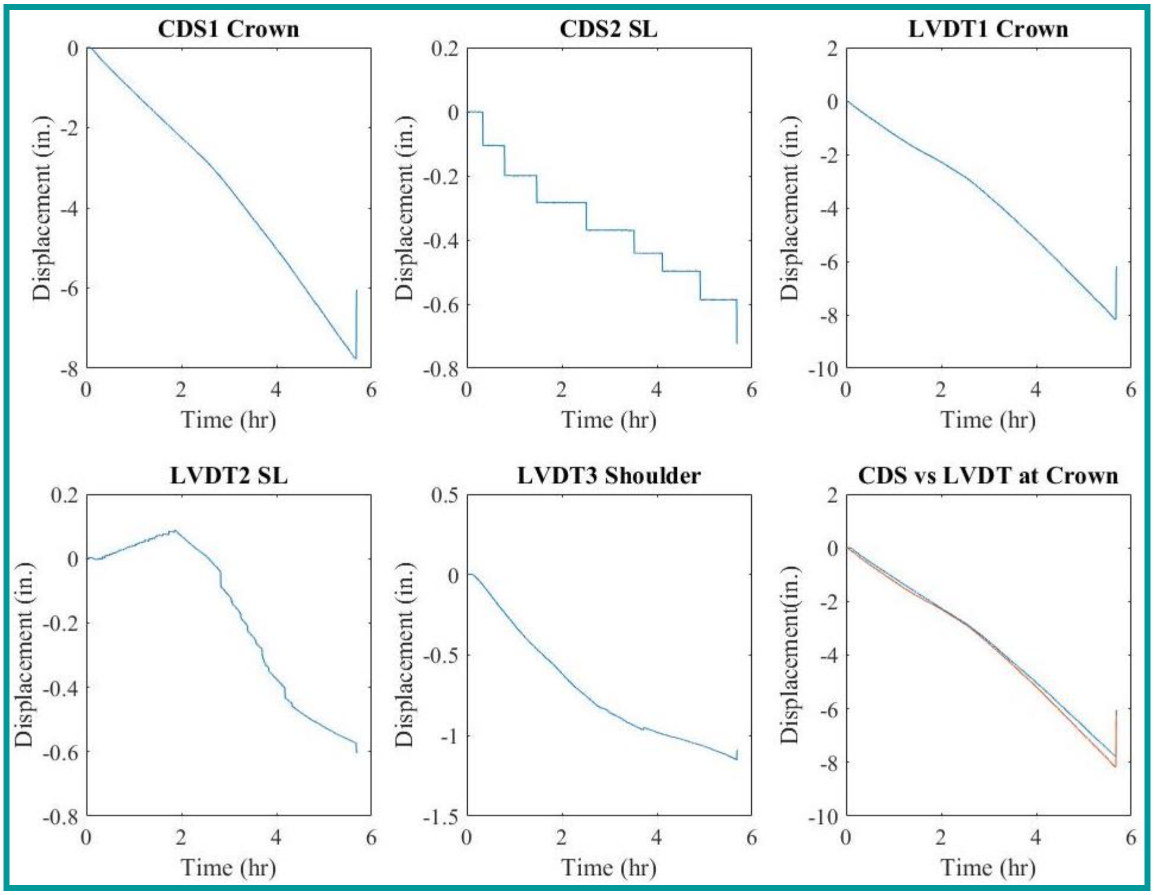

Figure A42: Results of LVDTs and CDSs at Different Locations – 47 in. ⨯ 71 in. Invert-cut Arch CMP (Note: CDS for springline did not work properly).

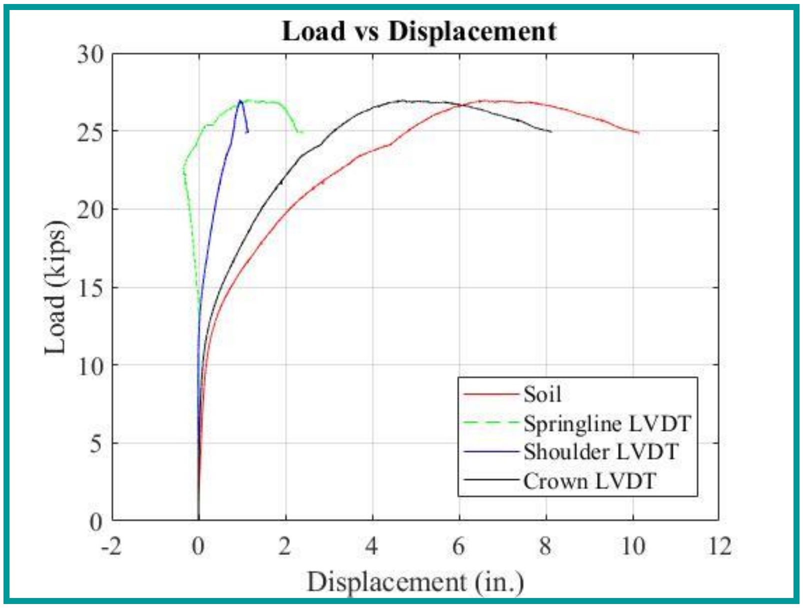

Figure A43: Load vs. Displacement – 47 in. ⨯ 71 in. Invert-cut Arch CMP.

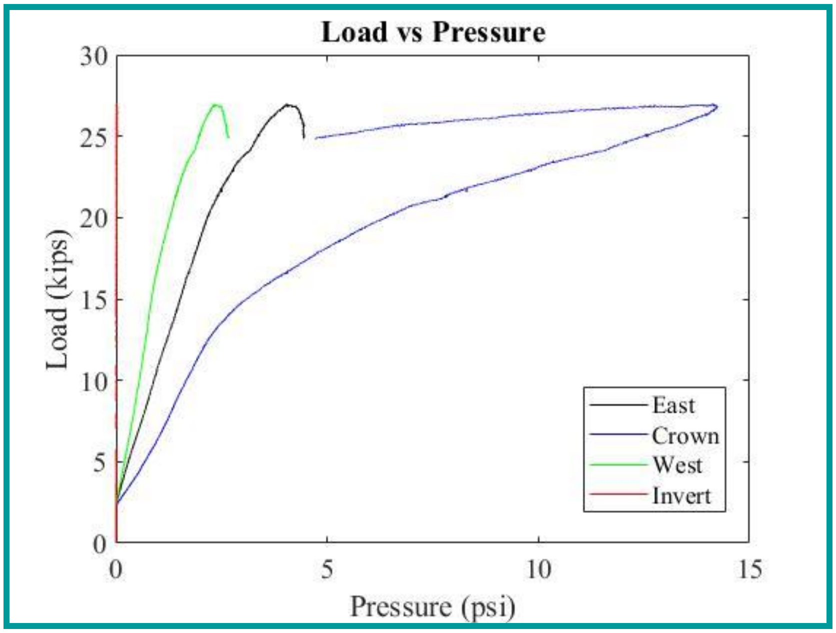

Figure A44: Vertical Load vs. Pressure around the CMP – 47 in. × 71 in. Invert-cut Arch CMP.

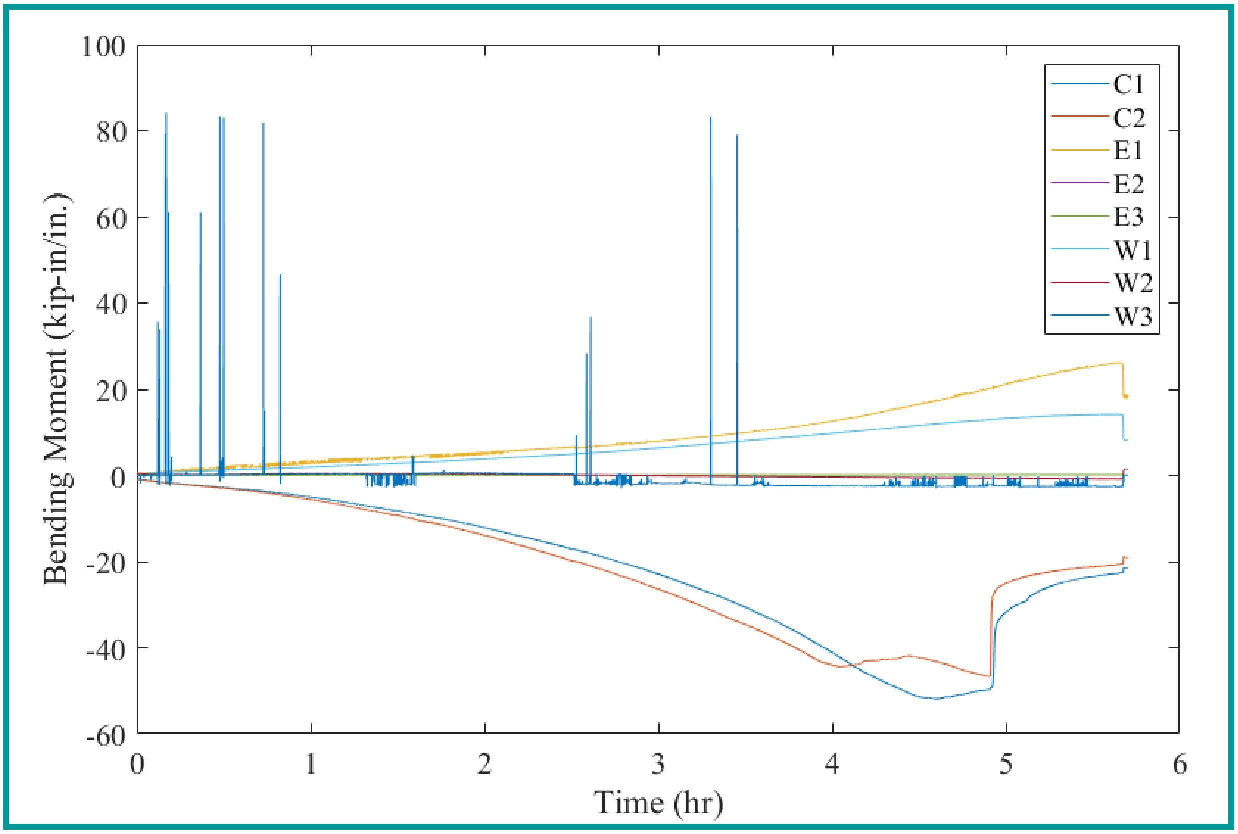

Figure A45: Circumferential Bending Moment (Middle Cross Section) – 47 in. × 71 in. Invert-cut Arch CMP.

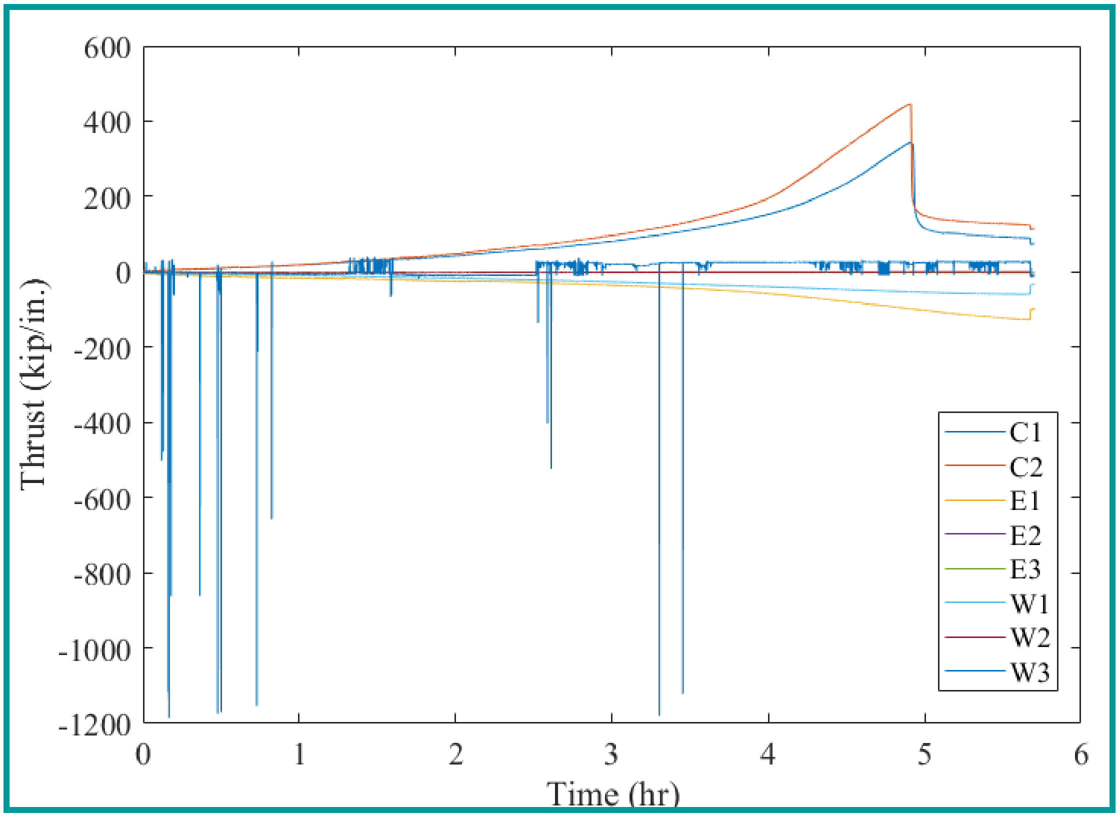

Figure A46: Circumferential Thrust Forces (Middle Cross Section) – 47 in. × 71 in. Invert-cut Arch CMP. (Note: the sensor W3 is damaged due to the large displacement of the pipe).

Results of 3rd Control Test Setup: Invert-cut 60 in. Circular CMP

60 in. Invert-cut Circular CMP

The third test was conducted on a sample of 60 in. invert-cut circular CMP. Load was applied using the hydraulic MTS actuator at a rate of 0.03 in./min and the system response was monitored using the instrumentation discussed in previous section. The results of 3rd control test setup (60 in. invert-cut circular CMP) are illustrated in Figures 47 to 63.

Test Results

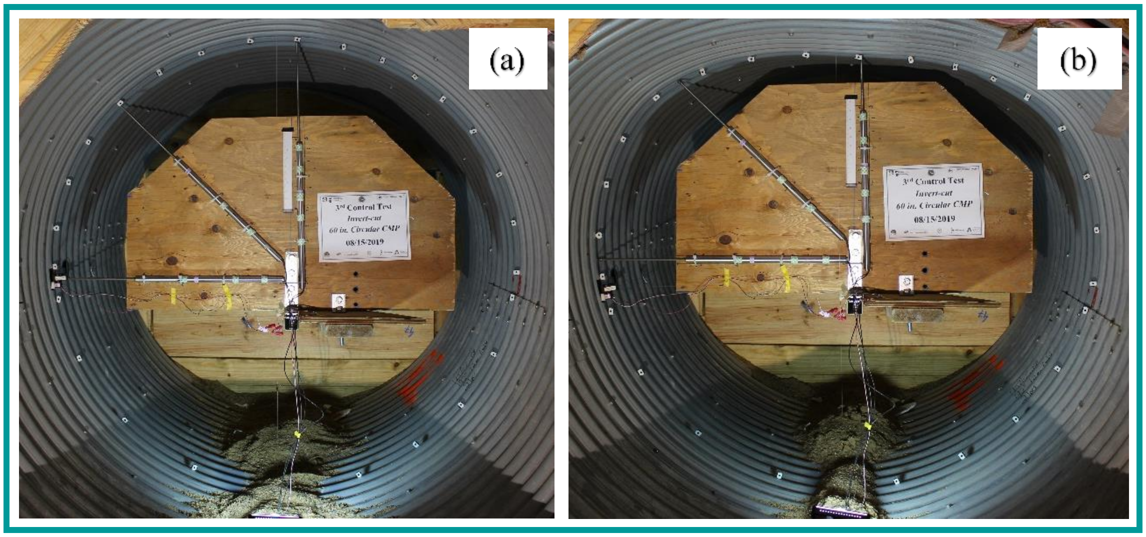

Figure A47: Circular Invert-cut: (a) before Loading, (b) after Loading – 60 in. Invert-cut Circular CMP.

Figure A48: Invert Section of the CMP after Test (the invert gap is completely closed) – 60 in. Invert-cut Circular CMP.

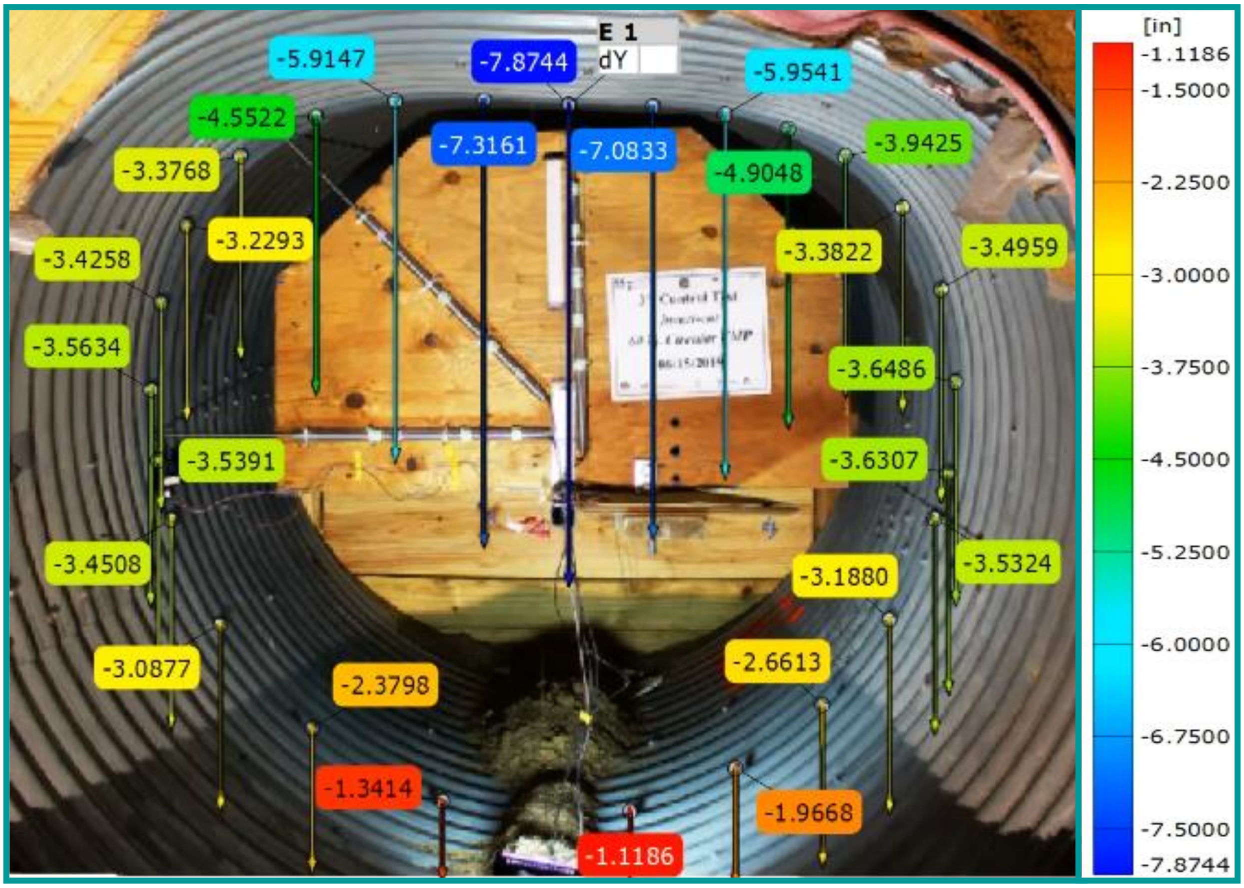

Figure A49: Result of DIC Measurement at the End of the Test – 60 in. Invert-cut Circular CMP.

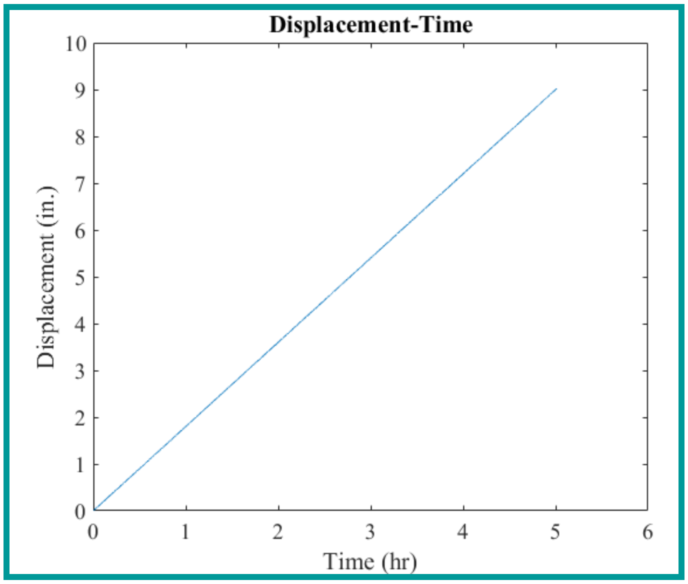

Figure A50: Load Rate of the Test (0.03 in./min) – 60 in. Invert-cut Circular CMP.

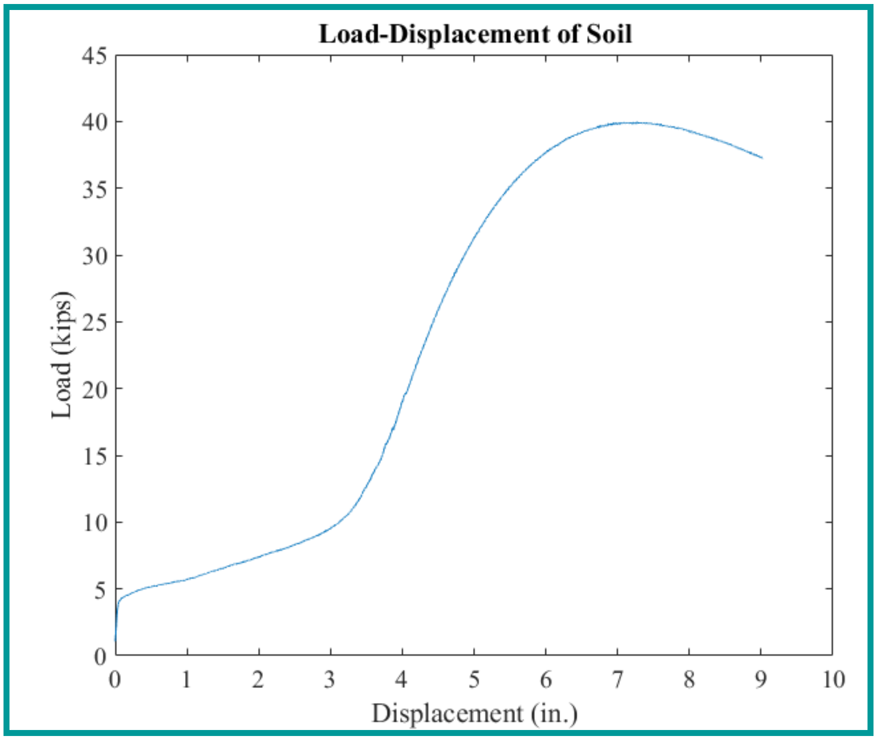

Figure A51: Load vs. Displacement on the Soil Surface – 60 in. Invert-cut Circular CMP.

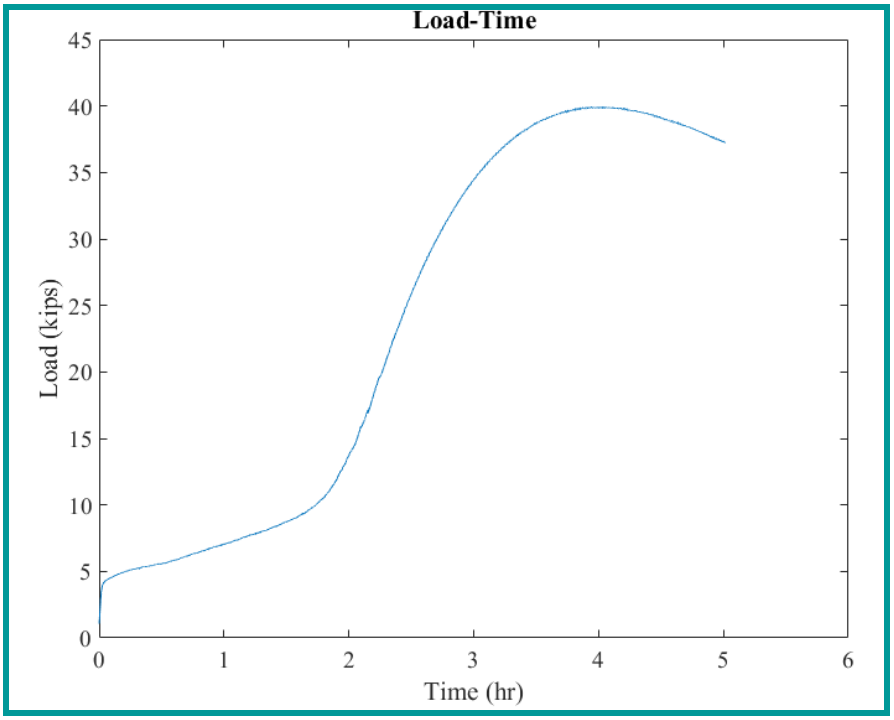

Figure A52: Load vs. Time for the Soil Surface – 60 in. Invert-cut Circular CMP.

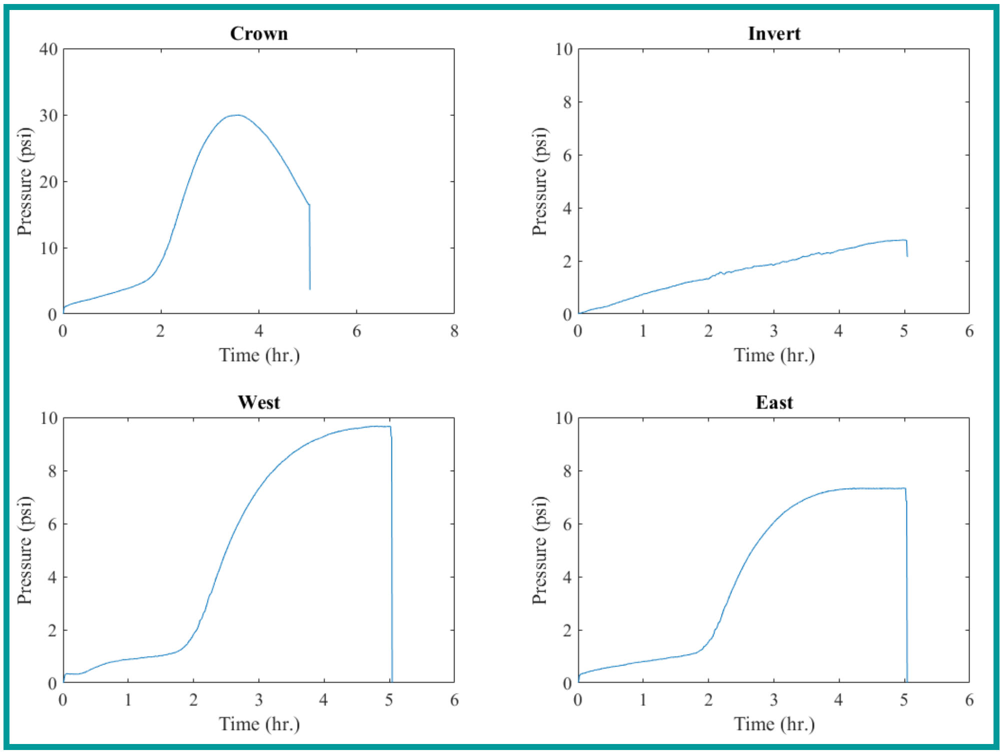

Figure A53: Earth Pressure Cells' Results around the CMP – 60 in. Invert-cut Circular CMP.

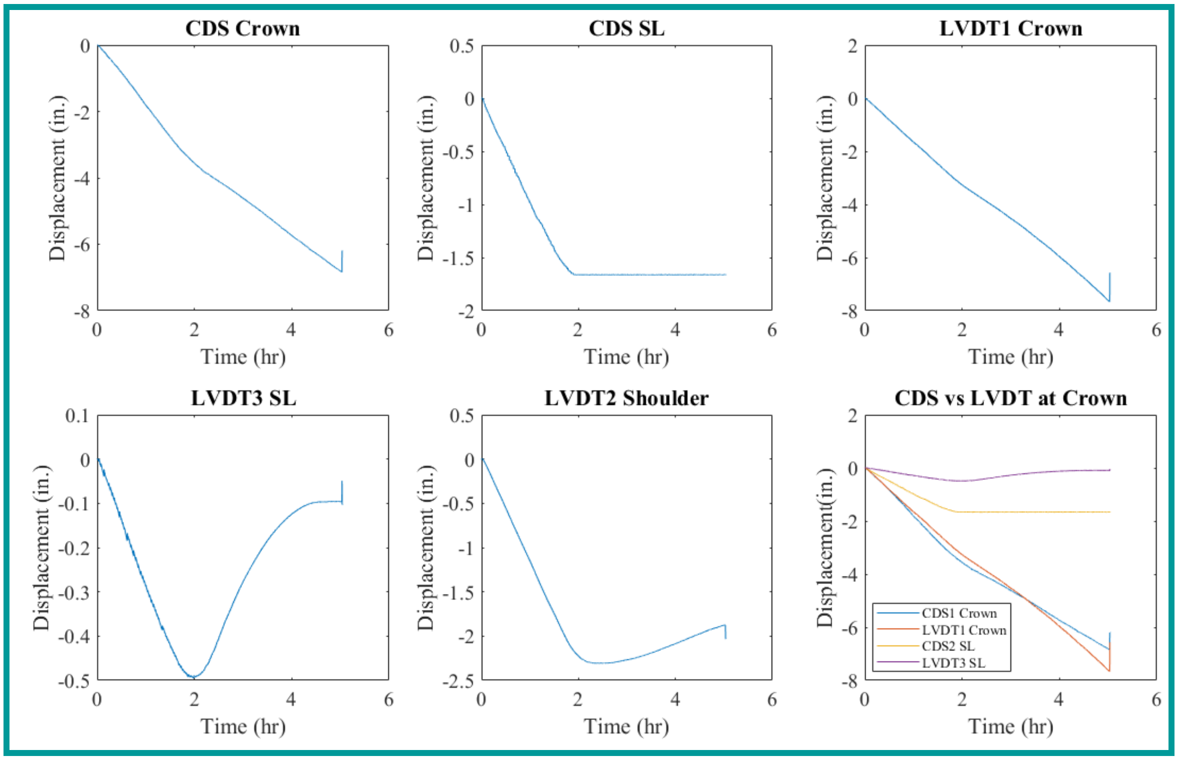

Figure A54: Results of LVDTs and CDSs at Different Locations – 60 in. Invert-cut Circular CMP. (Note: CDS for springline did not work properly).

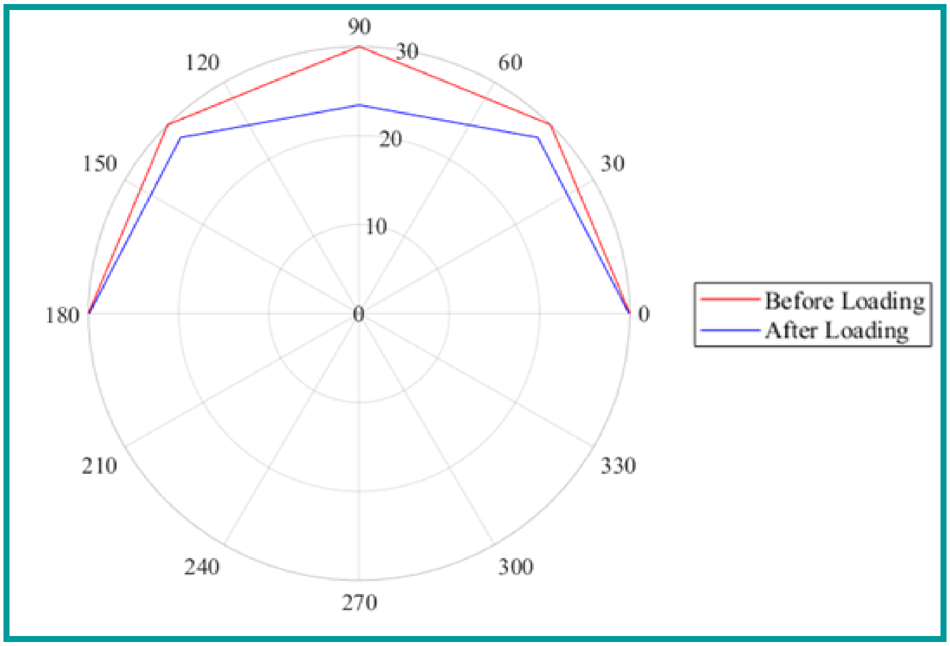

Figure A55: Pipe Profile at the end of the Test via LVDTs – 60 in. Invert-cut Circular CMP.

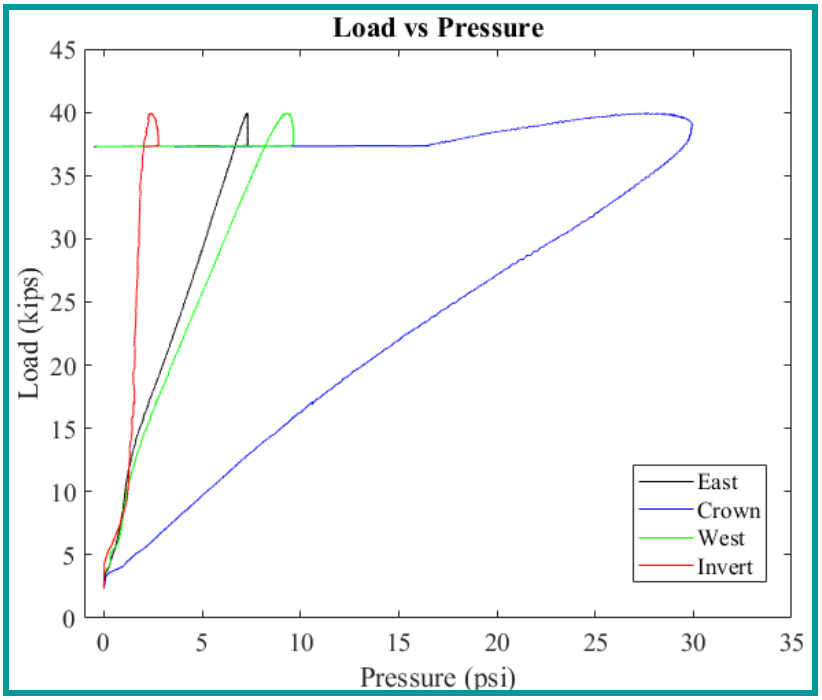

Figure A56: Vertical Load vs. Pressure around the 60 in. Invert-cut Circular CMP.

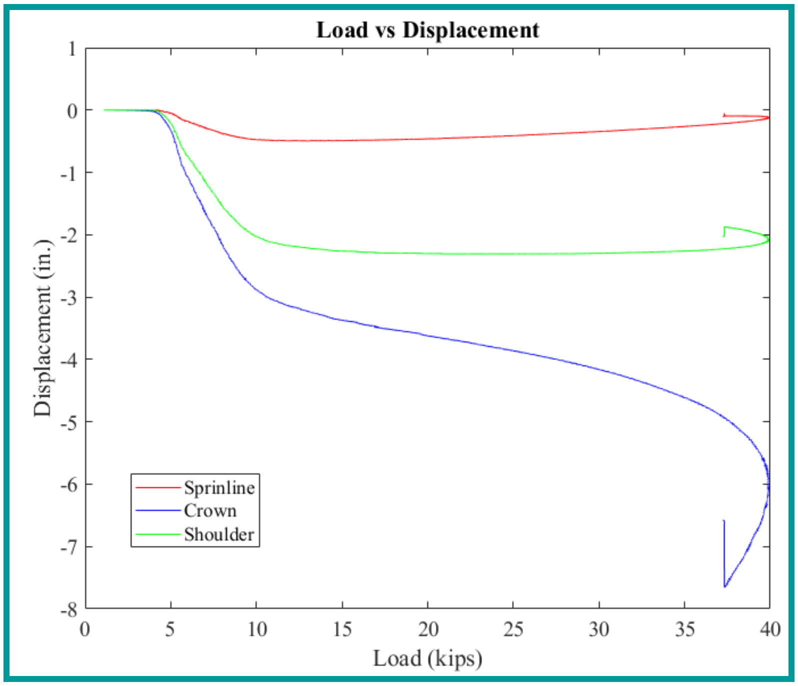

Figure A57: Displacement vs. Load at different Location Inside the 60 in. Invert-cut Circular CMP.

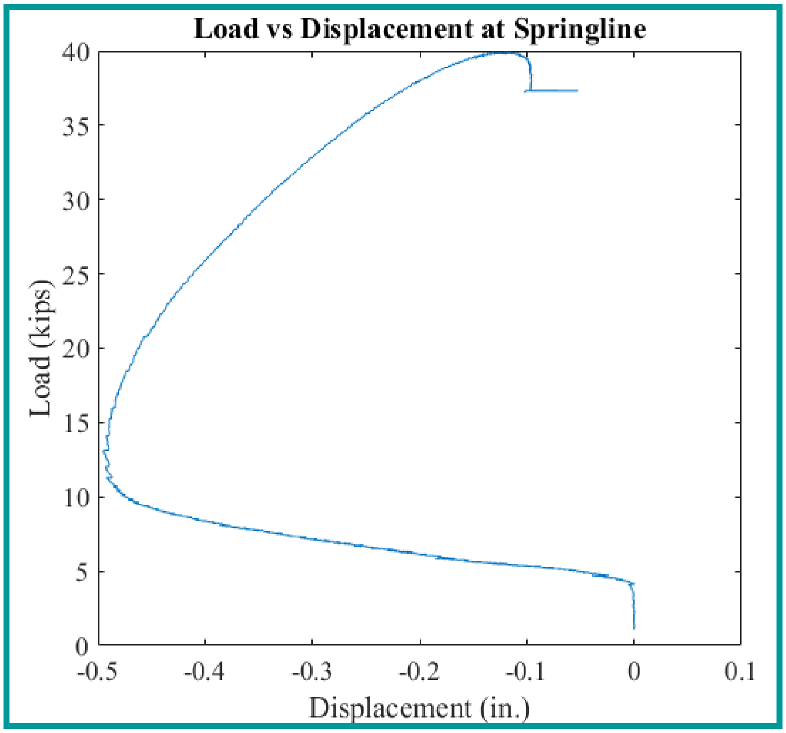

Figure A58: Load vs. Displacement for Springline – 60 in. Invert-cut Circular CMP.

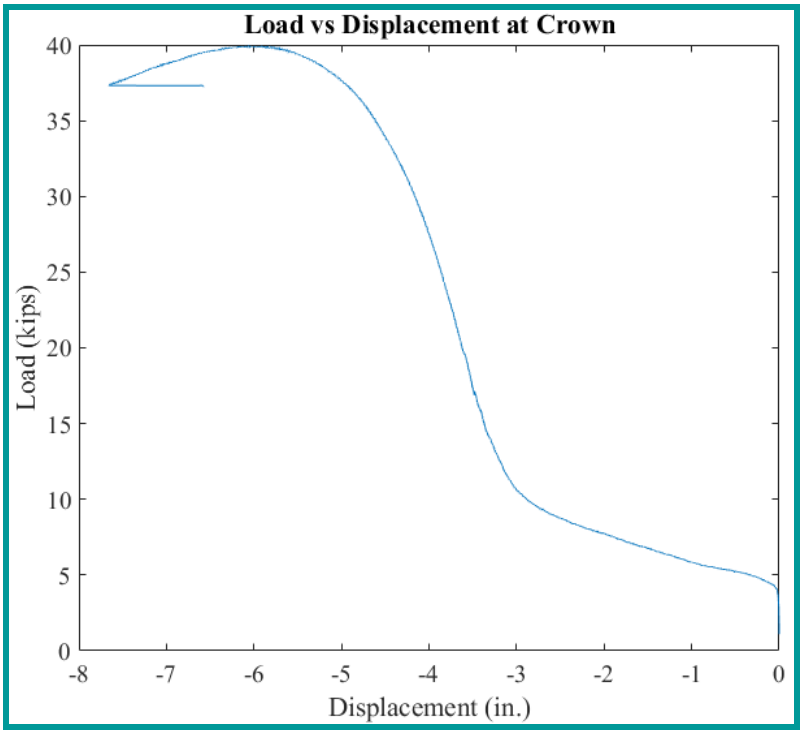

Figure A59: Load vs. Displacement for Crown – 60 in. Invert-cut Circular CMP.

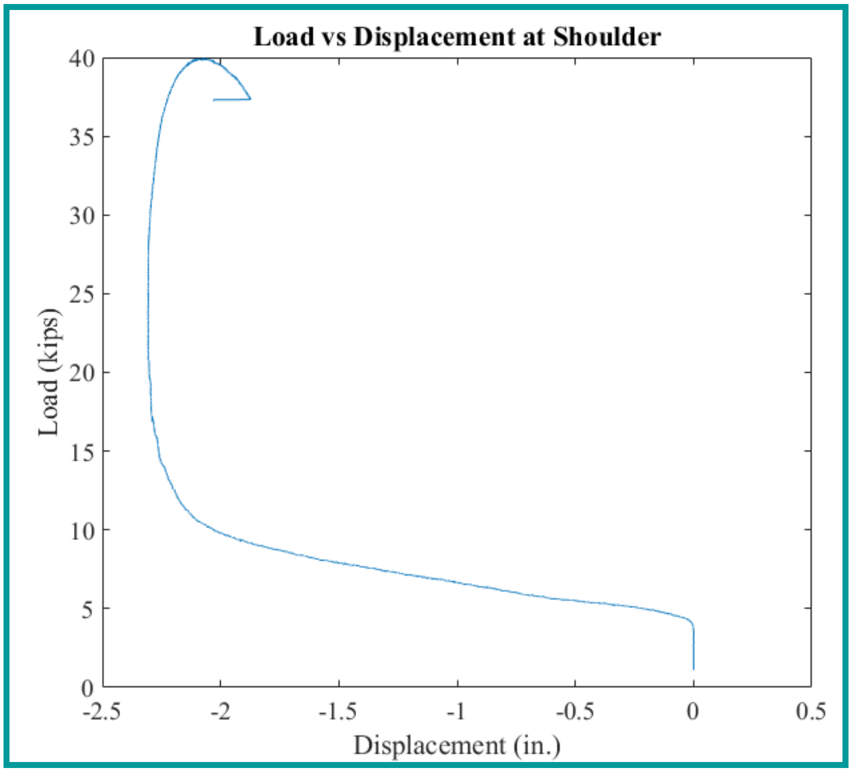

Figure A60: Load vs. Displacement for Shoulder – 60 in. Invert-cut Circular CMP.

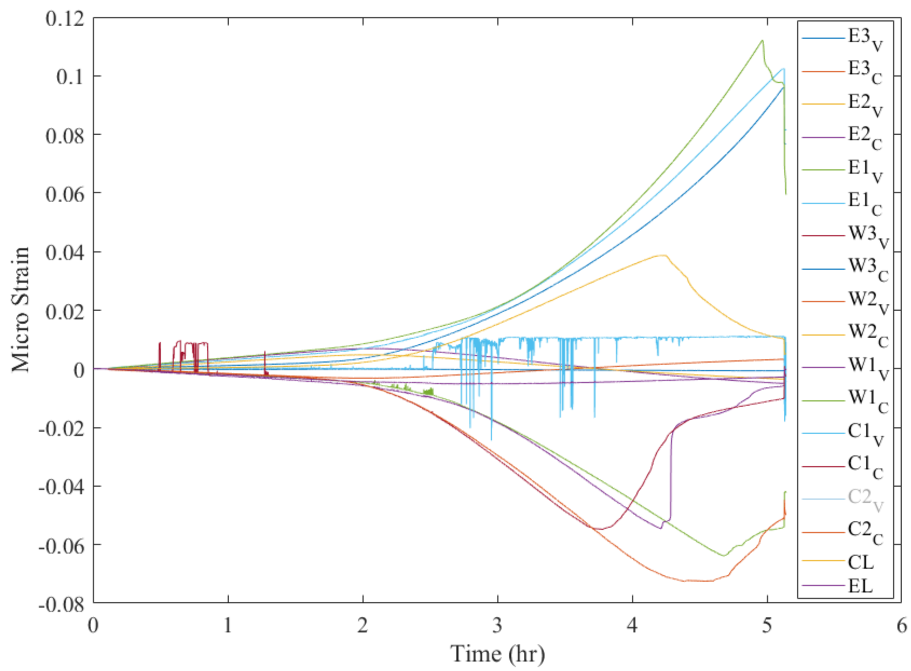

Figure A61: Strain Distribution (Middle Section) around the 60 in. Invert-cut Circular CMP.

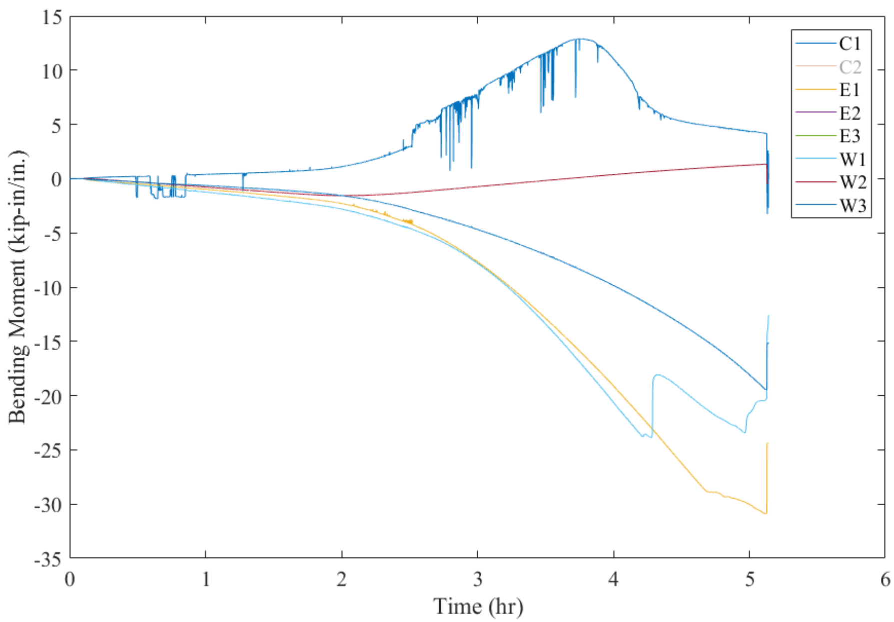

Figure A62: Circumferential Bending Moment – 60 in. Invert-cut Circular CMP.

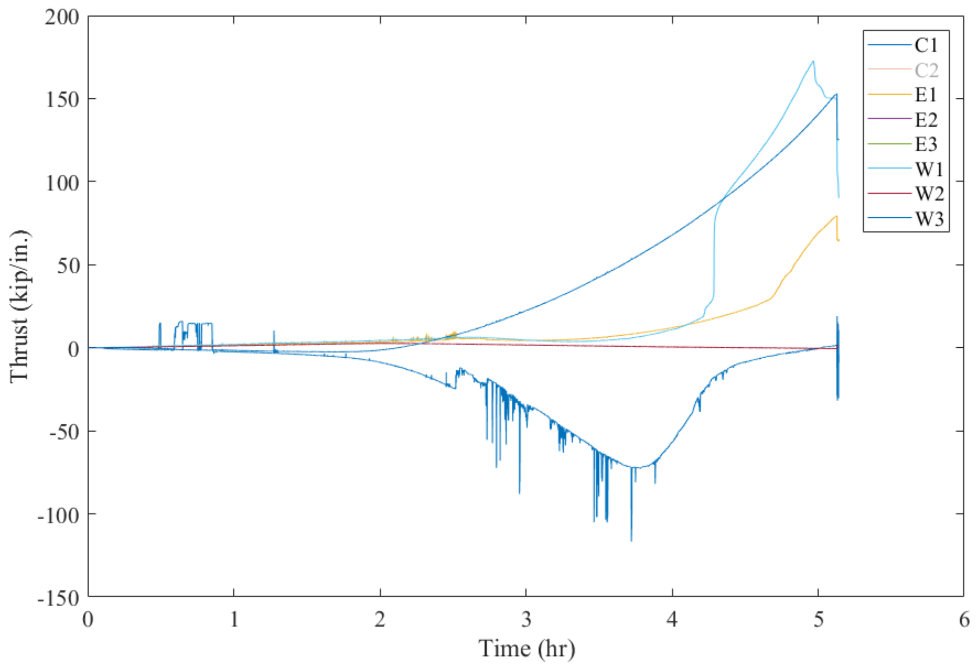

Figure A63: Circumferential Thrust Forces – 60 in. Invert-cut Circular CMP.

Appendix B

Finite Element Modeling

Structural Design Methodology for Spray Applied Pipe Liners (SAPLs) in Gravity Storm Water Conveyance Conduits

Task 10

Finite Element Modeling of Intact Circular Corrugated Metal Pipe (Draft Report)

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&
Samrat Raut
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Department of Civil Engineering
September 11, 2019

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1.0 Introduction

CURIE completed the first set of soil box tests on three bare CMPs, which include one intact circular CMP, one circular CMP with invert removed, and one intact arch CMP. The intact circular pipe was tested using the 10x20 in^2 load pad, while the invert-cut circular pipe was tested under the load pad size of 20x40 in^2. The switch of load pad size was to increase the bearing capacity of the soil as the soil was failed in punching shear failure before the bulking failure of the CMP pipe during the test on the intact circular CMP pipe. The larger load pad 20x40 in^2 was used to test the intact arch CMP pipe as well.

This report details the 3-D FEM model calibration and verification for the intact circular CMP pipe performed by our research team. The model shall be further developed to simulate the invert cut circular CMP pipe, which will be presented in the following quarterly report. The planed FEM modeling work is shown in Figure B1-1. This report presents the work on the modeling of intact circular CMP in the soil box.

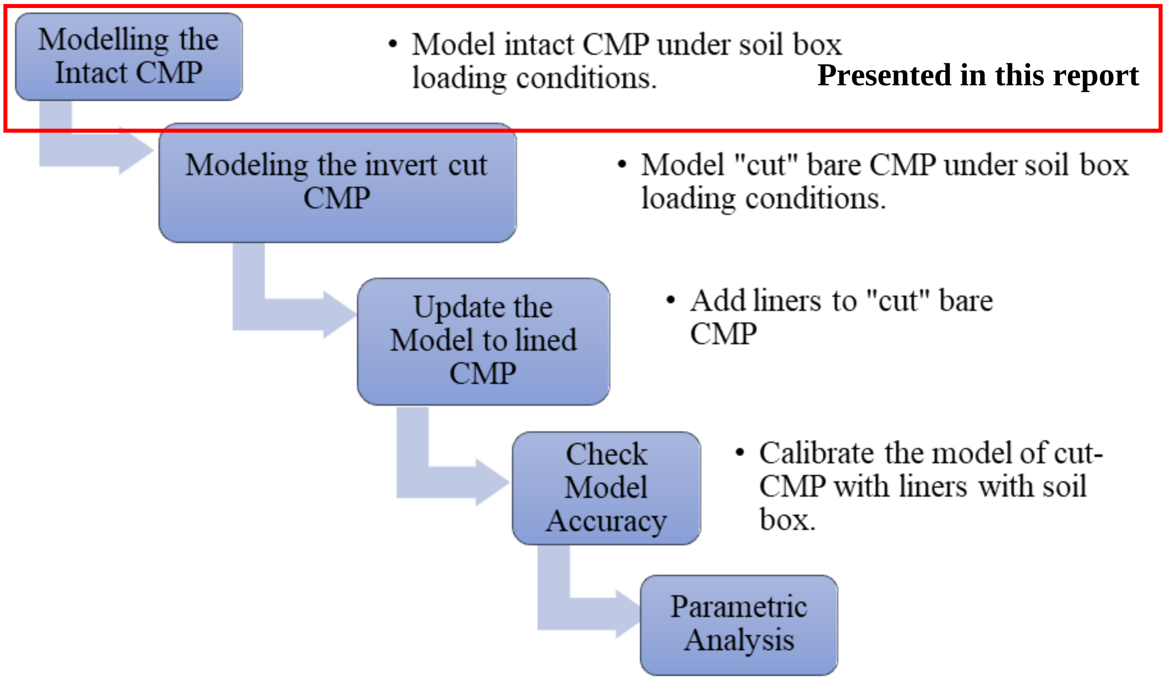


Figure B0-1 Planed FEM Modeling Work

2.0 Objective

The objective of this FEM modeling presented in this report is to calibrate the 3D FEM model of the intact circular CMP pipe and verify it with the measured bending moment, thrust, pipe deflection, and earth pressure.

3.0 FEM Model

3.1 Test Set-Up

The size of the partition cell for the circular CMP pipe is 6’x6’x 9’. A type of SP sand was used as the backfill soil, which consists of 2 ft. foundation and 5 ft. embedment and 1 ft. of sand cover. Additionally, a GP gravel was used for the top 1 ft. cover.

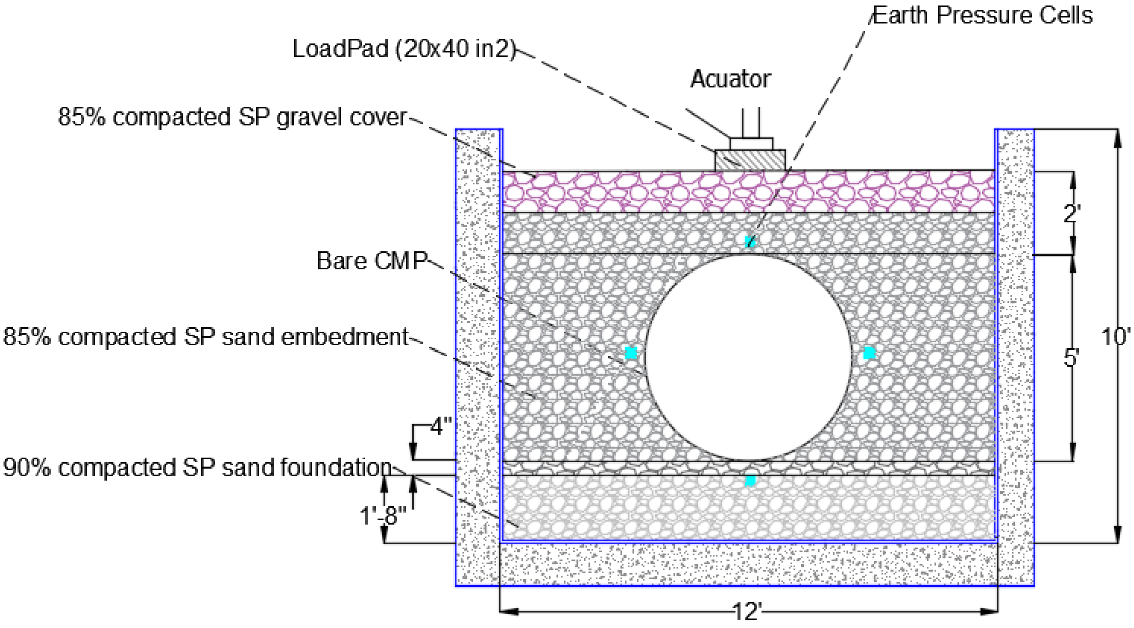


Figure B3-1:Sectional View of the Soil Box Set up

The soil box, including the intact circular CMP pipe, was model in ABAQUS. Two solid 3D parts were created in the ABAQUS model to represent the CMP pipe and the surrounding soil. The soil part was partition into two layers for the two soil types, SP and GP. Due to the complex geometry of the CMP profile, the 3D parts were created in third-party 3D modeling software and imported to ABAQUS. Due to the symmetry of the soil test cell, only half of the cell was created to reduce the computation time.

The pipe was modeled using shell element S4R while the soil was modeled using solid element C3D8R. For a comparison study, both solid elements and shell elements were used to model the CMP pipe. The model with shell elements provides results much closer to the experimental results than the model with solid elements. In this report, only the intact model is represented.

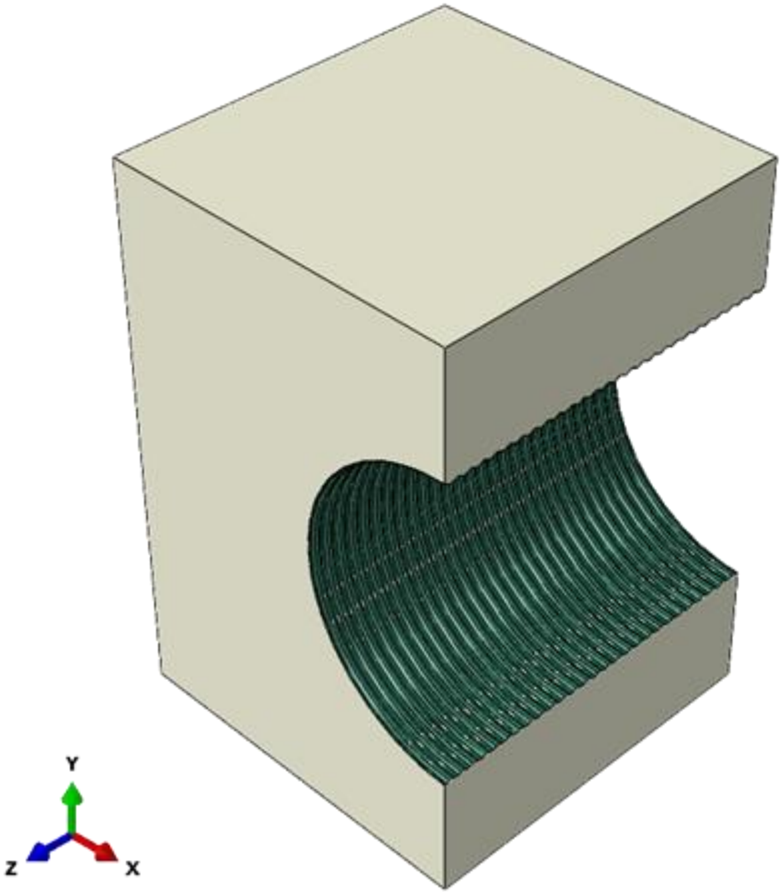


Figure B3-2 Model setup

3.2 Material Properties

i. Soil

Two types of soil: poorly graded sand (SP) and poorly graded Gravel (GP) classified according to ASTM D2487 were considered as the backfill and cover soils, respectively. The material properties used in the FEM model are listed in Table B1.

Drucker Prager Model, which is a three-dimensional pressure-dependent model, was used to model both sand and gravel. The property of the poorly graded sand was taken from the laboratory experiment carried at the geotech lab of UTA. The property of the poorly graded gravel (GP) was taken from Helwany (Helwany 2007). It is chosen as the representative soil properties that can be achieved with the selected soils in the soil box. The density used for the model was reduced to match the 85% compaction of the maximum dry density of the soil. Also, the soil Young’s moduli were chosen according to the ASTM D3839-14 considering the depth dependency of Young’s moduli. In the calibration process, the internal friction angle of the sand and gravel was adjusted slightly to better match the experiment results. The properties shown in Table B3-1 are the finalized values after the calibration process.

Table B3-1: Soil Properties

Property	Sand	Gravel
Density (pcf) (Max. dry density)	115	130
Young's Modulus (psi)	720	1100
Poisson Ratio	0.3	0.28
Angle of Friction	33.0	37.5
Dilation Angle	1	2

ii. CMP

The intact circular CMP pipe is made of corrugated steel sheets conforming to ASTM 929 with yield strength 33 ksi and ultimate strength 45 ksi. The modulus of elasticity of the steel is 29,000 ksi. The elastic-plastic model available in Abaqus was used to model the behavior of CMP steel.

Table B3-2 Properties of the steel

Property	Value
Density (lb./in3)	0.284
Elastic Modulus	29,000,000
Poisson’s Ratio	0.3
Yield Stress (psi)	33,000
Ultimate Stress	45,000

3.3 Boundary Conditions and Element Type

Half of the soil cell is modeled considering symmetry along the YZ- plane (as shown in Figure B3-3) with following boundary conditions:

- Restrained for the longitudinal movement in the front and back sides of the model domain.
- The bottom of the model is restrained from the vertical movement.
- The sides of the model are restrained from the horizontal movement.

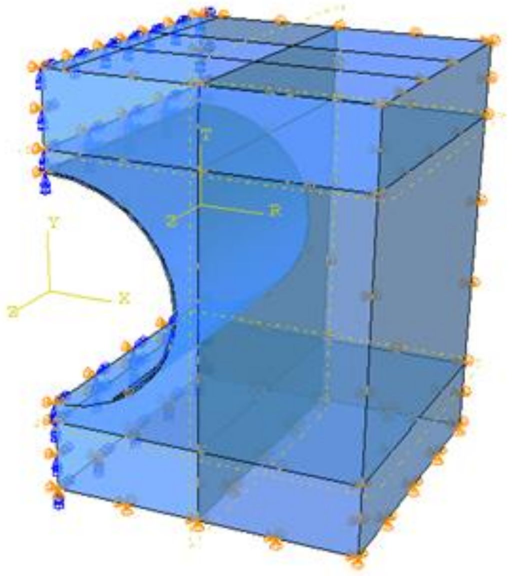


Figure B3-3: 3D-Model of the Soil Box for Boundary Condition

Hexahedral element, 8 nodes linear brick, reduced integration (C3D8R) solid elements are used to model the soil and 4-node doubly curved thin or thick shell, reduced integration (S4R) shell elements are used to model the CMP pipe.

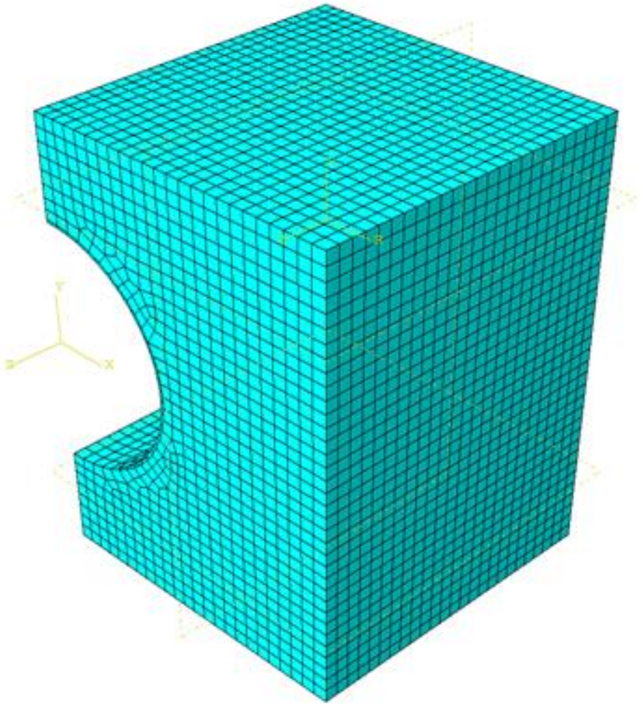


Figure B3-4: Meshed Soil Box

3.4 Interaction

One of the most essential parts of modeling the buried pipes in the soil is the interactions between the pipe and the soil. ABAQUS allows the user to define different interaction models for the interface between the pipe and soil. In this model, the interaction between the pipe and soil interface is represented using the surface-to-surface contact model where the pipe is treated as the master surface and the soil is treated as the slave surface. Considering the corrugated surface of the pipe a rough friction coefficient of 0.75 is defined between the CMP and soil, and the contact is defined as a hard contact i.e., the pipe does not “pierce” the soil but displaces it. This friction coefficient was the result of the optimization of the numerical results.

3.5 Model steps

The modeled was analyzed using the following steps in the ABAQUS. All the steps were defined for the static condition.

a. The first step was the activation the soil load which can also be referred as the geostatic step. The stage compaction process was not modeled. Instead, the entire soil profile was activated in one step.
b. Secondly, the gravity load of the pipe was activated, and the interaction between the soil and the pipe was established.
c. Lastly, the external load from the actuator was applied to the system using displacement-controlled method.

3.6 Mesh Sensitivity analysis

The finite element method approximates the unknown function over the domain. The domain was divided into small elements represented by the element nodes. The number of elements, i.e. element size, for the modeling domain dramatically affects the results from the analysis. If the size of the element is coarser, the model could become stiffer and yield inaccurate results, while the finer elements lead to more accurate results with the cost of computation time. Hence selecting the proper mesh size is one of the essential steps in the FEM analysis in order to make the model independent of the mesh size.

To determine the mesh sensitivity of the model, total energy, load-displacement for soil and pipe, and the Von Mises stress for the pipe were compared among the mesh sizes of 3.4, 3, 2.4 inches. For the soil, the differences in the values of plastic strain and load-displacement didn’t vary by a significant amount for mesh sizes 3.4, 3, 2.4 inches.

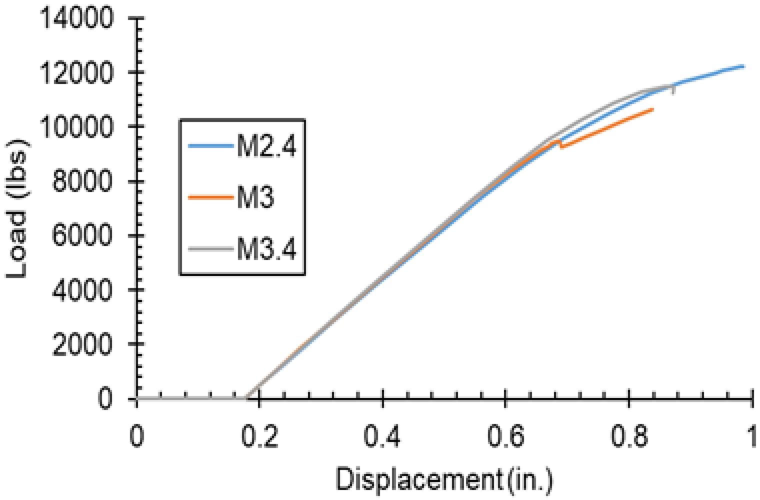


Figure B3-5 Load displacement plot for the soil

From Figure B3-5, Figure B3-77, Figure B3-88, the mesh size for the soil was taken as 2.4 in., while the mesh size of 1.5 in. was taken for pipe. Though mesh size of 2.4 in. could be adopted for the soil, but due to compatibility of the mesh sizes for the soil and the pipe, the mesh size for the soil in the vicinity of the pipe was chosen to be 1.5 in. (*Figure B3-6*).

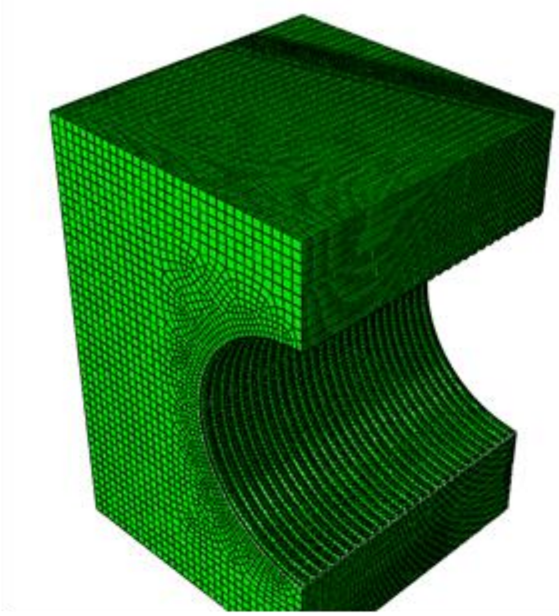


Figure B3-6 Mesh size distribution in the soil

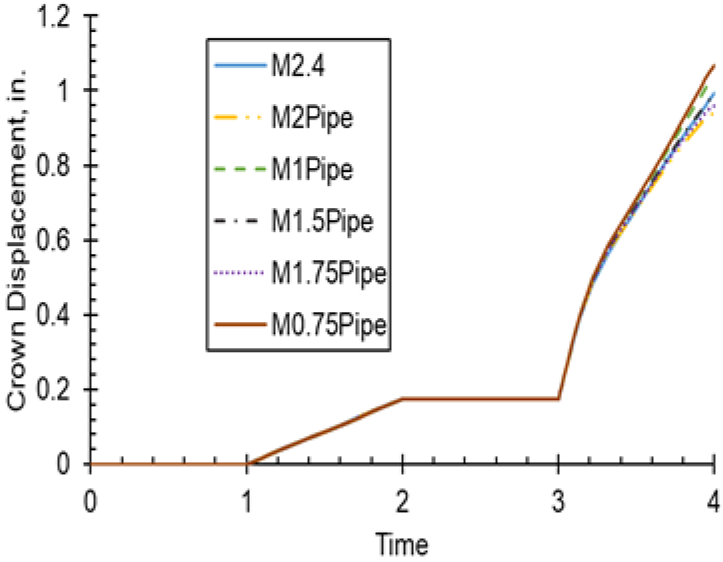


Figure B3-7 Load displacement plot for the pipe at the crown

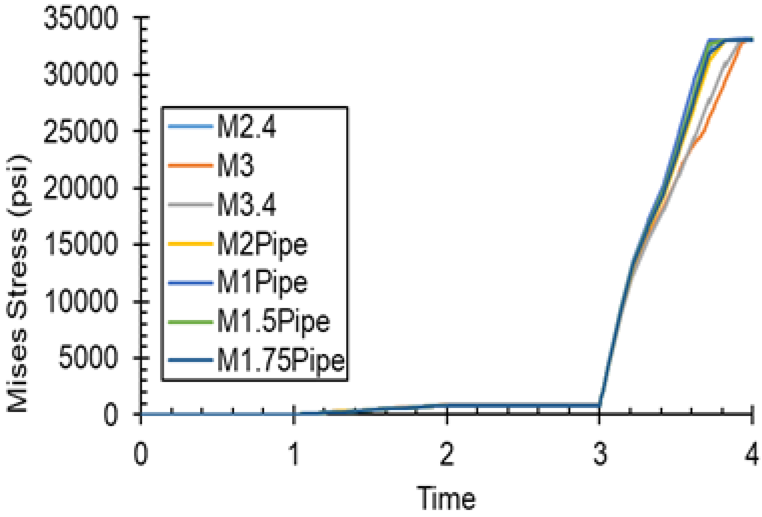


Figure B3-8 Von Mises Stress in the pipe

4.0 Results

4.1 Intact CMP

Before testing the lined pipes, the performance of the bare intact pipe and invert cut pipe are needed to provide the baselines. The test of the intact circular pipe was carried out first and then followed by the test on the invert-cut arch and circular pipe. The intact circular pipe was loaded using the 10x20 in^2 load pad. The FE element modeling of the laboratory test on intact CMP was performed using Abaqus according the steps mentioned in previous sections. The FE model was able to predict the pipe soil behavior until there was the failure of one system. In our model also, in accordance with the experimental results, the soil failed first before any significant deformation in the pipe. The development of the significant plastic strain in the loaded area could be seen in the model too. (Figure B4-1)

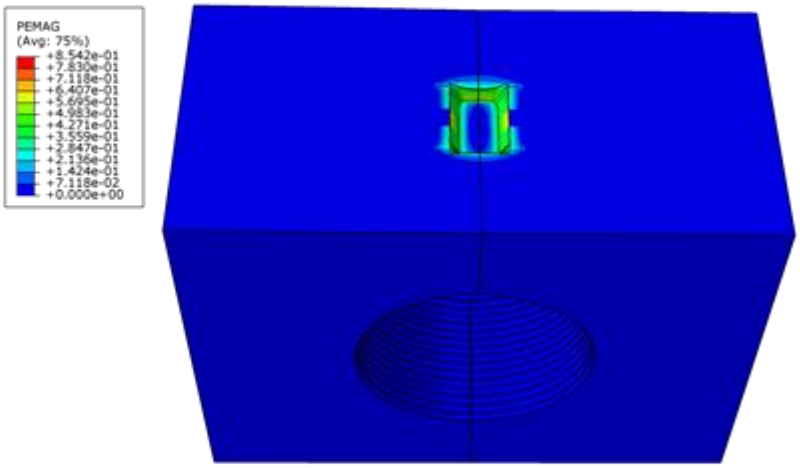
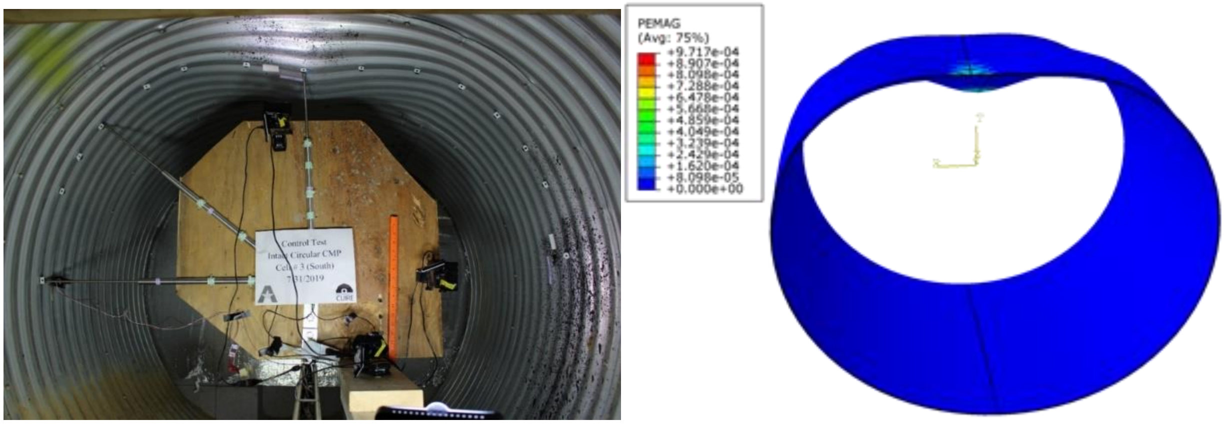
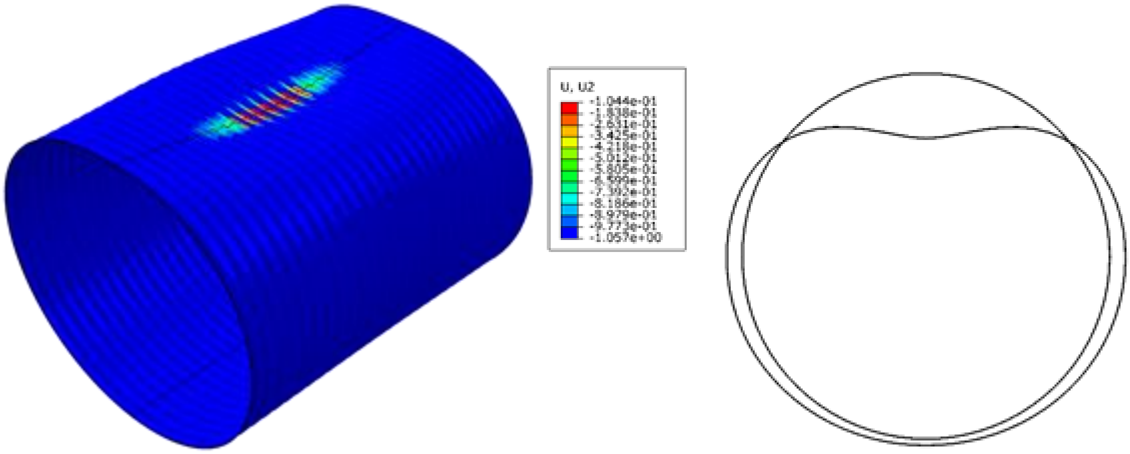


Figure B4-1 Plastic strain due to the soil failure in the loaded area

The FE model predicts the failure of the pipe in the local buckling which was observed in the experimental result too. In the test local buckling was observed in the crown region of the pipe, which was matched by the FEM results.



(a) (b)



(c) (d)

Figure B4-2 Plastic strain and deflection pattern in CMP (a) Experimental Result (b)(c),(d)FEM Result (scaled up)

4.1.1 Load-displacement plot

The load-displacement curve was plotted to investigate the behavior of the pipe under the applied load. The displacement shown in the plot only considers the displacement due to the external load and excludes the displacement due to the geostatic load or dead load due to backfill cover. The displacement obtained from the FEM model is taken at the crown of the pipe similar to the experimental setup in which LVDTs read the displacement of the crown only (Figure B4-5, Figure B4-6). The displacement plot is obtained with the maximum applied displacement at the load pad as 5 inches.

In the experiment (Figure B4-3, Figure B4-4) even after the cover soil failed, the experiment was continued, and as the pipe shared more load, the load-displacement curve rose again and dropped after the pipe buckled. However, this second rise could not be modeled using FEM as once the cover soil fails, any further increase in load causes large displacements, which cannot be defined by the soil model used, and hence, the FE model fails to converge.

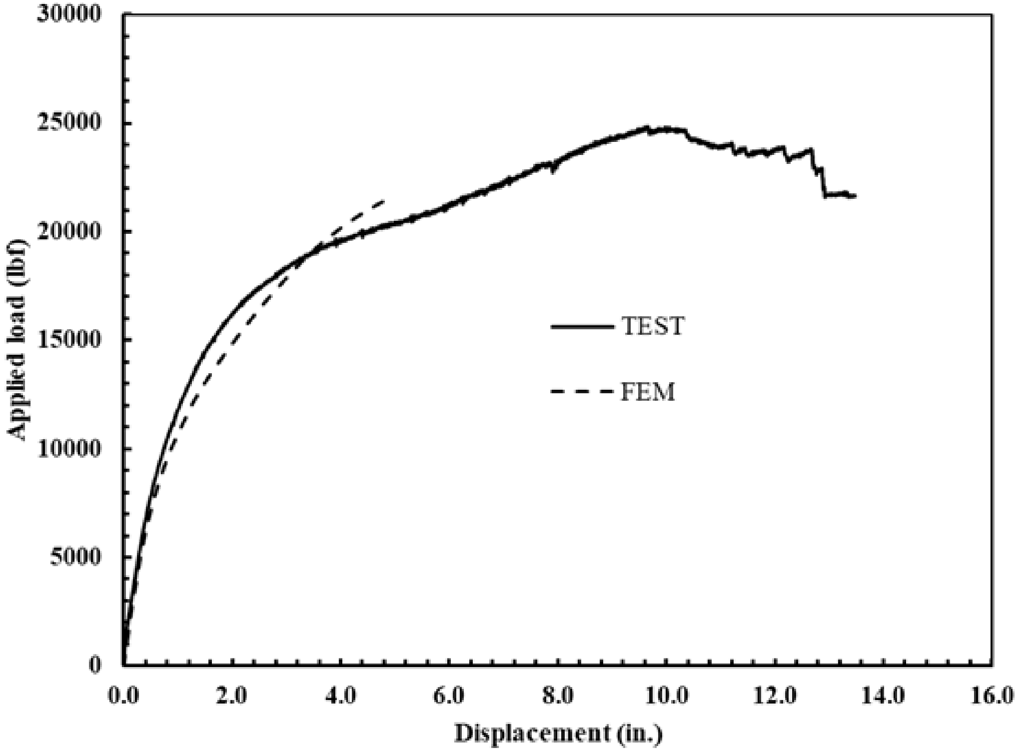


Figure B4-3 Load Displacement curve for soil

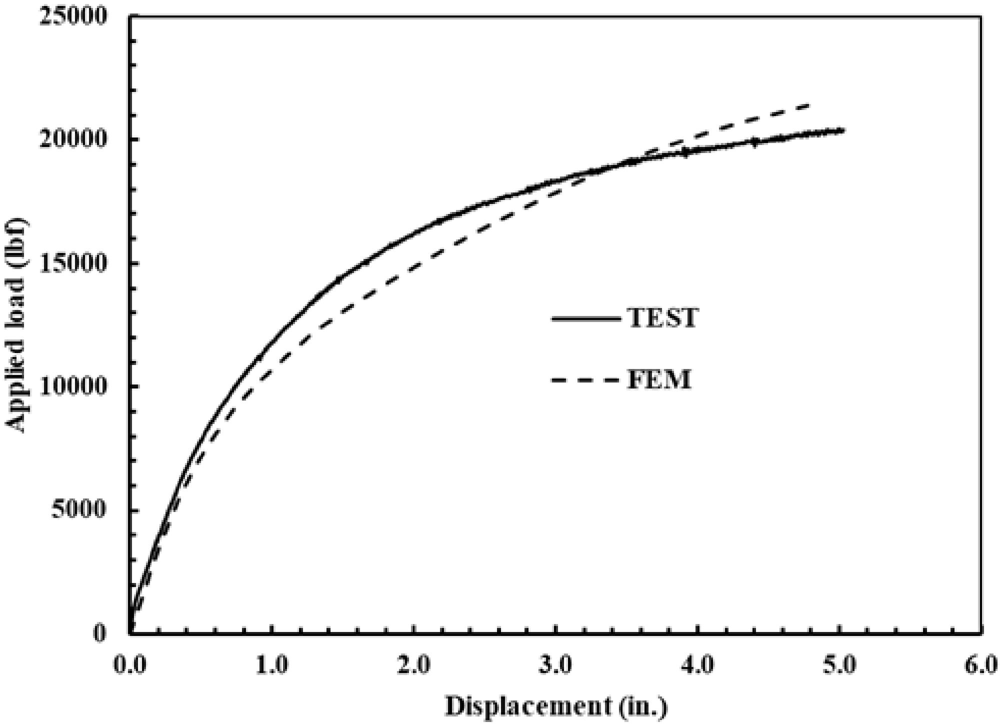


Figure B4-4 Load Displacement curve for soil at 5 in. displacement of soil

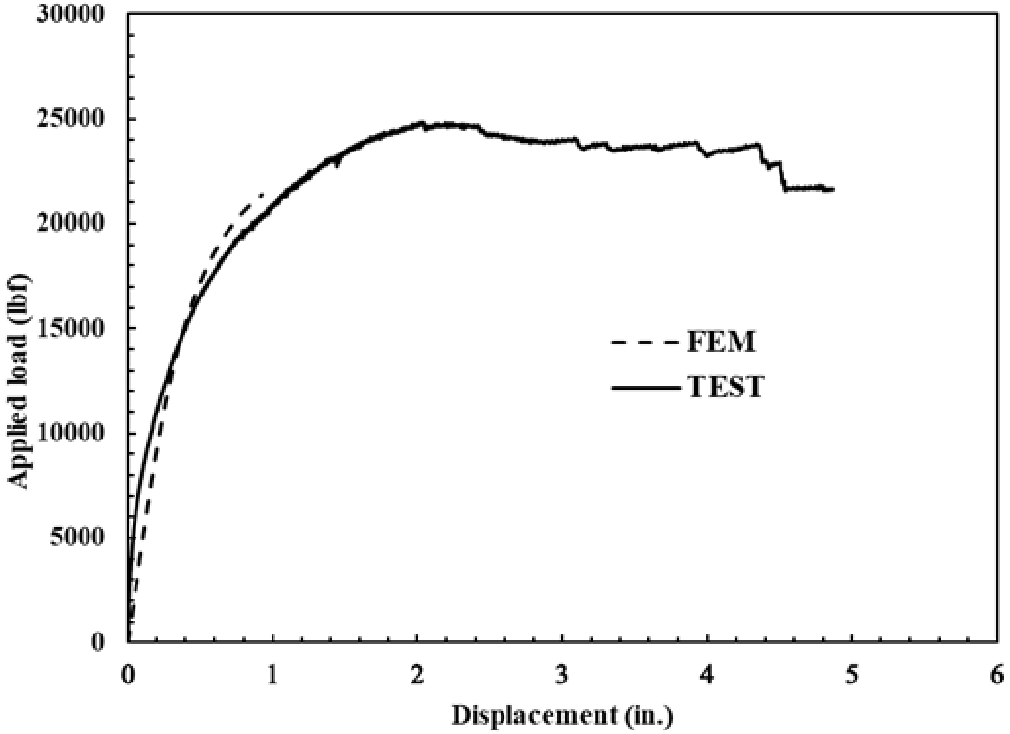


Figure B4-5 Load Displacement curve for pipe

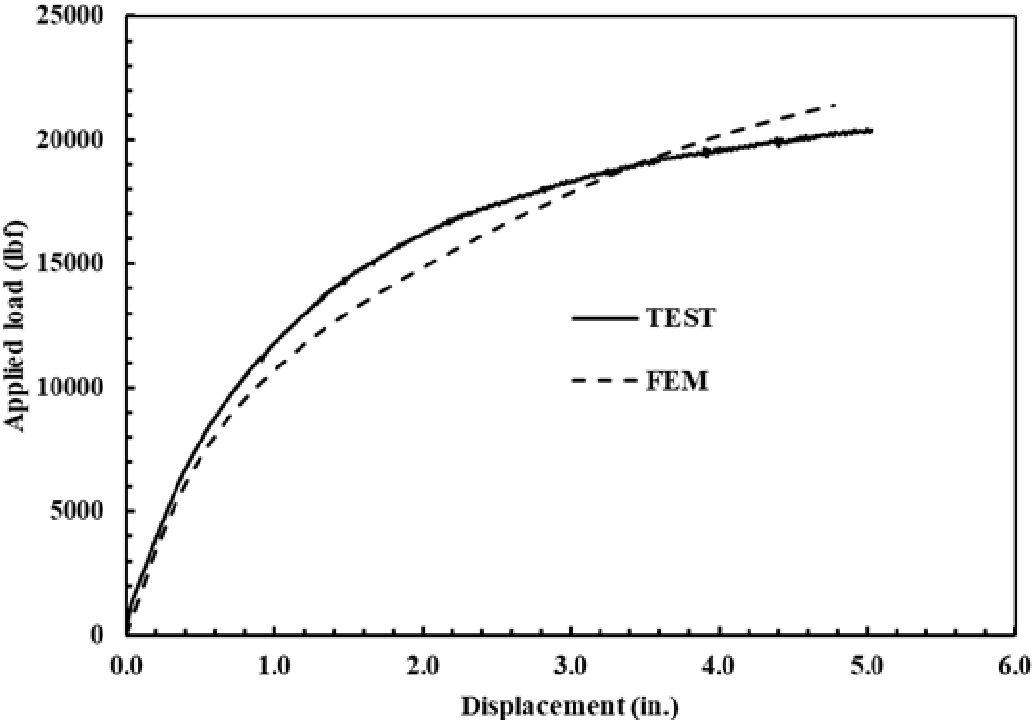


Figure B4-6 Load Displacement curve for pipe at 5 in. displacement of soil

The load vs. displacement plot shows a good match between the experimental and FEM results. The discrepancy between the load at the 5 in. displacement of soil for the experiment and FEM is about 5 %, while the discrepancy between the pipe crown displacement in the experiment and FEM is about only 1.5 % (Table B4-1).

Table B4-1 Comparison of the results from FEM and Experiment

Model	**Applied Displacement of soil (in.)**	**Maximum Applied Load (kips)**	**Max. vertical displacement of pipe at the crown**	**Discrepancy in displacement (%)**	**Discrepancy in load (%)**
Experimental	5	20.43	0.93		
FEM	5	21.4	0.92	1.08	4.75

4.1.2 Bending moment and thrust

The bending moment obtained from the finite element model at the end of analysis was compared with the bending moment obtained from the laboratory test at the same load/displacement level. Both bending moments and thrusts at the different locations showed good match with the experimental results.

The bending moments were compared when there was 5 in. displacement of soil at both FEM and Experimental results as shown in Figure B4-7. Except at the crown, the bending moment at the other positions show fair comparison. The maximum bending moment at the crown is 7.1 kip-in/in for experiment while from FEM it is calculated to be at 4.53 kip-in/in. Since the plastic deformation is seen at the crown at the 5 in. displacement of soil, so the bending moment theory may not be applied after the material is yielded. For that reason, bending moment at different load levels, before any plastic deformation, was calculated and the comparison was made. It is found (Figure B4-8) that even at the crown at the load levels of 5 and 10 kips the bending moment for experimental and FEM matches well (Table B4-2).

Also, the thrust around the pipe was calculated and the results are compared at the 5 in. displacement of the soil (Figure B4-9). The results showed fair comparison for the thrust except at the crown. The thrust is also plotted at the different levels of the loads, and good match was found between the FEM and experimental results (Figure B4-10, Table B4-3).

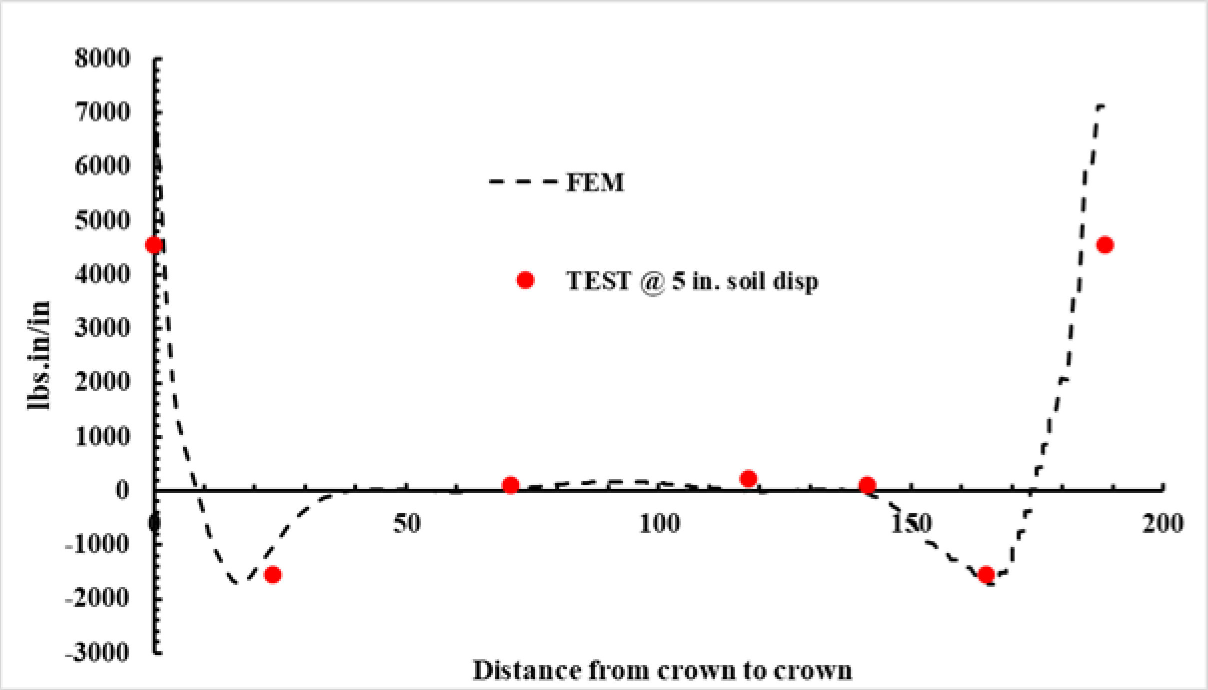


Figure B4-7 Bending Moment comparison at the 5 in displacement of soil

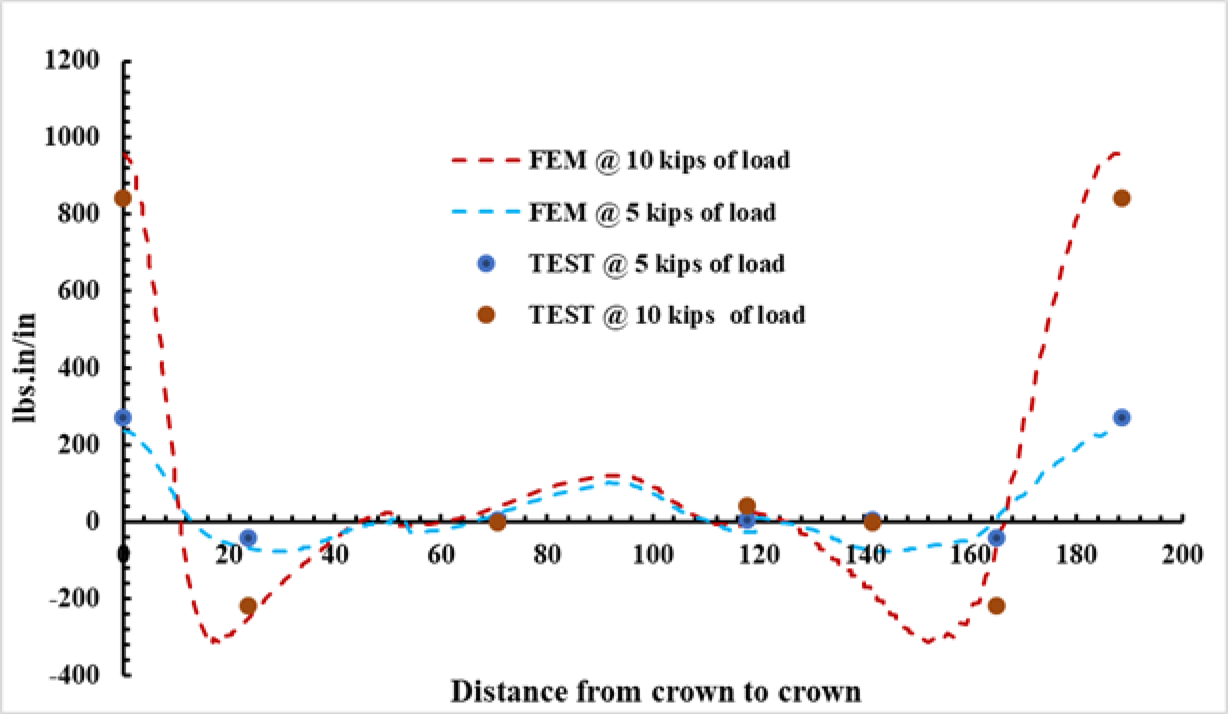


Figure B4-8 Bending moment comparison at 5 and 10 kips of load

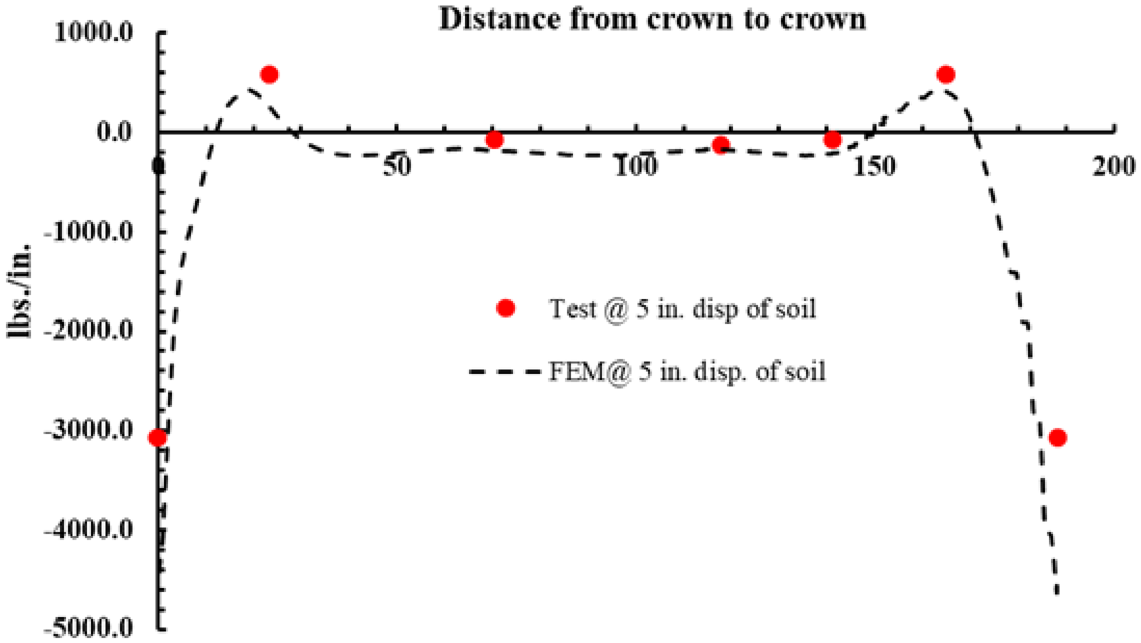


Figure B4-9 Thrust comparison at 5 in. displacement of soil

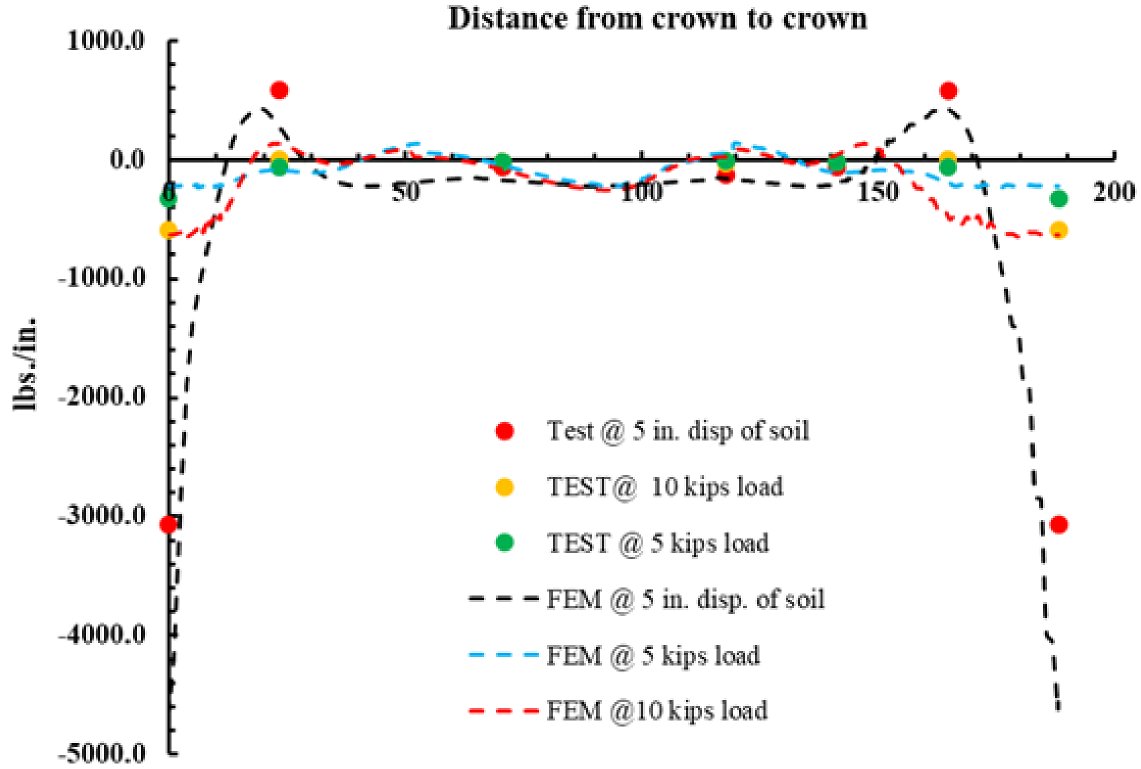


Figure B4-10 Thrust comparison at 5 and 10 kips of load

Table B4-2 Bending moment distribution at different position

Bending Moment @5 in. displacement of soil		
Position	**Experiment (lbs.in/in.)**	**FEM (lbs.in/in.)**
Crown	4537.968	7127.2
Shoulder	-1552.75	1680.38
Spring line	88.4	80.08
Haunch	213.4	180.34

Bending Moment @ 10 kips of load		
Position	**Experiment (lbs.in/in.)**	**FEM (lbs.in/in.)**
Crown	843.8	956.99
Shoulder	-218.7	243.56
Spring line	-1.9	-2.82
Haunch	42.8	36.58

Bending moment @ 5 kips of load		
Position	**Experiment (lbs.in/in.)**	**FEM (lbs.in/in.)**
Crown	271.5	326.74
Shoulder	-40.1	-99.04
Spring line	4.6	9.98
Haunch	5.6	4.5

Table B4-3 Thrust distribution at different positions

Thrust @ 5 in. displacement of soil		
Position	**Experiment (lbs/in.)**	**FEM (lbs/in.)**
Crown	-3074.03	-4559.08
Shoulder	663.40	407.34
Spring line	-82.93	-177.23
Haunch	-142.7	-174.62

Thrust @ 10 kips of load		
Position	**Experiment (lbs/in.)**	**FEM (lbs/in.)**
Crown	-597.835	-760.58
Shoulder	0	112.45
Spring line	-26.999	-59.42
Haunch	-34.713	27.13

Thrust @ 5 kips of load		
Position	**Experiment (lbs/in.)**	**FEM (lbs/in.)**
Crown	-327.5	-289.558
Shoulder	-65.5	-91.80
Spring line	-25.26	-37.23
Haunch	-11.51	94.91

4.1.3 Earth Pressure Distribution

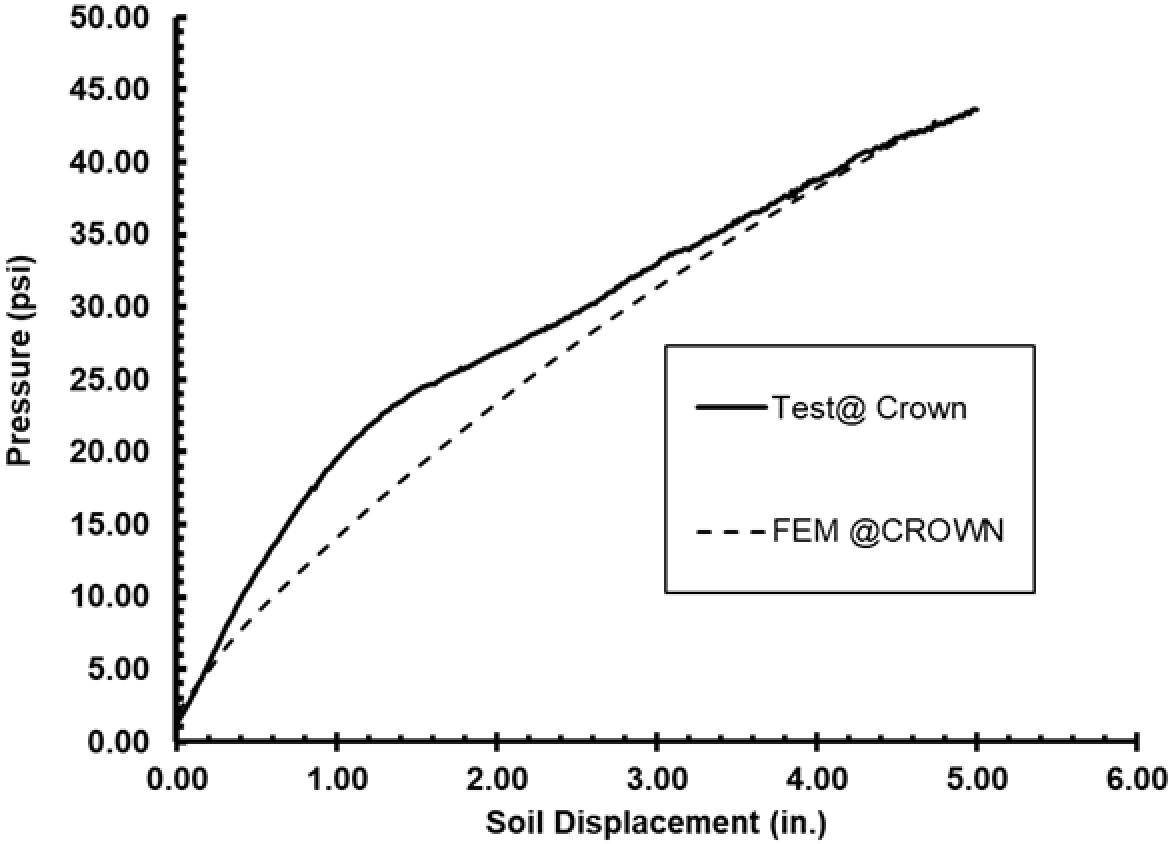


Figure B4-11 Earth pressure distribution just above the crown of the pipe

The earth pressure variation at the crown level of CMP obtained from earth pressure cell was compared with the variation of earth pressure at a similar location in the FE model. It is observed that (Figure B4-11) the FE model seems to predict the vertical stress at crown level well. The comparison was not made for earth pressures at springline and invert level as the regions showed extremely low measure pressure and the accuracy of the earth pressure cells at this range is low.

5.0 Conclusions

From the FEM results and its comparison with the experimental results, the following conclusions can be drawn.

a. The calibrated FEM model can predict well the load-soil displacement at the load pad, the pipe deformation, bending moment and thrust of the pipe, and the soil pressure.

b. The FEM model is validated until the soil fails. The post-failure behavior of the pipe past 5-inch soil displacement was not considered due to the complexity of the soil behavior involving large plastic flow of soil. At the end of the modeling step, the buckling of CMP pipe was observed in the FEM model.

6.0 Future Work

The finite element modeling of the intact pipe is now fully calibrated. The FEM work on the invert cut circular, and arch CMP are to be continued and will be reported in next quarterly report.

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